SIMULAÇÃO NUMÉRICA DO COMPORTAMENTO AO FOGO DE ESTRUTURAS MISTAS (LAJES)

Lucas Mognon Santiago Prates

Dissertação apresentada à

Escola Superior de Tecnologia e Gestão

Instituto Politécnico de Bragança

Para a obtenção do Grau de Mestre em

Engenharia da Construção

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Orientado por:

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À minha família,

Pelo apoio e amor incondicional.

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RESUMO

Este trabalho investiga o comportamento térmico de lajes mistas de aço e concreto com perfil de chapa colaborante sob condições controladas de acidente, correspondendo a um incêndio a atingir a superfície inferior. Esta solução mista consiste em uma cobertura de concreto no topo de um perfil de aço. O concreto é normalmente reforçado com uma malha de aço e também pode conter vergalhões individuais. O deck ou chapa colaborante também atua como reforço e consequentemente pode ser exposto a condições acidentais de incêndio.

Esta solução mista é amplamente utilizada em todos os tipos de edifícios e requer resistência ao fogo, de acordo com os regulamentos e normas. As lajes mistas precisam atender aos requisitos de segurança contra incêndio de acordo com os códigos de construção. A avaliação ao fogo deste tipo de elementos é normalmente feita utilizando testes de incêndio padrão.

Duas amostras foram preparadas para serem testadas e devem levar em consideração os critérios de estabilidade (R), Integridade (E) e isolamento (I). O objetivo desta investigação diz respeito à classificação de incêndio para o isolamento (I). A classificação de incêndio para isolamento (I) é avaliada por três métodos diferentes (simulação numérica, método simplificado e ensaios experimentais).

A simulação numérica foi realizada através da biblioteca de equações as derivadas parciais do Matlab e também através do programa ANSYS, considerando os efeitos térmicos da exposição a um fogo padrão. A resistência ao fogo é calculada para 196 configurações geométricas diferentes, sendo assim, 394 simulações numéricas foram realizadas a fim de avaliar o efeito da espessura da camada de concreto e da espessura da chapa colaborante de aço. A resistência ao fogo (I) aumenta com a espessura do concreto, de acordo com os resultados obtidos em ambos os métodos. Os resultados numéricos também são comparados com os ensaios experimentais e comparados com o método simplificado proposto no anexo D do Eurocódigo 4 e pela NBR 14323, que parecem estar inseguros.

Palavras-chave: Lajes mistas; Resistência ao fogo; Isolamento; Simulação Numérica; Ensaios experimentais.

ABSTRACT

This study investigates the thermal behaviour of composite steel and concrete slabs with profile steel deck under standard fire conditions corresponding to a fire from the bottom. This composite solution consists of a concrete topping cast on the top of a steel deck. The concrete is typically reinforced with a steel mesh and may also contain individual rebars. The deck also acts as reinforcement and may be exposed to accidental fire conditions from the bottom.

This composite solution is widely used in all types of buildings and requires fire resistance in accordance to regulations and standards. Composite slabs need to meet fire-safety requirements according to building codes. The fire assessment of this type of elements is normally done using standard fire tests.

Two samples were tested and should take into account the criterion for stability (R), Integrity (E) and insulation (I). The fire rating for (R) and (E) is not in the scope of this investigation. The fire rating for insulation (I) is evaluated by three different methods (numerical simulation, simple calculation and experimental tests).

Numerical simulation was performed using Matlab partial differential equation toolbox and by the software ANSYS, for the thermal effects of standard fire exposure. The fire rating is calculated for 196 different geometric configurations, therefore, 394 simulations were performed in order to evaluate the effect of the thickness of the concrete layer and the thickness of steel deck. The fire resistance (I) increases with the thickness of the concrete, according to the results obtained with both methods. The numerical results are also compared with the simplified method proposed in the Annex D of Eurocode 4 and the Brazilian standard NBR 14323:2013, which appears to be unsafe.

Keywords: Composite slabs; Fire resistance; Insulation; Numerical simulation, Experimental tests.

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NOTAÇÕES

Letras latinas

c_a	Calor específico do aço.
c_p	Calor específico do concreto.
$c_{p,peak}$	Pico do calor específico do concreto a uma determinada umidade.
$\dot{h}_{net}$	Fluxo de calor por unidade de área.
$\dot{h}_{net,c}$	Fluxo de calor por unidade de área por convecção.
$\dot{h}_{net,r}$	Fluxo de calor por unidade de área por radiação.
h	Profundidade ou altura da seção de aço.
h_1	Altura da parte de concreto de uma laje mista acima do deck.
h_2	Altura da parte de concreto de uma laje mista dentro do deck.
h_3	Espessura da betonilha situada no topo do concreto.
h_{eff}	Espessura efetiva de uma laje mista.
l_1, l_2, l_3	Dimensões específicas do perfil de chapa de aço reentrante ou do perfil de aço trapezoidal
u	Teor de umidade.
t	Duração da exposição ao fogo.

Letras gregas

α_c	Coeficiente de transferência de calor por convecção.
θ_a	Temperatura do aço.
θ_c	Temperatura do concreto.
θ_g	Temperatura do gás ao redor do membro exposto.
θ_m	Temperatura da superfície do elemento exposto ao fogo.
θ_r	Temperatura de radiação efetiva do ambiente de incêndio.

σ	Constante de Stefan-Boltzmann.
ε_f	Emissividade do fogo.
ε_m	Emissividade da superfície do elemento.
ϕ	Fator de forma.
ϕ_{inf}	Fator de forma do banzo inferior do elemento.
ϕ_{sup}	Fator de forma do banzo superior do elemento.
ϕ_{alma}	Fator de forma da alma do elemento.
λ_a	Condutividade térmica do aço.
λ_c	Condutividade térmica do concreto.
ρ_a	Massa específica do aço.
ρ_c	Massa específica do concreto.

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1 INTRODUÇÃO

Segundo R.M Lawson [1], lajes mistas com chapas colaborantes compreendem decks (ou lâminas) de aço perfilados como a fôrma permanente na parte inferior das lajes de concreto que se estendem entre as vigas de suporte. O deck age de forma conjunta com o concreto sob uma carga de serviço. Ele também suporta as cargas aplicadas antes que o concreto atinja sua resistência final. Uma malha leve de aço de reforço é normalmente colocada no concreto garantindo assim sua integridade e garante a distribuição das cargas aplicadas, ver Figura 1 e Figura 2.

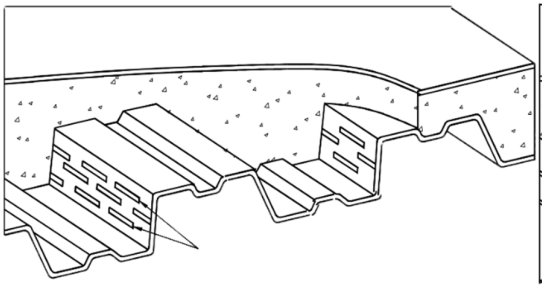


Figura 1: Laje com forma de aço trapezoidal incorporado [2].

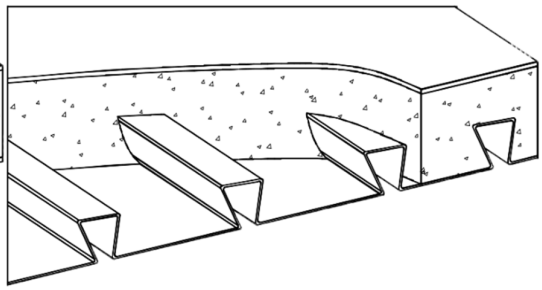


Figura 2: Laje com forma de aço reentrante incorporado [2].

O deck também possui a função de reforço, enquanto que as mossas presentes no deck garantem a ligação mecânica com o concreto. Consequentemente, a laje mista tem uma menor necessidade de varões de aço de reforço comparado a uma laje de concreto armado plana convencional, exigindo assim menos concreto. Outra vantagem das lajes mistas em relação às lajes planas convencionais é a redução do tempo de construção, uma vez que o deck serve como fôrma permanente [3].

Existem diversos tipos de perfis de aço comercializados ao redor do mundo, sendo possível encontrá-los com diversas características geométricas (distância entre nervuras, cobrimento lateral, largura, mossas, etc.). No caso dos perfis trapezoidais, a ligação mecânica do concreto ao perfil metálico é efetuada através de mossas (espécie de ranhuras) nas peças. Já nos perfis com cantos reentrantes essa ligação é garantida através do atrito causado pelo confinamento do concreto nas reentrâncias da forma [4].

Os perfis são muito finos por questões econômicas e físicas, geralmente entre 0.8mm e 1.2mm. Eles devem ser galvanizados para garantir durabilidade elevada

(resistência à corrosão sofrida pelo aço). Esta proteção adiciona 0.04mm à espessura total do elemento. As chapas perfiladas são geralmente prensadas ou laminadas a frio e tipicamente apresentam 0.8 a 1m de largura e 6m de comprimento. As chapas perfiladas são calculados para resistirem a esforços de flexão apenas numa direção (seção longitudinal que é paralela as reentrâncias) [5].

Lajes mistas são frequentemente utilizadas (nos setores comercial, industrial, do lazer, da saúde e da construção civil, devido à velocidade de construção e economia estrutural geral que pode ser alcançada. Embora este tipo de elemento seja mais frequentemente utilizado em construções com estruturas de aço, as lajes também podem ser apoiadas em alvenaria ou componentes de concreto [6].

Construções compostas tem-se tornado muito popular nos últimos anos e apresentam alguns benefícios [1]: Redução de 30 a 50% do peso de aço e aumento do valor da rigidez, possibilitando a redução da espessura da laje para o mesmo vão do compartimento e ainda mais espaço para infraestruturas de serviços.

O deck desempenha várias funções, sendo a mais importante do sistema estrutural, permitindo o suporte de cargas durante a construção, atuando ainda como plataforma de segurança para os trabalhos em altura, desenvolvendo uma ação colaborante na capacidade resistente, transfere as cargas no plano por ação do diafragma para as paredes de contraventamento ou de cisalhamento verticais, estabiliza as vigas contra um possível modo de instabilidade por flambagem lateral, atua ainda como reforço no caso das vigas compostas e ainda é responsável por distribuir as deformações de contração, evitando o aparecimento de fissuras, .

A construção de estruturas mistas apresenta várias vantagens em relação às alternativas de concreto pré-moldado ou *in situ*, uma vez que apresentam períodos de construção consideravelmente reduzidos, conforme referido por J W Rackham *et al*. [6]. Conjuntos de decks podem ser posicionados na estrutura através de gruas e os perfis individuais podem ser instalados à mão. Utilizando esse processo, o tempo de grua é reduzido, além disso 400m² de deck pode ser instalado por uma equipe apenas num dia, dependendo do formato e tamanho da estrutura. O uso do deck como plataforma de trabalho também acelera o processo construtivo. Como o aço de reforço é mínimo, grandes áreas podem ser concretadas rapidamente, e pisos podem ser concretados em rápida sucessão. O deck é facilmente manuseado, cortado no seu comprimento e é menos suscetível a problemas de tolerância. Os conectores de cisalhamento podem ser soldados

ou fixados através do deck. Os anexos e aberturas para zonas de serviços podem ser facilmente feitos.

J W Rackham *et al*. [6] também ressalta o fator sustentável relacionado a construção utilizando perfis metálicos, já que o aço possui a capacidade para ser reciclado repetitivamente sem que se verifique qualquer redução nas suas propriedades inerentes. Isso torna as construções mistas de perfis de aço uma solução sustentável. A sustentabilidade é um fator decisivo para os clientes, sendo que pelo menos 94% de todos os produtos das construções em aço podem ser ou reutilizados ou reciclados após a demolição de um edifício.

As normas nacionais e internacionais possuem métodos simplificados de cálculo, que nem sempre garantem projetos seguros ou econômicos, sendo assim, métodos avançados de cálculo permitem uma análise mais rigorosa do desemprenho térmico e estrutural quando o elemento for levado a altas temperaturas.

O anexo D do Eurocódigo EN 1994-1-2 [7], permite o cálculo do tempo de resistência ao fogo de lajes mistas para a componente de isolamento, quando submetidos à curva de incêndio padrão ISO834 de 1999 [8]. Este trabalho, por meio de simulações numéricas, visa comparar o modelo numérico desenvolvido através da comparação com outros modelos já existentes e com resultados de ensaios experimentais. Neste estudo foram realizadas 384 simulações numéricas bidimensionais de seções de lajes mistas de concreto e aço, sendo considerados duas geometrias diferentes com deck trapezoidais, conforme Figura 3, e duas geometrias com deck reentrante, conforme Figura 4. Os dados foram analisados e comparados com os resultados dos métodos simplificados atualmente disponíveis.

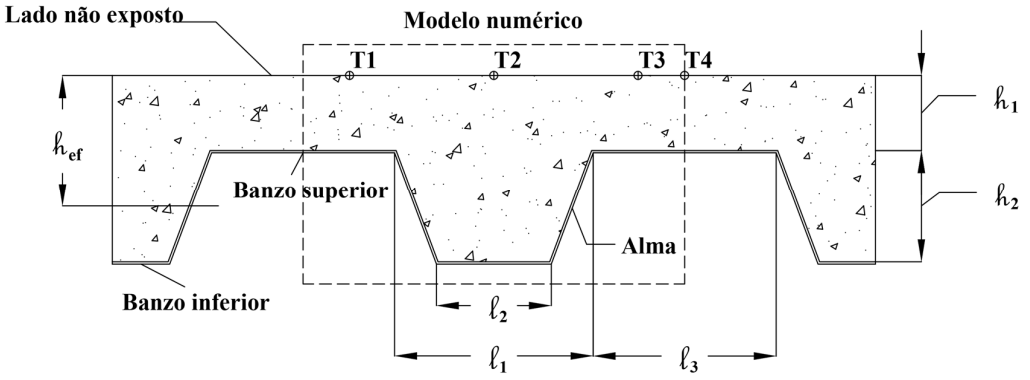


Figura 3: Geometria da laje com deck metálico trapezoidal (adaptado de EN 1994-1-2 [7]).

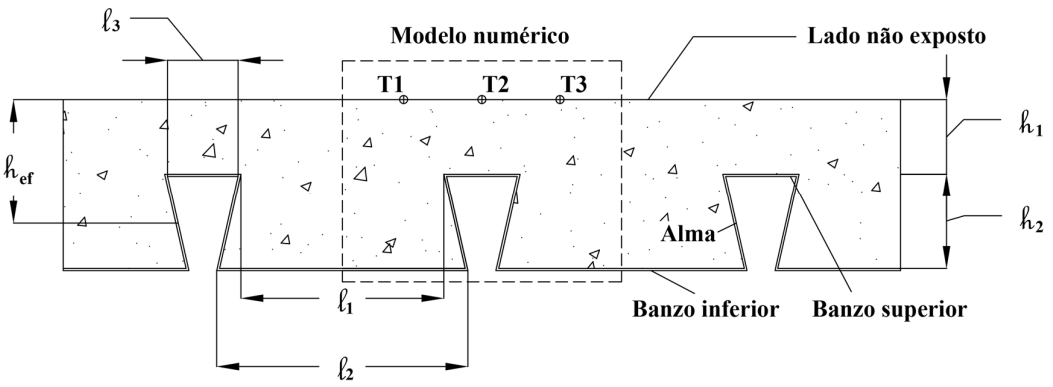


Figura 4: Geometria da laje com deck metálico reentrante (adaptado de EN 1994-1-2 [7]).

1.1 Motivação

O comportamento de estruturas mistas, em especial lajes mistas de concreto e aço, vem-se mostrando uma importante linha de pesquisa. Muitos trabalhos experimentais de elementos isolados e modelos numéricos foram e ainda são desenvolvidos para a análise de lajes mistas. Essas pesquisas levaram ao desenvolvimento de diversas metodologias que preveem o tempo de resistência desses elementos sobre a ação de um incêndio padrão, contribuindo para o entendimento e melhorias nos projetos estruturais, aumentando a segurança de pessoas e bens.

Com a evolução da tecnologia computacional, diversos métodos para análises estruturais vêm sendo desenvolvidos, pois a análise por métodos avançados de cálculo é mais barata e apresenta bons resultados quando comparada aos ensaios experimentas, por isso o desenvolvimento de novos métodos numéricos é de extrema importância para agregar conhecimentos e proporcionar melhorias nos métodos de análise de elementos estruturais.

Os programas computacionais permitem a modelação de elementos submetidos à ação do fogo, contudo existem novas ferramentas para análise da ação térmica que não necessitam de licença para sua utilização. Novos estudos realizados utilizando estas ferramentas são de grande relevância pois possibilitam um maior número de pesquisas voltados para esta área contribuindo assim para o conhecimento sobre estruturas mistas sob a ação do fogo.

Diversos modelos têm sido desenvolvidos para o cálculo da capacidade de resistência de carga (R) para elementos submetidos à ação do fogo, contudo poucos

modelos visam a análise do fator isolamento (I), que também é de extrema importância na segurança de edifícios em situação de incêndio.

Os resultados numéricos obtidos, devidamente analisados e comparados, permitem que futuros trabalhos possam adotar os métodos e parâmetros utilizados nas análises numéricas do presente trabalho para a geração de novo conhecimento e dar origem a novos resultados a respeito do tema abordado. Espera-se também que o trabalho possa contribuir para o dimensionamento de lajes mistas de concreto e aço com chapa de aço colaborante, no que se refere às revisões das normas vigentes, sendo o objetivo a contribuição para a melhoria da segurança estrutural e o desenvolvimento cientifico do tema abordado.

1.2 Objetivos e problemática

Este trabalho visa o desenvolvimento de modelos numéricos, utilizando os programas Matlab® R2017a e ANSYS ® v 18.2 para a simulação de lajes mistas de concreto e aço expostas ao fogo. Foram propostos modelos bidimensionais, utilizando o método dos elementos finitos, para a solução de equações às derivadas parciais para a análise do efeito térmico da ação de um incêndio. Este modelos foram desenvolvidos com o propósito de se encontrar a temperatura crítica no lado não exposto da seção transversal de uma laje submetida à curva padrão de incêndio ISO 834 [8].

Serão estudadas quatro geometrias de lajes mistas, sendo duas geometrias definidas com perfis trapezoidais e duas geometrias com perfis reentrantes. Os resultados numéricos obtidos serão comparados com os resultados obtidos através do método simplificado de cálculo disposto no Eurocódigo EN 1994-1-2 [7] no anexo D, e com as recomendações impostas pela NBR 14323:2013 [9] e ainda comparados com os resultados dos ensaios experimentais de uma geometria com perfis trapezoidais.

O trabalho também visa o desenvolvimento de conhecimentos em programação científica, desenvolvendo programação com Matlab.

1.3 Organização da tese

Ao longo deste capítulo apresenta-se uma breve introdução, a proposta de trabalho, o estado da arte, apresentando alguns dos principais estudos relacionados com

o tema em estudo, além de uma breve análise das possíveis variáveis influentes na análise numérica.

O segundo capítulo apresenta as ações térmicas em estruturas mistas de aço e concreto, bem como os mecanismos de transferência de calor, o método simplificado de cálculo, as curvas de incêndio nominais, as propriedades térmicas dos materiais, e por fim os fundamentos da engenharia de segurança contra incêndio.

O terceiro capitulo é dedicado a apresentar os procedimentos normativos para se obter a elevação de temperatura dos elementos estruturais por meio de modelos avançados de cálculo. São apresentadas as estratégias utilizadas para a modelagem numérica utilizando a toolbox de equações às derivadas parciais do Matlab R2017a e o programa ANSYS ® 18.2.

No quarto capítulo são apreciados os procedimentos normativos de ensaio para estruturas mistas de concreto e aço, após isso, é demonstrada a preparação das amostras destinadas aos ensaios experimentais para obtenção do tempo de resistência ao fogo de lajes mistas. São ainda apresentados os resultados dos testes experimentais.

No quinto capítulo são apresentados e discutidos os resultados dos métodos avançados de cálculo.

No sexto capítulo são comparados os resultados dos métodos avançados de cálculo com os resultados obtidos nos testes experimentais, e com as normativas vigentes em Portugal e no Brasil para o cálculo do tempo de resistência ao fogo de lajes mistas no critério de isolamento. Neste capítulo é ainda apresentado uma nova proposta de cálculo para determinação do tempo de resistência ao fogo.

No sétimo capítulo são apresentadas as conclusões do trabalho, e também sugestões para trabalhos futuros.

1.4 Estado da arte

Em 1983, ECCS [10] publicou algumas regras de cálculo aplicadas ao dimensionamento prático de lajes de concreto compostas com um perfil de aço exposto a um incêndio padrão. O critério de desempenho foi baseado em uma simplificação dos critérios mais gerais de resistência ao fogo, conforme especificado na ISO 834.

Em 1990, Hamerlinck *et al*. [11] desenvolveram um modelo de simulação numérica que prevê o comportamento de lajes mistas de concreto e aço. Esse modelo

consiste em uma análise térmica e mecânica da seção de corte para uma análise estrutural e o modelo foi verificado através de testes experimentais. As simulações numéricas consistem em um modelo térmico bidimensional que leva em consideração a dependência da temperatura das propriedades dos materiais, a evaporação da umidade e também a arbitrariedade das condições de exposição ao fogo. Os testes experimentais foram conduzidos em doze espécimes, utilizando diferentes tipos de perfis metálicos e avaliando o efeito do perfil metálico para lajes com a mesma espessura de concreto. Todos os testes foram efetuados no centro tecnológico TNO. Os resultados numéricos apresentaram valores satisfatórios que conseguem prever a evolução da temperatura quando comparados com as medições dos ensaios experimentais.

Em 1991, Hamerlinck, A.F [12] realizou um estudo com o intuito de propor um modelo matemático que consiga reproduzir o comportamento de lajes mistas expostas ao fogo. Esse estudo foi motivado pelo artigo em que Hamerlinck afirma que as recomendações propostas pelo ECCS, em muitos casos se apresentavam muito conservativas, o que leva ao desperdício de materiais, e em outros casos se apresentava não conservativa, justificando o desenvolvimento de um modelo mais preciso. Foi utilizado um modelo que descreve o comportamento de lajes mistas expostas a um incêndio e uma verificação experimental foi realizada para validação dos resultados. O modelo utilizado permite o cálculo das temperaturas em função do tempo e também o cálculo das respostas mecânicas da laje. O modelo de transferência de calor aplicado é verificado em duas partes, separando a influência de dois importantes parâmetros, um que descreve a condução na laje e parâmetros que descrevem a transferência de calor (convecção e radiação). Hamerlinck conclui que os dados previstos não apresentaram grande diferenças dos dados experimentais.

Em 1995, Ralph Hamerlinck [13] realizou uma análise dos métodos disponíveis para o cálculo térmico e mecânico voltados para as lajes mistas e chegou à conclusão que o Eurocódigo EN 1994-1-2 apresenta um método fácil de executar, contudo estudos na área são necessários para tornar esses cálculos mais precisos. Ele enfatizou que dois fatores devem ser analisados com cuidado. O primeiro são as regras para a contribuição do perfil metálico no cálculo da capacidade de momento positivo e o segundo fator é a influência da quantidade de reforço na região de momento negativo para prevenir falhas nessas zonas.

Em 1996, K. Both [14] desenvolveu um modelo numérico para prever a progressão das temperaturas numa laje mista de concreto e aço. Foram considerados os

efeitos da fusão da camada de zinco presente no perfil metálico, sendo este efeito simulado através de uma emissividade do perfil dependente da temperatura. Também foi levada em consideração a evaporação da umidade através de uma relação de temperatura com o calor específico do concreto. Doze testes com diferentes perfis foram realizados para determinar a influência da espessura de concreto e do perfil metálico na performance térmica da seção, com o objetivo de verificar o modelo numérico já desenvolvido. O modelo apresentou resultados satisfatórios que mostravam semelhanças com os resultados obtidos nos testes experimentais realizados.

No ano de 1997, C. Both *et al*. [15] realizaram estudos sobre o comportamento ao fogo de lajes mistas. Os testes realizados tinham o objetivo de estabelecer modelos numéricos, que permitiam assim uma simulação adequada do comportamento das lajes ao fogo. Segundo os autores, a resposta térmica e mecânica da laje exposta ao fogo pode ser estimada utilizando o programa de elementos finitos DIANA. Através dos modelos numéricos validados para a resposta térmica, foi realizado um estudo para a dedução de regras mais simples de cálculo permitindo uma avaliação mais rápida e econômica de lajes mistas.

Em 1998, C. Both [16] desenvolveu sua tese de doutorado com o objetivo de estudar a resistência ao fogo de lajes mistas. O autor apresenta uma pesquisa sobre a literatura já existente sobre o objeto de estudo, compreendendo uma descrição breve dos métodos de cálculos já existentes e um resumo dos trabalhos numéricos e experimentais relevantes.O autor considerou ainda que os estudos experimentais já realizados sobre o comportamento ao fogo de lajes contínuas eram escassos. Desta forma, foram realizados testes de resistência ao fogo em escala real, em diferentes tipos de lajes mistas, com o intuito de estudar o comportamento térmico e mecânico de sistemas com dois vãos. Também foi desenvolvido um método numérico baseado no modelo de elementos finitos, que foi validado através dos ensaios experimentais para o comportamento térmico e mecânico. Como o modelo numérico apresentou bons resultados, foi ainda realizada uma série de estudos paramétricos. Foram aimda apresentados métodos simplificados de cálculo para a determinação da resistência ao fogo de lajes mistas. Estes métodos foram baseados numa série de extensivos estudos paramétricos, nos quais a geometria do perfil metálico era variada, utilizando diversos tipos de perfis. Posteriormente, foi realizada uma comparação entre o antigo e o novo modelo simplificado de cálculo, comparando-os com o modelo avançado de cálculo. Desta forma foi possível observar que, para todos os parâmetros estudados, o novo modelo simplificado de cálculo apresentava melhores

resultados para a determinação da resistência ao fogo de lajes mistas. Através desse estudo uma nova fórmula para o cálculo foi proposta, vindo anos depois a ser adotada pelo Eurocódigo EN 1994-1-2 [7].

Em 1999, Abdel-Halim *et al*. [17] investigaram o comportamento de lajes mistas expostas ao fogo. Os testes foram realizados experimentalmente levando em consideração apenas influência térmica nas lajes. Os ensaios foram realizados com critérios de resistência de parada para a integridade e isolamento da laje. No primeiro teste, a falha por isolamento ocorreu aos 86 minutos e para o segundo teste aos 80 minutos. A integridade da laje apresentou falhas após 192 minutos no caso um e após 180 minutos no caso dois. As conclusões foram que como o cobrimento metálico se separa do concreto, pode-se assumir que ele não possui nenhuma contribuição para a resistência da laje durante um incêndio. Segundo os autores, mais testes são necessários, tendo em consideração que diversos fatores não foram avaliados.

Também em 1999, Bailey *et al*. [18] apresentaram os resultados de 2 testes experimentais em escala real (edifício completo) realizados pela *Building Research Establishment*, no Reino Unido, demonstrando que o desempenho da estrutura sob a ação do fogo se apresentava diferente do que é esperado pelos códigos de resistência ao fogo e também demonstrando que estes eram conservativos. Os dois testes evidenciaram que o comportamento do elemento é diferente do que é normalmente obtido em testes padrões de resistência ao fogo de pequena escala. Também concluíram que o principal fator que contribuiu para a resistência ao fogo da estrutura foi a laje, que apresentou bons resultados, o que mostra que esse tipo de laje tem uma boa resistência ao fogo inerente.

Em 2001, S. Lamont *et al*. [19] realizaram uma análise da transferência de calor em lajes de estrutura mista no edifício de Cardington, em Broadgate, no Reino Unido. Foram realizados quatro testes em diferentes andares do edifício. A estimativa das temperaturas através da laje foi feita através do software de transferência de calor adaptativa HADAPT para modelação da transferência de calor através da laje mista. O modelo desenvolvido apresentou resultados satisfatórios para os testes 1-3, contudo para o teste 4 apresentou dados que segundo os autores não são confiáveis.

Em 2002, C. Both *et al*. [20] realizaram diversos testes de resistência ao fogo de lajes mistas de concreto e aço à escala real e devidamente instrumentados, visando o estudo do comportamento térmico e mecânico dessas lajes. Também foram produzidas simulações numéricas baseadas em modelos de elementos finitos, que foram validados através dos testes experimentais, para a avaliação térmica e mecânica de lajes mistas.

Após isso, esses dados obtidos foram comparados com os resultados do modelo simplificado de cálculo do Eurocódigo EN 1994-1-2 [7]. Ao analisarem esses dados, concluíram que o modelo simplificado não apresenta resultados coerentes, podendo ser conservativos e simultaneamente inseguros. Um novo modelo simplificado de cálculo foi proposto, melhorando a curva de dispersão e tornando o cálculo de resistência ao fogo de lajes mistas mais coerente. Os autores concluem que as atuais regras para avaliação de resistência ao fogo das lajes mistas, indicadas no Eurocódigo EN 1994-1-2 [7], podem ser significativamente melhoradas.

Em 2002, Lim *et al*. [21] realizaram testes de resistência ao fogo de dois tipos de lajes de concreto num forno para testes ao fogo de BRANZ. Seis lajes foram testadas, compreendendo três lajes planas reforçadas com perfis metálicos e três lajes mistas de concreto com perfis metálicos colaborantes. As três lajes planas foram testadas com diferentes quantidades de aço de reforço para investigar o efeito desses elementos no controle de fissuras que garantem a integridade do elemento. Todas as lajes foram submetidas a uma carga distribuída de 3.0kPa e foram aquecidas na sua parte inferior, seguindo a curva padrão ISO 834, durante três horas. As lajes suportaram a duração completa dos testes sem ruir. Os testes apresentaram resultados positivos e os resultados de resistência obtidos foram superiores aos das recomendações impostas pelos regulamentos.

Em 2004, Lim *et al*. [22] desenvolveram um modelo numérico para determinar o comportamento de dois tipos de lajes de concreto reforçadas, utilizando o programa de elementos finitos não linear SAFIR, desenvolvido na Universidade de Liége. Testes experimentais foram realizados para a validação do modelo numérico. O modelo desenvolvido apresentou resultados de acordo com os obtidos através dos testes, contudo, os testes apresentaram resultados de temperaturas um pouco abaixo da previsão dos modelos numéricos. Esse fenômeno foi explicado através da deformação do perfil metálico na parte inferior da laje, o que provocou um descolamento da superfície inferior de concreto, criando uma camada isolante de ar entre o perfil metálico e a camada de concreto.

Em 2012, Dilip Banerjee [23] realizou um relatório que resume a caracterização do ambiente térmico do forno e o comportamento térmico dos membros durante os testes de incêndio realizados pelo *The National Institute of Standards and Technology* (NIST), estes testes tinham o objetivo de investigar os eventos ocorridos no colapso das torres gêmeas. O principal objetivo desses testes foi entender a influência de três importantes

fatores no comportamento da resistência ao fogo de lajes compostas: espessura do revestimento à prova de fogo no aço, condições de restrição do teste e escala do teste (por exemplo, escala real comparada à escala reduzida). O relatório visa discutir os resultados de dois testes realizados em escala real, cujos dados são comparados aos resultados numéricos obtidos de um modelo de elementos finitos para a transferência de calor de uma seção representativa de uma laje mista. Para os dois testes analisados, o modelo numérico apresentou temperaturas maiores do que as atingidas nos testes experimentais. Para a parte mais próxima ao perfil metálico, essa inconsistência era sistemática, ao contrário dos outros locais onde foram medidos, que apresentavam uma variação no erro, quando comparados aos modelos numéricos. Esta situação mostra que a parcela de concreto (juntamente com a variação das propriedades térmicas devido aos diferentes níveis de umidade) é responsável por uma grande parte de influência no comportamento térmico.

Em 2014, J. Kolšek *et al*. [24] desenvolveram e validaram um modelo numérico totalmente generalizado para a análise de lajes mistas de concreto e aço com comportamento estrutural semelhante a vigas sob a ação do fogo. Esse modelo é generalizado no sentido que emprega submodelos para todos os fenômenos físicos e suas consequências que são reconhecidos como potencialmente influentes na resposta ao fogo de estruturas mistas. O modelo levou em consideração a não linearidade do material e de sua geometria, uma conexão de contato arbitrária com possíveis deslizamentos e elevações normais e tangenciais. Também foi considerada a umidade no concreto e os correspondentes fenômenos químicos e físicos (transferência de massa de vapor de água, espaços vazios, água livre, evaporação, condensação, desidratação, etc.). Outro fator analisado é o dano térmico e mecânico no concreto e por fim, fenômenos de alta temperatura relacionados ao material (endurecimento / amolecimento do material, fluência etc.). O modelo proposto foi verificado através de ensaios experimentais desenvolvidos por Guo e Bailey em 2011 [25]. A comparação apresentou uma boa concordância na maioria dos termopares analisados. Por fim, os autores chegaram à conclusão que nos cálculos da resposta estrutural ao fogo a influência das finas camadas da chapa de aço pode ser importante em lajes mistas semelhantes a estruturas de vigas e, consequentemente, são necessários mais modelos e ensaios experimentais para a análise desses fenômenos.

Em 2017, Guo-Qiang Li *et al*. [26] efetuaram testes em lajes mistas com deck de aço, com duração de 90 minutos e concluíram que o Eurocódigo EN 1994-1-2 apresenta

equações de cálculo conservativas e que também poderiam ser usadas para outras geometrias, além dos limites especificados. Os ensaios experimentais foram desenvolvidos na Universidade de Tongji, China, e a temperatura média do forno estava abaixo da curva padrão ISO 834. A temperatura na superfície inferior da laje (acima do deck de aço) era 100 ºC abaixo da temperatura do forno em média. Já a temperatura no lado não exposto era inferior a 100 ºC, sendo a classificação de resistência ao fogo determinada pela estabilidade.

Em 2017 e 2018, Jian Jiang *et al*. [27], [3], realizaram uma investigação sobre a influência de diversos parâmetros que afetam o desempenho térmico de lajes mistas com decks de perfil metálicos expostas ao efeito do fogo. Foi utilizado um modelo detalhado de elementos finitos que representa a laje de concreto com elementos sólidos e o perfil metálico como um elemento de casca. O modelo desenvolvido foi validado através de outros estudos experimentais já realizados. Após essa validação, uma série de estudos foram realizados, com o objetivo de investigar a influência de fatores como: condições de fronteira, propriedades térmicas do concreto e geometria da laje em relação a distribuição de temperatura. O estudo concluiu que a resistência ao fogo de acordo com o isolamento térmico é geralmente governada pela máxima temperatura no lado não exposto da laje. Também concluíram que a emissividade do aço possui uma grande influência na distribuição de temperatura e é proposto um novo parâmetro de emissividade dependente da temperatura para uma melhor percepção da progressão de temperatura nas lajes mistas. Outro fator que demostrou relevância foi a percentagem de umidade no concreto, sendo que a cada 1% a mais de umidade garante 5 min a mais de resistência da laje. E por fim a altura da parte contínua da laje apresentou grande influência na transferência de calor através da seção da laje mista, aumentando o tempo de resistência ao fogo do elemento.

1.5 Breve análise de edificações completas em situação de incêndio

Analisar estruturas de uma forma global sobre a situação de incêndio é de extrema importância para que se possa entender as interações entre os diferentes elementos estruturais, e também analisar o comportamento individual de cada um, bem como o entendimento do sistema como um todo. Um entendimento do comportamento estrutural

de um edifício sobre situação de incêndio só pode ser obtido através da análise de todos seus elementos. Apesar destes testes em escala real serem extremamente caros, eles são necessários [28].

Inúmeros testes de estruturas completas em situação de incêndio foram realizados em todo o mundo. Contudo, em termos de proporcionar conhecimentos do comportamento estrutural, a análise do acidente no edifício Broadgate, em Londres, e os ensaios em Cardington, no Reino Unido, apresentam a maior quantidade de informação capaz de gerar novo conhecimento [28].

Apesar de não ser exatamente um ensaio, a experiência no edifício em Broadgate proporcionou uma melhor visão no comportamento de uma estrutura mista completa em situação de incêndio. Segundo Y.C.Wang [28], os resultados dessa análise subsequente a este incêndio teve uma função essencial na decisão de realizar ensaios em larga escala em um edifício completo de oito andares com estrutura de aço no "*UK BRE's Cardington laboratory*". O acidente de Broadgate ocorreu em um edifício de 14 andares, em processo de construção em Londres no ano de 1990. O incêndio, que durou ao todo 4 horas e 30 minutos, ocorreu quando o alojamento do empreiteiro da obra no primeiro andar que estava localizado em volta das colunas de aço pegou fogo. Essas colunas, que estavam localizadas próximas ao alojamento, não possuíam proteção contra o fogo. Como resultado, altas temperaturas foram registradas, sendo que, durante uma parte substancial do tempo de incêndio, essas temperaturas atingiram 1000ºC. O alojamento foi completamente destruído, porém, a estrutura metálica persistiu ao incêndio sem colapsar. A estrutura foi reconstruída em 30 dias e nenhuma vida foi perdida [28].

Um dos mais relevantes estudos sobre o comportamento ao fogo de estruturas mistas em situação de incêndio ocorreu no "*Cardington Laboratory of the Building Research Establishment*", no Reino Unido. Nesse estudo, um edifício de oito andares foi construído em um hangar localizado em Cardington, em Bedfordshire, ver Figura 5 e Figura 6. A estrutura foi projetada de acordo com a norma BS 5950 Parte 1 e verificado com as determinações do Eurocódigo, com o intuito de simular um edifício comercial real. De todos os dados obtidos através desse ensaio, deve-se ressaltar uma observação extremamente importante sobre o desempenho das lajes durante o incêndio. Nas análises convencionais e regras de cálculo, o método mais comum é considerar este elemento como o banzo de compressão de uma viga composta sob flexão. Se este método for utilizado, devido às altas temperaturas verificadas no suporte das vigas metálicas, as vigas mistas do teste em Cardington deveriam ter falhado pelo peso aplicado pelas lajes.

Contudo, não foi isso que aconteceu. Isso sugere que, na verdade, a carga dos pavimentos mistos de aço e concreto resistiu devido a outro fenômeno, que foi posteriormente identificado como a ação da tensão de membrana [28]. Esse fenômeno permite que a laje possa suportar parte ou todo carregamento, que antes era suportado pelas vigas [29].

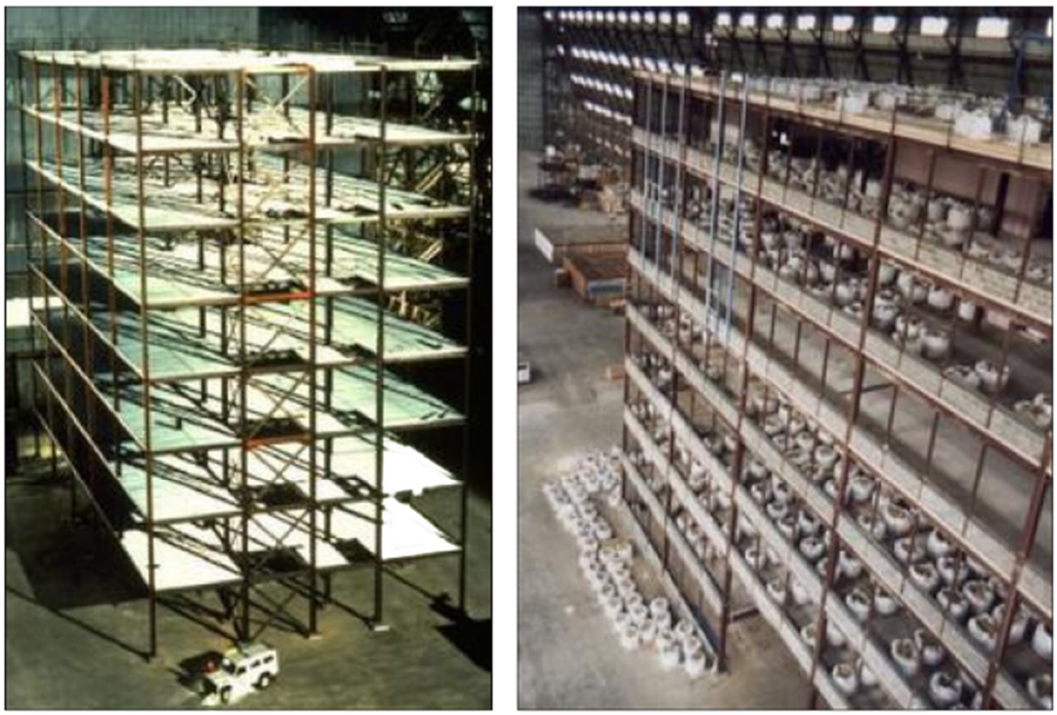


Figura 5: Laboratório de Cardington, estrutura de oito pavimentos em escala real. Fonte: “Steel and Composite Structures Behaviour and design for fire safety” [28]

Figura 6: Um dos seis ensaios sobre situação de incêndio em um edifício de oito andares em Cardington, Fonte: “Advances in research on fire engineering of steel structures” [30].

Assim sendo, uma das principais observações e conclusões que se pode retirar dos ensaios ocorridos em Cardington é que o real e superior desempenho de uma estrutura completa em situação de incêndio não pode ser avaliada através de uma análise de elementos estruturais isolados [31].

Posteriormente, em 2009, Yong Wang [30] discute o colapso do *World Trade Center*, causado pelo atentado terrorista de 11 de Setembro de 2001, que também é considerado um marco que gerou ainda mais estudos sobre o comportamento de estruturas de aço e concreto sob situação de incêndio. Segundo o autor, os estudos a partir dessa tragédia foram focados na "robustez estrutural", visando evitar o colapso progressivo da estrutura devido a situação de incêndio, como se pode ver no caso do *World Trade Center*. O ataque terrorista acabou danificando a proteção de algumas treliças dos pavimentos, e essas acabaram ficando sob a ação de temperaturas muito mais elevadas que aquelas que permitiam que esses elementos funcionassem apenas sob flexão. Assim, as treliças do pavimento desenvolveram um mecanismo de catenária para suportar o carregamento gravitacional, puxando os pilares da edificação [31].

Devido à formação desse mecanismo de catenária, as treliças foram incapazes de prover suporte lateral para o sistema vertical, o que causou um aumento do comprimento de flambagem para a altura de alguns pavimentos, reduzindo drasticamente a capacidade de carga dos pilares. Uma vez que o sistema vertical diretamente relacionado com o incêndio, causado pela aeronave, sofreu a flambagem, se tornou impossível evitar o colapso total do edifício devido as grandes forças dinâmicas que foram produzidas [30].

Mais recentemente, outro incêndio aconteceu no centro de São Paulo, no Brasil, onde um edifício de 24 andares desabou, após um incêndio em um dos andares que se alastrou pelo edifício, ver Figura 7. O prédio possuía uma estrutura de concreto armado, porém devido à ocupação irregular dos moradores, seu interior era repleto de materiais que funcionaram como combustível para o incêndio, como as divisórias feitas com placas de madeira. Outro fator relevante foi a retirada dos elevadores uma vez que isso criou dutos de ar no fosso que agiram como uma chaminé, contribuindo para a propagação do incêndio. O incêndio teve início no quinto andar, aproximadamente às 1:30h e após 120 minutos ocorreu o desabamento do edifício, causando também danos nos prédios adjacentes.

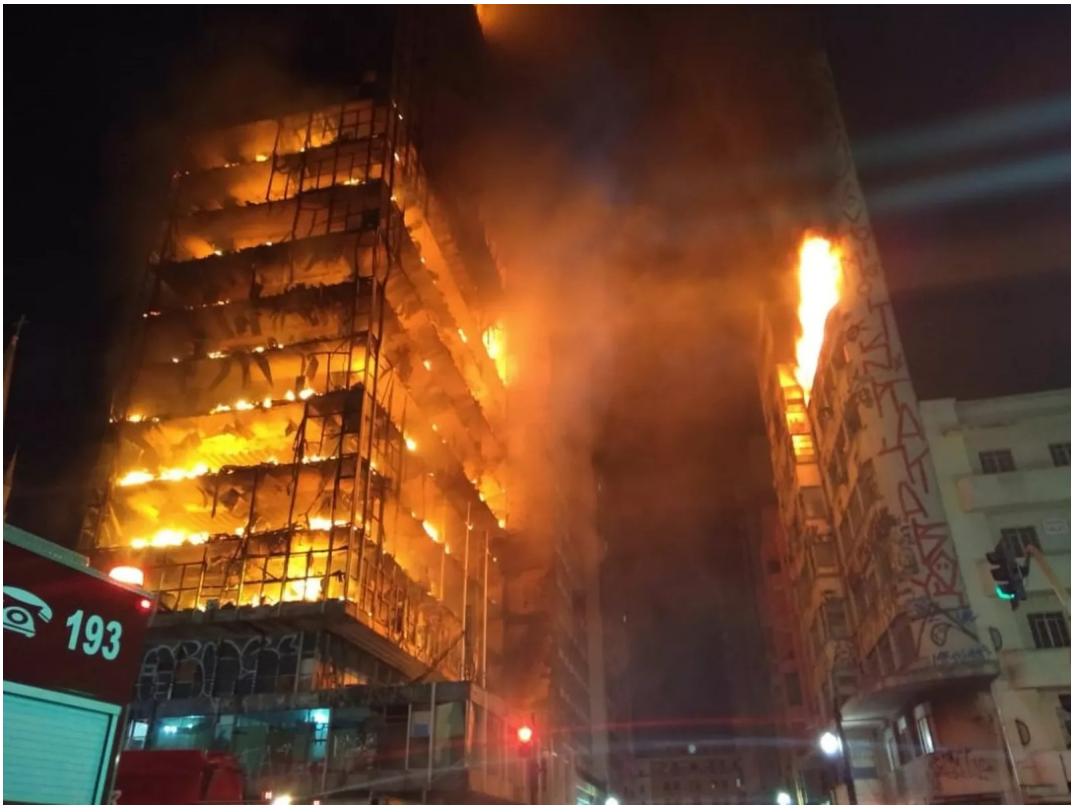


Figura 7: Incêndio no Edifício Wilton Paes de Almeida, São Paulo – Brasil. Fonte: (Divulgação/Corpo de Bombeiros [32]).

Após todos os casos discutidos nesta seção, é evidente que a simulação do comportamento das lajes em modelos mais realistas é de extrema importância. Porém, tal aspecto, devido a sua grande complexidade, está fora do escopo deste trabalho e poderá ser abordado em pesquisas futuras.

1.6 Influência das condições de fronteira

1.6.1 Coeficiente de transferência de calor por convecção

Os coeficientes de transferência de calor por convecção são determinados pelo Eurocódigo 1991-1-2 [33]. Segundo essas determinações, o coeficiente para o lado exposto ao fogo da laje deve ser de 25 W/(m²·K) para uma curva de incêndio padrão, de 35 W/(m²·K) para a curva de incêndio natural e de 50 W/(m²·K) para a curva de incêndio de hidrocarbonetos. Para o lado não exposto um valor de 4 W/(m²·K) pode ser adotado quando a transferência de calor por radiação é considerada, caso contrário, um coeficiente de 9 W/(m²·K) deve ser considerada para incluir o efeito da radiação. Em 1990,

Hamerlinck *et al*. [11] sugerem a utilização de um coeficiente de 15 W/(m²·K) para a parte da alma do perfil metálico exposto ao fogo, levando em consideração o fluxo de calor reduzido no espaço entre duas almas consecutivas, e também sugerem um coeficiente de 8 W/(m²·K) para o lado não exposto, também considerando o efeito da radiação. Sendo assim, em 2017, Jiang *et al*. [3] realizaram um estudo com o objetivo de estudar a influência de diversos parâmetros. Para o coeficiente de transferência de calor por convecção, pode-se notar que ao variar os coeficientes do lado não exposto, variações da progressão de temperatura podem ser observadas, e no lado não exposto a variação desse coeficiente apresenta notáveis diferenças na temperatura final da laje.

1.6.2 Influência da emissividade

Um valor de 0.7 para a emissividade é recomendado pelo Eurocódigo 1993-1-2 [34] para o aço, e pelo Eurocódigo 1992-1-2 [35] para o concreto, entretanto Hamerlinck *et al.* [11] sugerem uma emissividade dependente da temperatura para o perfil de aço exposto ao fogo, para que a fusão da camada de zinco protetora do perfil metálico seja levado em consideração. A variação da emissividade do material gera uma grande diferença na progressão de temperatura, quando comparada ao efeito do coeficiente de convecção na transferência de calor, que gera diferença nos resultados principalmente na seção mais fina da laje. Já na parte não exposta da laje, a variação da emissividade não apresenta uma influência significativa na progressão de temperatura [3].

1.6.3 Influência do fator de vista

O Eurocódigo 1994-1-2 [7] fornece a equação para o cálculo do fator de vista ou de forma para a parte superior da reentrância do perfil metálico. Já o fator de vista para a parte inferior da reentrância é sempre 1.0. No trabalho publicado por Jiang *et al.* [3], os autores mostram os efeitos da variação do fator de vista, realizando uma variação dos diferentes fatores de vistas na geometria do perfil metálico. Pode-se perceber que no critério de resistência ao fogo proposto pelo Eurocódigo 4, a variação do fator de vista é mais sensível na parte superior da reentrância do perfil metálico, isso devido à fina espessura da seção, causando assim uma maior interferência nas temperaturas do lado não exposto da laje.

2 AÇÃO TÉRMICA EM ESTRUTURAS MISTAS

Visando o estudo do comportamento de lajes mistas de concreto e aço em situação de incêndio, é necessário compreender quais as variáveis que interferem nos elementos estruturais. A avaliação da resistência de estruturas sob o efeito do fogo, seja de forma analítica, numérica ou experimental, é dependente da evolução da temperatura ao longo do tempo.

Os efeitos da elevação da temperatura em um elemento estrutural, principalmente em elementos mistos de aço e concreto, são muito mais complexos do que à temperatura ambiente. Neste capítulo serão apresentadas algumas dessas variáveis que são utilizadas pelos códigos prescritivos para o dimensionamento de um elemento estrutural em situação de incêndio.

2.1 Ação térmica

A resistência ao fogo pelo isolamento térmico de lajes mistas depende da evolução da temperatura. Segundo o Eurocódigo EN 1994-1-2 [7], a análise do elemento é feita de acordo com a temperatura média e máxima do lado não exposto ao fogo. Desta forma, é possível determinar se o elemento consegue apresentar o isolamento necessário no caso de um incêndio, assim o classificando de acordo com o tempo crítico. A classificação do tempo de resistência ao fogo depende desse valor e dos valores estabelecidos para os diferentes elementos de construção [36], que são utilizados no dimensionamento dos edifícios.

2.2 Equação do calor

Calor pode ser definido como uma forma de energia que é transferida de um sistema para outro como consequência de uma diferença de temperatura. Uma análise termodinâmica é centrada na quantidade de transferência de calor à medida que um sistema passa por um processo de um estado de equilíbrio para outro. A ciência que lida com a determinação das taxas de tais transferências de energia é a transferência de calor.

A transferência de energia como calor é sempre do meio de mais alta temperatura para o de mais baixa temperatura, e a transferência de calor cessa quando os dois meios atingem a mesma temperatura [37].

Existem três mecanismos básicos de transferência de calor: condução, convecção e radiação. Na condução, a energia ou o calor são trocados em sólidos na escala molecular, mas sem qualquer movimento de porções macroscópicas da matéria em relação à outra. Convecção é definida como a transferência de calor na interface entre um fluido e uma superfície sólida. Neste mecanismo, a troca de calor ocorre devido ao movimento do fluido. Esse movimento pode ser o resultado de uma força externa, fazendo com que o fluido flua sobre a superfície sólida em velocidade elevada. Esta forma de movimento é designada convecção forçada. A convecção também pode ocorrer devido ao fluxo induzido pela flutuação quando há um gradiente de temperatura no fluido, causando uma variação de densidade. Esta forma de movimento é designada convecção natural. Já a radiação é a troca de energia por ondas eletromagnéticas que, como a luz visível, podem ser absorvidas, transmitidas ou refletidas em uma superfície. Ao contrário da condução e convecção, a transferência de calor por radiação não requer nenhum meio intermediário entre a fonte de calor e o receptor.

Exceto nos casos mais simples, não é possível encontrar soluções analíticas para um problema de transferência de calor. Portanto, em aplicações de segurança contra incêndio, os problemas de transferência de calor geralmente são resolvidos experimentalmente ou numericamente. Os testes experimentais são caros e os seus resultados só podem ser aplicados às condições específicas que foram testados. A análise numérica da transferência de calor pode ser mais geral e está sendo amplamente utilizada. Uma compreensão dos três modos de transferência de calor é essencial para a seleção de fatores apropriados para a realização de análises numéricas de transferência de calor [28].

Segundo Ralph Hamerlinck [13], um incêndio é caracterizado pelo desenvolvimento da temperatura em função do tempo. Este desenvolvimento de temperatura depende de um grande número de fatores, como quantidade, tipo e distribuição do material combustível, bem como as dimensões e a ventilação do ambiente. Assim, na prática, o desenvolvimento da temperatura é diferente para cada cenário de incêndio. Existem diferentes modelos matemáticos que descrevem um incêndio natural, contudo, a curva de temperatura que será utilizada neste trabalho está descrita na norma internacional ISO834.

As ações térmicas normativas estão definidas no Eurocódigo EN 1991-1-2 [33], devido a um fluxo de calor que incide na superfície do elemento. Na superfície exposta o fluxo de calor líquido $\dot{h}_{net}$ deve ser determinado considerando a soma das parcelas da convecção e da radiação conforme a Equação (1). No lado não exposto, o fluxo de calor deve ser determinado usando a Equação (1), e utilizando um coeficiente de transferência de calor por convecção $\alpha_c = 4\left[W/m^2\right]$. O coeficiente de transferência de calor por convecção deve ser adotado como $\alpha_c = 9\left[W/m^2\right]$, quando se assumir que ele contém também os efeitos de transferência de calor por radiação.

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \left[W/m^2\right] \quad (1)$$

2.2.1 Transferência de calor por condução

Condução é a energia transferida das partículas mais energizadas de uma substância para as adjacentes que estão menos energizadas, como resultado de uma interação entre as partículas. A condução pode ocorrer em meios sólidos, líquidos ou gasosos [37].

A taxa de condução de calor através de um plano é proporcional à diferença de temperatura através da camada e da área de transferência de calor, mas é inversamente proporcional à espessura da camada. A lei física que governa esse fenômeno é denominada lei de Fourier, estabelecida em 1822, representada na sua forma diferencial pela Equação (2).

$$\dot{h}_{cond} = -\lambda \frac{dT}{dx} \quad (2)$$

Na Equação (2), $\frac{dT}{dx}$ é o gradiente de temperatura na direção do fluxo de calor $[K/m]$ e λ é a condutibilidade térmica do material $[W/m \cdot K]$. É possível observar que o parâmetro da condutividade térmica, que é uma propriedade de cada material, determina a maior ou menor facilidade o na condução de calor. Como os materiais estudados apresentam variação de suas propriedades de acordo com a temperatura, a condutibilidade térmica deve ser analisada a cada passo de tempo.

2.2.2 Transferência de calor por convecção

A convecção é o modo de transferência de energia entre uma superfície sólida e o líquido ou gás adjacente que está em movimento, e envolve os efeitos combinados de condução e movimento de fluido. Quanto mais rápido for o movimento do fluido, maior será a transferência de calor por convecção. Na ausência de qualquer movimento de fluido em massa, a transferência de calor entre uma superfície sólida e o fluido adjacente é por condução pura. Apesar da complexidade do efeito da convecção, a taxa de transferência de calor por convecção é proporcional à diferença de temperatura e é convenientemente expressa pela lei de Newton [37].

A componente do fluxo de calor por convecção é determinada pela Equação (3).

$$\dot{h}_{net,c} = \alpha_c (\theta_g - \theta_m) \left[W/m^2 \right] \tag{3}$$

Onde α_c é o coeficiente de transferência de calor por convecção em $\left[W/m^2 K \right]$, θ_g é a temperatura do gás ao redor do membro exposto em $[^o C]$ e θ_m é a temperatura da superfície do elemento exposto ao fogo em $[^o C]$. O valor do coeficiente de convecção α_c depende da velocidade do fluido ou do gás e segundo o Eurocódigo EN 1994-1-2 [7], deve ser considerado igual a 4 $\left[W/m^2 \right]$ ou a 9 $\left[W/m^2 \right]$ se o efeito da radiação estiver incluído para superfícies não expostas ao fogo, 25$\left[W/m^2 \right]$ para superfícies expostas à curva de incêndio ISO834 e 50 $\left[W/m^2 \right]$ para superfícies expostas à curva de incêndio dos hidrocarbonetos.

2.2.3 Transferência do calor por radiação

A transferência de calor por radiação é definida pela transferência de energia através de ondas eletromagnéticas como o resultado de mudanças nas configurações eletrônicas de átomos ou moléculas. Ao contrário da condução e convecção, a transferência de calor por radiação não necessita da presença de um meio intermediário. A quantidade de energia que pode ser irradiada por uma superfície é definida pela lei de Stefan-Boltzmann.

Segundo Wang [28], quando a energia térmica radiante passa por um meio, qualquer objeto em seu caminho pode absorver, refletir e transmitir a radiação térmica incidente. Assim sendo, são utilizados os termos para cada uma das interações: absortância (χ), refletividade (ψ), e transmitância (τ) como fatores que possibilitam representar as frações de radiação térmica incidente que um corpo absorve, reflete e transmite, respectivamente.

$$\chi + \psi + \tau = 1 \tag{4}$$

Radiação de corpo negro

Os três fatores na Equação (4) são funções da temperatura, do comprimento da onda eletromagnética e das propriedades da superfície do corpo incidente. Geralmente são feitas simplificações para cálculos de engenharia de incêndio. Um caso extremo é que toda a radiação térmica incidente é absorvida pelo corpo, ou seja, $\chi = 1$. Um corpo tão ideal é chamado de corpo negro [28].

A radiação térmica do corpo negro é de fundamental importância para a transferência de calor por radiação. O corpo negro possui muitas propriedades especiais, mas a mais importante é que ele é um emissor perfeito. Isso significa que nenhum outro corpo pode emitir mais radiação térmica por unidade de superfície que um corpo negro na mesma temperatura. A quantidade total de radiação térmica (E_b) emitida por uma superfície de corpo negro é uma função apenas da sua temperatura e é dada pela lei de Stefan-Boltzmann, conforme a Equação (5).

$$E_b = \sigma T^4 \tag{5}$$

Onde σ é a constante de Stefan-Boltzmann, cujo valor é de $5{,}67\times10^{-8}\ \left[W/m^2K^4\right]$ e T é a temperatura absoluta em Kelvin.

Radiação de corpo cinzento

Nenhum material emite e absorve radiação de acordo com as leis dos corpos negros. Em geral, um termo adicional é necessário para definir a energia radiante de uma superfície emissora. Isso é definido como a emissividade ε. Esse termo é definido como a razão da energia total emitida por uma superfície em relação a que seria emitida por uma superfície de corpo negro em uma mesma temperatura [28]. Assim, a energia total radiante emitida por uma superfície qualquer é dada pela Equação (6).

$$E_b = \varepsilon \sigma T^4 \tag{6}$$

Em geral, a emissividade de uma superfície depende do comprimento de onda da energia radiante, da temperatura da superfície e do ângulo de radiação. Entretanto, se a emissividade é independente desses fatores, a superfície radiante é chamada de superfície de corpo cinzento. Radiação de corpo cinza é adotada em cálculos de engenharia de incêndio.

De acordo com a lei de Kirchhoff, a emissividade de uma superfície é igual à sua absortância. Assim sendo, a componente do fluxo de calor por radiação é determinada pela Equação (7).

$$\dot{h}_{net,r} = \phi \times \varepsilon_f \times \varepsilon_m \times \sigma \left[(\theta_r + 273)^4 - (\theta_m + 273)^4 \right] \left[W/m^2 \right] \tag{7}$$

Onde ϕ representa o fator de forma; ε_f é a emissividade do fogo; ε_m é a emissividade da superfície do elemento; θ_r é a temperatura de radiação efetiva do ambiente de incêndio em $[^oC]$ e θ_m é a temperatura da superfície do elemento exposto ao fogo em $[^oC]$.

Segundo o Eurocódigo EN 1993-1-2 [34], o valor para a emissividade do aço é dado por $\varepsilon_m = 0{,}7$. Este mesmo valor também é usado para a emissividade do concreto, de acordo com o Eurocódigo EN 1992-1-2 [35]. Para as chamas, segundo Eurocódigo EN 1991-1-2 [33], o valor da emissividade é de $\varepsilon_f = 1{,}0$. O fator de forma ϕ pode ser considerado igual a 1,0 quando não for especificado.

2.2.4 Fator de forma

O fator de forma ϕ na Equação (7) quantifica a relação geométrica entre a superfície emitindo a radiação e a superfície que a recebe. Isso depende das áreas e orientações da superfície, assim como a distância entre elas [3].

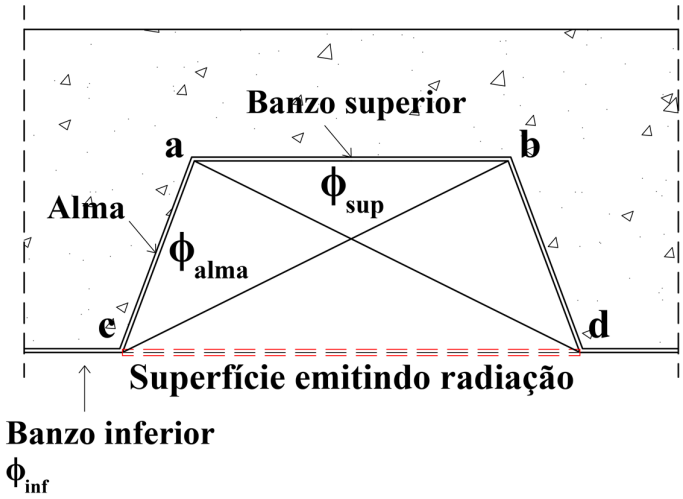


Figura 8: Esquema para o cálculo do fator de vista.

Para lajes mistas, o fator de forma do banzo inferior geralmente é dado como $\phi_{\text{inf}} = 1$. Os fatores de vista da alma e do banzo superior do perfil metálico são menores do que 1, devido a obstrução causada pela nervura. Esses valores podem ser calculados segundo o método de cordas cruzadas de Hottel [37], como demonstrado na Figura 8, sendo esse cálculo também adotado pelo Eurocódigo 4. As expressões resultantes para o fator de vista do banzo superior e da alma do perfil metálico, denominados ϕ_{sup} e ϕ_{alma}, respectivamente, são apresentados pelas equações (8), (9), (10) e (11), onde os parâmetros geométricos h_1, h_2, l_1, l_2 e l_3 para os tipos de lajes trapezoidais, estão definidos conforme a Figura 3, e para as lajes reentrantes, estão definidos conforme a Figura 4. O parâmetro l_1 é dado pelo comprimento total na parte superior da nervura, l_2 e l_3 são o comprimento do banzo inferior e do banzo superior do perfil metálico, respectivamente [3].

$$\phi_{\text{sup},trapezoidal} = \frac{ad + cb - ab - cd}{2ab} = \frac{\sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2} - \sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}}{l_3} \qquad (8)$$

$$\phi_{alma,trapezoidal} = \frac{ac + cd - ad}{2ac} = \frac{\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2} + (l_3 + l_1 - l_2) - \sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2}}{2\sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}} \quad (9)$$

$$\phi_{\sup,reentrante} = \frac{ad + cb - ab - cd}{2ab} = \frac{\sqrt{h_2^2 + \left(l_3 + \frac{l_1 - l_2}{2}\right)^2} - \sqrt{h_2^2 + \left(\frac{l_1 - l_2}{2}\right)^2}}{l_3} \quad (10)$$

$$\phi_{alma,reentrante} = \frac{ac + cd - ad}{2ac} = \frac{\sqrt{h_2^2 + \left(\frac{l_2 - l_1}{2}\right)^2} + (l_3 - (l_2 - l_1)) - \sqrt{h_2^2 + \left(l_3 + \frac{l_2 - l_1}{2}\right)^2}}{2\sqrt{h_2^2 + \left(\frac{l_2 - l_1}{2}\right)^2}} \quad (11)$$

Tabela 1: Fatores de vista calculados.

Geometria	$\phi_{\inf}$	ϕ_{alma}	$\phi_{\sup}$
L1/L2=84/40	1	0.563	0.720
L1/L2=105/60	1	0.567	0.723
L1/L2=112/135	1	0.094	0.137
L1/L2=108/135	1	0.102	0.160

2.3 Método simplificado de cálculo

O Eurocódigo EN 1994-1-2 [7] possibilita a determinação do tempo de resistência t_i de lajes mistas com deck em perfil metálico simplesmente apoiadas e contínuas, quando submetidas a um incêndio padrão. De acordo com o critério de isolamento térmico (I), a resistência ao fogo é dada pelo aumento de temperatura média (=140ºC) ou pelo aumento da temperatura máxima (=180ºC) em relação ao valor da temperatura média inicial (=20ºC) [7], assim o critério "I" pode ser determinado de acordo com a Equação (12).

$$t_i = a_0 + a_1.h_1 + a_2.\phi + a_3.A/L_r + a_4.1/l_3 + a_5.A/L_r\,1/l_3 \quad (12)$$

Em que:

$$A/L_r = h_2\,(l_1 + l_2)/2/\left[l_2 + 2\sqrt{h_2^2 + ((l_1 - l_2)/2)^2}\right] \quad (13)$$

Sendo t_i a resistência ao fogo de acordo com o isolamento, [min], A o volume de concreto da nervura por metro de comprimento da nervura, [mm³/m], L_r a área exposta por metro de comprimento da nervura, [mm²/m], $\frac{A}{Lr}$ é o fator de geometria da nervura, [mm], ϕ o fator de vista do banzo superior, l_3 o comprimento do banzo superior, conforme Figura 3 e Figura 4, [mm].

Os fatores parciais a_i são propostos para concreto com peso normal (NC), de acordo com a Tabela 2.

Tabela 2: Fatores parciais utilizados para o cálculo da resistência ao fogo (NC).

a_0	a_1	a_2	a_3	a_4	a_5
[min]	[min/mm]	[min]	[min/mm]	[min.mm]	[min]
-28.8	1.55	-12.6	0.33	-735	48

Em um estudo anterior [38], Piloto *et al.* concluíram que a resistência ao fogo de lajes mistas não depende da espessura do deck metálico, mas sim da espessura de concreto contínua, essa que é uma relação quadrática do parâmetro h_1. Esses resultados podem ser observados na Tabela 3.

Tabela 3: Resistência ao fogo de lajes de perfil trapezoidal em minutos completos (critério de isolamento).

Geometria	h1 [mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=84/40	t_i [min]	34	50	65	81	96	112	127	143	158	174	189	205	220	236
L1/L2=105/60	t_i [min]	38	53	69	84	100	115	131	146	162	177	193	208	224	239

A resistência ao fogo também foi calculada para duas geometrias reentrantes através das determinações do Eurocódigo 4 [7], conforme Tabela 4.

Tabela 4: Resistência ao fogo de lajes de perfil reentrante em minutos completes (critério de isolamento).

Geometria	h1 [mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=112/135	t_i [min]	54	69	85	100	116	131	147	162	178	193	209	224	240	255
L1/L2=108/135	t_i [min]	51	66	82	97	113	128	144	159	175	190	206	221	237	252

Já no Brasil, o método simplificado de cálculo para o critério de isolamento é apresentado no Anexo C da NBR 14323:2013 [9], no qual para que o critério de isolamento térmico (I) seja atendido, a espessura efetiva da laje h_{ef} calculada de acordo com a equação (14) deverá ser maior ou igual ao valor dado na Tabela 5, conforme o tempo requerido de resistência ao fogo.

$$h_{ef} = h_1 + \frac{h_2 \cdot (l_1 + l_2)}{2 \cdot (l_1 + l_3)} \tag{14}$$

As dimensões h_1, h_2, l_1, l_2 e l_3 são definidas para lajes trapezoidais e reentrantes na Figura 3 e Figura 4, respectivamente.

Tabela 5: Espessura efetiva mínima para determinado tempo requerido de resistência ao fogo para o isolamento térmico. Fonte: ABNT NBR 14323:2013 [9], adaptado.

Tempo requerido de resistência ao fogo (min)	Espessura efetiva mínima h_{ef} (mm)
30	60
60	80
90	100
120	120
180	150

2.4 Curvas de incêndio nominais

O Eurocódigo EN 1991-1-2 [33], indica três curvas nominais de incêndio distintas, sendo elas a curva de incêndio padrão ISO834 [8], a curva de incêndio de

hidrocarbonetos e a curva de incêndio de elementos exteriores. A Figura 9 apresenta sobrepostas as três curvas propostas pelo Eurocódigo.

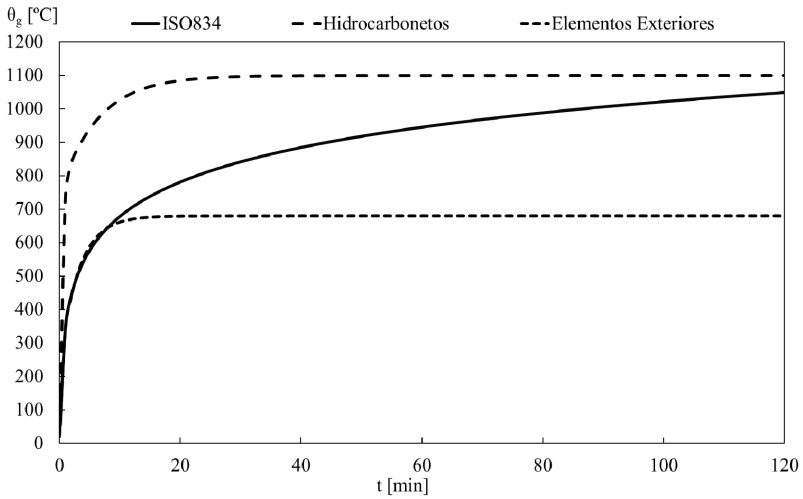


Figura 9: Curvas de incêndio nominais.

Neste trabalho será utilizada a curva de incêndio padrão ISO834 [8], melhor definida na seção seguinte 2.4.1.

2.4.1 Curva de Incêndio Padrão ISO834

O Eurocódigo EN 1991-1-2 [33] em conformidade com a norma ISO834 [8] fornece a equação que prevê a variação da temperatura em função do tempo, sendo o combustível a base de celulose como recomendação para determinar a resistência ao fogo de elementos estruturais quando sujeitos a condições de incêndio padrão.

A curva de incêndio padrão ISO834 [8] é definida pela expressão (15).

$$\theta_g = 20 + 345 \log_{10}(8t + 1) \tag{15}$$

Sendo θ_g a temperatura dos gases no compartimento em chamas em $[^{o}C]$ e t o tempo em minutos.

A curva de incêndio padrão tem sua evolução de temperatura em função do tempo apresentada no gráfico da Figura 9.

2.5 Propriedades térmicas dos materiais

Como o objetivo do trabalho é simular numericamente a equação do calor de forma a prever a distribuição das temperaturas em lajes compostas de elementos mistos é necessário o conhecimento das variáveis que interferem no desempenho térmico destes elementos.

2.5.1 Aço

Segundo o Eurocódigo EN 1993-1-2 [34], o calor específico é a quantidade de energia necessária para elevar a temperatura em 1ºC. O calor específico do aço c_a deve ser determinado através das expressões (16) a (19).

$20\ [^{o}C] \leq \theta_a < 600\ [^{o}C]$:

$$c_a = 425 + 7{,}73\times10^{-1}\theta_a - 1{,}69\times10^{-3}\theta_a^2 + 2{,}22\times10^{-6}\theta_a^3\ [J/kgK] \quad (16)$$

$600\ [^{o}C] \leq \theta_a < 735\ [^{o}C]$

$$c_a = 666 + \left(\frac{13002}{738-\theta_a}\right)[J/kgK] \quad (17)$$

$735\ [^{o}C] \leq \theta_a < 900\ [^{o}C]$

$$c_a = 545 + \left(\frac{17820}{\theta_a - 731}\right)[J/kgK] \quad (18)$$

$900\ [^{o}C] \leq \theta_a \leq 1200\ [^{o}C]$

$$c_a = 650\ [J/kgK] \quad (19)$$

Em que θ_a representa a temperatura do aço em $[^{o}C]$. A variação do calor específico do aço em função da temperatura pode ser observada no gráfico representado na Figura 10, sendo que a variação brusca desta propriedade está relacionada com a transformação alotrópica, da fase ferrítica para a fase austenítica.

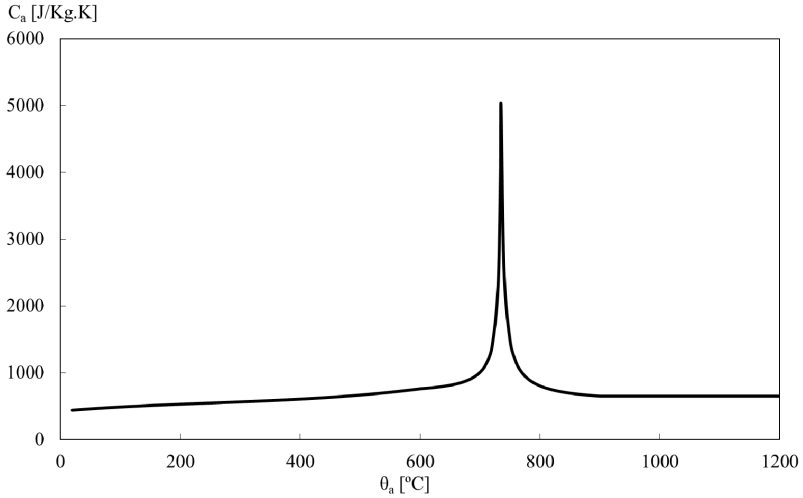


Figura 10: Calor específico do aço em função da temperatura.

A condutividade térmica do aço λ_a, segundo o Eurocódigo EN 1993-1-2 [34], é determinada através das expressões (20) e (21).

$20\ [^{o}C] \leq \theta_a < 800\ [^{o}C]$

$$\lambda_a = 54 - 3{,}33 \times 10^{-2}\,\theta_a\ [W/mK] \tag{20}$$

$800\ [^{o}C] \leq \theta_a \leq 1200\ [^{o}C]$

$$\lambda_a = 27{,}3\ [W/mK] \tag{21}$$

Em que θ_a representa a temperatura do aço em $[^{o}C]$. A variação da condutibilidade térmica do aço em função da temperatura pode ser observada no gráfico representado na Figura 11.

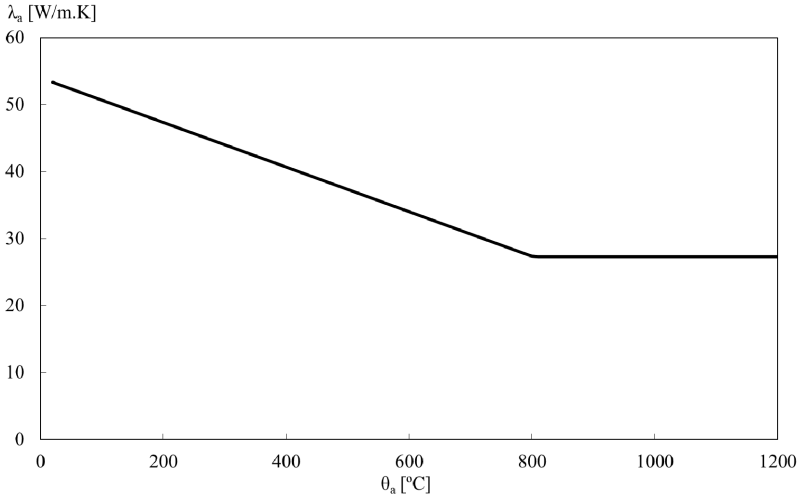


Figura 11: Condutibilidade térmica do aço em função da temperatura.

A densidade do aço ρ_a permanece constante, mesmo quando o material se encontra submetido a altas temperaturas. O valor desta propriedade é estabelecida como $\rho_a = 7850\ [kg/m^3]$ para o intervalo de temperatura $20\ [^{o}C] \leq \theta_a \leq 1200\ [^{o}C]$.

A densidade do aço em função da temperatura pode ser observada através do gráfico representado na Figura 12.

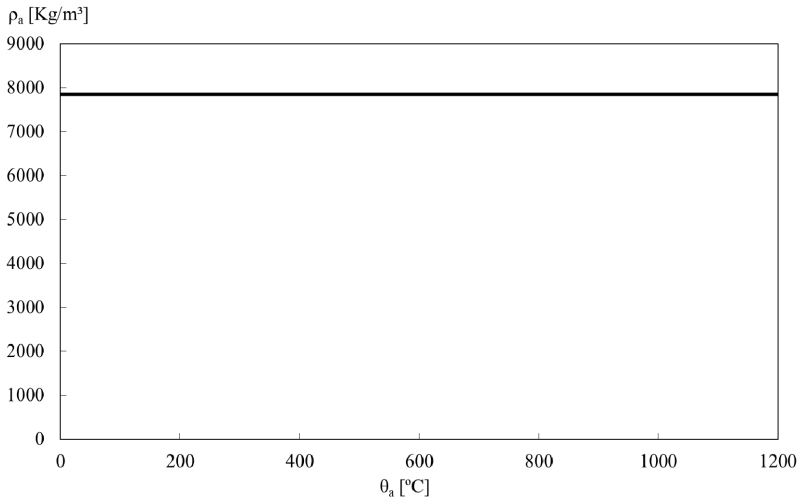


Figura 12: Densidade do aço em função da temperatura.

2.5.2 Concreto

Segundo o Eurocódigo EN 1992-1-2 [35], o calor específico do concreto c_p para um teor de umidade $(u = 0\%)$, utilizando agregado silicioso ou calcário pode ser determinado através das equações (22) a (25).

$20\ [^{o}C] \leq \theta_c \leq 100\ [^{o}C]$

$$c_p = 900\ [J/kgK] \tag{22}$$

$100\ [^{o}C] < \theta_c \leq 200\ [^{o}C]$

$$c_p = 900 + (\theta_c - 100)\ [J/kgK] \tag{23}$$

$200\ [^{o}C] < \theta_c \leq 400\ [^{o}C]$

$$c_p = 1000 + \left(\frac{\theta_c - 200}{2}\right)[J/kgK] \tag{24}$$

$400\ [^{o}C] < \theta_c \leq 1200\ [^{o}C]$

$$c_p = 1100\ [J/kgK] \tag{25}$$

Em que θ_c representa a temperatura do concreto em $[^{o}C]$.

Ainda de acordo com o Eurocódigo EN 1992-1-2 [35], quando o teor de umidade não for considerado explicitamente no método de cálculo, a função dada para o calor específico do concreto utilizando agregado silicioso ou calcário, pode ser modelada por um valor constante $c_{p,peak}$, situado entre 100ºC e 115ºC, decrescendo linearmente entre 115ºC e 200ºC. As equações (26) a (28) representam os valores constantes adotados para o calor específico do concreto de acordo com o teor de umidade.

$$c_{p,peak}(u = 0\%) = 900\ [J/kgK] \tag{26}$$
$$c_{p,peak}(u = 1{,}5\%) = 1470\ [J/kgK] \tag{27}$$
$$c_{p,peak}(u = 3\%) = 2020\ [J/kgK] \tag{28}$$

Através da Figura 13, pode-se observar graficamente o calor específico do concreto para os vários valores de teor de umidade.

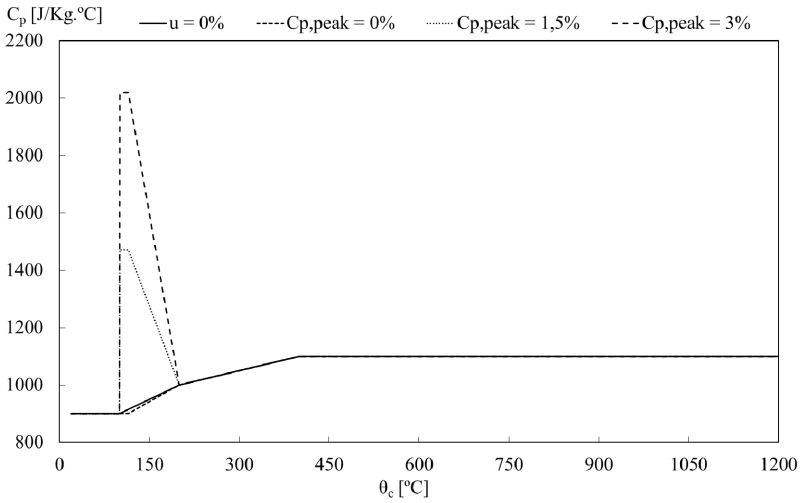


Figura 13: Calor específico do concreto em função da temperatura.

No presente trabalho, foi considerado um teor de umidade de 3% para o concreto, assim, o modelo permite ter em conta a vaporização das moléculas de água presentes no material.

A densidade do concreto ρ_c varia em função da elevação da temperatura, devido à perda de água existente no concreto. Para a temperatura ambiente, o concreto possui sua densidade igual a 2300 $\left[kg/m^3\right]$. O Eurocódigo EN 1992-1-2 [34] define a variação da densidade através das equações (29) a (32).

$20\ [^oC] \leq \theta_c \leq 115\ [^oC]$

$$\rho_c = 2300\ \left[kg/m^3\right] \tag{29}$$

$115\ [^oC] < \theta_c \leq 200\ [^oC]$

$$\rho_c = 2300 \times \left(1 - 0{,}02\left(\frac{\theta_c - 115}{85}\right)\right)\left[kg/m^3\right] \tag{30}$$

$200\ [^oC] < \theta_c \leq 400\ [^oC]$

$$\rho_c = 2300 \times \left(0{,}98 - 0{,}03\left(\frac{\theta_c - 200}{200}\right)\right)\left[kg/m^3\right] \tag{31}$$

$400\ [^oC] < \theta_c \leq 1200\ [^oC]$

$$\rho_c = 2300 \times \left(0{,}95 - 0{,}07\left(\frac{\theta_c - 400}{800}\right)\right)\left[kg/m^3\right] \tag{32}$$

Em que θ_c representa a temperatura do concreto em $[^oC]$.

A densidade do concreto em função da temperatura pode ser observada através do gráfico representado na Figura 14.

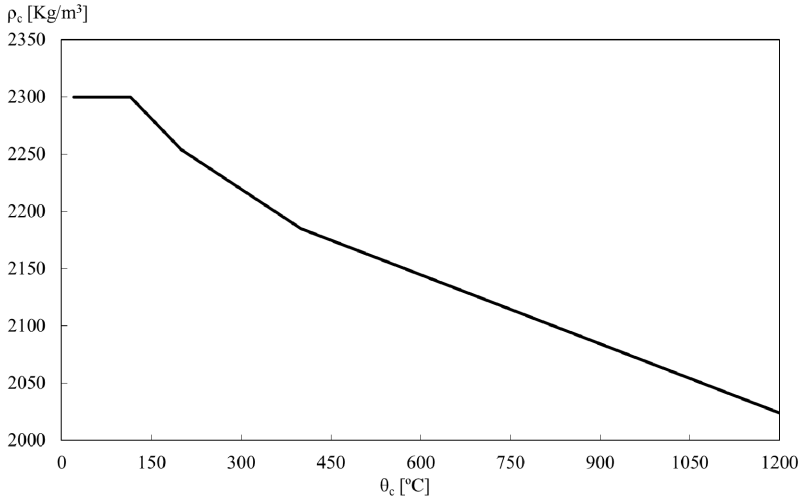


Figura 14: Densidade do concreto em função da temperatura.

De acordo com o Eurocódigo EN 1992-1-2 [35], a condutibilidade térmica do concreto λ_c deve ser tomada entre os seus limites inferior e superior em função da elevação da temperatura.

O limite inferior é determinado pela expressão (33).

$20\ [^oC] \leq \theta_c \leq 1200\ [^oC]$

$$\lambda_c = 1{,}36 - 0{,}136\left(\frac{\theta_c}{100}\right) + 0{,}0057\left(\frac{\theta_c}{100}\right)^2\ [W/mK] \tag{33}$$

Já o limite superior é determinado pela expressão (34).

$20\ [^oC] \leq \theta_c \leq 1200\ [^oC]$

$$\lambda_c = 2 - 0{,}2451\left(\frac{\theta_c}{100}\right) + 0{,}0107\left(\frac{\theta_c}{100}\right)^2\ [W/mK] \tag{34}$$

Sendo que θ_c representa a temperatura do concreto em $[^oC]$.

No presente trabalho, e de acordo com o Eurocódigo EN 1994-1-2 [7], foi utilizado o limite superior para a condutibilidade térmica do concreto como poderá ser observado graficamente através da Figura 15.

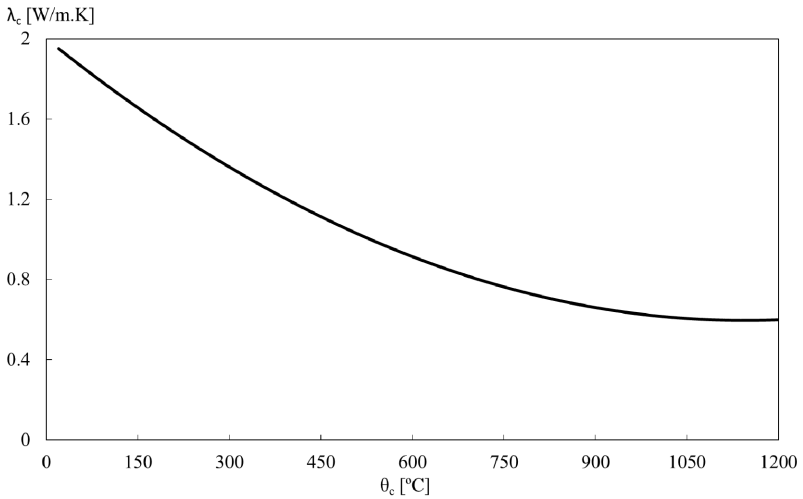


Figura 15: Condutibilidade térmica do concreto em função da temperatura.

2.6 Segurança contra incêndios em edifícios

2.6.1 Tempo requerido de resistência ao fogo

O tempo requerido de resistência ao fogo é definido como o tempo em que os elementos estruturais de um edifício devem garantir certas funções de suporte de carga (R), de isolamento térmico (I) e de estanqueidade (E) durante todo o período de um incêndio. Para fins de normalização, esse tempo deve ser calculado através de uma curva de incêndio padrão, o cálculo do tempo de resistência ao fogo pode ser realizado através da curva padrão ISO 834, ou a curva americana estabelecida na norma ASTM E119 "*Standard Test Methods for Fire Tests of Building Construction and Materials*", ou também a curva da norma inglesa BS 476 "*Fire tests on building materials and structures*". Essas normas têm como objetivo não apenas analisar a resposta dos materiais, produtos ou elementos sobre a exposição ao fogo, mas também a capacidade de resistência da construção, definindo a classe de resistência ao fogo que o elemento deve possuir, em função do risco de incêndio, tipo de ocupação, dos materiais que é constituída e também de sua altura.

Os regulamentos de Portugal apresentam as exigências requeridas aos elementos estruturais e também elementos apenas de compartimentação para a classificação dos elementos através de algumas qualificações básicas: (R) que significa a capacidade de suporte de carga, (I) para o isolamento térmico, e (E) que considera a estanqueidade do elemento contra as chamas e gases quentes. Para cada qualificação existem nove classes que indicam o tempo em que essa estrutura se qualifica. Por exemplo, um elemento REI 90 deve apresentar capacidade de suporte de carga, isolamento térmico e estanqueidade durante 90 minutos cumprindo a função para qual foi dimensionado, sendo que (R) prevalece sobre (E) e este último prevalece sobre (I).

A ideia do dimensionamento de elementos para um determinado tempo de resistência ao fogo tem como objetivo garantir que a estrutura consiga desempenhar sua função durante um tempo mínimo, para que a evacuação com segurança dos ocupantes da edificação ocorra, visando também o acesso das operações de combate ao incêndio e minimizando os danos nas edificações adjacentes.

2.6.2 Contextualização dos Aspectos Normativos

Internacionalmente a padronização dos testes de resistência ao fogo, em forma de normas e recomendações, foi estabelecida pela ASTM, a "*American Society for Testing and Materials*" em 1911, sob o título "*Standard Tests for Fireproofs Constructions*". Em 1932, a BSI "*British Standard Institution*", publicou a norma BS 476, intitulada "*Fire Tests on Buildings, Materials and Structures*", a qual, com as devidas revisões e ampliações ainda é utilizada, e tem por base ensaios de elementos isolados em fornos de resistência ao fogo.

No Brasil, foi a partir da década de 1970 que surgiram os principais regulamentos existentes referente ao desempenho de estruturas em situações de incêndio, que eram basicamente a adaptação da legislação estrangeira. As normas de segurança contra incêndio tiveram por finalidade fixar os requisitos mínimos necessários nas edificações e no exercício das atividades profissionais, estabelecendo especificações para a segurança contra incêndio [39].

Atualmente, a norma NBR 14323:2013 [9], estabelece os critérios para o projeto de estruturas de aço e concreto em situações de incêndio. Já a NBR 14432:2001 [40], que trata das exigências de resistência ao fogo de elementos construtivos de edificações, se encontra em processo de revisão.

Na Europa, a década de 1980 marca o lançamento dos primeiros códigos europeus, os Eurocódigos, que em 1989 se tornariam as normas europeias – EN, sob a responsabilidade do Comitê Europeu de Normalização. O conjunto de diretrizes abrange um total de dez normas técnicas, dividas em diversas partes que estabelecem especificações técnicas em três idiomas oficiais, o inglês, francês e alemão, visando unificar os critérios e normativas de cálculo e dimensionamento de estruturas.

Em Portugal o Eurocódigo EN 1991-1-2, "*Actions on Structures Exposed to Fire*", trata da ação térmica em estruturas expostas ao fogo. Já o Eurocódigo EN 1994-1-2, "*Design of Composite Steel and Concrete Structures*", trata em seu texto principal, juntamente com seus anexos os conceitos e regras necessárias para o projeto estrutural de incêndio de estruturas mistas de aço e concreto, sendo esse de extrema importância para o escopo deste trabalho.

2.6.3 Ações de segurança contra incêndios no Brasil

Em 2001 a Associação Brasileira de Normas Técnicas (ABNT) publicou as "*Exigências de resistência ao fogo de elementos construtivos de edificações – Procedimento*" [40]. Esta norma visou estabelecer as condições a serem atendidas pelos elementos estruturais e de compartimentação, para que durante um incêndio, não ocorra o colapso estrutural do edifício.

Em 2015, o Corpo de Bombeiros do Estado de São Paulo publicou a INSTRUÇÃO TÉCNICA Nº 08/2018 "*Segurança estrutural contra incêndio*" [41], esta que, como a NBR 14432, visa estabelecer as condições a serem atendidas pelos elementos estruturais e de compartimentação que integram as edificações. Esta instrução técnica é o documento mais atualizado para determinação do tempo requerido de resistência ao fogo no Brasil.

Nesta seção, será utilizado como referência a Instrução Técnica Nº 08/2018 uma vez que este é o documento mais atualizado em vigor. Esta regulamentação de segurança entende que existem 12 tipos de ocupação principais, que são subdivididas em suas categorias de acordo com o seu uso. As edificações estão divididas em grupos de A até M, existindo também subdivisões determinando maiores características do uso da edificação. Por exemplo, uma edificação do tipo comercial pode ser classificada como um comércio com baixa carga de incêndio, ou de pequeno porte C-1, comércio com média e alta carga de incêndio, ou de grande e médio porte C-2 e centros comerciais C-3,

implicando assim diferentes tempos requeridos de resistência ao fogo. Existe ainda outra categorização em 8 classes, de P1 até P8 que está relacionada à altura da edificação que cria subdivisões para edifícios de até 250m, e também duas classes S1 e S2, relativas a profundidade do subsolo. As várias classificações e o tempo de resistência requeridos estão descritos na Figura 16, adaptada da Instrução Técnica nº 08/2015 [41].

Grupo	Ocupação/Uso	Divisão	Profundidade do subsolo		Altura da edificação							
			Classe S2 Hs > 10m	Classe S1 Hs <= 10m	Classe P1 h ≤ 6m	Classe P2 6m < h ≤ 12m	Classe P3 12m < h ≤ 23m	Classe P4 23m < h ≤ 30m	Classe P5 30m < h ≤ 80m	Classe P6 80m < h ≤ 120m	Classe P7 120m < h ≤ 150m	Classe P8 150m < h ≤ 250m
A	Residencial	A-1 a A-3	90	60	30	30	60	90	120	120	150	180
B	Serviços e hospedagem	B-1 e B-2	90	60	30	60	60	90	120	150	180	180
C	Comercial Varejista	C-1	90	60	60	60	60	90	120	150	150	180
		C-2 e C-3	90	60	60	60	60	90	120	150	150	180
D	Serviços profissionais, pessoais e técnicos	D-1 a D-4	90	60	30	60	60	90	120	120	150	180
E	Educacional e cultura física	E-1 a E-6	90	60	30	30	60	90	120	120	150	180
F	Locais de reunião de público	F-1, F-2, F-5, F-6, F-8, F-10	90	60	60	60	60	90	120	150	180	-
		F-3, F-4, F-7	90	60	Ver item A.2.3.3.		30	60	60	90	120	-
		F-9	90	60	30	60	60	90	120	-	-	-
G	Serviços automotivos	G-1 e G-2 não abertos lateralmente e G-3 a G-5	90	60	30	60	60	90	120	120	150	-
		G-1 e G-2 abertos lateralmente	90	60	30	30	30	30	60	120	120	-
H	Serviços de saúde e institucionais	H-1 e H-4	90	60	30	60	60	90	120	150	180	-
		H-2, H-3, H-5 e H-6	90	60	30	60	60	90	120	150	180	-
I	Industrial	I-1	90	60	30	30	30	60	120	-	-	-
		I-2	120	90	30	30	60	90	120	-	-	-
		I-3	120	90	60	60	90	120	120	-	-	-
J	Depósitos	J-1	60	30	Ver item A.2.3.4.		30	30	60	-	-	-
		J-2	90	60	60	60	60	60	60	-	-	-
		J-3	90	60	60	60	60	120	120	-	-	-
		J-4	120	90	60	60	90	120	120	-	-	-
L	Explosivos	L-1, L-2 e L-3	120	120	120	-				-	-	-
M	Especial	M-1	150	150	150	-				-	-	-
		M-2	-		120	120	-	-	-	-	-	-
		M-3	120	90	60	60	90	120	-	-	-	-
		M-4	120	90	90	90	120	120	120	150	-	-

Figura 16: Tempo de resistência ao fogo segundo a classificação das edificações brasileiras.
Fonte: Instrução Técnica nº 08/2015 [41], adaptado.

No Brasil, as lajes mistas de concreto seguem as recomendações normativas da ABNT NBR 14323:2013 [9] na qual os elementos necessitam apresentar uma altura efetiva mínima que influencia diretamente na resistência ao fogo. Esses elementos são divididos em quatro categorias, apresentando um tempo de resistência ao fogo de 30, 60, 90 e 120 minutos. A Tabela 5, previamente citada, mostra os tempos de resistência ao fogo para uma laje mista de concreto e aço.

A norma brasileira também permite uma redução no valor de sua espessura efetiva mínima requerida, no critério de isolamento térmico, caso a laje seja revestida na face superior por material incombustível. Essa redução deve ser calculada em função da relação entre as condutividades térmicas dos dois materiais. Caso a laje seja constituída de um concreto de baixa densidade, os valores apresentados na Tabela 5 poderão ser reduzidos em 10%.

2.6.4 Ações de segurança contra incêndio em Portugal

O regulamento técnico nacional de Portugal entrou em vigor no começo de 2009. O Decreto -Lei n.º 220/2008, de 12 de Novembro foi alterado pelo Decreto-Lei n.º 224/2015 de 9 de outubro, que aprovou o regime jurídico de segurança contra incêndio em edifícios (SCIE), determina, por meio da Portaria n.º 1532/2008 de 29 de Dezembro, publicada pelo Ministério da administração interna, as disposições e técnicas gerais do regime jurídico de Segurança Contra Incêndio em Edifícios – SCIE [42].

As exigências requeridas para a garantia da segurança contra incêndio de um edifício, partes de edifícios ou recintos estão classificadas em 12 utilizações tipo, 4 categorias de risco e 3 classes de resistência ao fogo.

A regulamentação técnica disposta pela SCIE visa a segurança contra incêndio em edifícios e recintos no que se refere às condições exteriores comuns, às condições de comportamento ao fogo, isolamento e proteção, às condições de evacuação, às condições das instalações técnicas e equipamentos e sistemas de segurança e às condições de autoproteção, sendo estas últimas igualmente aplicáveis aos edifícios e recintos já existentes à data de entrada em vigor do Decreto - Lei n.º 220/2008, de 12 de Novembro [42].

A Tabela 6 demonstra a classificação dos edifícios e recintos quanto a utilização tipo.

Tabela 6: Utilizações tipo de edifícios e recintos. Fonte: Nota técnica n.º 01 - Utilizações-tipo de edifícios e recintos [43].

Classes de construção	Uso
Tipo I	Habitacionais
Tipo II	Estacionamentos
Tipo III	Administrativos
Tipo IV	Escolares
Tipo V	Hospitalares e lares de idosos
Tipo VI	Espetáculos e de reuniões públicas
Tipo VII	Hoteleiros e restauração
Tipo VIII	Comerciais e gares de transporte
Tipo IX	Desportivos e de lazer
Tipo X	Museus e galerias de arte
Tipo XI	Bibliotecas e arquivos
Tipo XII	Industrias, oficinas e armazéns

A Tabela 7 representa a classificação do edifício quanto a categoria de risco levando em consideração a altura efetiva do edifício.

Tabela 7: Classificação em relação a categoria de risco. Fonte: Nota técnica n.º 06 – Categorias de risco [44].

Categoria	Altura do edifício (h)	Número de pavimentos abaixo do plano de referência (n)
1ª	h ≤ 9m	≤ 1
2ª	9m < h ≤ 28m	≤ 3
3ª	28m < h ≤ 50m	≤ 5
4ª	h > 50m	> 5

A Tabela 8 demonstra a resistência ao fogo padrão mínima imposta pela Portaria n.º 1532/2008 [42] de elementos com função de apenas suporte ou de suporte e compartimentação.

Tabela 8: Resistência ao fogo padrão mínima de elementos estruturais de edifícios. Fonte: Portaria n.º 1532/2008 [42], adaptado.

Utilização-tipo	Categorias de risco				Função do elemento estrutural
	1ª	2ª	3ª	4ª	
I, III, IV, V, VI, VII, VIII, IX e X	R30	R60	R90	R120	Apenas suporte
	REI 30	REI 60	REI 90	REI 120	Suporte e compartimentação
II, XI e XII	R60	R90	R120	R180	Apenas suporte
	REI 60	REI 90	REI 120	REI 180	Suporte e compartimentação

2.7 Critérios de resistência

Lajes mistas de concreto e aço desempenham duas funções principais, resistir a carga aplicada e separar compartimentos. Certos critérios devem ser respeitados, como a capacidade de carga (R) que representa a resistência contra ruina ou deformação excessiva sobre carga estrutural. Também deve ser levado em consideração o isolamento (I), este que limita o aumento de temperatura no lado não exposto da laje, e pôr fim, a

integridade (E) que nada mais é do que a habilidade da laje para resistir à penetração das chamas ou gases quentes pelas fissuras e aberturas causadas durante a deformação da laje submetida ao calor [10]. O tempo necessário para falha em qualquer um dos casos apresentados (REI) é dado como a classificação de resistência ao fogo da laje, mesmo que o critério de falha de outra categoria não tenha sido atingido até muito tempo depois [10].

2.7.1 Capacidade de carga

O critério de capacidade de carga requer que a laje não pare de desempenhar a função de resistir à carga para qual foi construída, e durante os testes, o colapso da laje é evitado visando a prevenção contra danos que esse evento pode causar na fornalha e em outros equipamentos. Isso é obtido através da limitação da defecção vertical ou através da taxa de deflexão vertical [10].

2.7.2 Isolamento

Para que o critério de isolamento seja cumprido, a temperatura máxima no lado não exposto não deve ultrapassar 180ºC em qualquer ponto o valor da temperatura média inicial, ou a temperatura média no lado não exposto não deve exceder 140ºC o valor da temperatura média inicial. Devido à forma perfilada da laje, cuidados devem ser levados em consideração na análise para que o critério de isolamento seja verificado. Teoricamente, as temperaturas nos pontos mais finos da laje deveriam ser mais altas do que nos pontos mais grossos, entretanto, testes práticos mostram que na verdade essas diferenças são pequenas. Na teoria, também é possível verificar que a passagem de calor pelas juntas resulte em uma distribuição de temperatura não uniforme no lado não exposto. Contudo, lajes mistas são produzidas *in situ* e essa complicação não deverá ocorrer [10].

2.7.3 Integridade

Este critério é a medida de habilidade da construção resistir à passagem das chamas e gases quentes pelas fissuras. Ele é determinado pela ignição das almofadas de algodão colocadas próximas ao lado não exposto da laje. A maioria das normas nacionais são baseadas nesse princípio apesar de algumas diferenças existirem [10].

Para lajes mistas de aço e concreto, o critério de integridade não é difícil de se verificar. A principal razão é que, como mencionado antes, a laje é realizada *in situ*. Isso significa que as juntas são adequadamente seladas. Qualquer fissura que ocorra no concreto durante a exposição ao fogo não é importante porque o perfil metálico vai prevenir a penetração das chamas e gases quentes [10].

3 MÉTODOS AVANÇADOS DE CÁLCULO

Os métodos avançados de cálculo permitem prever o comportamento e o desempenho térmico de diversos elementos estruturais. Para a análise das lajes mistas estudadas neste trabalho, um dos métodos avançados de cálculo foi desenvolvido no Matlab R2017a através da toolbox "*Partial Differential Equation Toolbox™*" e o outro através da ferramenta computacional ANSYS® v. 18.2. Os dois modelos são baseados no método de elementos finitos para a modelagem numérica 2-D de uma seção da laje mista composta de concreto e aço.

Num modelo inicial, foi desenvolvida a discretização por diferenças finitas da equação do calor, contudo essa solução apresentou uma grande complexidade para a criação de geometrias irregulares, o que é o escopo deste trabalho. Por esta razão optou-se pela utilização da PDE toolbox, em vez de implementar o elemento finito de raiz.

Foi utilizado um modelo de elementos finitos bidimensional para as simulações numéricas. A seção transversal da laje foi discretizada numa malha de elementos finitos para resolver a análise térmica transiente não linear, onde é considerado o contato térmico perfeito entre os elementos e os materiais. O método dos elementos finitos requer a solução da equação (35) no domínio da seção transversal (Ω) e da equação (36) para as condições de contorno expostas ao fogo (∂Ω).

$$\nabla\left(\lambda_{(T)}.\nabla T\right) = \rho_{(T)}.Cp_{(T)}.\partial T/\partial t \qquad (\Omega) \qquad (35)$$

$$\lambda_{(T)}.\nabla T.\vec{n} = \alpha_c\left(T_g - T_m\right) + \phi.\varepsilon_m.\varepsilon_f.\sigma.\left(T_g^4 - T_m{}^4\right) \qquad (\partial\Omega) \qquad (36)$$

Nestas equações: T_m representa a temperatura do material; $\rho_{(T)}$ define a massa específica; $Cp_{(T)}$ define o calor específico; $\lambda_{(T)}$ define a condutividade térmica; α_c especifica o coeficiente de convecção; T_g representa a temperatura do gás do compartimento de incêndio, usando um fogo padrão ISO 834 [8] aplicado à parte inferior da laje, ϕ especifica o fator de vista; ε_m representa a emissividade de cada material (em

ambos os casos é igual a 0,7); ε_f especifica a emissividade do fogo e σ representa a constante de Stefan-Boltzmann.

A análise paramétrica utiliza 4 valores diferentes para a espessura do deck de aço (SDT = 0.7, 0.8, 1.0 e 1.2 mm) das lajes trapezoidais e 3 valores para o deck de aço reentrante (SDT = 0.9; 1.0; e 1.2 mm), sendo essas espessuras baseadas em modelos comerciais. Foram ainda consideradas duas diferentes geometrias para as lajes trapezoidais, uma fictícia: L1 / L2 (84/40 mm / mm) e uma comercial L1 / L2 (105/60 mm / mm) baseada no modelo comercializado pela empresa O-FELIZ [45] e duas geometrias para as lajes reentrantes, que assim como as trapezoidais, são compostas por uma fictícia: L1 / L2 (108/135 mm / mm) e uma comercial: L1 / L2 (112/135 mm / mm) [46]. Também foram adotados 14 valores diferentes para a profundidade do concreto acima do convés (h1 = 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160 e 170 mm). Todas as restantes dimensões permanecem fixas.

3.1 Modelo inicial

Nesta secção apresenta-se uma pequena descrição do trabalho desenvolvido para a implementação de um modelo numérico que visa resolver a equação de transferência de calor, baseado na discretização por diferenças finitas. O domínio consiste numa superfície retangular constituída por um material cujas propriedades térmicas dependem da temperatura. Existem igualmente condições de fronteira específicas para cala um dos lados. No lado inferior (Sul) incide um fluxo de calor constante, no lado superior (Norte) existe perda de calor por radiação e convecção, nos lados esquerdo (Oeste) e direito (Este) existe isolamento.

3.1.1 Discretização da equação do calor

A equação de transferência de calor é baseada no equilíbrio de energia, fazendo um balanço em duas direções do espaço, sendo apresentada na Equação (35), podendo ser reescrita através da Equação (37).

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y} \right) \tag{37}$$

Em que ρ representa a densidade do material, k representa a condutividade térmica e c_p é o calor específico do material.

Pela discretização por diferenças finitas considera-se uma malha ortogonal, regular com espaçamentos $\Delta x \times \Delta y$. Desta forma o valor da temperatura pode ser calculado em cada um dos nós da malha.

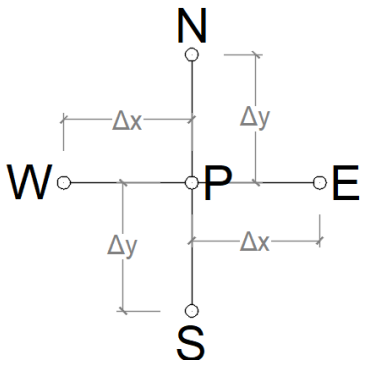


Figura 17 – Um nó da malha discretizada por diferenças finitas

Considerando um nó genérico P, este tem quatro nós adjacentes, nomeadamente, os nós N (Norte), E (Este), W (Oeste) e S (Sul), tal como ilustrado na Figura 17. A discretização da Equação (37), no nó P, por diferenças finitas, centradas no espaço e com avanço no tempo, através de um esquema implícito, conduz à seguinte equação e consequentes simplificações:

$$\rho c\left(\frac{T_p - T_p^o}{\Delta t}\right) = \frac{k_E\left(\frac{T_E - T_P}{\Delta x}\right) - k_W\left(\frac{T_p - T_w}{\Delta x}\right)}{\Delta x} + \frac{k_N\left(\frac{T_N - T_P}{\Delta y}\right) - k_S\left(\frac{T_p - T_S}{\Delta y}\right)}{\Delta y} \quad (38)$$

$$(=)\frac{\Delta x \Delta y \rho c\left(T_p - T_p^o\right)}{\Delta t} = \frac{\Delta y k_E}{\Delta x}\left(T_E - T_p\right) - \frac{\Delta y k_W}{\Delta x}\left(T_p - T_W\right) + \frac{\Delta x k_N}{\Delta y}\left(T_N - T_p\right) - \frac{\Delta x k_S}{\Delta y}\left(T_p - T_S\right) \quad (39)$$

$$(=)A_{P_O}\left(T_p - T_p^o\right) = A_E\left(T_E - T_p\right) - A_W\left(T_p - T_W\right) + A_N\left(T_N - T_p\right) - A_S\left(T_p - T_S\right) \quad (40)$$

$$(=)A_{p_o}T_p - A_{p_o}T_p^o = -A_E T_E - A_E T_p - A_W T_p + A_W T_W + A_N T_N - A_N T_p - A_S T_p + A_S T_S \quad (41)$$

$$(=)(A_{p_o} + A_E + A_W + A_N + A_S)T_p = A_E T_E + A_W T_W + A_N T_N + A_S T_S + A_{p_o} T_p^o \quad (42)$$

$$(=)A_pT_p = A_ET_E + A_WT_W + A_NT_N + A_ST_S + b_o \quad (43)$$

$$(=)A_pT_p - A_ET_E - A_WT_W - A_NT_N - A_ST_S = b_o \quad (44)$$

Sendo:

$b_o = A_{p_o}T_p^o$ e $A_{p_o} = \frac{\Delta x \Delta y \rho c}{\Delta t}$

$A_S = \frac{\Delta x k_S}{\Delta y}$; $A_W = \frac{\Delta y k_W}{\Delta x}$; $A_E = \frac{\Delta y k_E}{\Delta x}$; $A_N = \frac{\Delta x k_N}{\Delta y}$

$A_p = (A_{p_o} + A_E + A_W + A_N + A_S)$

Consequentemente, a obtenção das temperaturas ao longo da malha implica a resolução da equação (45)

$$A_pT_p - A_ET_E - A_WT_W - A_NT_N - A_ST_S = b_o \quad (45)$$

para cada um dos nós da malha, resultando num sistema de equações, genericamente representado pela equação (46)

$$Ax = b \quad (46)$$

Em que A é a matriz dos coeficientes do sistema, x é o vetor das incógnitas do sistema (as temperaturas) e b é o vetor dos termos constantes do sistema onde são incluídas as condições iniciais assim como as condições de fronteira.

Em consequência do varrimento da malha de baixo para cima e da esquerda para a direita, a matriz dos coeficientes do sistema é pentadiagonal (ver Figura 18). A diagonal principal é constituída pelos coeficientes A_P. Abaixo da diagonal principal encontram-se os termos A_W e A_S. Acima se encontram os termos A_E e A_N. Os afastamentos destas diagonais são diretamente definidos pelas dimensões horizontais e verticais da malha. Na Figura 18, pode ver-se a localização destes coeficientes na matriz A. As cruzes correspondem a elementos não nulos enquanto que as posições vazias são constituídas por zeros.

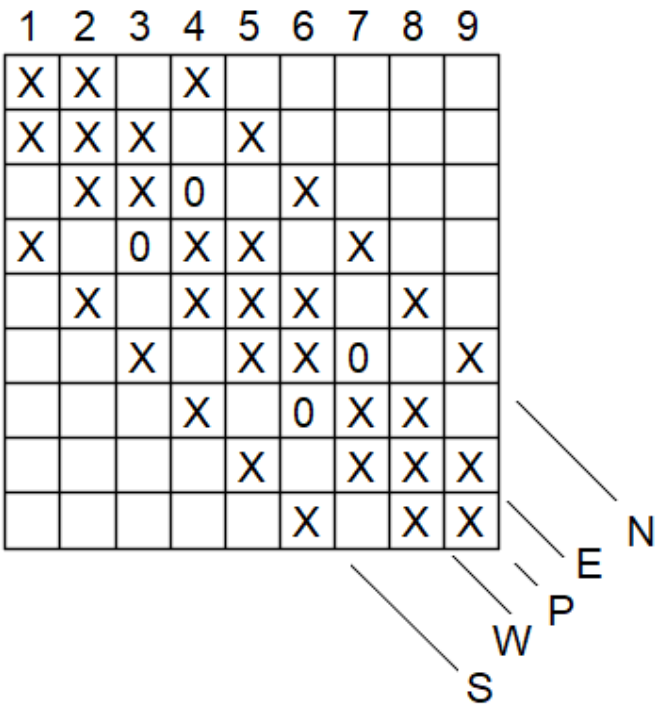


Figura 18: Estrutura da matriz dos coeficientes do sistema resultante da discretização da equação do calor por diferenças finitas.

Este tipo de sistema, em que a maior parte dos coeficientes da matriz A são zeros, são conhecidos como sistemas esparsos. Para tirar partido desta estrutura, a implementação computacional da sua resolução armazena em memória apenas os termos não-nulos. Desta forma, é possível resolver sistemas de grandes dimensões que resultam de malhas com muitos nós.

Os coeficientes do sistema de equações (A_P, A_E, A_W, A_N, A_S) não são constantes ao longo do tempo devido ao fato das propriedades dos materiais (ρ , c, k_P, k_E, k_W, k_N, k_S) serem dependentes da temperatura. Desta forma, em cada passo de tempo é necessário fazer um ciclo iterativo interno que visa estabilizar os valores das propriedades do material. Partindo dos valores iniciais das propriedades do material, são calculadas as temperaturas no domínio. Com essas temperaturas recalculam-se os valores das propriedades do material. Repete-se este processo até um número máximo de iterações, parando sempre que, de uma iteração para a outra, a variação (absoluta ou relativa) das temperaturas seja inferior a certa tolerância.

As condições de fronteira na extremidade inferior (Sul) caracterizam-se por um fluxo de calor constante q_S, para cada instante de tempo, assim a variação da temperatura na vertical será dada pela equação (47).

$$\frac{\partial T}{\partial y} = \frac{q_S}{k_S} \tag{47}$$

Substituindo esta derivada na equação discretizada correspondente aos nós situados na fronteira sul obtem-se a equação (48).

$$\frac{k_N\left(\frac{T_N - T_P}{\Delta y}\right) - k_S\left(\frac{T_P - T_S}{\Delta y}\right)}{\Delta y} = \frac{k_N\left(\frac{T_N - T_P}{\Delta y}\right) - q_S}{\Delta y} \tag{48}$$

Tendo em conta as reorganizações dos termos anteriormente apresentadas, esta simplificação implica que nas equações correspondentes aos nós da fronteira sul $A_S = 0$ e $b = b_0 - \Delta y \times q$. Pelo que em termos de construção do sistema $A_X = b$, as condições de fronteira implicam que nas equações correspondentes aos nós da fronteira sul, os termos da diagonal A_S sejam nulos e os coeficientes do vetor dos termos independentes incluam os efeitos do fluxo q_S.

Na fronteira superior (Norte), existe um fluxo q_N que inclui os efeitos de convecção e de radiação. Nesta fronteira a variação da temperatura é dada pela equação (49).

$$\frac{\partial T}{\partial y} = \frac{q_N}{-k_N} \tag{49}$$

Substituindo esta derivada na equação discretizada correspondente aos nós situados na fronteira norte obtem-se a equação (50)

$$\frac{k_N\left(\frac{T_N - T_P}{\Delta y}\right) - k_S\left(\frac{T_P - T_S}{\Delta y}\right)}{\Delta y} = \frac{k_S\left(\frac{T_p - T_S}{\Delta y}\right) - q_N}{\Delta y} \tag{50}$$

Esta simplificação implica que nas equações correspondentes aos nós da fronteira norte $A_N = 0$ e $b = b_0 - \Delta y \times q_N$. Pelo que em termos de construção do sistema $A_X = b$, estas condições de fronteira implicam que nas equações correspondentes aos nós da fronteira norte, os termos da diagonal A_N sejam nulos e os coeficientes do vetor dos termos independentes incluam os efeitos do fluxo q_N.

Na fronteira direita (Este), a condição de isolamento implica que $\frac{\partial T}{\partial x} = 0$.

Em consequência, a discretização da equação de transferência de calor pode ser simplificada para a equação (51).

$$\frac{k_E\left(\frac{T_E - T_P}{\Delta x}\right) - k_S\left(\frac{T_P - T_W}{\Delta x}\right)}{\Delta x} = \frac{-k_S\left(\frac{T_P - T_W}{\Delta x}\right)}{\Delta x} \tag{51}$$

Pelo que nas equações correspondentes aos nós da fronteira este $A_E = 0$ e $b = b_0$. Pelo que em termos de construção do sistema $A_X = b$, estas condições de fronteira implicam que nas equações correspondentes aos nós da fronteira Este, os termos da diagonal A_E sejam nulos e os coeficientes do vetor dos termos independente incluam apenas as condições ditadas pelo passo de tempo anterior (b_0). Da mesma forma, o isolamento na fronteira esquerda (Oeste), implica que $\frac{\partial T}{\partial x} = 0$, assim obtemos a equação (52).

$$\frac{k_E\left(\frac{T_E - T_P}{\Delta x}\right) - k_S\left(\frac{T_P - T_W}{\Delta x}\right)}{\Delta x} = \frac{k_E\left(\frac{T_E - T_P}{\Delta x}\right)}{\Delta x} \tag{52}$$

Assim nas equações correspondentes aos nós da fronteira Oeste $A_W = 0$ e $b = b_0$. Pelo que em termos de construção do sistema $A_X = b$, estas condições de fronteira implicam que nas equações correspondentes aos nós da fronteira Oeste, os termos da

diagonal A_W sejam nulos e os coeficientes do vetor dos termos independente incluam apenas as condições ditadas pelo passo de tempo anterior (b_0).

3.2 Matlab PDE toolbox

Devido à irregularidade das geometrias a serem estudadas, o método anteriormente descrito tornou-se inviável, assim a toolbox de equações diferencial parciais passou a ser utilizada, uma vez que esta oferece funções para a resolução da equação de transferência de calor em domínios 2-D e 3-D com geometrias arbitrárias definidas pelo utilizador. O modelo foi desenvolvido através da aplicação de algumas funções principais, conforme a Figura 19.

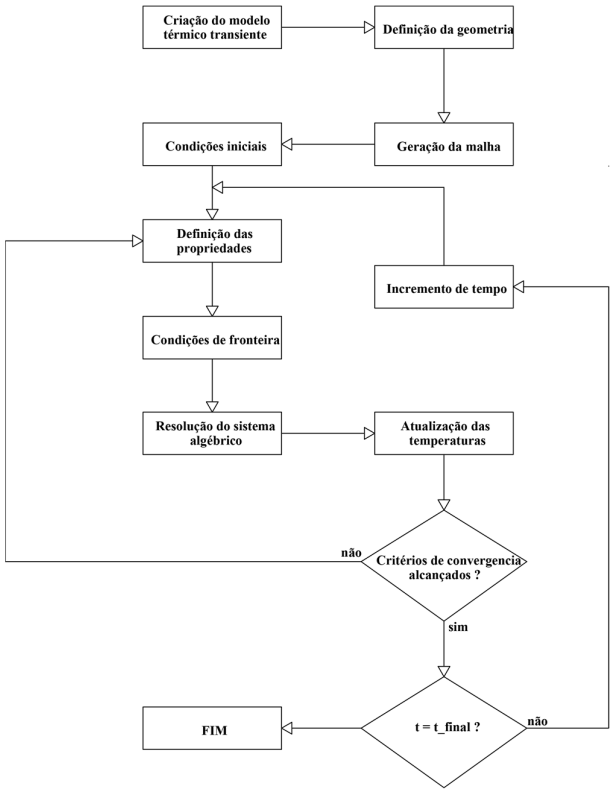


Figura 19: Fluxograma do modelo aplicado no programa Matlab.

Embora esta *toolbox* funcione em regime de "caixa negra", a sua implementação apresenta várias semelhanças com o método de resolução previamente implementado, e descrito na secção anterior. Após definição da geometria do domínio, são inseridas as condições iniciais e de fronteira assim como as propriedades do material através de

pequenos programas desenvolvidos em Matlab. A *toolbox* permite fazer a discretização do domínio por elementos finitos triangulares cuja dimensão máxima pode ser controlada pelo utilizador. Segue-se a resolução por um esquema implícito cujo passo de tempo máximo pode também ser definido pelo utilizador. Os parâmetros de controle do ciclo iterativo interno, que visa estabilizar as temperaturas, podem igualmente serem definidos pelo utilizador, nomeadamente o número máximo de iterações e as tolerâncias absolutas e relativas de variação da temperatura.

Esta biblioteca permite a resolução de vários tipos de equações às derivadas parciais para problemas padrão, como por exemplo: difusão, transferência de calor, mecânica estrutural, eletroestática, magnetostática e eletromagnetismo de energia CA, bem como sistemas acoplados e personalizados de PDEs [47].

O programa "*Partial Differential Equation Toolbox*" [47] tem uma função para o refinamento global e uniforme de malha para qualquer geometria 2D. O programa divide cada triângulo em quatro triângulos semelhantes, criando novos cantos na parte lateral, ajustando-se para limites curvos. Permitindo assim determinar a precisão da solução numérica comparando os resultados de uma sequência de malhas sucessivamente refinadas. Se a solução for suave o suficiente, resultados mais precisos podem ser obtidos por extrapolação.

Os elementos finitos disponíveis para análises térmicas bidimensionais são: elemento linear triangular de três nós, conforme Figura 20, e o elemento quadrático triangular de seis nós, conforme Figura 21. Nesse estudo foram utilizados os elementos lineares triangulares de três nós, uma vez que após análises preliminares este foi o que apresentou melhores resultados na resolução da equação, levando em consideração o tempo de simulação e os resultados de temperaturas obtidos.

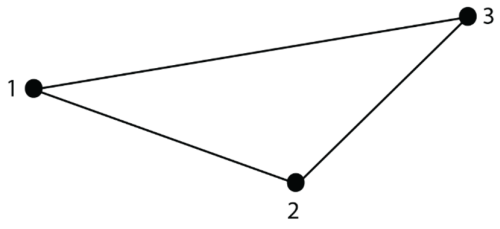


Figura 20: Elemento linear 2-D, exibindo seus números de nós.

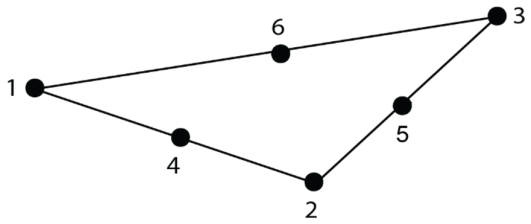


Figura 21: Elemento quadrático 2-D, exibindo seus números de nós.

3.2.1 Modelo de elementos finitos

A biblioteca e equações diferenciais parciais do Matlab foi utilizada para a análise deste modelo térmico, utilizando o método dos elementos finitos [47]. O modelo geométrico foi criado através dos pontos específicos de cada geometria a ser analisada. O domínio é discretizado em uma malha usando elementos triangulares lineares com tamanho máximo igual a 0,01m através da função (`generateMesh`), conforme pode-se ver na Figura 22 até a Figura 25. A equação (35) é resolvida por meio de um esquema implícito com um passo de tempo máximo definido como 1s. As propriedades térmicas (calor específico, densidade e condutividade) dos materiais (concreto e aço) dependem da temperatura, obrigando a utilização de funções dependentes da temperatura para o cálculo das propriedades dos materiais, sendo estas aplicadas no modelo através da função (`thermalProperties`). Consequentemente, em cada passo de tempo, os valores dessas propriedades são determinados por meio de um processo iterativo baseado no cálculo do fluxo de calor. O critério de convergência é baseado na tolerância absoluta, definida como 10^{-6} ou com base na tolerância relativa, definida como 10^{-3} e em um número máximo de iterações igual a 25.

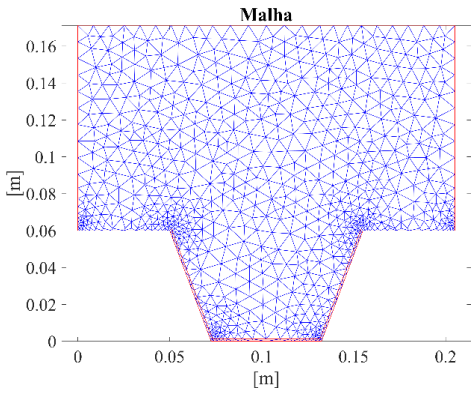


Figura 22: Malha de elementos finitos usada para a laje trapezoidal (L1/L2=105/60mm/mm, h1=110 mm, SDT=1.2mm).

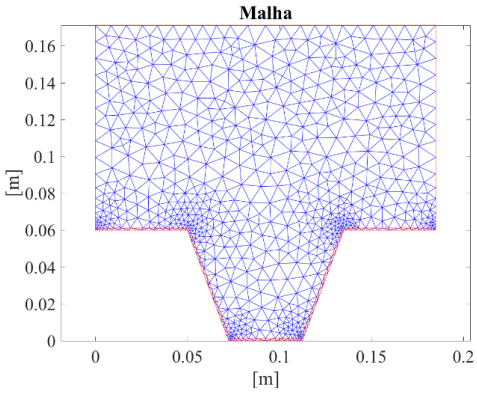


Figura 23: Malha de elementos finitos usada para a laje trapezoidal (L1/L2=84/40mm/mm, h1=110 mm, SDT=1.2mm).

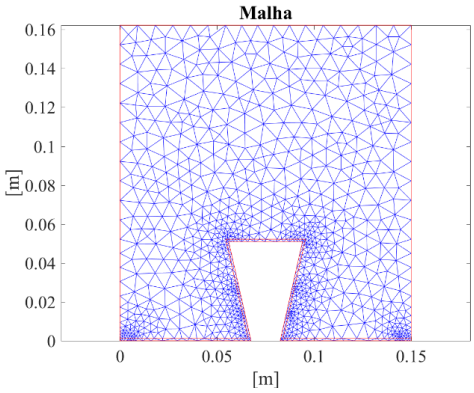


Figura 24: Malha de elementos finitos usada para a laje reentrante (L1/L2=112/135mm/mm, h1=110 mm, SDT=1.2mm).

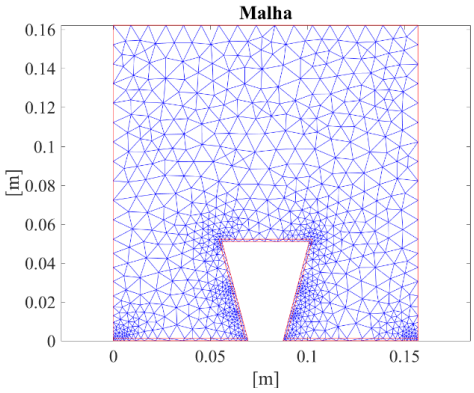


Figura 25: Malha de elementos finitos usada para a laje trapezoidal (L1/L2=108/135mm/mm, h1=110 mm, SDT=1.2mm).

A análise de malhas foi realizada para malhas com tamanho de elemento máximo (Hmax) de 0.1 m, 0.01 m, 0.001 m e 0.004 m. Os resultados obtidos estão apresentados na Tabela 9.

Tabela 9: Análise de malhas para o modelo numérico.

Hmax (m)	Tempo de resolução (s)	Tempo crítico (t_i), em minutos
0,1	105,17	42
0,01	105,73	42
0,004	235,49	42
0,001	593,47	42

Devido ao extenso número de simulações que o trabalho visa realizar, o modelo com o menor tempo de resolução deve ser adotado. Como a diferença entre a malha de 0,01 m e 0,1 m não é significativa e a malha com elementos melhores se apresenta mais homogênea, a malha de 0,01 m foi aplicada em todos os modelos.

3.2.2 Condições de fronteira

Uma temperatura uniforme inicial é aplicada a todos os nós da malha (20ºC) através da função (`thermalIC`). A parte inferior do perfil metálico é submetida a condições de incêndio padrão, usando um coeficiente de convecção de $25\left[W/m^2 \cdot K\right]$ e uma emissividade do fogo ε_f igual a 1. A parte superior da laje é submetida a um coeficiente de convecção de $9\left[W/m^2 \cdot K\right]$ para incluir o efeito de radiação [33]. Através de um fluxo de calor podem-se aplicar essas condições de fronteira nos lados da geometria já criada através da função (`thermalBC`). Esses parâmetros são representados na Figura 26 e Figura 27.

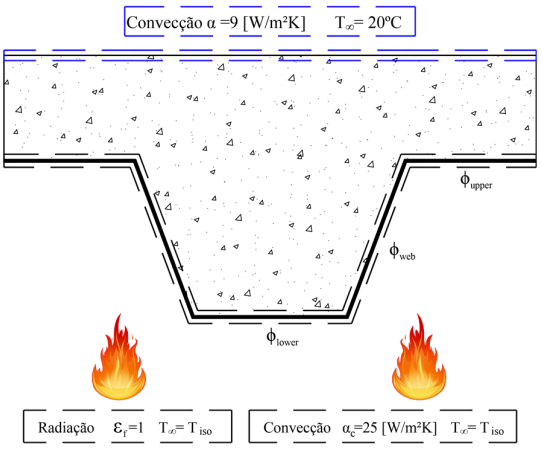


Figura 26: Condições de fronteira para lajes com perfil metálico trapezoidal.

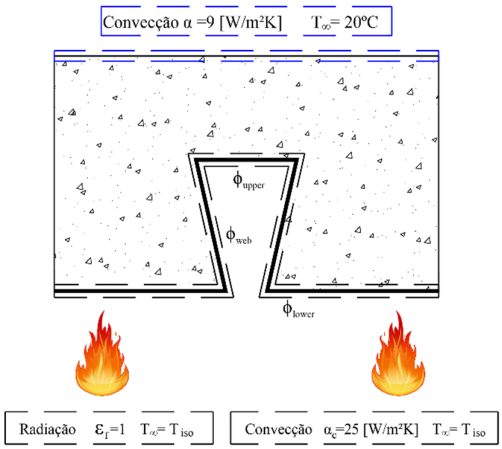


Figura 27: Condições de fronteira para lajes com perfil metálico reentrante.

3.3 ANSYS

Foi ainda utilizado o programa ANSYS Mechanical APDL v 18.2, com interface gráfica para resolução da equação diferencial. Este programa utiliza o método de elementos finitos para resolver problemas lineares e não lineares de modelagens térmicas em regime transiente e estacionário.

3.3.1 Modelo de elementos finitos

O modelo foi criado geometricamente utilizando a interface gráfica do programa ANSYS, com a localização de todos os pontos da geometria a ser criada e através das funções *Keypoints, Lines, Areas e Volumes*. Após isso, as linhas foram divididas em segmentos, permitindo a definição da malha bidimensional.

O modelo numérico utiliza um elemento finito 2-D (PLANE55), veja Figura 28, com quatro nós e um grau de liberdade por nó (temperatura). Este elemento utiliza funções de interpolações lineares com integração completa, usando dois pontos de Gauss em cada direção. Este elemento é aplicado para a análise térmica transiente ou estacionária de um elemento 2-D. O elemento também pode compensar o fluxo de calor de transporte de massa de um campo de velocidade constante [48].

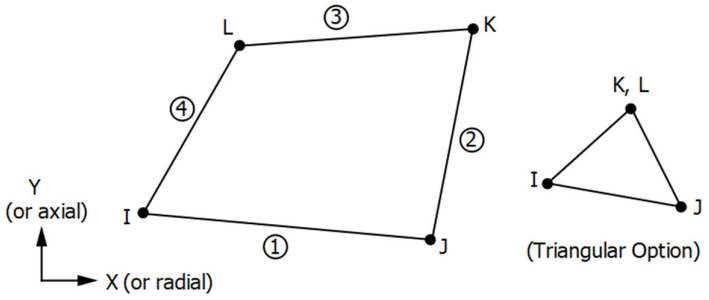


Figura 28: Geometria do elemento PLANE55

A malha foi criada com um tamanho de elementos de 0.04mm para uma melhor disposição dos elementos na geometria irregular a ser estudada. O incremento de tempo é tipicamente de 60 s, com a possibilidade de ser reduzido para 1 s. O critério de convergência baseia-se no cálculo do fluxo de calor, para um valor de referência de 10^{-6} e um valor de tolerância de 0,1%. O modelo usa elementos finitos quadrilaterais para modelar a plataforma de aço e a parte de concreto, como se pode ver da Figura 29 até a Figura 32.

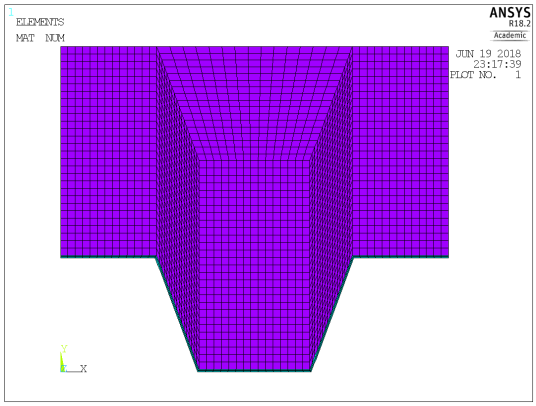


Figura 29: Malha de elementos finitos usada para a laje reentrante (L1/L2=105/60mm/mm, h1=110 mm, SDT=1.2mm).

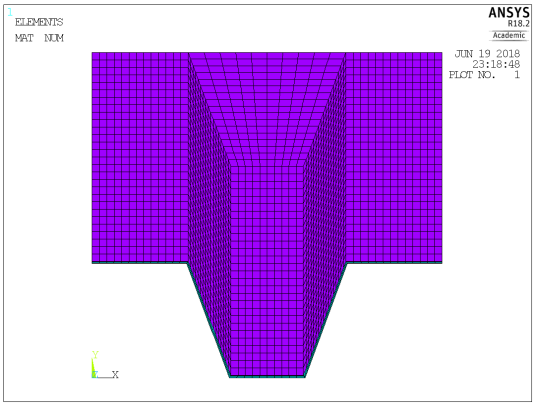


Figura 30: Malha de elementos finitos usada para a laje reentrante (L1/L2=84/40mm/mm, h1=110 mm, SDT=1.2mm).

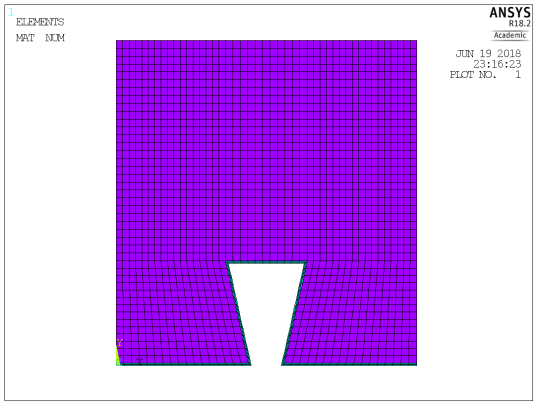


Figura 31: Malha de elementos finitos usada para a laje reentrante (L1/L2=112/135mm/mm, h1=110 mm, SDT=1.2mm).

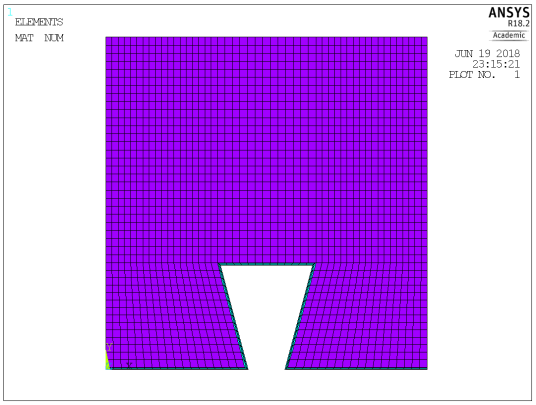


Figura 32: Malha de elementos finitos usada para a laje reentrante (L1/L2=108/135mm/mm, h1=110 mm, SDT=1.2mm).

3.3.2 Condições de fronteira

Foi definida uma tabela com a definição da evolução da temperatura, considerando uma curva nominal de incêndio padrão ISO 834 nos 3 nós para definição do compartimento (*enclosure)*. Estes 3 compartimentos implicam 3 diferentes fatores de vista na superfície exposta ao incêndio. Após isso foram definidas as opções de radiação: constante de Stefan-Boltzmann igual a $5.67 \cdot 10^{-8} \left[W / m^2 \cdot K^4 \right]$, temperatura *OFFSET* de 273.15 que define a diferença entre o zero absoluto e o valor zero da escala de temperatura a ser utilizada. Como condição inicial de fronteira, todas as temperaturas nos nós dos elementos foram definidas como 20ºC no tempo igual a zero. Foram definidas as condições de fronteira de convecção com base no coeficiente de convecção constante de $25 \left[W / m^2 \cdot K \right]$ e uma temperatura do compartimento conforme a ISO 834. Esses coeficientes foram aplicados nas superfícies diretamente afetadas pelo incêndio. Para a

radiação foram definidas as condições de fronteira selecionando as superfícies e aplicado o fator de vista diferente. Todos esses parâmetros são representados na Figura 26 e Figura 27.

4 ENSAIOS EXPERIMENTAIS

Foram realizados dois ensaios experimentais com a mesma geometria do modelo real O-FELIZ. Ambas as amostras representam apenas uma parte das dimensões normais das lajes mistas. Estes espécimes permitem a verificação do comportamento de isolamento para caracterização da resistência ao fogo. Cada laje apresenta 1,15 m de largura e 1,2 m de comprimento. As espessuras das lajes foram fixadas em 40 mm. As lajes utilizavam a mesma proporção e quantidade de aço de reforço que normalmente é utilizado em lajes. A laje modelo H60 [45] é apresentada na Figura 33, onde é possível observar a geometria deste modelo.

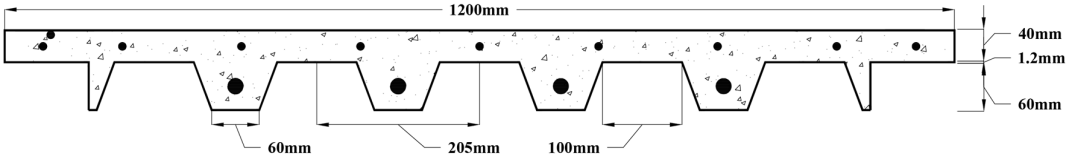


Figura 33: Modelo da laje, e sua respectiva geometria.

O concreto de peso normal é usado para os espécimes. A resistência à compressão do concreto é de 20 MPa. A resistência à compressão do concreto foi determinada por testes compressão de corpos de prova cúbicos, cujas dimensões são determinados pela norma EN 12390-1:2000 [49], conduzidos 28 dias após o concreto ser moldado, de acordo com a norma EN 12390-3:2009 [50].

Os espécimes foram preparados e instrumentados de acordo com as normas vigentes. Os testes foram conduzidos até um máximo de 76 min ou antes do tempo final, se a laje estiver deformada a um ponto iminente de colapso estrutural, o que poderia causar danos do forno.

4.1 Normas utilizadas

As normas de ensaios utilizadas para a obtenção do tempo de resistência ao fogo de lajes mistas de concreto e aço foram a EN 1363-1 (*Fire Resistance Tests – General Requirements*), EN 1365-2 (*Fire resistance tests for loadbearing elements - Part 2:*

Floors and roofs) e o Eurocódigo EN 1994-1-2 (*Design of composite steel and concrete structures - Part 1-2: General rules - Structural fire design*).

4.1.1 EN 1363-1

A EN 1363-1 estabelece os princípios gerais para determinar a resistência ao fogo de diferentes elementos de construção, quando submetidos a condições normais de exposição ao fogo [51]. Um forno especialmente projetado é necessário para submeter a amostra de teste às condições de teste. O sistema de controle da temperatura do forno, o equipamento de controle e monitorização a pressão dos gases quentes dentro do forno, o quadro no qual o elemento pode ser inserido e submetido a condições adequadas de aquecimento, pressão e suporte. O arranjo para carregamento e contenção do corpo de prova deve ser apropriado, incluindo controle e monitoramento do equipamento de carga para medir a temperatura no forno e no corpo de prova. Em alguns casos, o sistema para medir a deflexão do corpo de prova é necessário. Além disso, em alguns casos, são necessários dispositivos específicos para avaliar a integridade e estabelecer critérios de desempenho conforme o estabelecido. Para casos muito especiais, o equipamento para medir a concentração de oxigênio dos gases do forno também é necessário. Essa norma também especifica o cálculo e as tolerâncias sobre os sistemas, incluindo algumas informações sobre os sensores, como os termopares de disco e os termopares de placa.

Os critérios de desempenho utilizados neste estudo para validar os ensaios de resistência ao fogo de lajes mistas, sem carga, são os critérios de isolamento (I). Por definição, é o tempo, em minutos completos, para o qual o elemento consegue manter sua função de separação durante o teste sem desenvolver temperaturas em sua superfície não exposta, que aumentam a temperatura média acima da temperatura média inicial em mais de 140ºC ou também, aumentem, em qualquer local, a temperatura de qualquer ponto acima da temperatura média inicial em mais de 180 ºC [51]. A falha do critério de desempenho de isolamento (I) indicam automaticamente que o critério de "integridade (E)" deixou de ser cumprido. O critério de integridade (E), neste caso, é definido como o tempo em que a chama ou fumaça passam através de alguma fissura para o lado não exposto.

4.1.2 EN 1365-2

A EN 1365-2 contém os procedimentos para realizar os testes experimentais para determinar a resistência ao fogo de lajes de pavimentos e telhados com exposição ao fogo na parte inferior [52].

Para a realização destes experimentos, é necessária a utilização de um bastidor para fixação da amostra, com elevada rigidez e baixa expansão térmica. A dimensão da amostra deve ser definida de acordo com a seguinte regra: se o comprimento ou a largura do elemento de construção for menor que 3 m, a amostra deve ser testada em seu tamanho real. Se uma das dimensões do elemento de construção é maior que 3m, a dimensão não deve ser inferior a 3m no teste. Contudo, as dimensões da laje nesta investigação foram restringidas pela dimensão da abertura do forno, é recomendado que o tamanho máximo da laje seja aproximado de 1m. Esta norma também fornece informações sobre a instrumentação. O controle de temperatura do forno deve ser feito por termopares de placa em seu interior, com a maior superfície virada para o piso do forno. Deve haver um para cada 1,5m² de superfície a ser testada. No caso de lajes com tempo de resistência ao fogo por isolamento esperado superior a 5 minutos, os termopares de disco devem ser fixados no lado não exposto para obter a média da temperatura máxima desenvolvida, ver secção 4.3. Para amostras de teste com menos de 6 m² de área exposta, um mínimo de quatro termopares de placa deve ser utilizados.

Assim, serão colocados 11 termopares para medir a temperatura média, um no centro da amostra, outros quatro no centro de cada quadrante da laje e mais 6 para complementação das análises visando a comparação dos modelos numéricos. Para a medição da temperatura máxima é recomendado a utilização de 7 ou mais termopares [52].

4.1.3 EN 1994-1-2

O Eurocódigo EN 1994-1-2 exemplifica o cálculo de estruturas mistas de aço e concreto, para a situação de incêndio [7]. Como o objetivo deste estudo é avaliar o parâmetro de isolamento de lajes mistas, os espécimes a serem estudados experimentalmente foram realizados sem a necessidade de resistir a ação de cargas, assim em sua construção, todos os elementos utilizados foram os mínimos necessários.

4.1.4 Instalações laboratoriais

Os testes foram realizados no Laboratório de Estruturas e Resistência dos Materiais do Instituto Politécnico de Bragança. O forno e o quadro utilizados são dispostos na Figura 34.

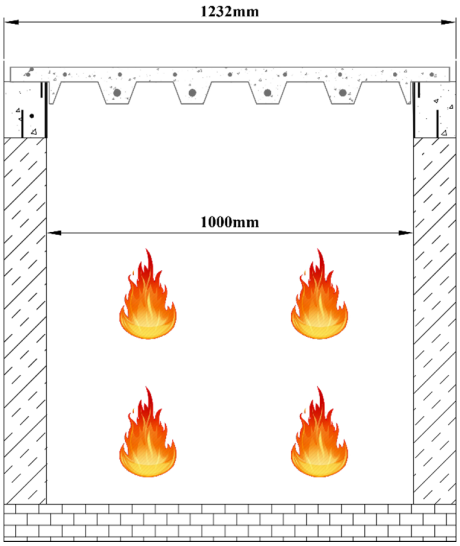


Figura 34: Geometria do forno.

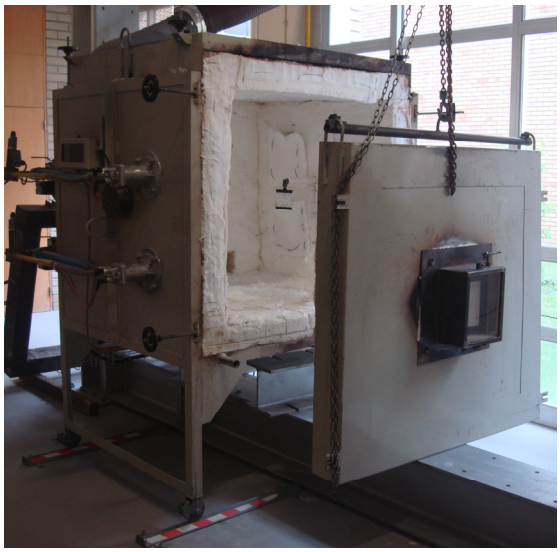


Figura 35: Forno.

O forno tem capacidade para amostras de dimensões de 1x1m e funciona a gás natural usando quatro queimadores com defasagem em altura e profundidade, cada um com 90kW de potência máxima. A temperatura do forno a gás seguiu a curva ISO834 de fogo padrão. O forno tem uma porta na frente e uma abertura no topo. O volume livre total é de 1m³. O quadro estava alinhado com a abertura do topo. O sistema de aquisição de dados é um sistema MGC Plus fabricado pela empresa HBM, com 3 módulos com 8 canais cada, e foi utilizado com frequência de aquisição de 1Hz. Um total de 22 canais estavam disponíveis para medições de temperaturas. Além do sistema de aquisição, foi utilizada uma câmera térmica Infra Vermelho (IR), modelo FLIR BT Série T365, para captar a temperatura de uma zona pequena do lado não exposto. A frequência de aquisição da câmera foi de 1,25 fotogramas por segundo, com uma amplitude de temperatura entre 15 °C e 300 °C e uma resolução de 320x240 pixels.

4.2 Especificação dos termopares

Para as medições de temperatura na laje, foram usados três tipos de termopares. Todos os termopares são do tipo K com fios de 0,7 mm de diâmetro. A temperatura do lado exposto da laje foi medida com um termopar soldado na parte superior da chapa de aço. Para medir a temperatura no concreto, foi utilizado um termopar soldado em anilhas de metal. Em alguns casos, estes cabos foram torcidos e mantidos no lugar com uma massa fixadora e com uma camada de massa isolante para garantir que durante a concretagem a solda continuasse isolada. Para medir a temperatura do forno foram usados termopares de placa. As dimensões e especificações de construção destes termopares são dadas na EN 1363-1 [51], ver Figura 36. O termopar de disco de cobre foi usado para medir as temperaturas no lado não exposto da laje, conforme especificado na EN 1365-2 [52], sendo as suas dimensões especificadas na Figura 37. Estes discos de cobre são protegidos com uma almofada de isolamento feita com uma fibra de silicato, que é usada para fixar estes sensores à superfície, uma vez que não deve haver adesivo entre o disco de cobre e a superfície a ser medida.

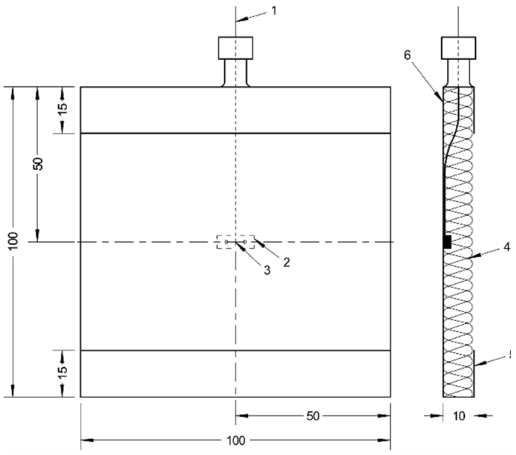


Figura 36: Termopares de placa (Dimensões em mm). Fonte: EN 1353-1 [51].

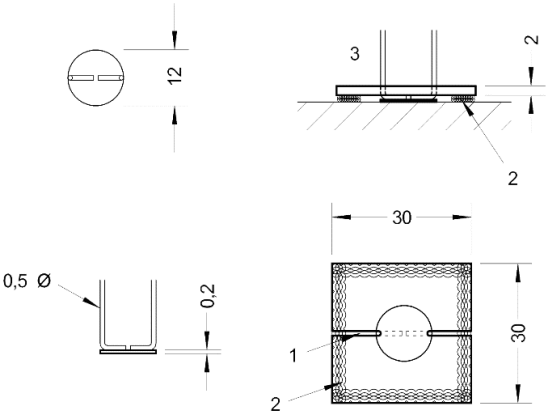
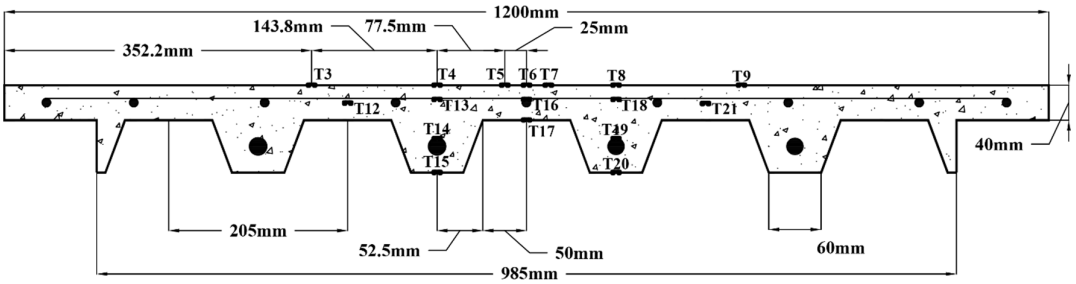


Figura 37: Termopares de disco (Dimensões em mm) Fonte: EN 1353-1 [51].

O layout dos termopares foi baseado em padrões para testes da EN 1363-1 [51] e EN 1365-2 [52], com termopares adicionais para validação numérica. Mais termopares foram incluídos através da profundidade da laje para obter mais resultados durante os ensaios. Os sensores são identificados na Figura 38 e Figura 39 para todos os 21 termopares usados em cada espécime.



Seção A-A

Figura 38: Visão em corte da posição dos termopares.

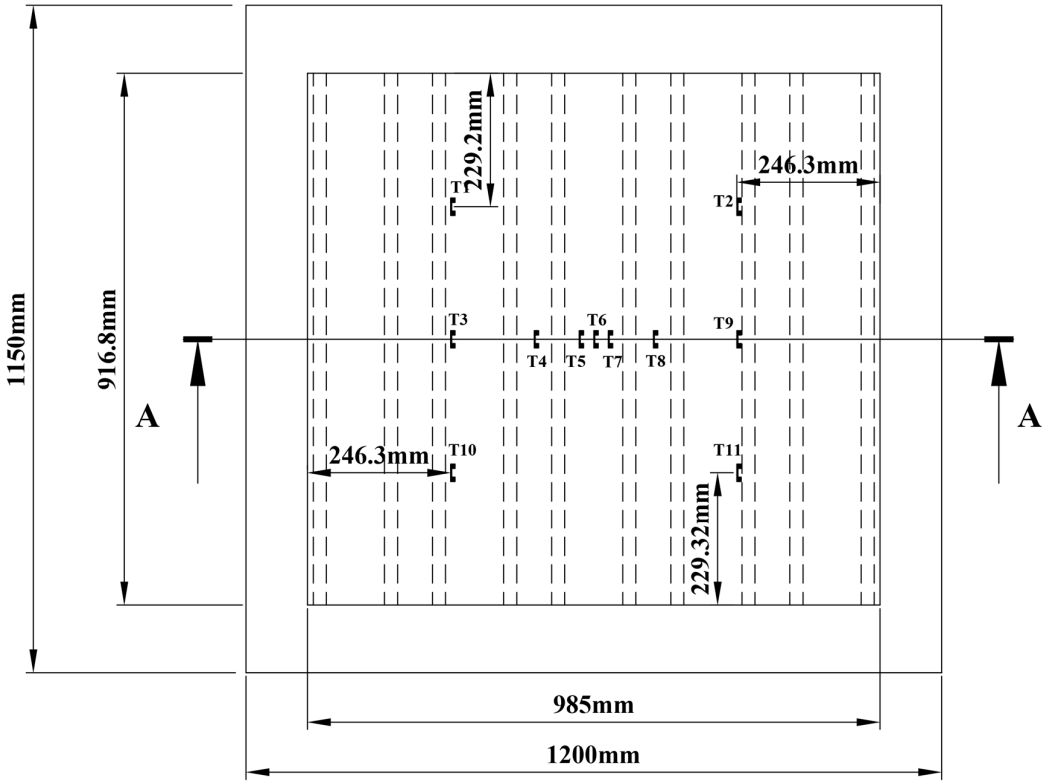


Figura 39: Visão em planta da localização dos termopares.

Sendo o posicionamento dos termopares demostrados na Figura 38 e Figura 39, para os termopares T1, T2, T3, T4, T5, T6, T7, T8, T9, T10 e T11, foram utilizados termopares de disco para a medição das temperaturas do concreto na face não exposta, já para os termopares T12 e T21 foram utilizados termopares soldados em anilhas e metal, para a medição de temperaturas do concreto no interior da seção. Os termopares T13, T14, T16, T18 e T19 foram soldados nos varões de aço e utilizados para a medição da temperatura nesses elementos. E por fim os termopares T15, T17 e T20 foram soldados ao perfil metálico colaborante e são responsáveis pela medição das temperaturas na parte mais exposta ao incêndio da laje.

4.3 Preparação e instrumentação das amostras

Primeiramente, as chapas metálicas de 1,2mm de espessura foram cortadas e rebitadas para obtenção da geometria já calculada, visando o posicionamento correto da laje no forno. Após isso, foi montada a fôrma em madeira de contraplacado marítimo, ver Figura 41. O próximo passo foi a colocação soldada dos termopares que ficariam ligados diretamente aos elementos metálicos e também o posicionamento dos varões de aço para reforço. Assim todos os termopares para a medição de temperatura no interior da seção já estavam dispostos, como se pode observar na Figura 42 e Figura 43. Após o teste de todos os termopares já posicionados, foi realizada a concretagem das lajes, conforme apresentado na Figura 44 e Figura 45.

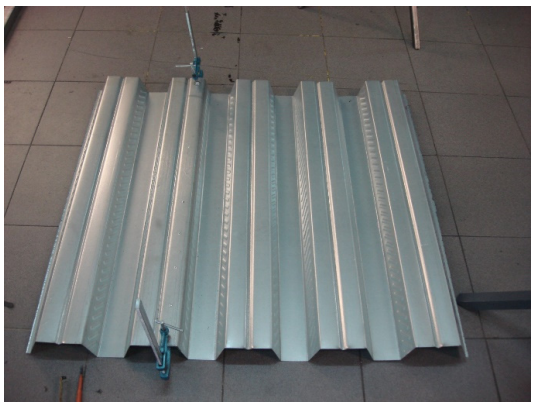


Figura 40: Corte e rebitagem da chama metálica.

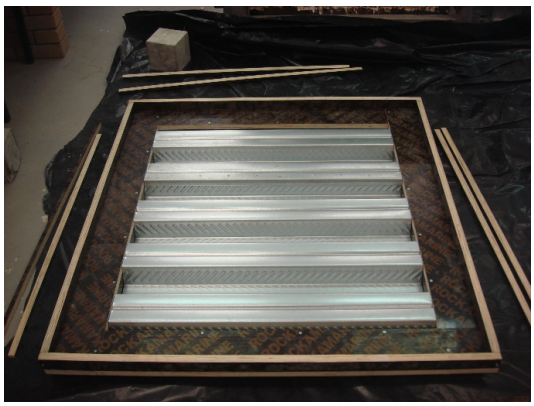


Figura 41: Montagem da fôrma para concretagem.

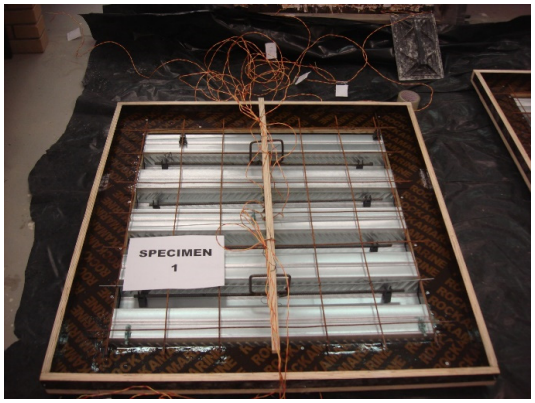


Figura 42: Posicionamento dos termopares e aço de reforço no espécime 1.

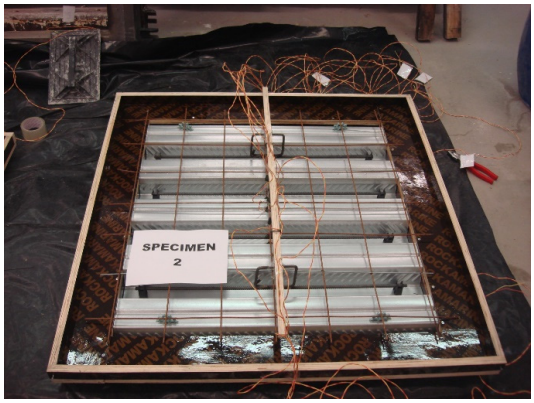


Figura 43: Posicionamento dos termopares e aço de reforço no espécime 2.

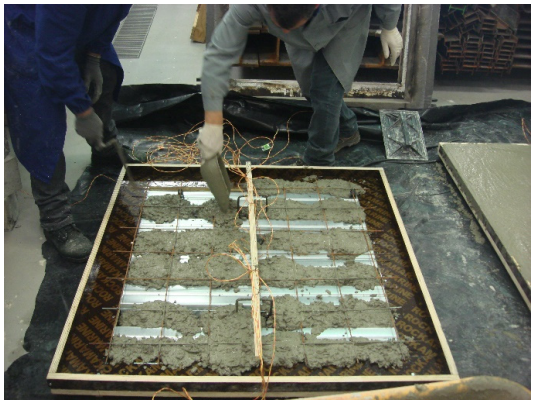


Figura 44: Concretagem do espécime 1.

Figura 45: Concretagem do espécime 2.

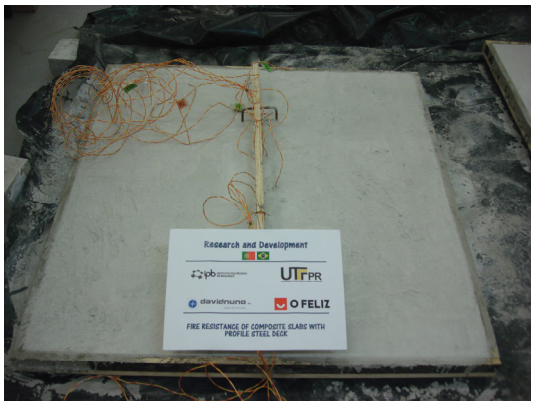


Figura 46: Espécime 1 após a cura do concreto.

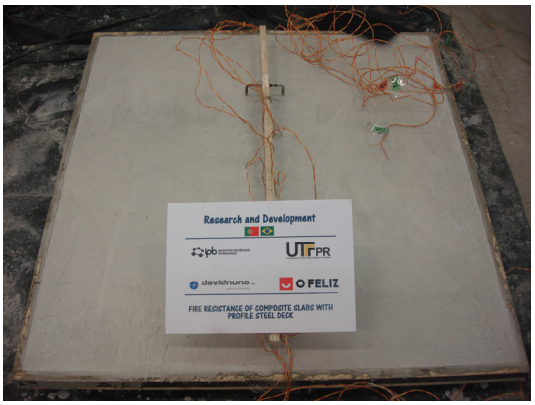


Figura 47: Espécime 2 após a cura do concreto.

4.4 Ensaio espécime 1

Após a preparação do forno, posicionamento da câmera, a laje foi colocada na sua posição, veja Figura 49. O ensaio foi iniciado às 17:07h e o espécime foi submetido a uma situação de incêndio padrão conforme a ISO 834 [8], veja Figura 48, durante 63 min. Nesta figura está representada a curva nominal e a curva real do forno, obtida por medição através do termopar de placa.

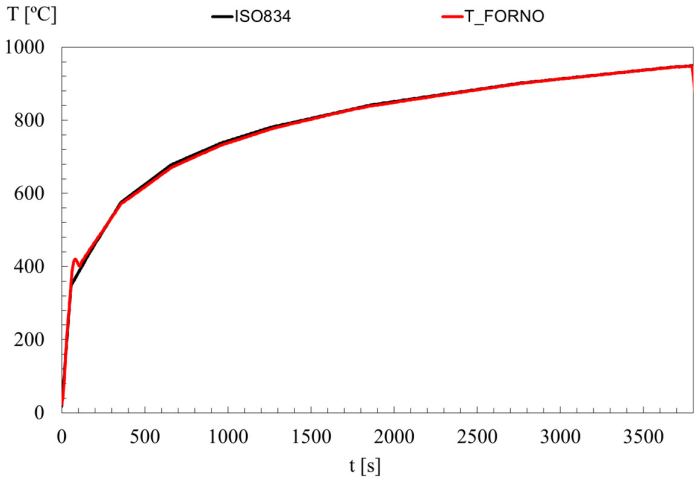


Figura 48: Comparação da temperatura do forno no ensaio 1 com a norma ISO 834.

No decorrer do ensaio pode-se perceber uma deformação da laje, causando um afastamento da parte superior em relação ao forno, conforme a Figura 51. Durante o ensaio o perfil metálico apresentou um descolamento da parte superior de concreto, assim criando um vazio entre os dois elementos. No final do ensaio, após o arrefecimento, ocorreu o descolamento total do perfil metálico, devido ao rompimento das ligações entre os dois perfis utilizados, veja Figura 52.

Figura 49: Espécime 1 pronto para ser ensaiado.

Figura 50: Estado da laje após 50 min de ensaio.

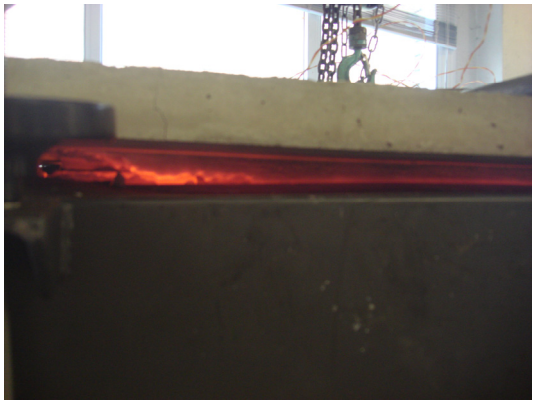


Figura 51: Levantamento da laje causado pela deformação devido ao incêndio.

Figura 52: Descolamento do perfil metálico após o ensaio.

A evolução das temperaturas foi obtida através dos termopares soldados dispostos pela seção da laje e também pelos termopares de disco na parte não exposta. Os resultados são apresentados em dois gráficos separados (veja a Figura 53 para os locais expostos e intermediários e a Figura 54 para os locais não expostos). Durante o ensaio ocorreu o descolamento do termopar T15 devido as excessivas deformações do perfil metálico. A temperatura do lado não exposto é caracterizada por T1, T2, T3, T4, T5, T6, T7, T8, T9, T10 e T11, enquanto a temperatura para medições intermediárias é caracterizada por T12, T13, T14, T15, T16, T17, T18, T19, T20 e T21.

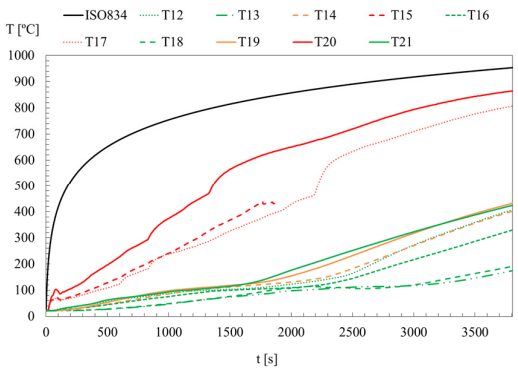


Figura 53: Evolução de temperaturas nos termopares internos (Espécime 1).

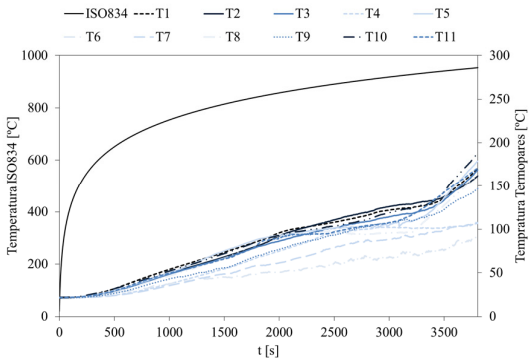


Figura 54: Evolução de temperaturas no lado não exposto (Espécime 1).

A evolução de temperatura média e máxima na superfície não exposta é baseada em medições obtidas a partir de termopares de disco, localizados no centro ou próximo ao centro da seção e de cada quadrante [51], ver termopares T1, T2, T3, T4, T5, T6, T7,

T8,T9, T10 e T11. A temperatura máxima foi determinada pela temperatura mais alta registrada por qualquer um dos termopares não expostos. A Figura 55 representa a evolução média da temperatura (TMED) e da temperatura máxima (TMAX) na laje 1. O tempo de resistência ao fogo para o critério de isolamento na laje foi atingido através da temperatura média após 62 min,

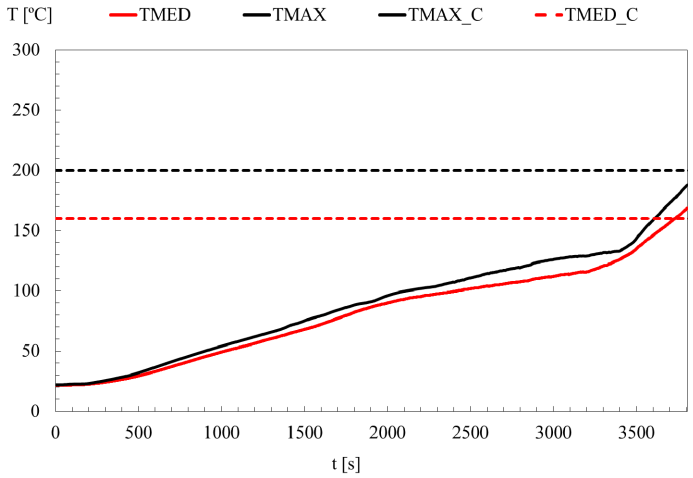


Figura 55: Evolução de temperatura no lado não exposto no espécime 1 (TMAX e TMED).

Devido a uma limitação da distância para o posicionamento da câmera causado pela dimensão do pórtico de suporte ao forno, ela foi posicionada para medir as temperaturas apenas num quadrante da amostra. Este quadrante estava localizado próximo ao termopar T10, e possuía dimensões de 46x51cm. Com câmera térmica de infra vermelho é possível perceber as diferentes distribuições de temperatura na laje devido as diferentes espessuras. Foi ainda definida uma região, área Ar1, para medição da temperatura média, máxima e mínima. Após 60 min de incêndio é possível identificar uma temperatura máxima de 257.8ºC e uma temperatura média de 173.6ºC, como pode ser visto da Figura 56 até Figura 59.

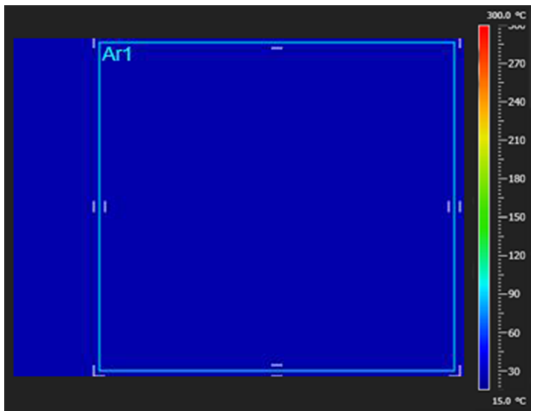


Figura 56: Campo de temperaturas para t = 0 min (Câmera térmica).

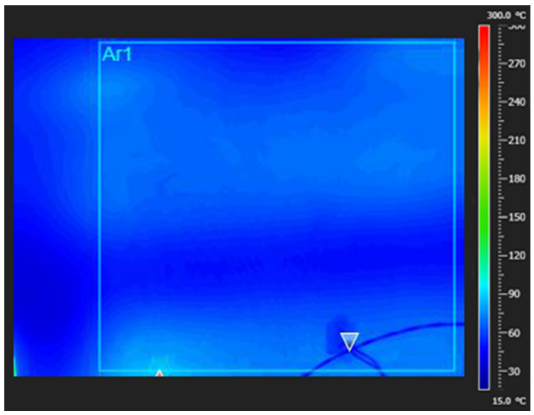


Figura 57: Campo de temperaturas para t = 20 min (Câmera térmica).

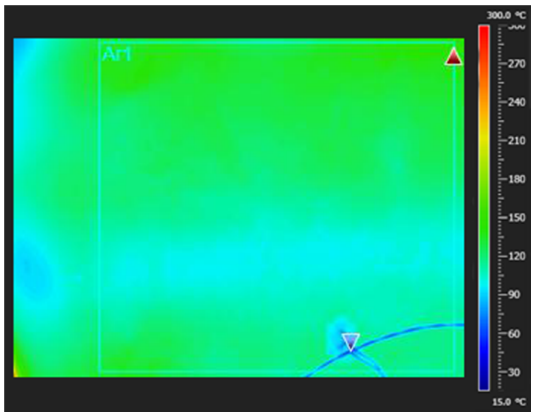


Figura 58: Campo de temperaturas para t = 40 min (Câmera térmica).

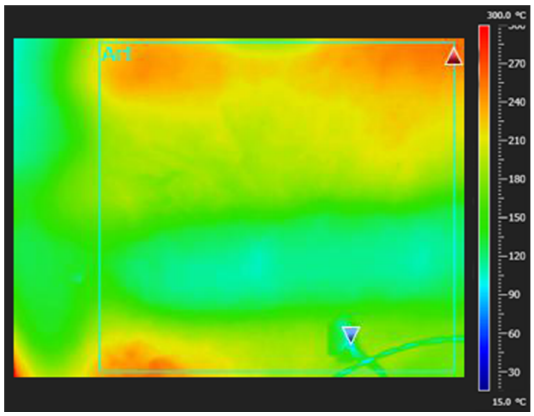


Figura 59: Campo de temperaturas para t = 60 min (Câmera térmica).

Segundo a câmera térmica, o tempo de resistência ao fogo para o critério de isolamento na laje foi atingido através da temperatura máxima após 48 min, como pode ser verificado através da Figura 60.

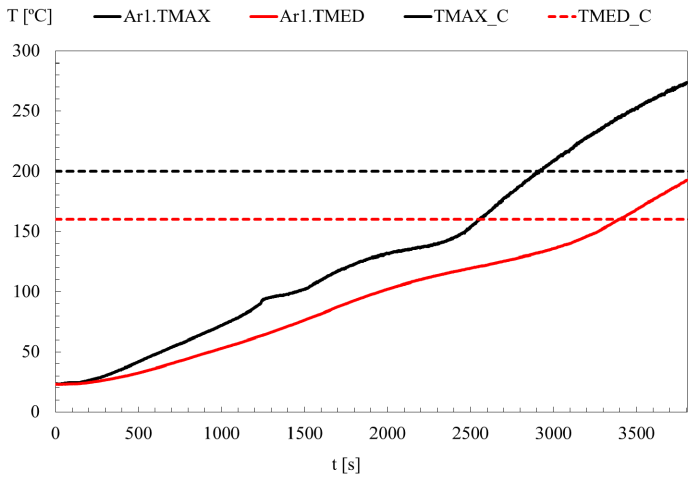


Figura 60: Campo de temperaturas do lado não exposto na área Ar1 no espécime 1 (Câmera térmica).

4.5 Ensaio espécime 2

Após a preparação do forno e, posicionamento da câmera, a laje foi colocada na sua posição, veja Figura 62. O ensaio teve início às 16:31h e o espécime foi submetido a uma situação de incêndio padrão conforme a ISO 834 [8] , durante 74 min, veja Figura 61. Nesta figura está representada a curva nominal e a curva real do forno, obtida por medição através do termopar de placa.

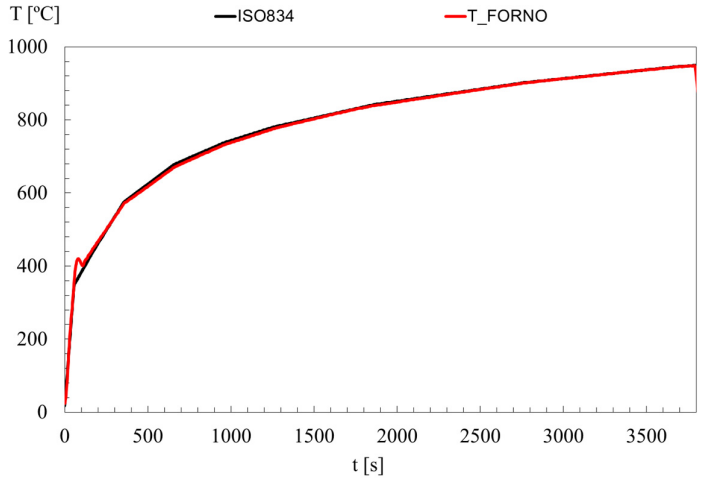


Figura 61: Comparação da temperatura do forno no ensaio 2 com a norma ISO 834.

Assim como no primeiro ensaio, pode-se perceber uma deformação da laje, causando um afastamento da parte superior em relação ao forno, conforme a Figura 64. Durante o ensaio o perfil metálico também apresentou um descolamento da parte inferior de concreto, assim criando um vazio entre os dois elementos. No final do ensaio e após arrefecimento, assim como no espécime 1, foi possível confirmar o descolamento total do perfil metálico, devido ao rompimento das ligações entre os dois perfis utilizados (ligação rebitada), veja Figura 65.

Figura 62: Espécime 2 pronto para ser ensaiado.

Figura 63: Estado da laje após 70 min de ensaio.

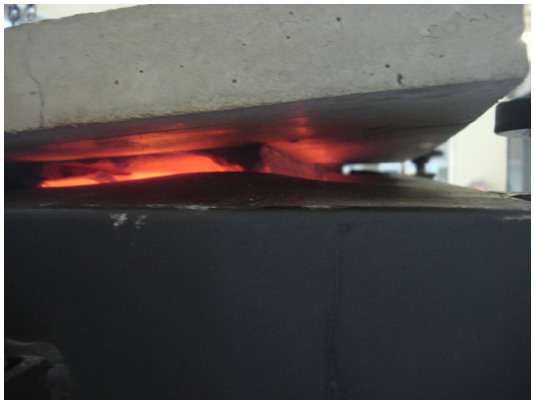


Figura 64: Efeito de levantamento da laje no espécime 2.

Figura 65: Descolamento do perfil metálico do espécime 2 após o ensaio.

A evolução das temperaturas foi obtida através dos termopares soldados dispostos pela seção da laje e também pelos termopares de disco na superfície não exposta. Os resultados são apresentados em dois gráficos separados (veja a Figura 66 para os locais expostos e intermediários e a Figura 67 para os locais não expostos). A temperatura do lado não exposto é caracterizada por T1, T2, T3, T4, T5, T6, T7, T8, T9, T10 e T11,

enquanto a temperatura para medições intermediárias é caracterizada por T12, T13, T14, T15, T16, T17, T18, T19, T20 e T21.

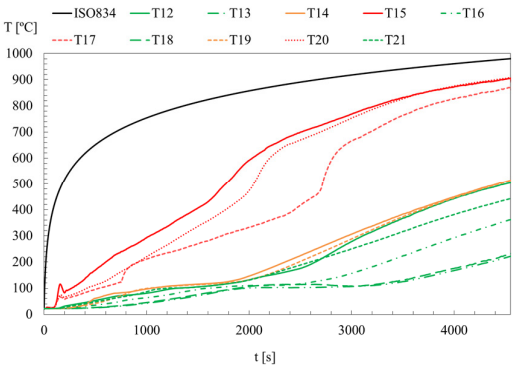


Figura 66: Evolução de temperaturas nos termopares internos (Espécime 2).

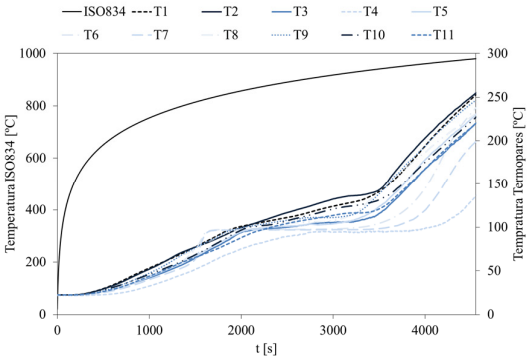


Figura 67: Evolução de temperaturas no lado não exposto (Espécime 2).

A Figura 55 representa a evolução média da temperatura (TMED) e da temperatura máxima (TMAX) na laje 2, obtida a partir das medições da superfície não exposta. O tempo de resistência ao fogo para o critério de isolamento na laje foi atingido através da temperatura média após 63 min,

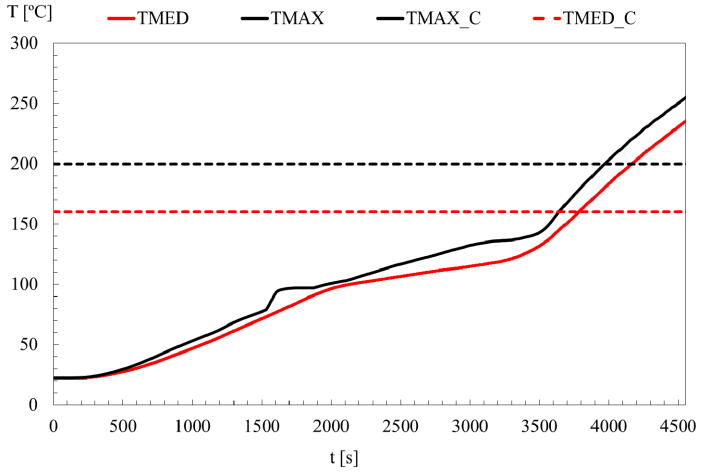


Figura 68: Evolução de temperatura no lado não exposto no espécime 2 (TMAX e TMED).

Assim como no primeiro ensaio, a câmera térmica de infravermelho foi posicionada para medir as temperaturas num quadrante da amostra. Este quadrante estava localizado próximo ao termopar T10, e possuía dimensões de 46x51 cm. Com câmera

térmica é possível perceber as diferentes distribuições de temperatura na laje devido as diferentes espessuras existentes nessa região da laje. Foi utilizada a região com uma área Ar1 para medição da temperatura média, mínima e máxima. Após 70 min de incêndio é possível identificar uma temperatura máxima de 346.3ºC e uma temperatura média de 263.8ºC, como pode ser visto da Figura 69 até Figura 72.

Figura 69: Campo de temperaturas para t = 10 min (Câmera térmica).

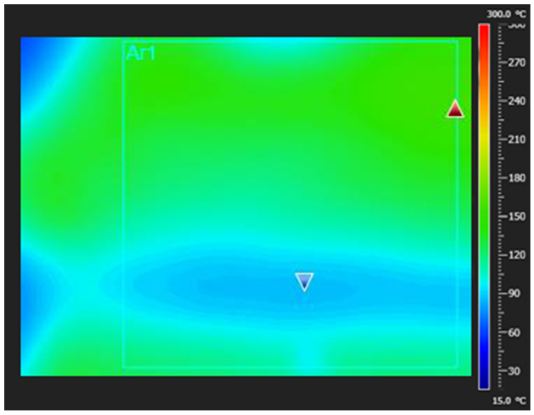


Figura 70: Campo de temperaturas para t = 30 min (Câmera térmica).

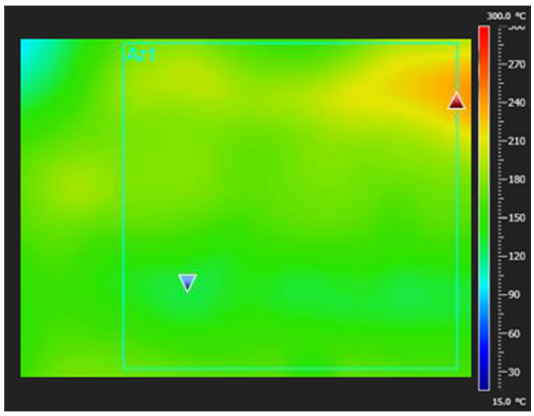


Figura 71: Campo de temperaturas para t = 50 min (Câmera térmica).

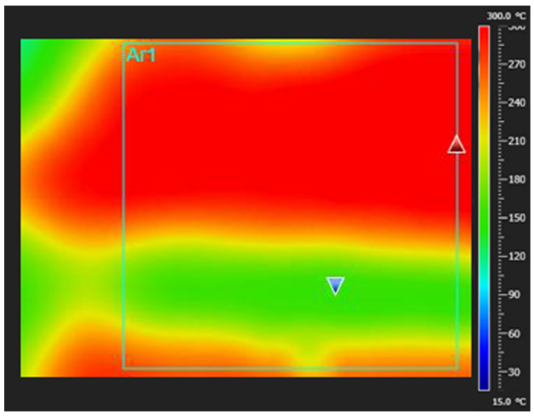


Figura 72: Campo de temperaturas para t = 70 min (Câmera térmica).

Segundo a câmera térmica o tempo de resistência ao fogo para o critério de isolamento na laje foi atingido através da temperatura máxima após 42 min, como pode ser verificado através da Figura 73.

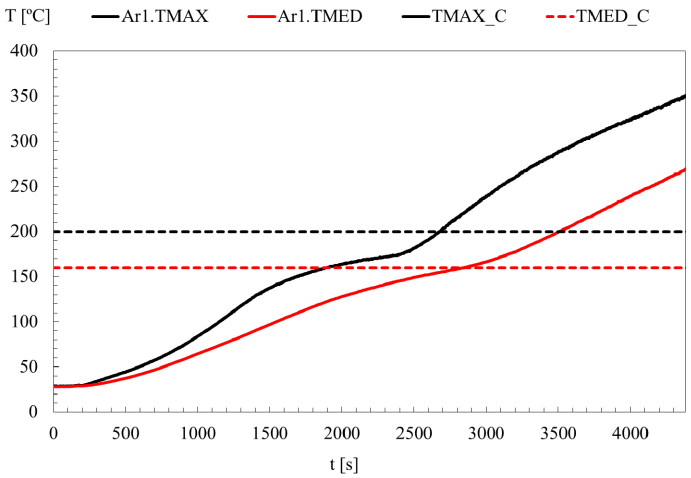


Figura 73: Campo de temperaturas do lado não exposto na área Ar1 no espécime 2 (Câmera térmica).

5 RESULTADOS NUMÉRICOS

Os valores para temperatura média foram obtidos através de uma média pesada das temperaturas determinadas nos nós T1, T2 e T3 e para obtenção da temperatura máxima foi utilizado o nó T2 na geometria reentrante e o nó T4 para geometria trapezoidal, podemos observar as posições dos nós analisados para geometria trapezoidal através da Figura 74 e a Figura 75, e para a geometria reentrante conforme a Figura 76 e a Figura 77.

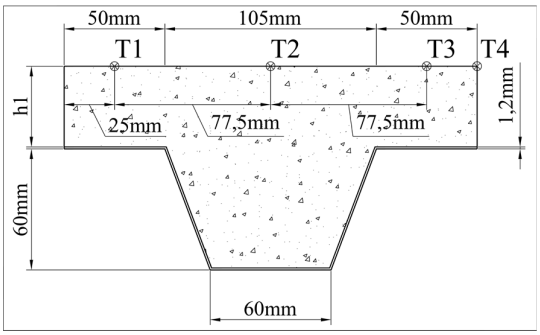


Figura 74: Nós de obtenção de temperatura geometria (L1/L2=105/60).

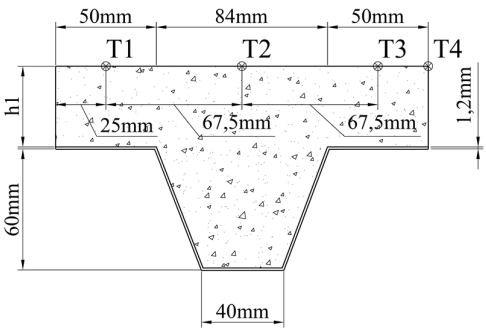


Figura 75: Nós de obtenção de temperatura geometria (L1/L2=84/40).

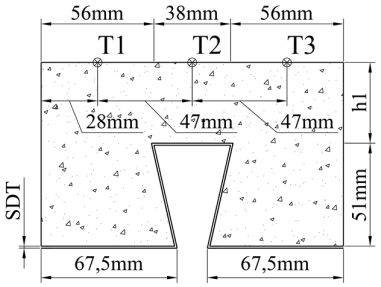


Figura 76: Nós de obtenção de temperatura geometria (L1/L2=112/135).

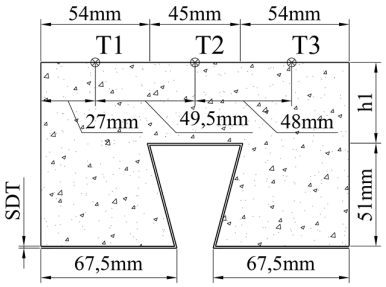


Figura 77: Nós de obtenção de temperatura geometria (L1/L2=108/135).

Pode observar-se a evolução da temperatura média (TMED=140+20ºC) e temperatura máxima (TMAX=180+20ºC) para as lajes trapezoidais nas lajes trapezoidais na Figura 86 e Figura 87 e para as lajes reentrantes, na Figura 96 e Figura 97, de acordo com o primeiro critério a ser alcançado para cada simulação. As simulações foram

desenvolvidas para um tempo final de 7200 s, e caso nenhum dos critérios de resistência ao fogo foi alcançado, as simulações foram repetidas para um tempo final de 14400 s.

Como o tempo máximo para as simulações foi definido como 14400 s, algumas lajes não alcançaram os critérios de resistência ao fogo durante este período (ti> 240 min). Pode-se perceber que o tempo de resistência ao fogo é diretamente proporcional aos parâmetros h1, L1 e L2, isso pode ser explicado devido ao fato que quando esses parâmetros aumentam, consequentemente a quantidade de concreto da seção da laje também aumenta.

Foi observado que o tempo de resistência ao fogo não apresentava variação maior que um minuto completo com a espessura do perfil metálico, sendo assim os resultados apresentados foram os da espessura que apresentava o tempo de resistência mais crítico.

5.1 Matlab

O campo de temperatura para o exemplo de geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm) é apresentado até o tempo crítico de resistência ao fogo, para intervalos de igual a 30, 60, 90 e 120 minutos, ver gráficos da Figura 78 a Figura 81. A resistência ao fogo esperada é igual a 7231 s que corresponde a 120 minutos completos. Este valor é inferior a 146 min, que é o valor determinado pelo modelo simplificado proposto no Eurocódigo 4 (ver Tabela 3).

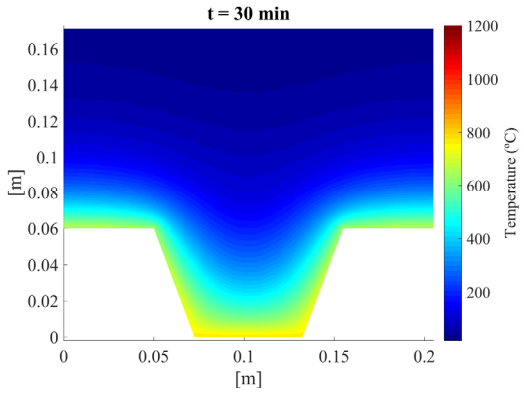


Figura 78: Campo de temperatura após 30 min, para a laje com geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

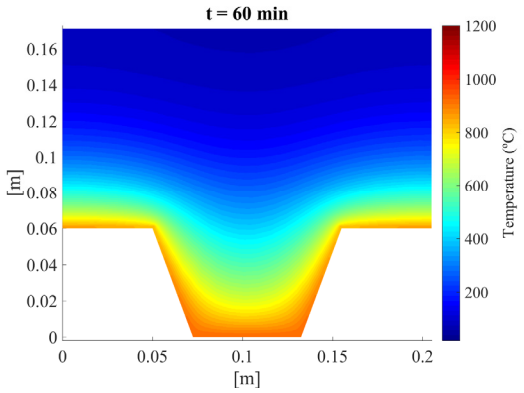


Figura 79: Campo de temperatura após 60 min, para a laje com geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

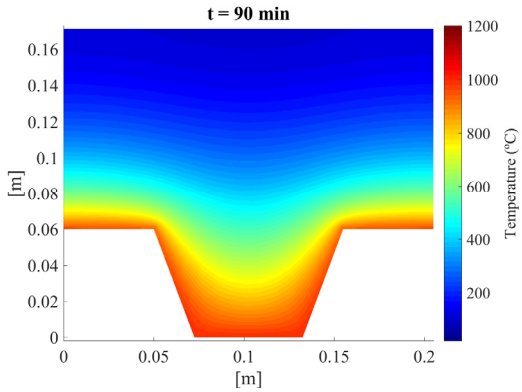


Figura 80: Campo de temperatura após 90 min, para a laje com geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

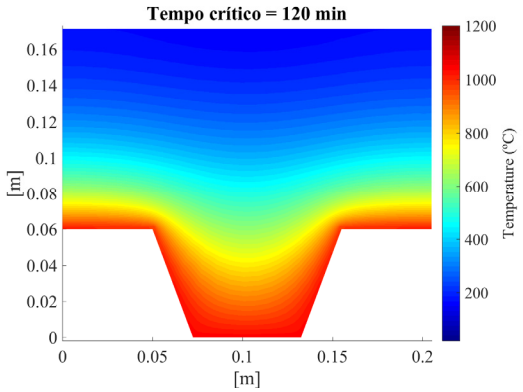


Figura 81: Campo de temperatura no tempo crítico (t= 120 min), para a laje com geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

O campo de temperatura para o exemplo de geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm) é plotada até o tempo crítico de resistência ao fogo, para um tempo igual a 28, 57, 86 e 115 minutos, ver gráficos da Figura 82 a Figura 85. A resistência ao fogo esperada é igual a 6913 s que corresponde a 115 minutos completos. Este valor é inferior a 143 min, que é o valor determinado pelo modelo simplificado proposto no Eurocódigo 4 (ver Tabela 3).

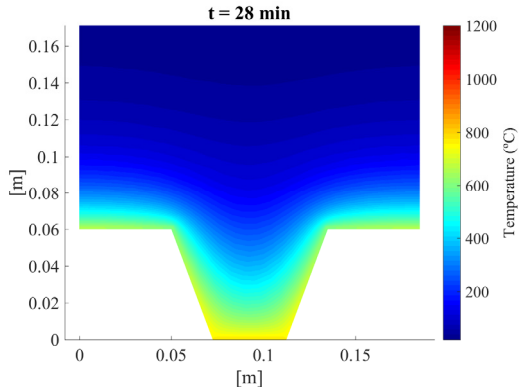


Figura 82: Campo de temperatura após 28 min, para a laje com geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

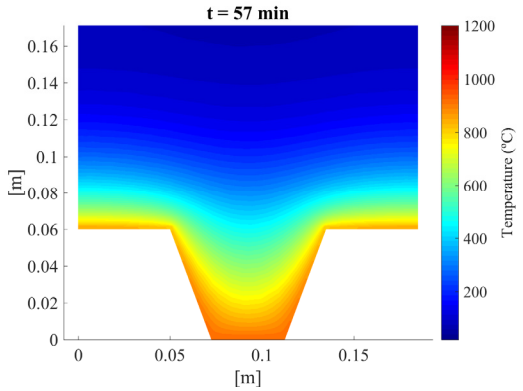


Figura 83: Campo de temperatura após 57 min, para a laje com geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

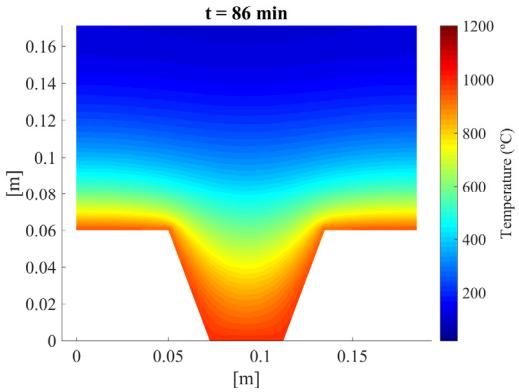


Figura 84: Campo de temperatura após 86 min, para a laje com geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

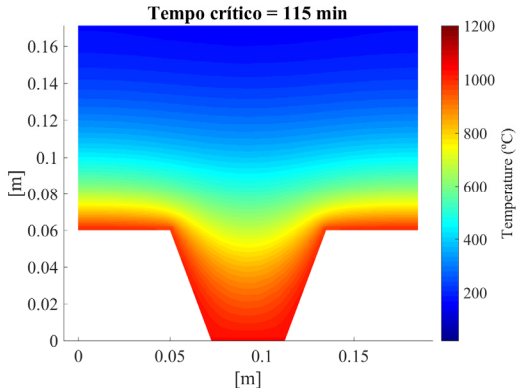


Figura 85: Campo de temperatura no tempo crítico (t= 115 min), para a laje com geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

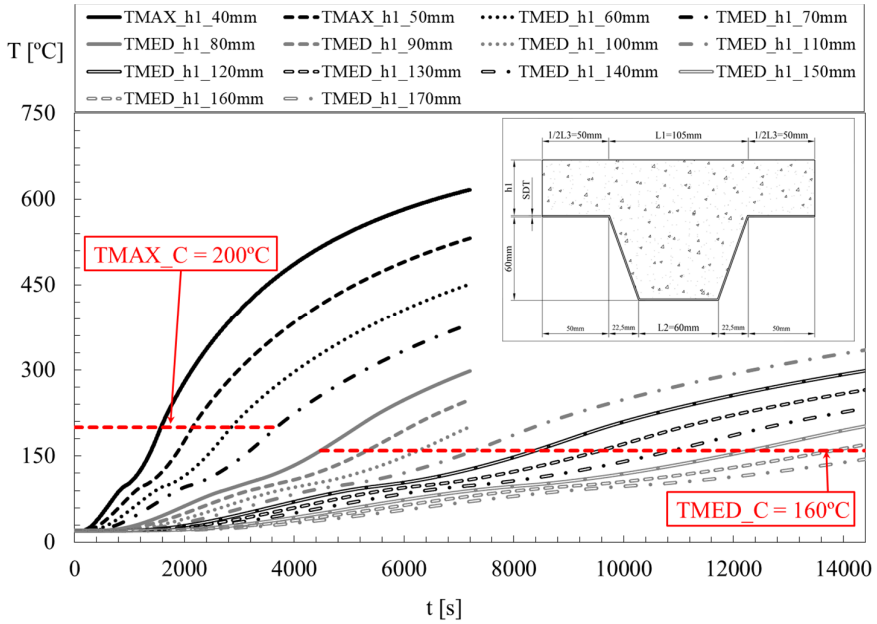


Figura 86: Evolução de temperatura no lado não exposto na laje trapezoidal com geometria (L1/L2=105/60 mm/mm). Análise no Matlab.

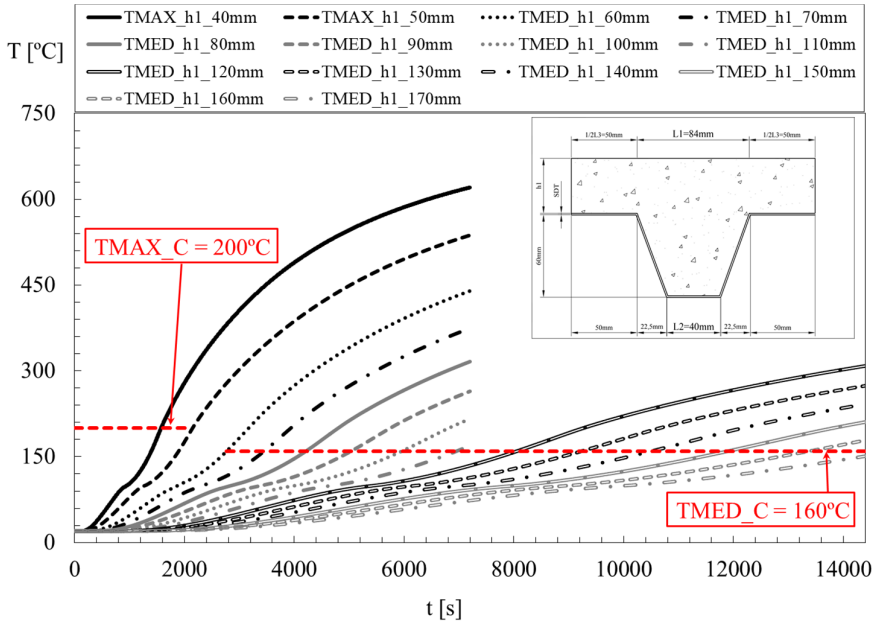


Figura 87: Evolução de temperatura no lado não exposto na laje trapezoidal com geometria (L1/L2=84/40 mm/mm). Análise no Matlab.

O tempo de resistência ao fogo simulado pelo Matlab para as lajes de perfil trapezoidal é apresentada na Tabela 10. Pode-se perceber que o critério dominante para a determinação do tempo de resistência ao fogo é a temperatura média. É possível perceber ainda que nas lajes com geometrias (L1/L2=105/60 mm/mm), conforme Figura 86, devido a uma maior quantidade de concreto concentrado no banzo inferior e, consequentemente curvas de progressão de temperaturas menores, o critério de temperatura máxima é crítico até parâmetros de h1= 70 mm A partir desse valor de parâmetro h1, o critério dominante é a temperatura média. Para as lajes com geometrias (L1/L2=84/40 mm/mm), veja Figura 87, podem-se verificar curvas de progressão de temperaturas maiores, devido a menor massa de concreto na seção. Outro fator interessante é que o critério de temperatura máxima só é dominante até parâmetros de h1 = 50 mm, após isso todos os tempos de resistência são obtidos pela temperatura média. Isso ocorre pelo fato de que a temperatura máxima é determinada no meio da seção do banzo superior e devido à baixa quantidade de concreto no banzo inferior, o aumento da temperatura na seção inteira é mais rápido. Pode-se perceber que com a variação de geometria o tempo de resistência ao fogo apresenta uma diferença de até 7 minutos.

Tabela 10: Tempo de resistência ao fogo da laje com deck trapezoidal em minutos completos (critério de isolamento). Análise no Matlab.

Geometria	h1[mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=84/40	t_i[min]	26	36	46	57	70	84	99	115	134	153	175	198	222	>240
L1/L2=105/60	t_i[min]	26	36	47	61	74	88	104	120	139	159	181	205	229	>240

Para o exemplo de geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm) o tempo crítico de resistência ao fogo é apresentado, para um tempo igual a 36, 73, 110 e 146 minutos, ver gráficos da Figura 88 a Figura 91. A resistência ao fogo esperada é igual a 8872 s que corresponde a 146 minutos completos. Este valor é inferior a 162 min, que é o valor determinado pelo modelo simplificado proposto no Eurocódigo 4 (ver Tabela 4).

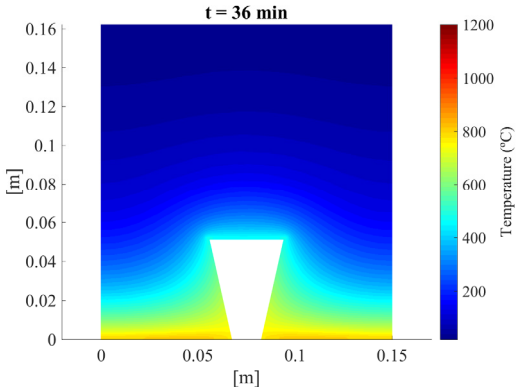


Figura 88: Campo de temperatura após 36 min, para a laje com geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

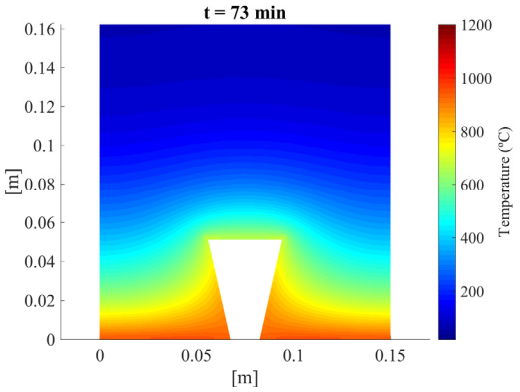


Figura 89: Campo de temperatura após 73 min, para a laje com geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

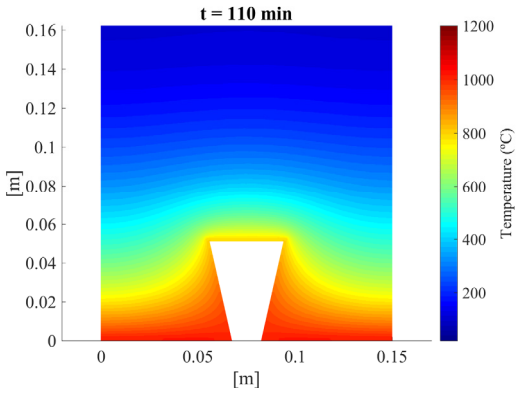


Figura 90: Campo de temperatura após 110 min, para a laje com geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

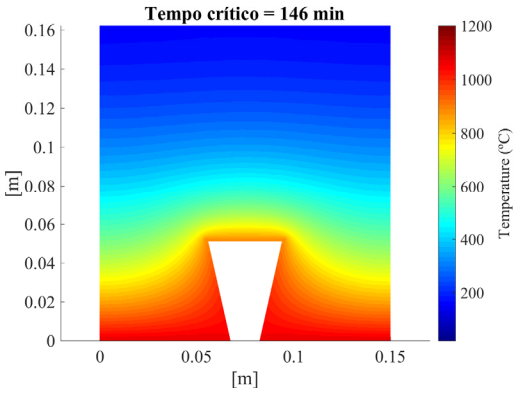


Figura 91: Campo de temperatura no tempo crítico (t= 146 min), para a laje com geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

Para o exemplo de geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm), o tempo crítico de resistência ao fogo é apresentado para um tempo igual a 36, 72, 108 e 144 minutos, ver gráficos da Figura 92 a Figura 95. A resistência ao fogo esperada é igual a 8743 s que corresponde a 144 minutos completos. Este valor é inferior a 159 min, que é o valor determinado pelo modelo simplificado proposto no Eurocódigo 4 (ver Tabela 4).

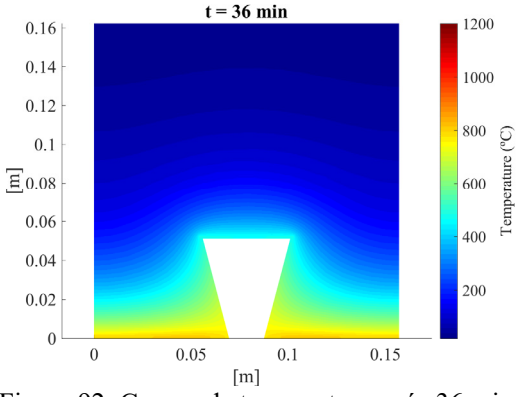


Figura 92: Campo de temperatura após 36 min, para a laje com geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

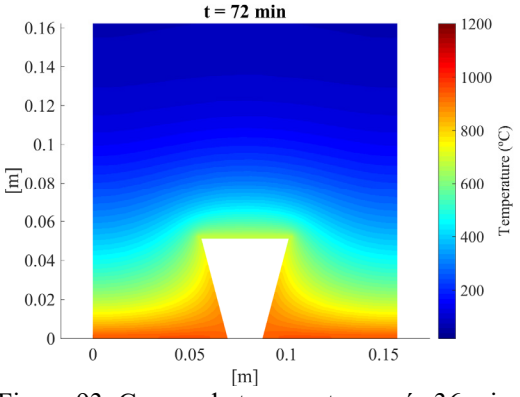


Figura 93: Campo de temperatura após 36 min, para a laje com geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

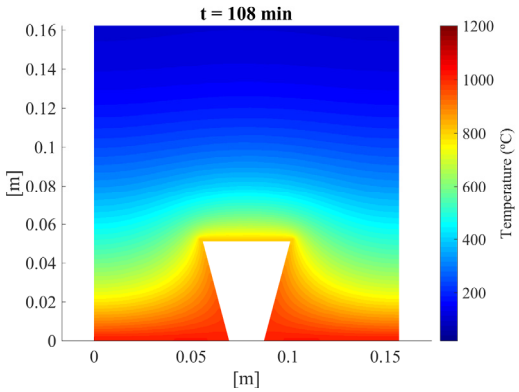


Figura 94: Campo de temperatura após 36 min, para a laje com geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

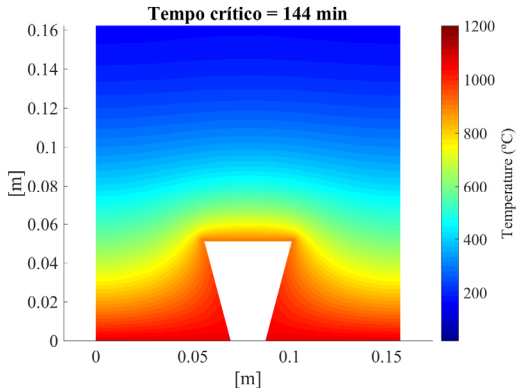


Figura 95: Campo de temperatura no tempo crítico (t= 146 min), para a laje com geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm). Análise no Matlab.

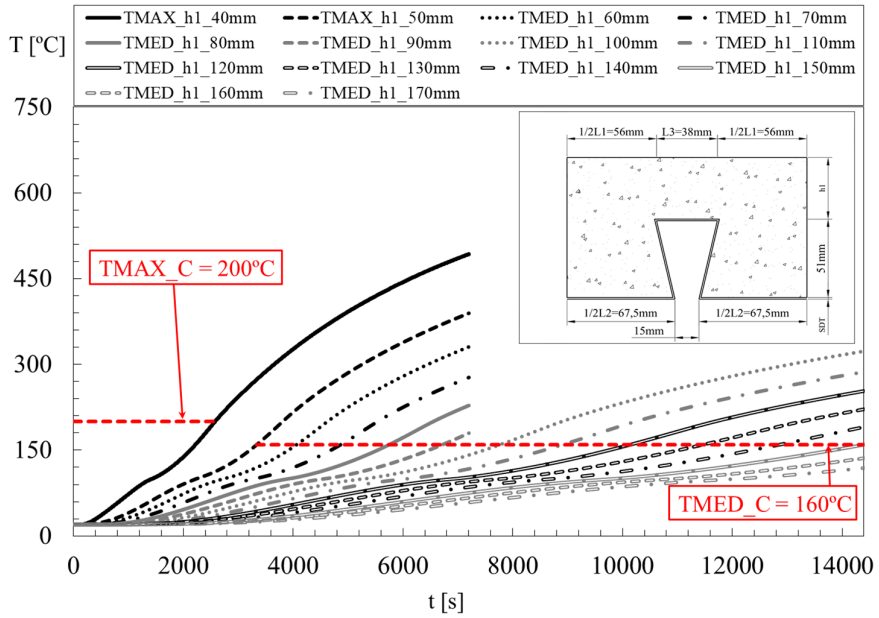


Figura 96: Evolução de temperatura no lado não exposto na laje reentrante com geometria (L1/L2=112/135 mm/mm). Análise no Matlab.

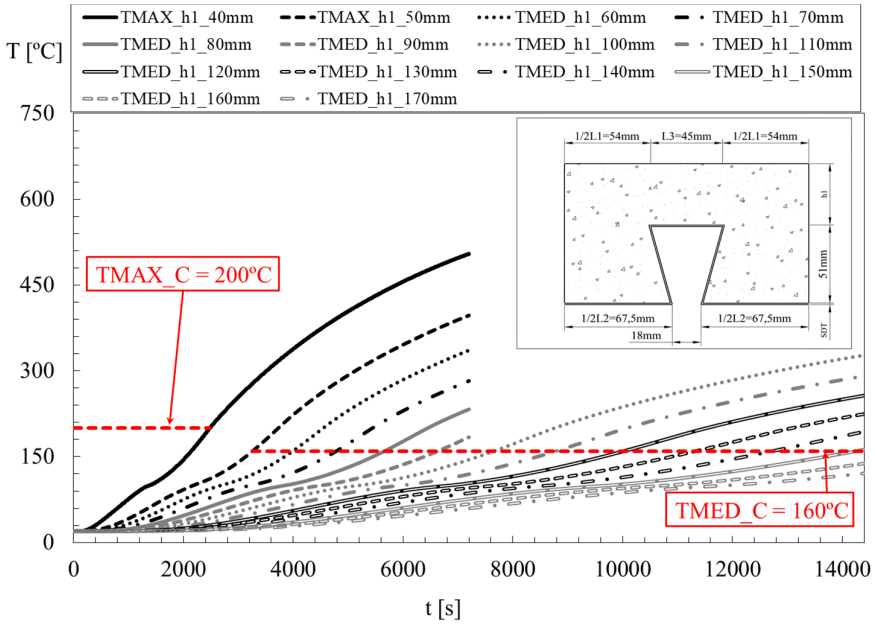


Figura 97: Evolução de temperatura no lado não exposto na laje reentrante com geometria (L1/L2=108/135 mm/mm). Análise no Matlab.

O tempo de resistência ao fogo simulado pelo Matlab para as lajes de perfil reentrante é apresentada na Tabela 11. Pode-se perceber que assim como nas lajes trapezoidais, o critério dominante para a determinação do tempo de resistência ao fogo é a temperatura média. É possível verificar que nas lajes com geometrias (L1/L2=112/135 mm/mm) e (L1/L2=84/40 mm/mm), conforme Figura 96 e Figura 97, devido a geometria reentrante, a quantidade de concreto no perfil é maior, o que aumenta o tempo de resistência ao fogo, e assim curvas de progressão de temperaturas menores. O critério de temperatura máxima é crítico até parâmetros de h1= 40 mm, a partir desse valor, o critério dominante é de temperatura média. Pode-se constatar ainda que a variação dos parâmetros L1 e L2 nas lajes reentrantes não resulta em grande variação do tempo de resistência, variações de apenas 5 % a 2 % no tempo de resistência ao fogo foram observadas.

Tabela 11: Tempo de resistência ao fogo da laje com deck reentrante em minutos completos (critério de isolamento). Análise no Matlab.

Geometria	h1[mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=112/135	t_i[min]	42	55	67	80	95	111	129	147	168	190	214	239	>240	>240
L1/L2=108/135	t_i[min]	40	53	65	79	93	109	126	145	165	187	211	236	>240	>240

A evolução da temperatura também foi calculada para a geometria utilizada nos ensaios experimentais de acordo com os locais adotados para o posicionamento dos termopares. Os resultados são apresentados em dois gráficos separados; de acordo com os locais de medição (ver Figura 98 para os locais não expostos e Figura 99 para os locais intermediários). A temperatura do lado não exposto é caracterizada por T1, T2, T3, T4, T5, T6, T7, T8, T9, T10 e T11, enquanto a temperatura para medições intermediárias é caracterizada por T12, T13, T14, T16, T18, T19 T21, T15, T20 e T17.

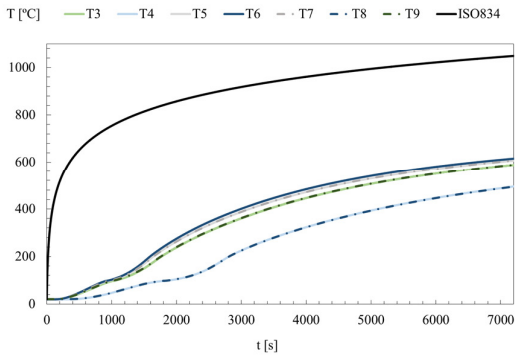


Figura 98: Evolução de temperatura para o lado não exposto.

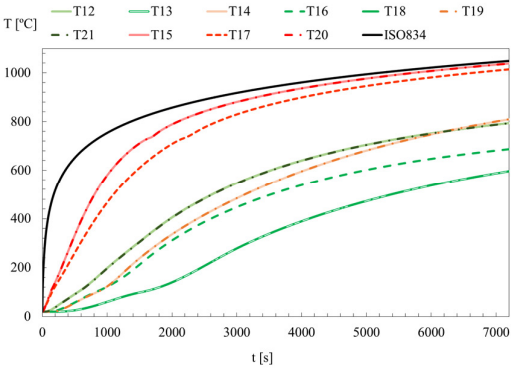


Figura 99: Evolução de temperatura para localizações intermediárias.

O aumento médio e máximo da temperatura na superfície não exposta é baseado em medições obtidas a partir dos termopares de disco, localizados no centro ou próximo ao centro da laje e também de cada um de seus quadrantes [51], ver termopares T1, T2, T6 , T10 e T11. A temperatura máxima foi determinada pela temperatura mais alta registrada por qualquer um dos termopares não expostos. A Figura 100 representa a evolução média (TMED) e máxima (TMAX) das temperaturas na laje mista.

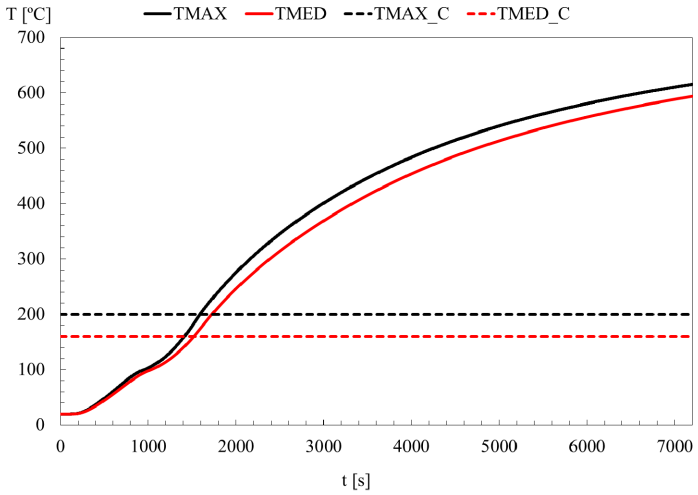


Figura 100: Evolução de temperatura no lado não exposto (T_MAX e T_MED).

A Figura 100 também apresenta os critérios de desempenho para a classificação do tempo de resistência contra incêndio de isolamento (TMAX_C = 180 + 20 ºC ou TMED_C = 140 + 20 ºC). A temperatura máxima é obtida através do histórico de tempo do termopar T6 que é o que apresenta a temperatura mais alta durante a simulação. Cinco termopares foram utilizados para o cálculo de T_MED (T1, T2, T6, T10 e T11). A resistência ao fogo esperada é igual a 1528 s que corresponde a 25 minutos completos. Este valor é inferior a 38 min, ou seja, o valor determinado pelo modelo simplificado proposto no Eurocódigo EN1994-1-2 (ver Tabela 3) também é inferior ao valor de 30 min para uma laje com espessura efetiva de 64,15 mm proposto na NBR 14323:2013 (ver Tabela 5).

O campo de temperaturas é apresentado para os tempos iguais a 6, 12, 19 e 25 minutos, o último que representa o tempo crítico, ver gráficos da Figura 101 a Figura 104.

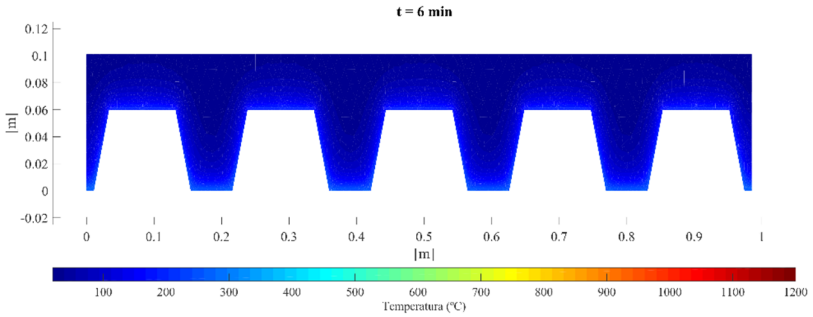


Figura 101: Campo de temperatura após 6 min, para a laje de geometria (L1 / L2 = 105/60, h1 = 40 mm, SDT = 1,2 mm).

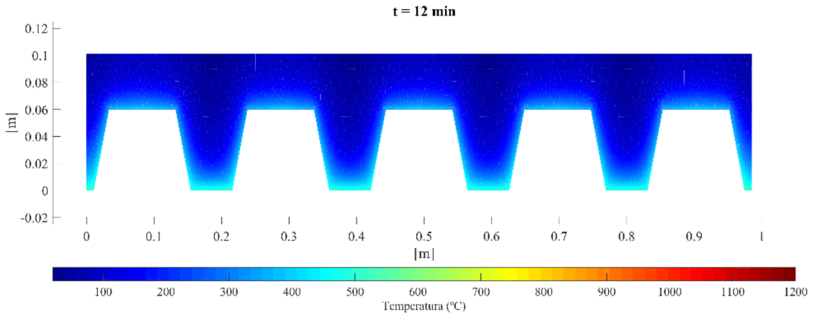


Figura 102: Campo de temperatura após 12 min, para a laje de geometria (L1 / L2 = 105/60, h1 = 40 mm, SDT = 1,2 mm).

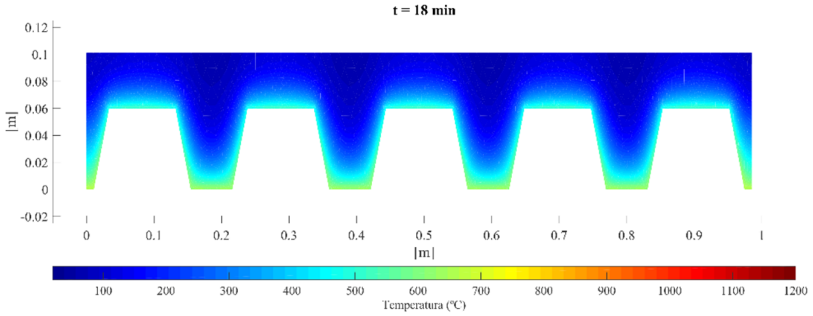


Figura 103: Campo de temperatura após 18 min, para a laje de geometria (L1 / L2 = 105/60, h1 = 40 mm, SDT = 1,2 mm).

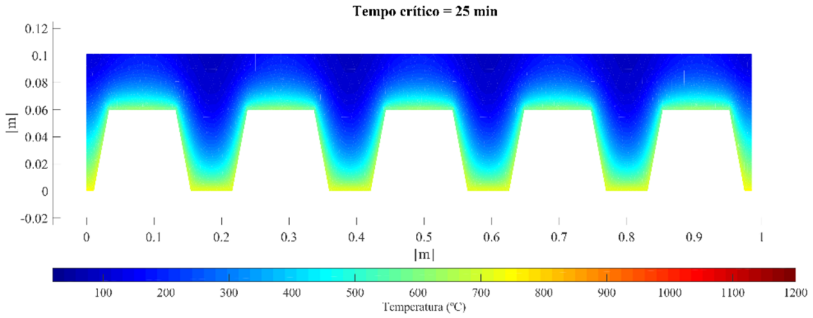


Figura 104: Campo de temperatura para o tempo crítico (25min), para a laje de geometria(L1 / L2 = 105/60, h1 = 40 mm, SDT = 1,2 mm).

5.2 Ansys

O campo de temperatura para o exemplo de geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm) é apresentada até o tempo crítico de resistência ao fogo, para um tempo igual a 28, 57, 86 e 114 minutos, ver gráficos da Figura 105 à Figura 108. A resistência ao fogo esperada é igual a 6891 s que corresponde a 114 minutos completos. Este valor é inferior a 146 min, que é o valor determinado pelo modelo simplificado proposto no Eurocódigo 4 (ver Tabela 3)

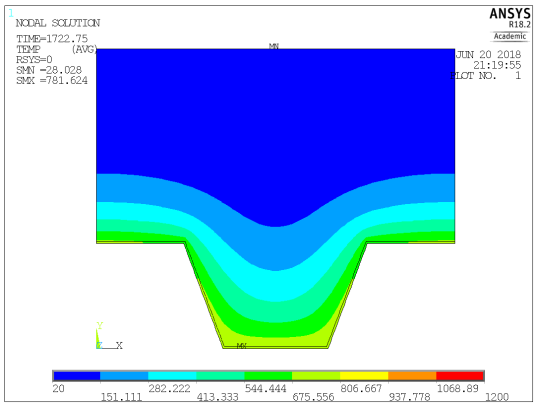


Figura 105: Campo de temperatura após 28 min, para a laje com geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm). Análise no ANSYS

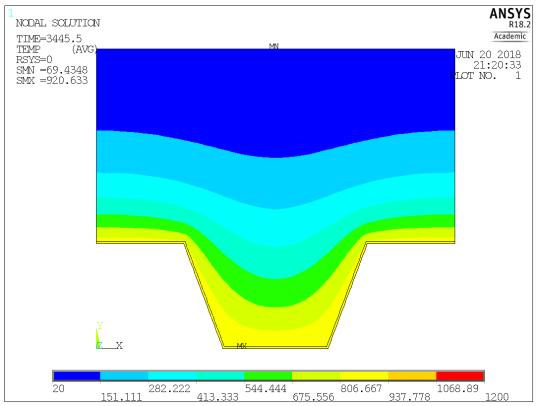


Figura 106: Campo de temperatura após 57 min, para a laje com geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm). Análise no ANSYS

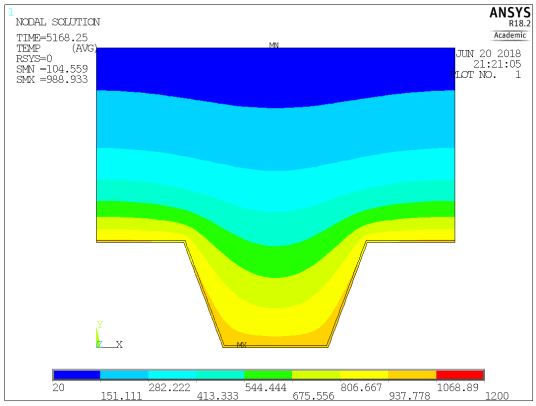


Figura 107: Campo de temperatura após 86 min, para a laje com geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm). Análise no ANSYS

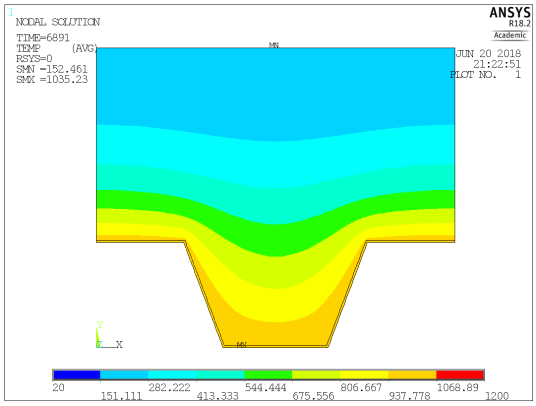


Figura 108: Campo de temperatura no tempo crítico (t= 114 min), para a laje com geometria (L1/L2=105/60, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

O campo de temperatura para o exemplo de geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm) é apresentado até o tempo crítico de resistência ao fogo, para um tempo igual a 27, 54, 81 e 109 minutos, ver gráficos da Figura 109 a Figura 112. A resistência ao fogo esperada é igual a 6547 s que corresponde a 109 minutos completos. Este valor é inferior a 143 min, que é o valor determinado pelo modelo simplificado proposto no Eurocódigo 4 (ver Tabela 3)

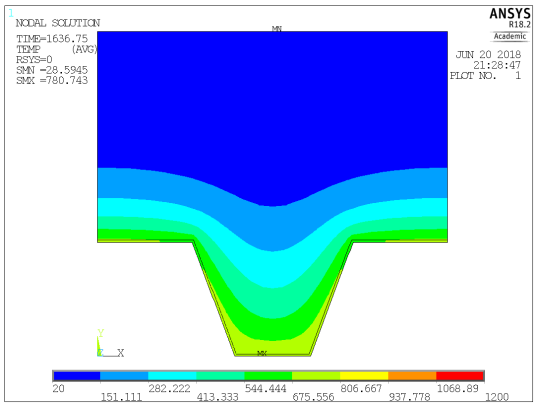


Figura 109: Campo de temperatura após 27 min, para a laje com geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

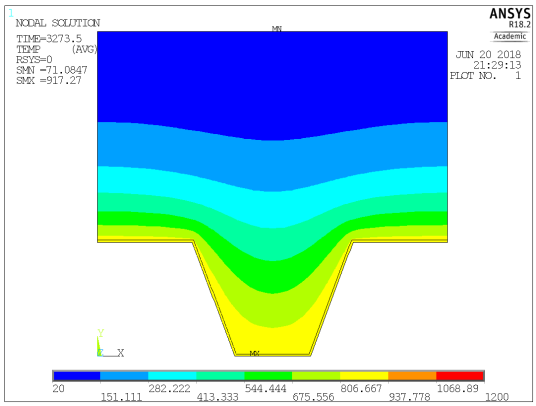


Figura 110: Campo de temperatura após 54 min, para a laje com geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

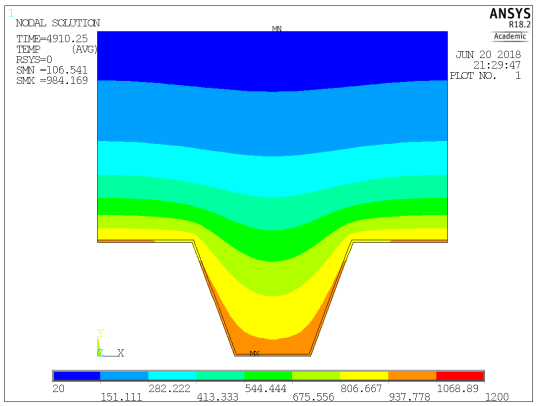


Figura 111: Campo de temperatura após 81 min, para a laje com geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

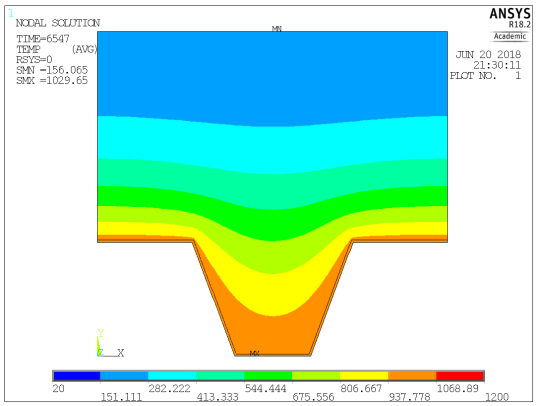


Figura 112: Campo de temperatura no tempo crítico (t= 109 min), para a laje com geometria (L1/L2=84/40, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

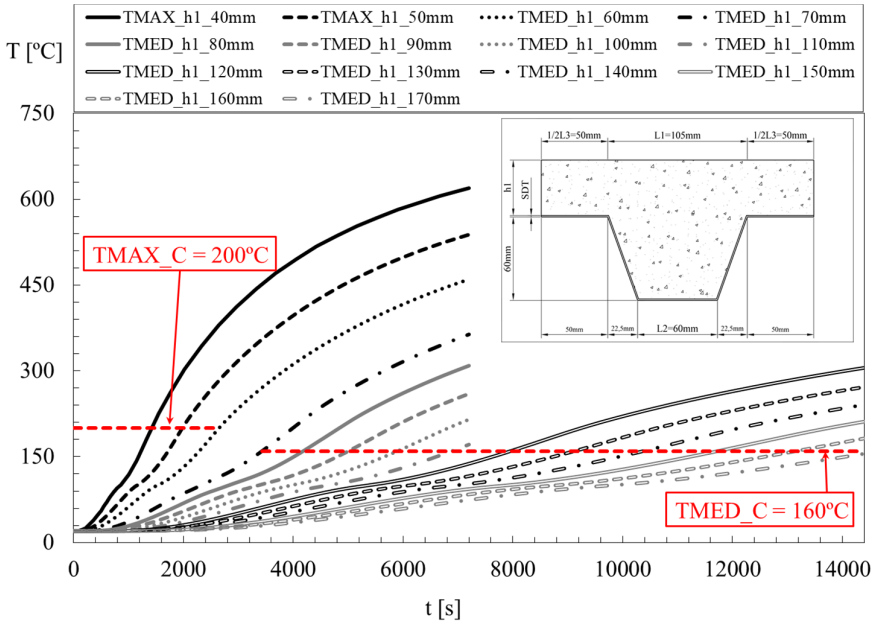


Figura 113: Evolução de temperatura no lado não exposto na laje trapezoidal com geometria (L1/L2=105/60 mm/mm). Análise no ANSYS.

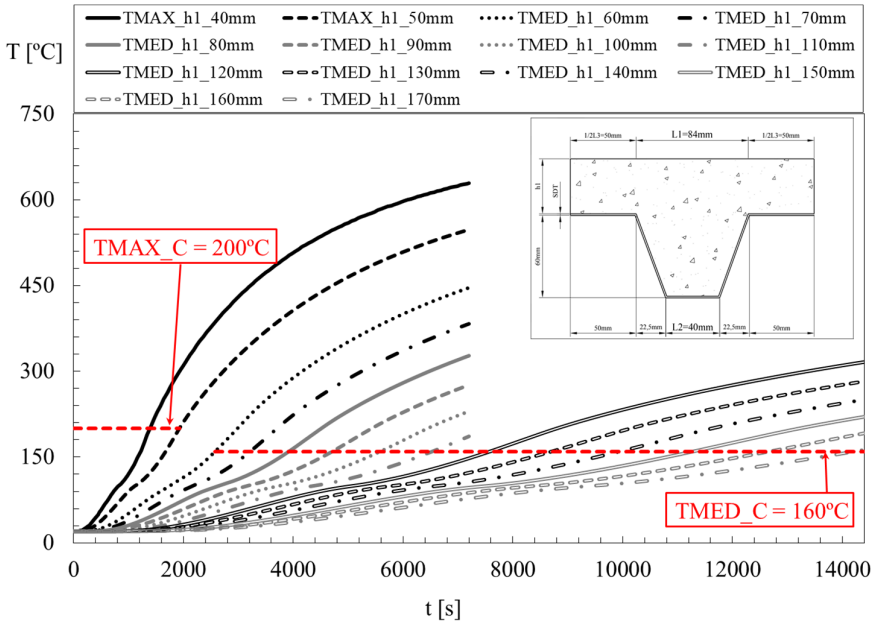


Figura 114: Evolução de temperatura no lado não exposto na laje trapezoidal com geometria (L1/L2=84/40 mm/mm). Análise no ANSYS.

O tempo de resistência ao fogo simulado pelo ANSYS para as lajes de perfil trapezoidal é apresentado na Tabela 12. Pode-se perceber que as progressões de temperaturas são similares às obtidas pelas simulações no Matlab. No modelo avançado desenvolvido no ANSYS, o critério dominante para a determinação do tempo de resistência ao fogo é a temperatura média. Pode-se perceber que nas lajes com geometrias

(L1/L2=84/40 mm/mm), veja Figura 113, o critério de temperatura máxima é crítico até parâmetros de h1= 60 mm, a partir desse valor o critério dominante é de temperatura média. Para as lajes com geometrias (L1/L2=105/60 mm/mm), o critério de temperatura máxima só é dominante até parâmetros de h1 = 50 mm, após isso todos os tempos de resistência são obtidos através da temperatura média.

Tabela 12: Tempo de resistência ao fogo da laje com deck trapezoidal em minutos completos (critério de isolamento). Análise no ANSYS.

Geometria	h1[mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=84/40	t_i[min]	23	32	43	53	65	78	93	109	126	145	166	188	211	236
L1/L2=105/60	t_i[min]	24	33	44	57	70	83	98	114	132	152	173	195	219	>240

Para o exemplo de geometria (L1/L2=112/135, h1=110 mm, SDT=1.2mm) o ,tempo crítico de resistência ao fogo é apresentado para um tempo igual a 34, 69, 104 e 139 minutos, ver gráficos da Figura 115 a Figura 118. A resistência ao fogo esperada é igual a 8370 s, que corresponde a 139 minutos completos. Este valor é inferior a 162 min, que é o valor determinado pelo modelo simplificado proposto no Eurocódigo 4 (ver Tabela 4).

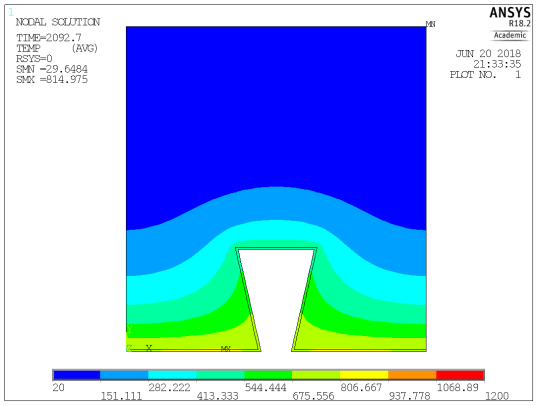


Figura 115: Campo de temperatura após 34 min, para a laje com geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

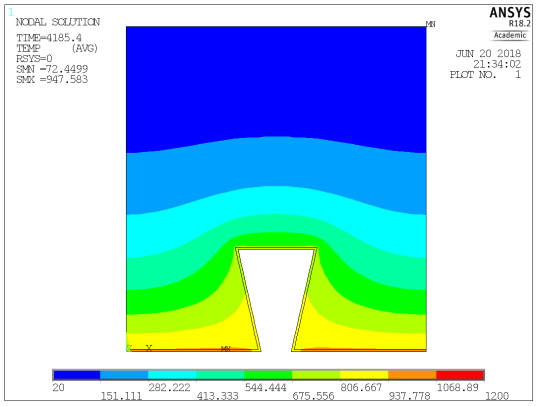


Figura 116: Campo de temperatura após 69 min, para a laje com geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

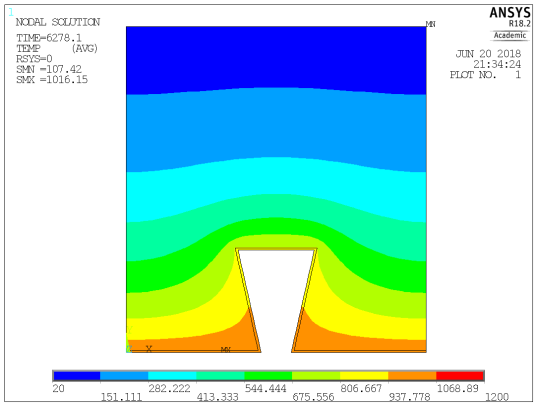


Figura 117: Campo de temperatura após 104 min, para a laje com geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

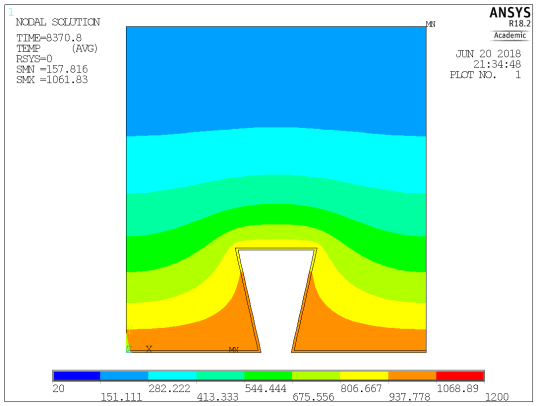


Figura 118: Campo de temperatura no tempo crítico (t= 139min), para a laje com geometria (L1/L2=112/135, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

Para o exemplo de geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm), o tempo crítico de resistência ao fogo é apresentado para um tempo igual a 34, 68, 103 e 137 minutos, ver gráficos da Figura 119 a Figura 122. A resistência ao fogo esperada é igual a 8240 s, que corresponde a 137 minutos completos. Este valor é inferior a 159 min, que é o valor determinado pelo modelo simplificado proposto no Eurocódigo 4 (ver Tabela 4).

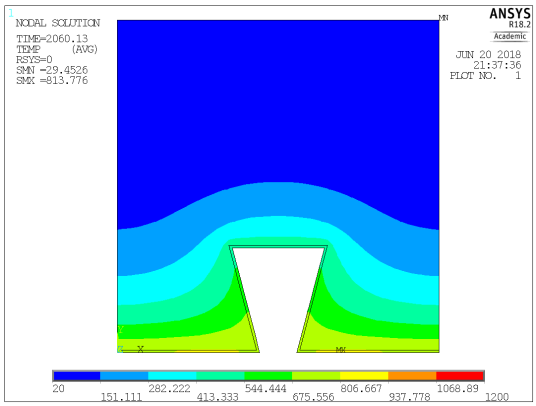


Figura 119: Campo de temperatura após 34 min, para a laje com geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

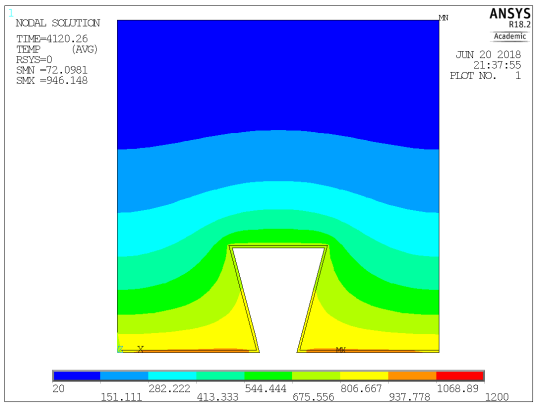


Figura 120: Campo de temperatura após 68 min, para a laje com geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

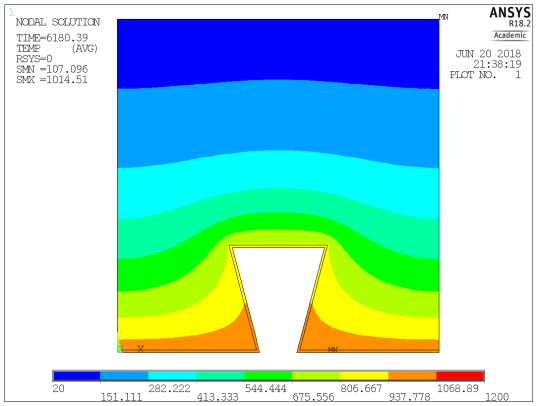


Figura 121: Campo de temperatura após 103 min, para a laje com geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

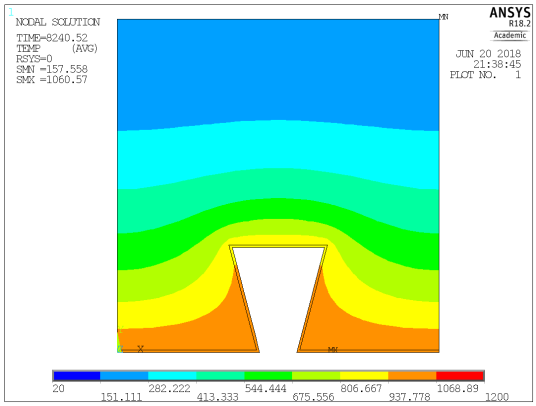


Figura 122: Campo de temperatura no tempo crítico (t= 137 min), para a laje com geometria (L1/L2=108/135, h1=110 mm, SDT=1.2 mm). Análise no ANSYS.

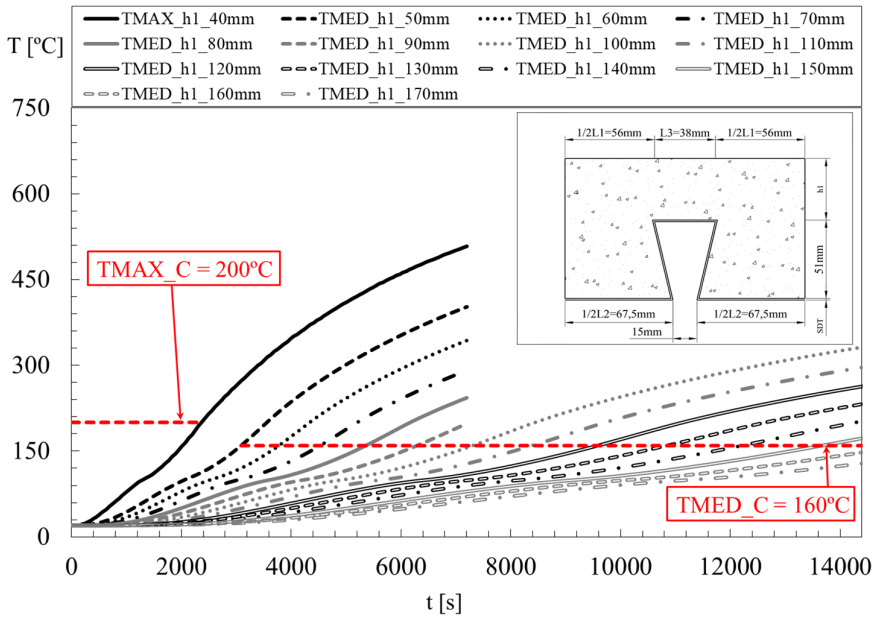


Figura 123: Evolução de temperatura no lado não exposto na laje reentrante com geometria (L1/L2=112/135 mm/mm). Análise no ANSYS.

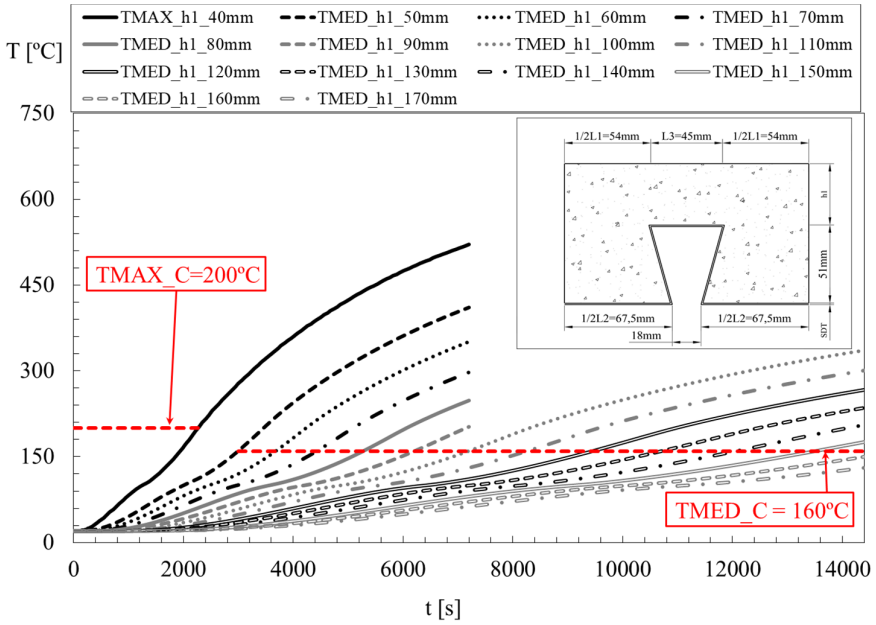


Figura 124: Evolução de temperatura no lado não exposto na laje reentrante com geometria (L1/L2=108/135 mm/mm). Análise no ANSYS.

O tempo de resistência ao fogo simulado pelo ANSYS para as lajes de perfil reentrante é apresentado na Tabela 13. É possível notar que, assim como nas lajes trapezoidais, o critério dominante para a determinação do tempo de resistência ao fogo é a temperatura média. Para as lajes com geometrias (L1/L2=112/135 mm/mm) e (L1/L2=84/40 mm/mm), veja Figura 123 e Figura 124, o critério de temperatura máxima é crítico até parâmetros de h1= 40 mm, a partir disso o fator dominante é de temperatura média. Pode-se perceber que com a variação dos parâmetros L1 e L2 nas lajes reentrantes o tempo de resistência não apresenta grande variação, sendo essa variação de um a três minutos.

Tabela 13: Tempo de resistência ao fogo da laje com deck reentrante em minutos completos (critério de isolamento). Análise no ANSYS.

Geometria	h1[mm]	40	50	60	70	80	90	100	110	120	130	140	150	160	170
L1/L2=112/135	t_i[min]	39	51	62	75	89	104	121	139	159	184	203	227	>240	>240
L1/L2=108/135	t_i[min]	38	49	61	73	87	102	119	137	156	177	200	224	>240	>240

5.3 Influência dos parâmetros geométricos da laje

O fator mais significante na determinação da resistência ao fogo de lajes mistas (ver Figura 3 e Figura 4) expostas ao fogo é a altura da parte contínua superior da laje, h_1 [3]. Através das simulações numéricas realizadas, pode-se perceber que quanto maior o parâmetro h_1, menor a temperatura no lado não exposto da laje. Este parâmetro possui a maior influência no critério de resistência ao fogo das lajes mistas, ver Figura 125 a Figura 128.

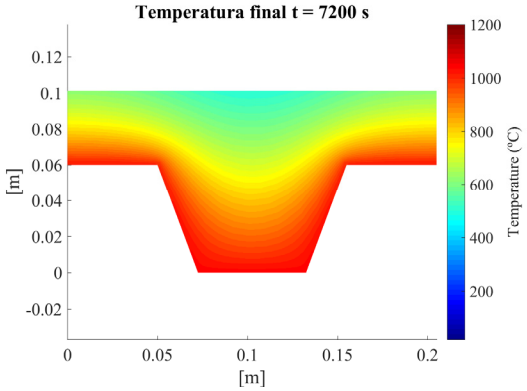


Figura 125: Temperatura após 120 min de uma laje trapezoidal com h_1 = 40 mm e L1/L2=105/60(mm)

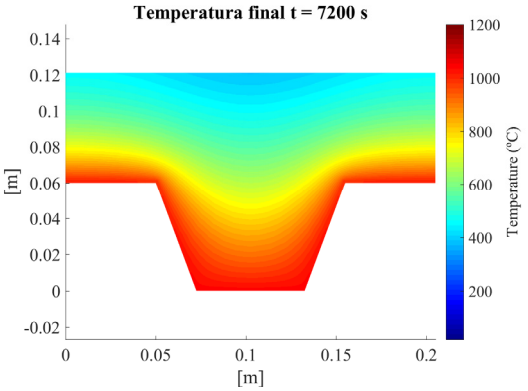


Figura 126: Temperatura após 120 min de uma laje trapezoidal com h_1 = 80 mm e L1/L2=105/60mm/mm

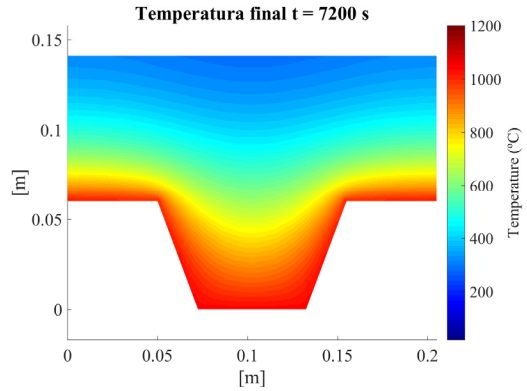


Figura 127: Temperatura após 120 min de uma laje trapezoidal com h_1 = 60 mm e L1/L2=105/60mm/mm

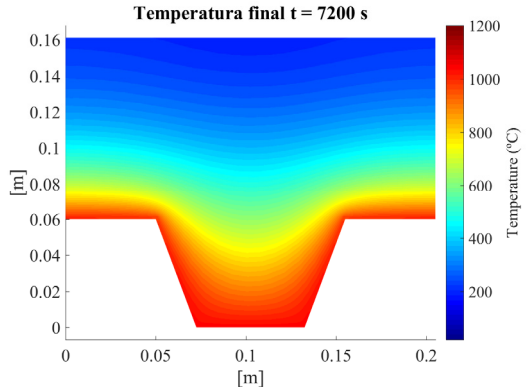


Figura 128: Temperatura após 120 min de uma laje trapezoidal com h_1 = 100 mm e L1/L2=105/60mm/mm

A influência de h_2 está diretamente relacionada com a distribuição de temperaturas no meio da laje, entretanto o acréscimo de h_2 acarreta um aumento da massa de concreto na seção da laje, e consequentemente diminui as curvas de temperaturas no

lado não exposto da laje, contudo essa variação não é tão representativa como a variação do parâmetro h_1. A variação de l_1 e l_2 também possui um efeito semelhante ao causado pelo parâmetro h_2, já que a massa de concreto também está diretamente relacionada à variação de l_1 e l_2. A diferença está na distribuição das temperaturas mais baixas na parte superior da laje, porém a variação na parte mais fina da seção não é afetada pela variação desses parâmetros [3].

O comprimento da parte superior da reentrância da laje, definido como l_3, afeta diretamente a transferência de calor na parte mais fina da laje, onde a máxima temperatura ocorre, entretanto, possui pequena influência na maior seção da laje. Por mais que a temperatura na parte fina da laje aumente de acordo com a progressão de l_3, esse efeito é muito pequeno [3].

6 COMPARAÇÃO DE RESULTADOS

6.1 Comparação Numérico – Experimental

Através das análises numéricas e experimentais é possível perceber uma grande diferença entre as temperaturas na posição dos termopares obtidas através do modelo avançado de cálculo, veja Figura 98 e Figura 99, e os resultados obtidos nos ensaios experimentais, conforme a Figura 53 e Figura 54 para o espécime 1, e Figura 66 e Figura 67 para o espécime 2. Após a análise da progressão de temperatura média e máxima no lado não exposto, podemos realizar a comparação entre os resultados obtidos, conforme pode se verificar da Figura 129 até a Figura 132.

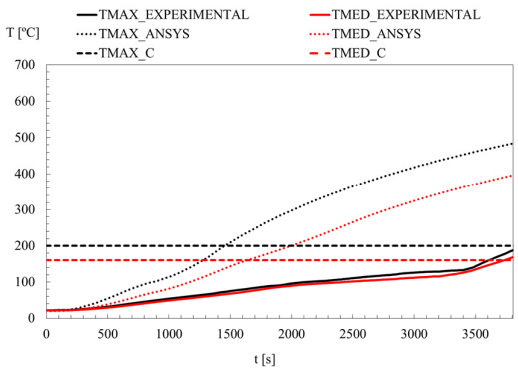


Figura 129: Evolução de temperatura média e máxima (Espécime 1 - ANSYS).

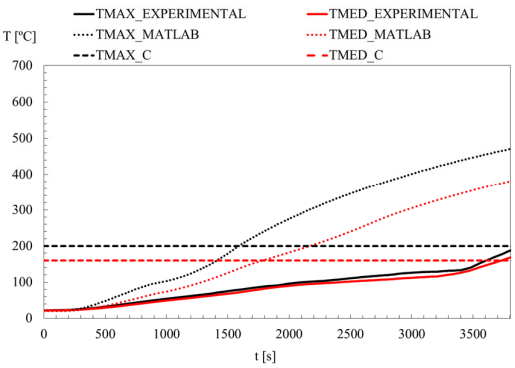


Figura 130: Evolução de temperatura média e máxima (Espécime 1 - Matlab).

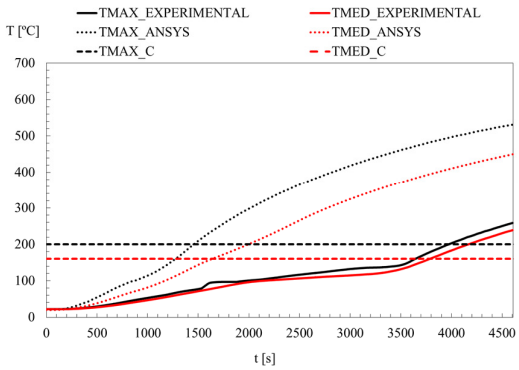


Figura 131: Evolução de temperatura média e máxima (Espécime 2 - ANSYS).

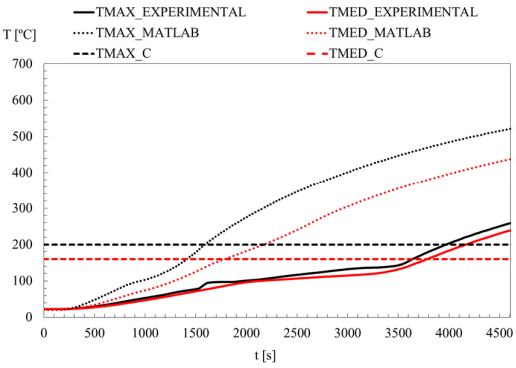


Figura 132: Evolução de temperatura média e máxima (Espécime 2 - Matlab).

O método avançado de cálculo desenvolvido no Matlab previa um tempo de resistência ao fogo para o critério de isolamento de 26 min para a geometria de laje estudada nos ensaios experimentais, e o modelo no ANSYS previa um tempo de resistência de 23 min. Porém nas análises experimentais pode-se verificar um tempo de resistência ao fogo de 62 min para o espécime 1, e de 63 min para o espécime 2. Diversos fatores podem explicar essa grande diferença no tempo de resistência, sendo o principal deles o princípio do contato térmico perfeito adotado no modelo numérico, visto que nos ensaios experimentais, por conta da deformação dos elementos, observou-se um descolamento de até 3 cm do perfil metálico em relação a camada de concreto superior. Outro fator que se verificou foi a concentração de água no centro do espécime, causando um efeito de estagnação da temperatura nos termopares não expostos do centro, devido ao efeito de evaporação da água. Jian Jiang *et al.* [3] também ressalta a influência da mudança na emissividade do deck de aço galvanizado como resultado do derretimento da camada de zinco, afirmando que o valor de emissividade do material recomendado pelo Eurocódigo 4 [7] de 0.7 é conservador, sugerindo um valor de emissividade dependente da temperatura para esse tipo de material.

6.2 Comparação Matlab - ANSYS

A Figura 133 e a Figura 134 representam a comparação da resistência ao fogo entre os dois métodos numéricos de solução (modelo avançado desenvolvido no Matlab e modelo avançado desenvolvido no ANSYS) pela progressão de h_{eff}, veja equação (14). Verifica-se que o modelo desenvolvido no Matlab apresenta resultados satisfatórios, apresentando uma diferença maior que 10 % em apenas 8 dos 160 casos analisados, para simulações de até 4 horas, quando comparado ao programa comercial ANSYS ® 18.2. Observa-se também que o Matlab fornece geralmente tempos críticos de resistência ao fogo maiores do que os do ANSYS. Esta diferença pode estar relacionada com a diferença da malha de elementos finitos.

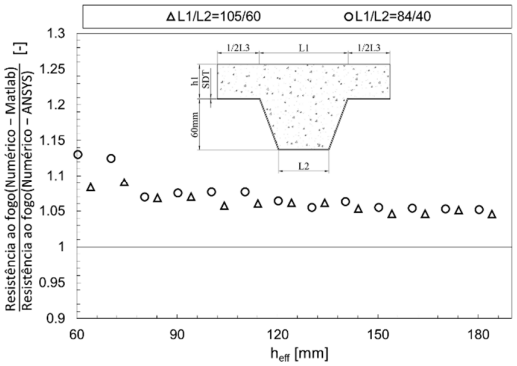


Figura 133: Comparação de resultados numéricos.

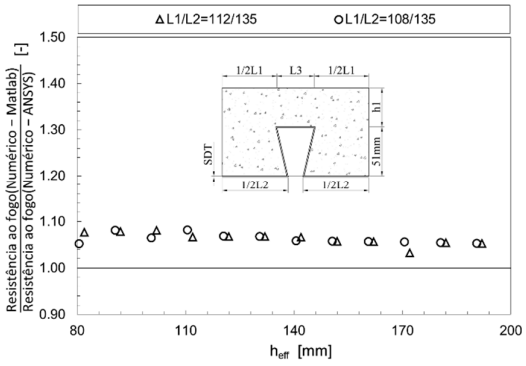


Figura 134: Comparação de resultados numéricos.

6.3 Comparação Matlab – Eurocódigo EN 1994-1-2

A Figura 135 e a Figura 136 representam a comparação da resistência ao fogo entre os dois métodos de resolução (modelo avançado desenvolvido no Matlab e método simplificado proposto pelo Eurocódigo 4) pela progressão de h_{eff}. Valores menores que 1 devem ser considerados inseguros.

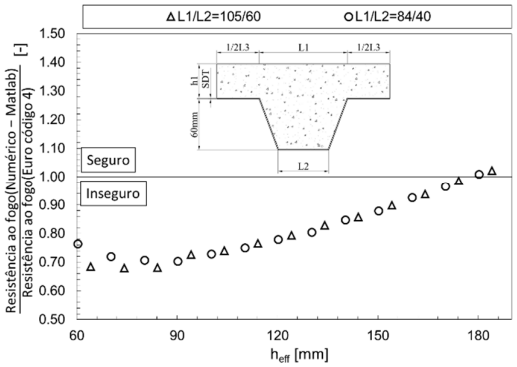


Figura 135: Resultados para lajes trapezoidais comparados ao Eurocódigo 4. Análise no Matlab.

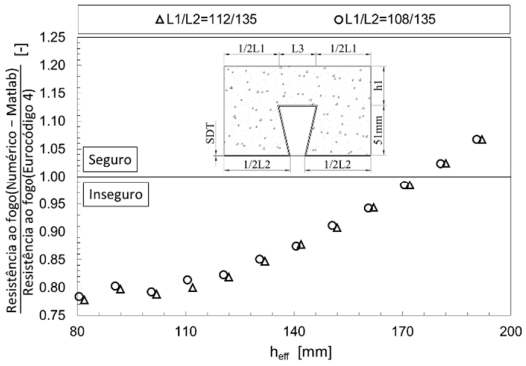


Figura 136: Resultados para lajes reentrantes comparados ao Eurocódigo 4. Análise no Matlab.

Pode-se perceber que para mais de 86 % dos casos estudados, para simulações de até 4 horas, o Matlab apresenta um tempo crítico de resistência ao fogo menor que o determinado pelo Eurocódigo EN 1994-1-2.

6.4 Comparação ANSYS - Eurocódigo EN 1994-1-2

A Figura 137 e a Figura 138 representam a comparação da resistência ao fogo entre os dois métodos de resolução (modelo avançado desenvolvido no ANSYS e método simplificado proposto pelo Eurocódigo 4) pela progressão de h_{eff}. Valores menores que 1 devem ser considerados inseguros.

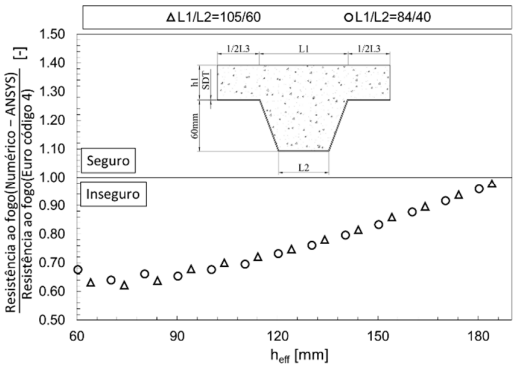


Figura 137: Resultados para lajes trapezoidais comparados ao Eurocódigo 4. Análise no ANSYS.

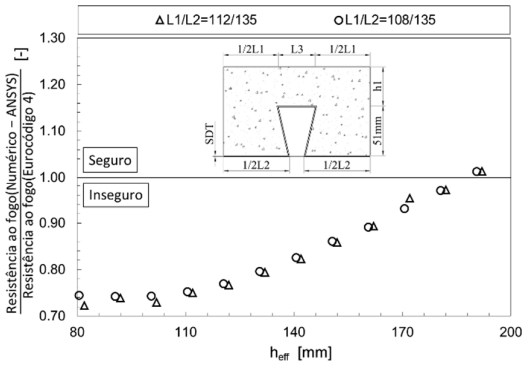


Figura 138: Resultados para lajes reentrantes comparados ao Eurocódigo 4. Análise no ANSYS..

É possível observar que para mais de 96% dos casos analisados, para simulações de até 4 horas, o ANSYS apresenta um tempo crítico de resistência ao fogo menor que o determinado pelo Eurocódigo EN 1994-1-2.

6.5 Comparação Matlab – NBR 14323

A Figura 139 e a Figura 140 representam a comparação da resistência ao fogo entre os dois métodos de solução (modelo avançado desenvolvido no Matlab e método simplificado proposto pela NBR 14323) pela progressão de h_{eff}. Valores menores que 1 devem ser considerados inseguros. Devido aos valores dispostos pela NBR 14323 [9], apresentados na Tabela 5, os resultados apresentam grande discrepância do modelo numérico. Os tempos de resistência ao fogo dispostos na NBR 14323 estão classificados por patamares de h_{eff} e esse parâmetro é definido até 150 mm o que causa um dimensionamento para o isolamento térmico antieconômico em geometrias com

$h_{eff} > 160\,mm$, em contrapartida para geometrias com $h_{eff} < 160\,mm$ as recomendações estão inseguras.

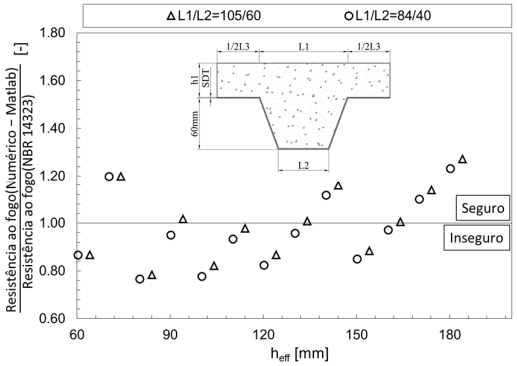


Figura 139: Resultados para lajes trapezoidais comparados à NBR 14323. Análise no Matlab.

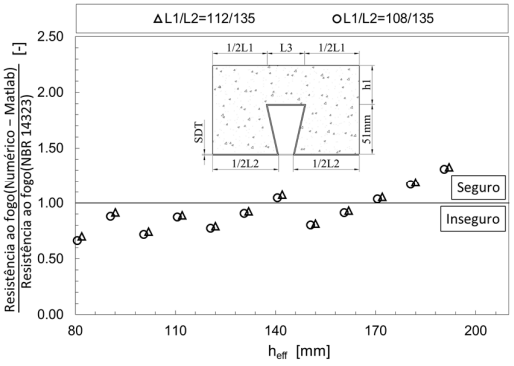


Figura 140: Resultados para lajes reentrantes comparados à NBR 14323. Análise no Matlab.

6.6 Comparação ANSYS – NBR 14323

A Figura 141 e a Figura 142 representam a comparação da resistência ao fogo entre os dois métodos de resolução (modelo avançado desenvolvido no ANSYS e método simplificado proposto pela NBR 14323) pela progressão de h_{eff}. Valores menores que 1 devem ser considerados inseguros. Assim como na análise anterior, os resultados apresentam grande discrepância do modelo numérico.

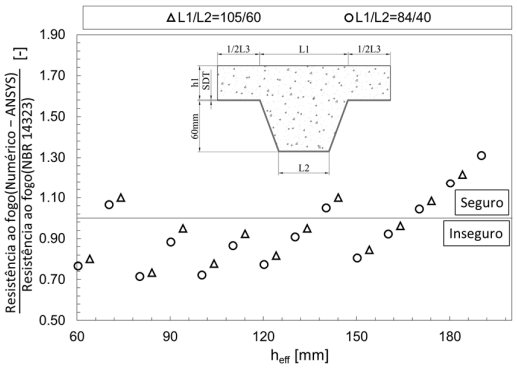


Figura 141: Resultados para lajes trapezoidais comparados à NBR 14323. Análise no ANSYS.

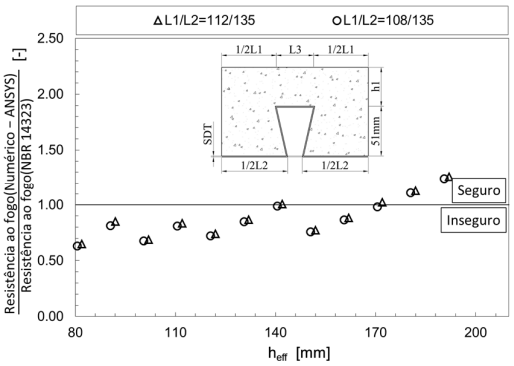


Figura 142: Resultados para lajes reentrantes comparados à NBR 14323. Análise no ANSYS.

6.7 Comparação final

Os resultados do método numérico desenvolvido no Matlab são comparado com os resultados experimentais existentes, com recomendações antigas e com as normas vigentes para determinar a resistência ao fogo das lajes de concreto com perfis de aço. A resistência ao fogo é apresentada em relação à espessura efetiva h_{eff} na Figura 143.

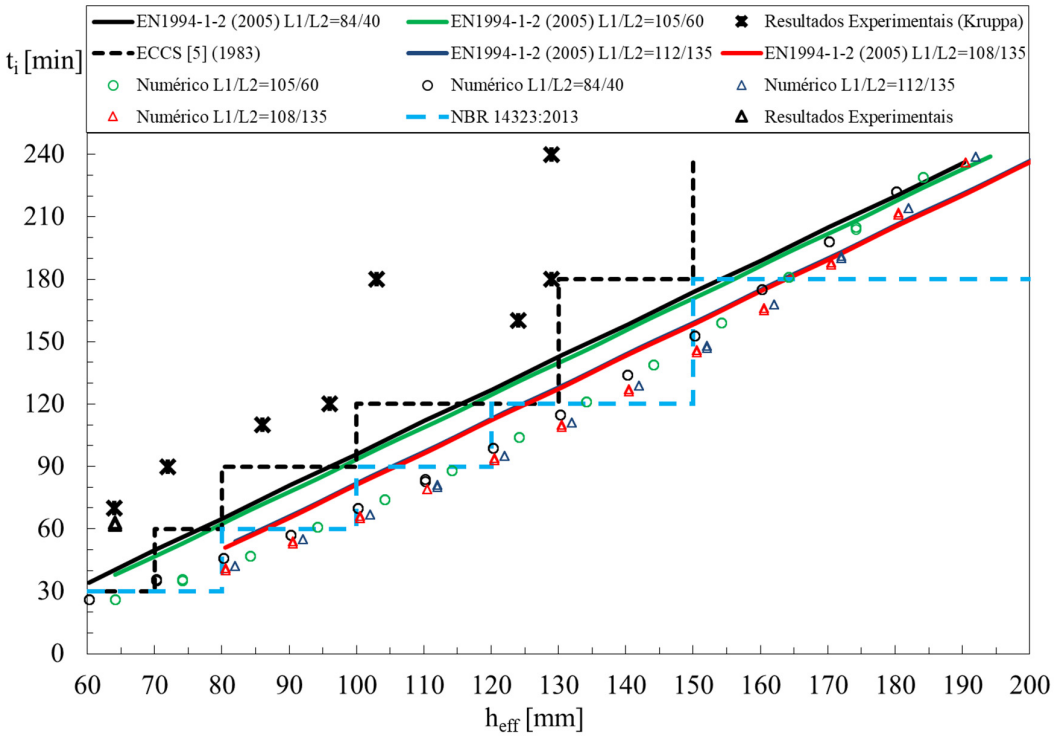


Figura 143: Resistência ao fogo para a espessura efetiva da laje.

A resistência ao fogo obtida pelas simulações numéricas, em todos os casos, apresenta divergências quando comparada aos demais resultados. Isso significa que as propostas para o método simplificado de cálculo do Eurocode 4 e da NBR 14323 podem estar inseguras ou antieconômicas, principalmente no caso da NBR 14323 no qual o cálculo é apresentado para patamares de h_{eff} sendo o valor máximo 150 mm. De acordo com os resultados numéricos, existe uma dependência não linear entre a resistência ao fogo e a espessura efetiva que não está incluída na equação (12). Uma dependência quadrática pode ser proposta para levar este parâmetro em consideração (Equação (53),

resultando em um coeficiente de determinação de 0.9968). Uma progressão da equação proposta pode ser verificada na Figura 144.

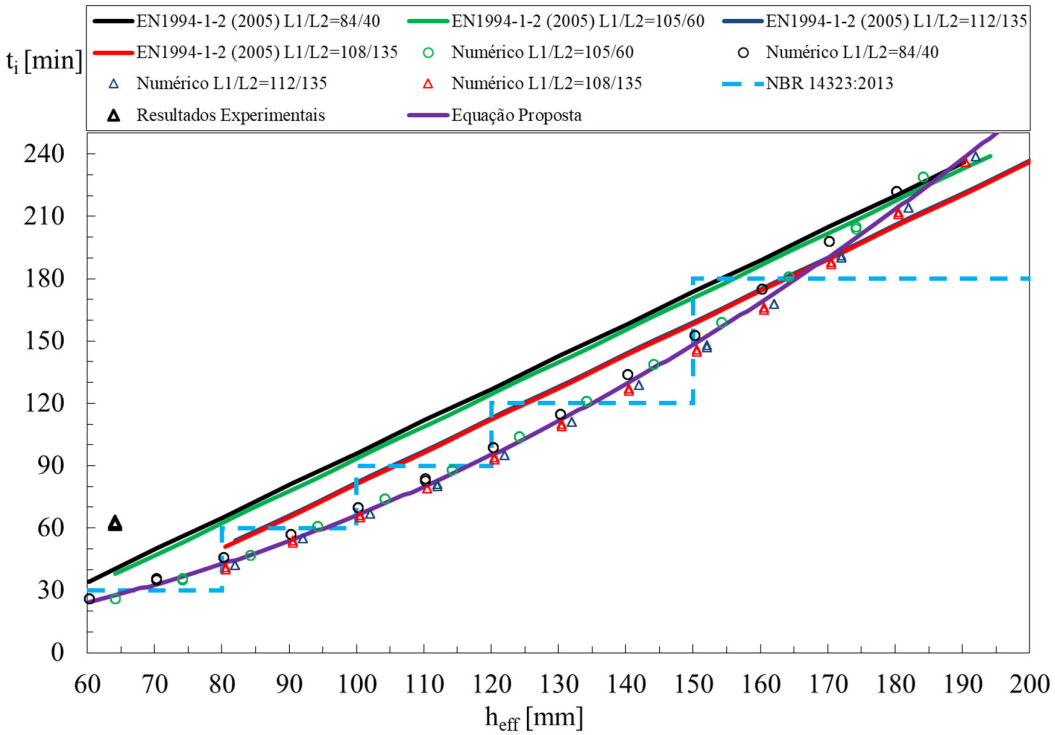


Figura 144: Equação proposta para a determinação do tempo de resistência ao fogo para o critério de isolamento.

$$t_i = 0.006561 \cdot h_{eff}^{\ 2} + 0.004995 \cdot h_{eff} \tag{53}$$

A modelagem numérica de elementos estruturais semelhantes [19, 22] demonstra que as temperaturas experimentais medidas na superfície exposta durante um incêndio são geralmente menores do que aquelas resultantes da simulação numérica. Esses pesquisadores mencionam que esse comportamento é provavelmente causado pela deformação do deck de aço e também devido ao descolamento na interface entre o concreto e o deck de aço, criando uma camada gasosa extra de isolamento. Esses dois fatores podem explicar os valores experimentais mais baixos de temperatura na superfície não exposta, o que equivale a um maior tempo de resistência ao fogo nos experimentos.

7 CONCLUSÃO

Este trabalho apresenta diversas metodologias, analíticas, experimentais e numéricas, para o cálculo do tempo de resistência ao fogo segundo o critério de isolamento (I) de lajes de concreto com chapa de aço colaborante. Para um estudo paramétrico, o tempo de resistência ao fogo de diversas geometrias foi calculado através dos métodos simplificados de cálculo dispostos no Eurocódigo EN 1994-1-2 e na NBR 14323:2013. Um procedimento baseado na resolução numérica da equação de transferência de calor pelo método de elementos finitos foi desenvolvido no programa Matlab, através da PDE toolbox. Paralelamente a isto, um procedimento numérico com o mesmo objetivo de análise térmica foi desenvolvido no programa comercial ANSYS ® v18.2. Na análise térmica, os modelos numéricos apresentam os campos de temperaturas de uma seção da laje, e seu respectivo tempo de resistência ao fogo.

Para a comparação do modelo numérico, foram realizados dois ensaios experimentais de lajes mistas com perfil metálico trapezoidal que apresentaram tempos de resistência ao fogo para o critério de isolamento muito superiores aos obtidos numericamente. Os modelos numéricos foram utilizados para a realização de um estudo paramétrico realizado para quatro diferentes geometrias com variação da espessura do perfil metálico, de acordo com os valores disponíveis comercialmente.

As simulações numéricas permitem determinar a resistência ao fogo deste elemento estrutural com relação ao critério de isolamento. A comparação dos diversos resultados obtidos entre os cálculos através dos métodos simplificados e dos modelos avançados, prediz uma menor resistência ao fogo para o critério de isolamento (I) do que as apresentadas nas normativas atuais, baseadas no método de cálculo simplificado. Esta resistência ao fogo foi definida pelo aumento da temperatura no lado não exposto da laje. A resistência ao fogo obtida com o método de cálculo simplificado, proposto no Eurocódigo EN 1994-1-2, parece ser insegura, considerando que 93 % dos casos estudados neste trabalho tiveram valores críticos de tempo menores que os obtidos com o Eurocódigo 4. Já para a NBR 14323:2013, os resultados obtidos numericamente demonstram a inconsistência dos tempos de resistência recomendados pela norma, sendo inseguros até uma h_{eff} de 160 mm e a partir disso se tornam completamente antieconômicos, conforme Figura 143. Uma nova fórmula para o cálculo do tempo de

resistência ao fogo em relação a h_{eff} é proposta de acordo com os resultados obtidos através do modelo numérico desenvolvido neste trabalho.

A nova fórmula proposta incorpora uma dependência não linear entre a altura efetiva h_{eff} e o tempo de resistência ao fogo. Essa dependência não linear não é levada em consideração por nenhum dos códigos utilizados nesse trabalho e sua incorporação permite uma avaliação mais segura da resistência ao fogo de uma laje composta.

7.1 Trabalhos futuros

Os estudos na análise de estruturas submetidas a ação de incêndio são de extrema importância e grande complexidade. Diversos estudos complementares podem agregar aos resultados já obtidos e gerar novos conhecimentos nesta área. A seguir, algumas sugestões para a continuação deste estudo são apresentadas:

- Ampliar a série de ensaios experimentais de lajes de concreto com perfil metálico colaborante;

- Em conjunto com ensaios experimentais, um estudo dos parâmetros apresentados pelo Eurocódigo para o desenvolvimento de métodos avançados de cálculo;

- Realizar uma análise mecânica em conjunto com a ação térmica para determinação do tempo de resistência ao fogo de lajes mistas;

- Realização de um estudo paramétrico com uma maior variedade de geometrias para verificar se a nova formula proposta contempla todos os tipos de lajes.

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Anexo A

Análise térmica da seção transversal

Método avançado de cálculo para lajes trapezoidais: Matlab.

LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.7mm

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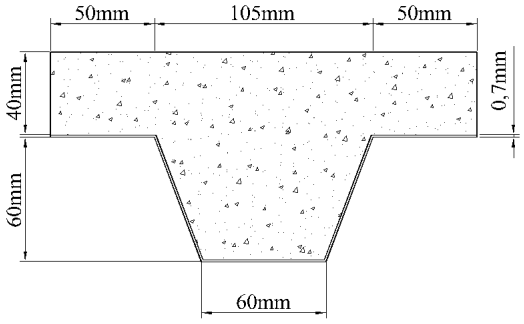

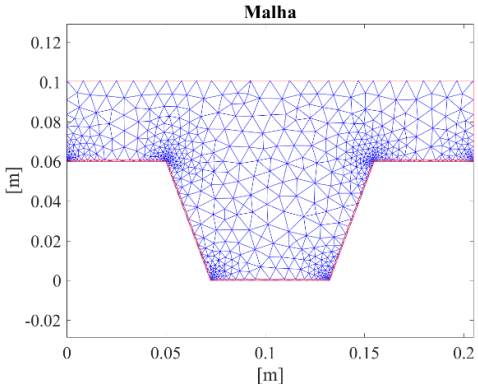

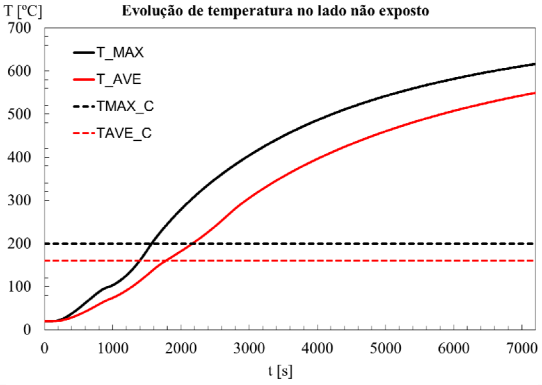

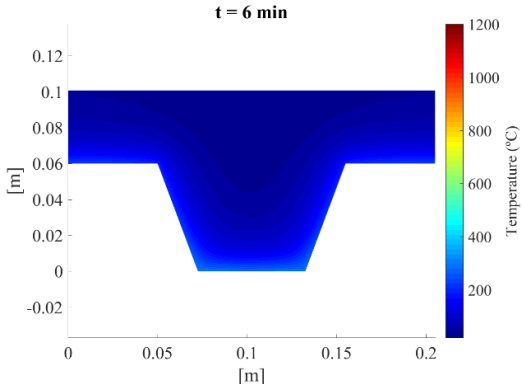

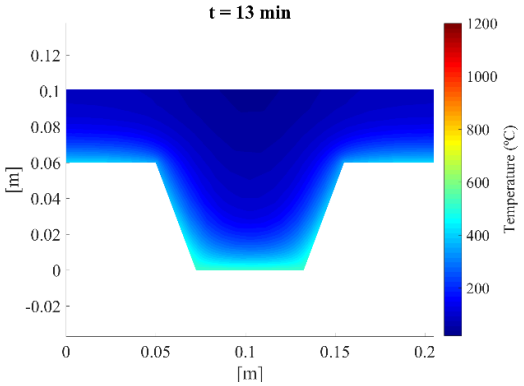

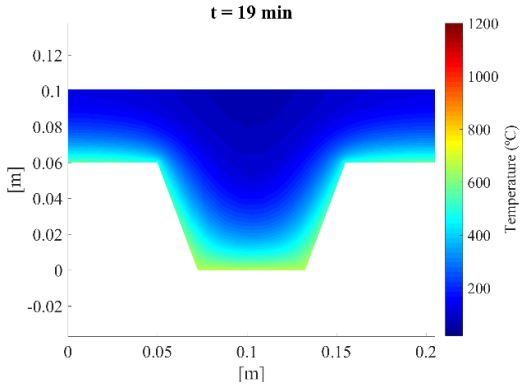

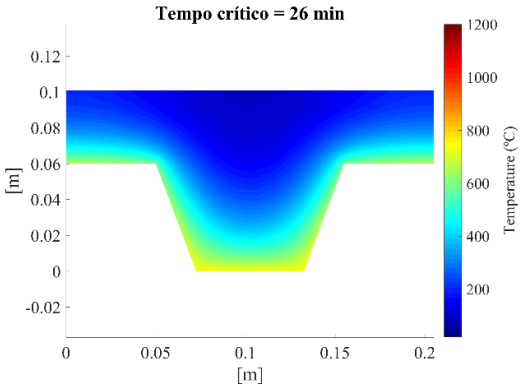

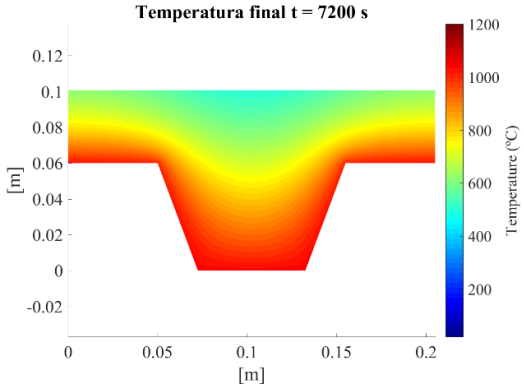

LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.8mm

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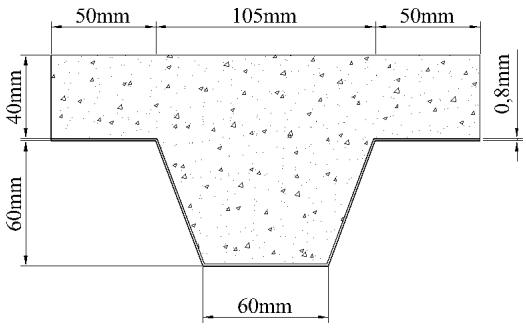

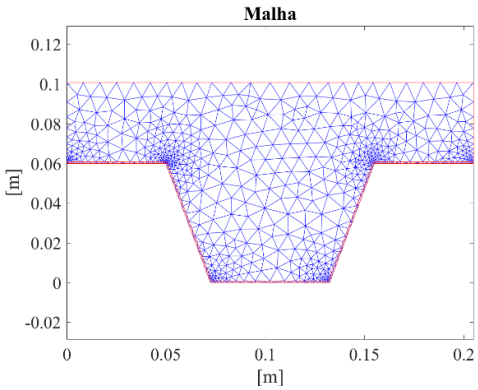

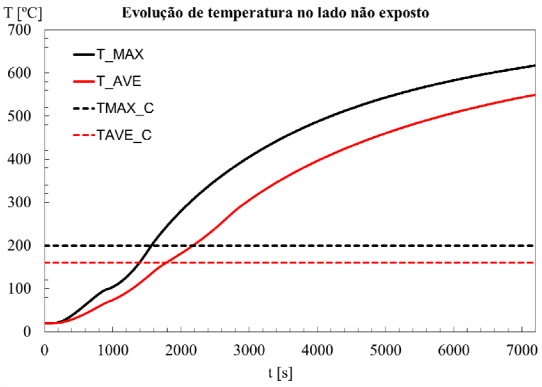

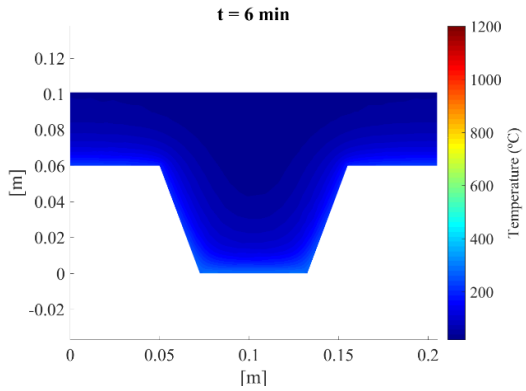

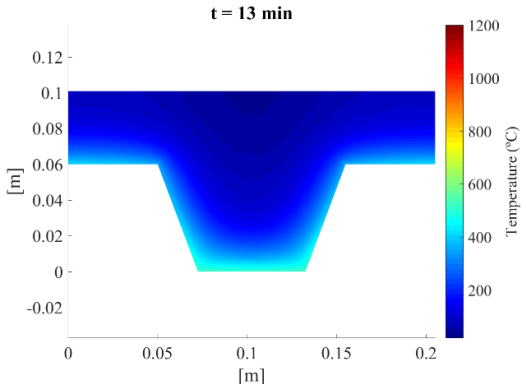

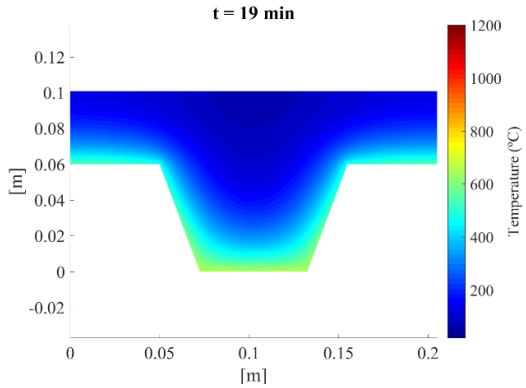

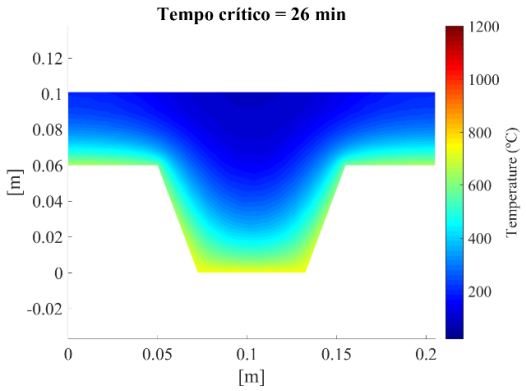

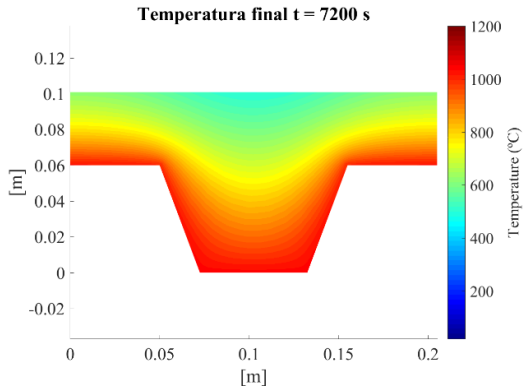

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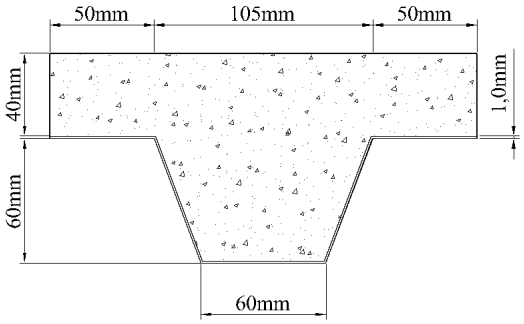
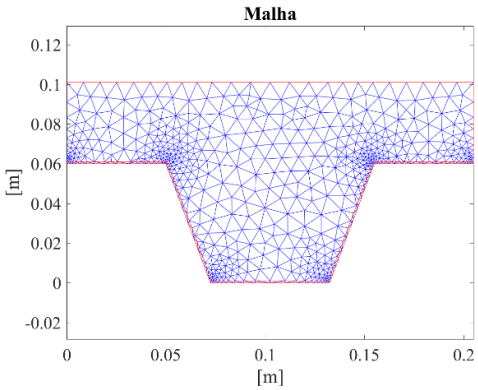
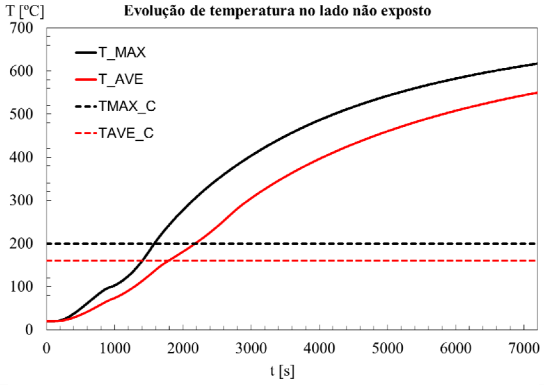
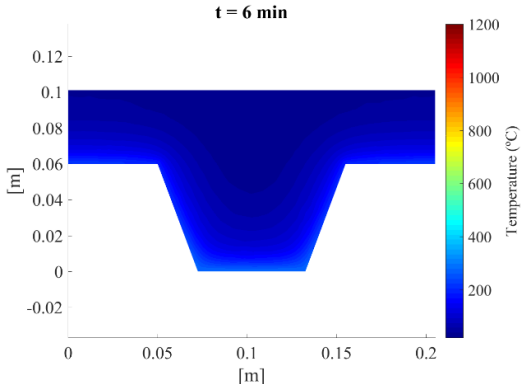
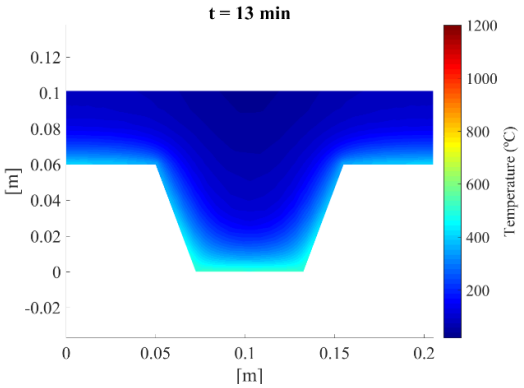
GEOMETRIA

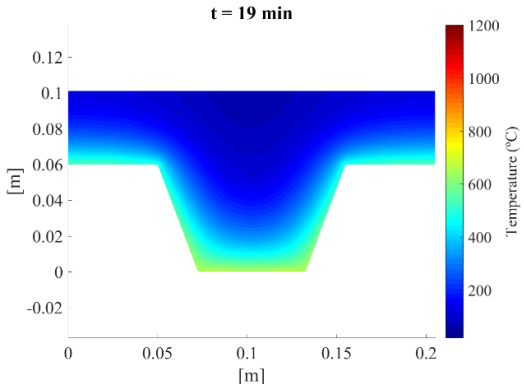


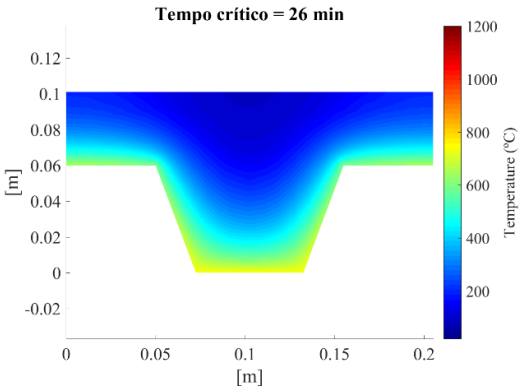


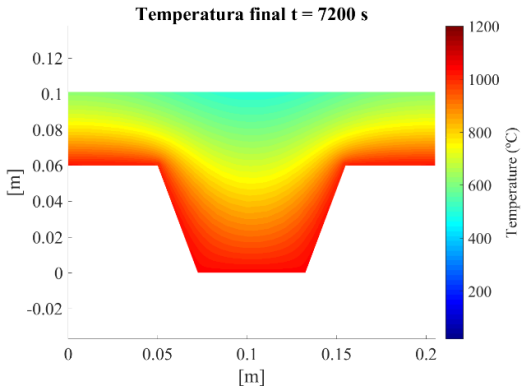












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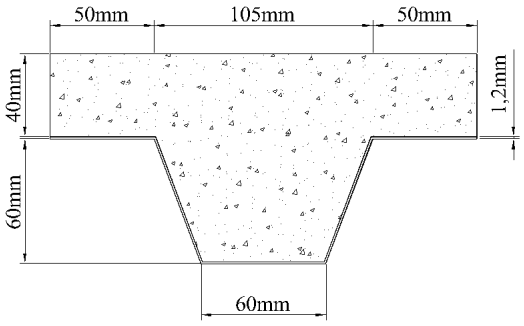

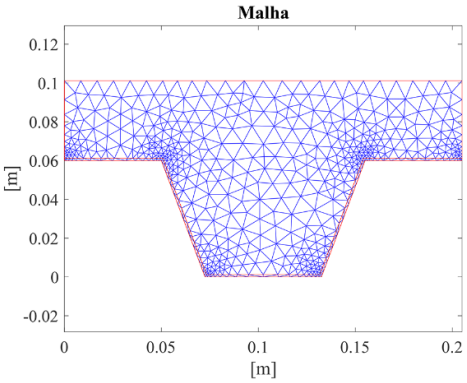

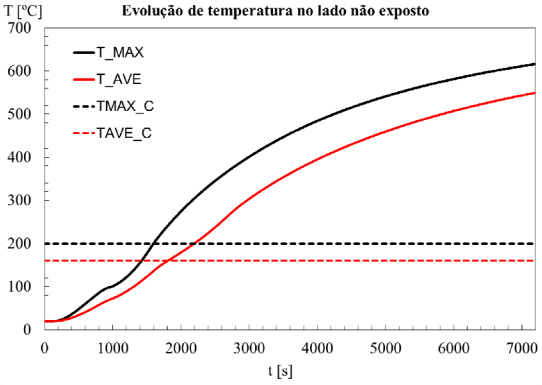

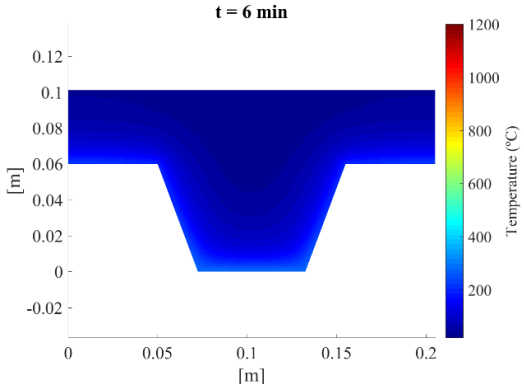

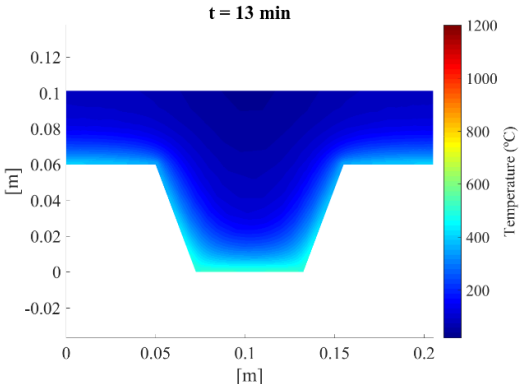

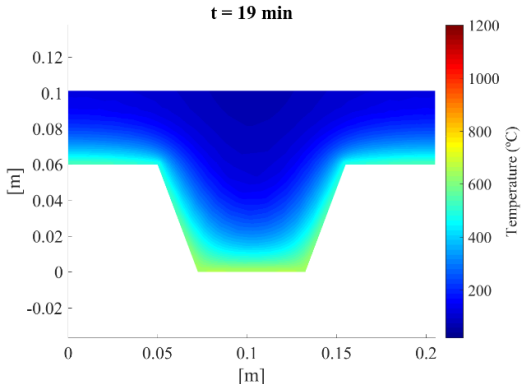

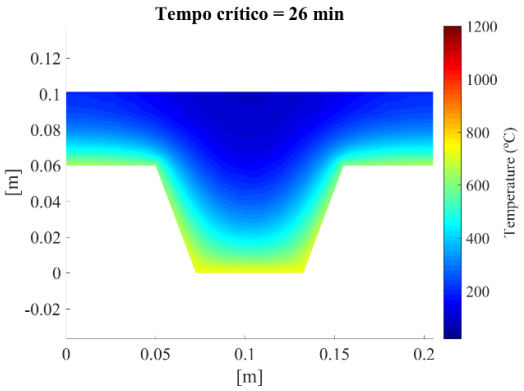

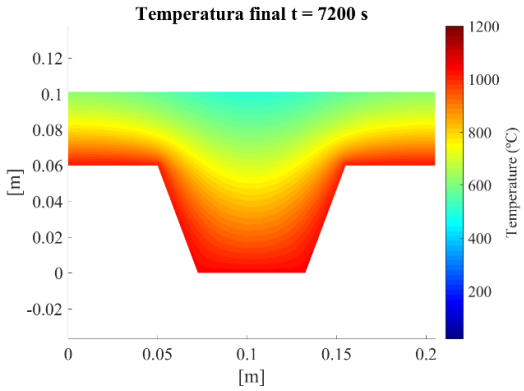

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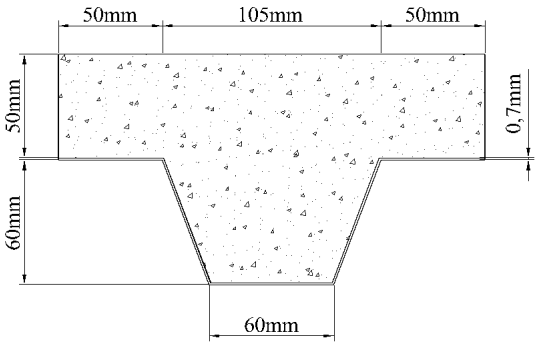

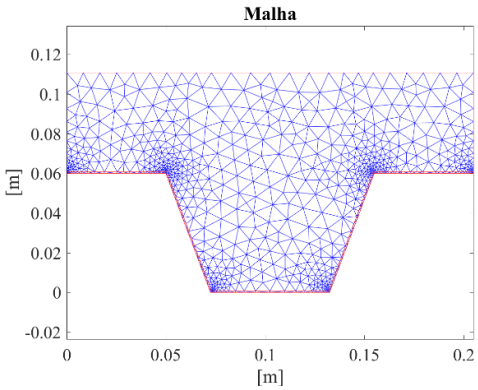

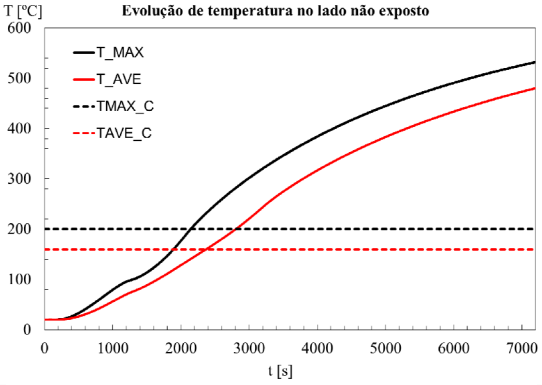

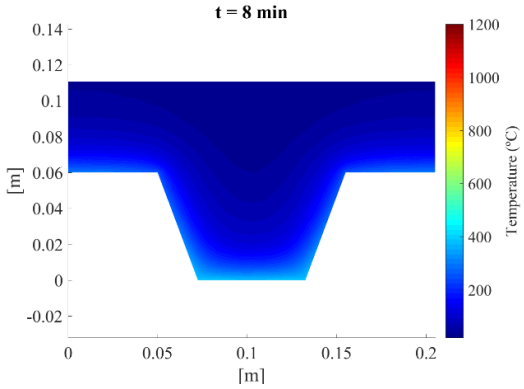

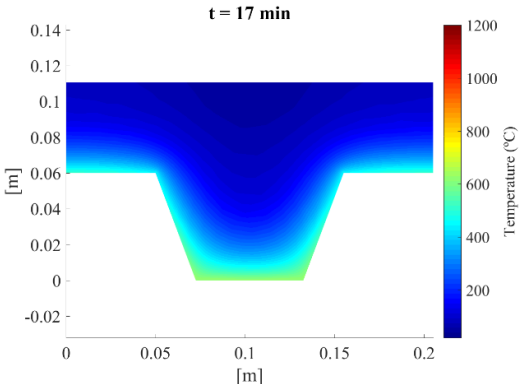

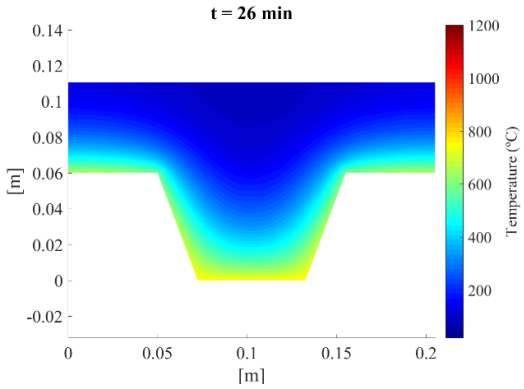

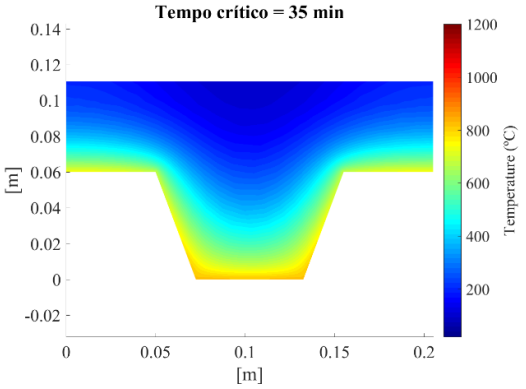

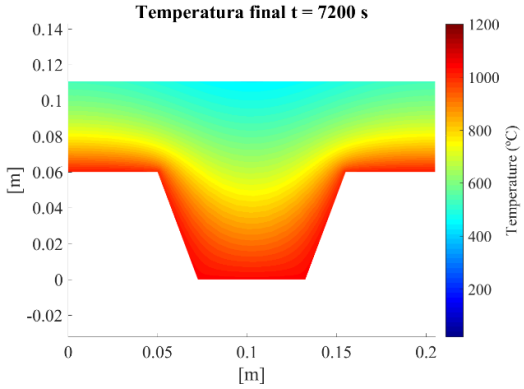

LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.8mm

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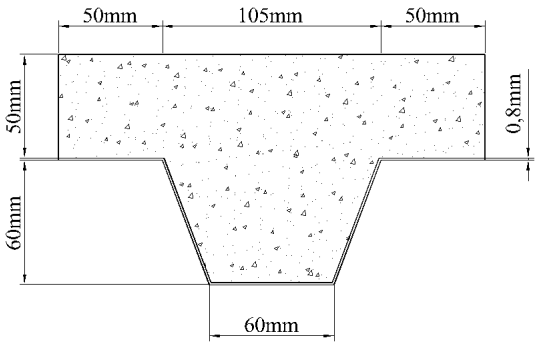
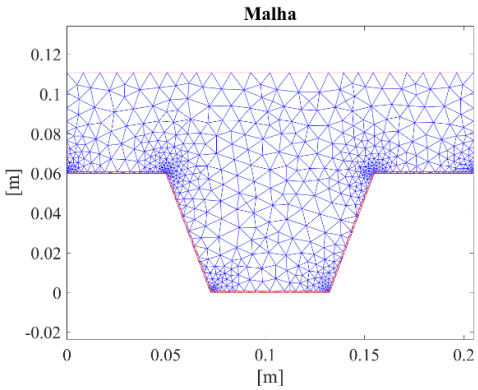
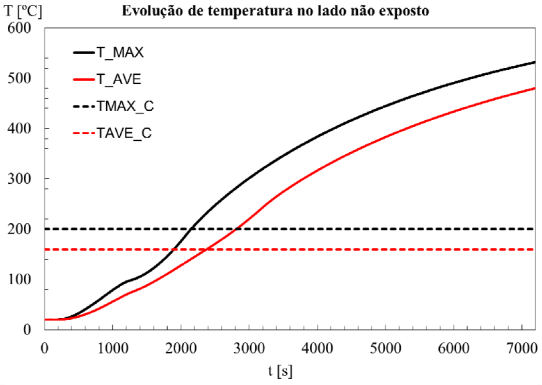
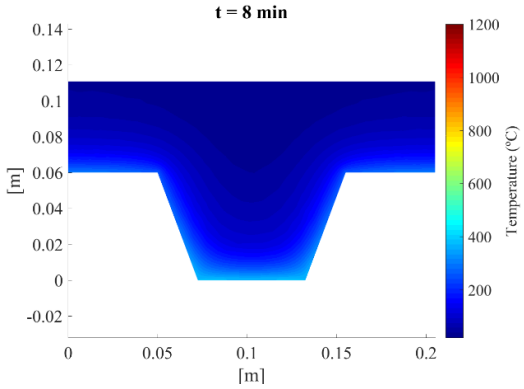
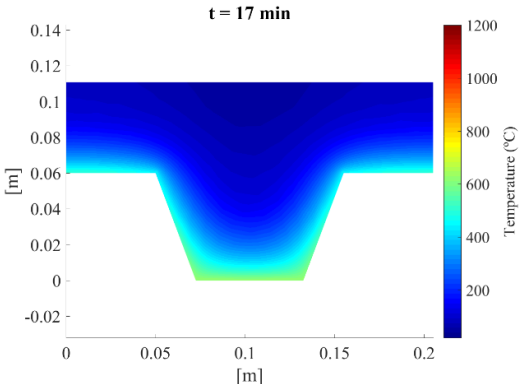
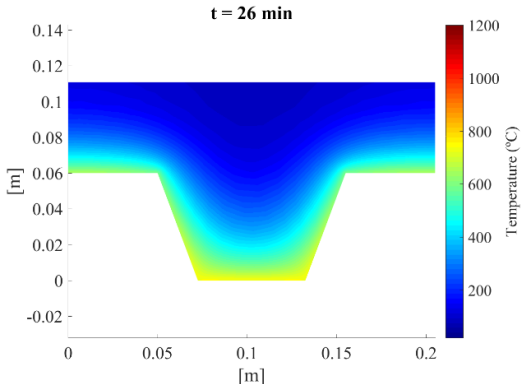


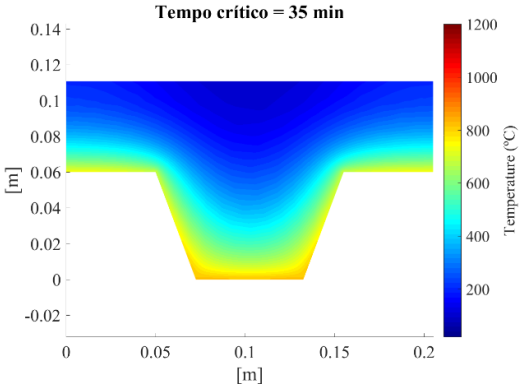


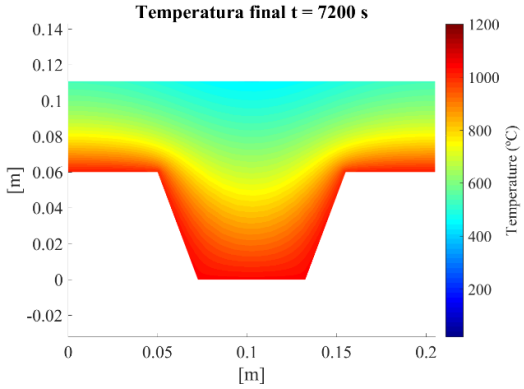






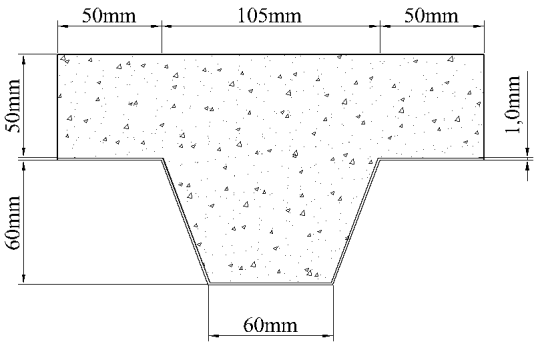


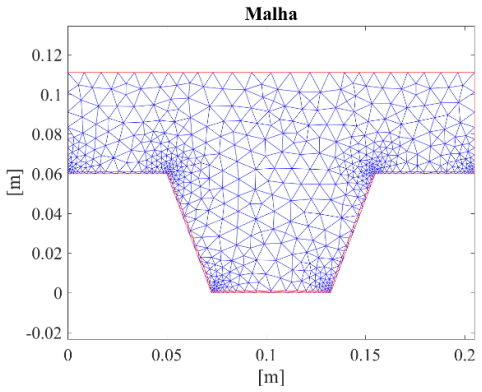


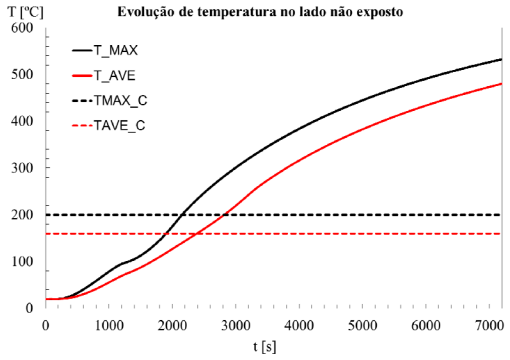


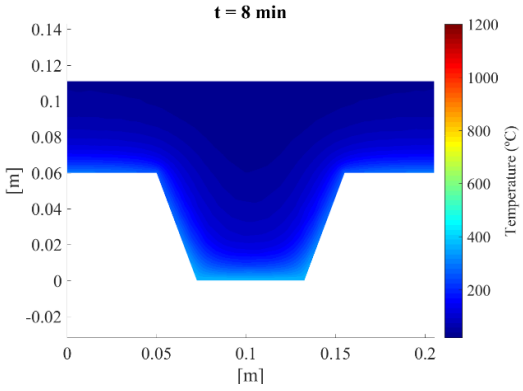
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.0mm

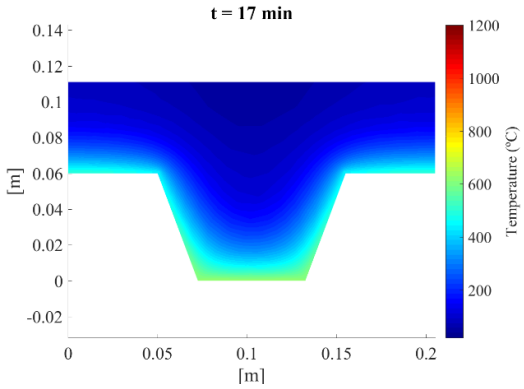
GEOMETRIA

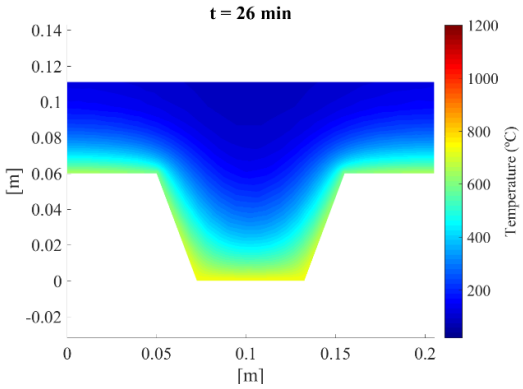


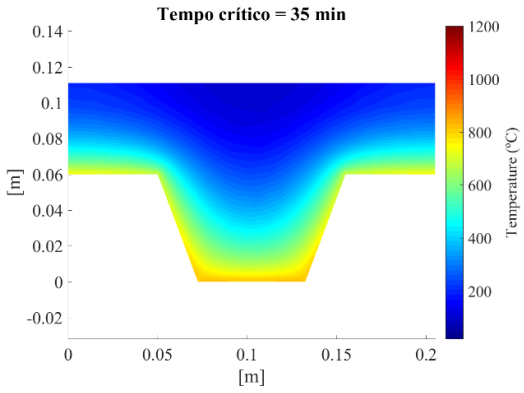


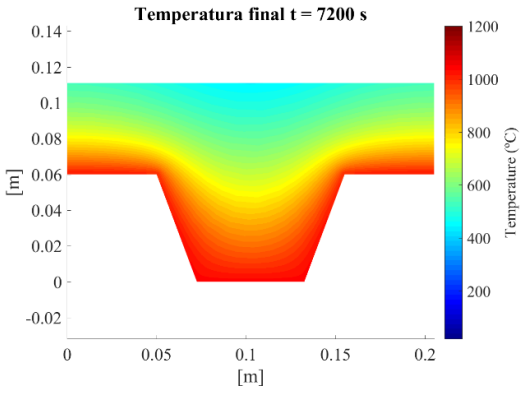






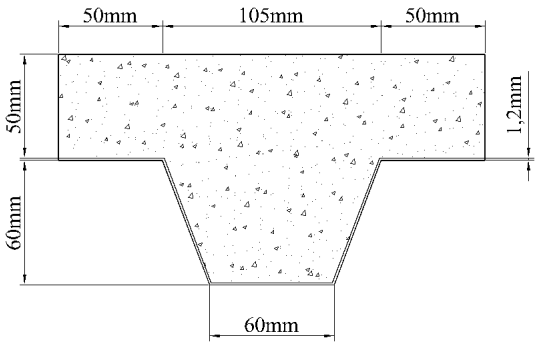


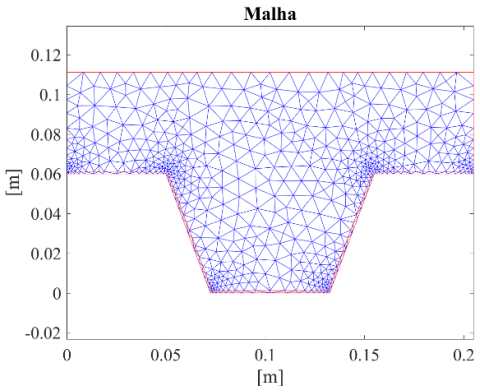


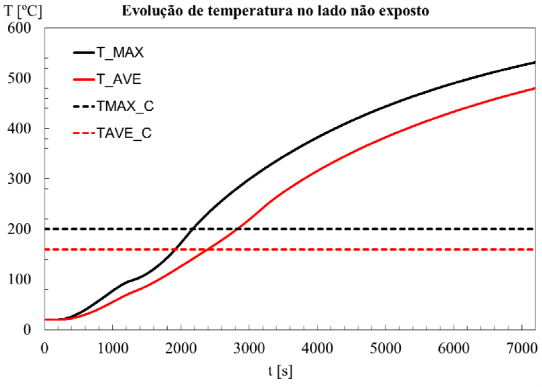


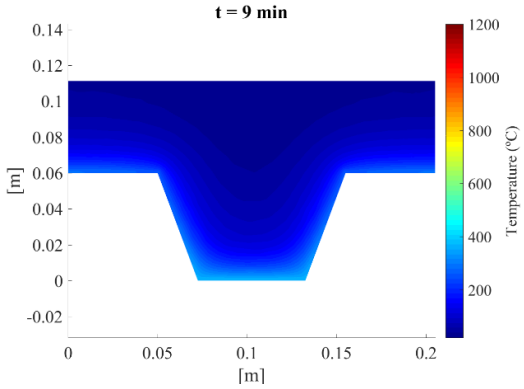
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.2mm

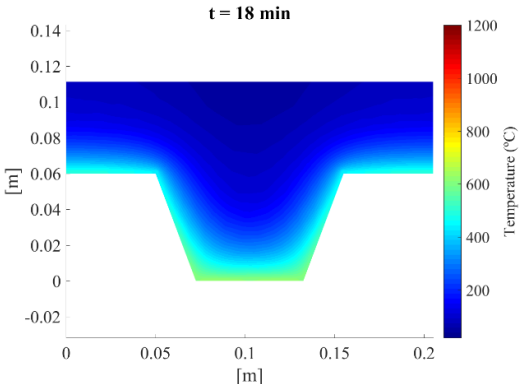
GEOMETRIA

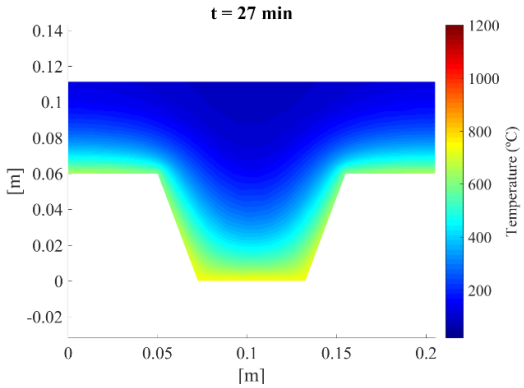


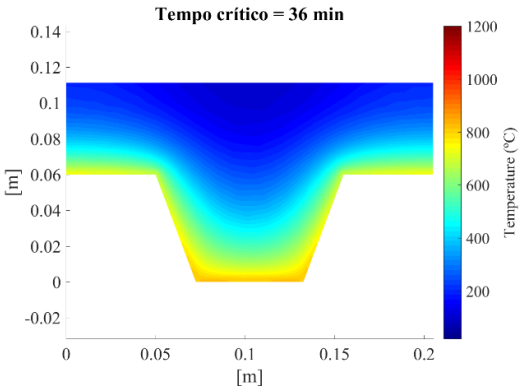


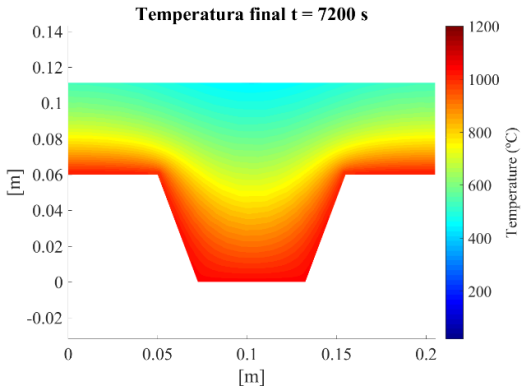




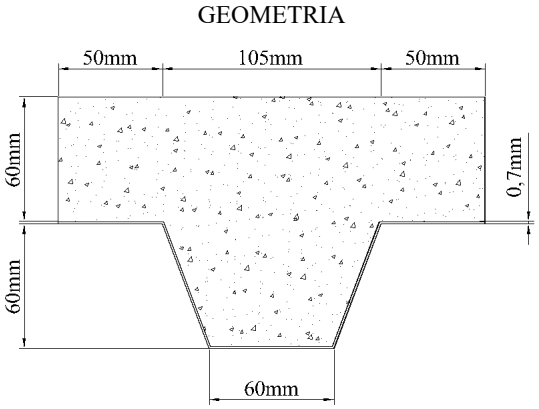


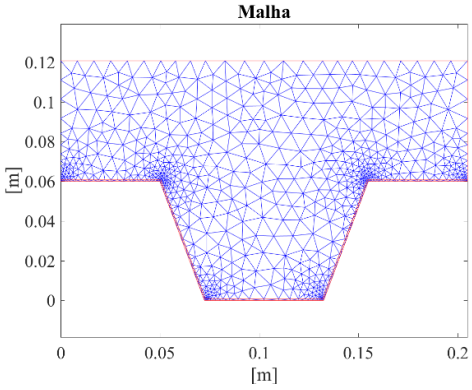


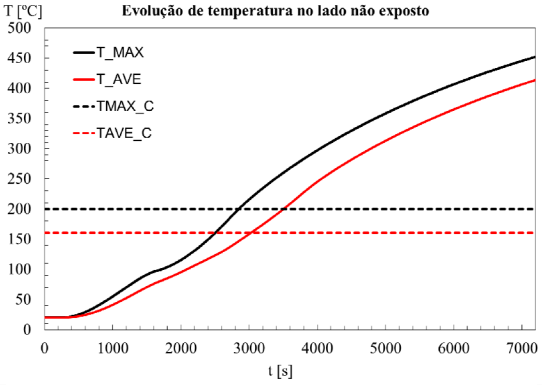


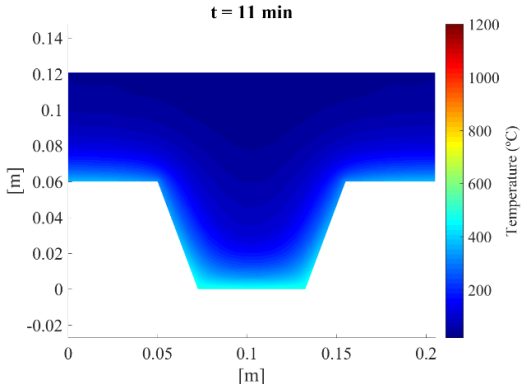


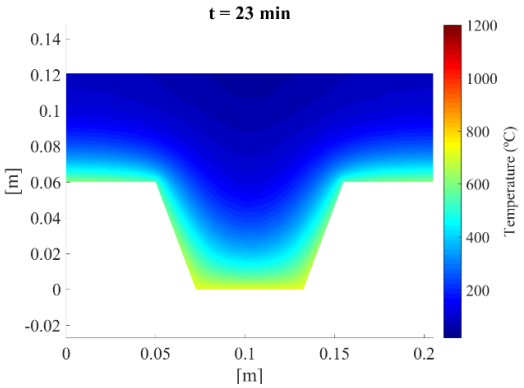
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.7mm

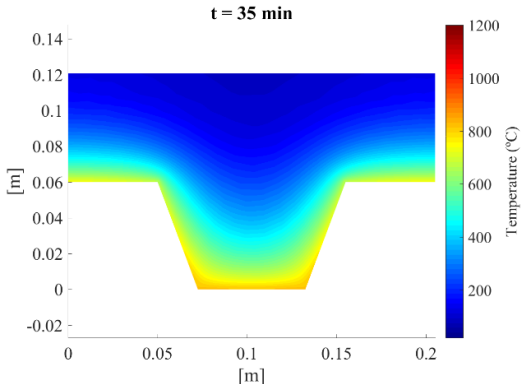


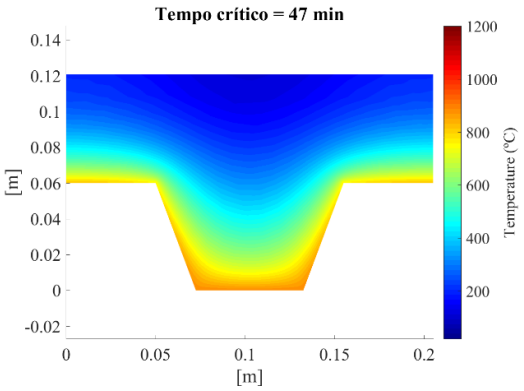


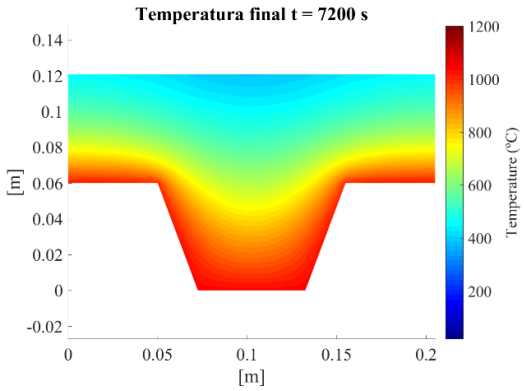




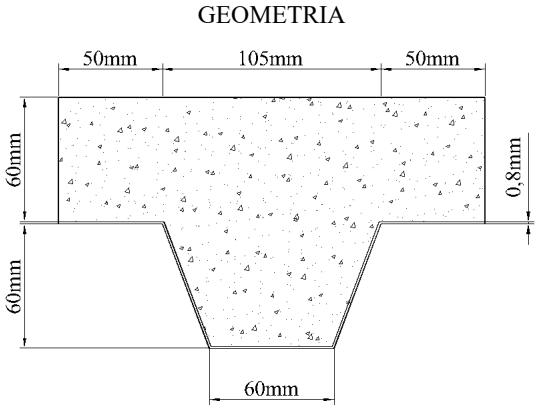


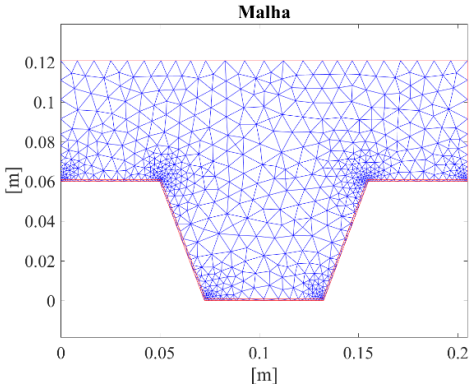


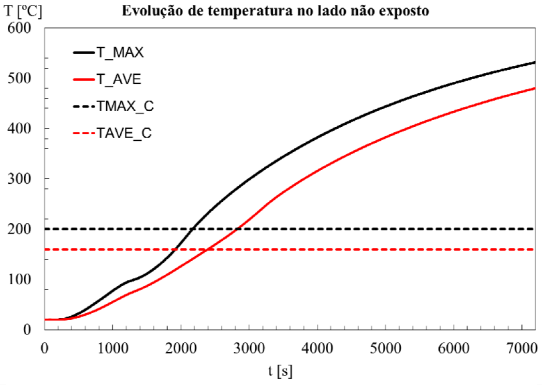


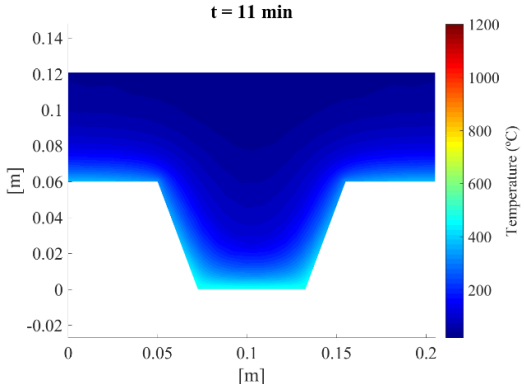


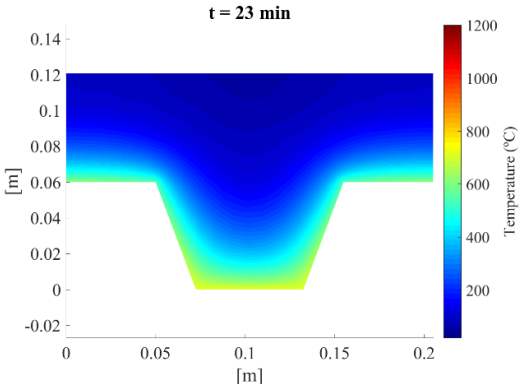
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.8mm

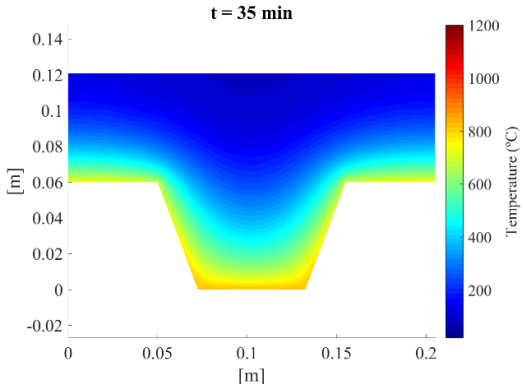


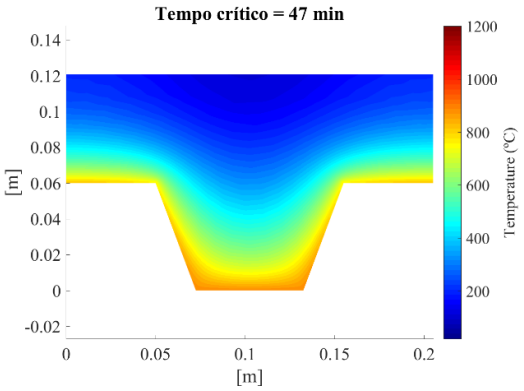


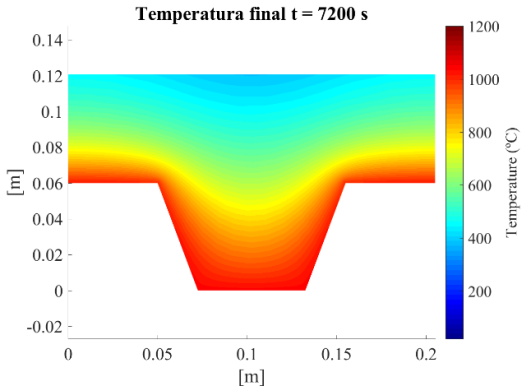




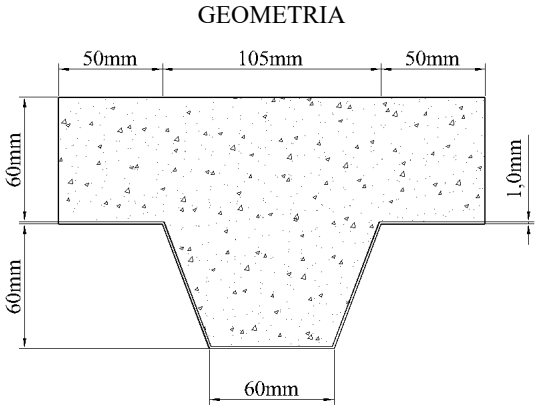


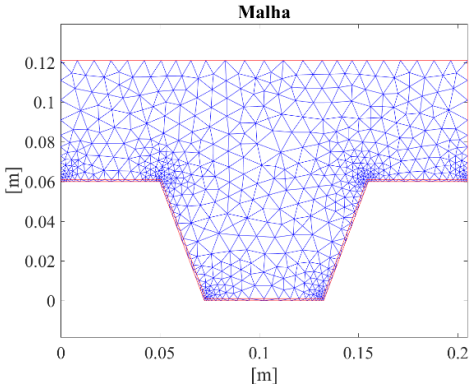


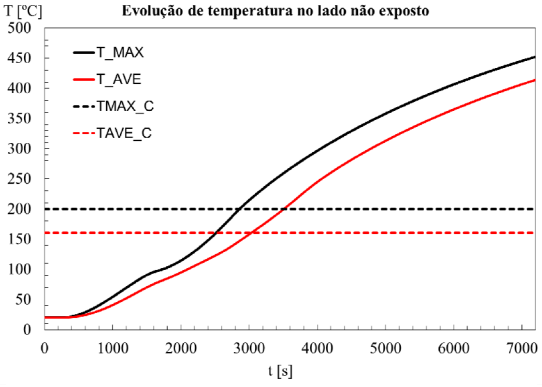


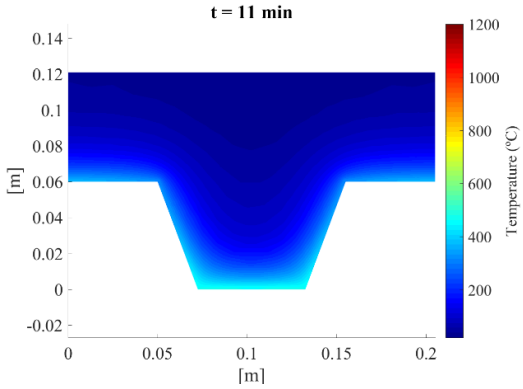


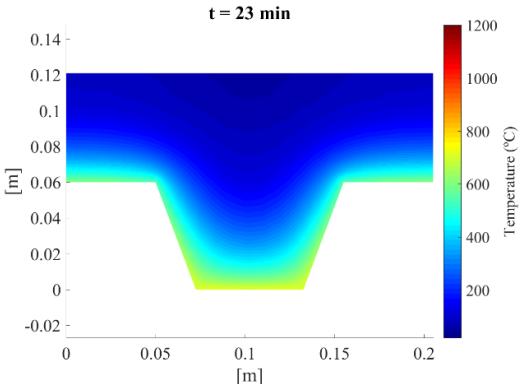
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.0mm

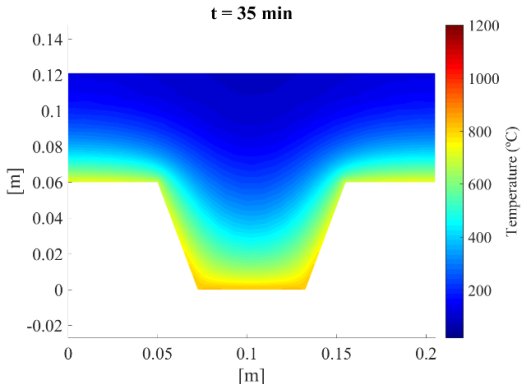


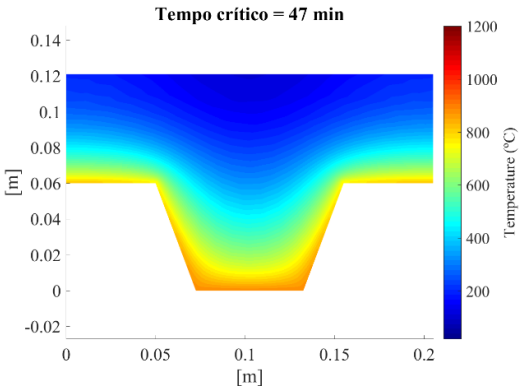


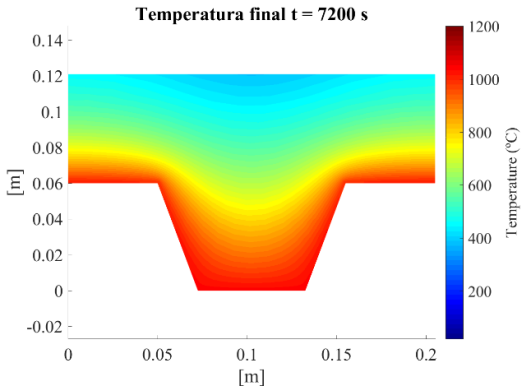




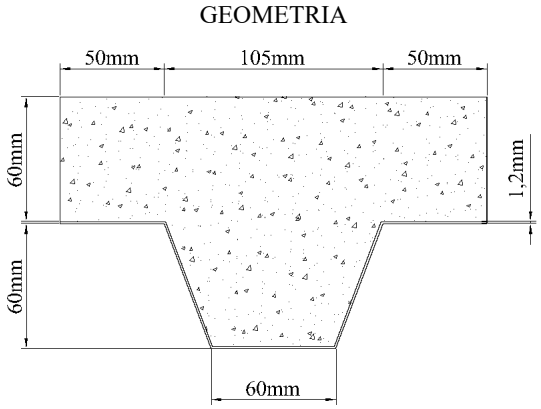


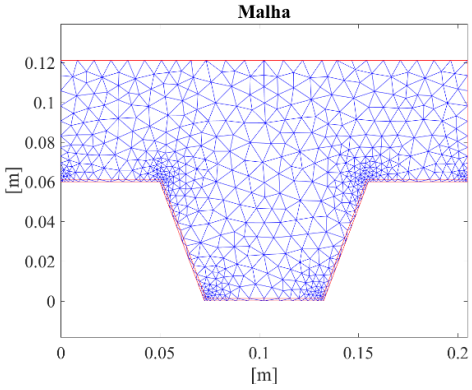


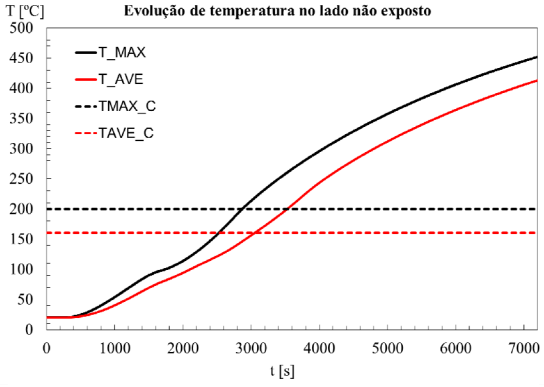


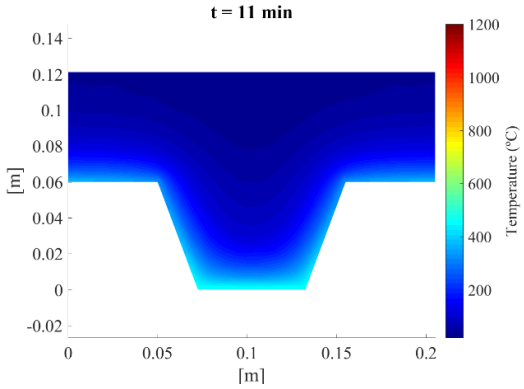


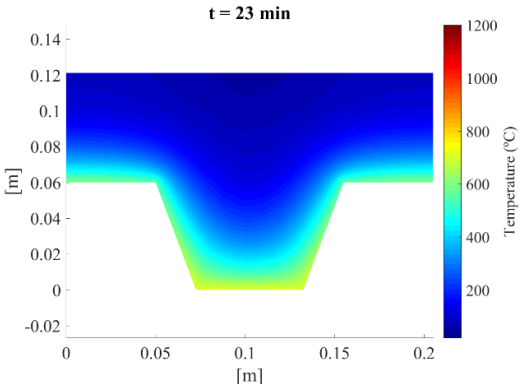
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.2mm

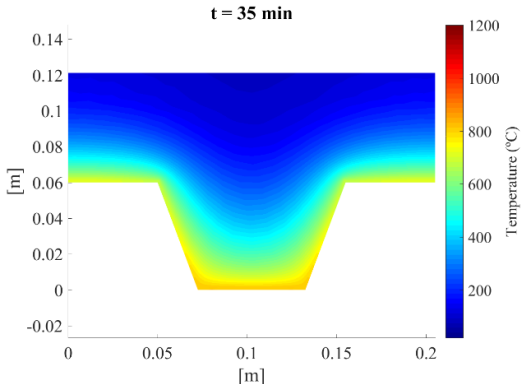


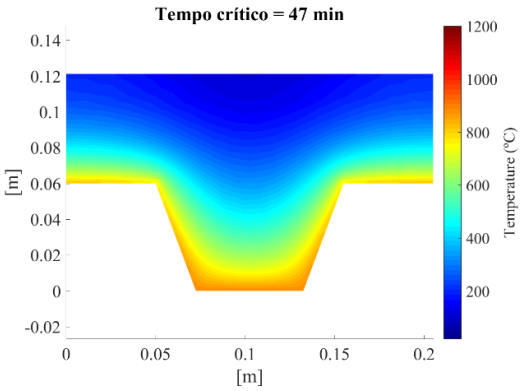


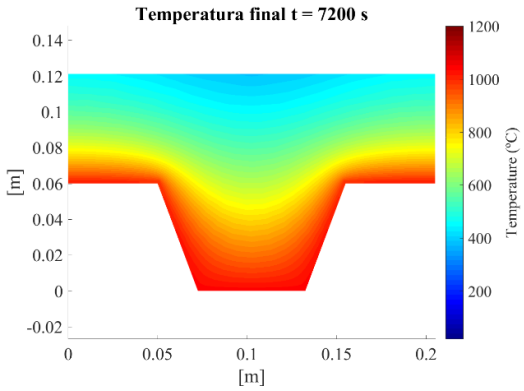




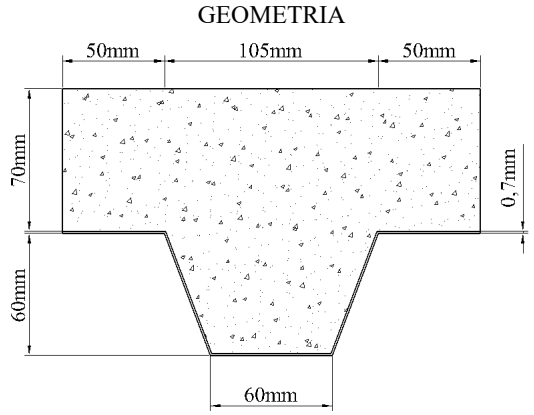


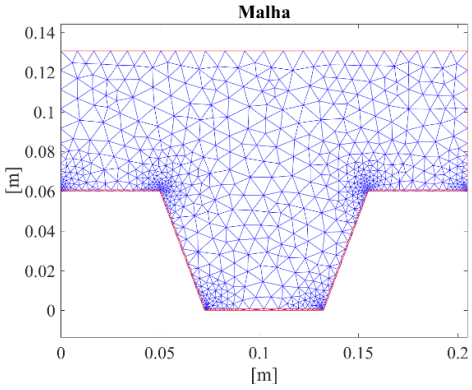


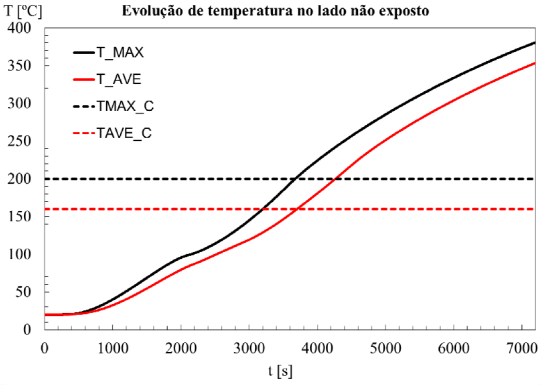


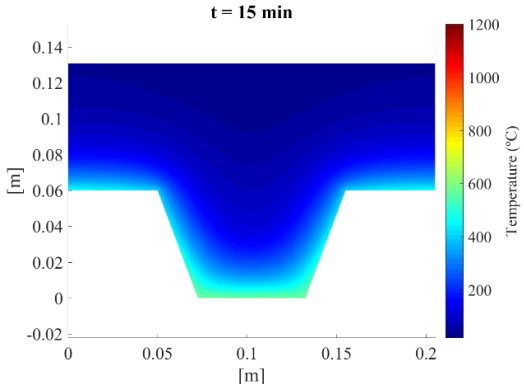


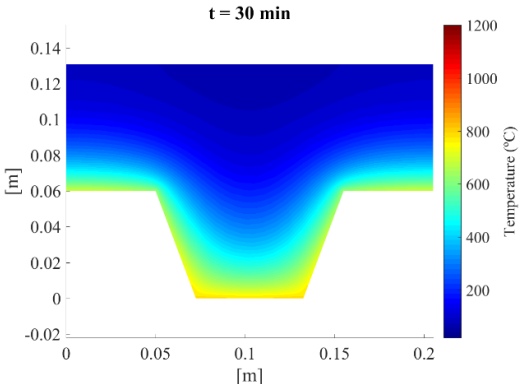
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.7mm

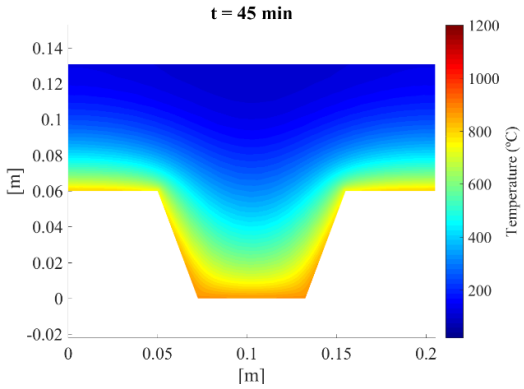


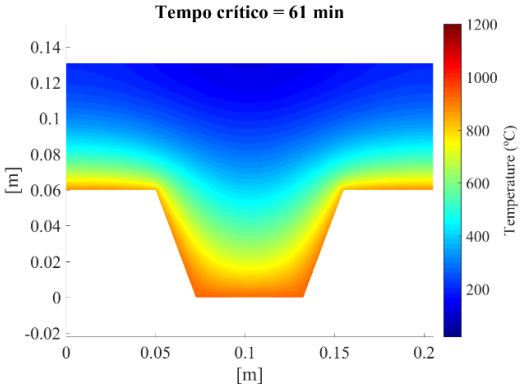


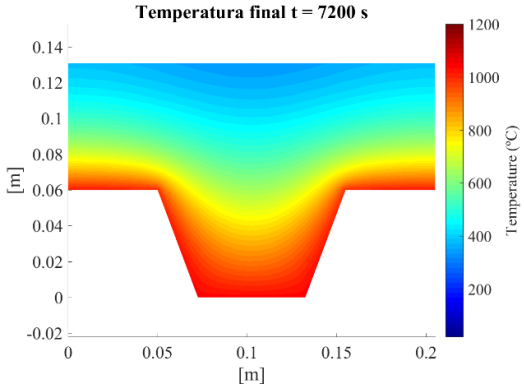




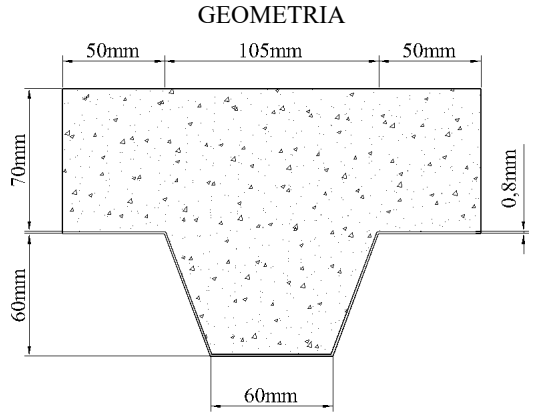


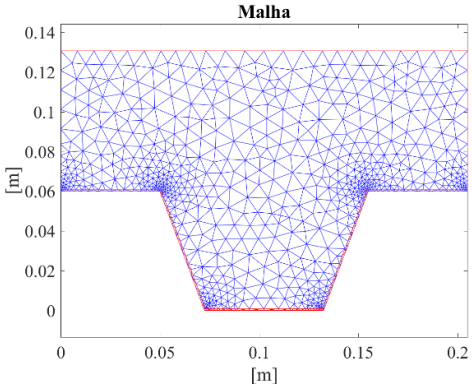


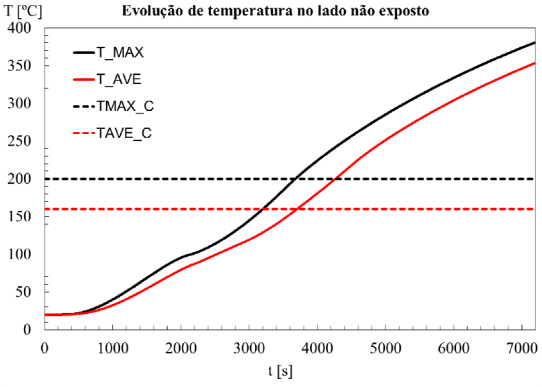


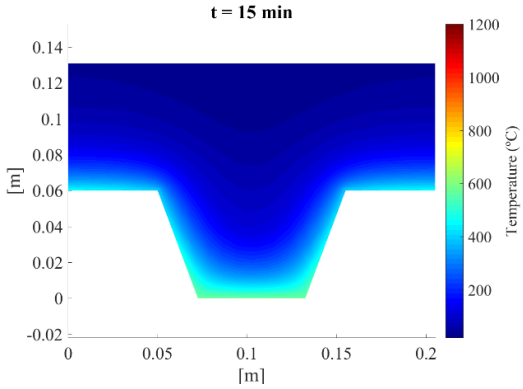


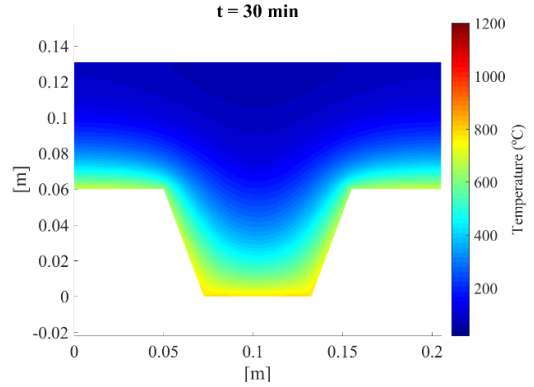
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.8mm

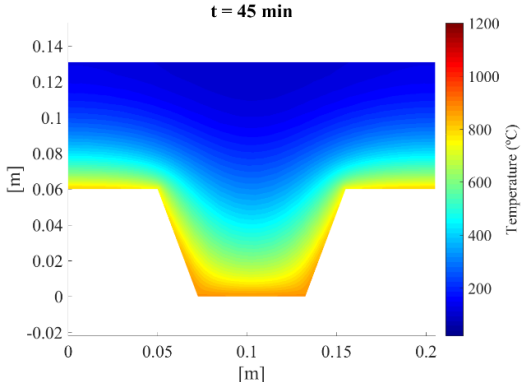


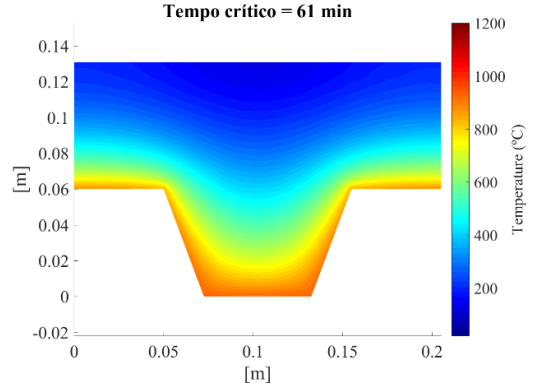


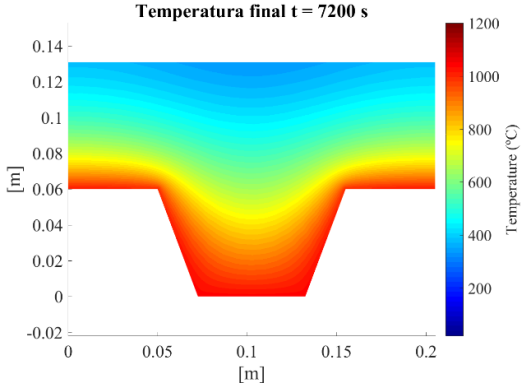




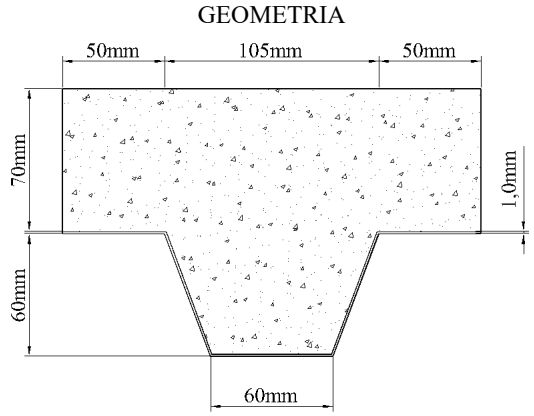


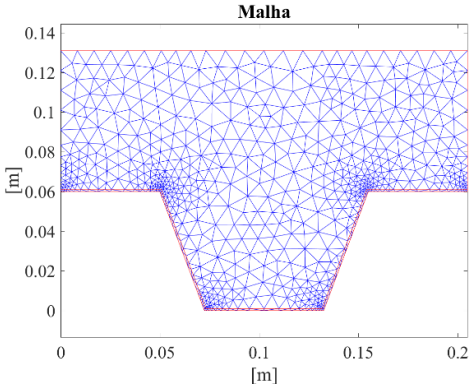


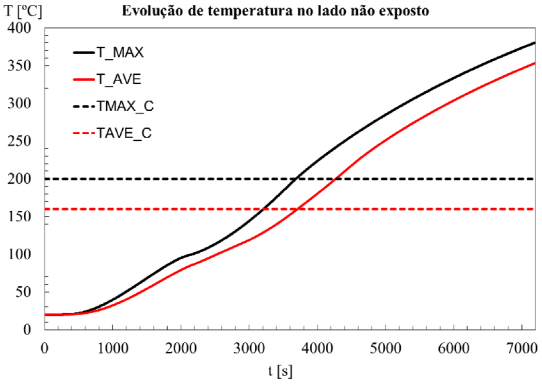


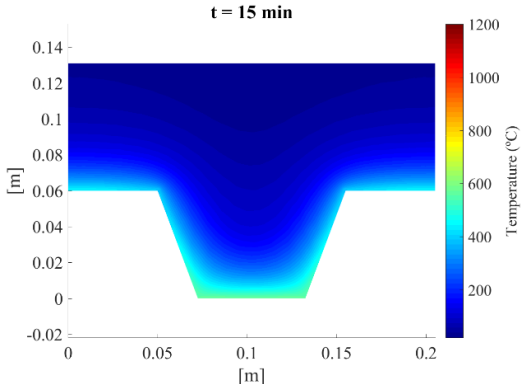


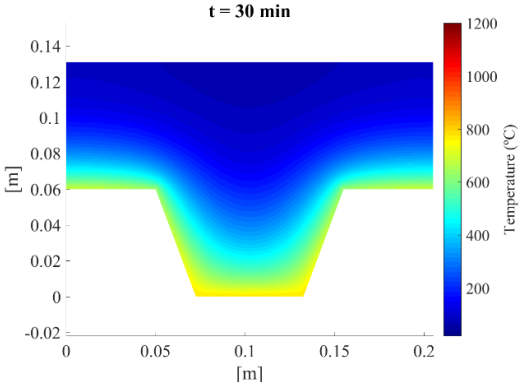
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.0mm

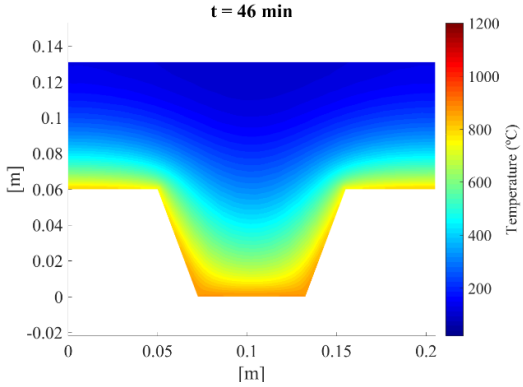


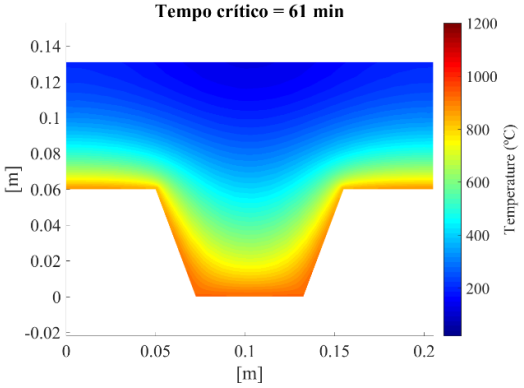


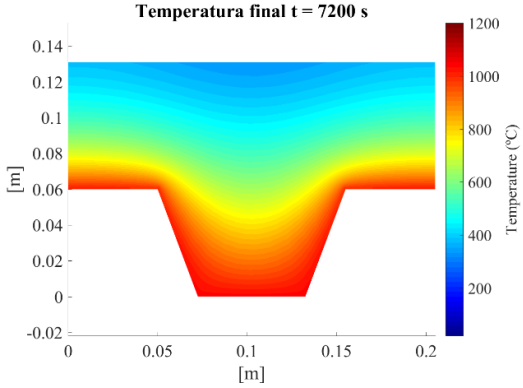




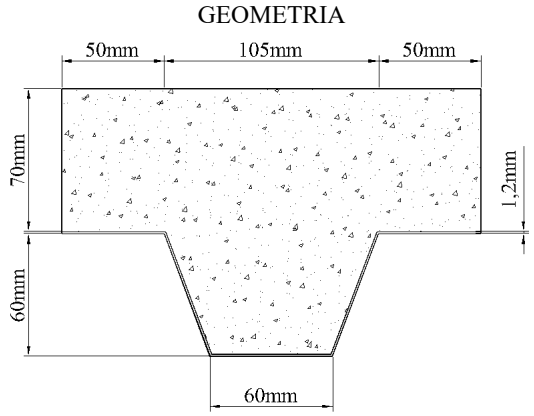


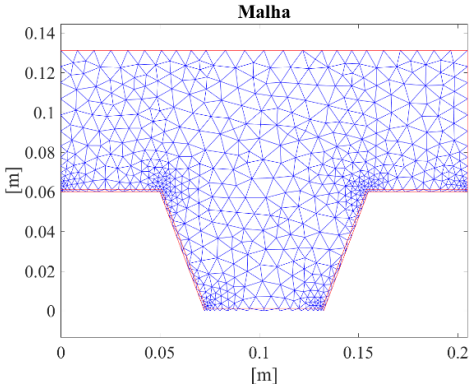


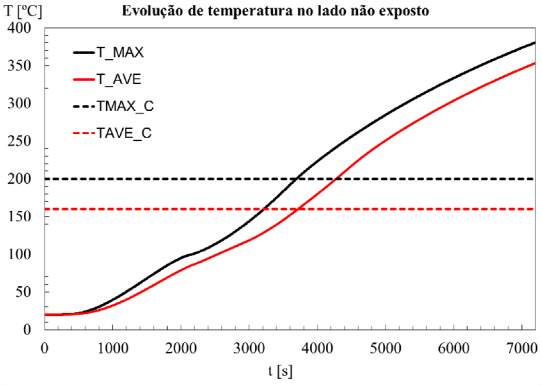


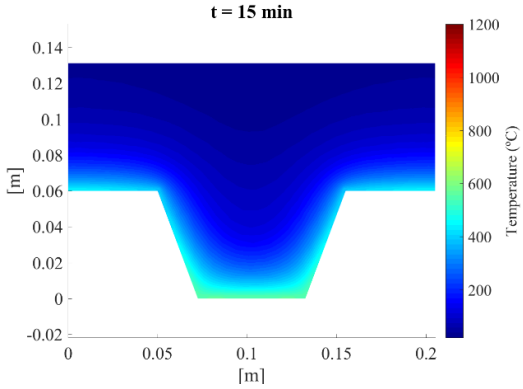


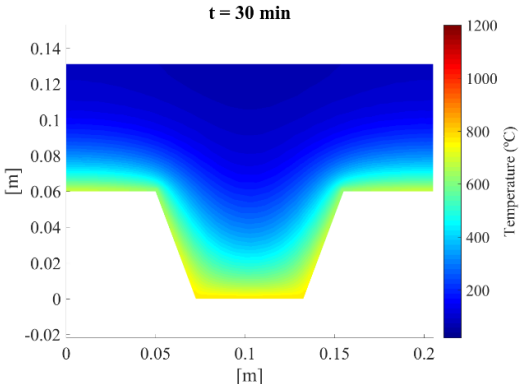
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.2mm

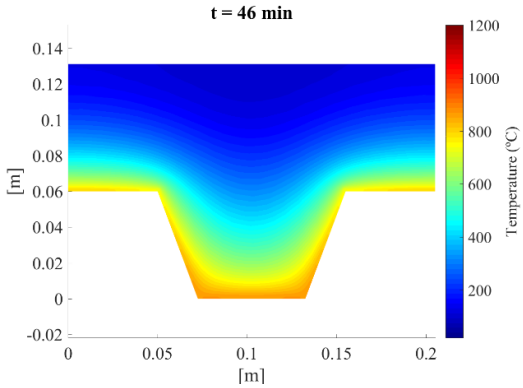


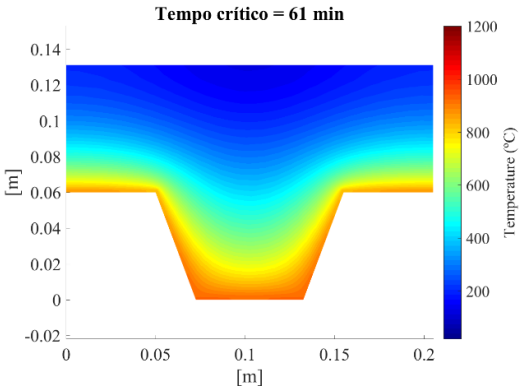


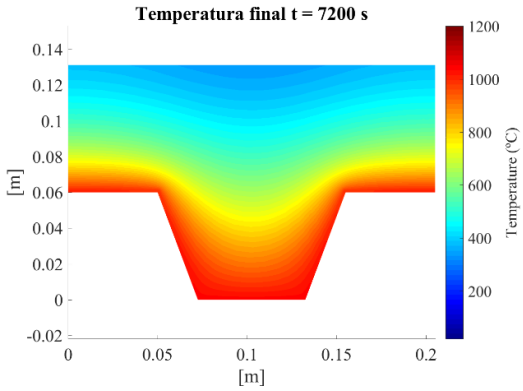




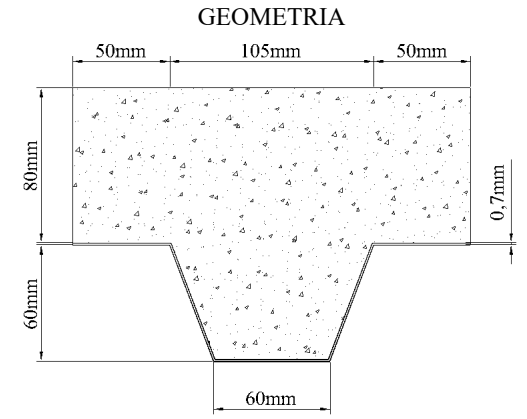


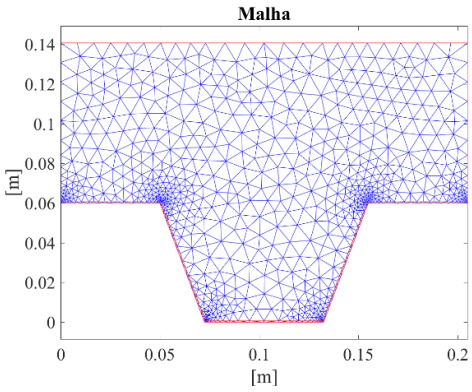


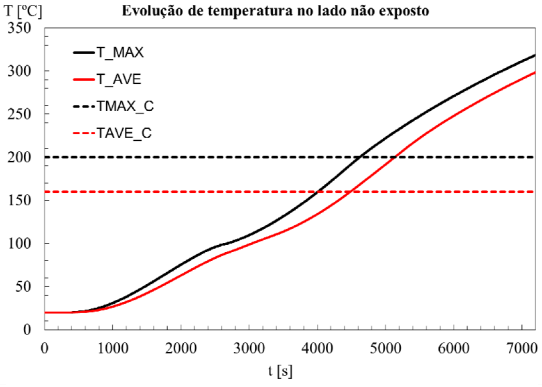


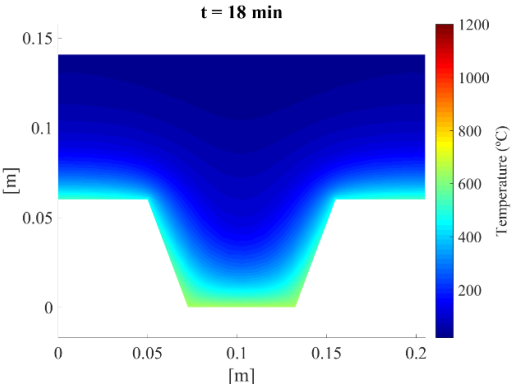


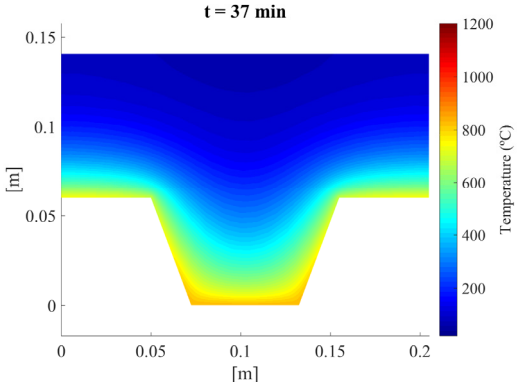
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.7mm

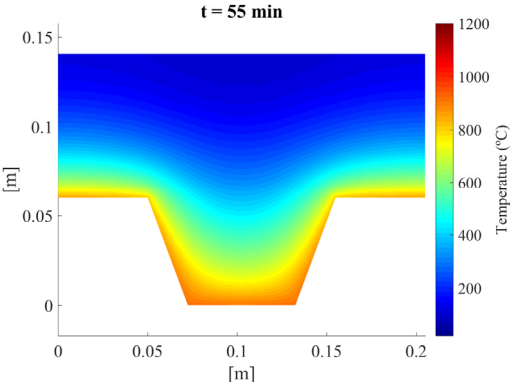


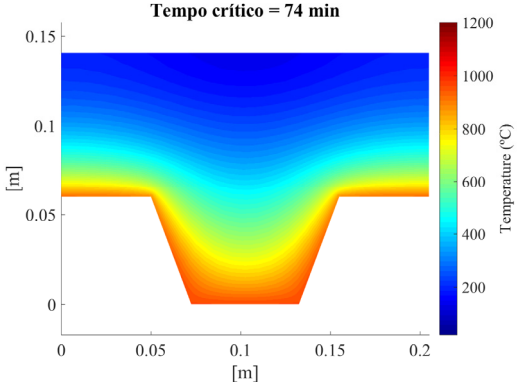


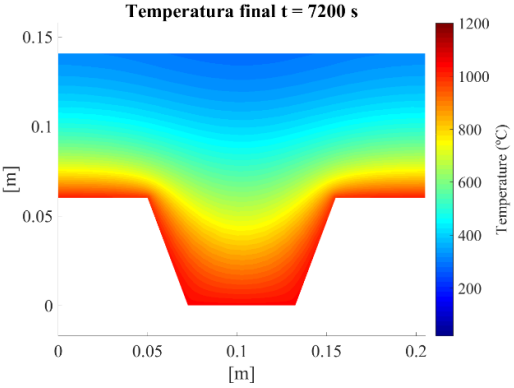




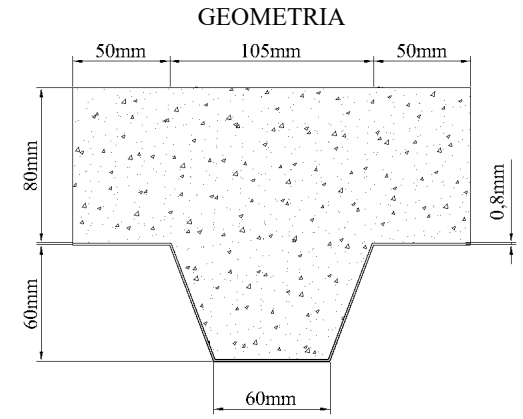


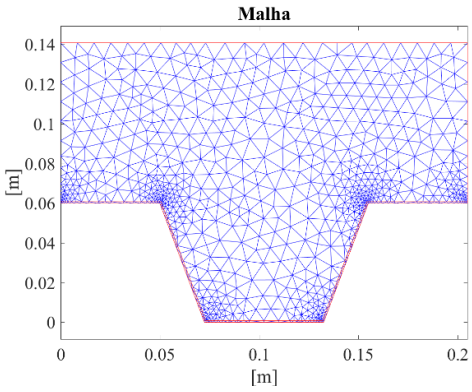


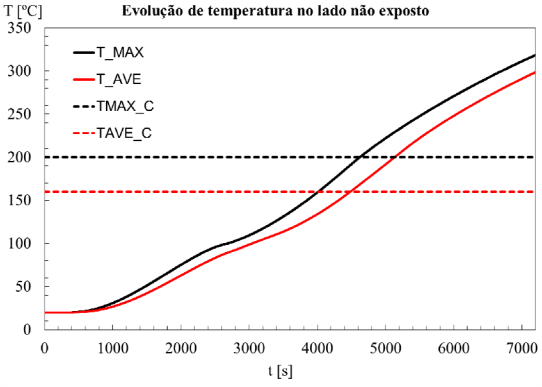


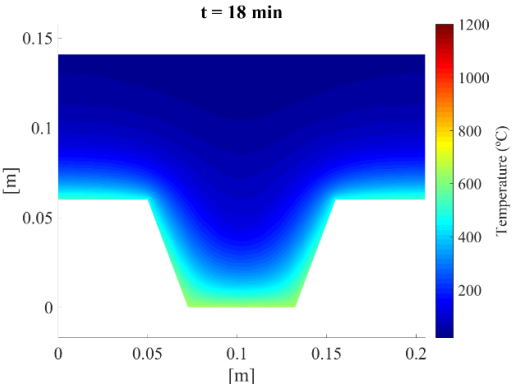


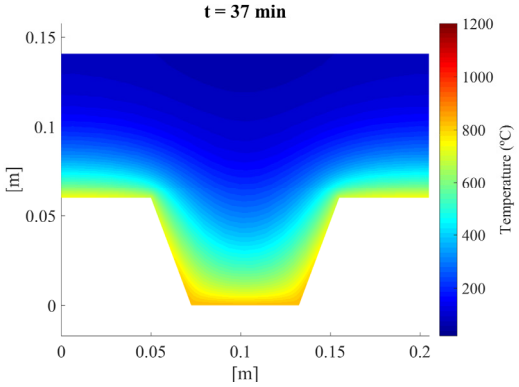
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.8mm

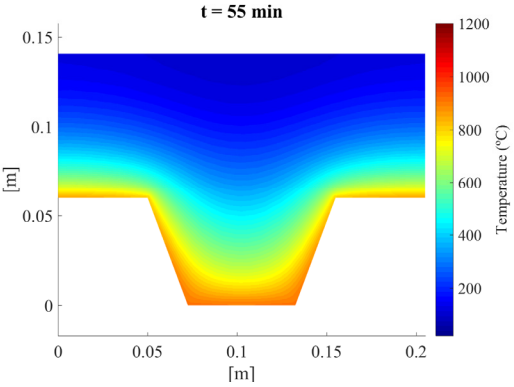


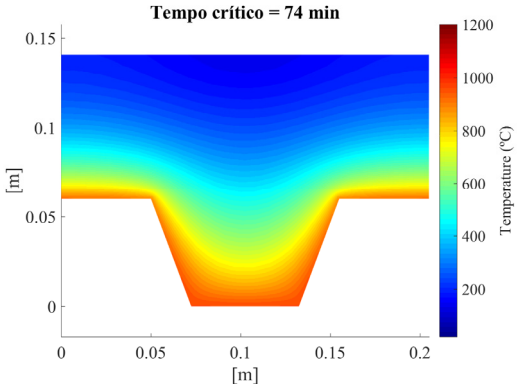


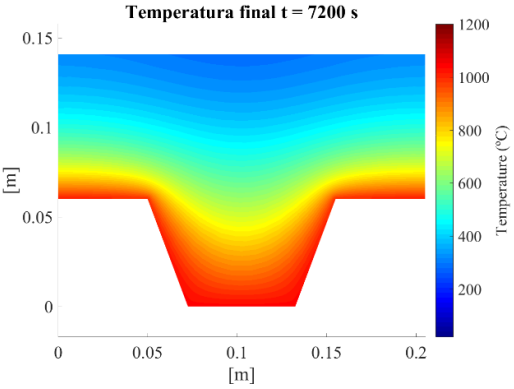




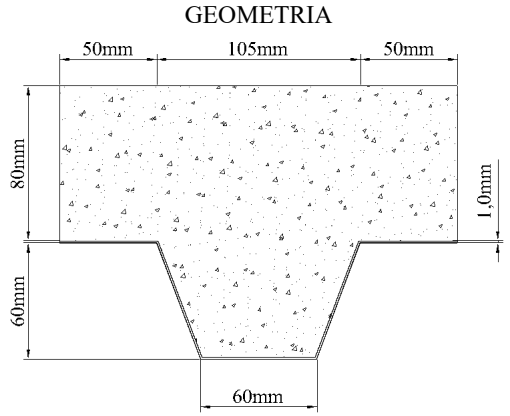


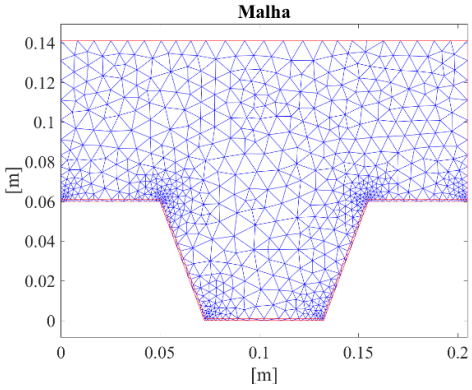


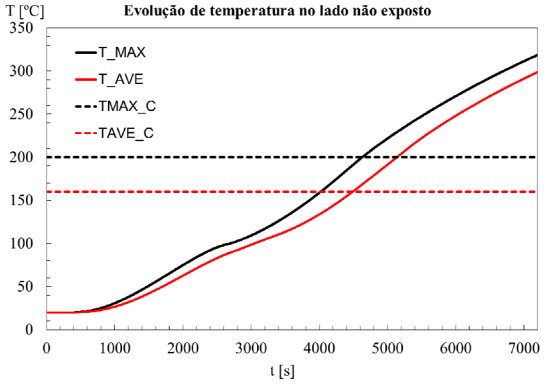


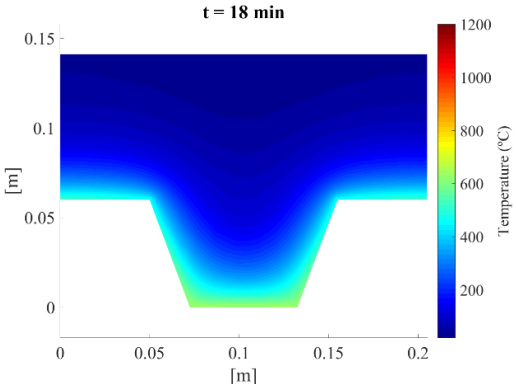


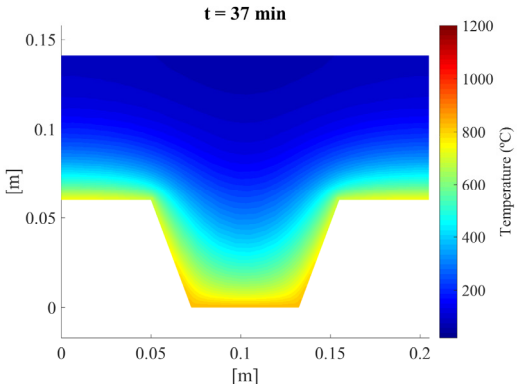
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.0mm

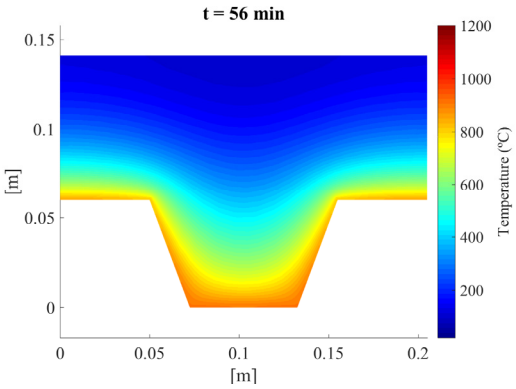


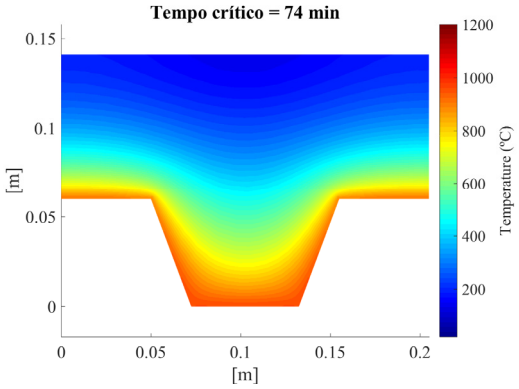


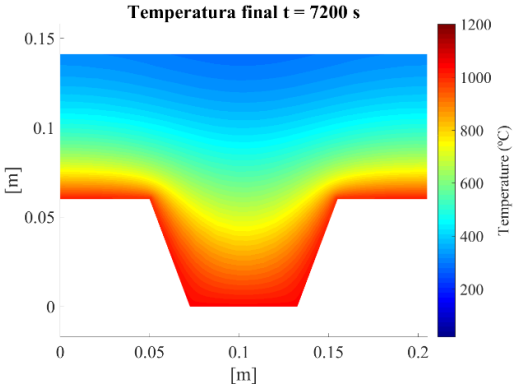




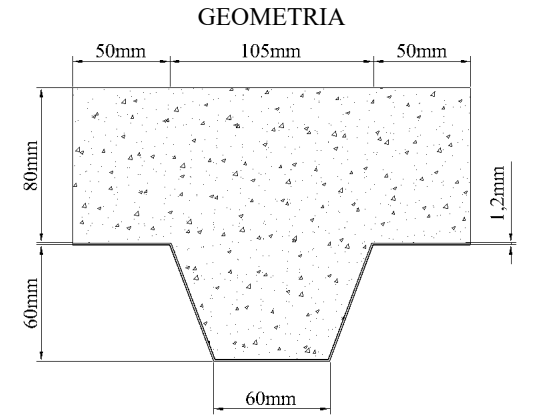


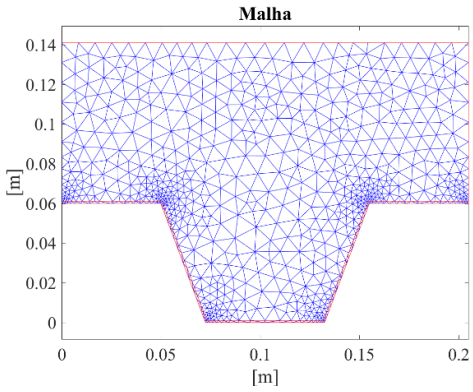


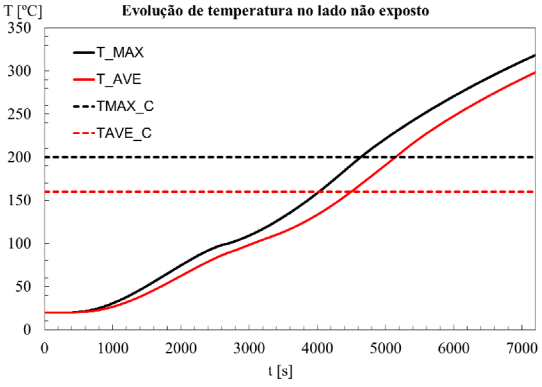


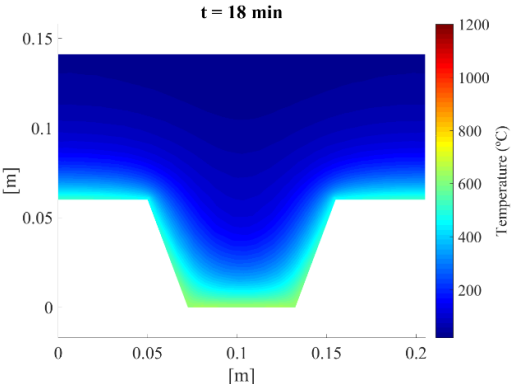


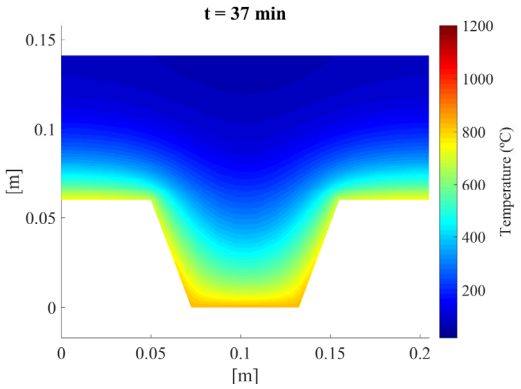
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.2mm

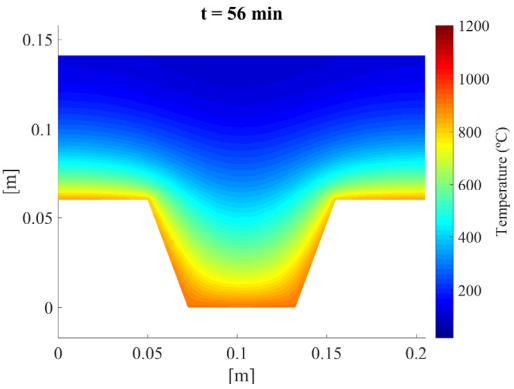


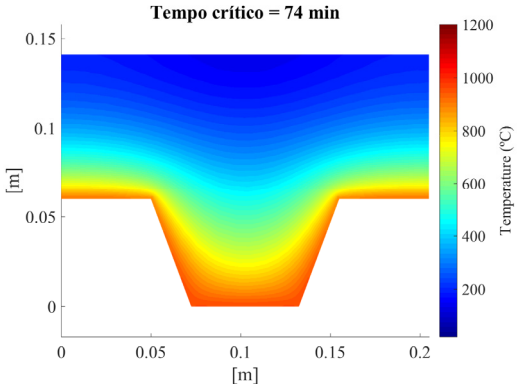


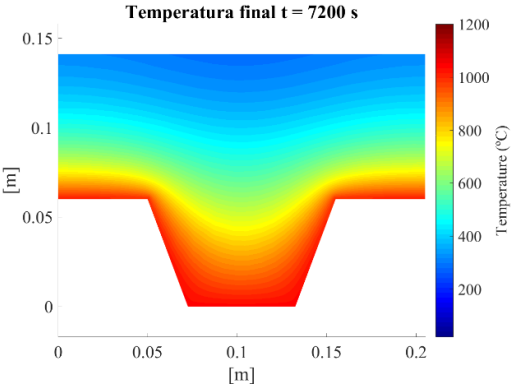




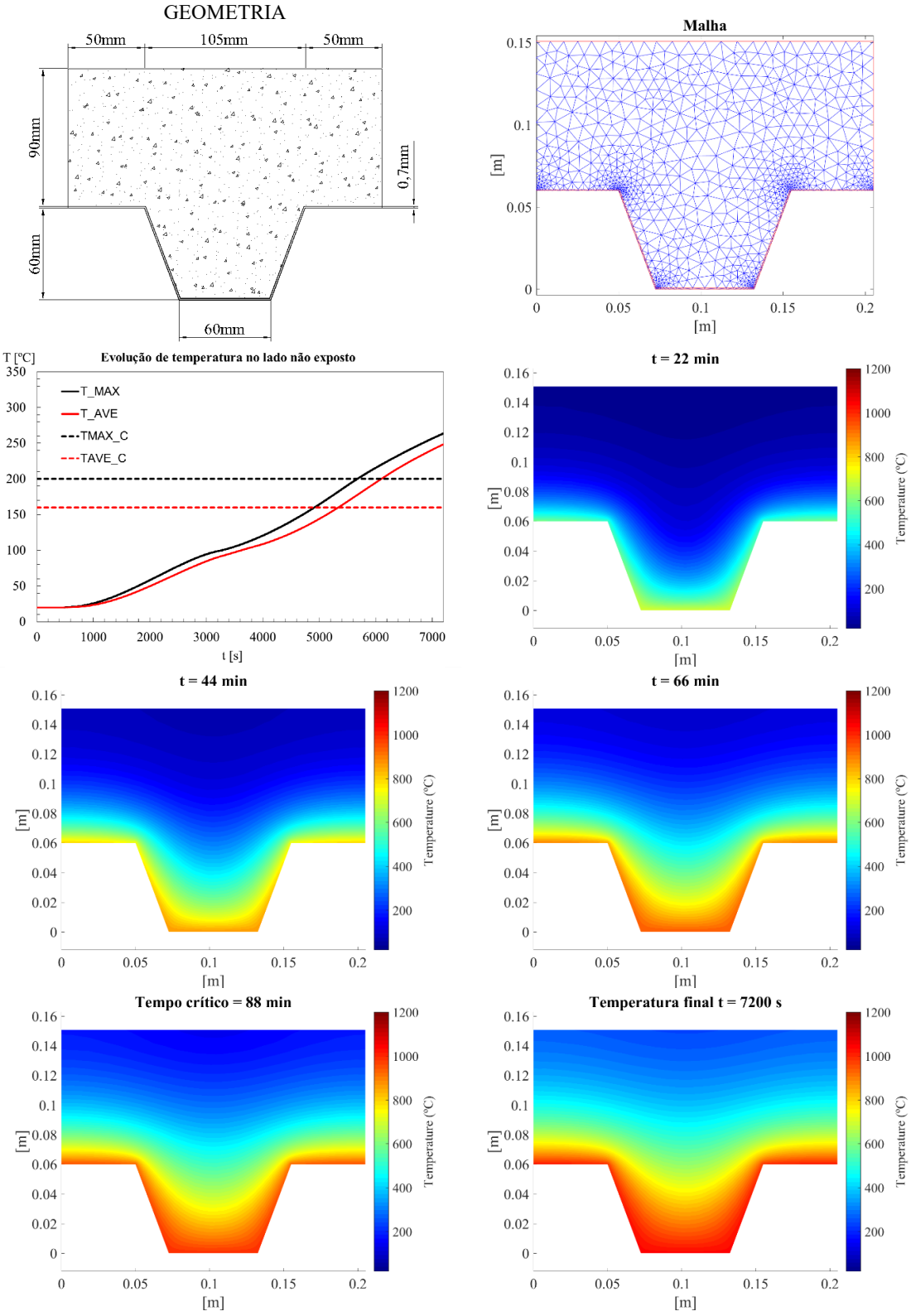




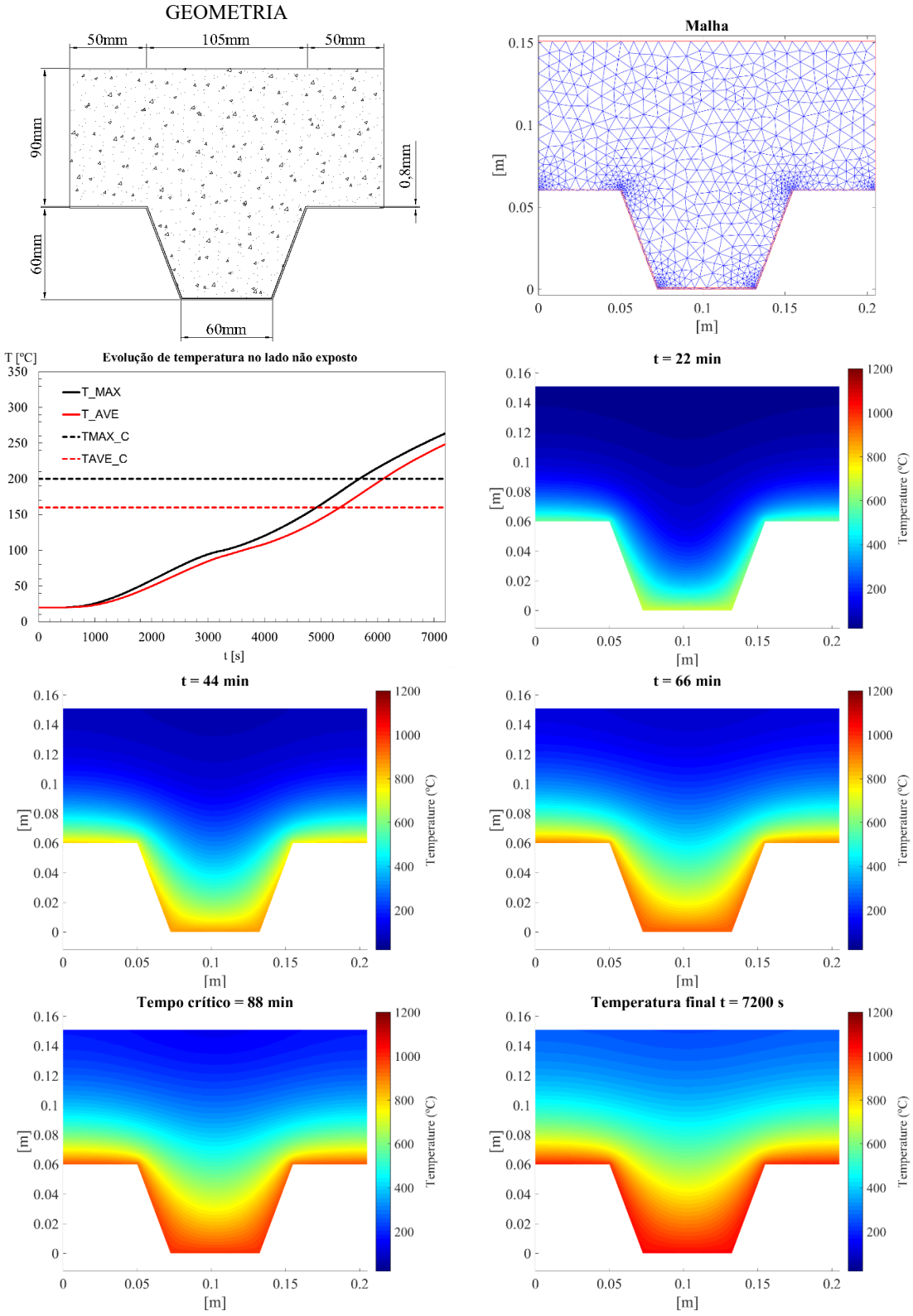




LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.7mm

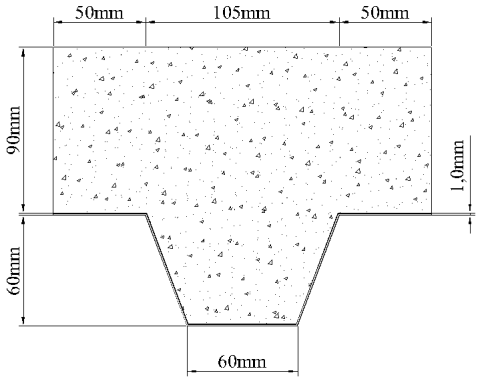


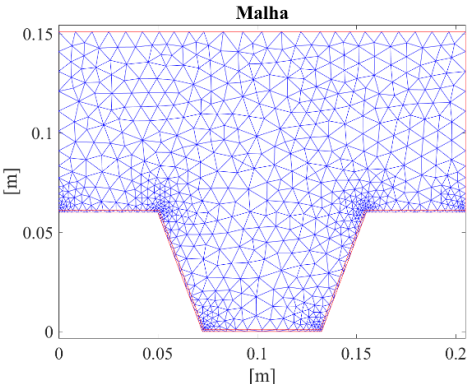
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.8mm

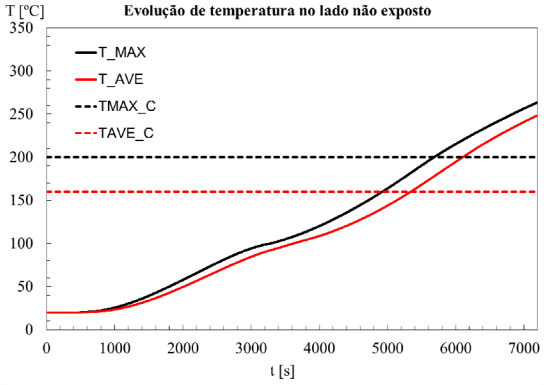


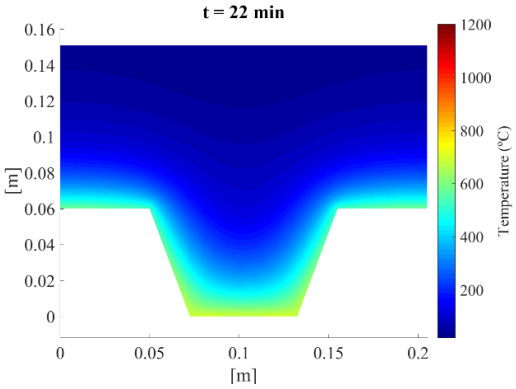
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.0mm

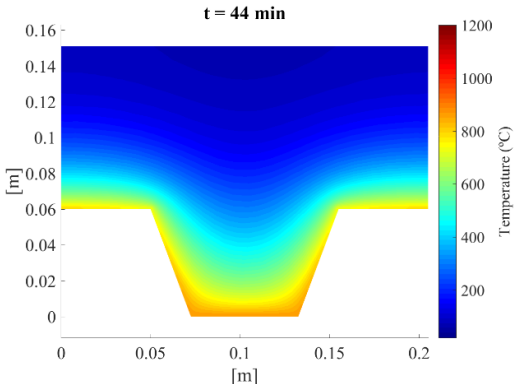
GEOMETRIA

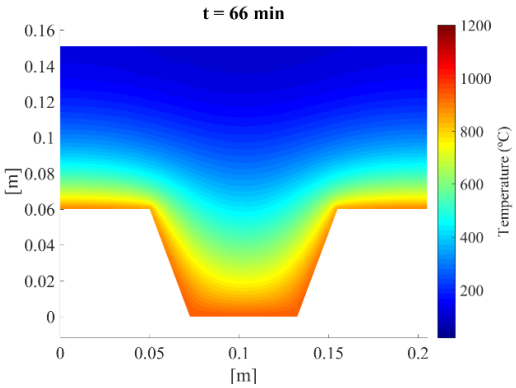


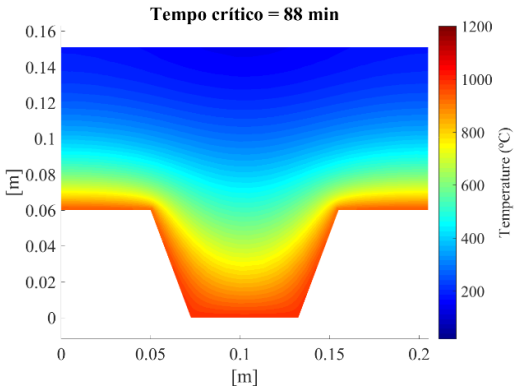


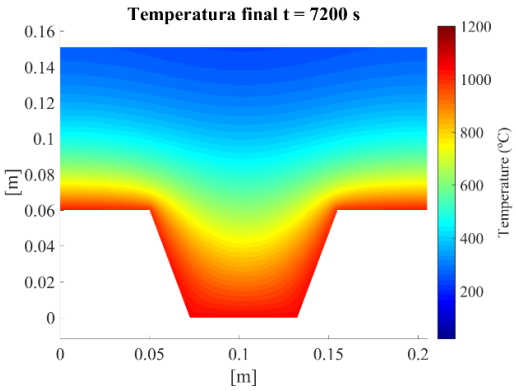




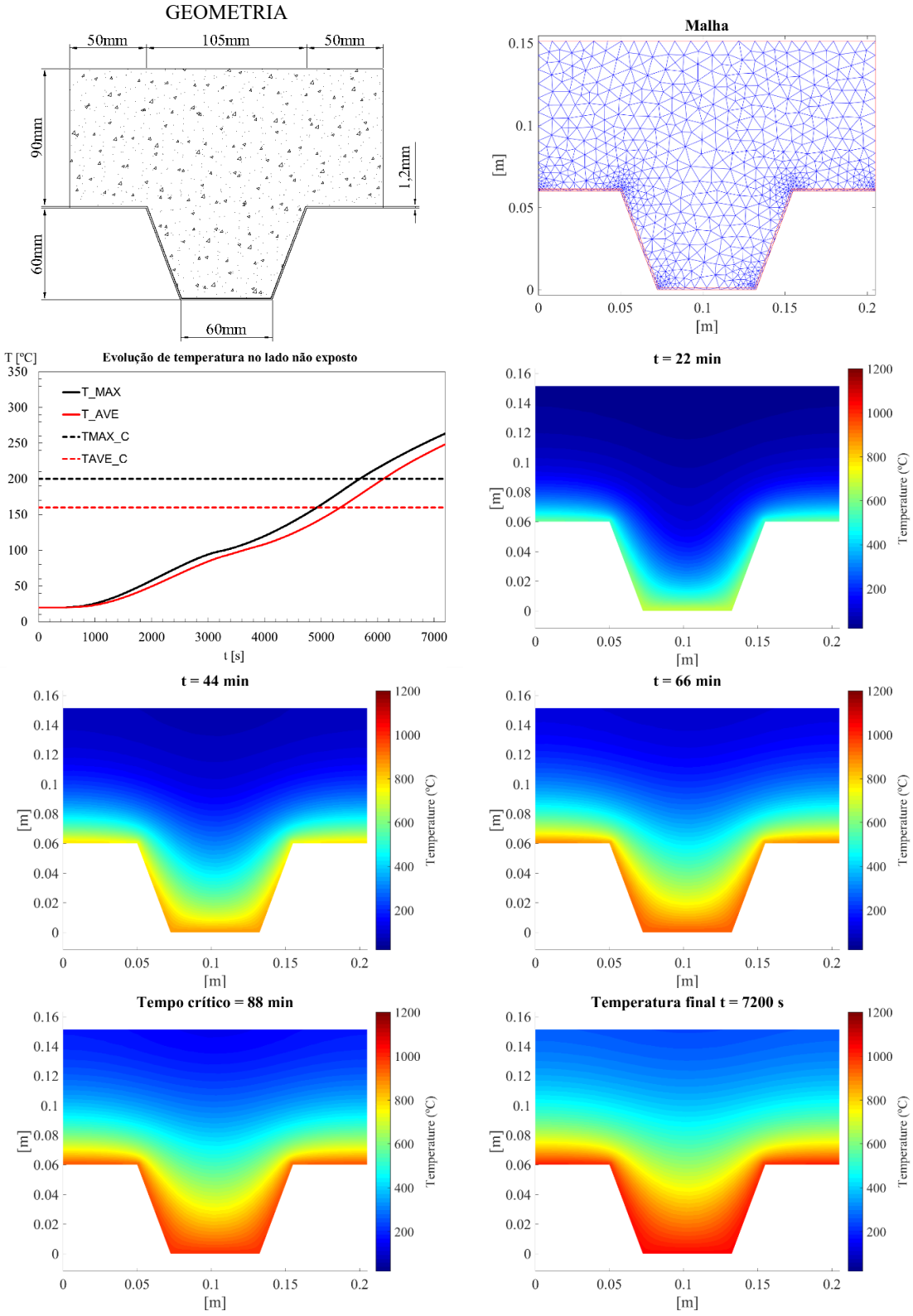




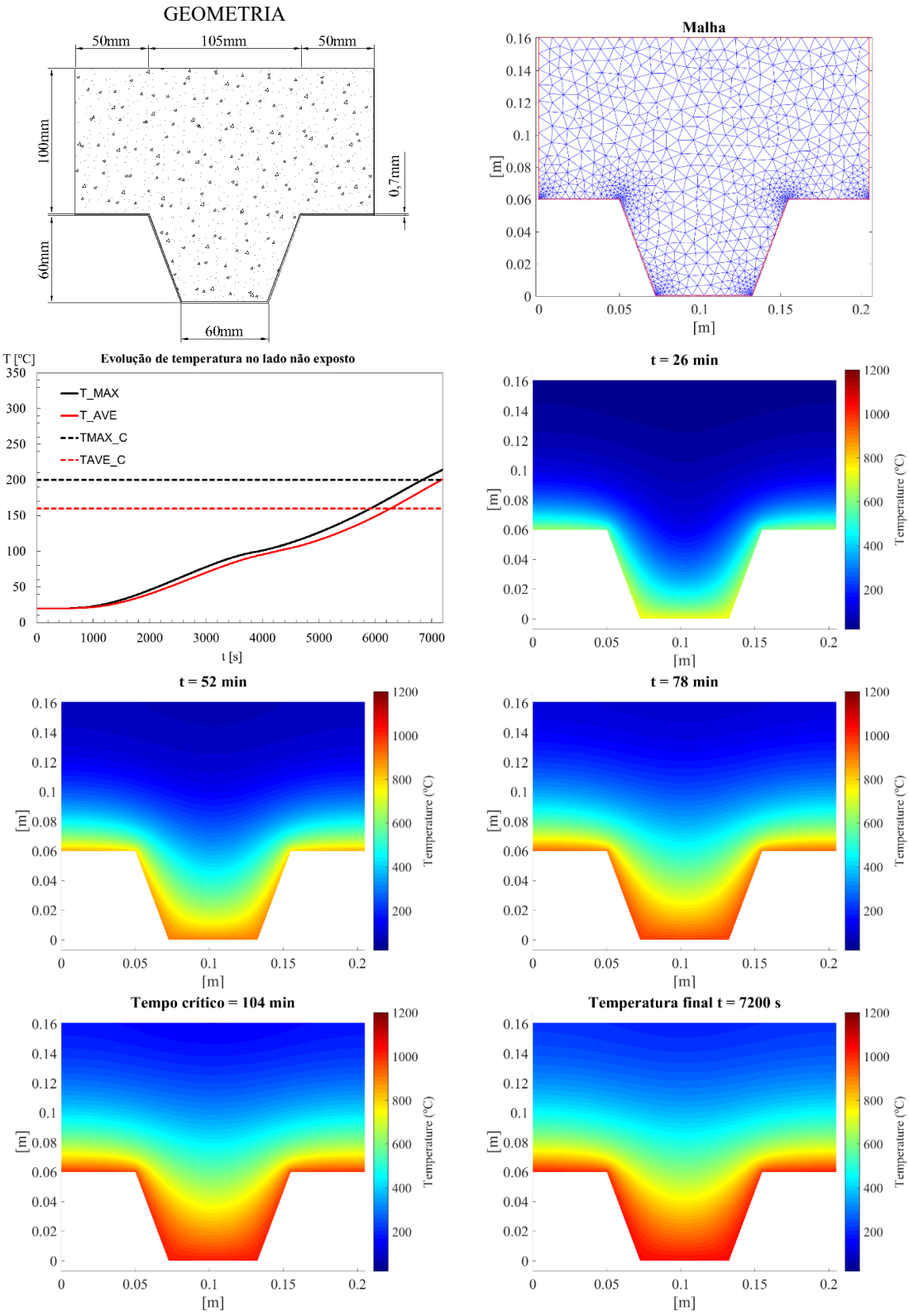




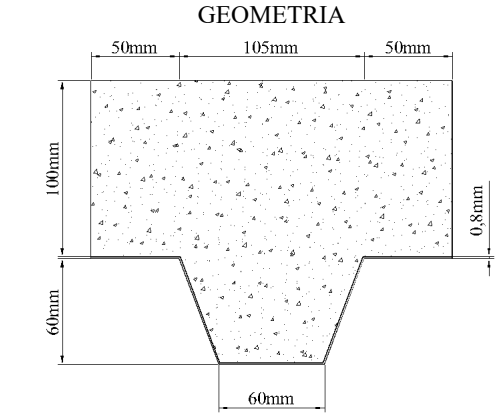
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.2mm

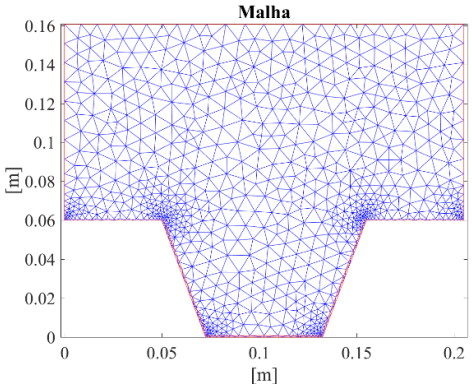


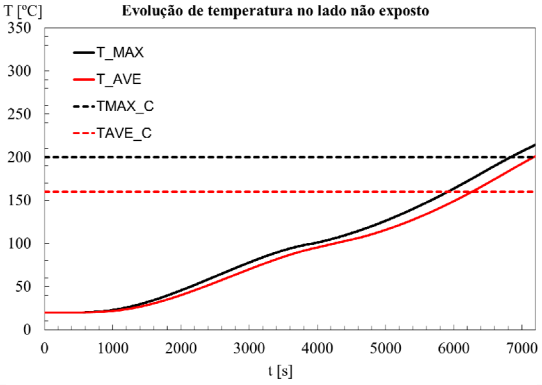
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.7mm

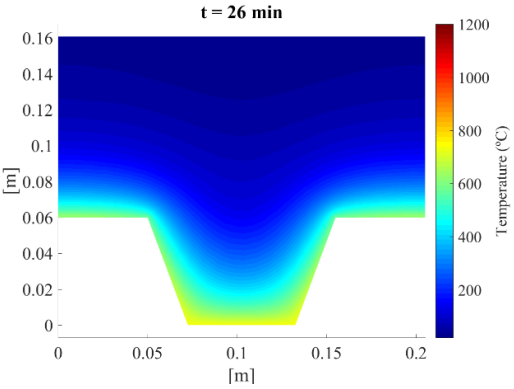


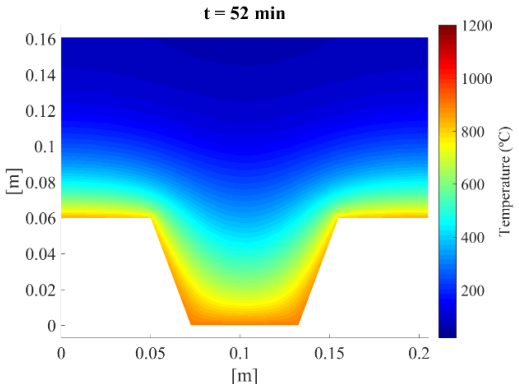
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.8mm

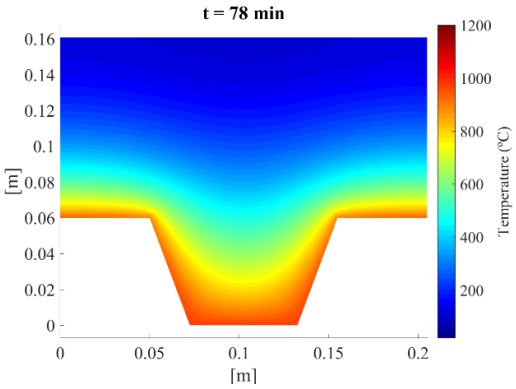


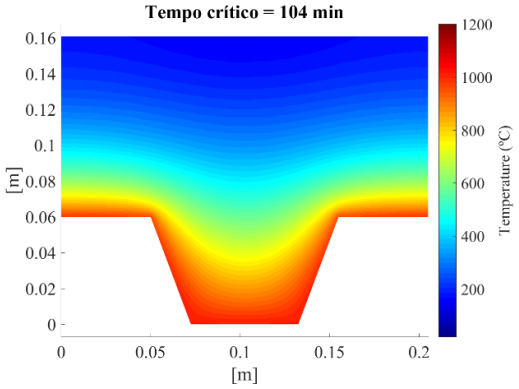


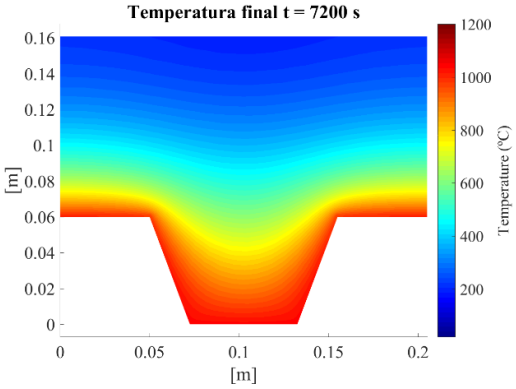




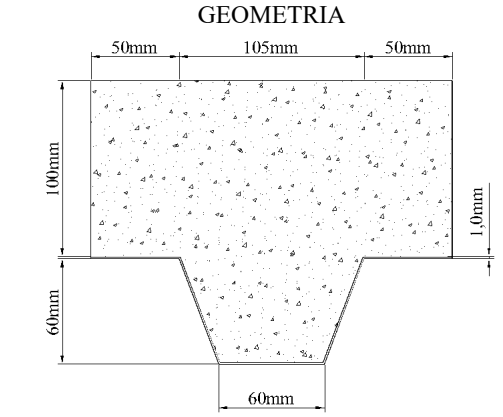


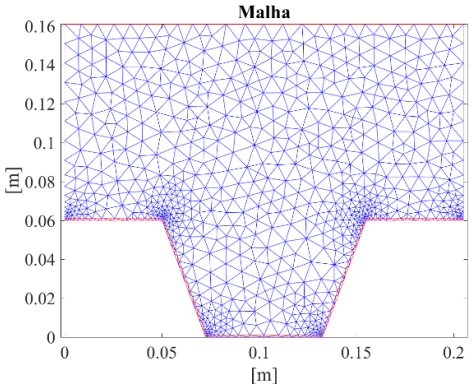


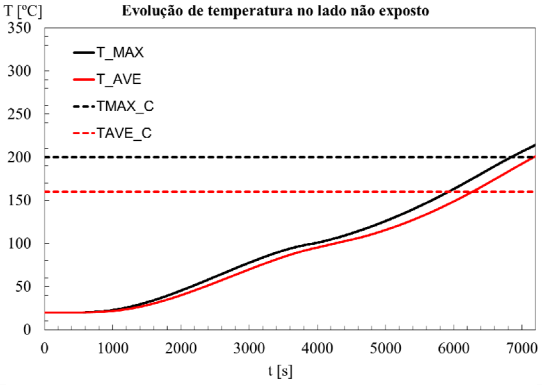


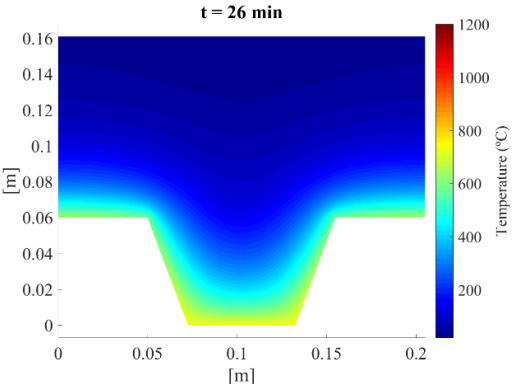


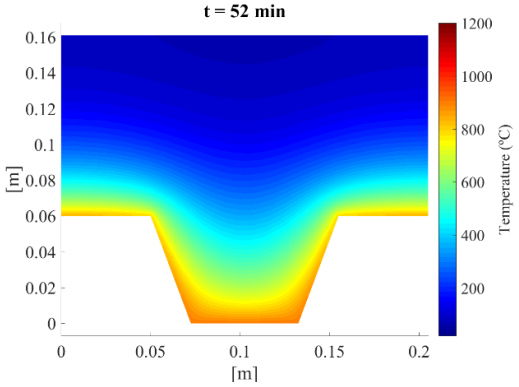
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.0mm

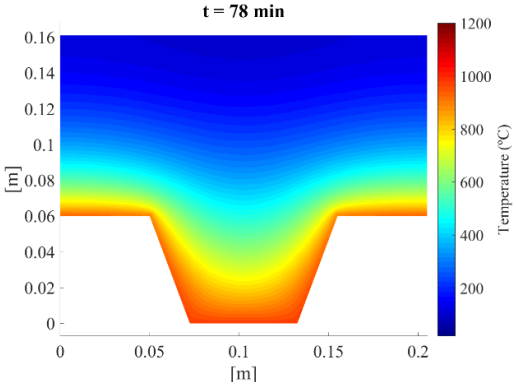


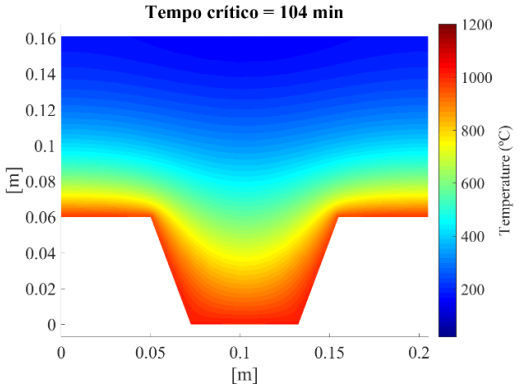


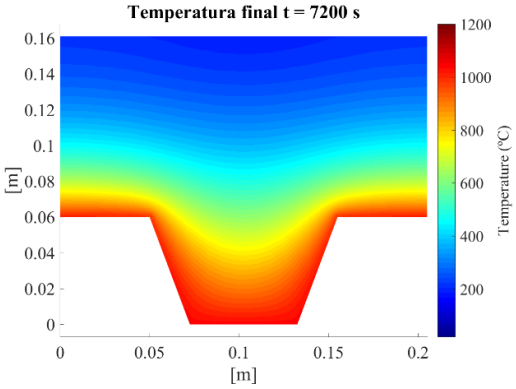




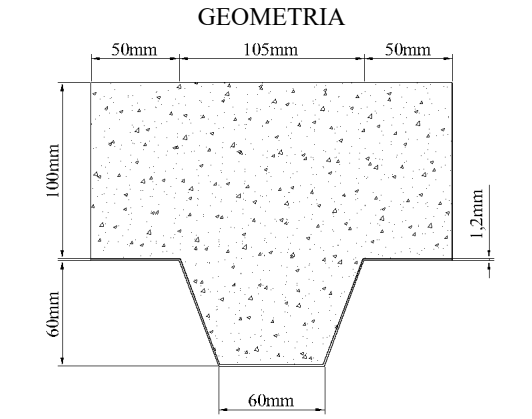


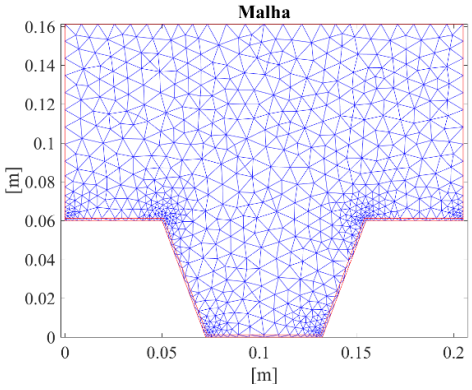


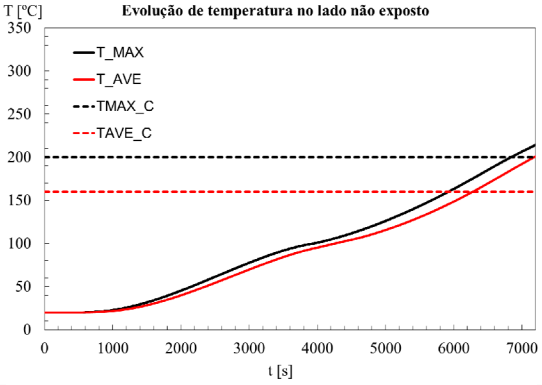


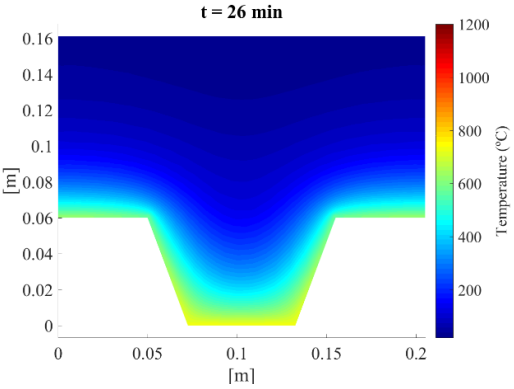


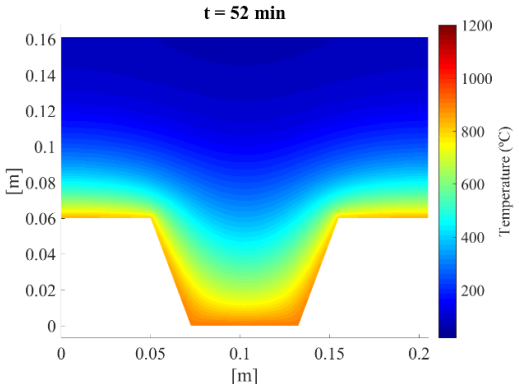
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.2mm

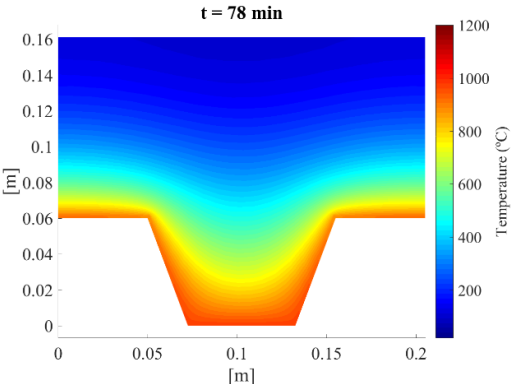


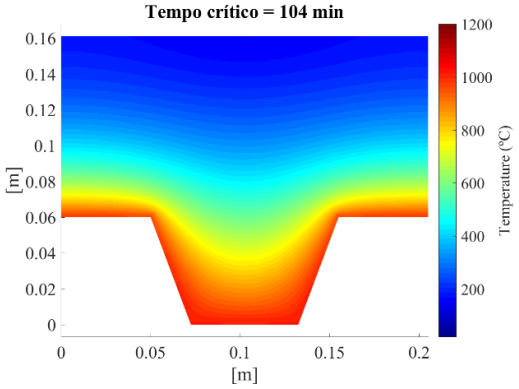


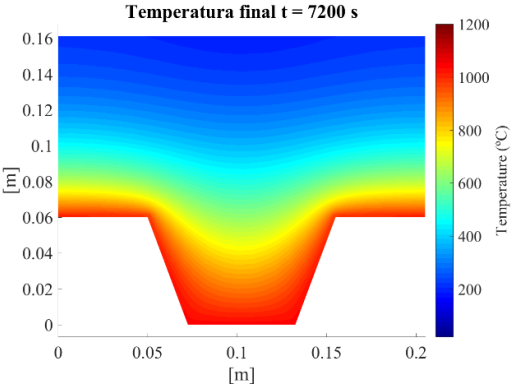






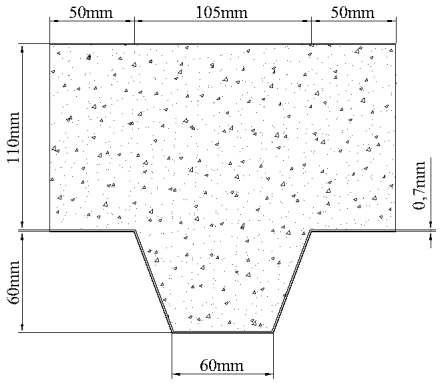


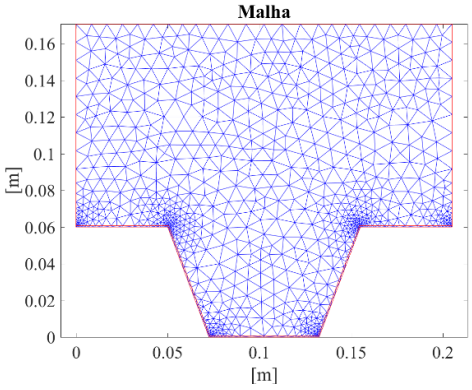


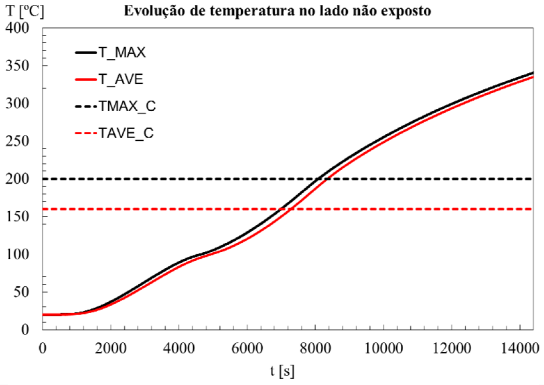


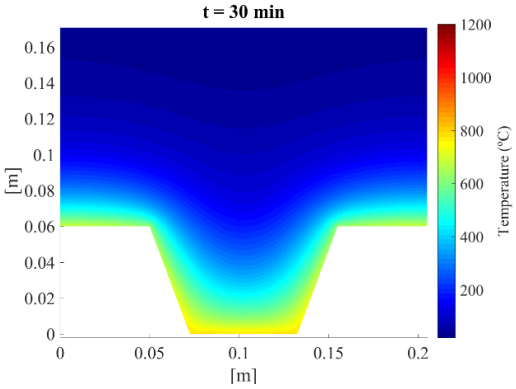
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.7mm

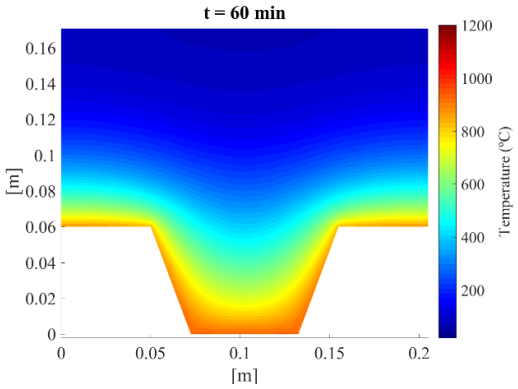
GEOMETRIA

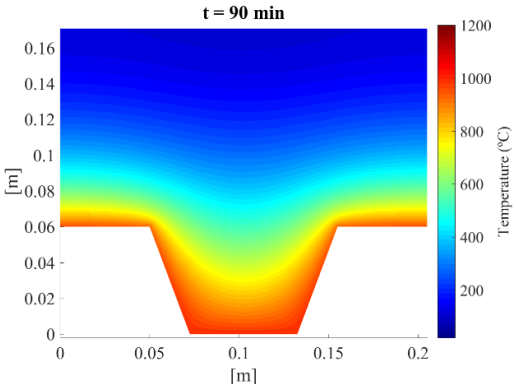


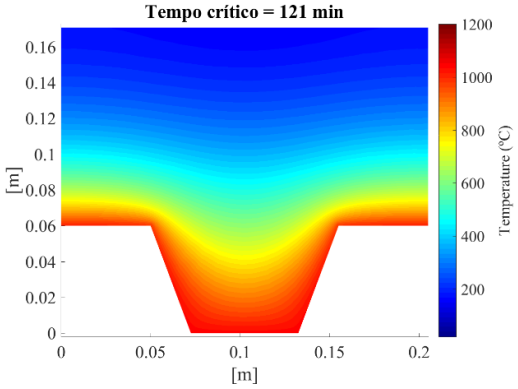


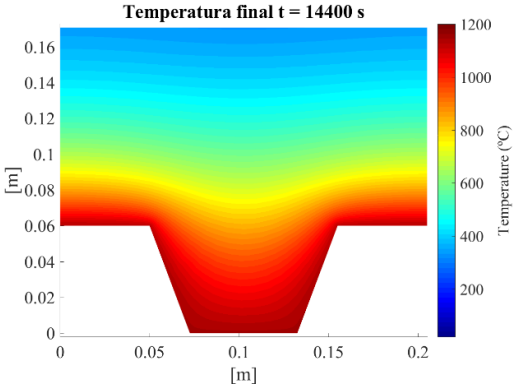




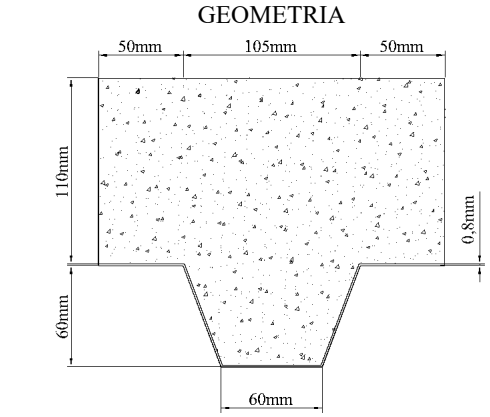


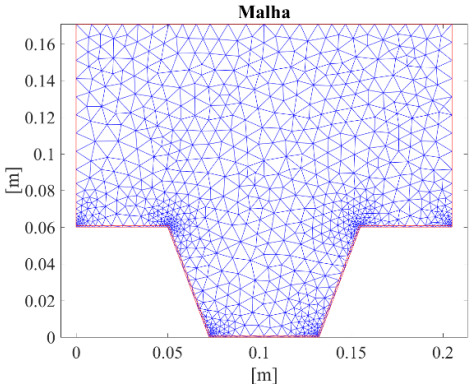


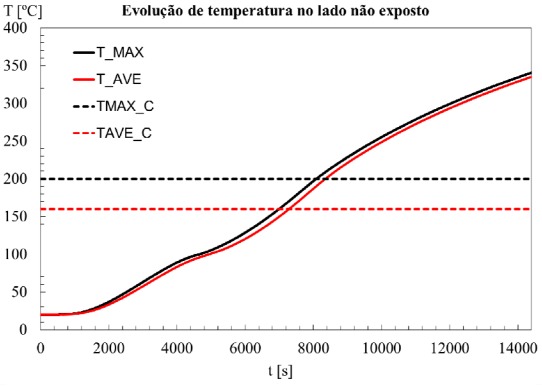


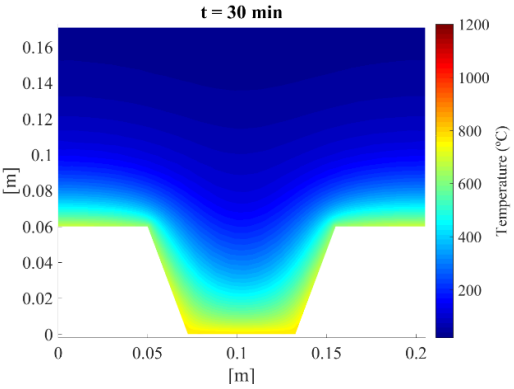


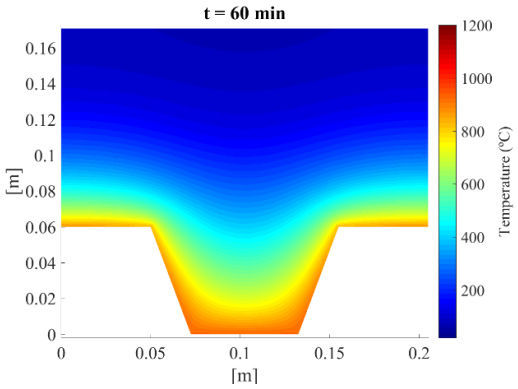
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.8mm

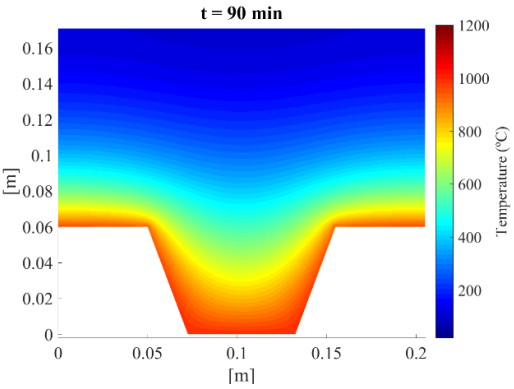


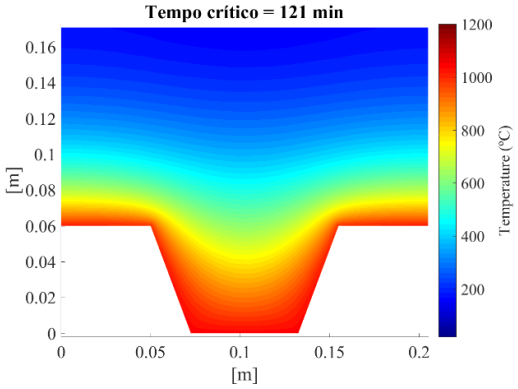


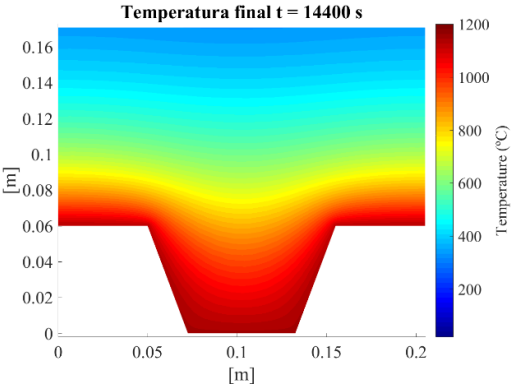




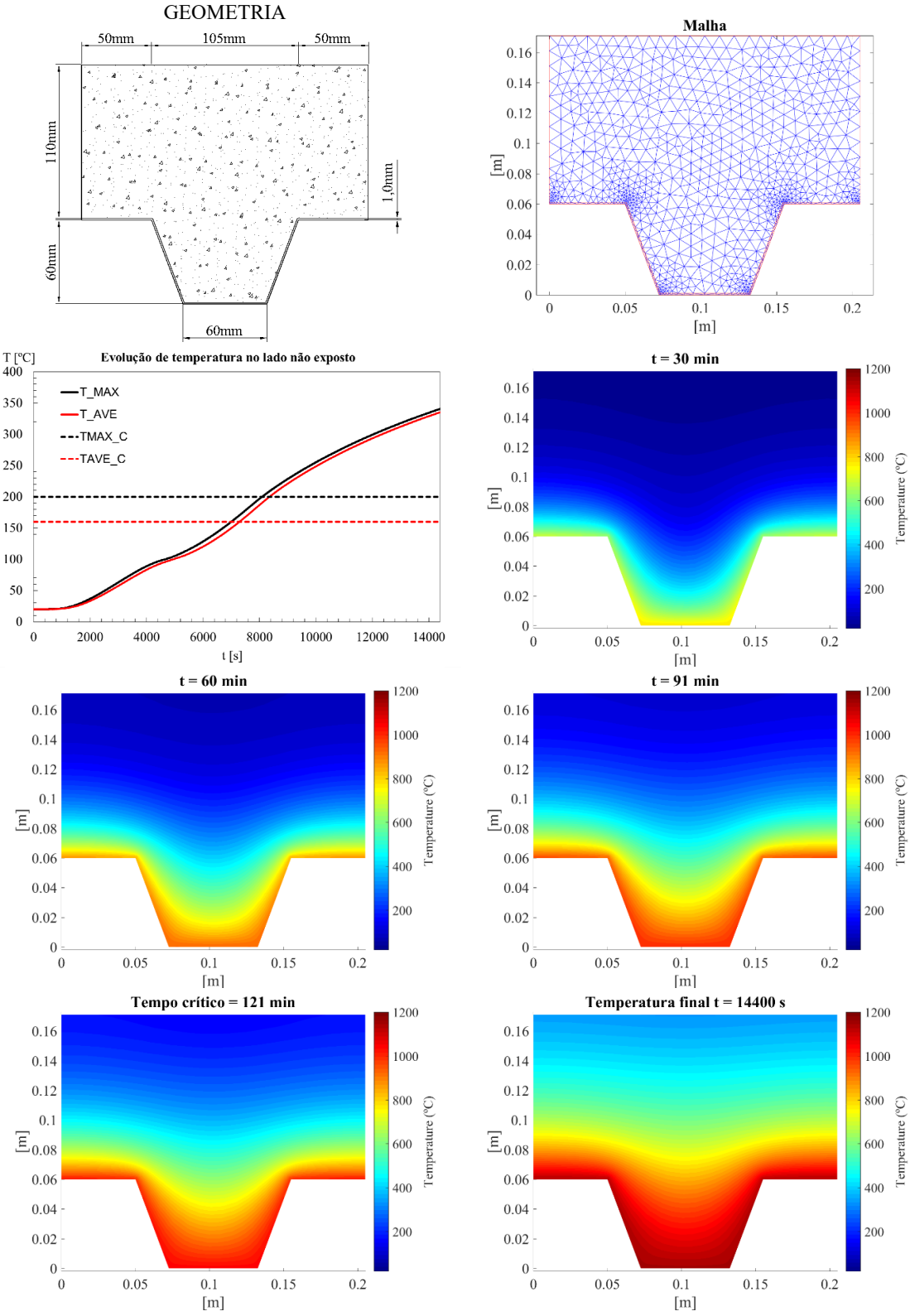




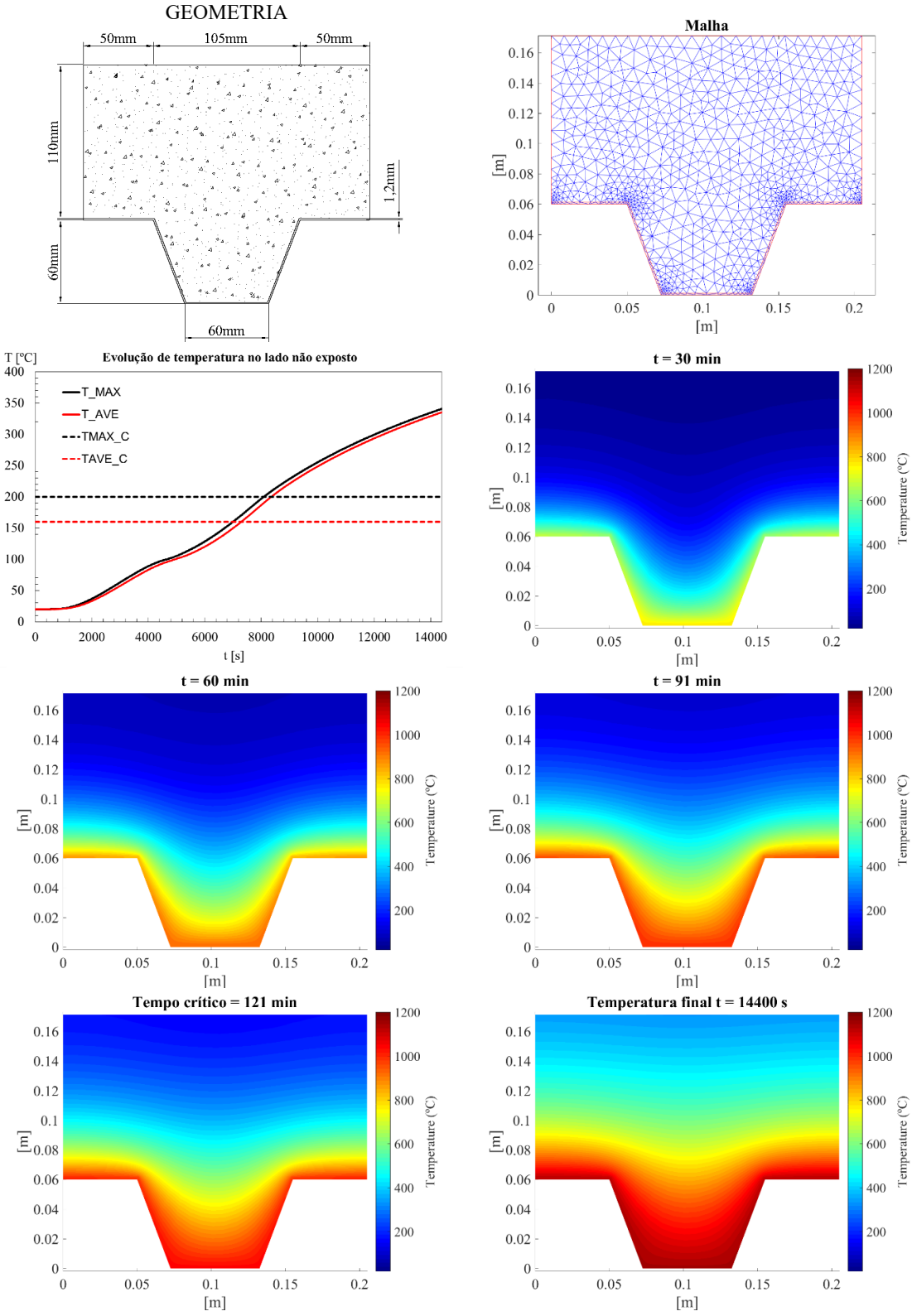




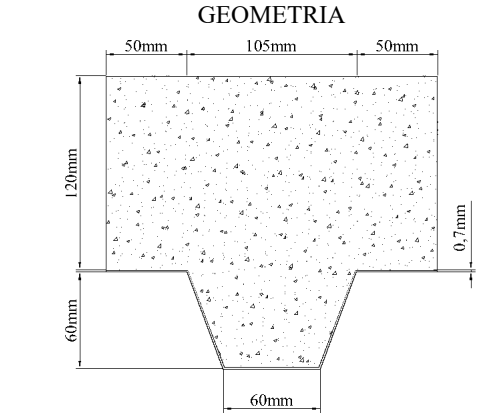
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.0mm

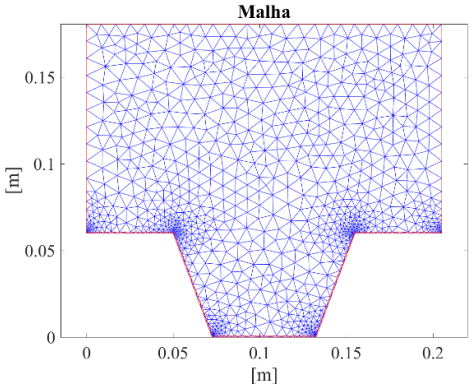


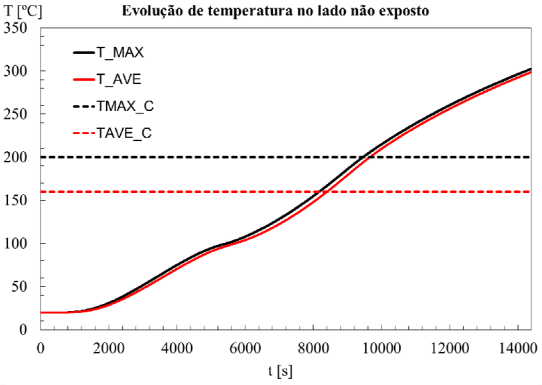
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.2mm

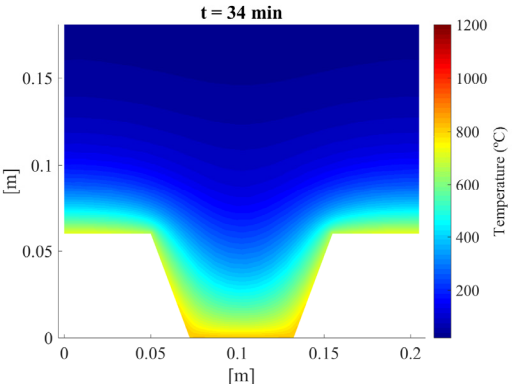


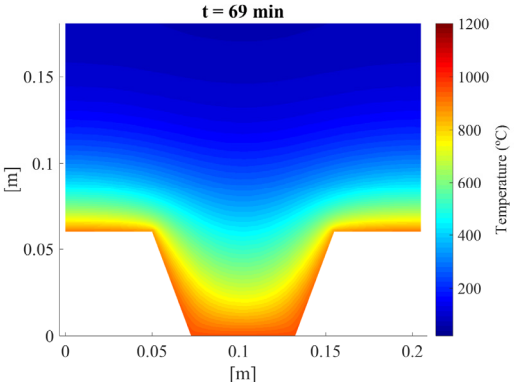
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.7mm

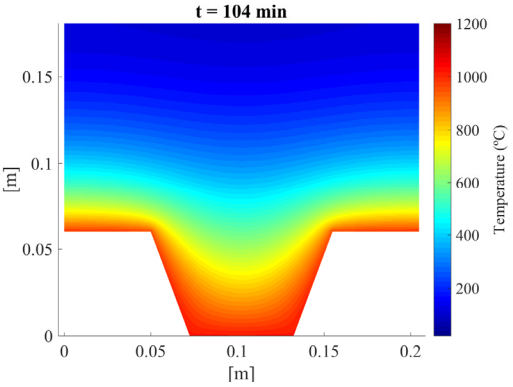


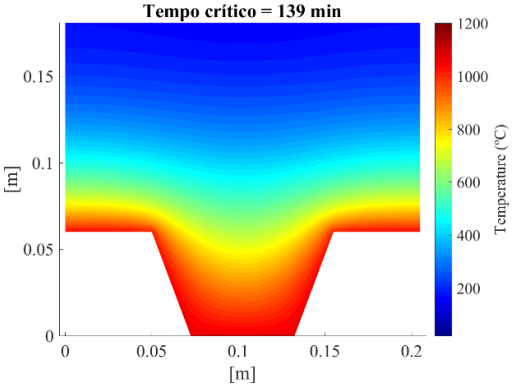


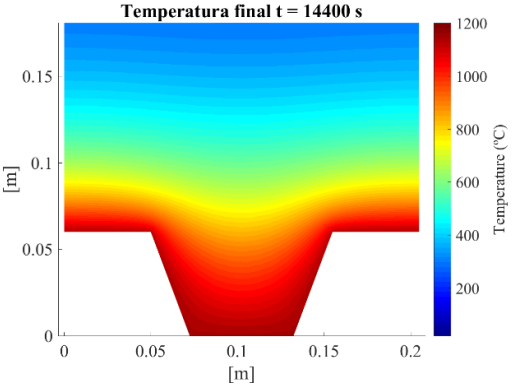




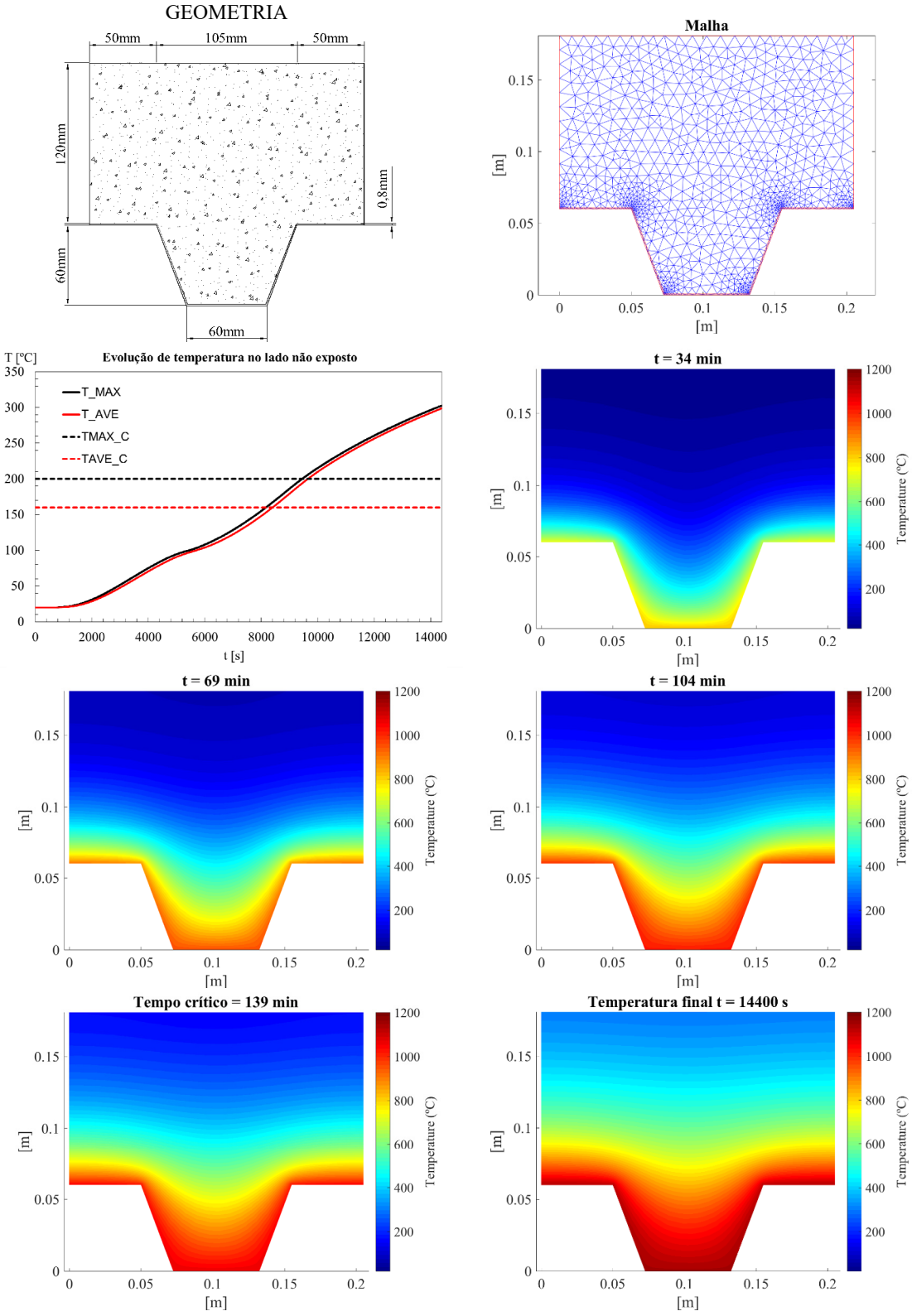




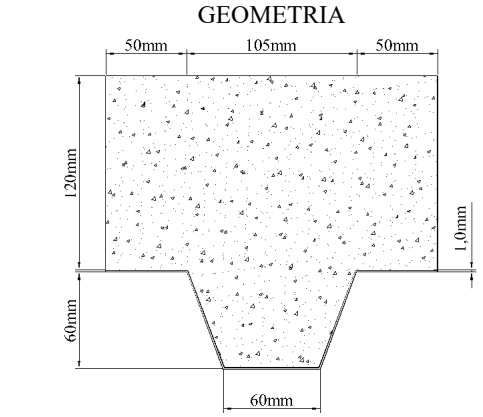


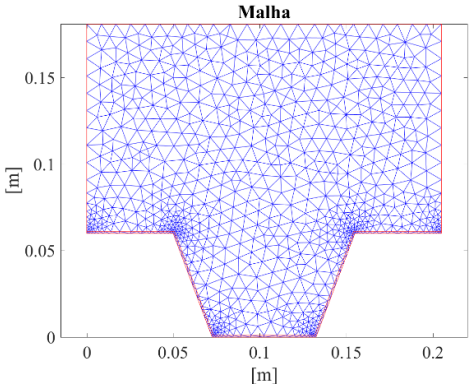


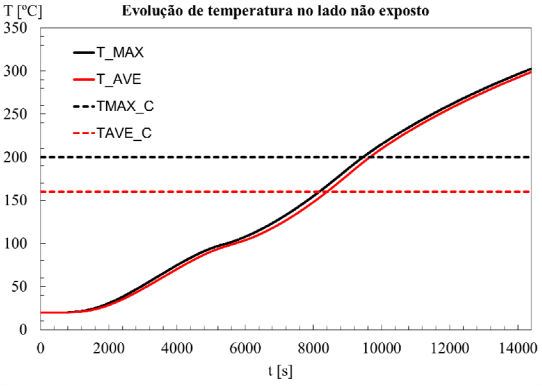
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.8mm

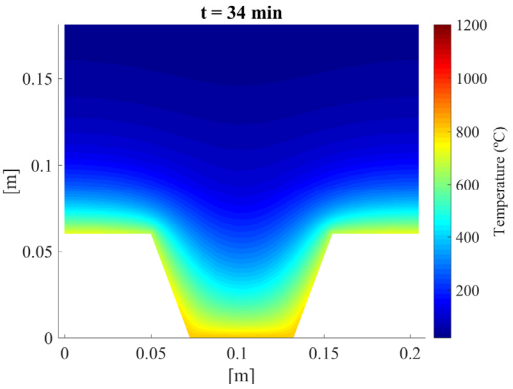


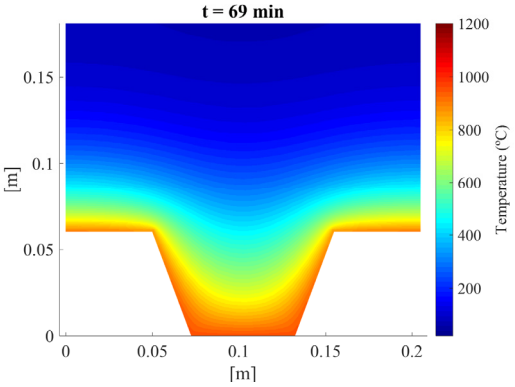
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.0mm

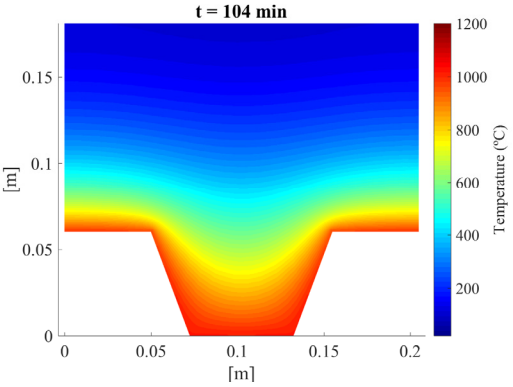


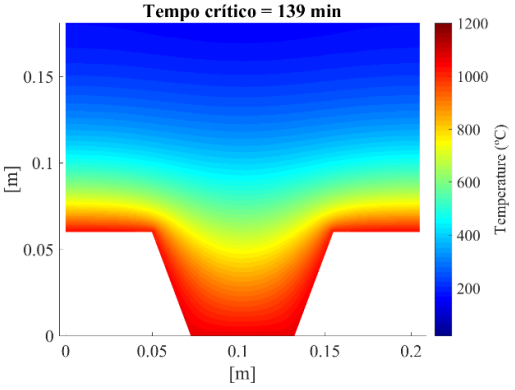


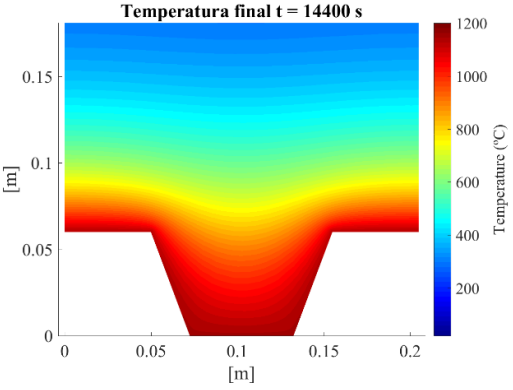




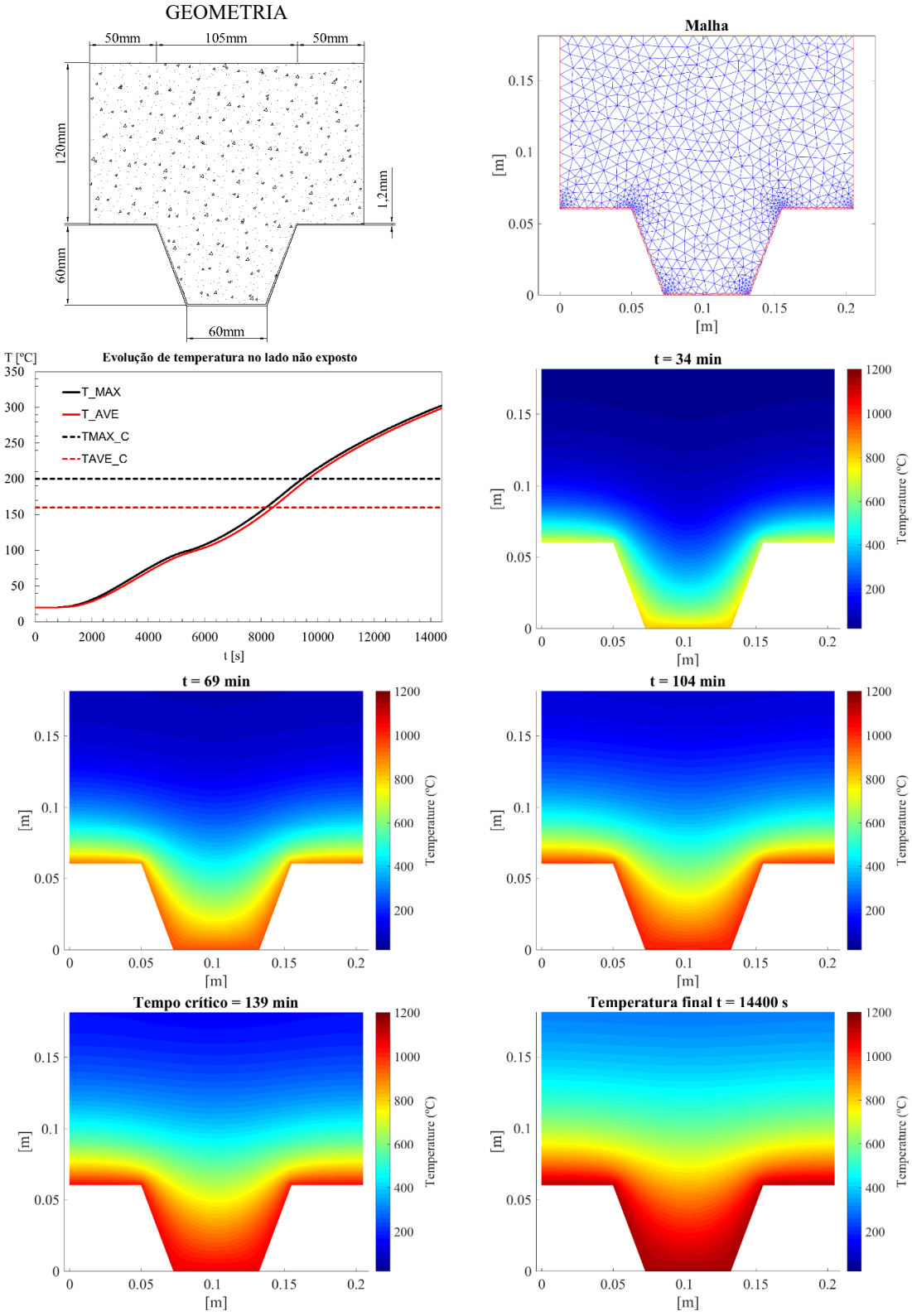




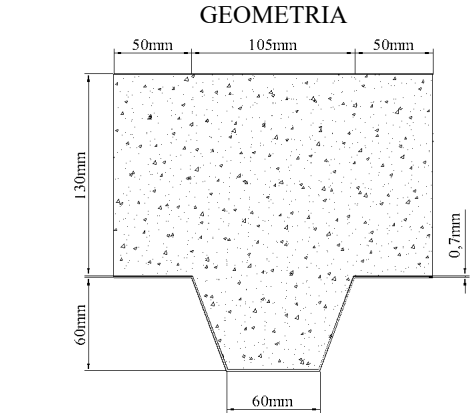


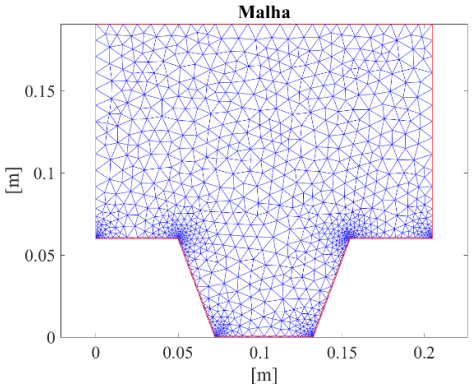


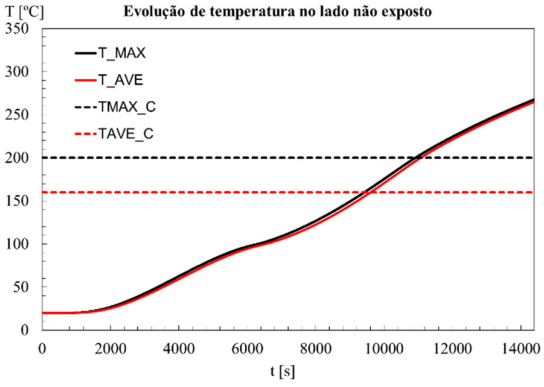
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.2mm

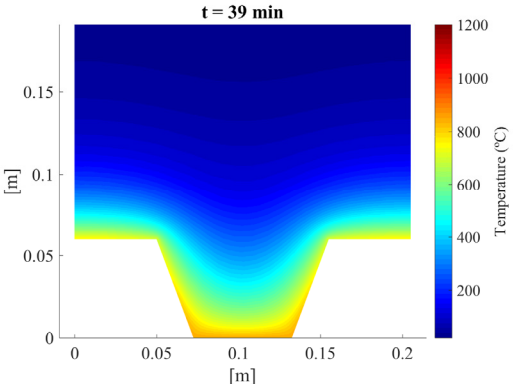


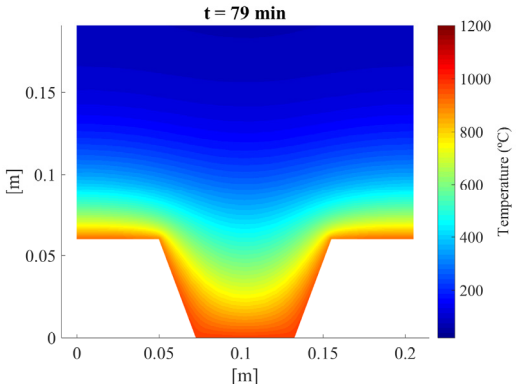
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.7mm

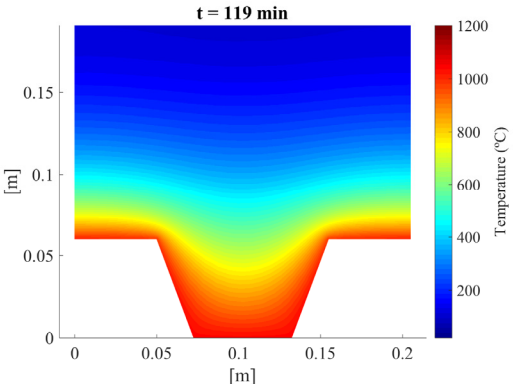


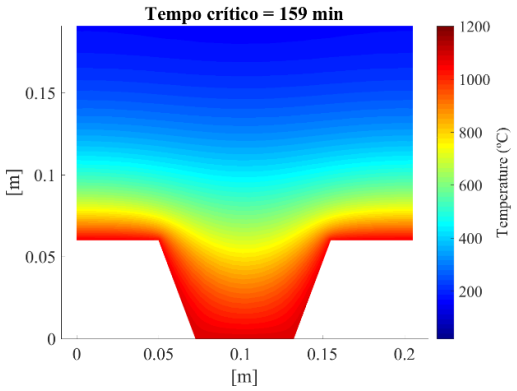


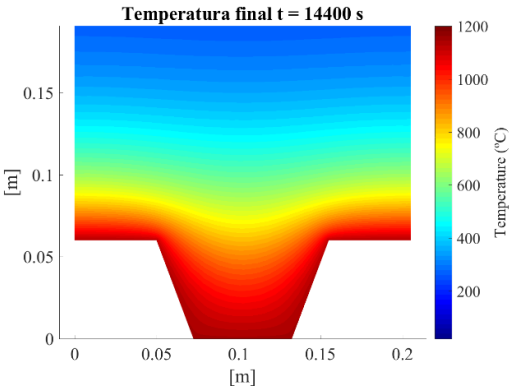




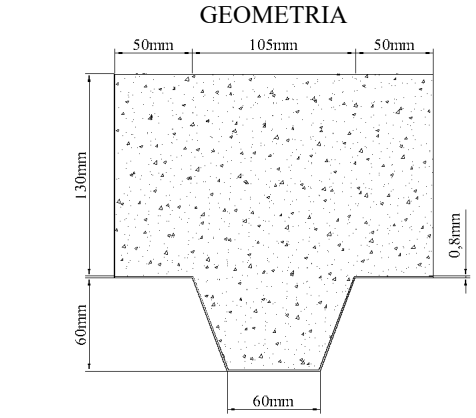


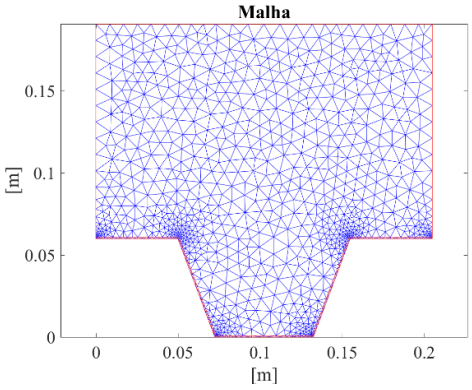


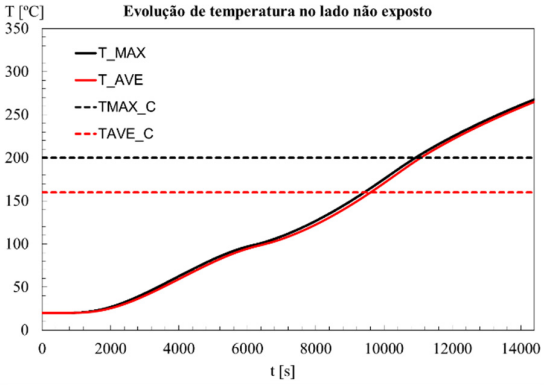


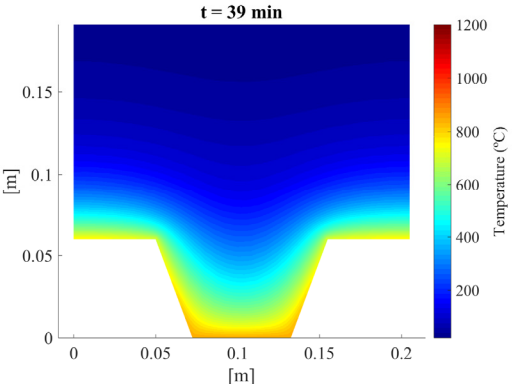


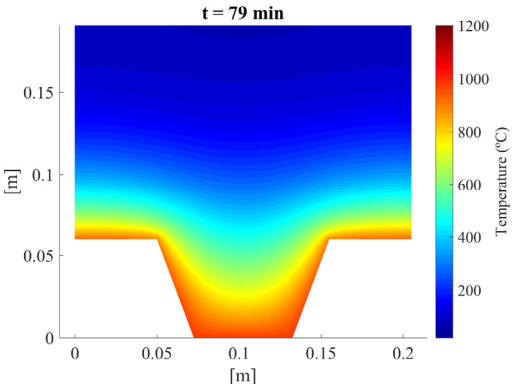
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.8mm

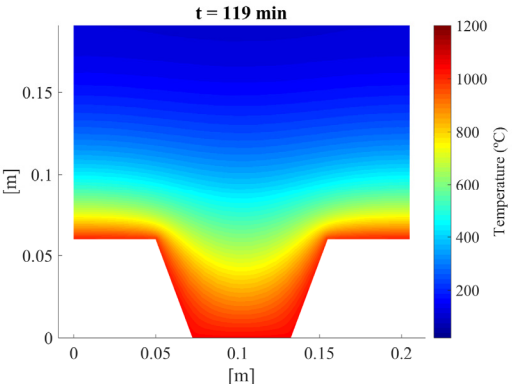


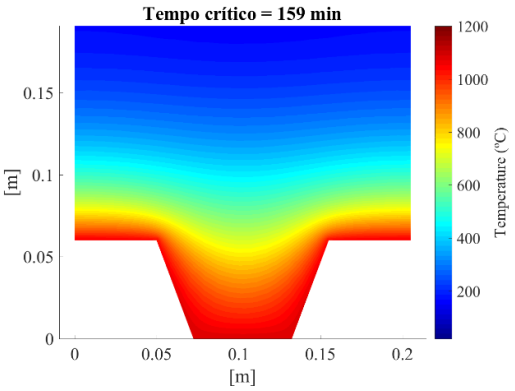


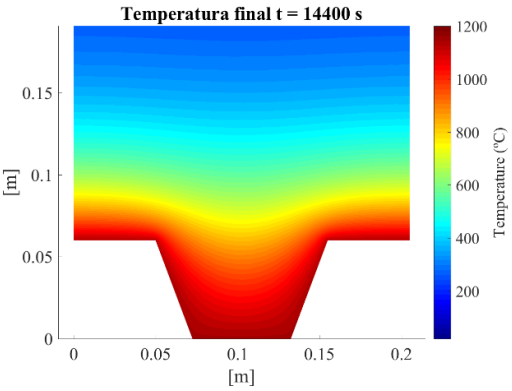




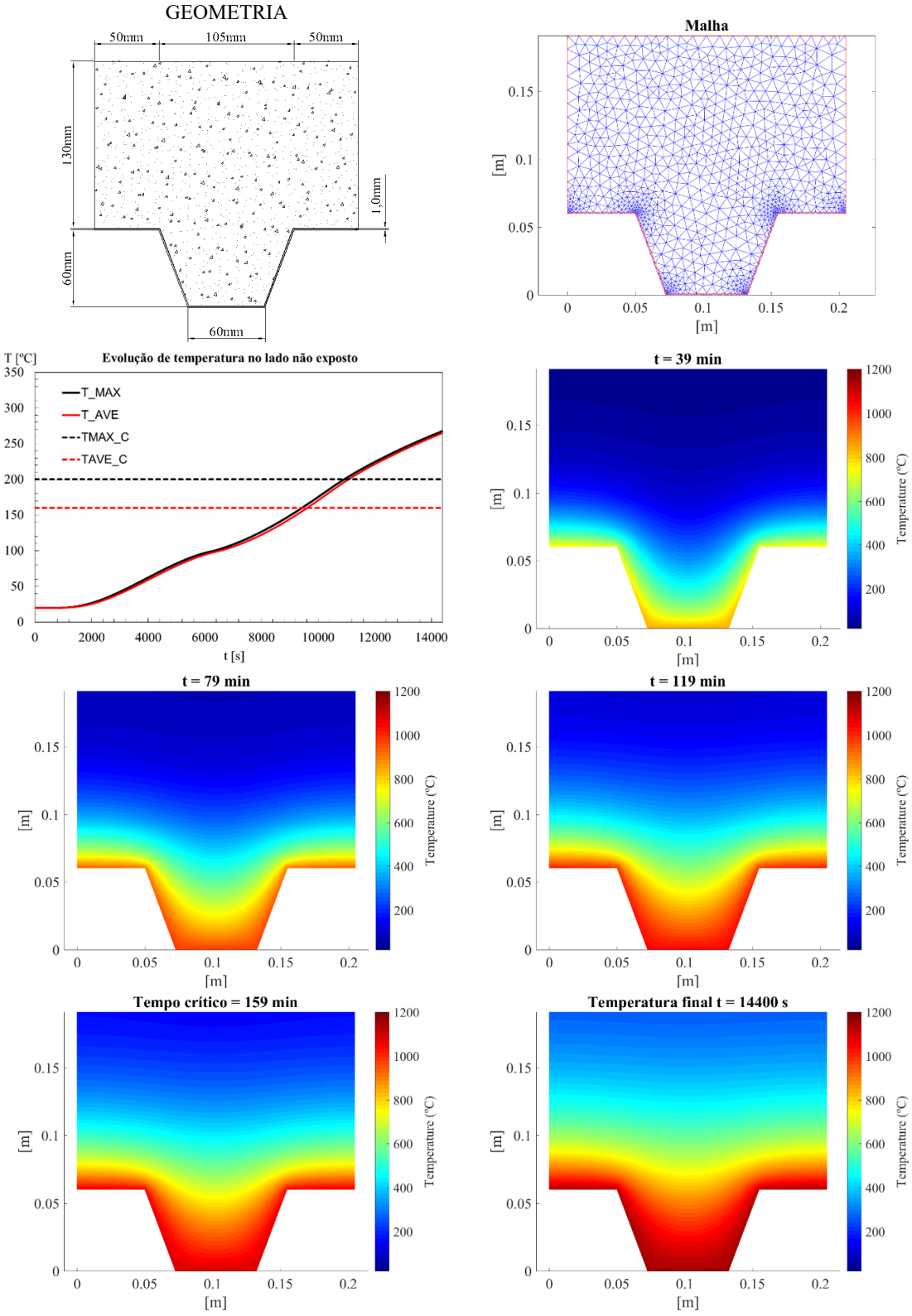




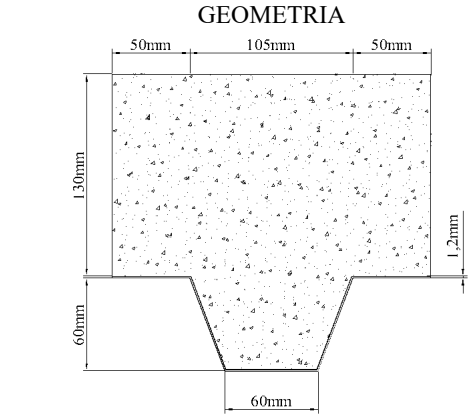


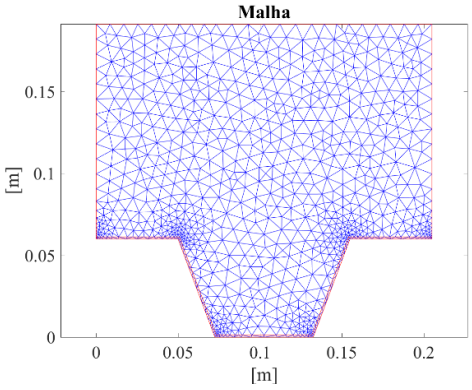


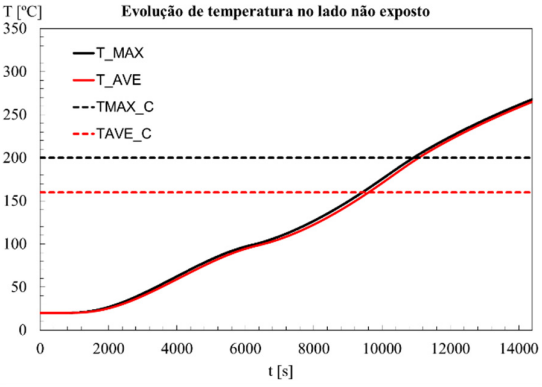
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.0mm

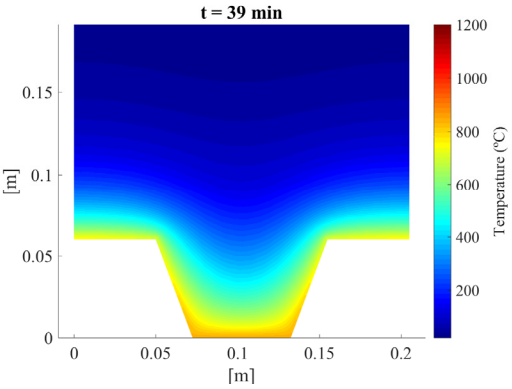


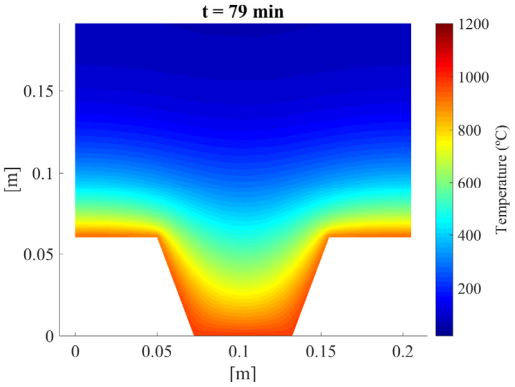
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.2mm

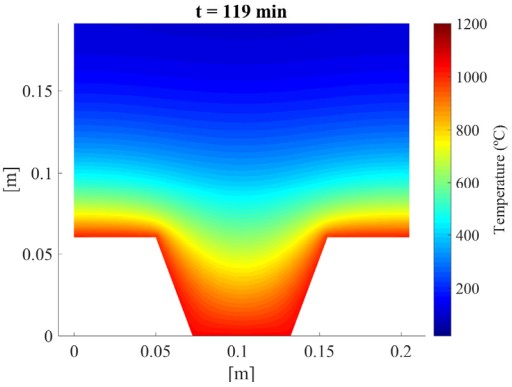


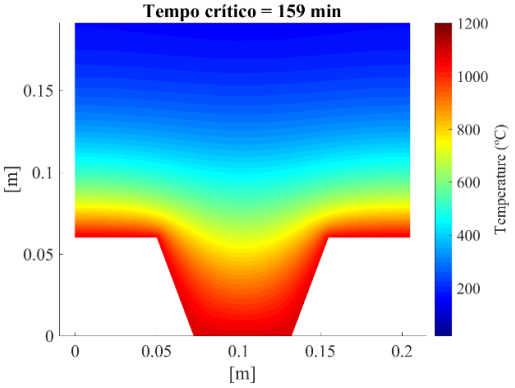


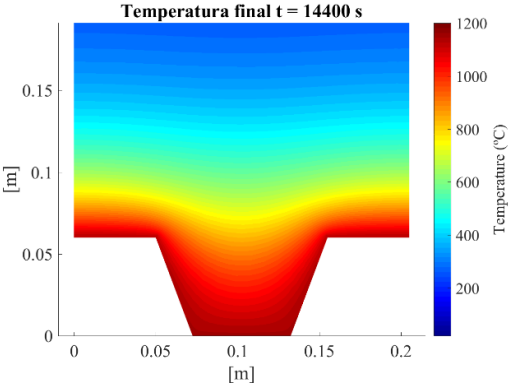




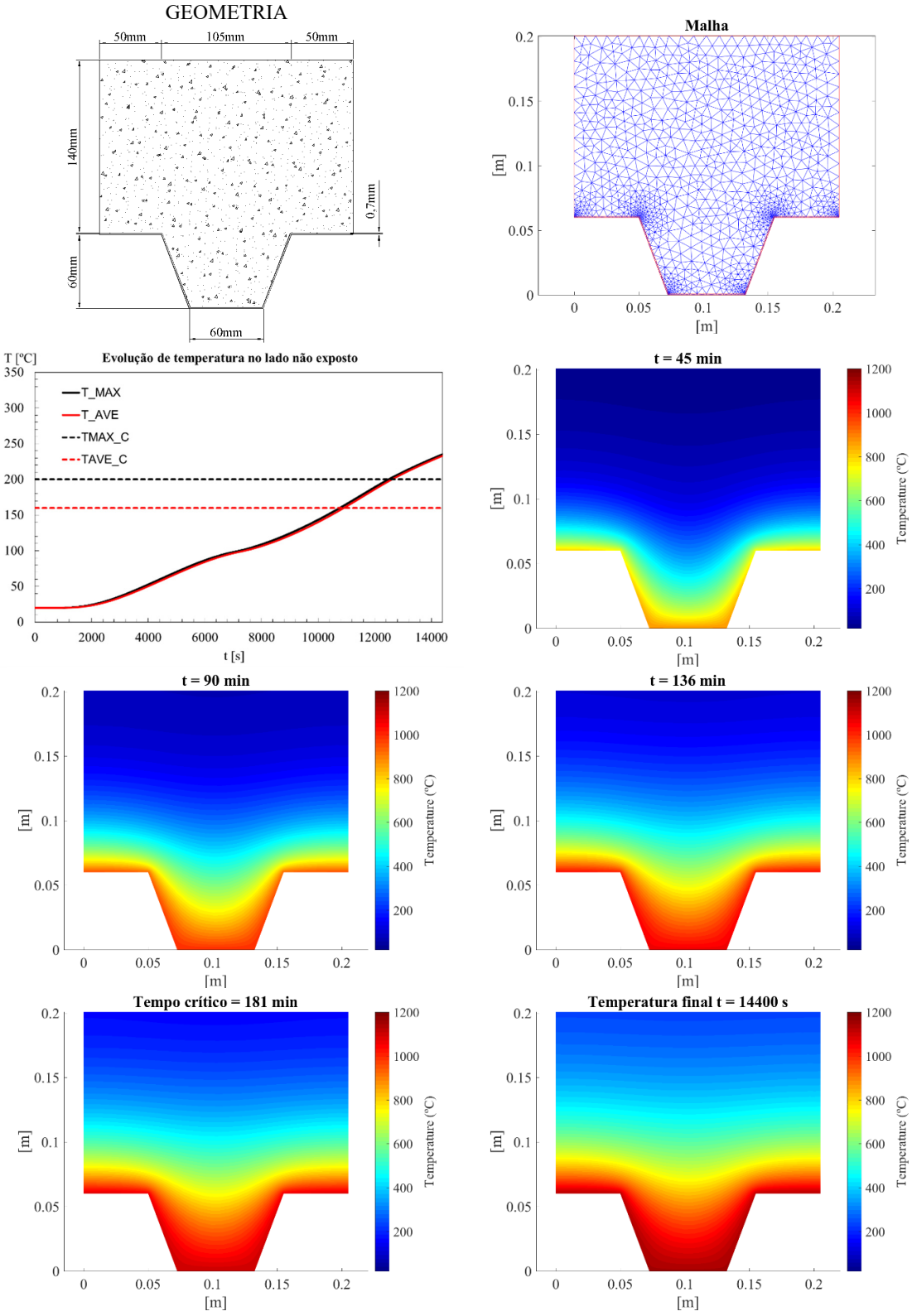








LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.7mm



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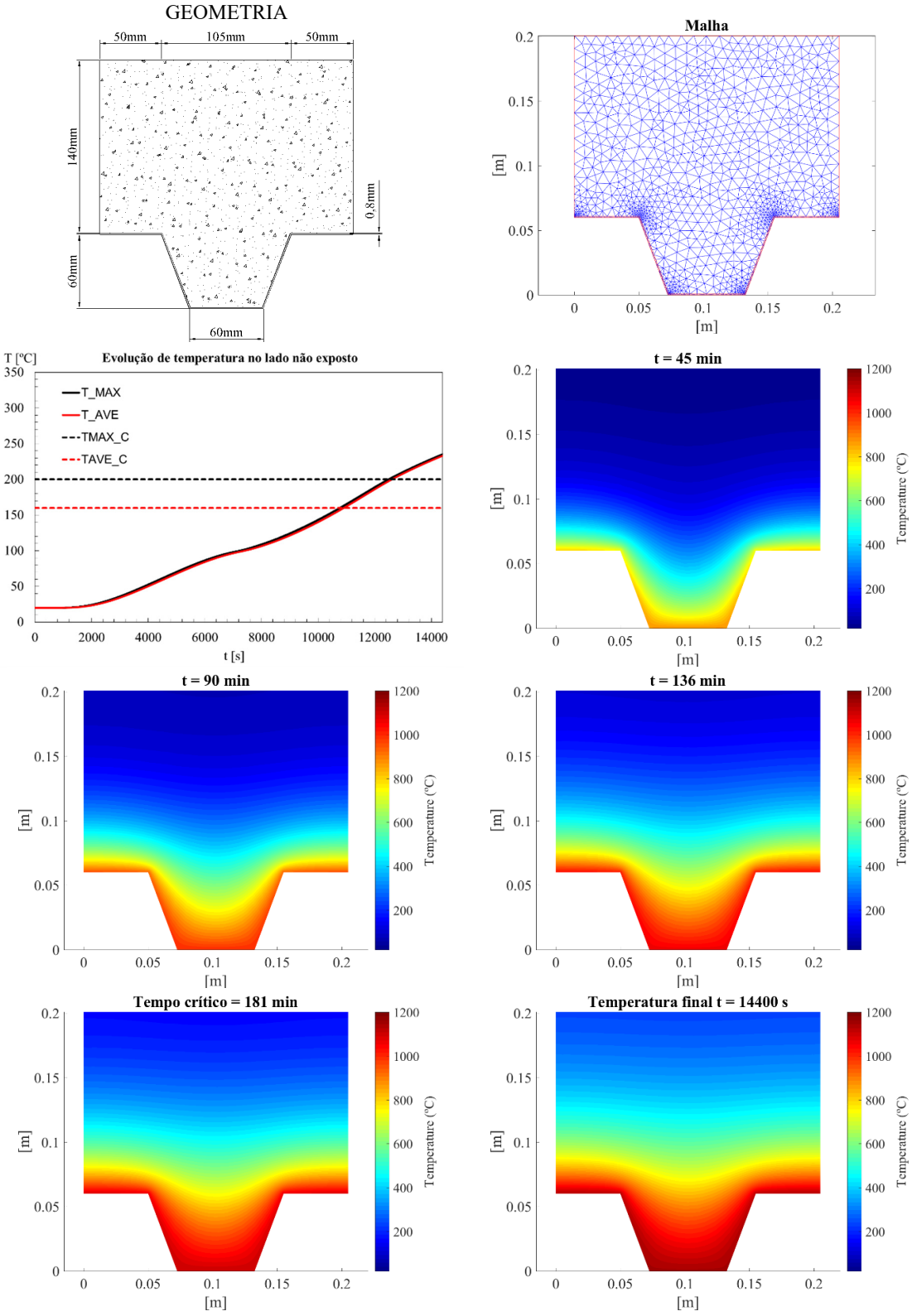
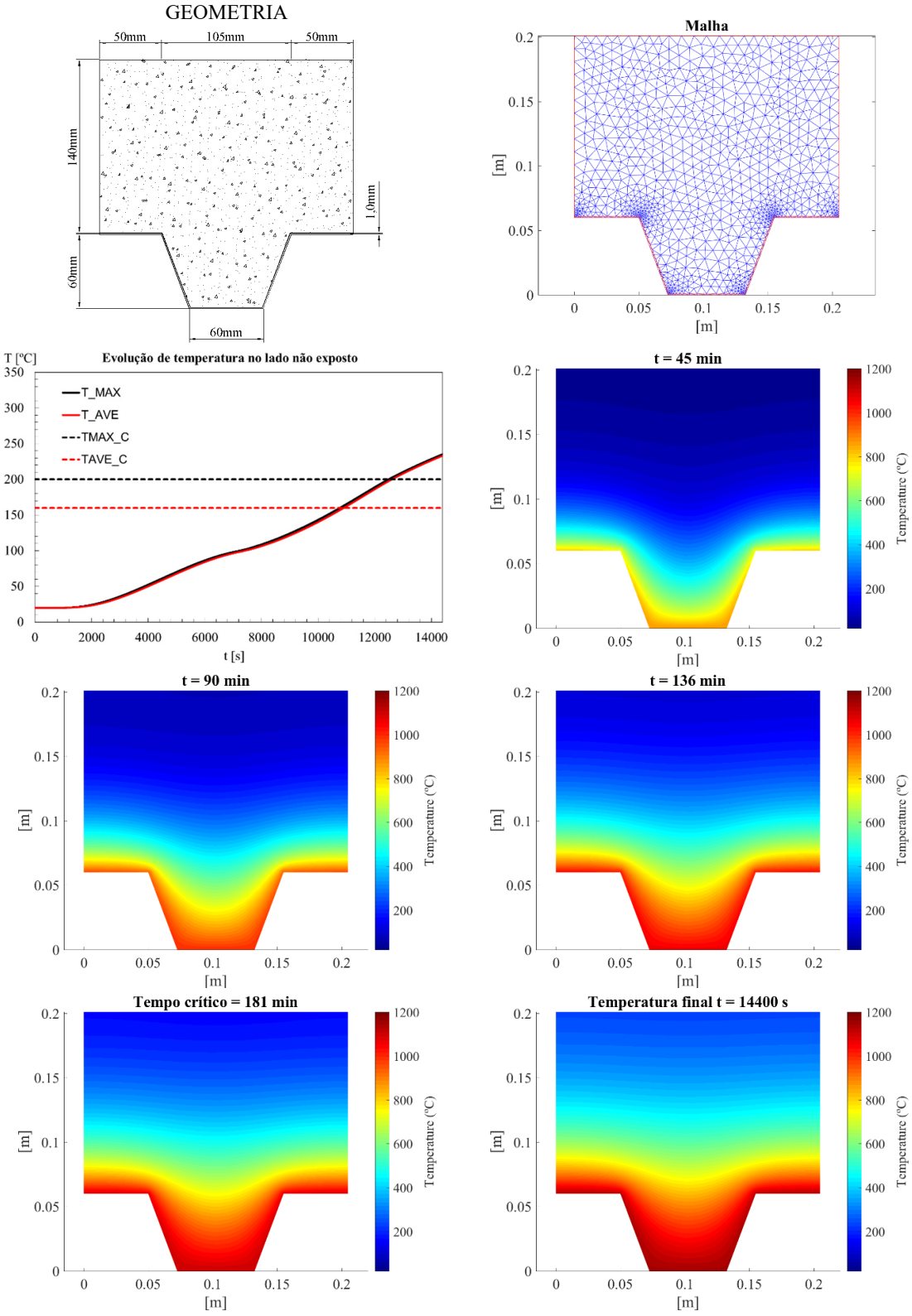
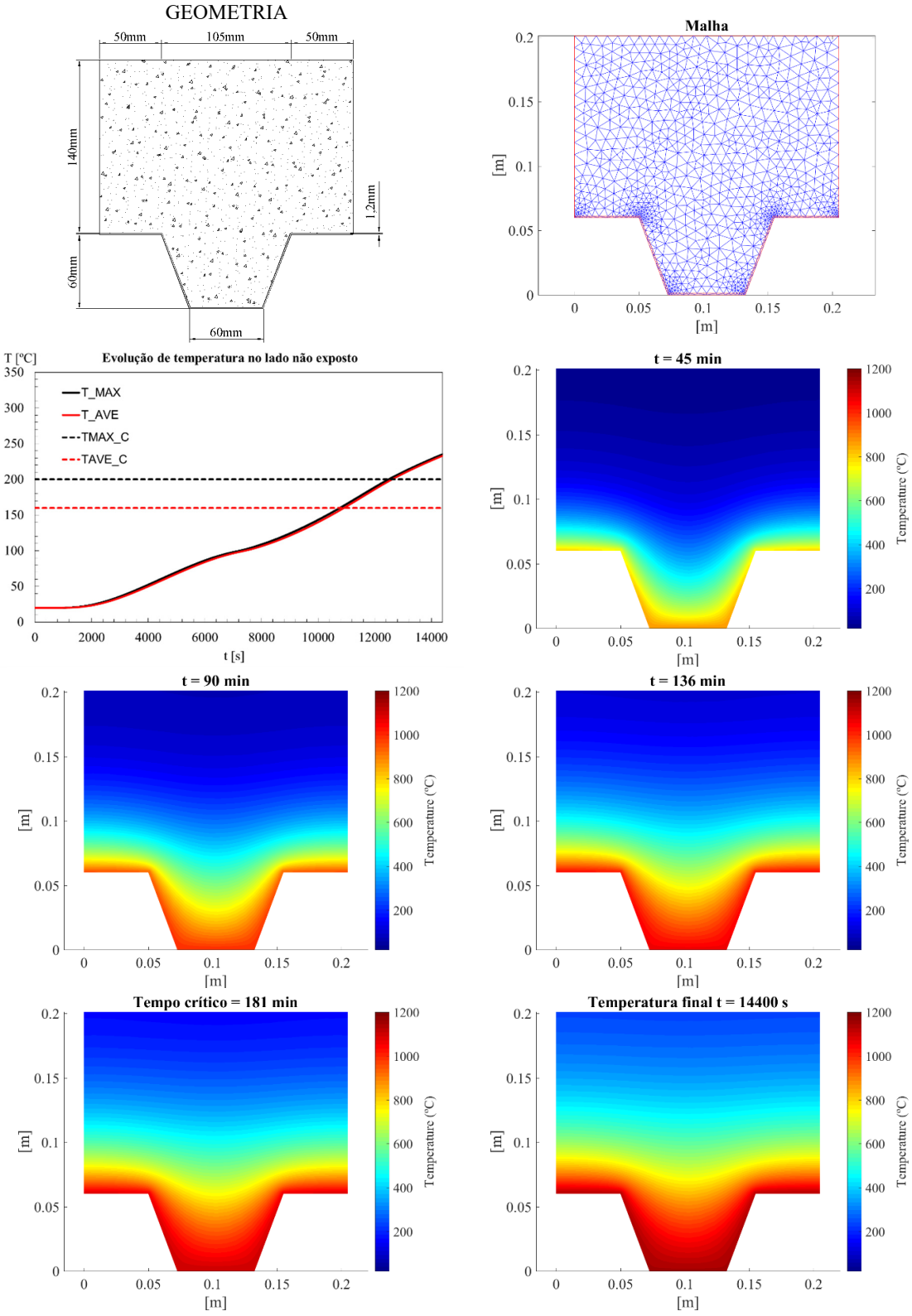


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.0mm

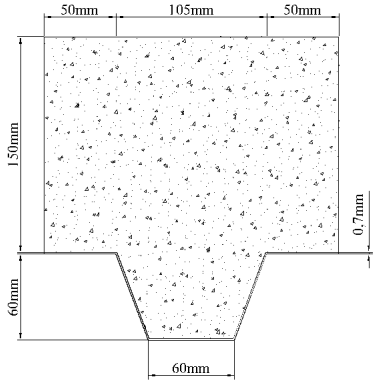


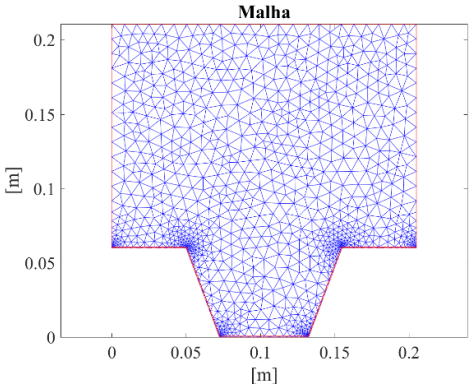
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.2mm

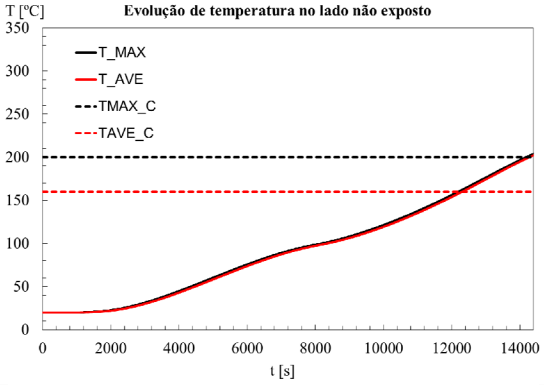


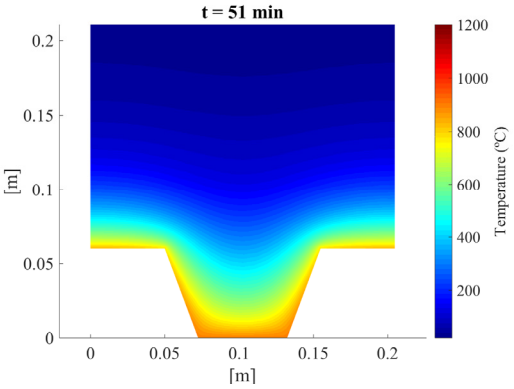
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.7mm

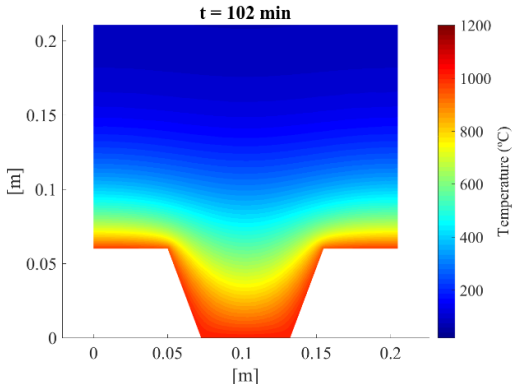
GEOMETRIA

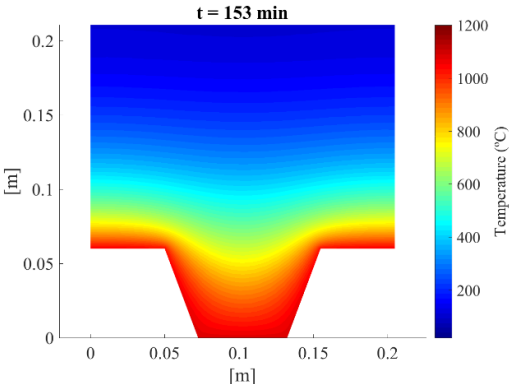


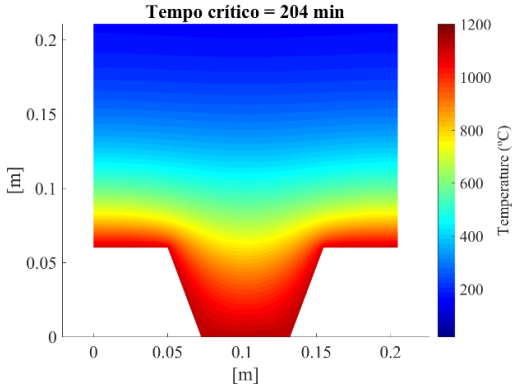


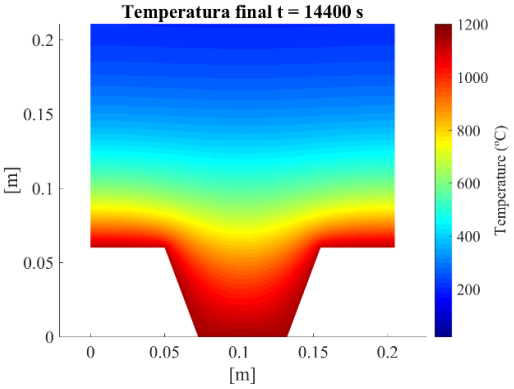




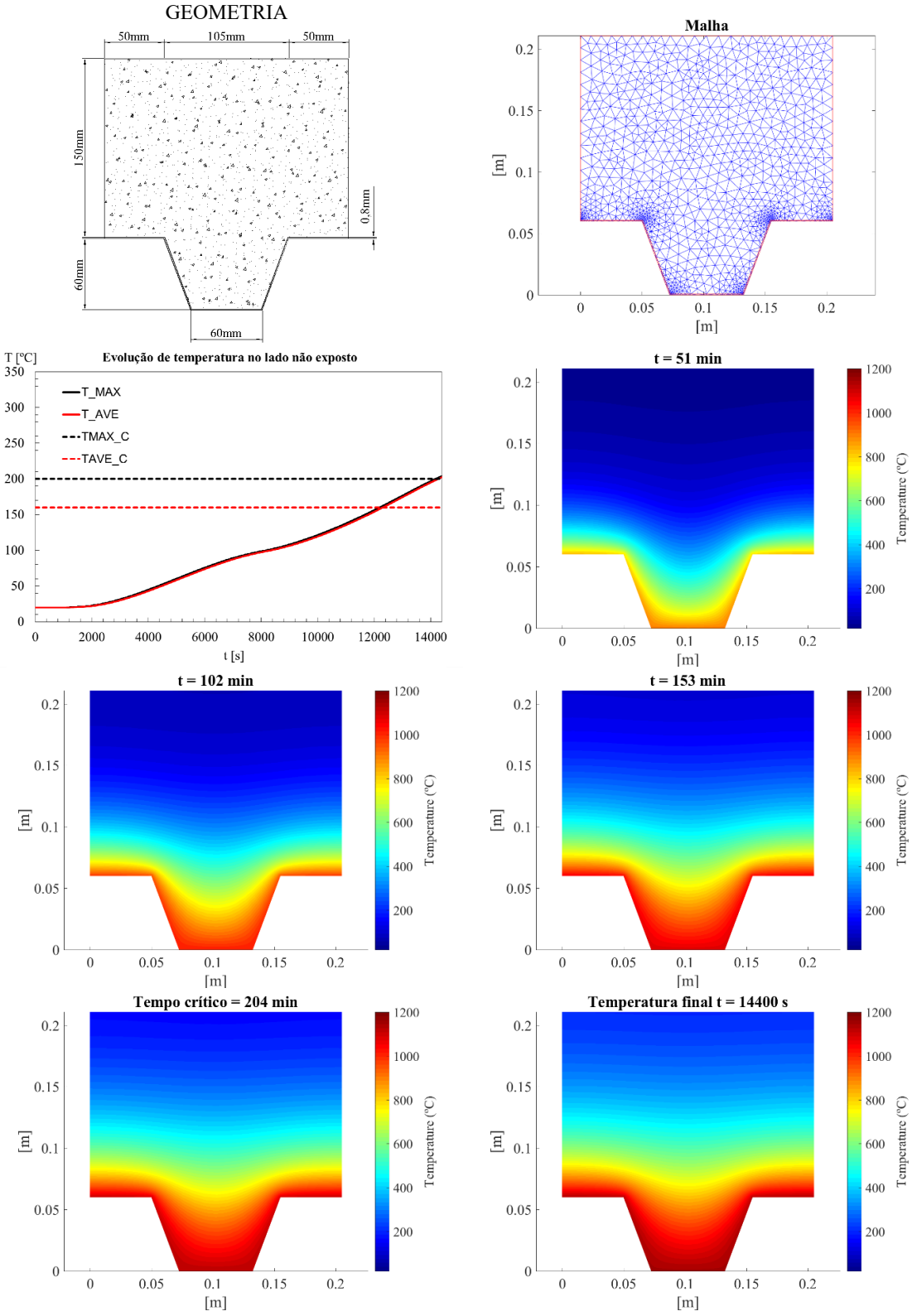




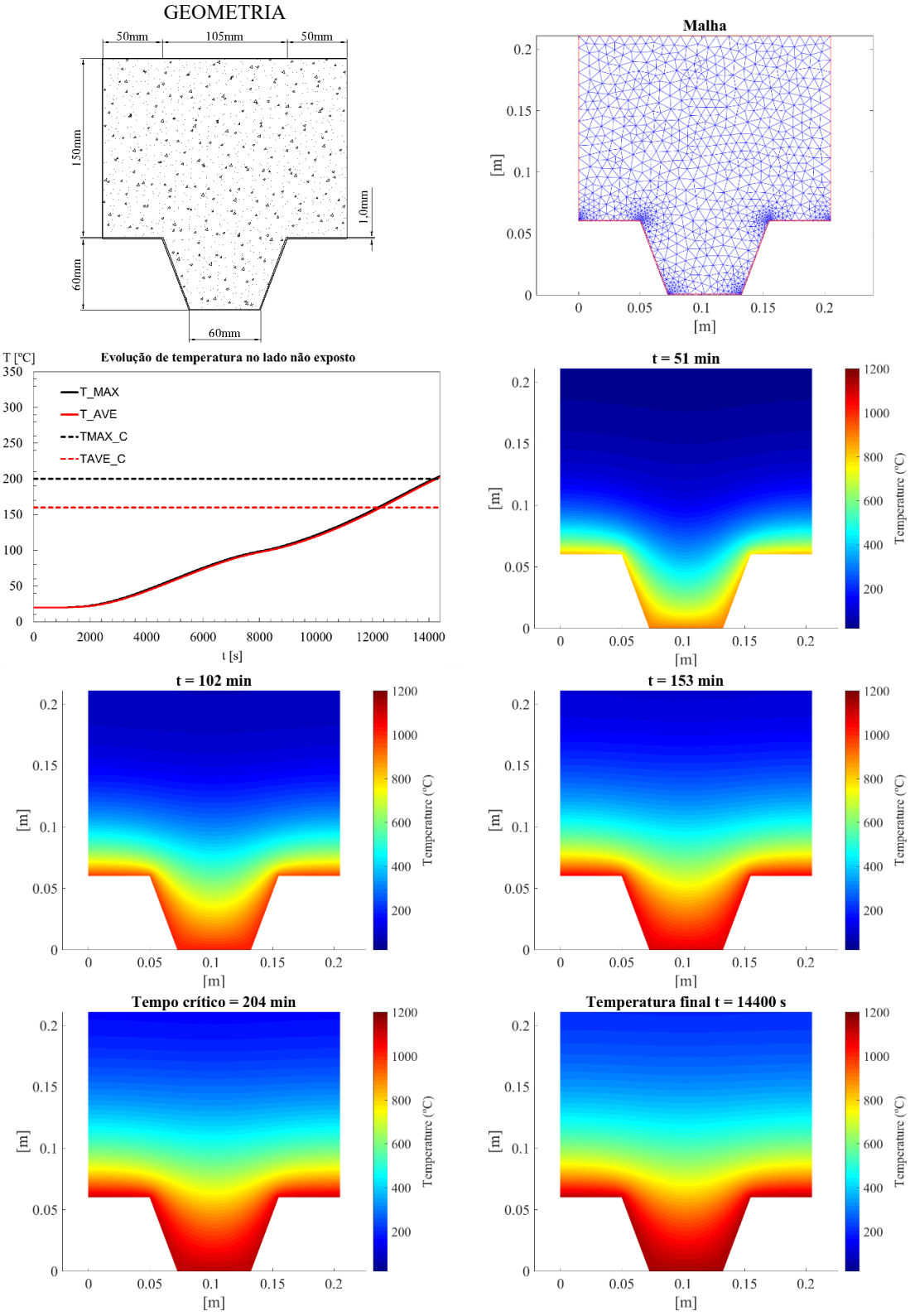




LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.8mm

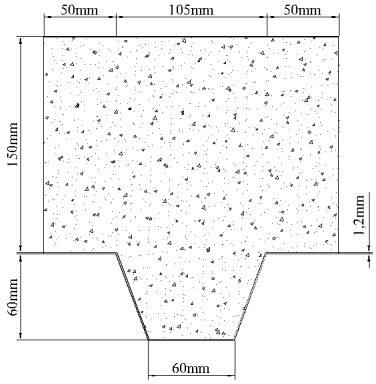


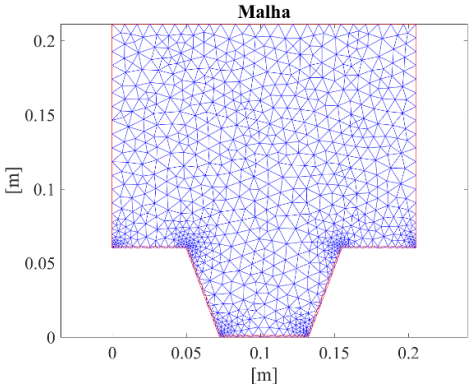
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.0mm

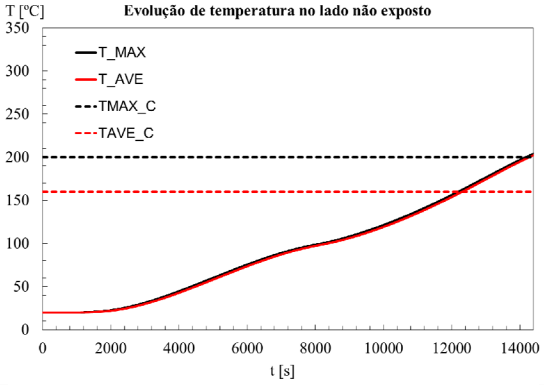


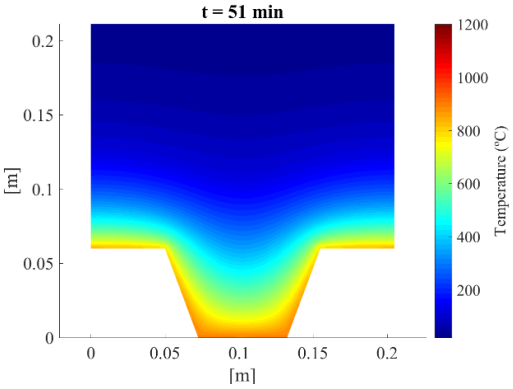
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.2mm

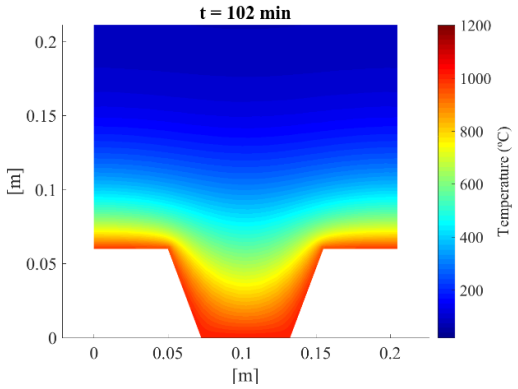
GEOMETRIA

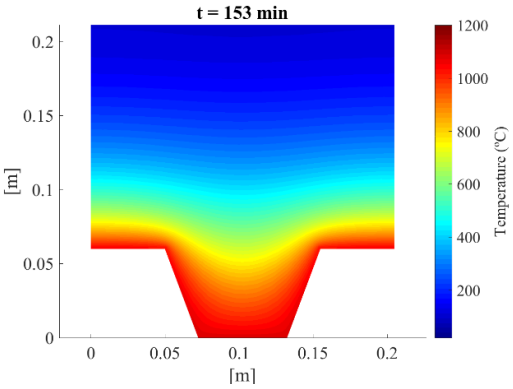


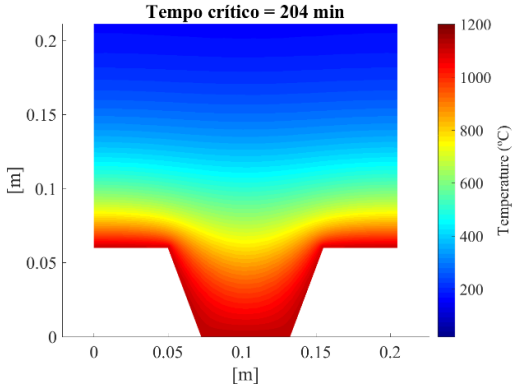


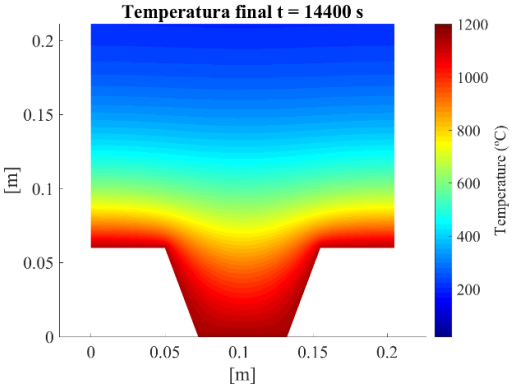




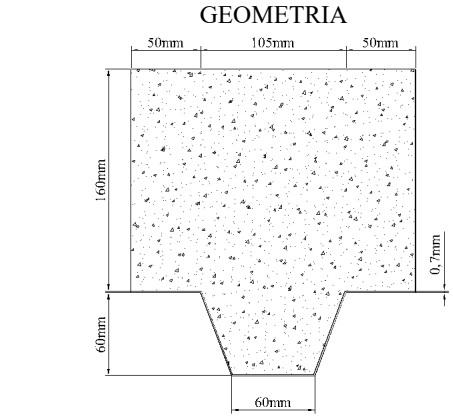


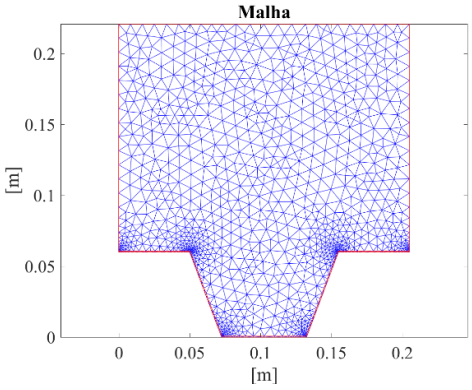


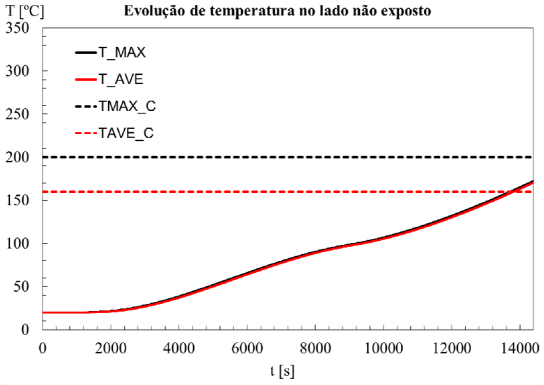


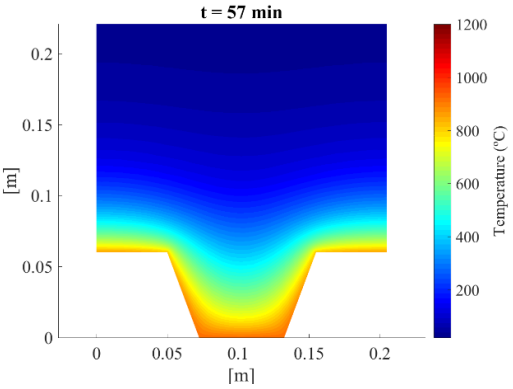


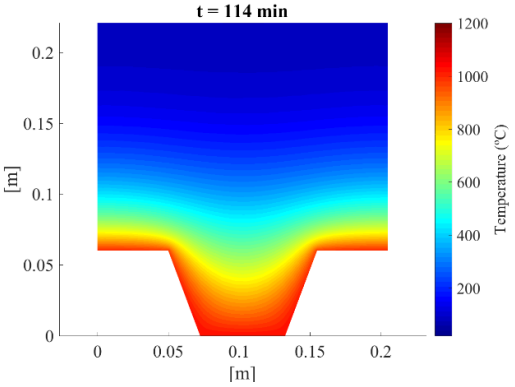
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.7mm

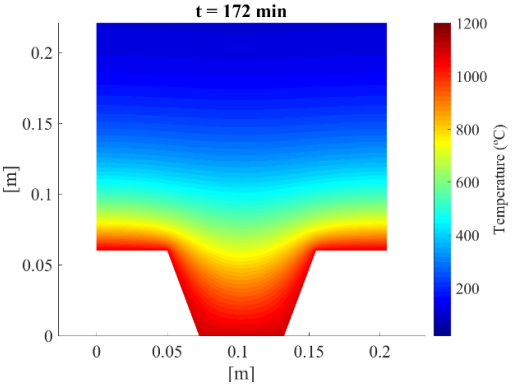


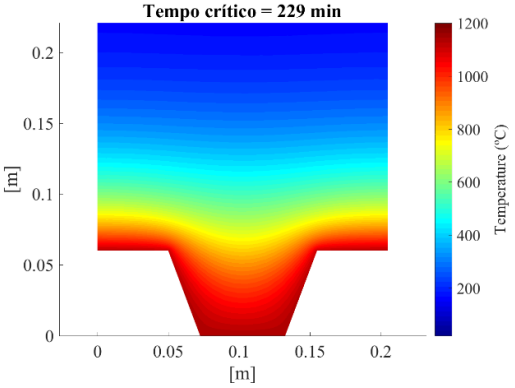


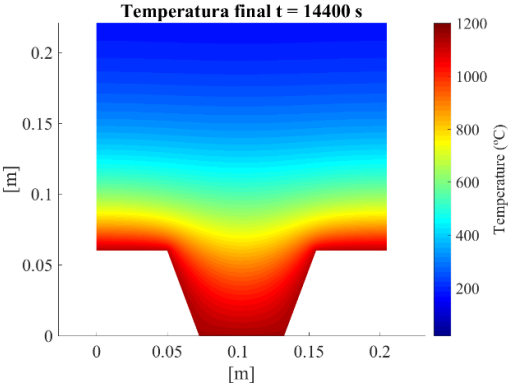




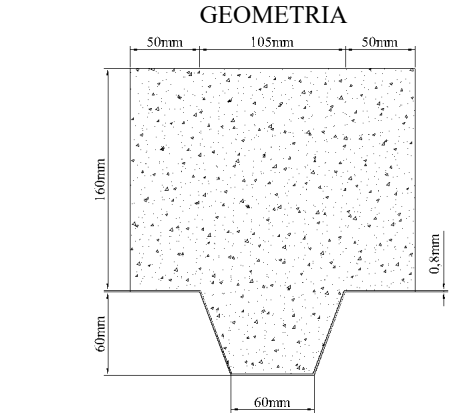


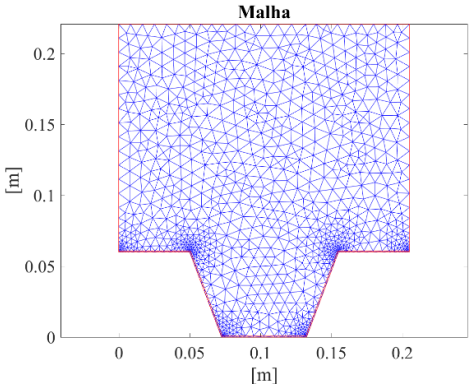


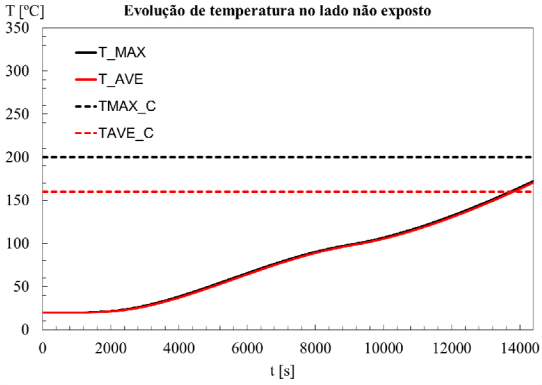


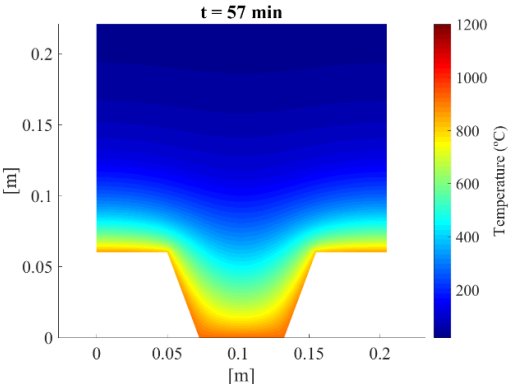


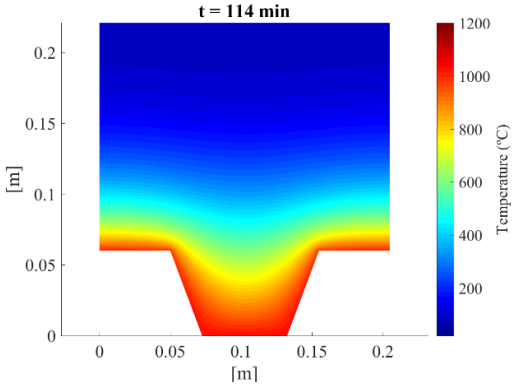
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.8mm

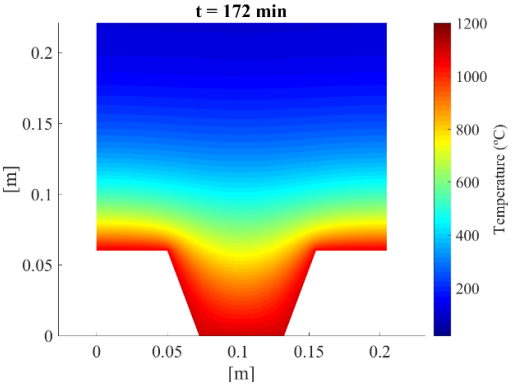


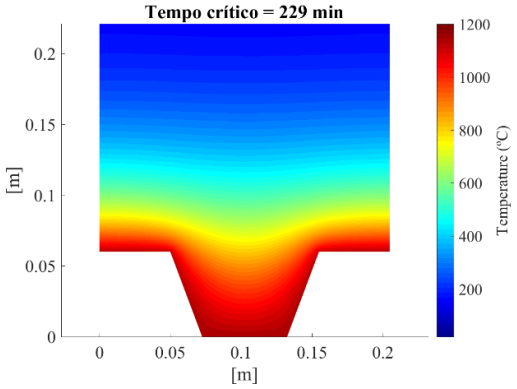


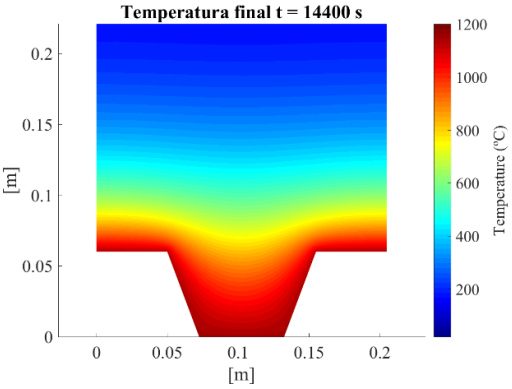




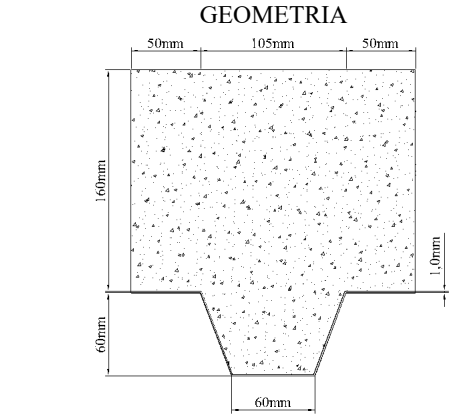


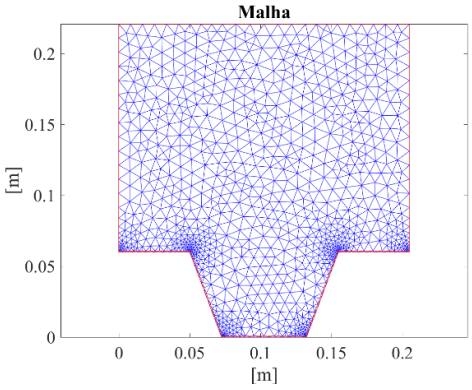


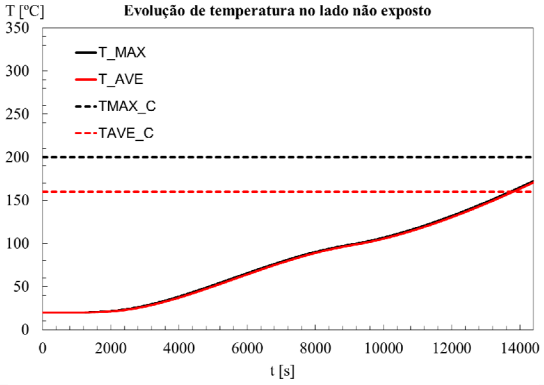


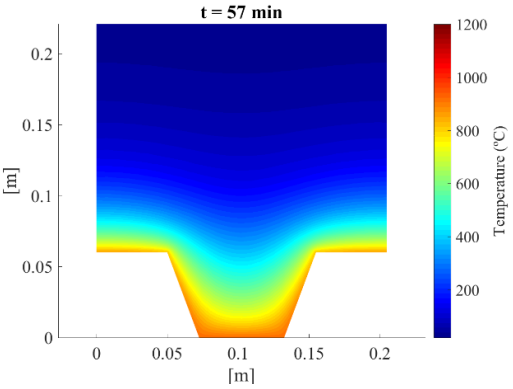


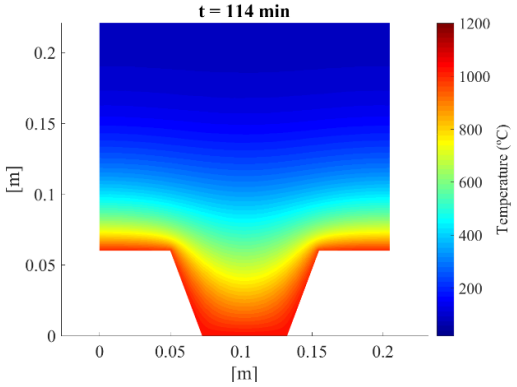
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.0mm

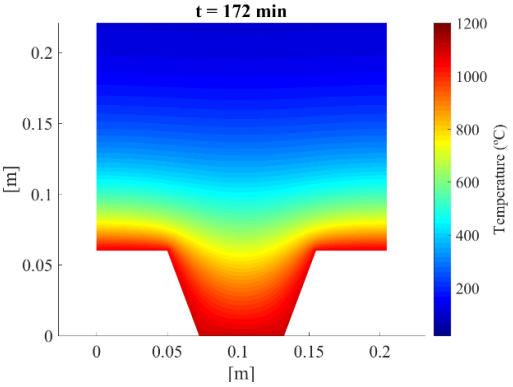


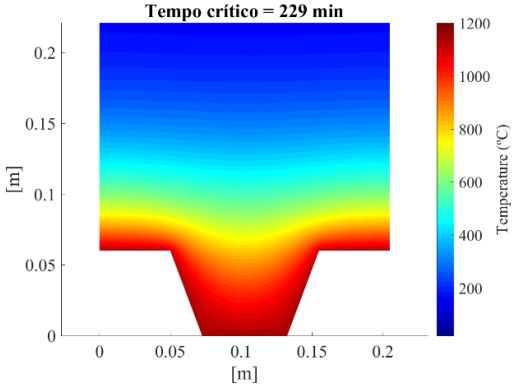


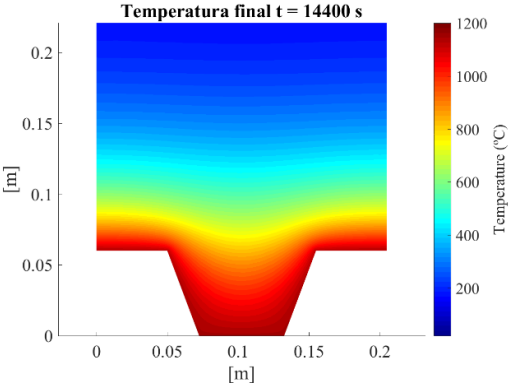




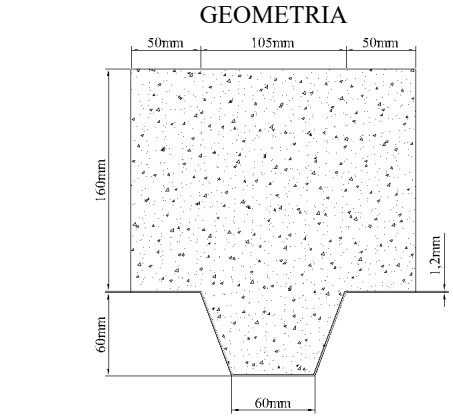


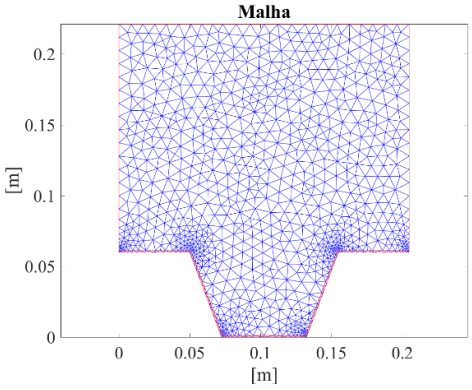


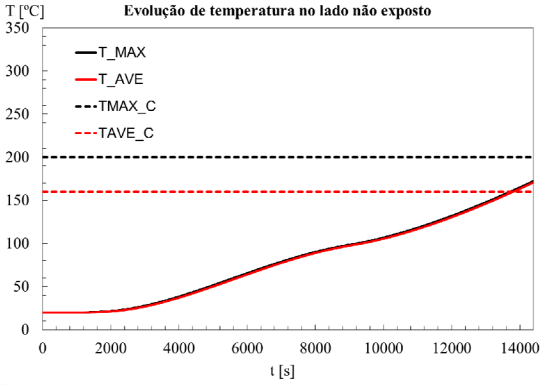


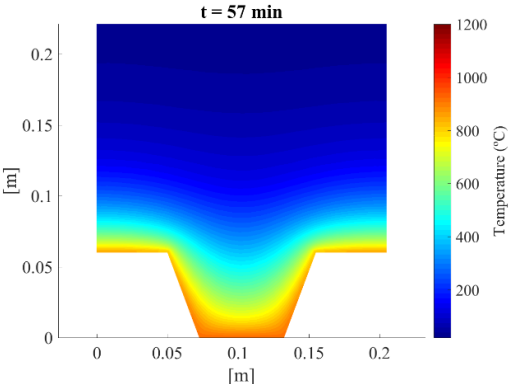


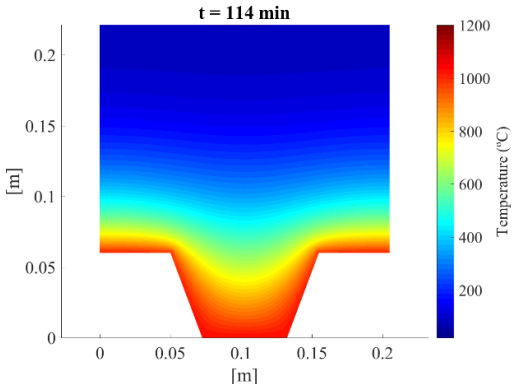
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.2mm

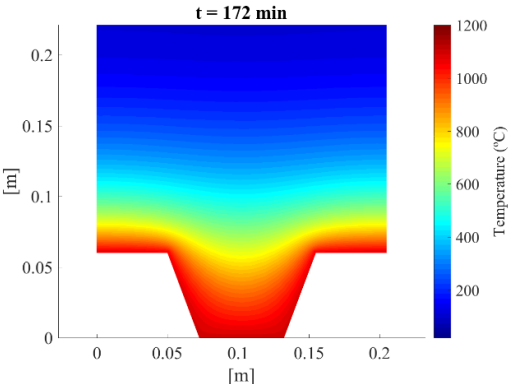


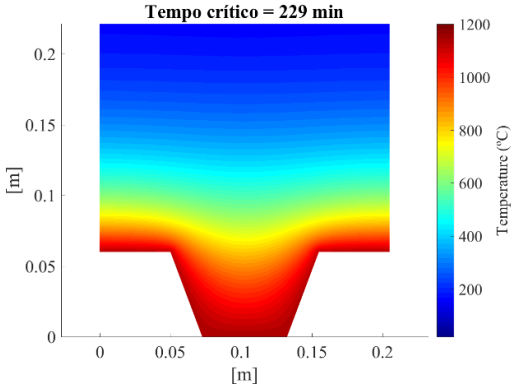


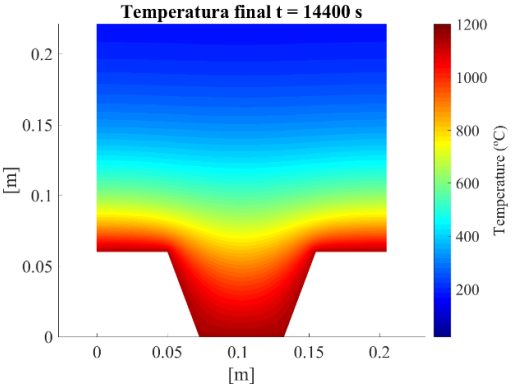




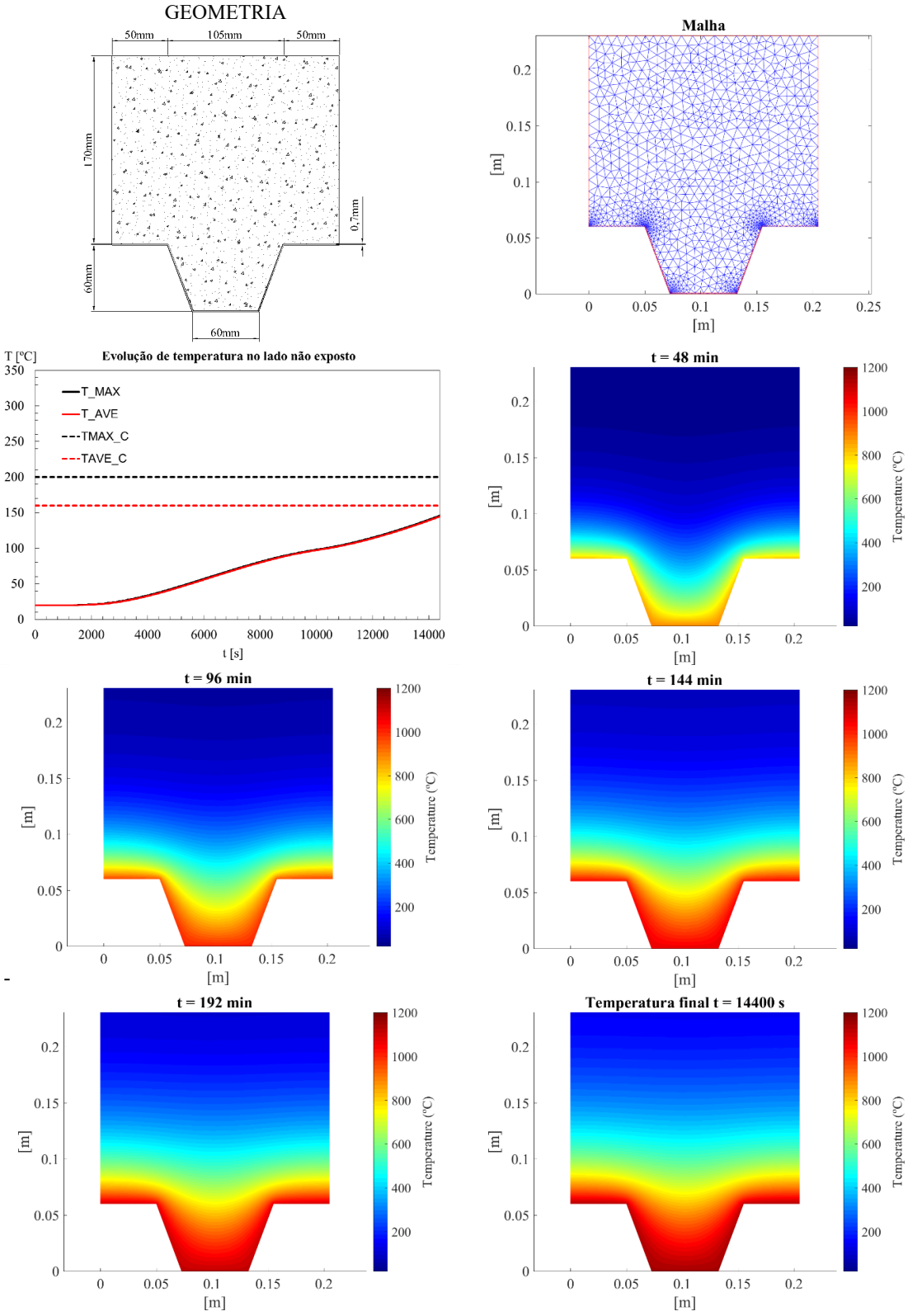




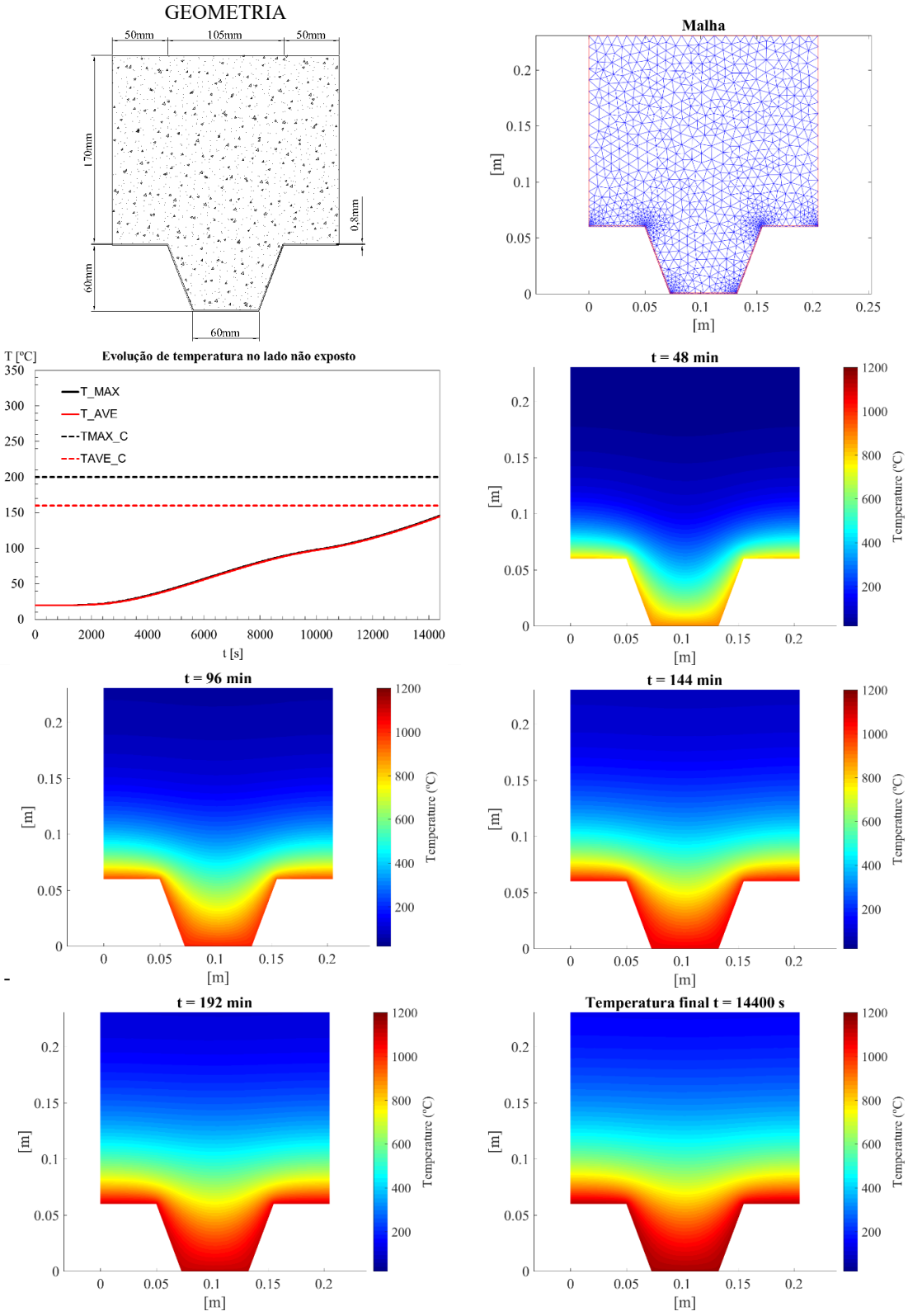




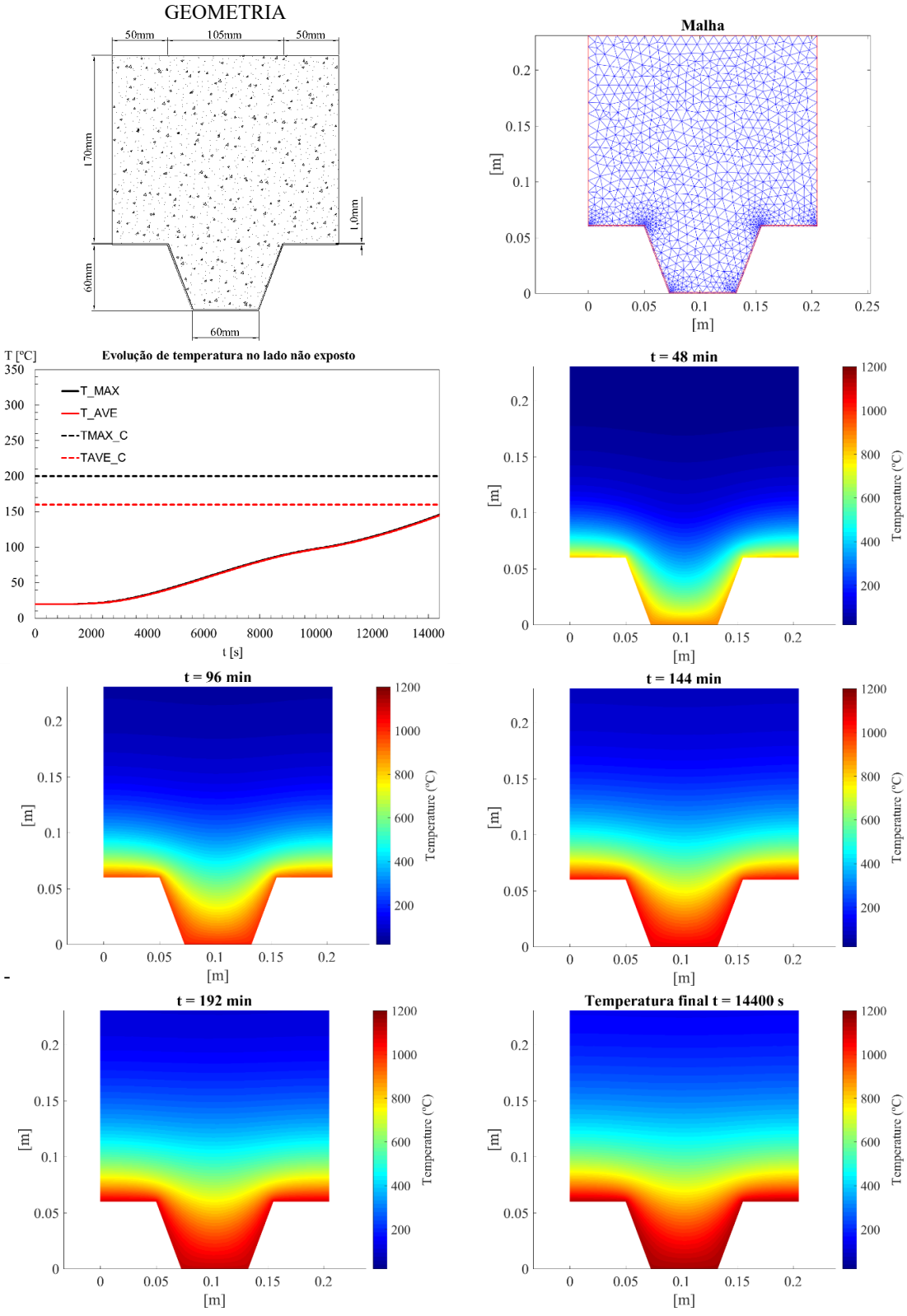
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.7mm



LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.8mm



LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.0mm



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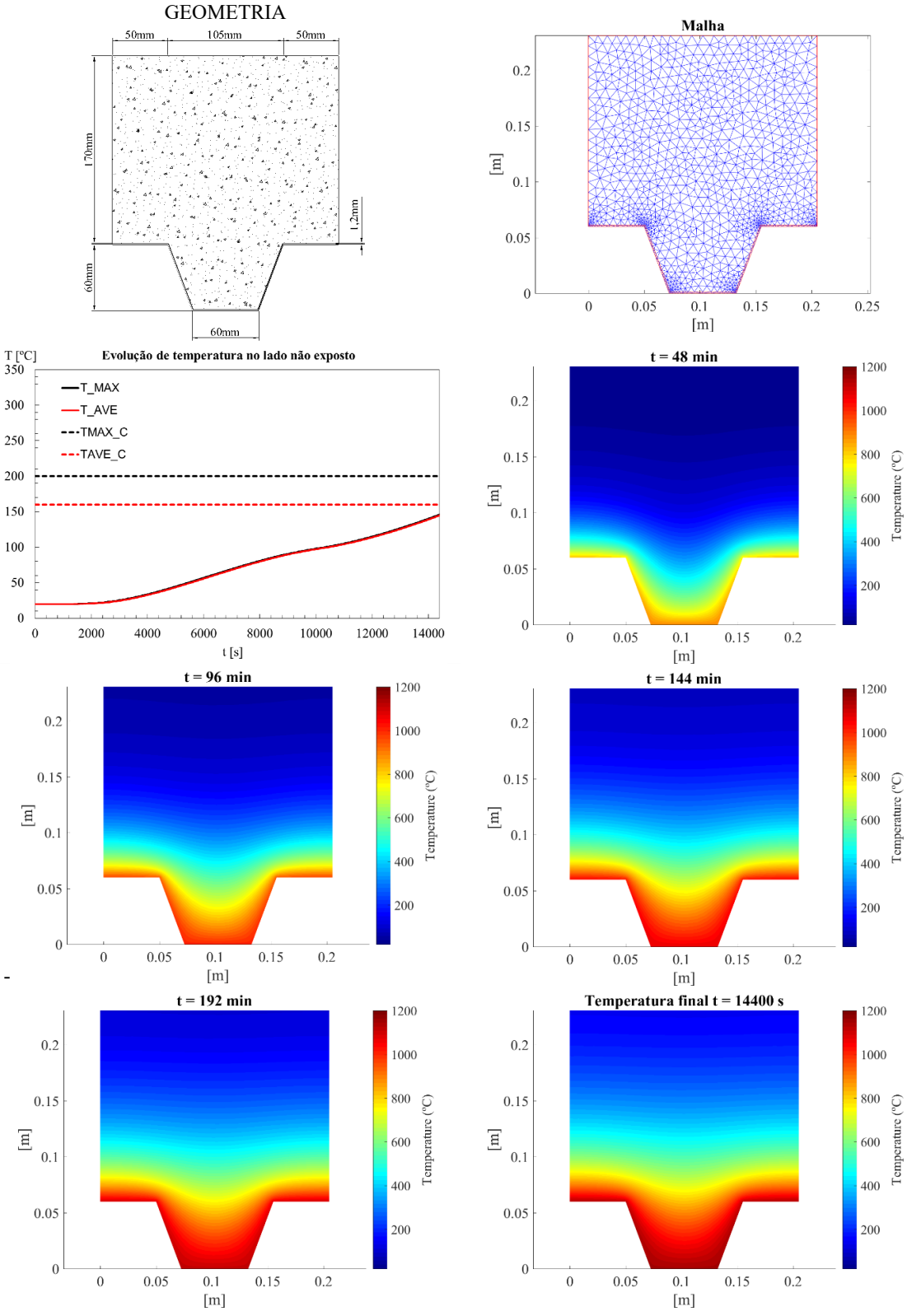

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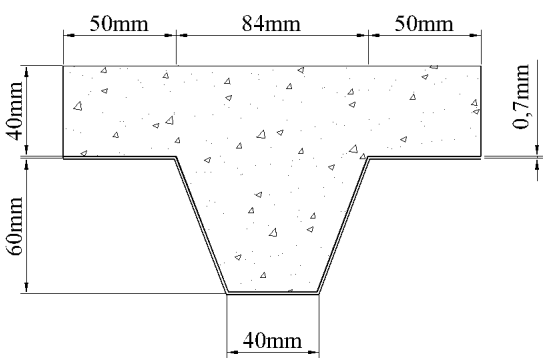
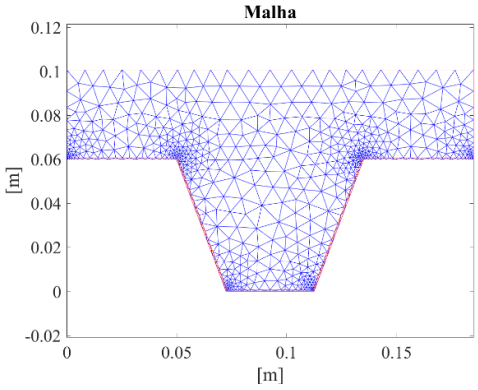
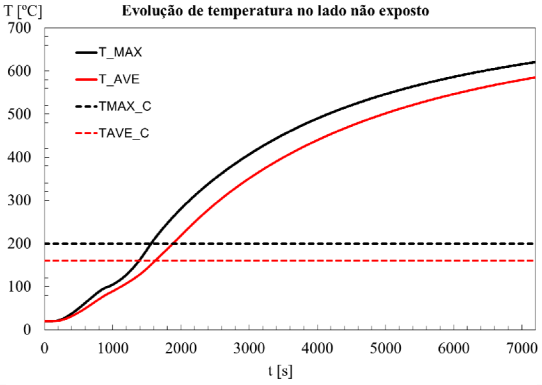
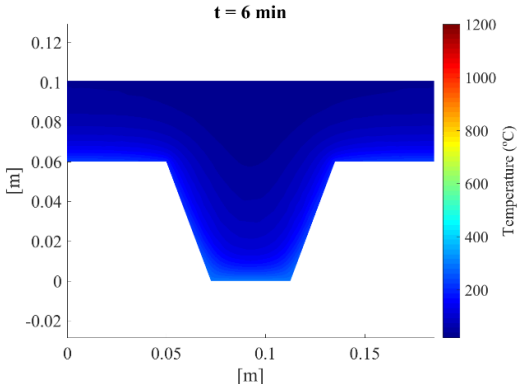
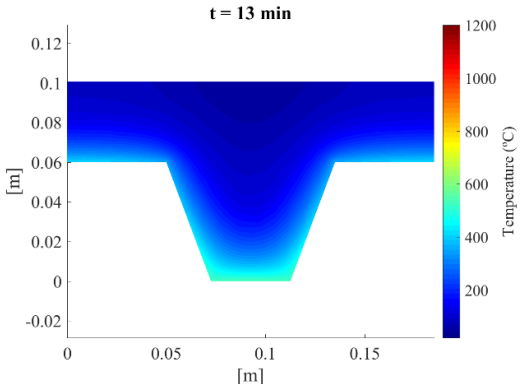
GEOMETRIA

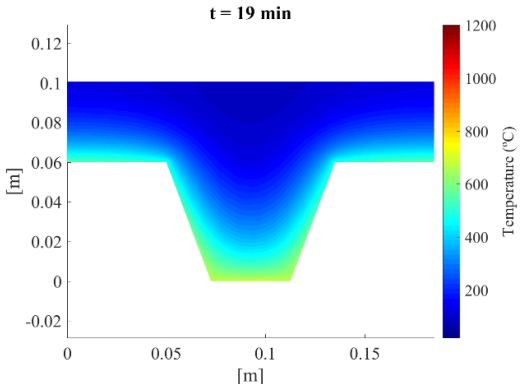


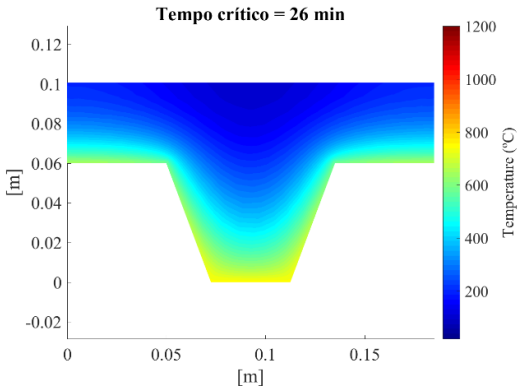


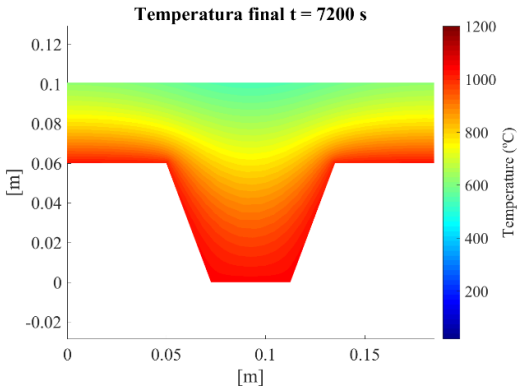






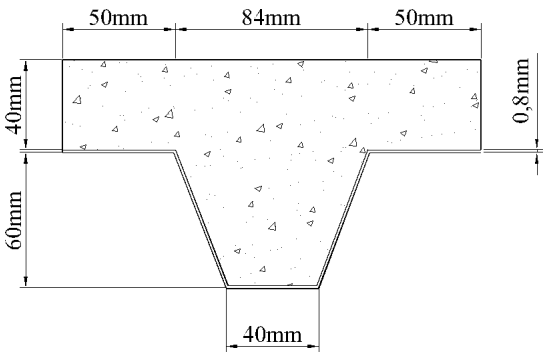


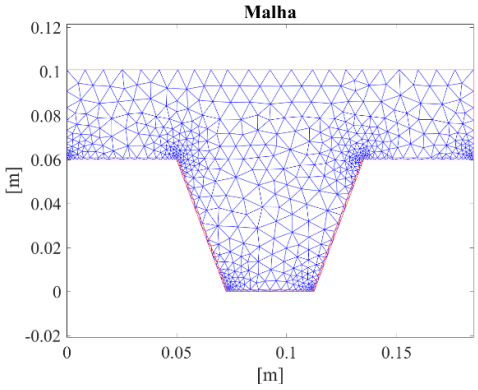


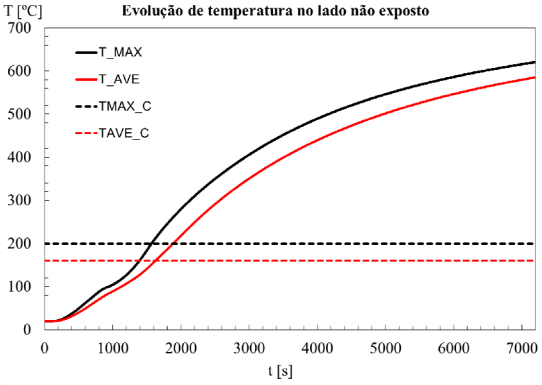


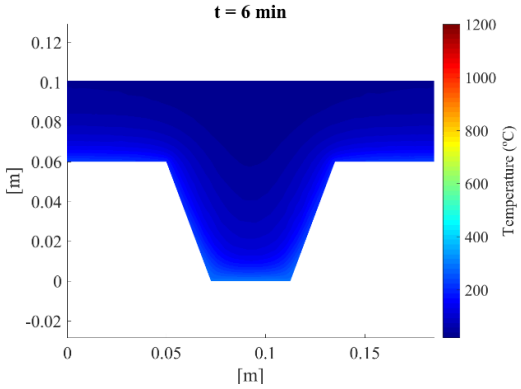
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.8mm

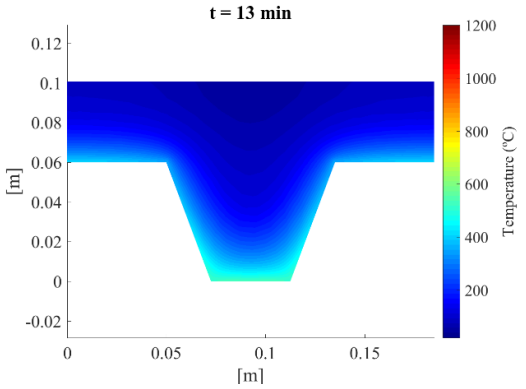
GEOMETRIA

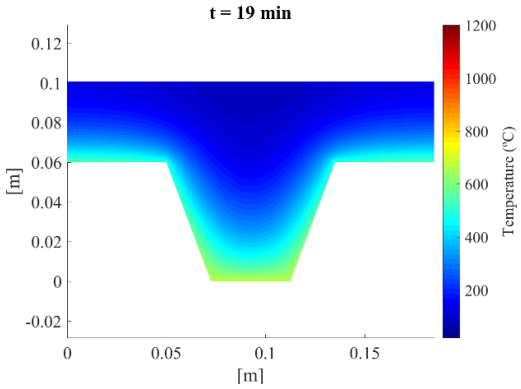


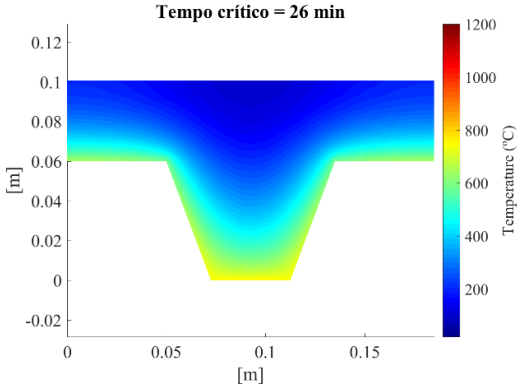


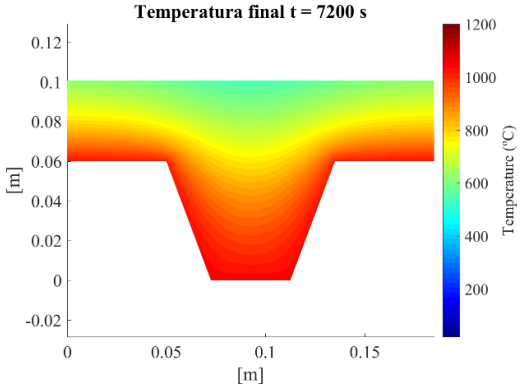






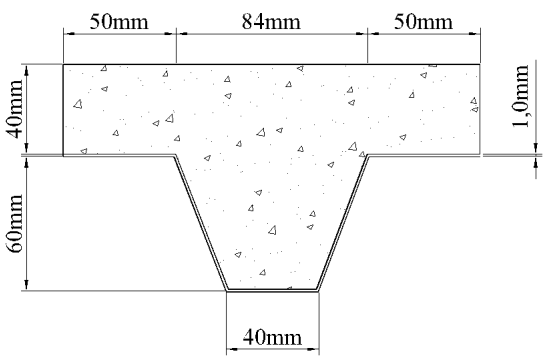


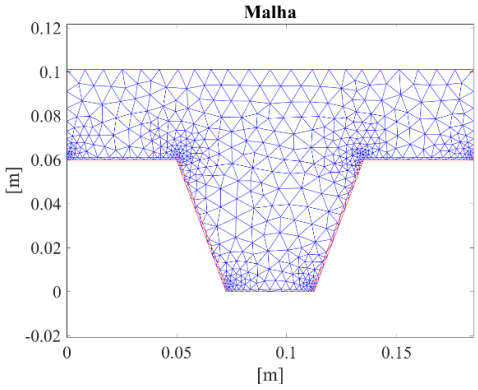


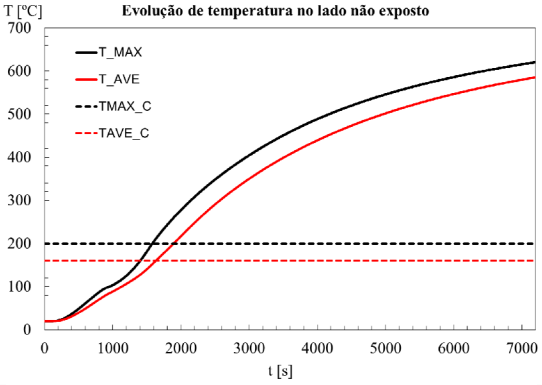


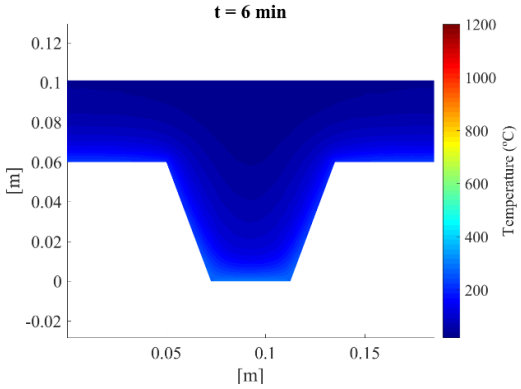
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.0mm

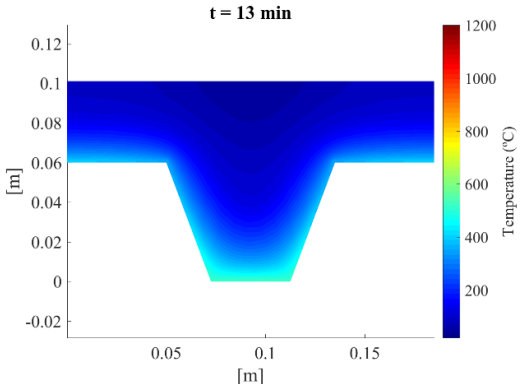
GEOMETRIA

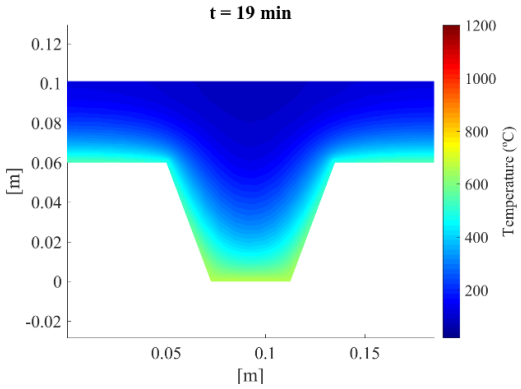


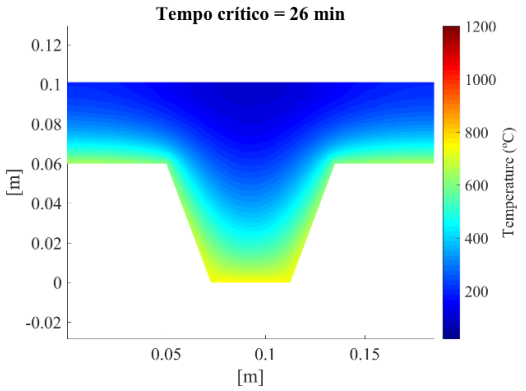


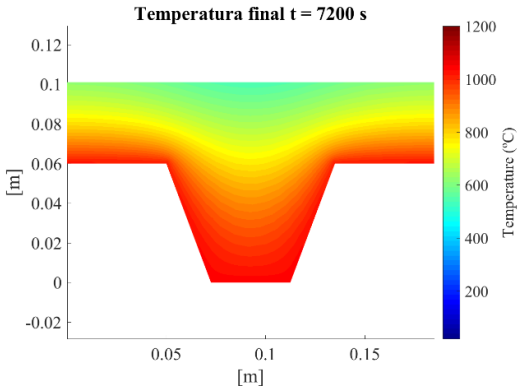




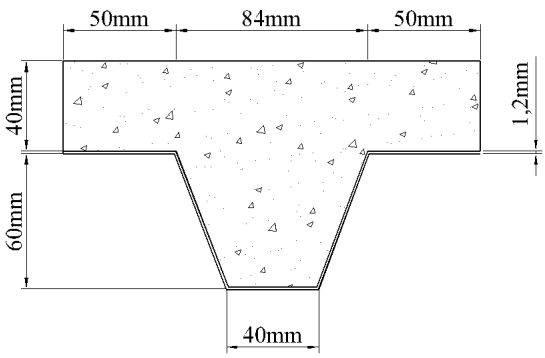


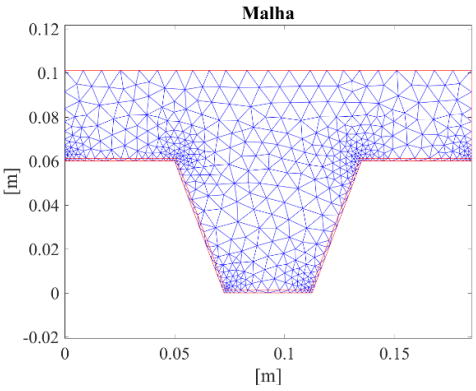


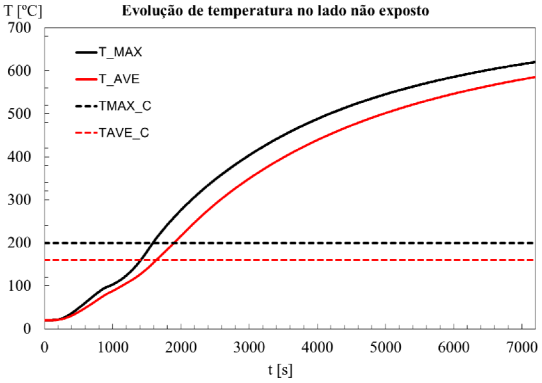


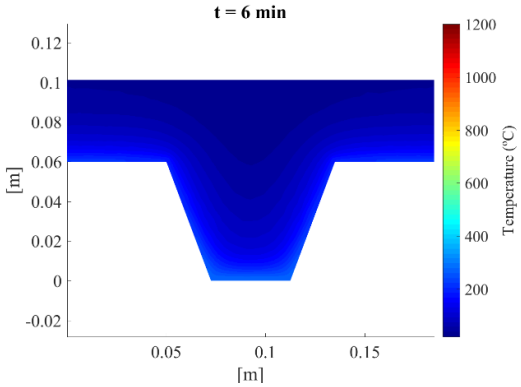


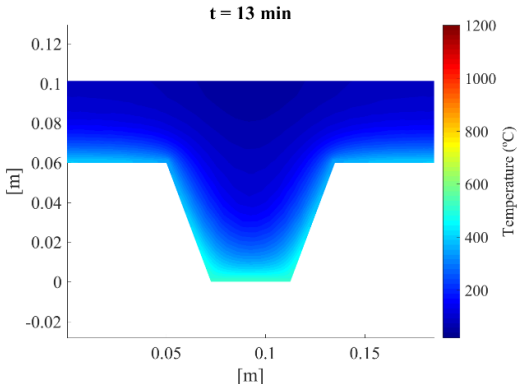
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.2mm

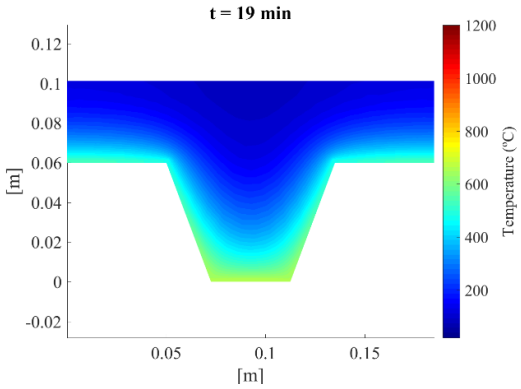


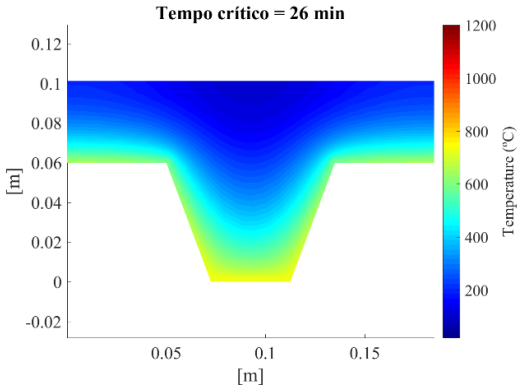


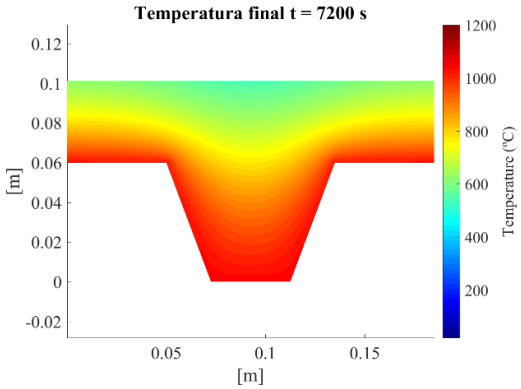






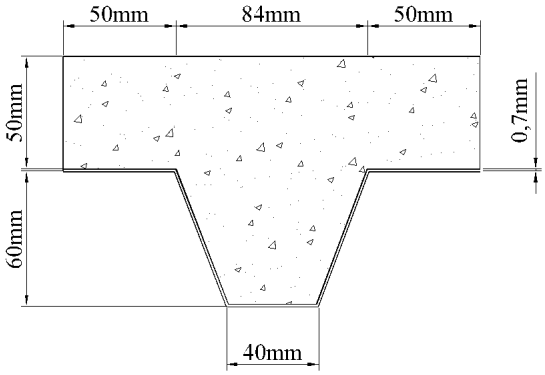


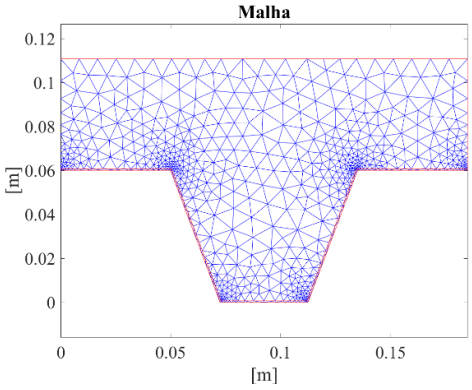


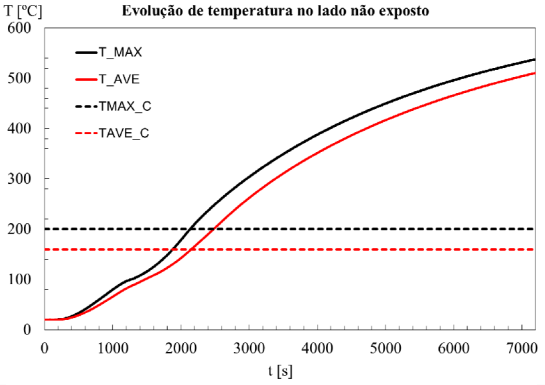


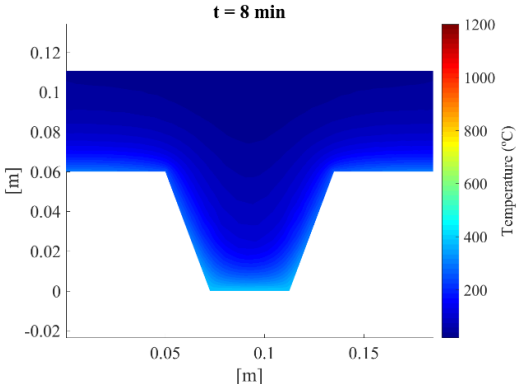
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.7mm

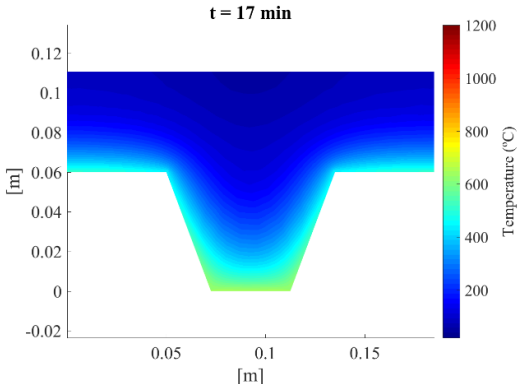
GEOMETRIA

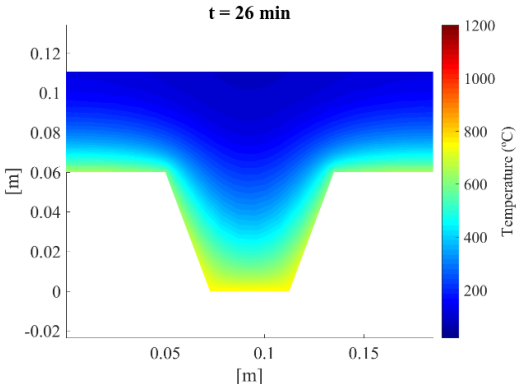


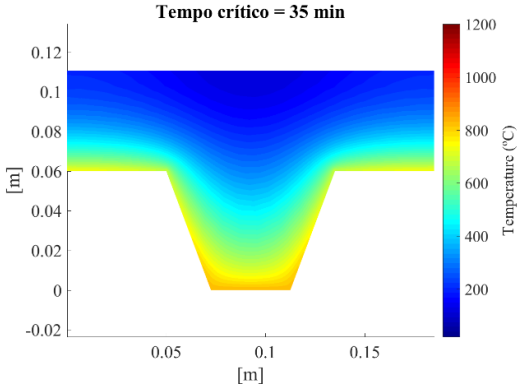


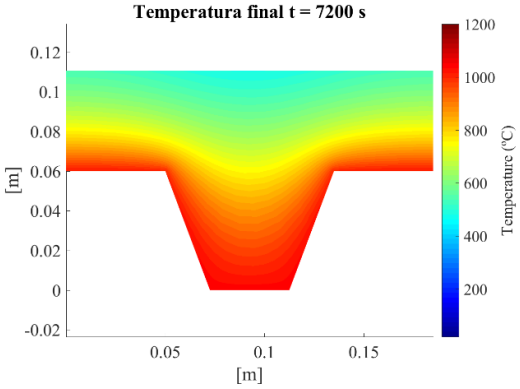






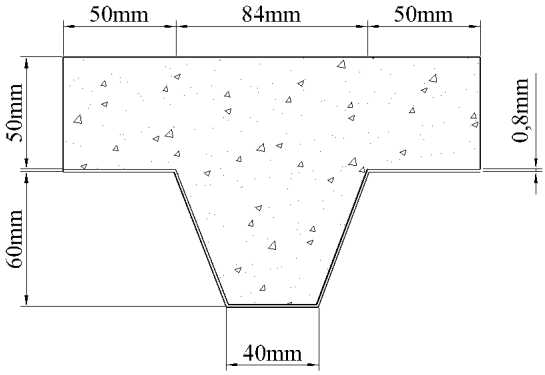


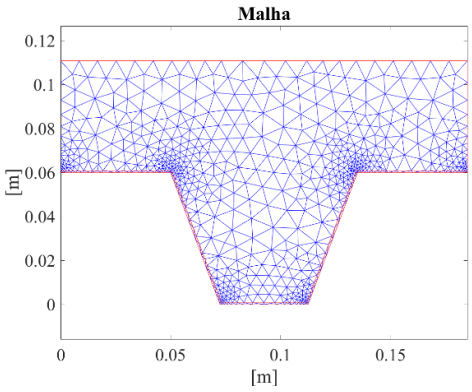


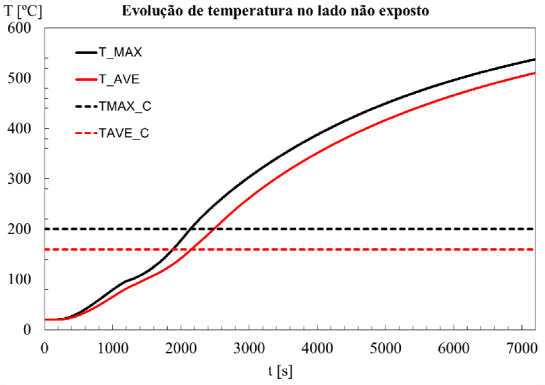


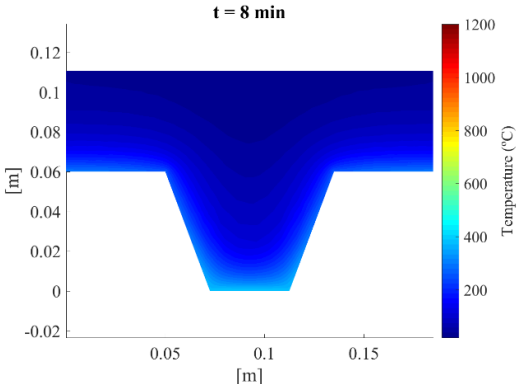
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.8mm

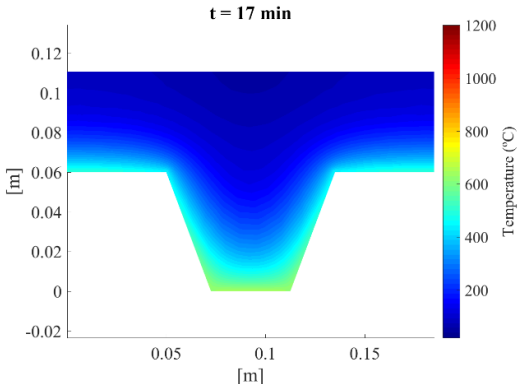
GEOMETRIA

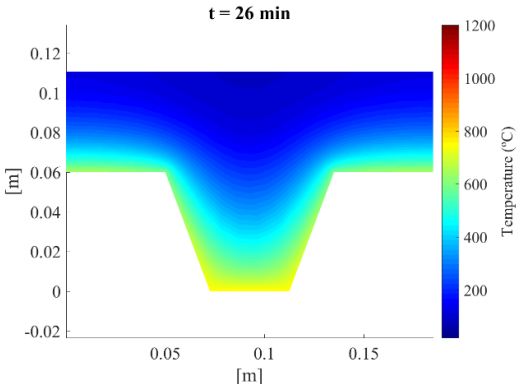


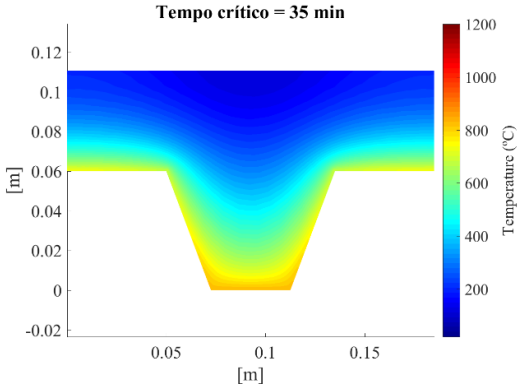


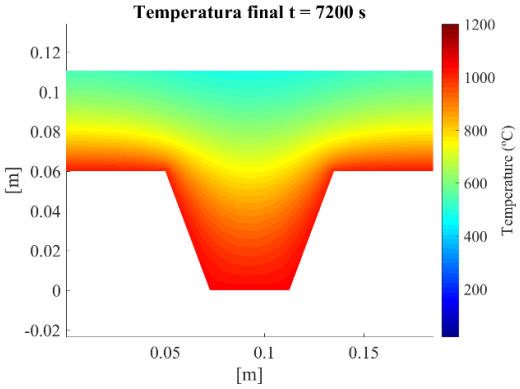




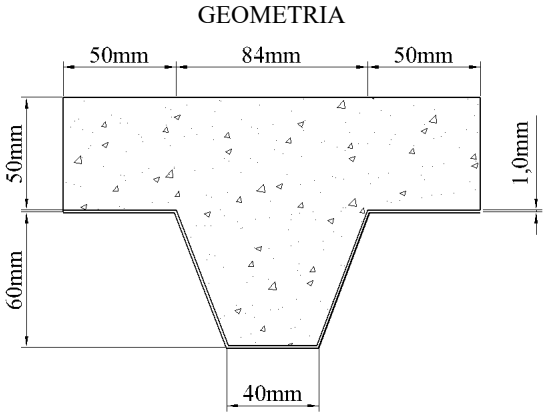


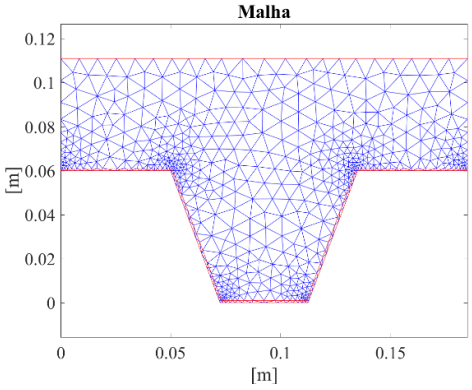


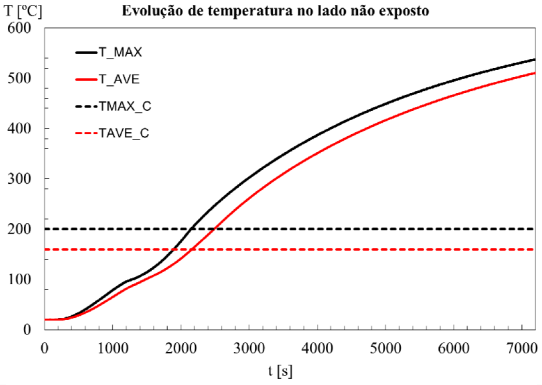


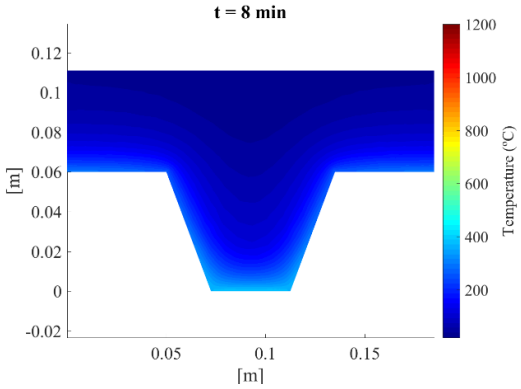


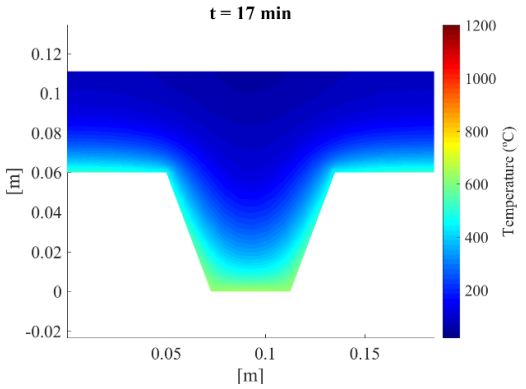
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.0mm

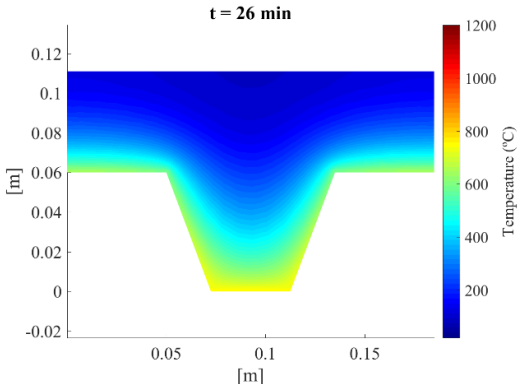


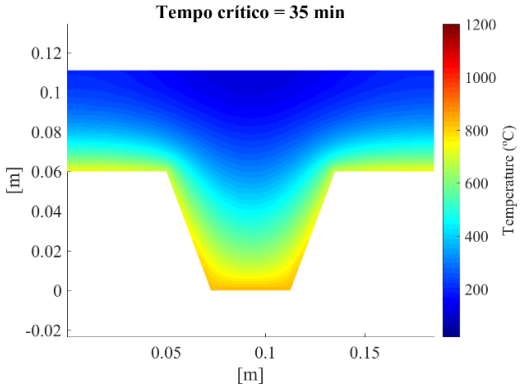


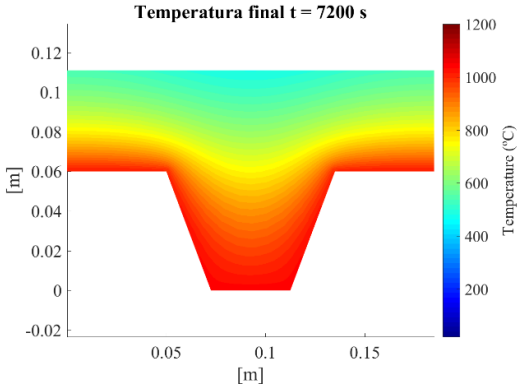




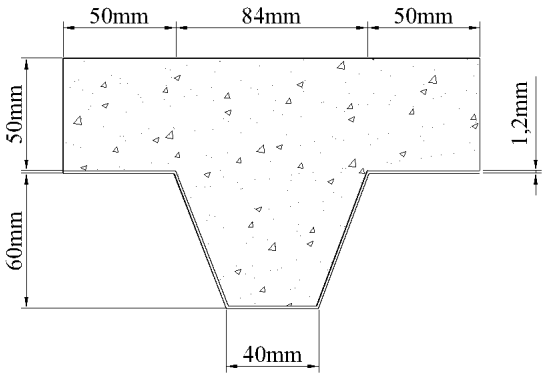


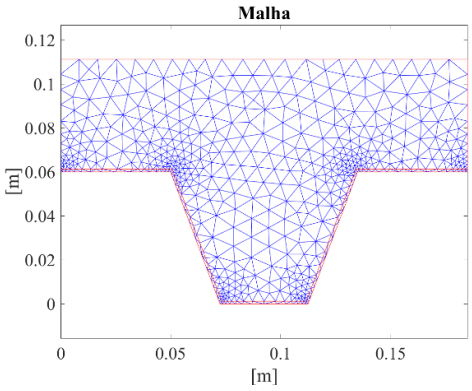


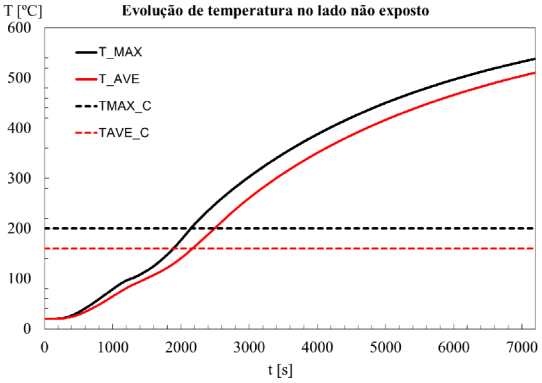


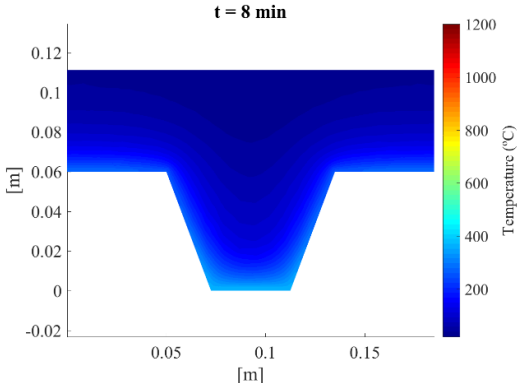


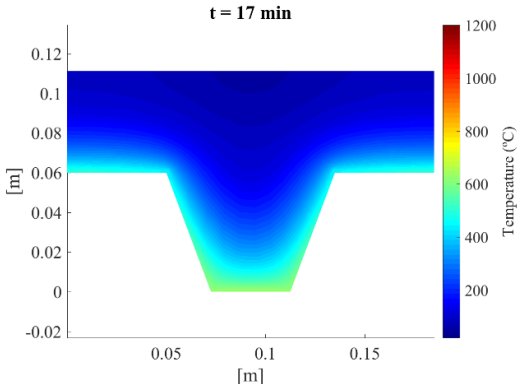
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.2mm

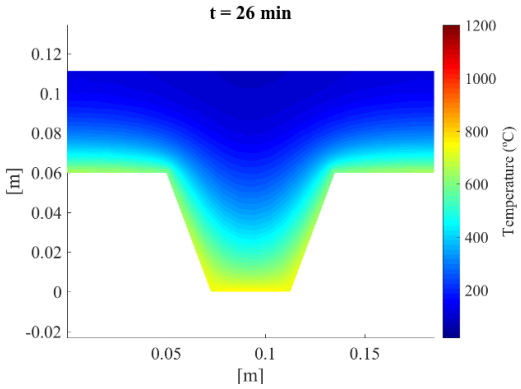


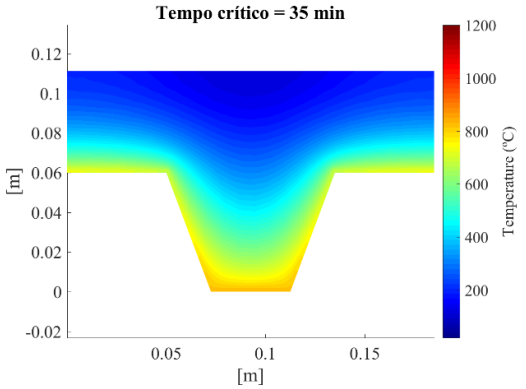


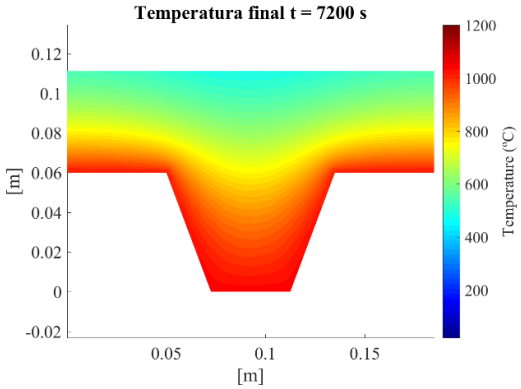




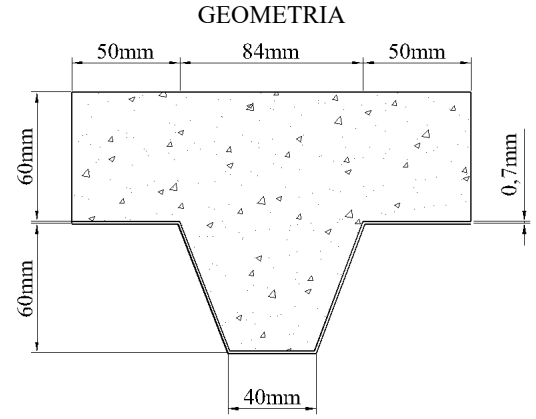


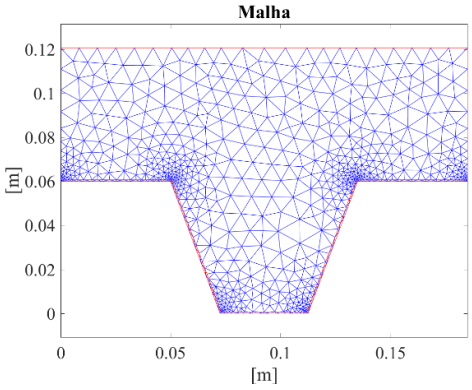


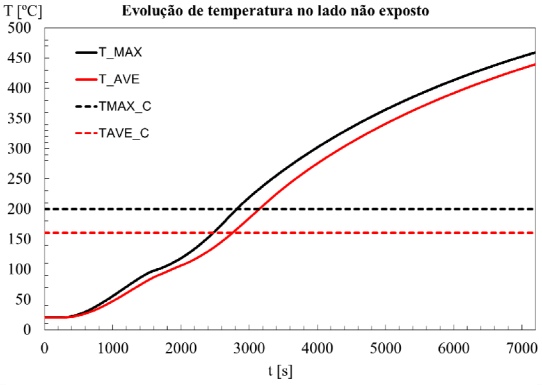


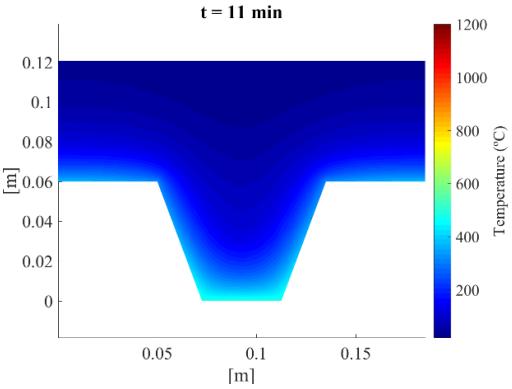


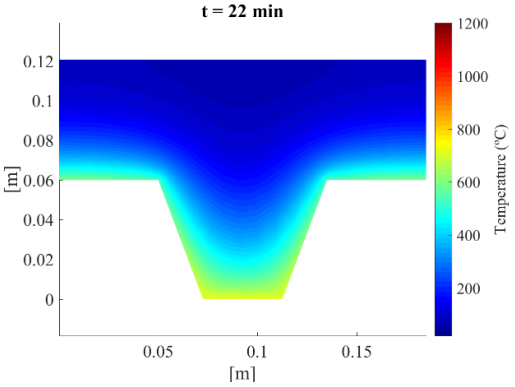
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.7mm

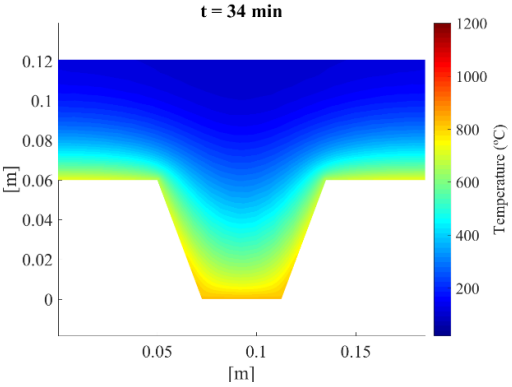


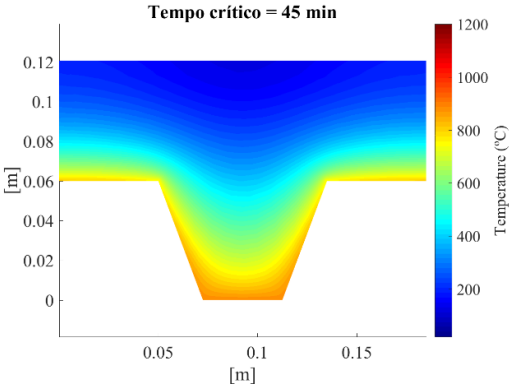


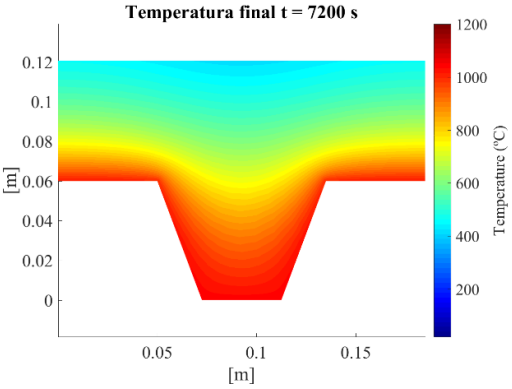




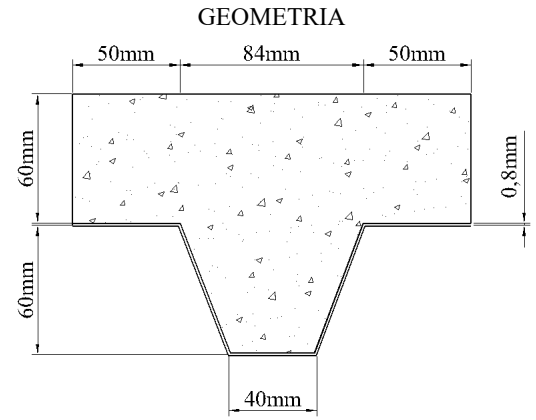


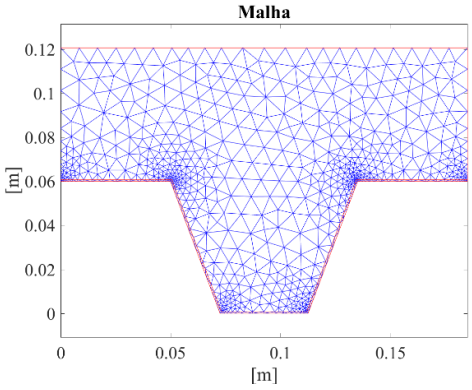


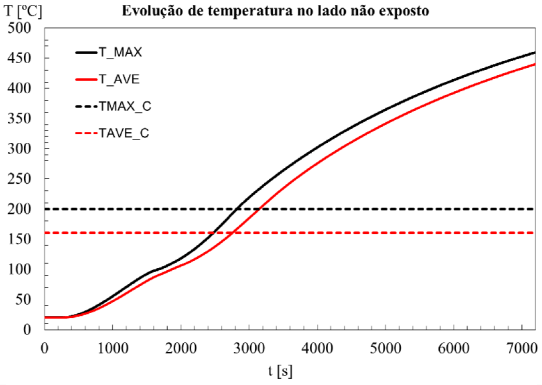


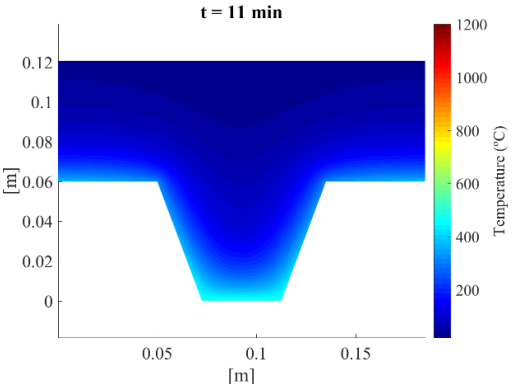


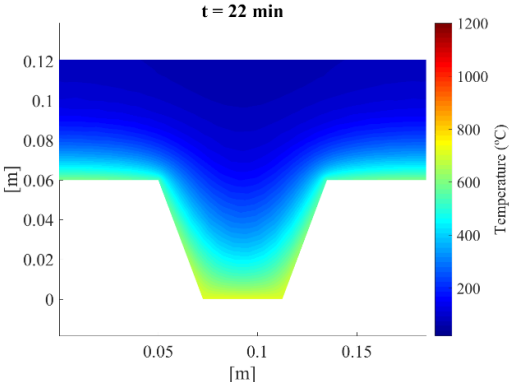
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.8mm

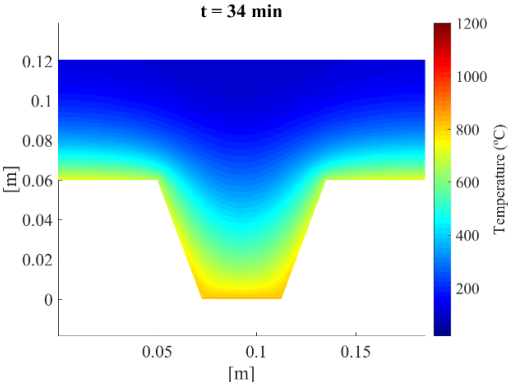


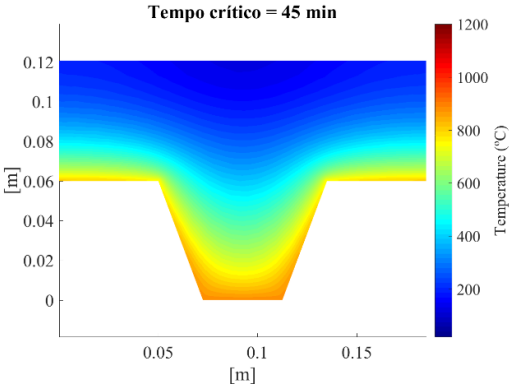


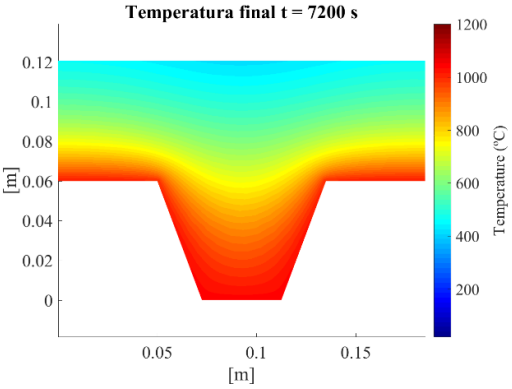




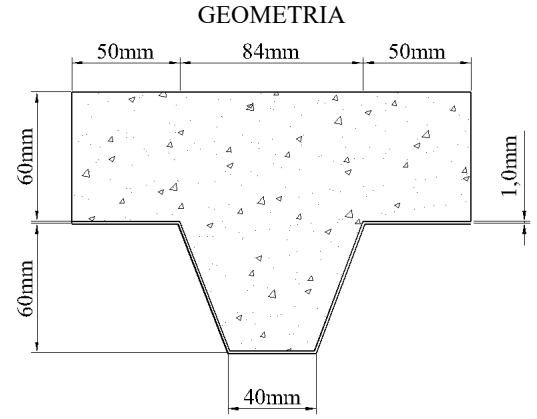


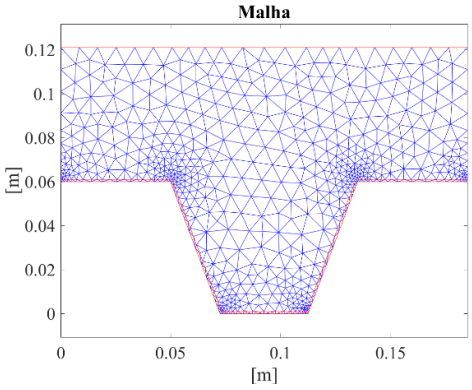


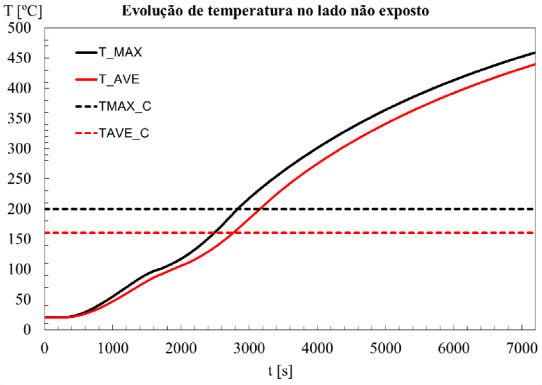


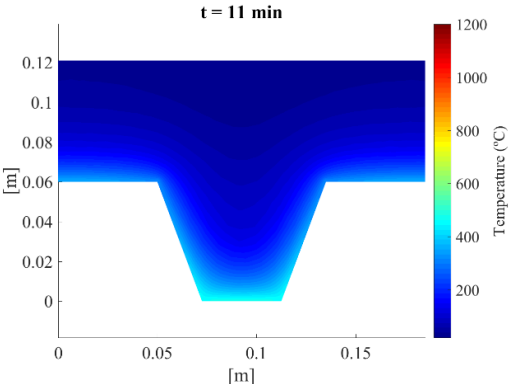


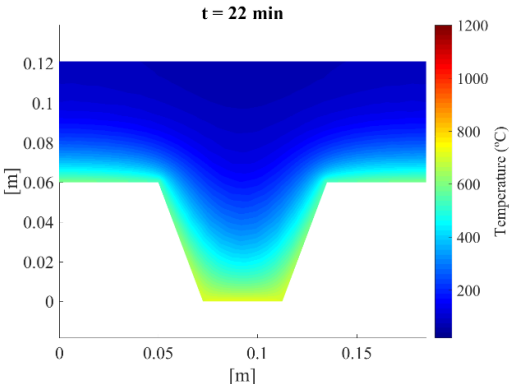
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.0mm

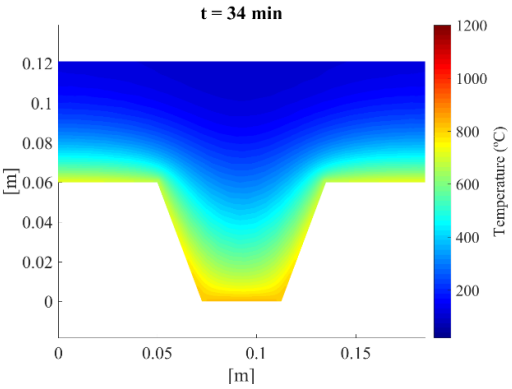


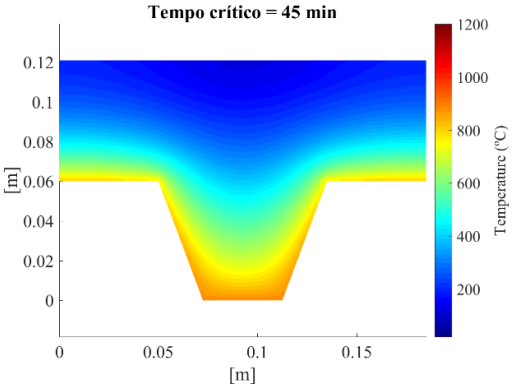


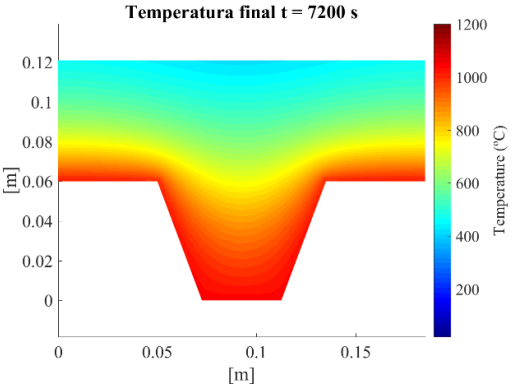




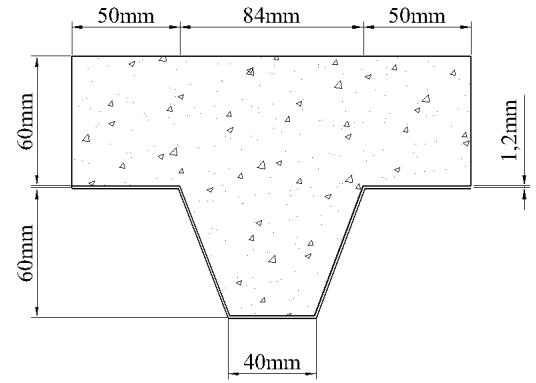


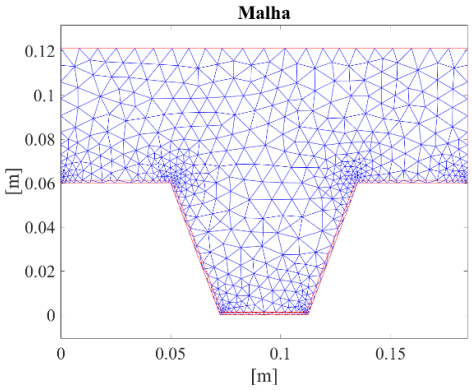


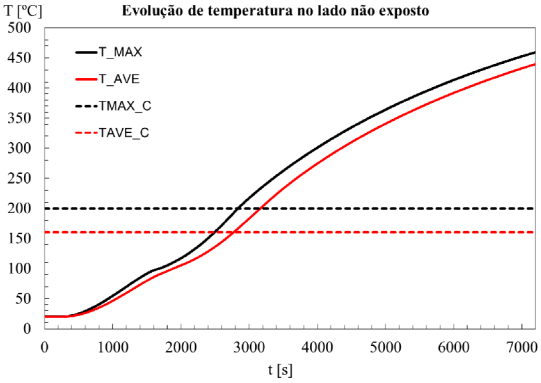


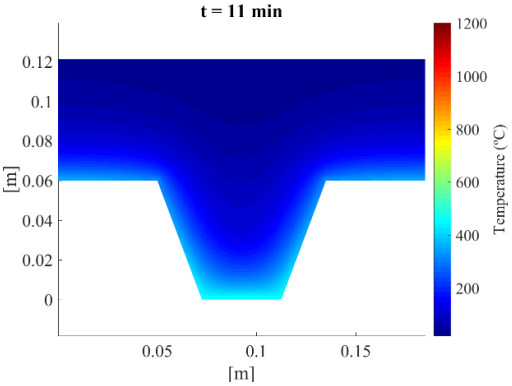


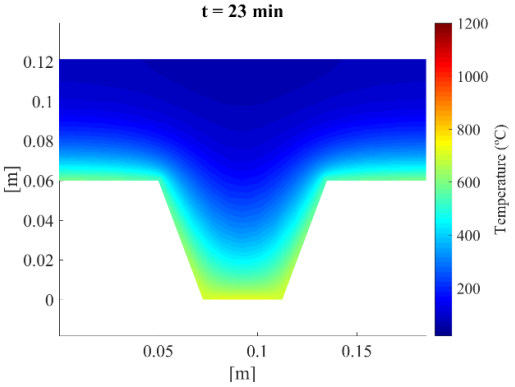
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.2mm

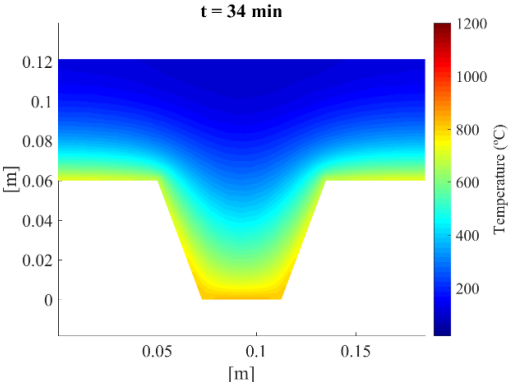


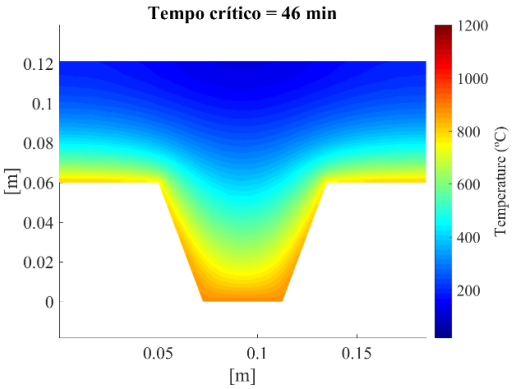


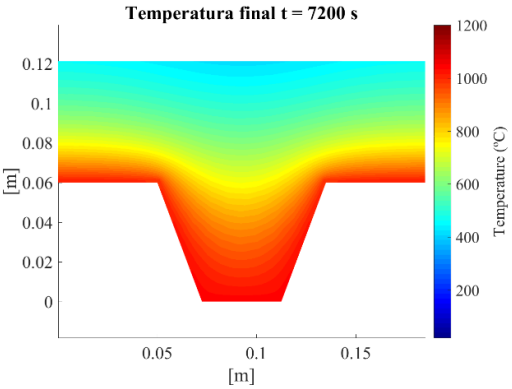




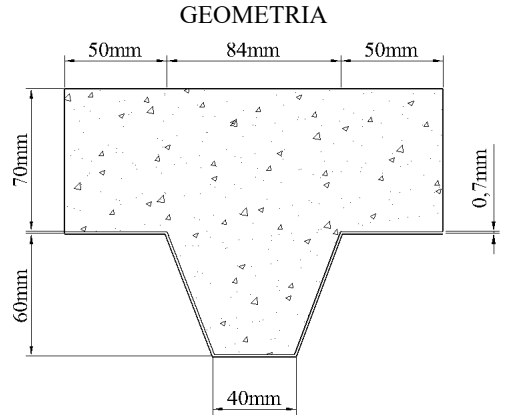


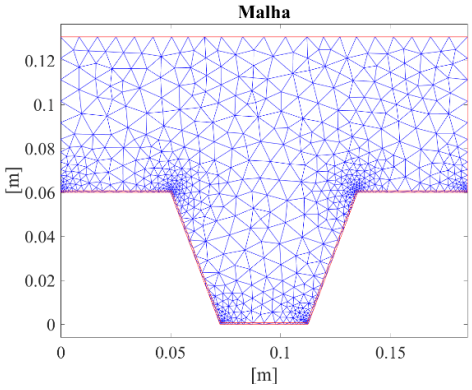


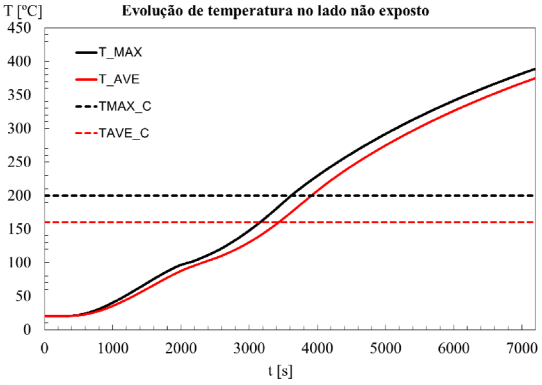


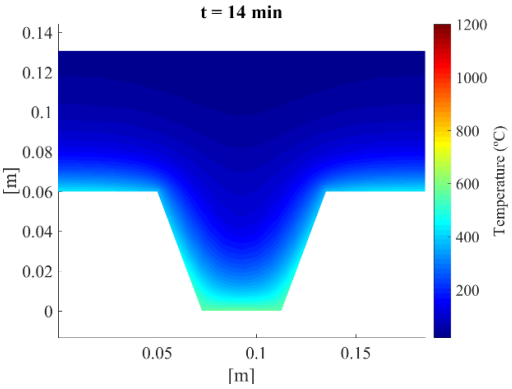


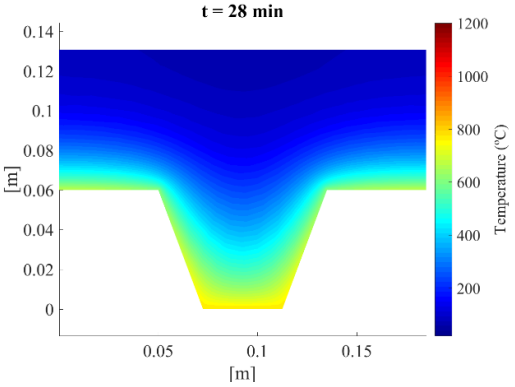
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.7mm

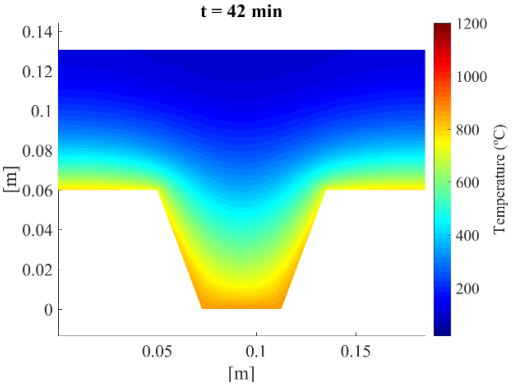


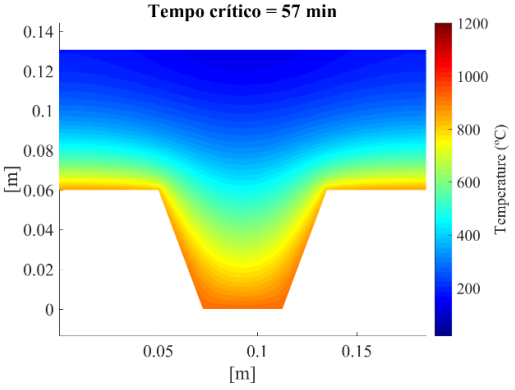


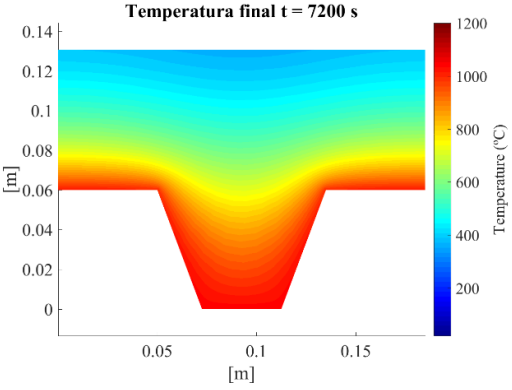




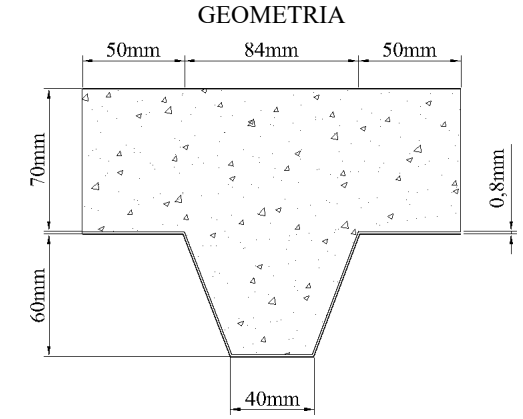


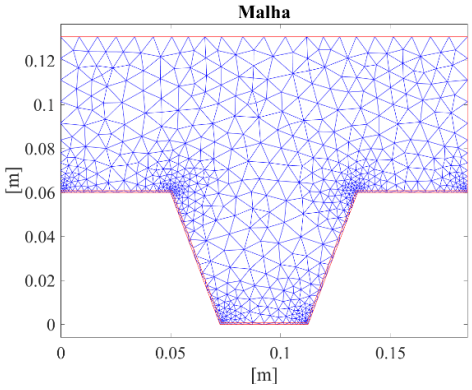


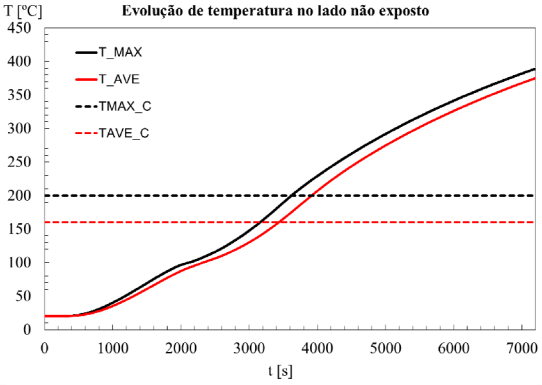


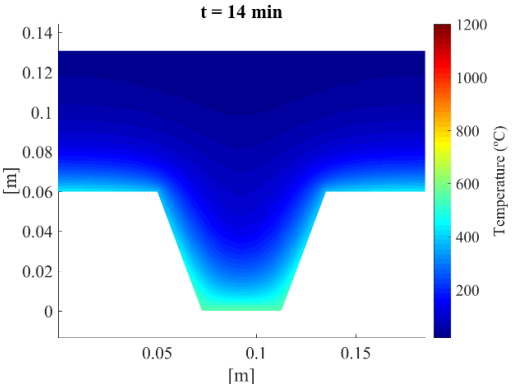


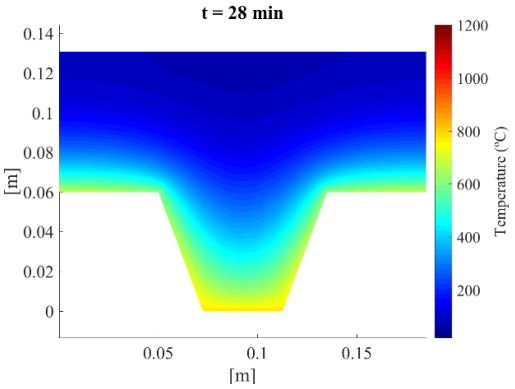
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.8mm

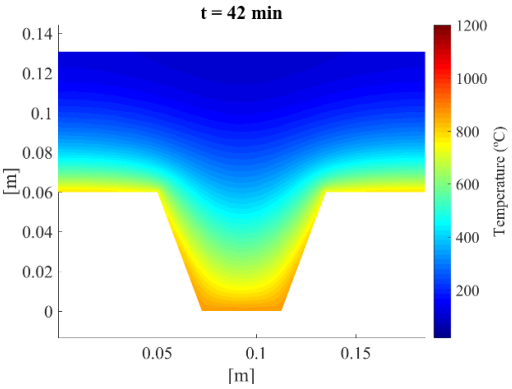


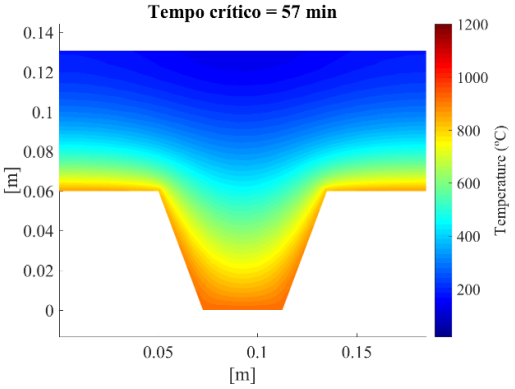


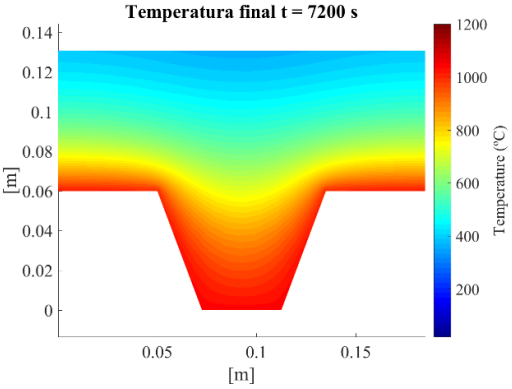




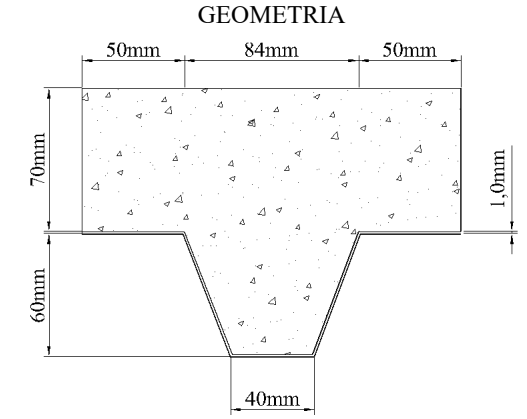


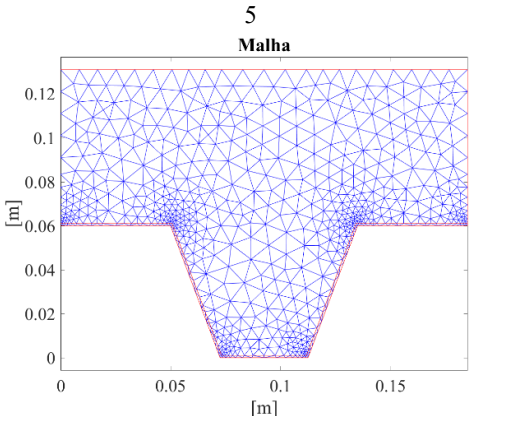


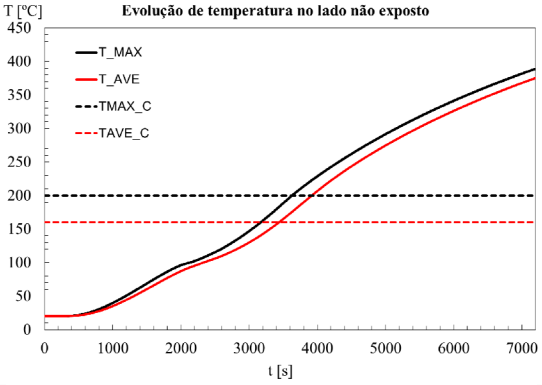


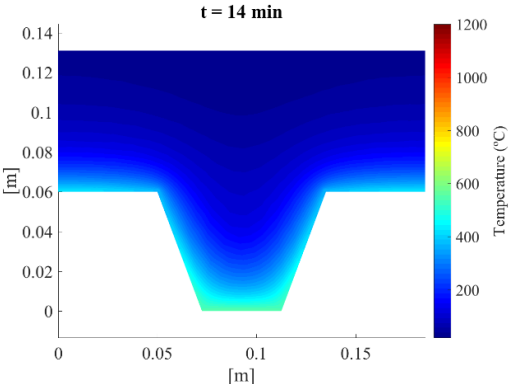


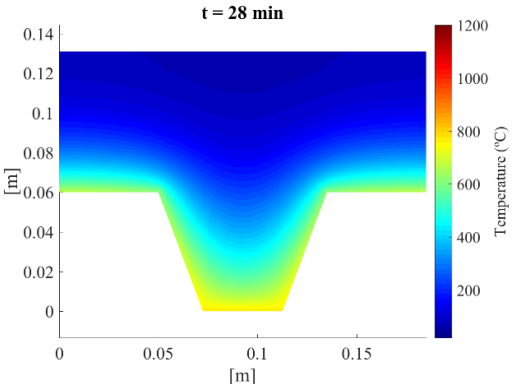
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.0mm

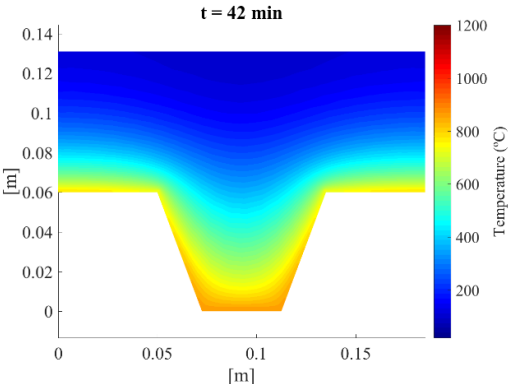


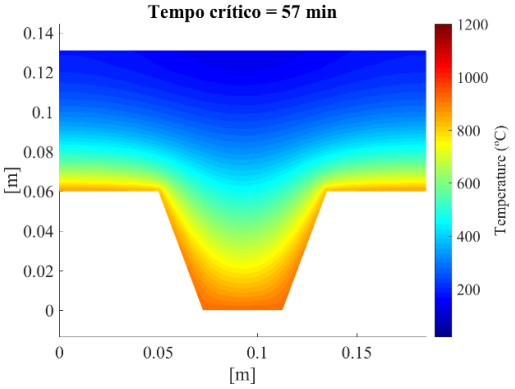


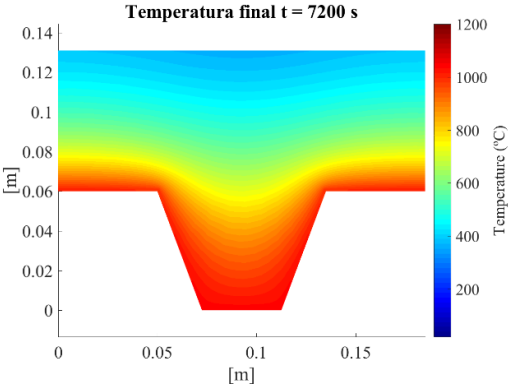




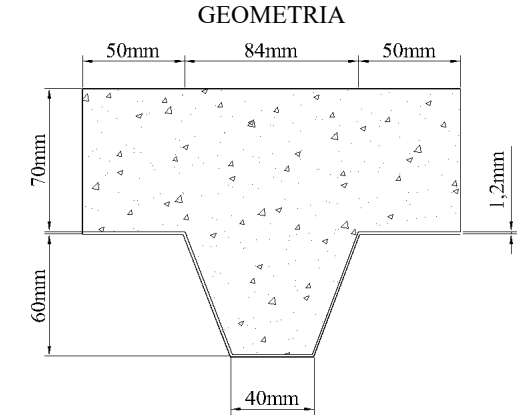


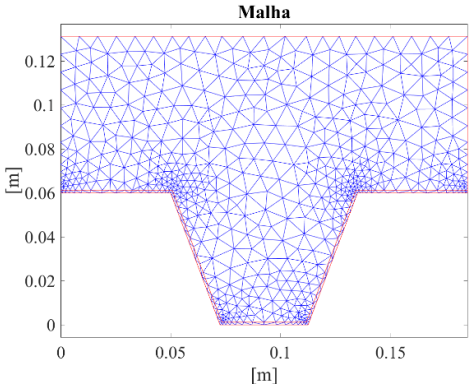


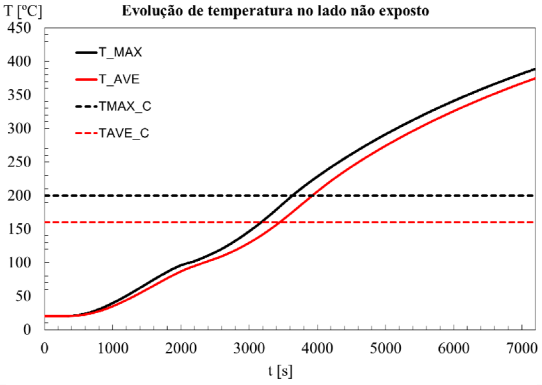


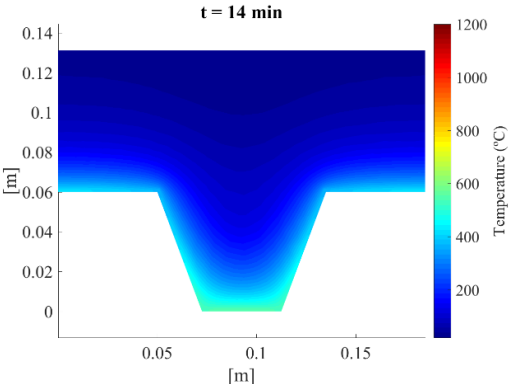


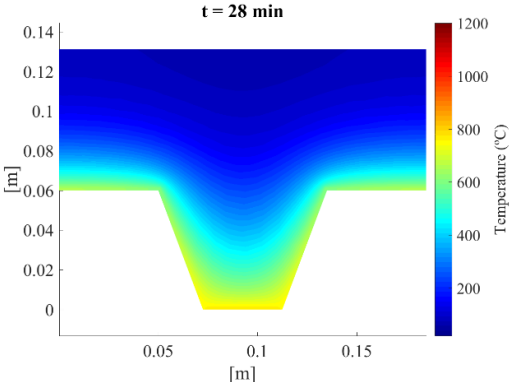
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.2mm

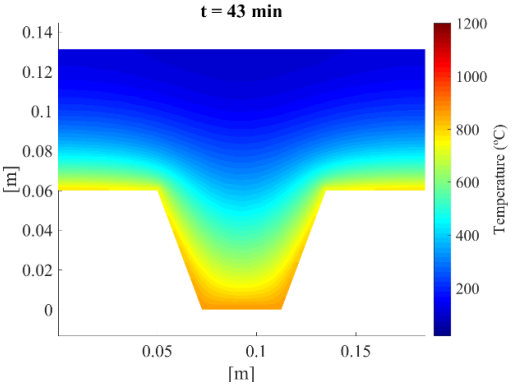


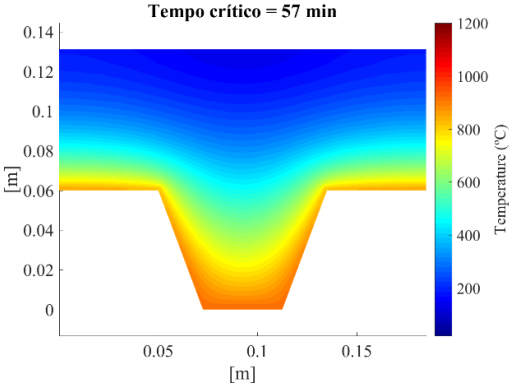


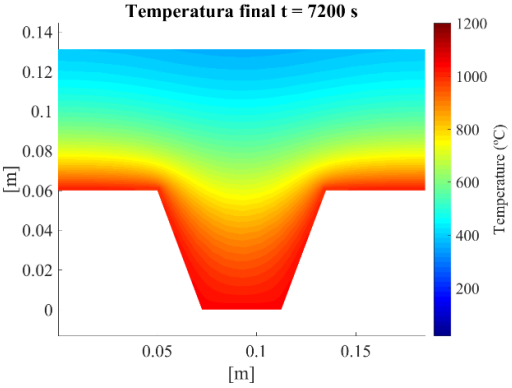




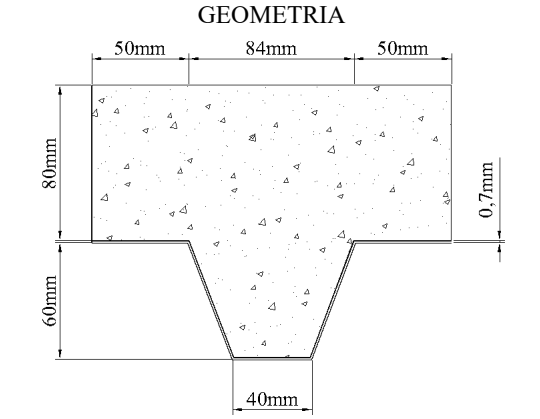


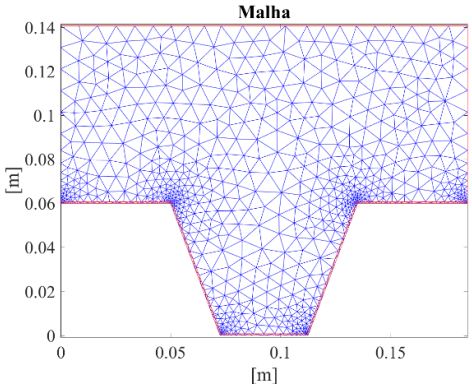


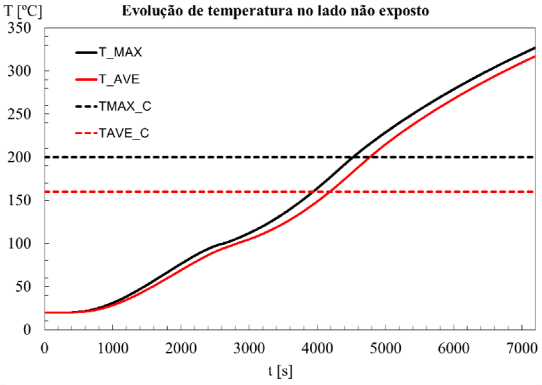


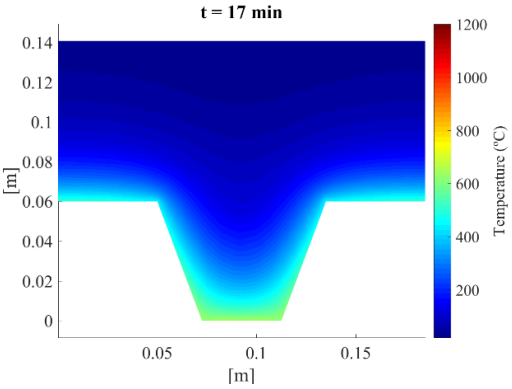


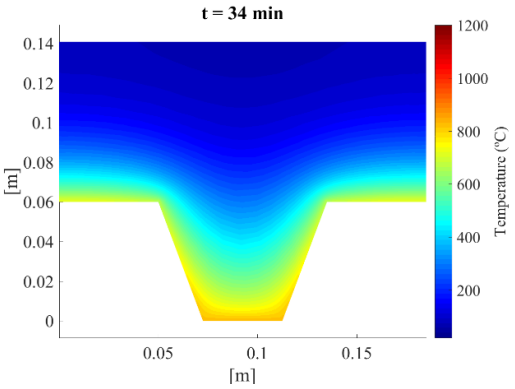
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.7mm

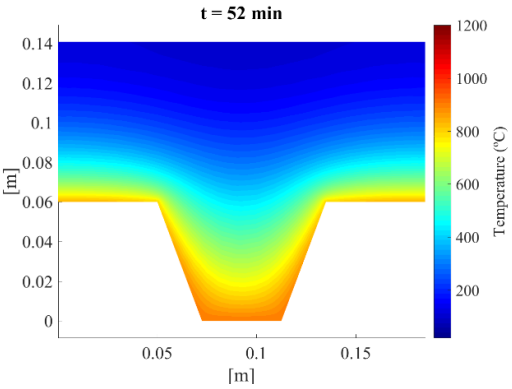


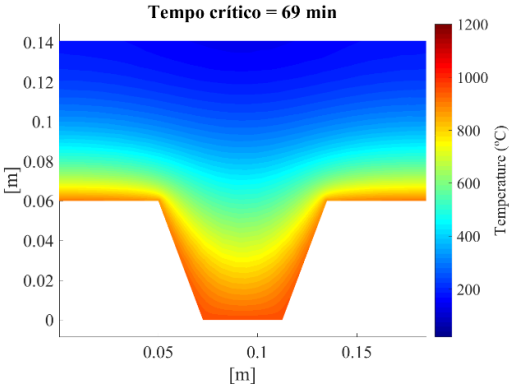


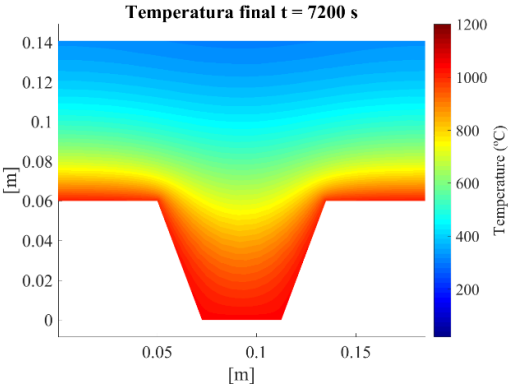




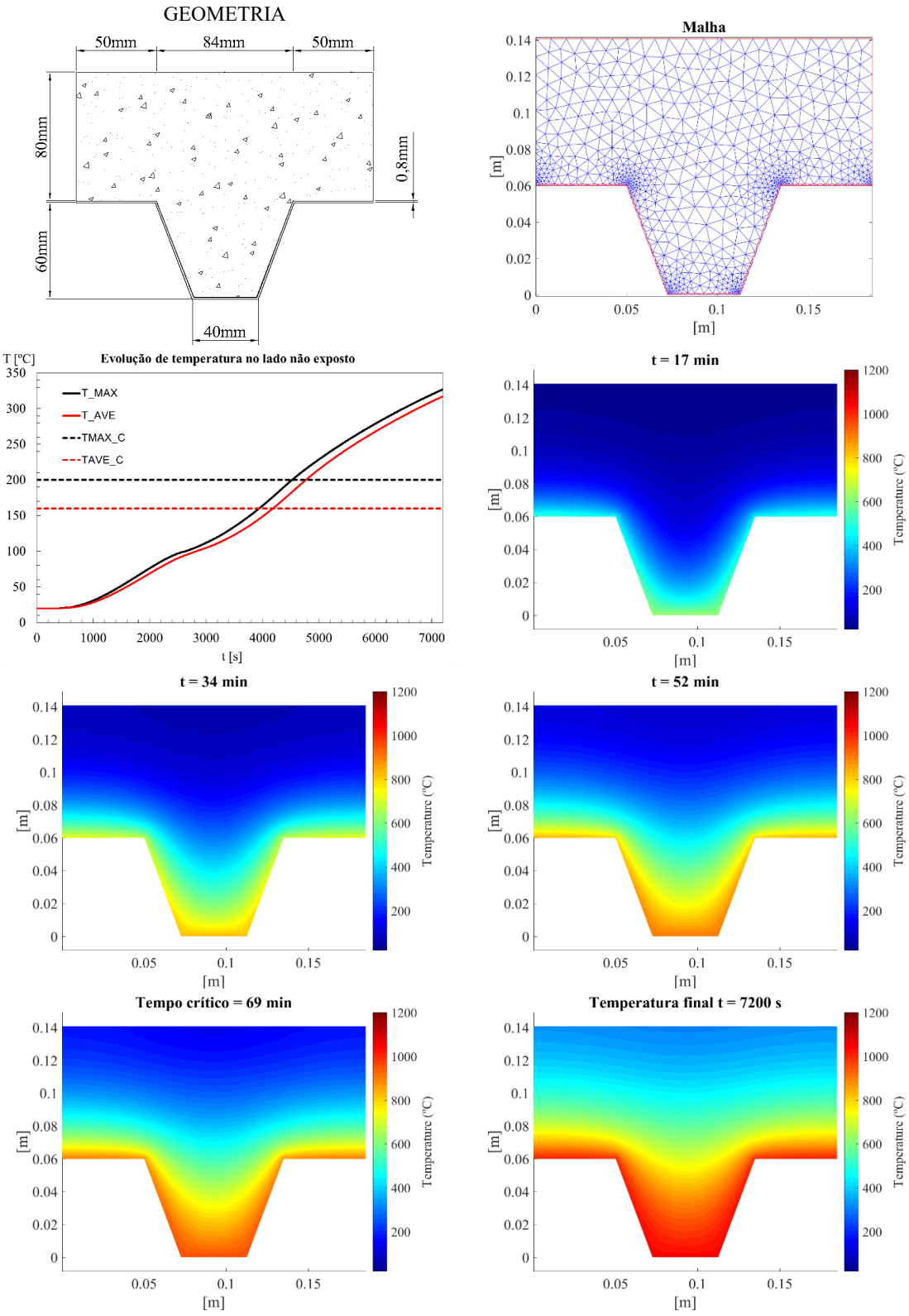




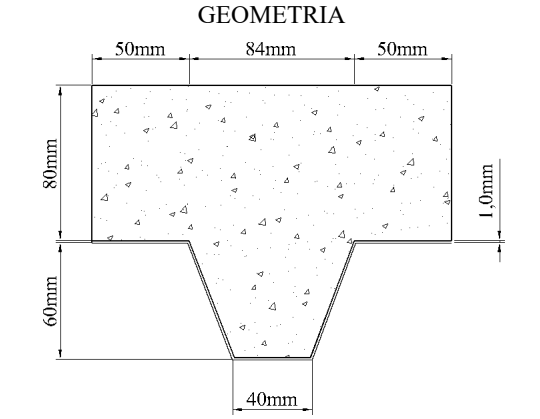


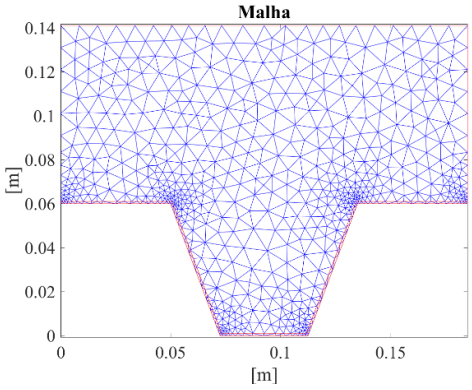


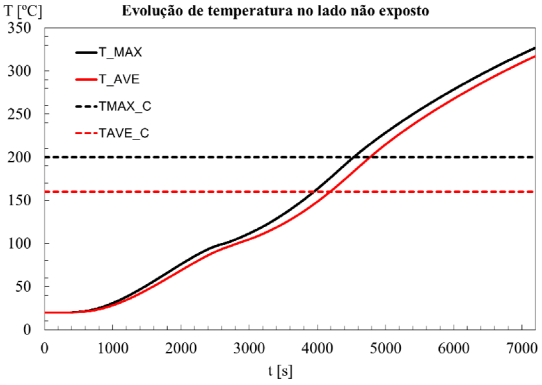
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.8mm

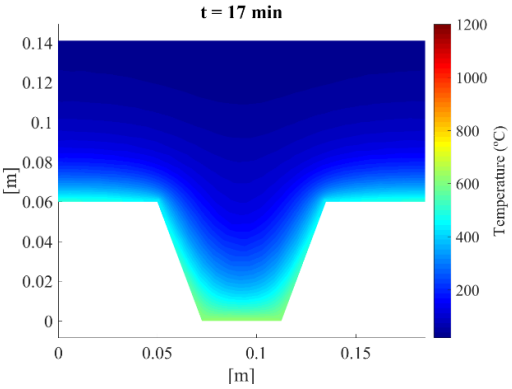


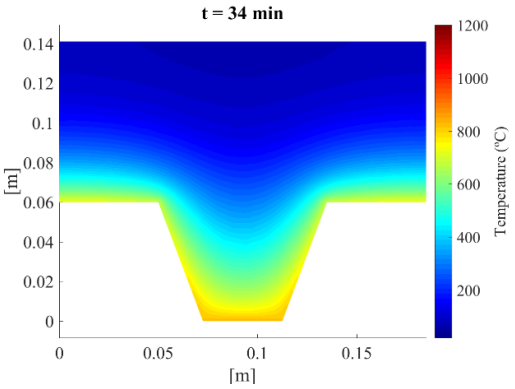
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.0mm

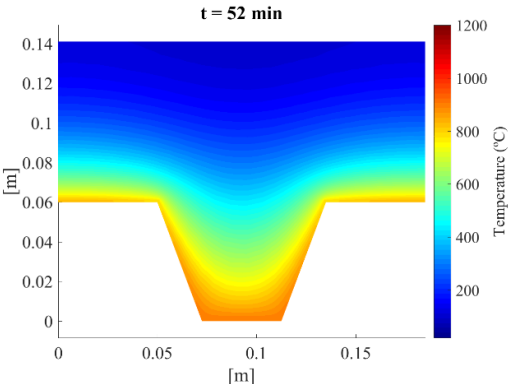


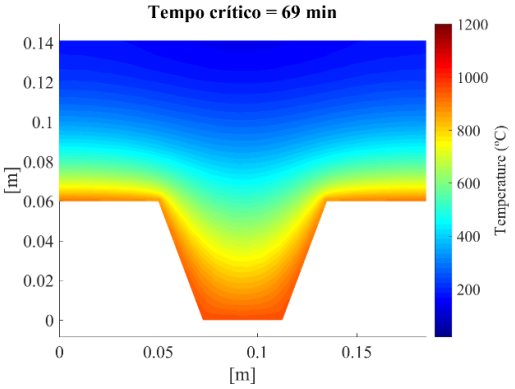


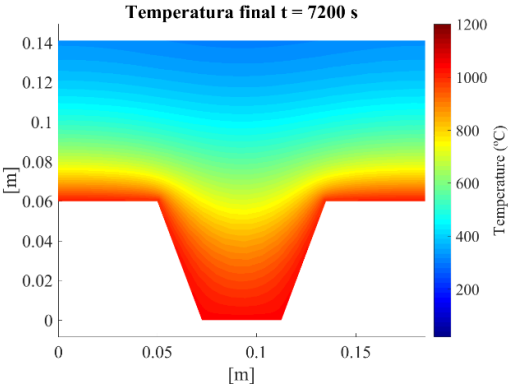




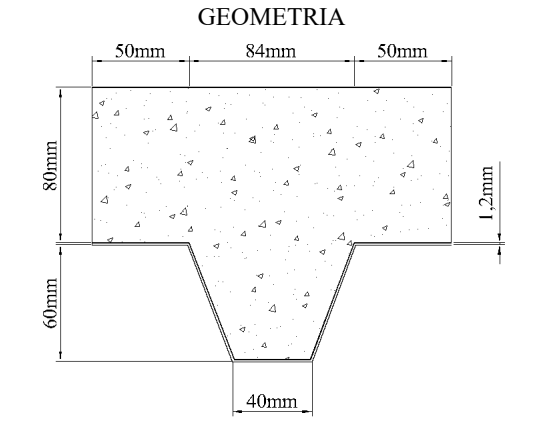


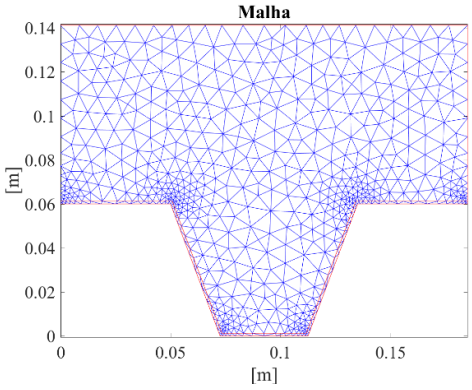


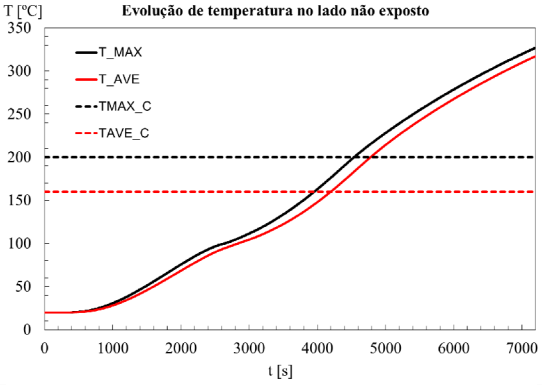


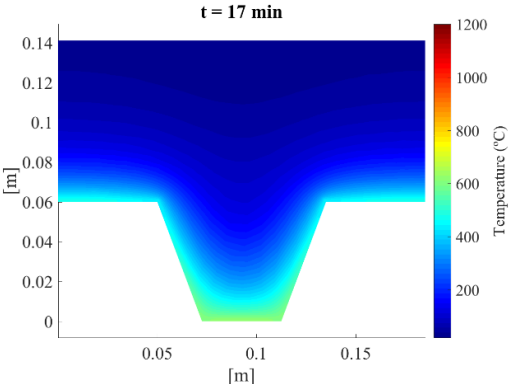


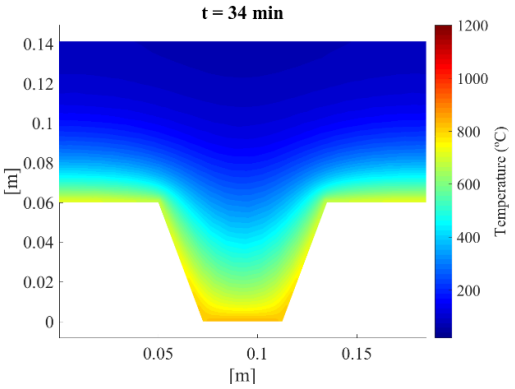
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.2mm

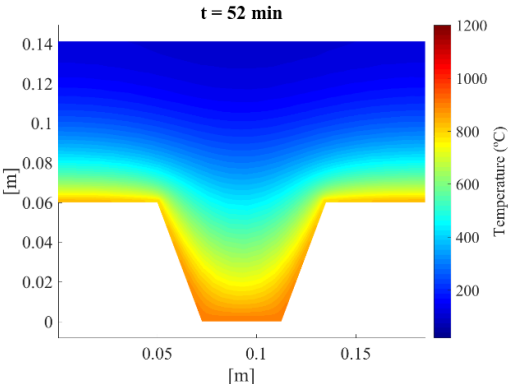


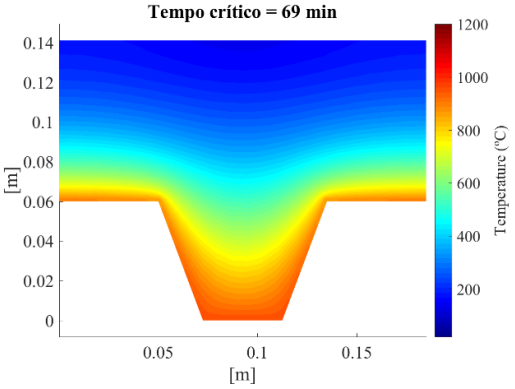


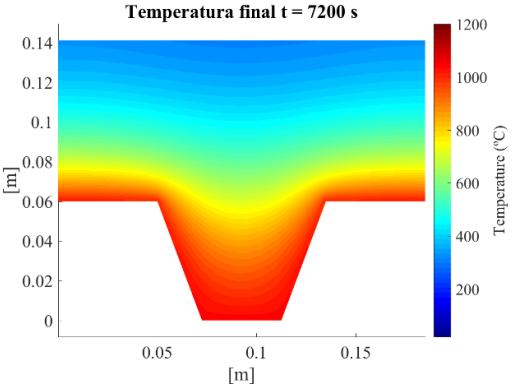




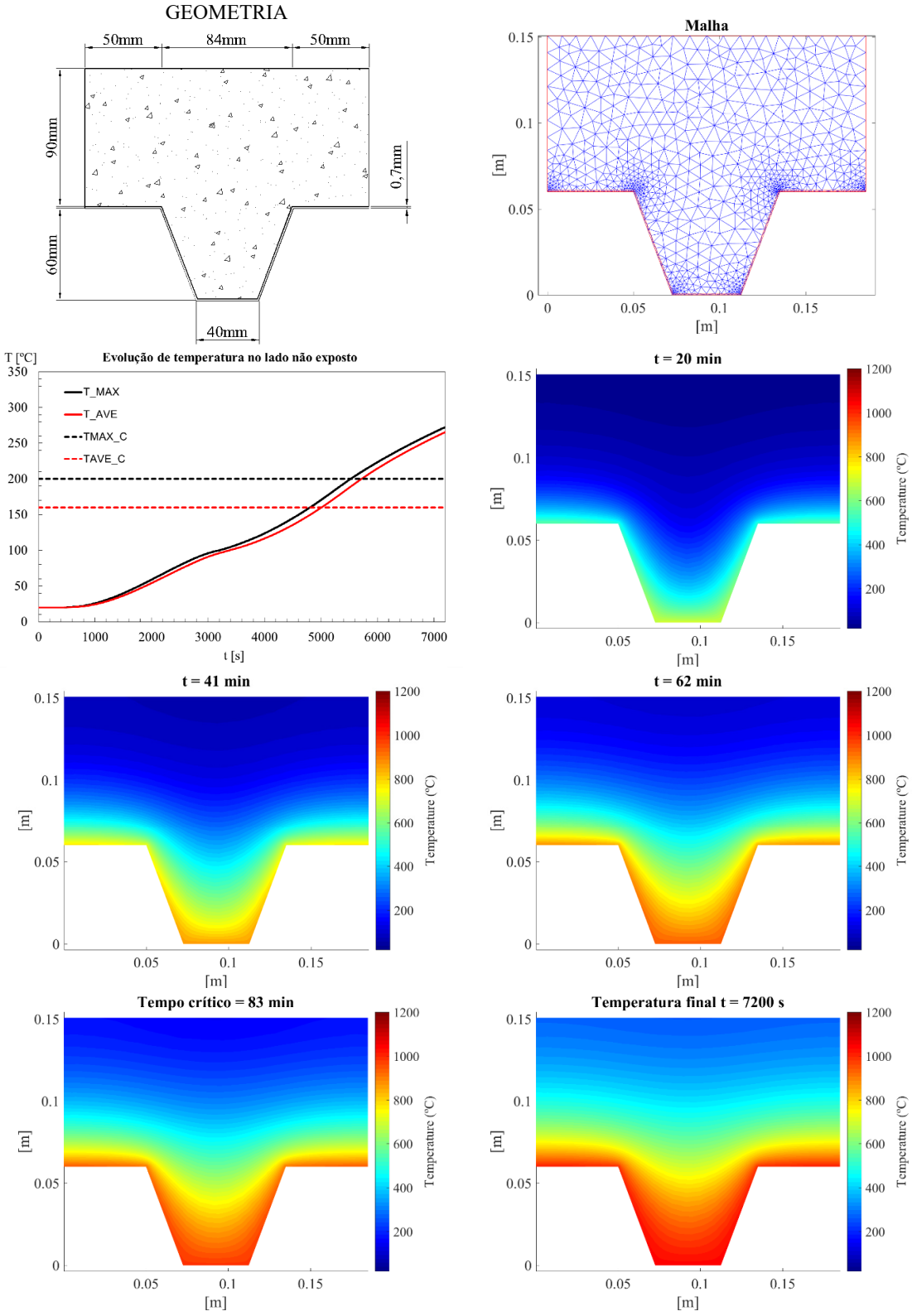




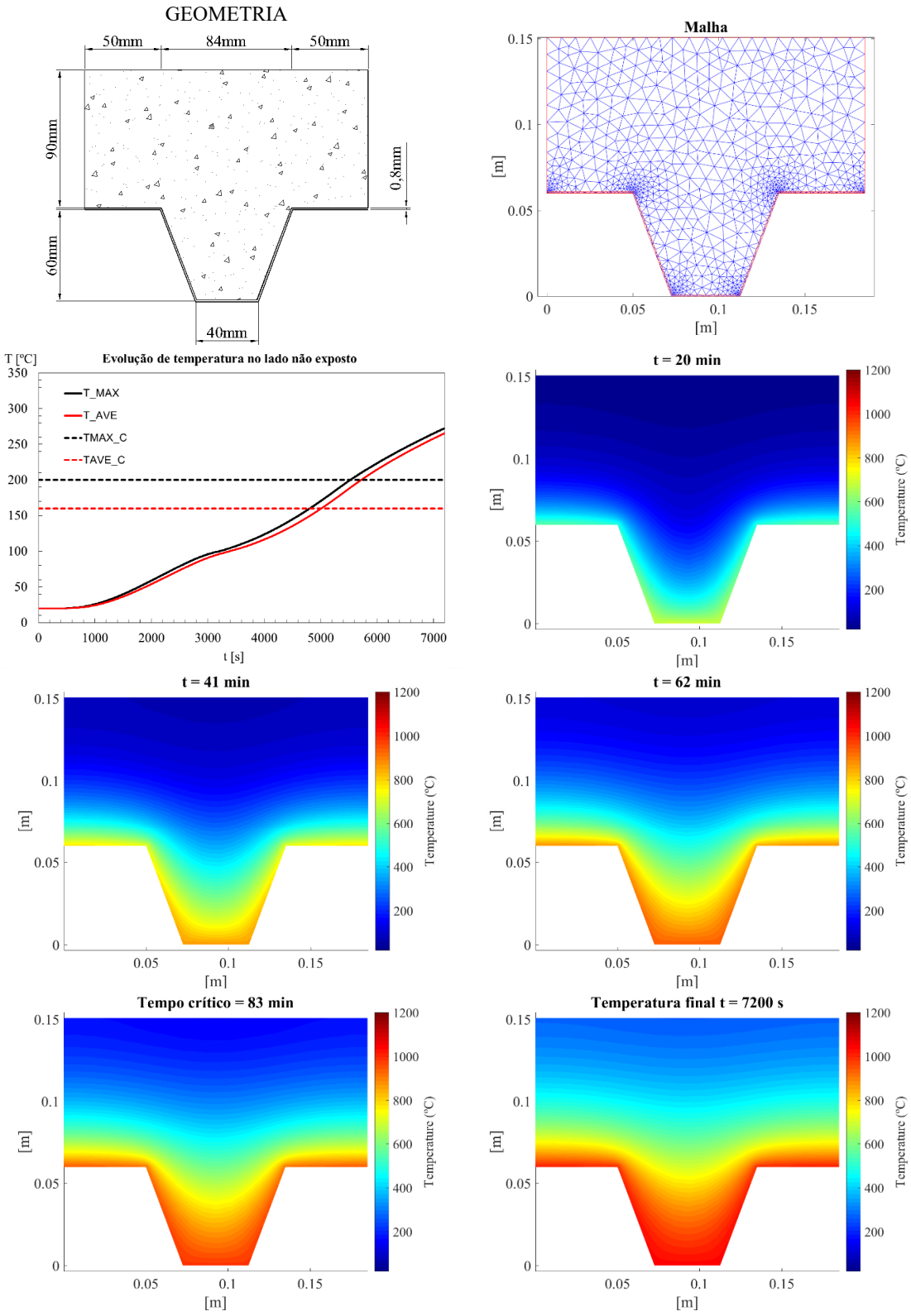




LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.7mm



LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.8mm



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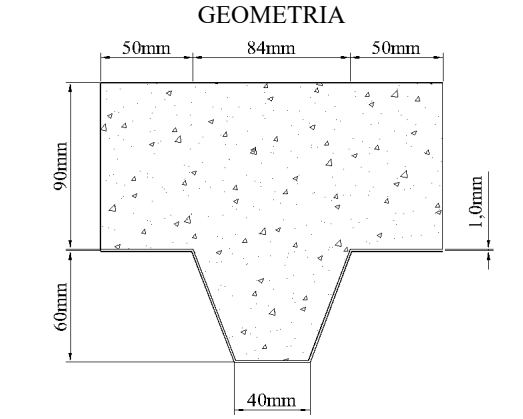
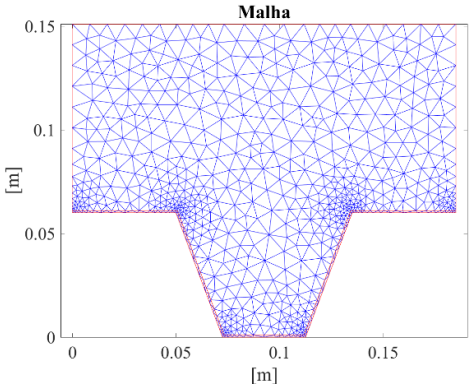
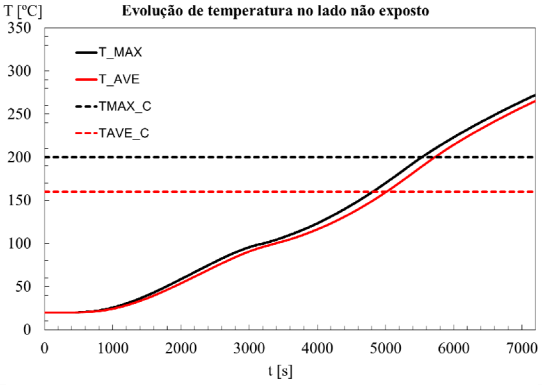
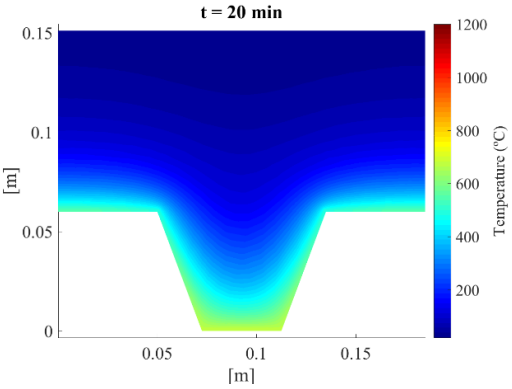
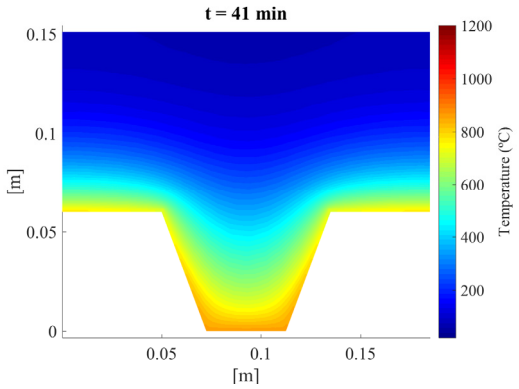
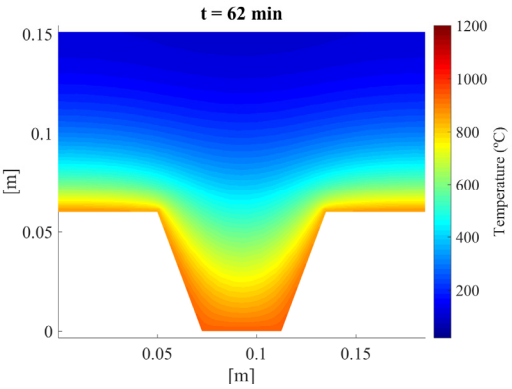


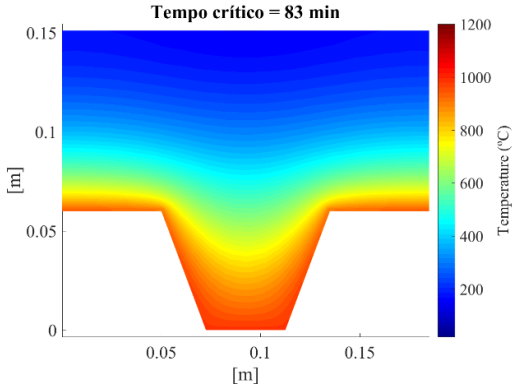


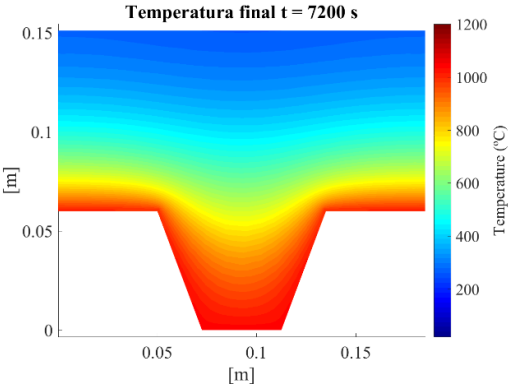




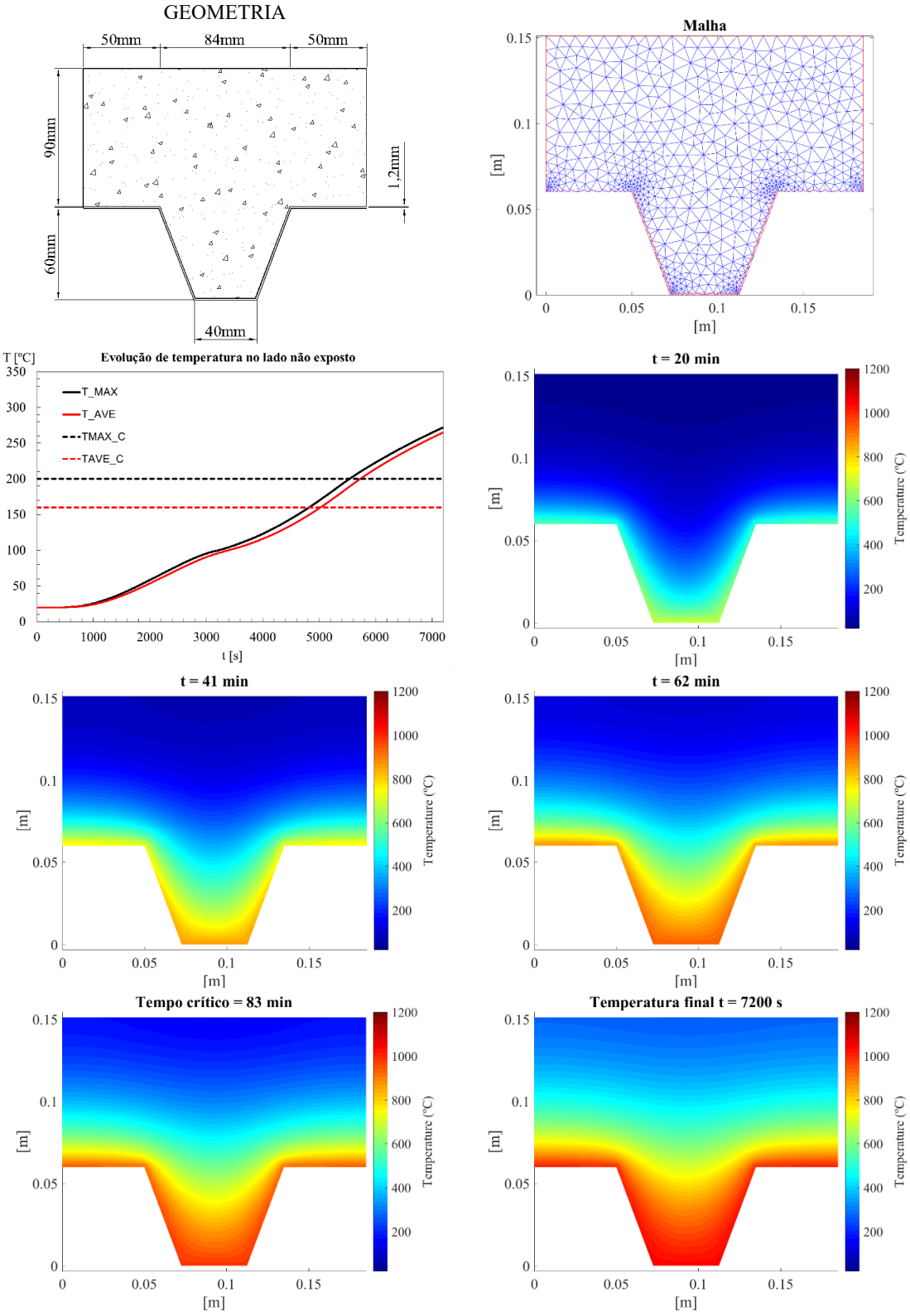




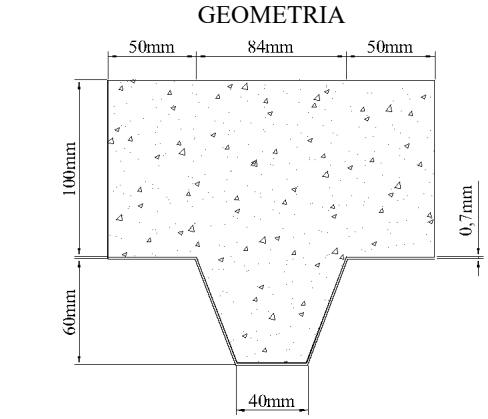


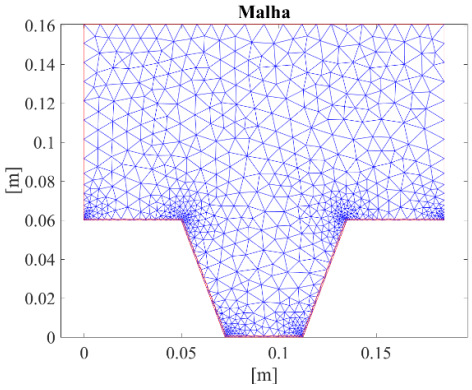


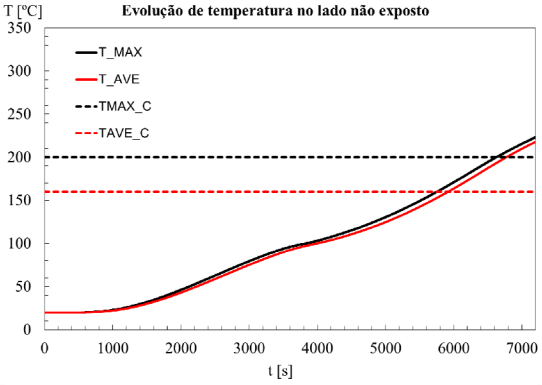
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.2mm

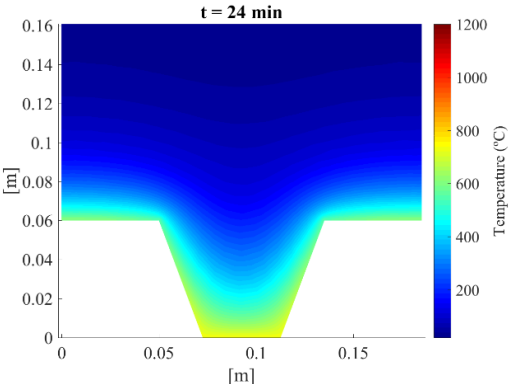


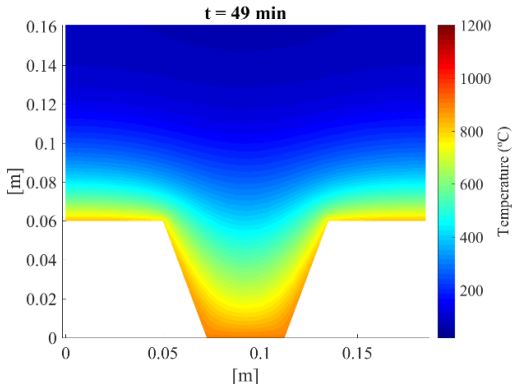
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.7mm

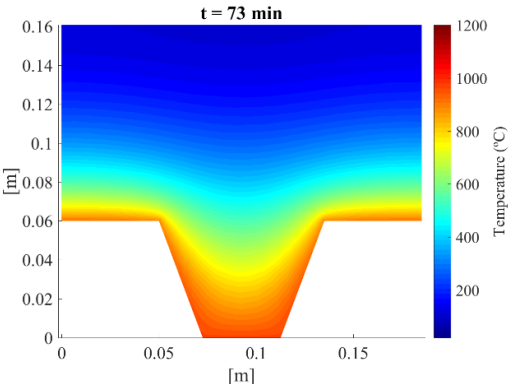


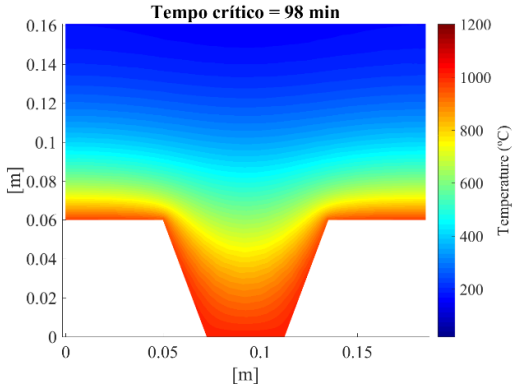


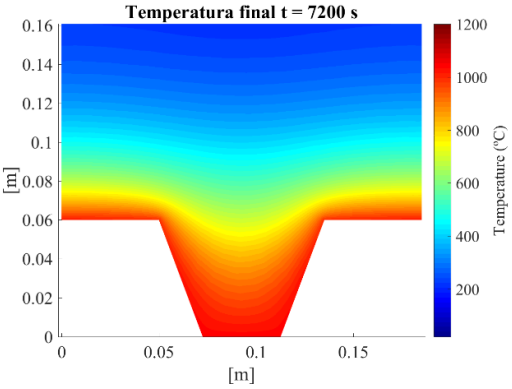




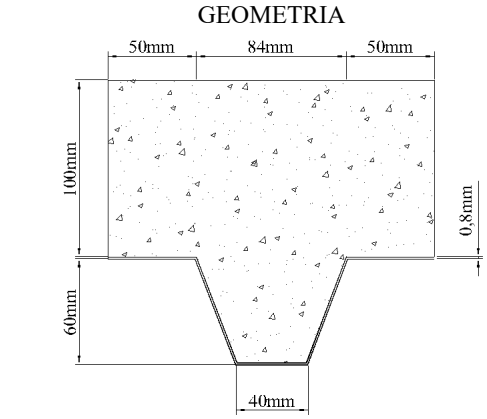


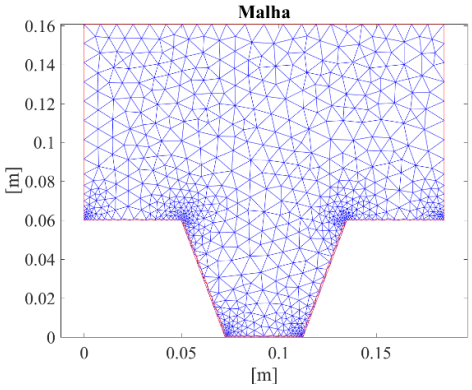


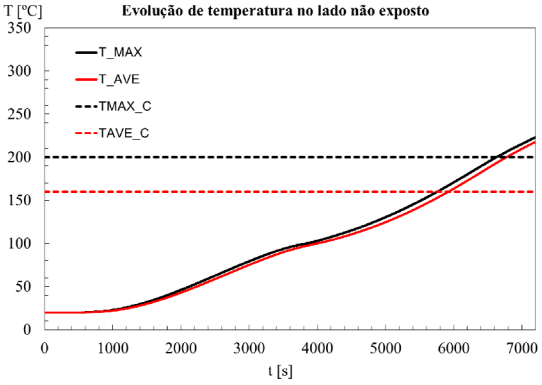


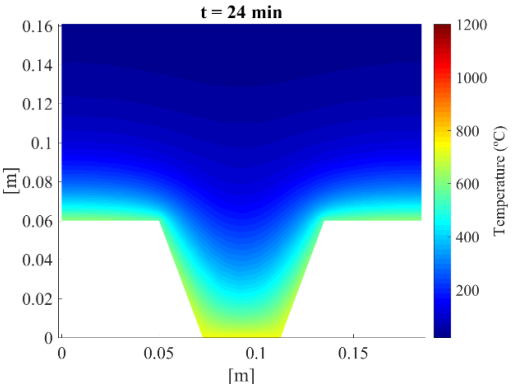


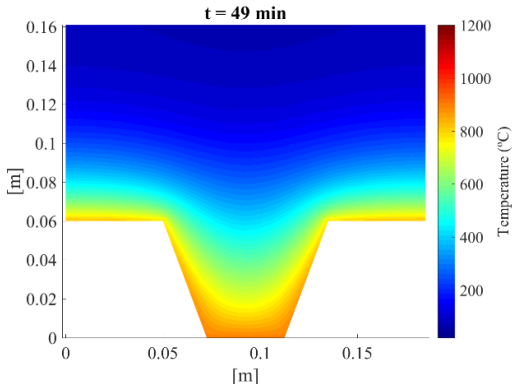
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.8mm

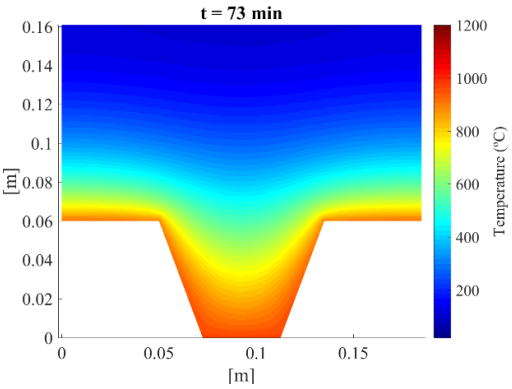


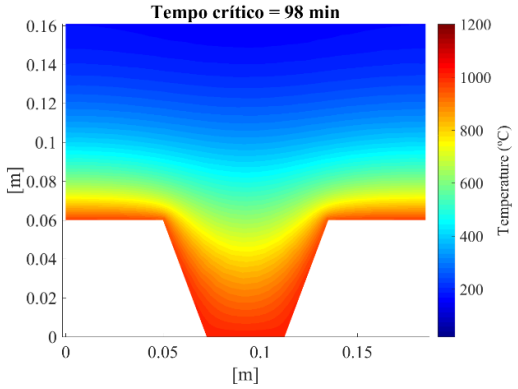


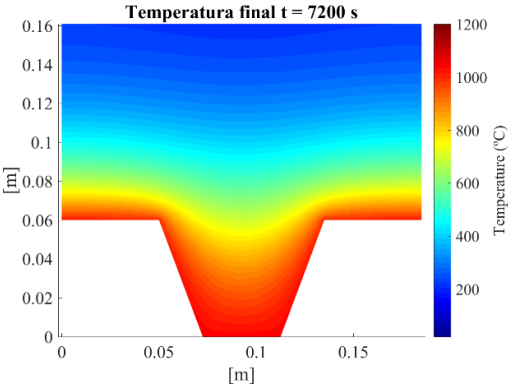




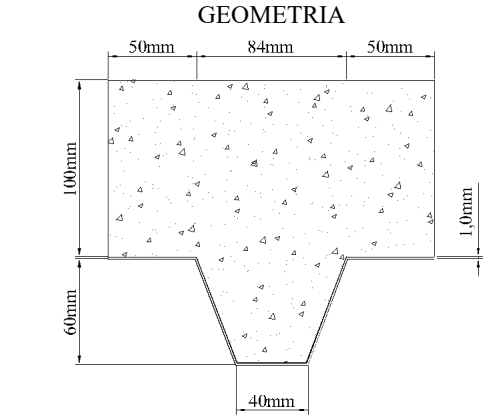


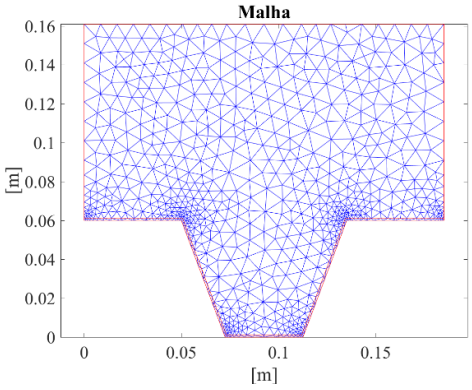


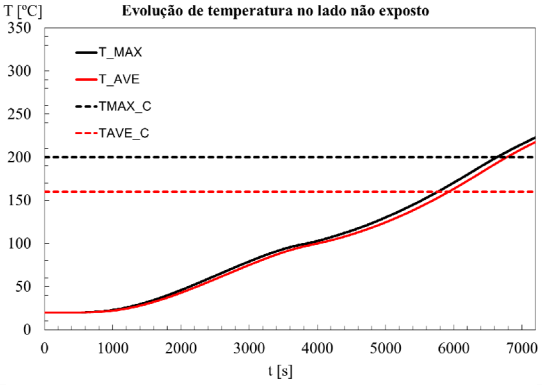


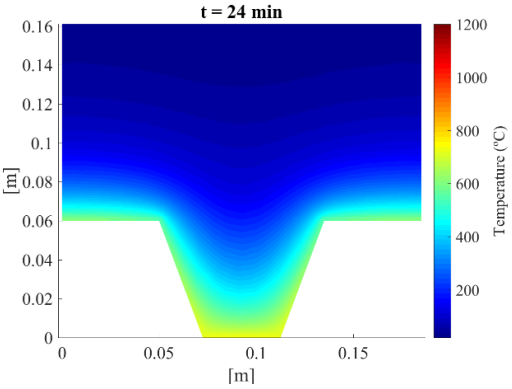


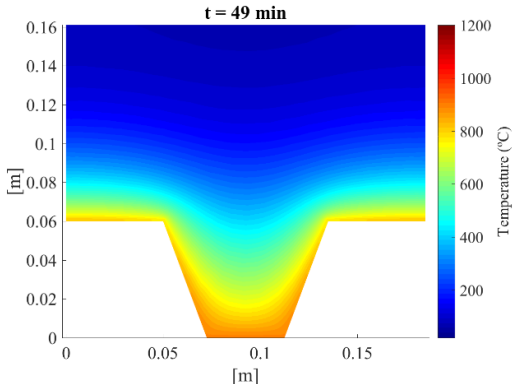
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.0mm

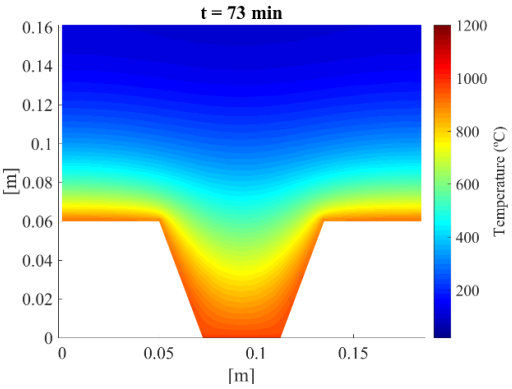


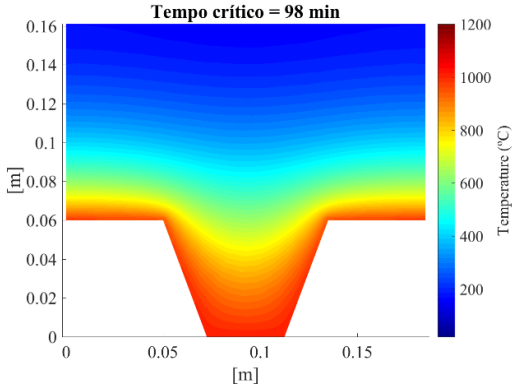


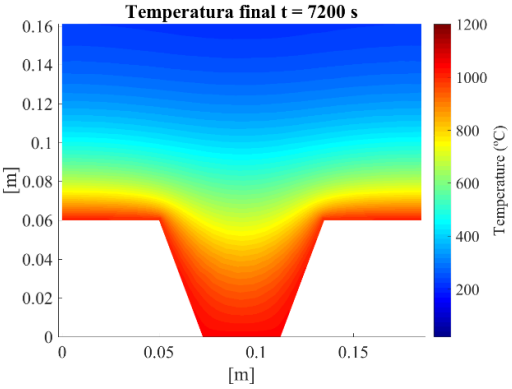




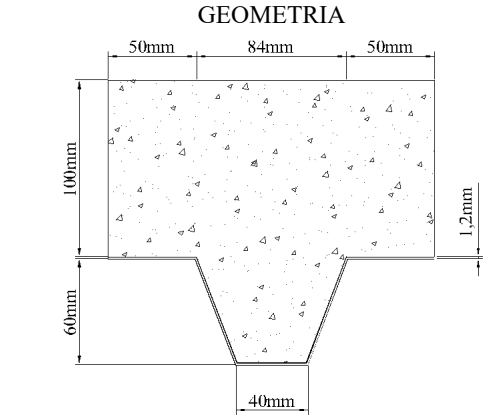


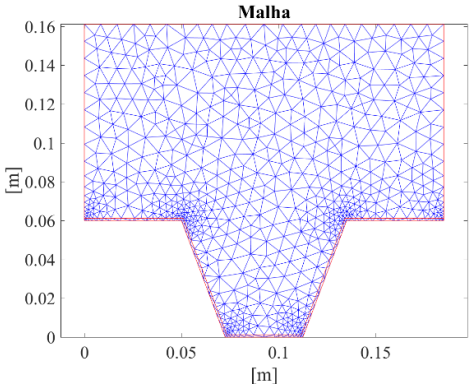


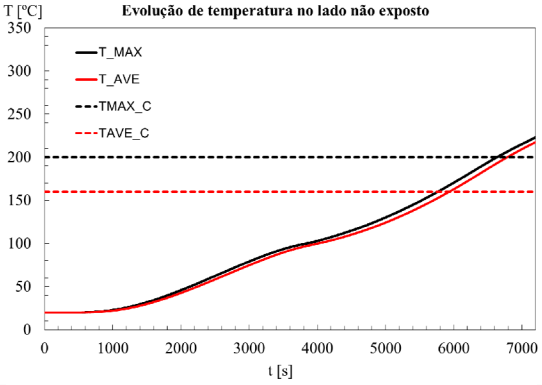


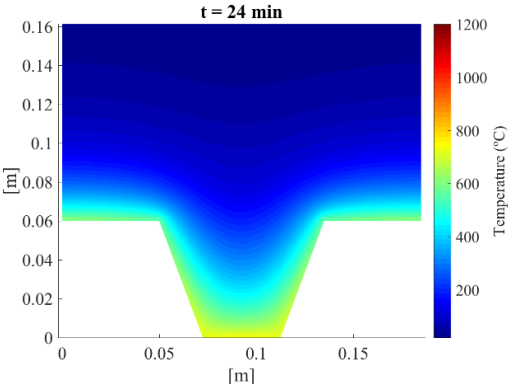


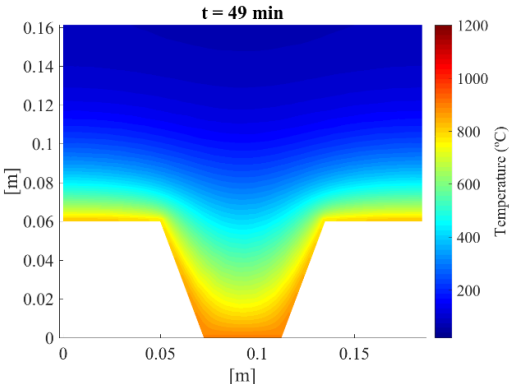
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.2mm

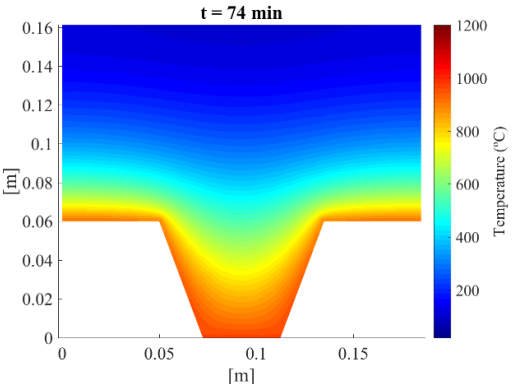


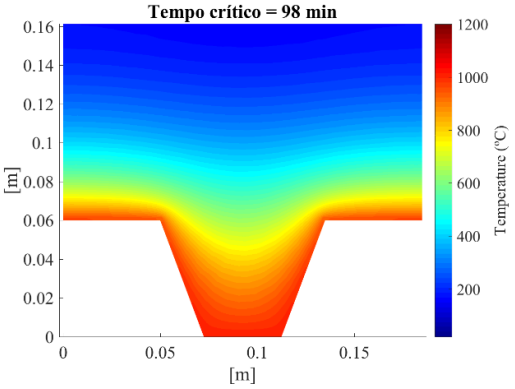


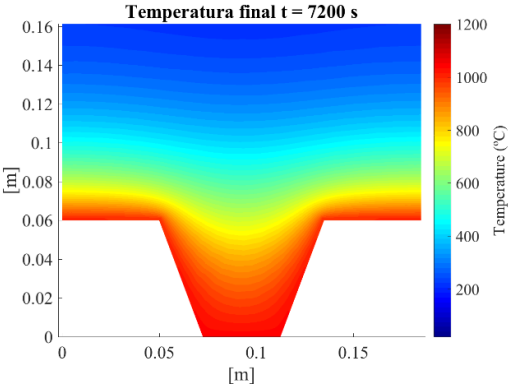




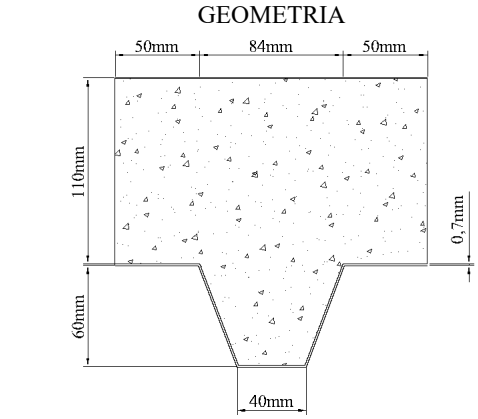


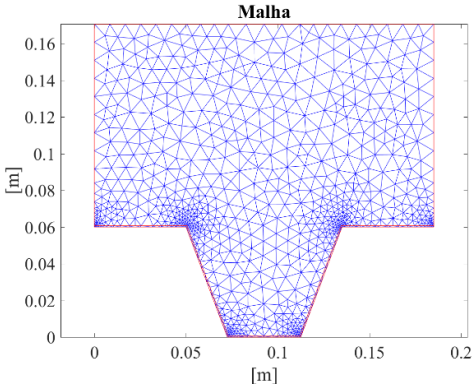


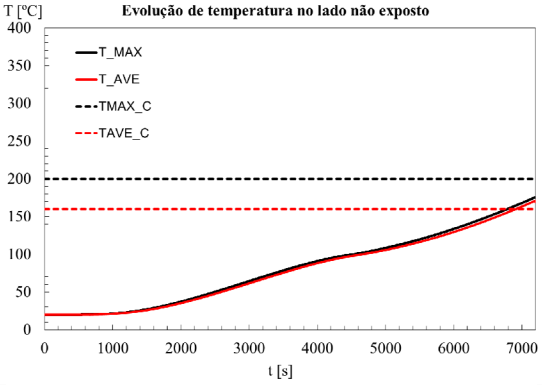


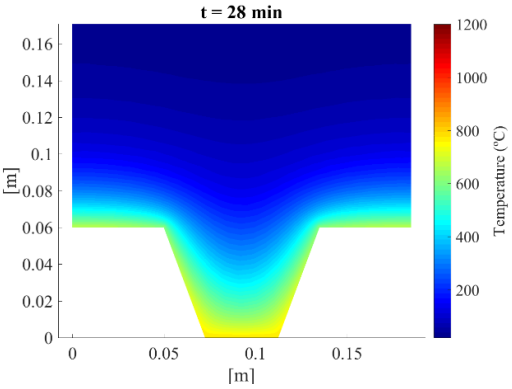


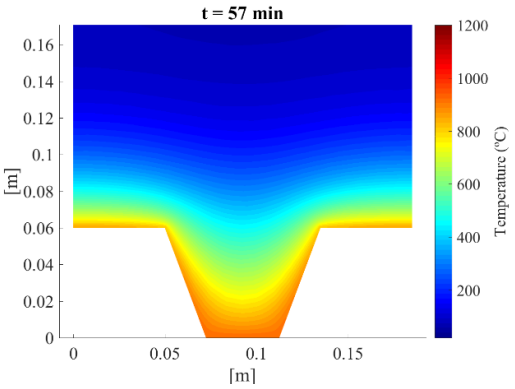
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.7mm

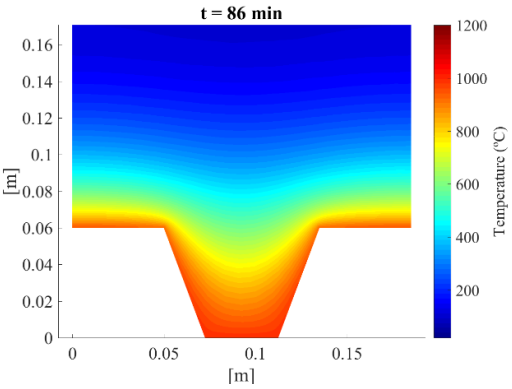


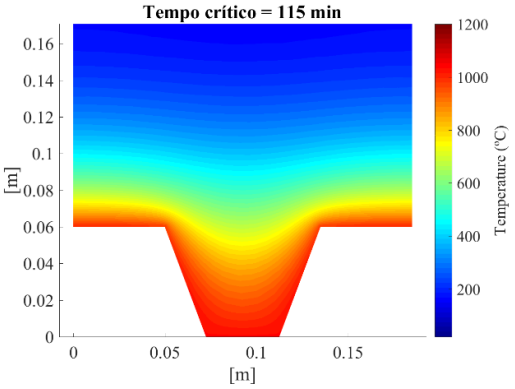


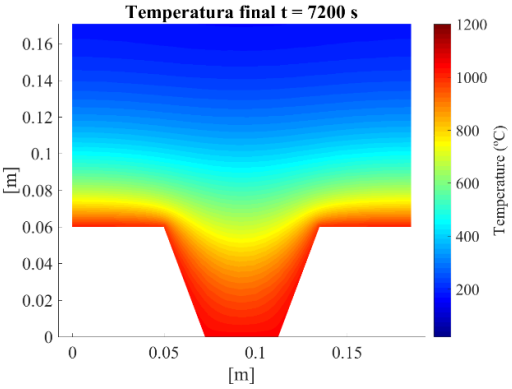




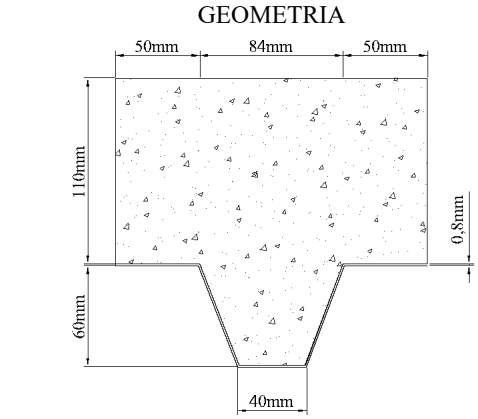


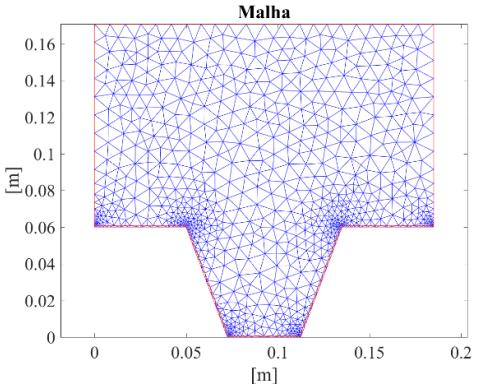


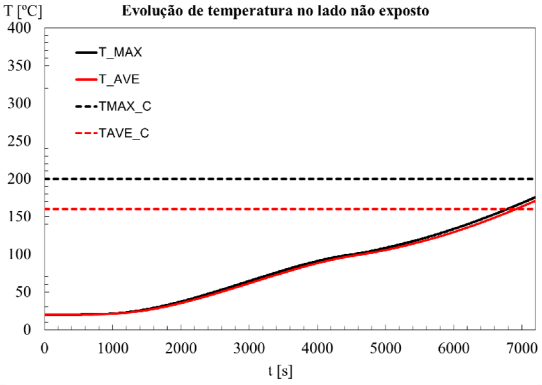


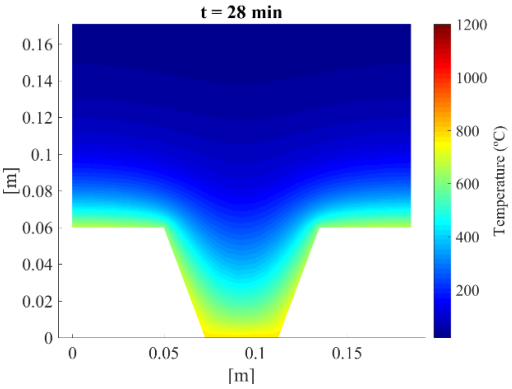


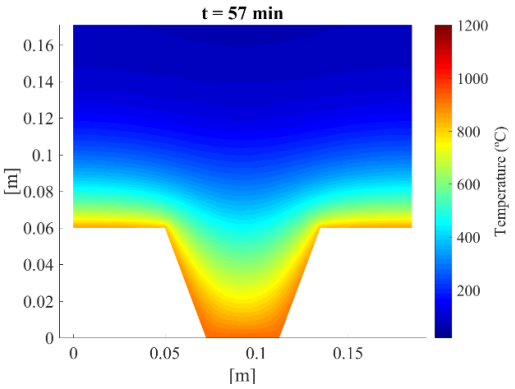
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.8mm

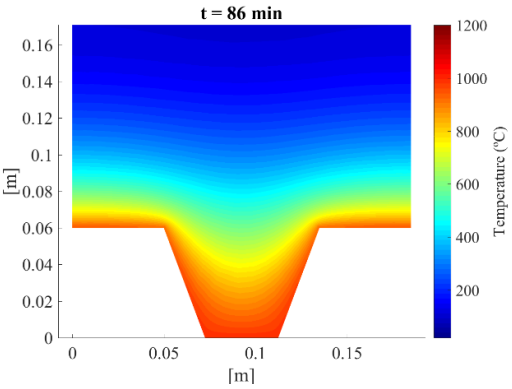


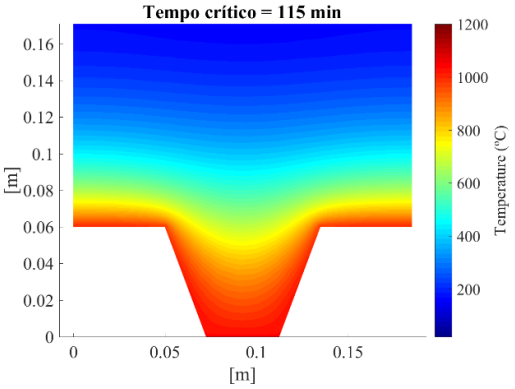


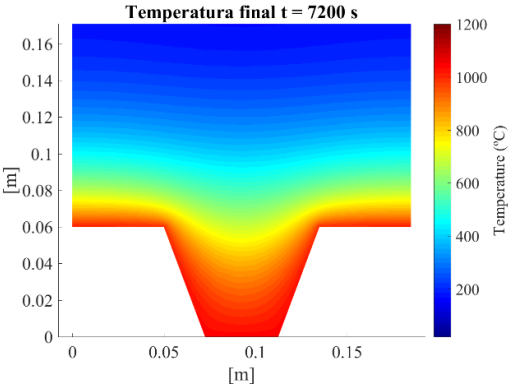




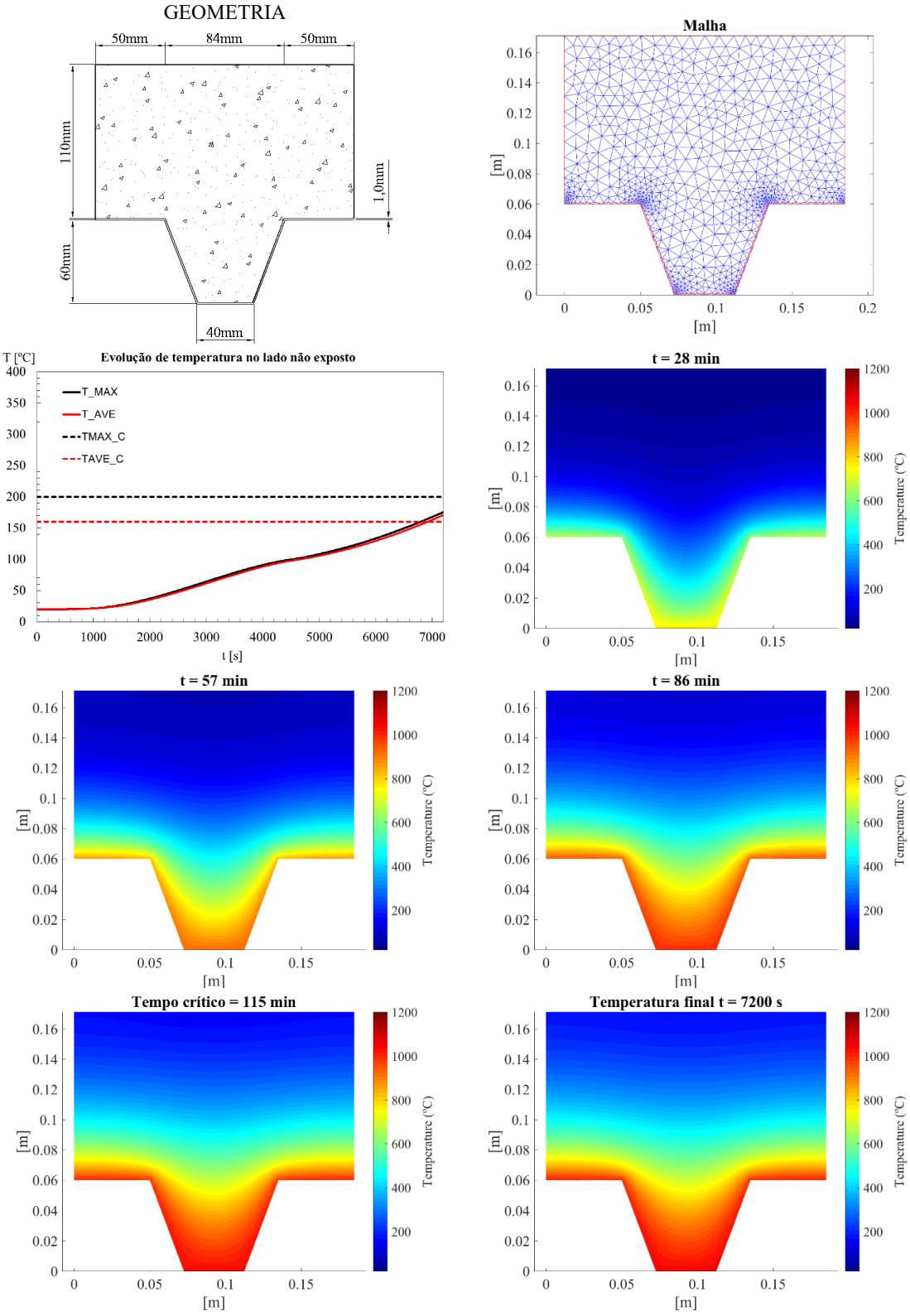




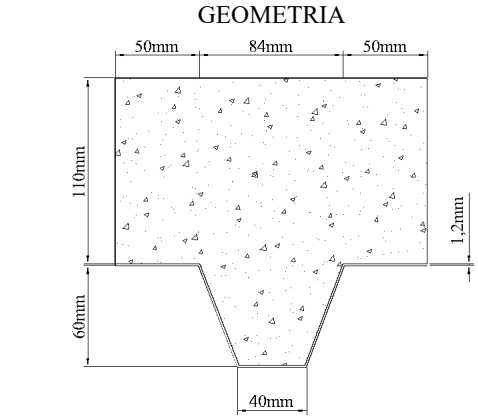


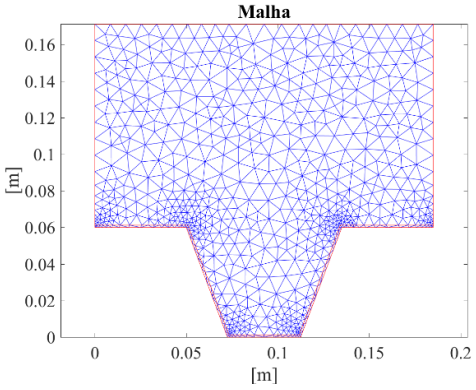


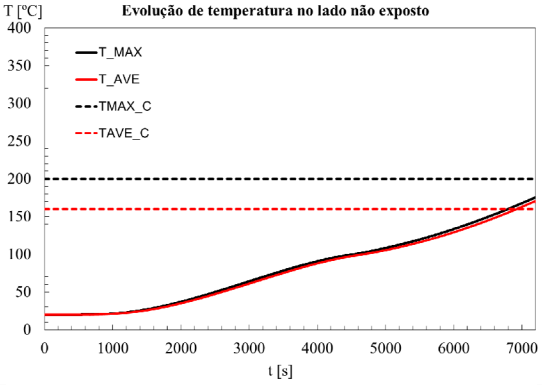
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.0mm

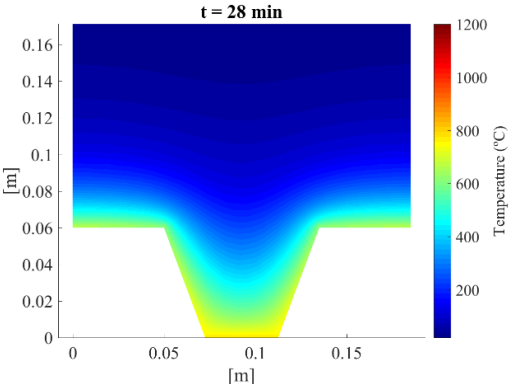


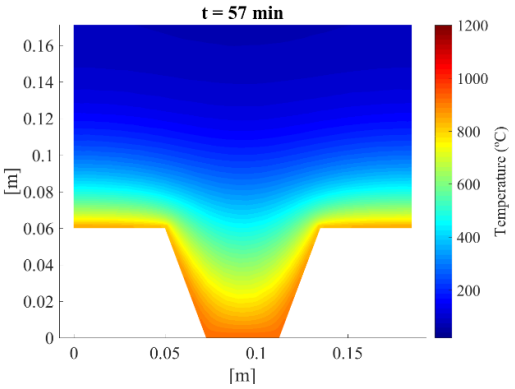
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.2mm

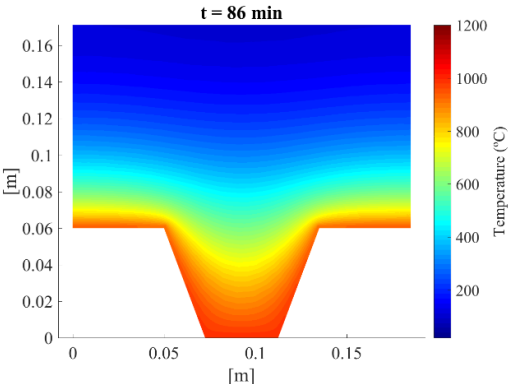


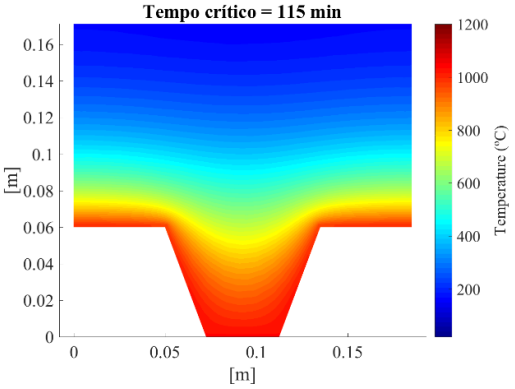


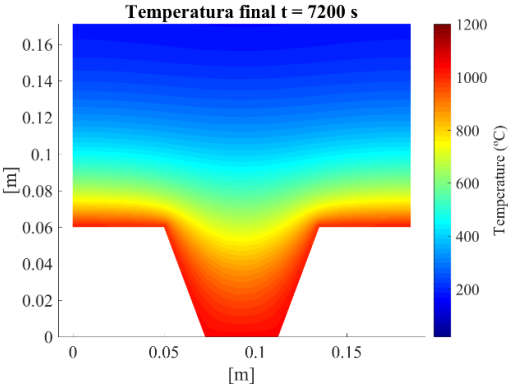




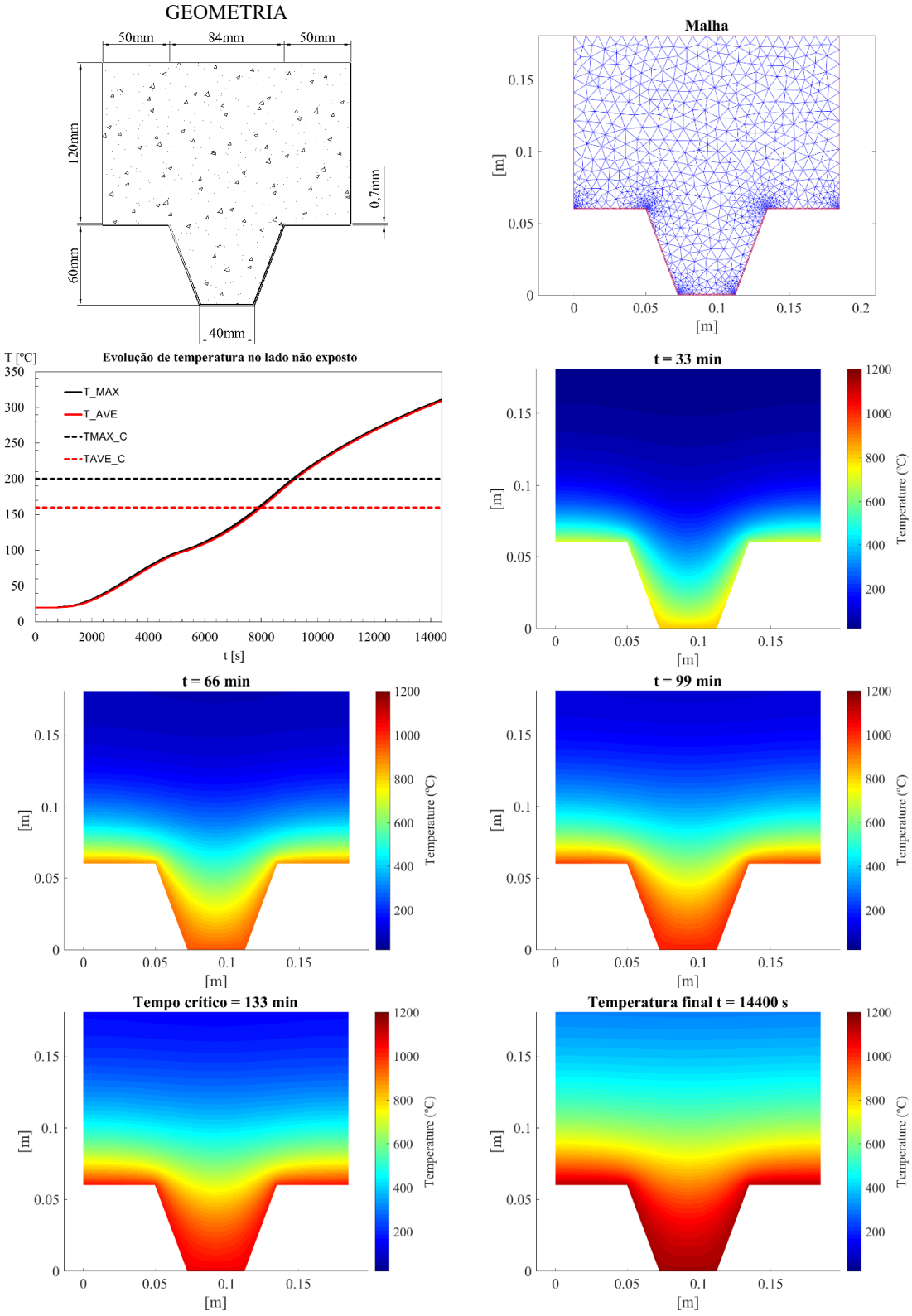




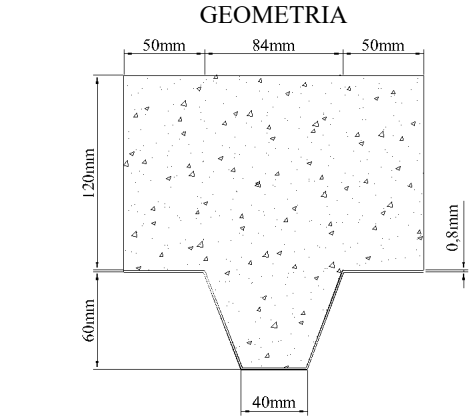


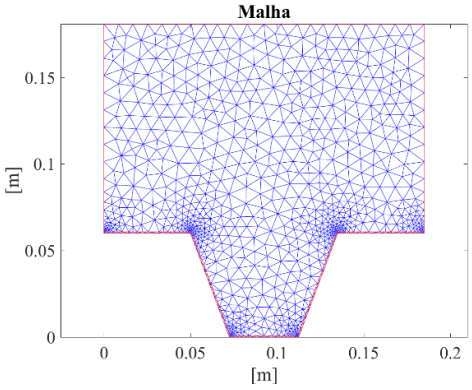


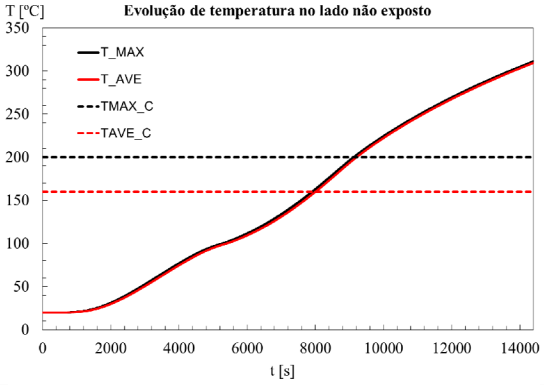
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.7mm

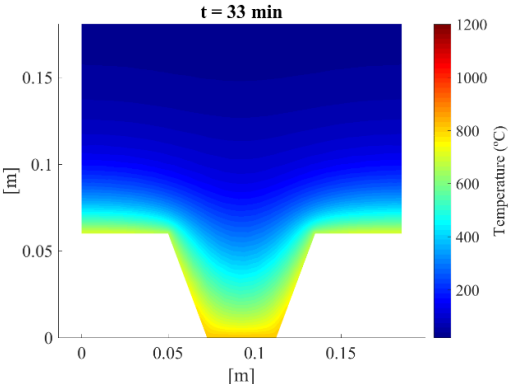


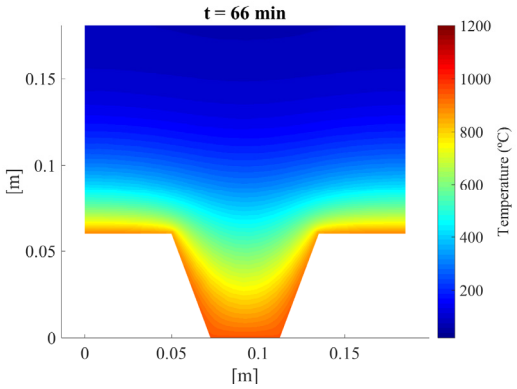
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.8mm

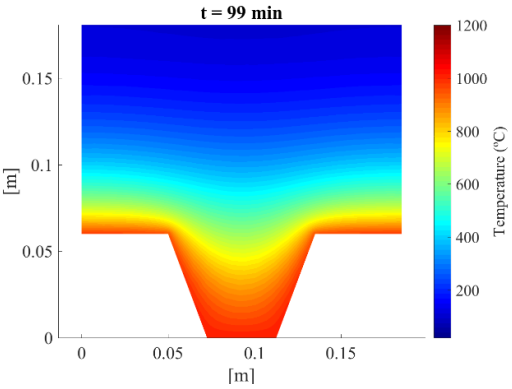


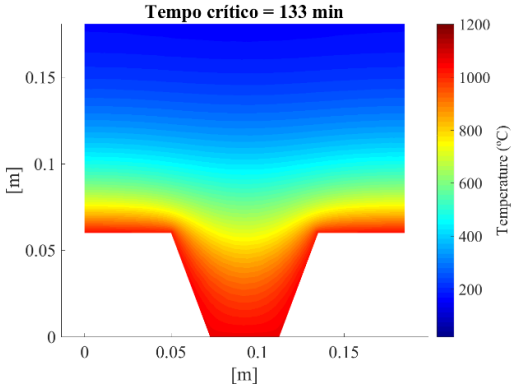


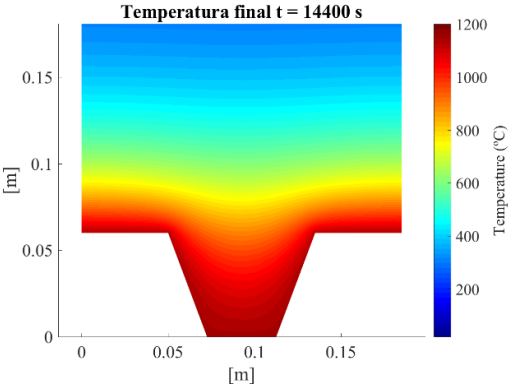




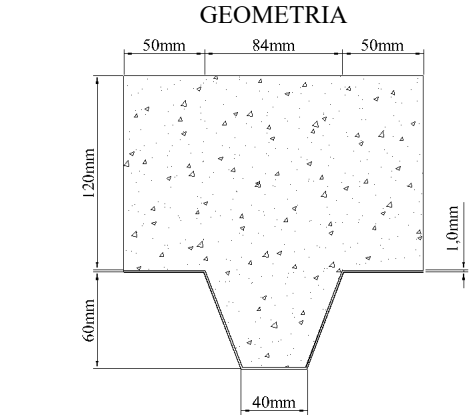


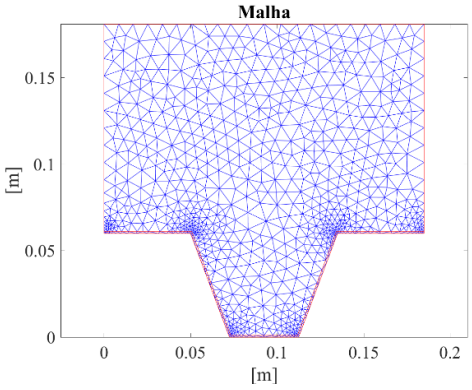


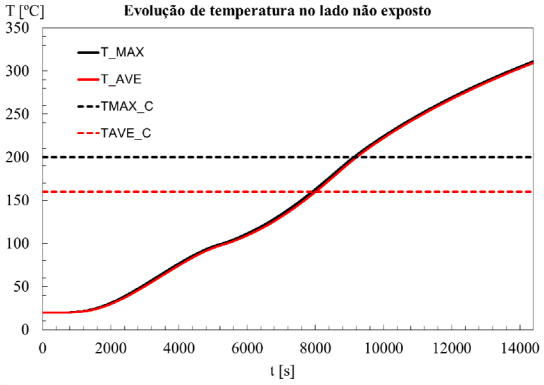


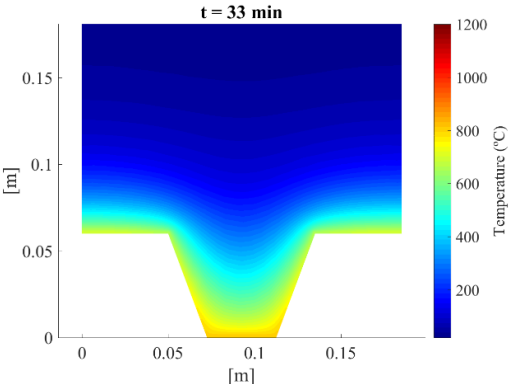


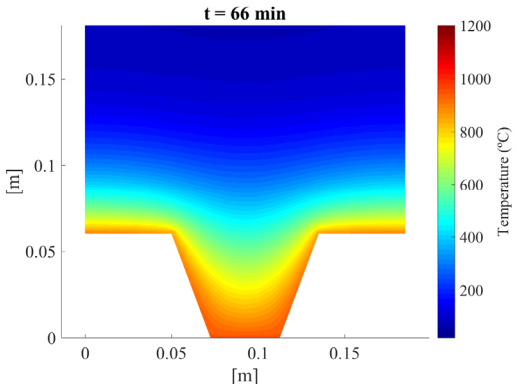
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.0mm

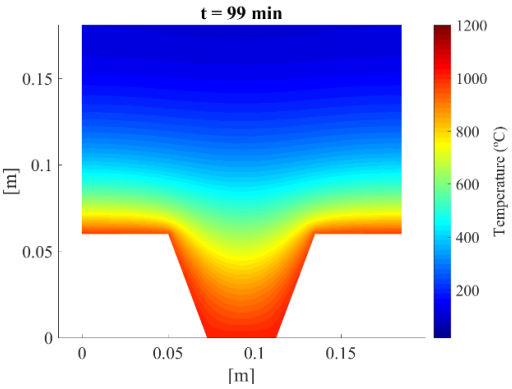


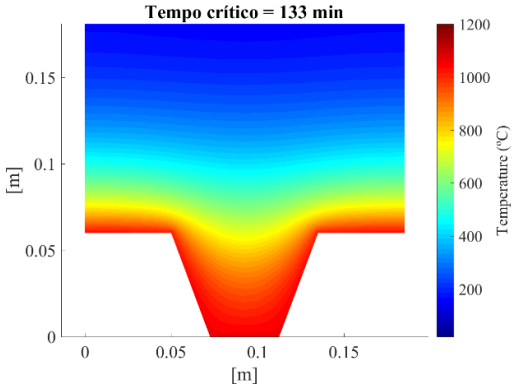


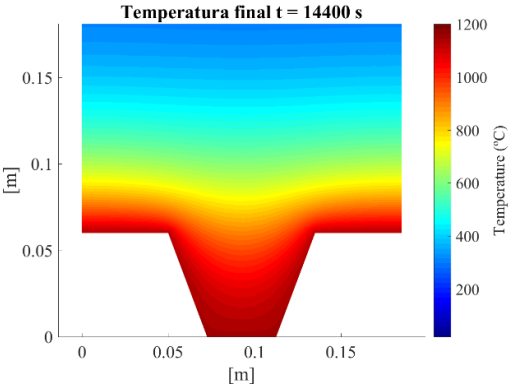




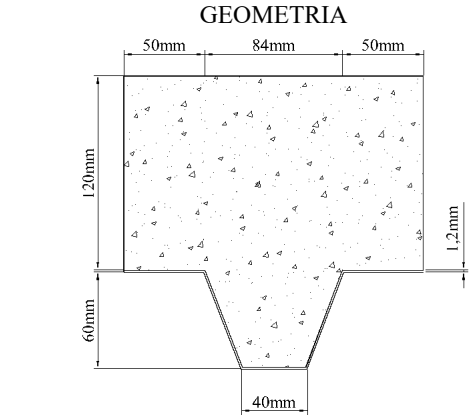


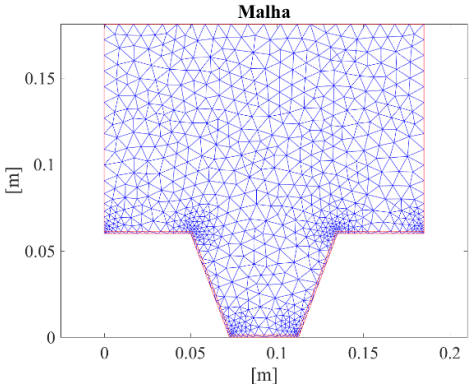


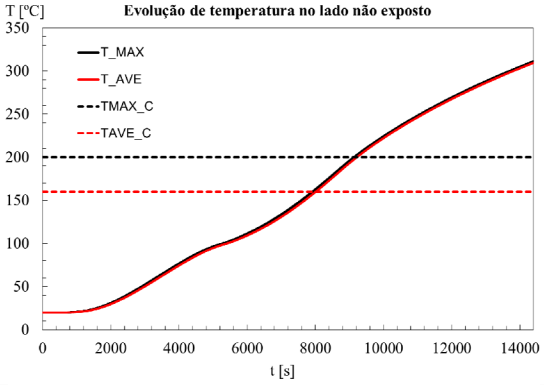


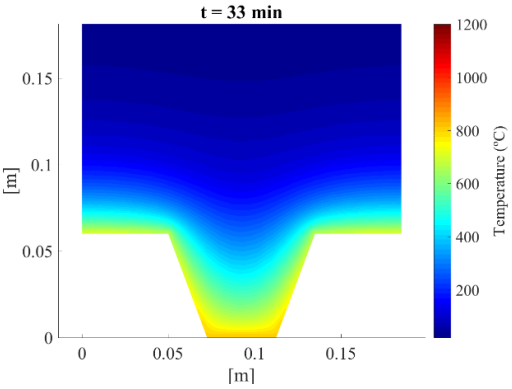


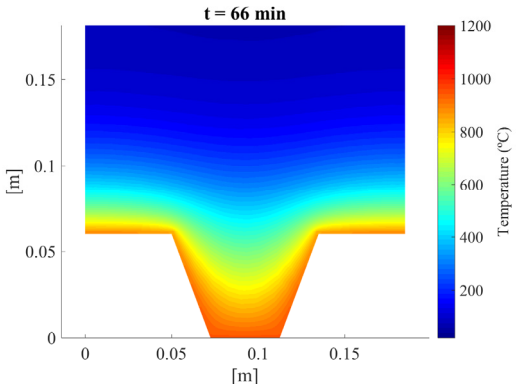
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.2mm

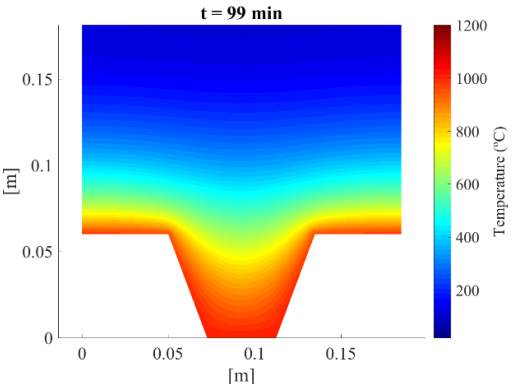


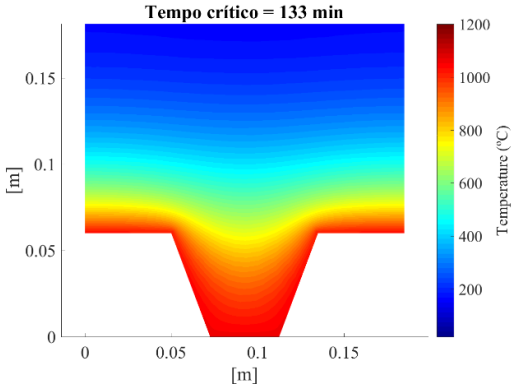


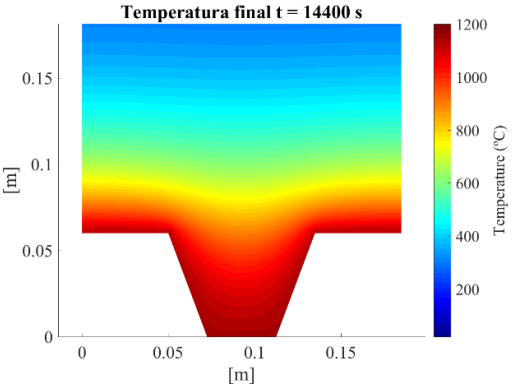




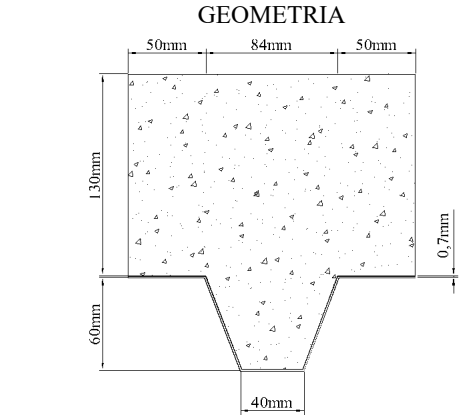


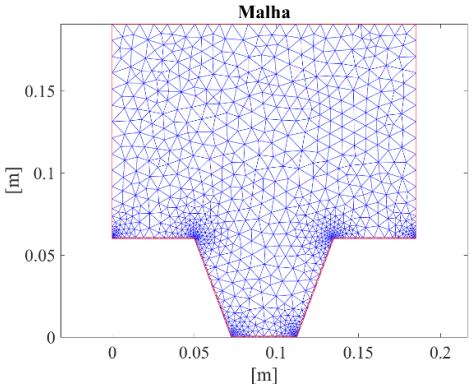


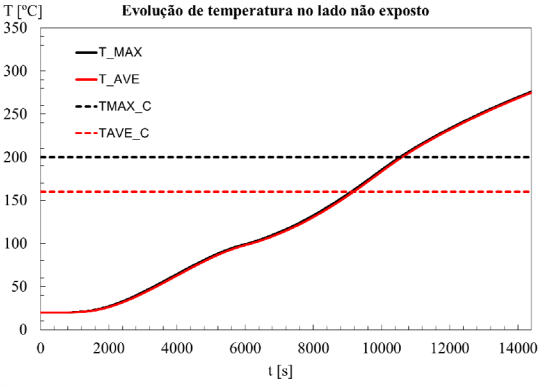


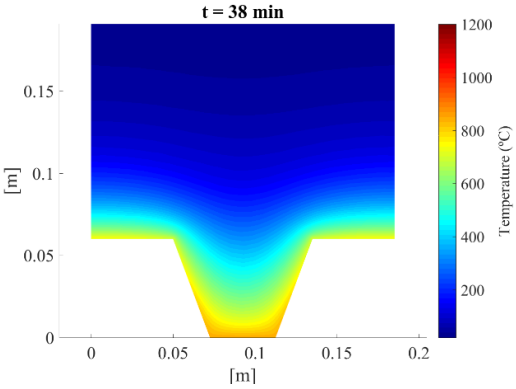


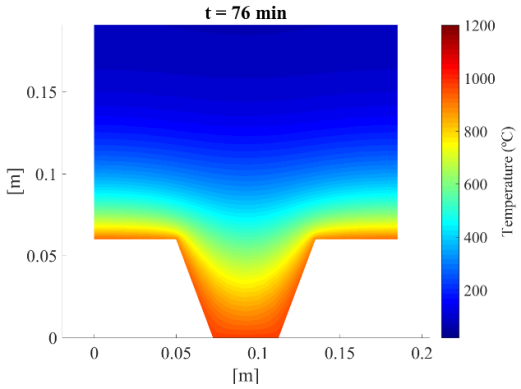
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.7mm

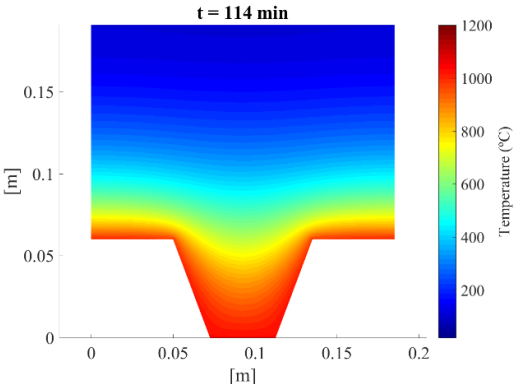


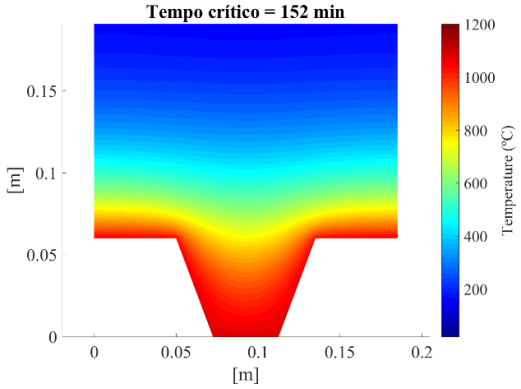


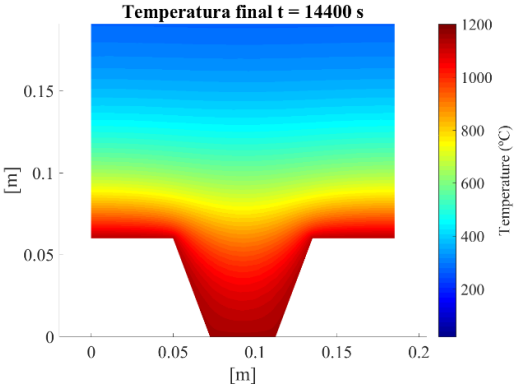




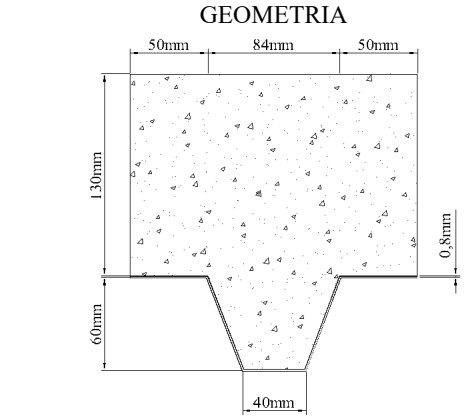


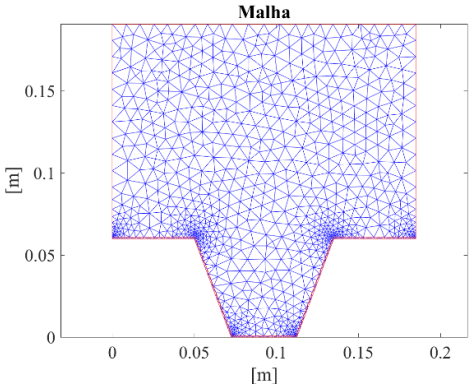


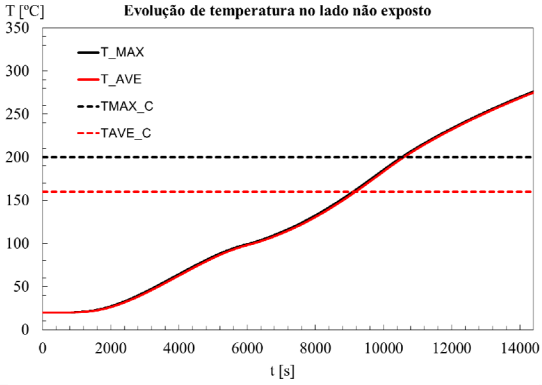


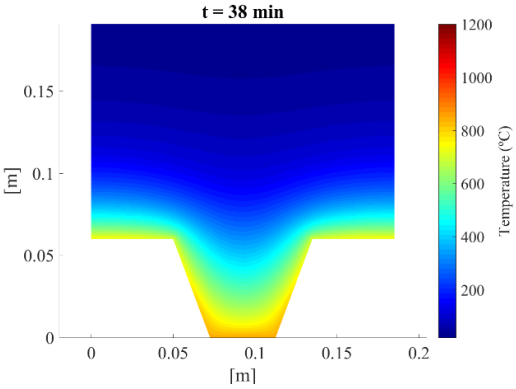


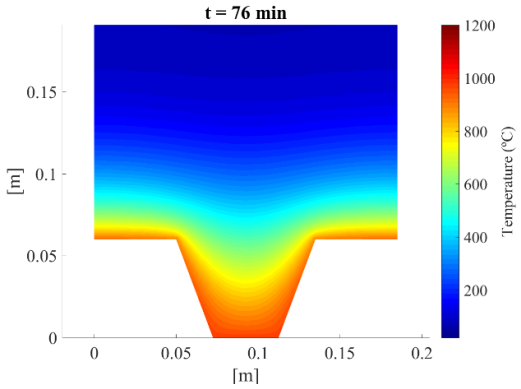
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.8mm

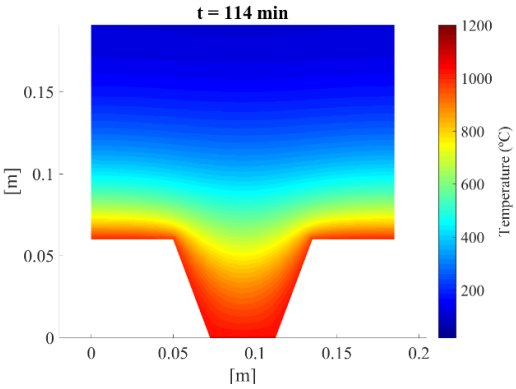


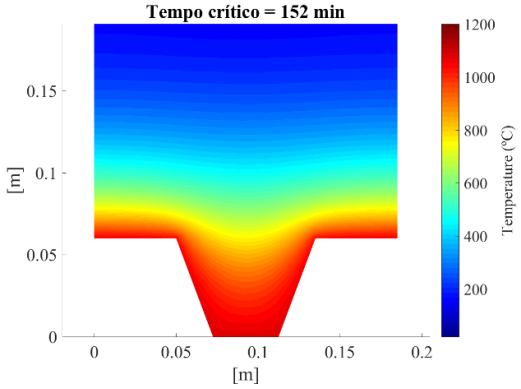


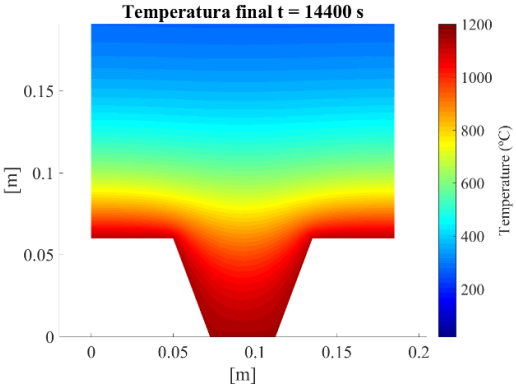




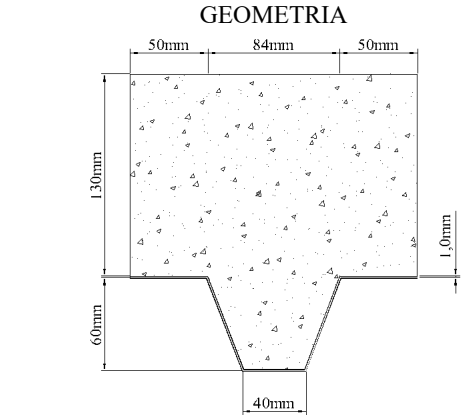


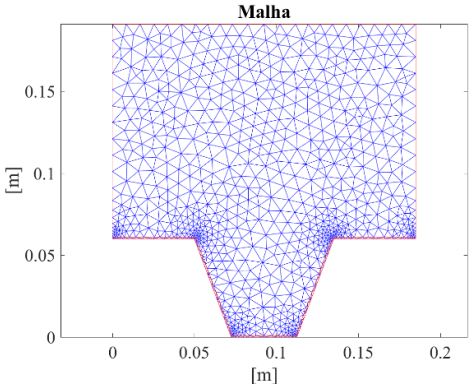


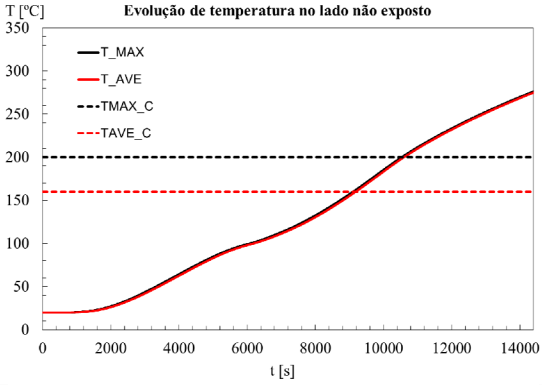


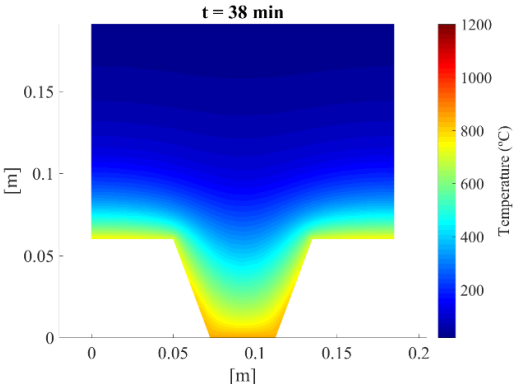


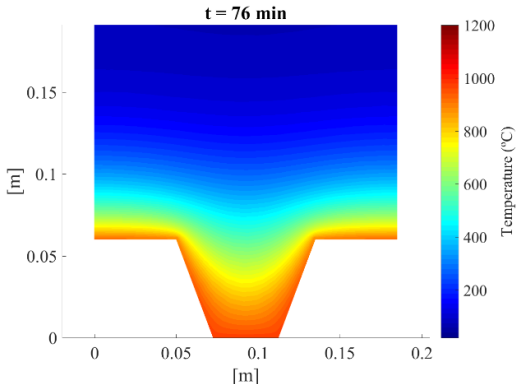
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.0mm

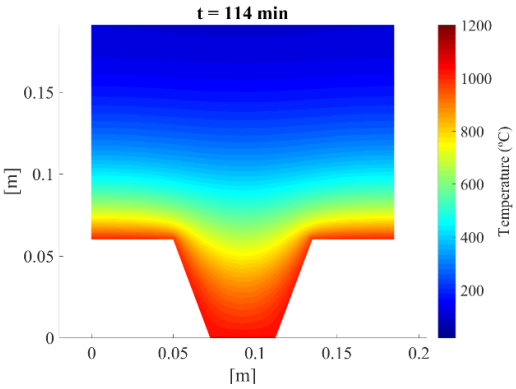


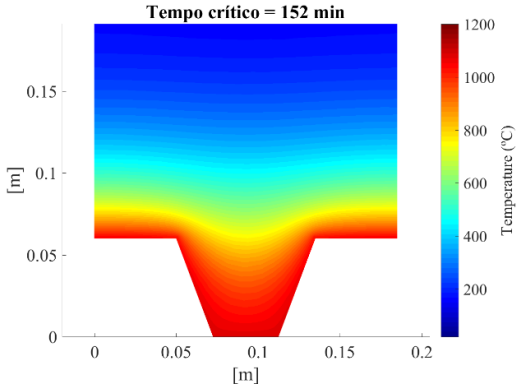


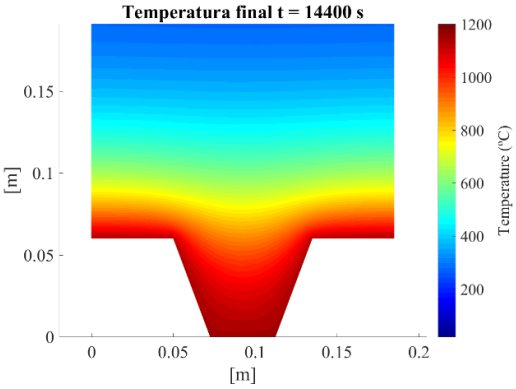




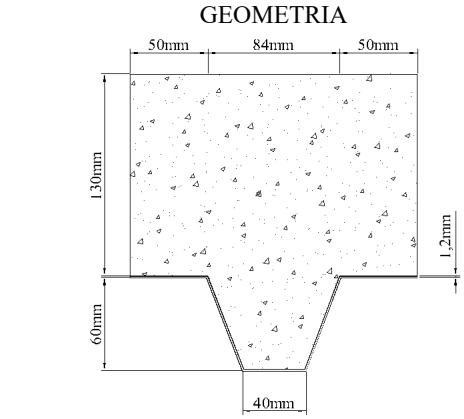


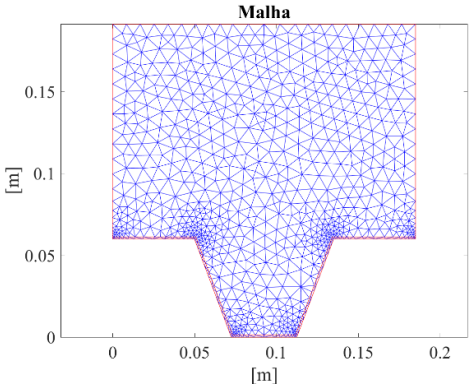


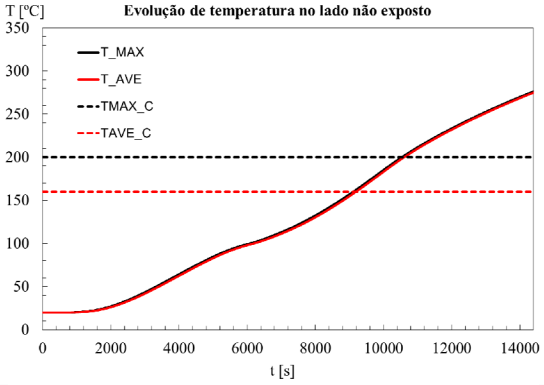


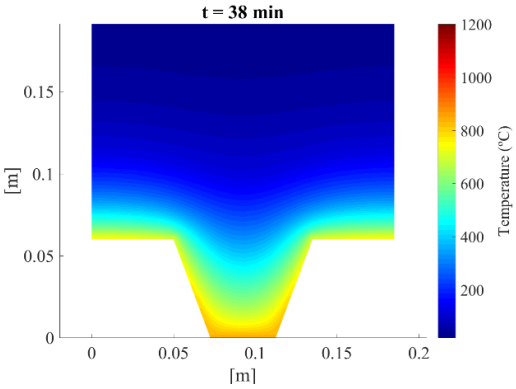


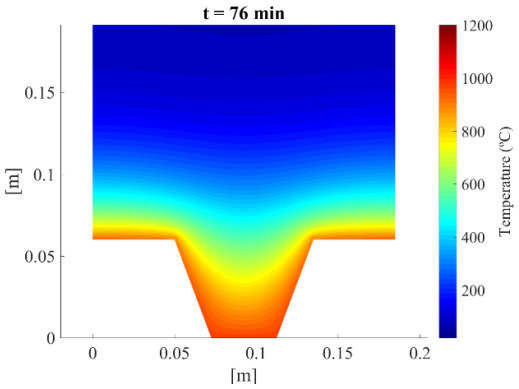
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.2mm

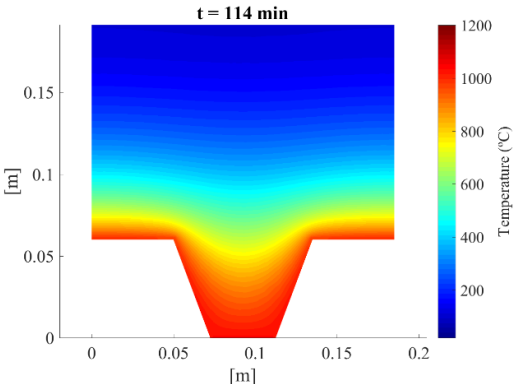


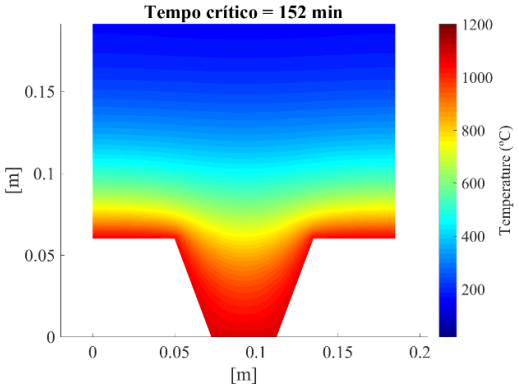


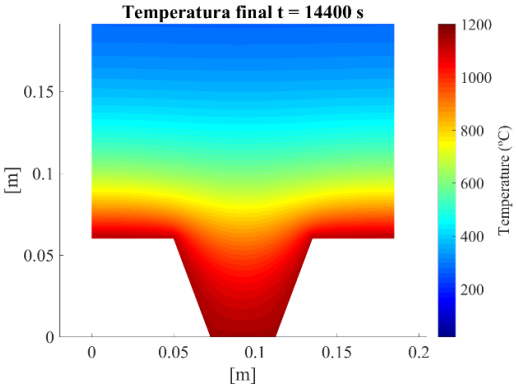




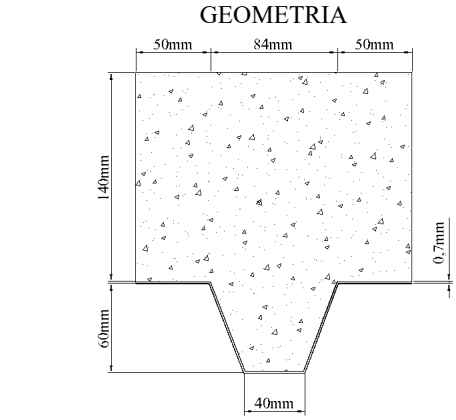


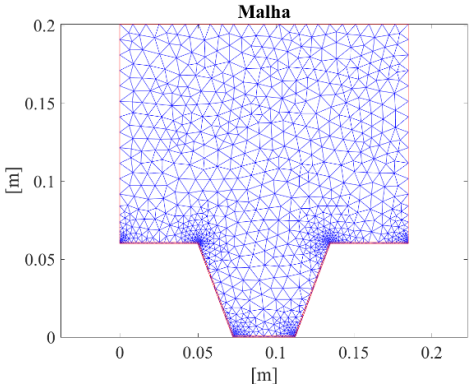


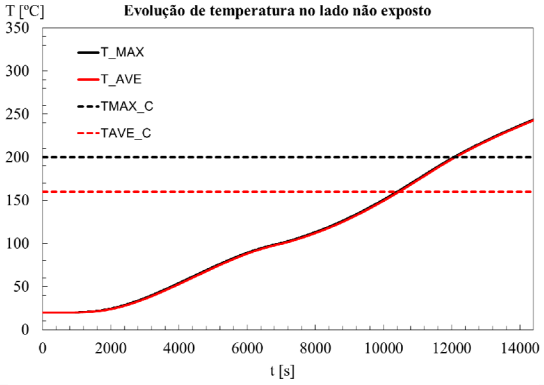


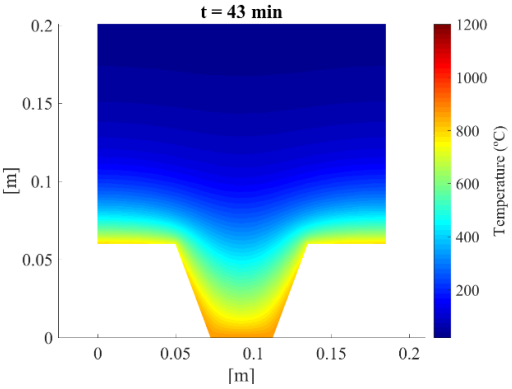


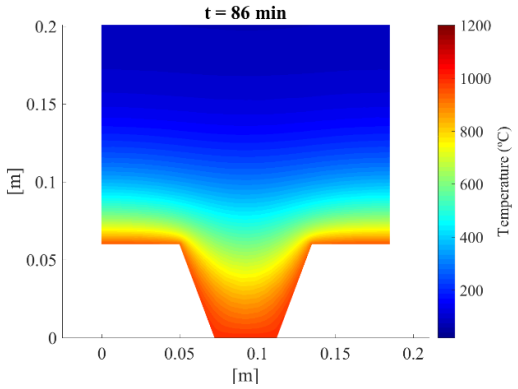
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.7mm

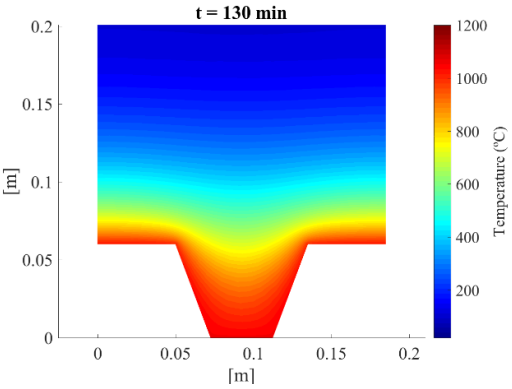


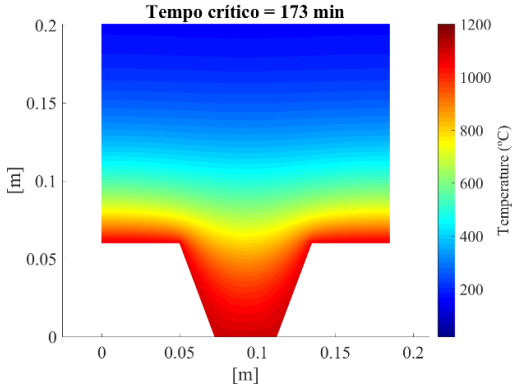


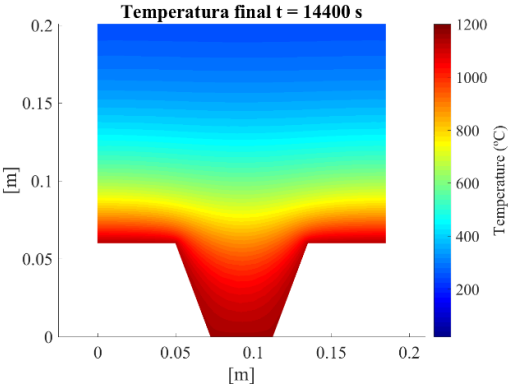




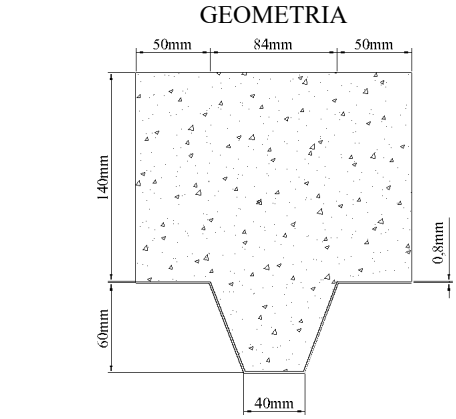


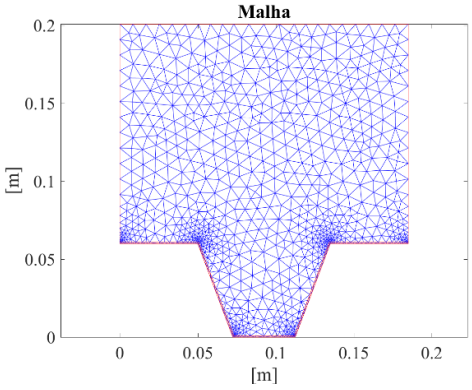


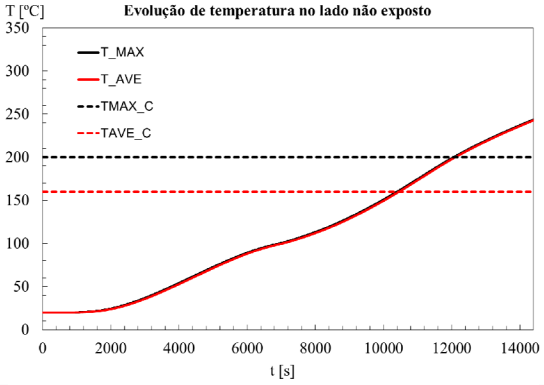


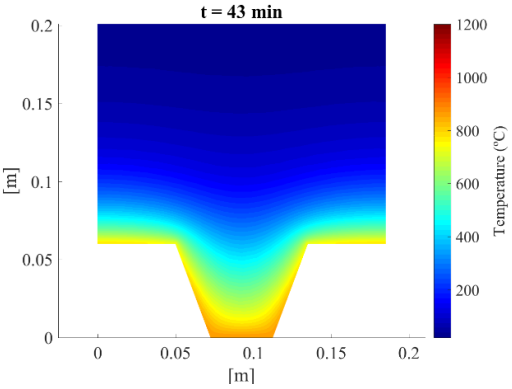


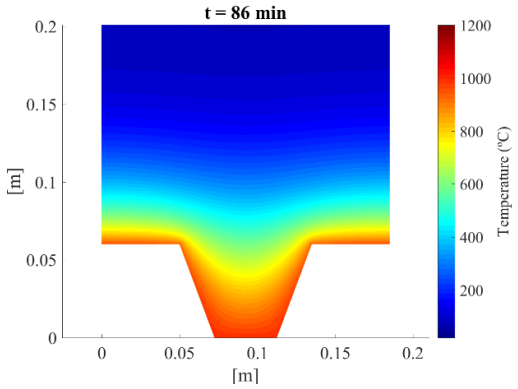
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.8mm

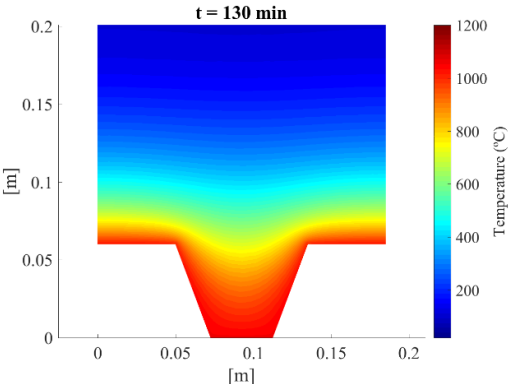


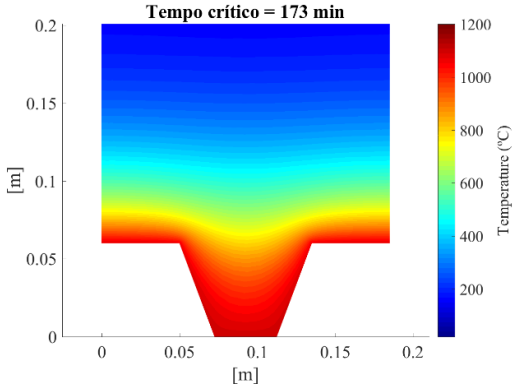


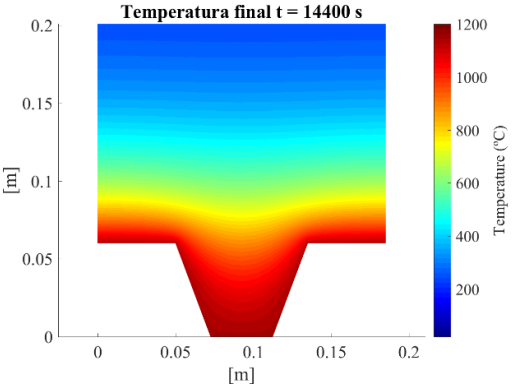




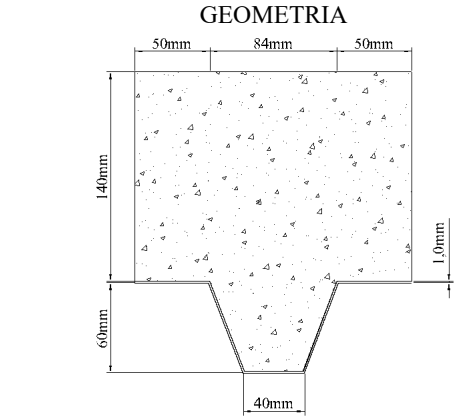


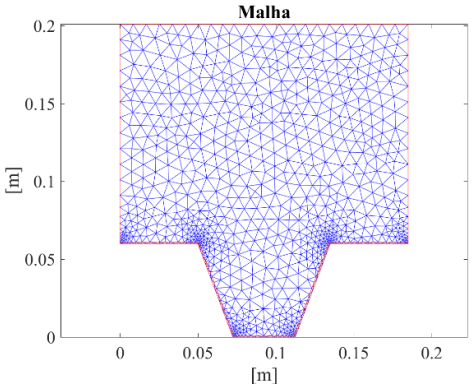


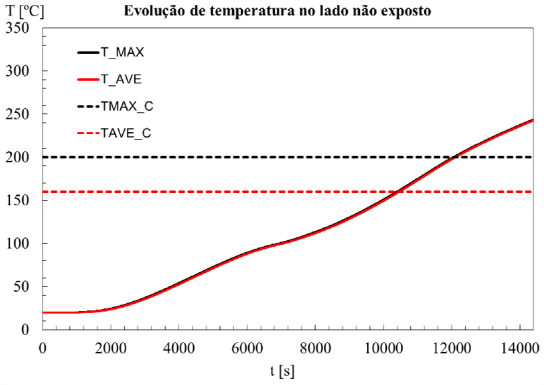


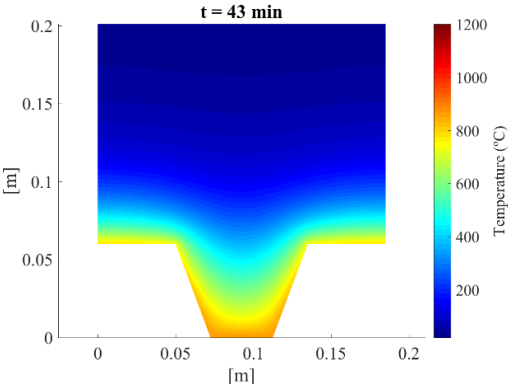


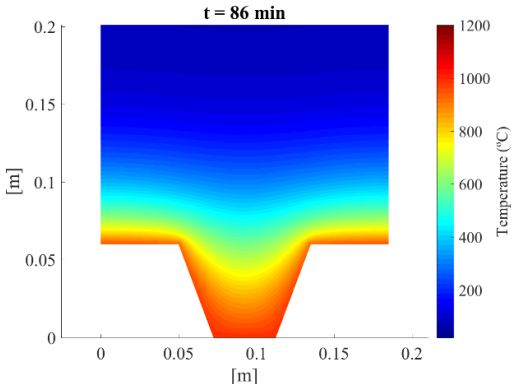
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.0mm

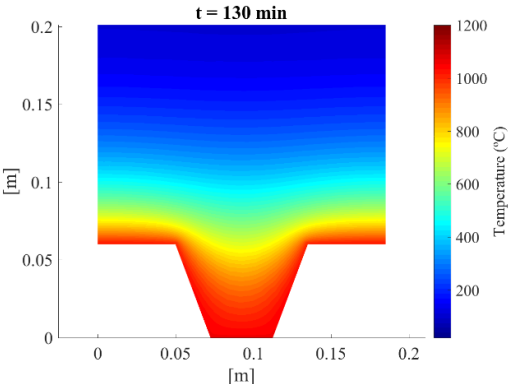


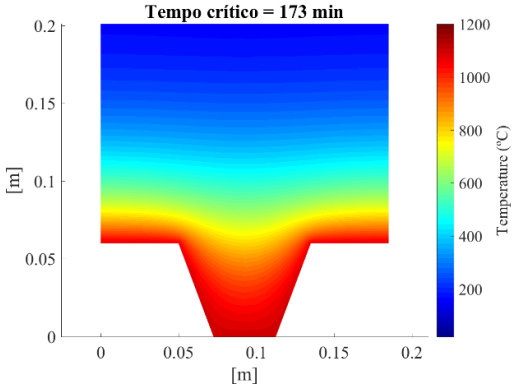


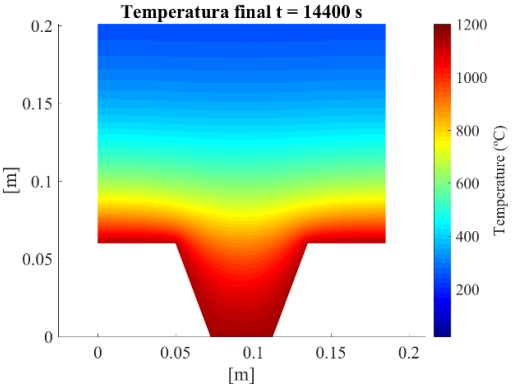




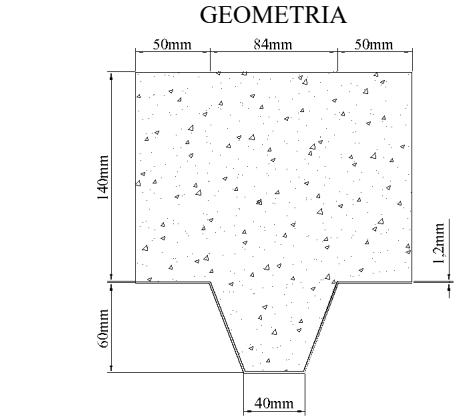


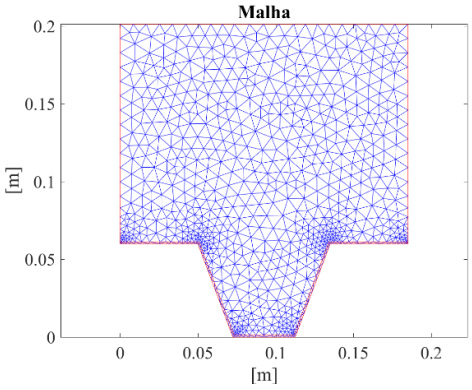


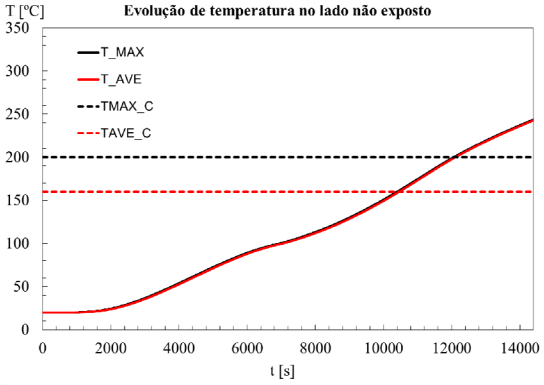


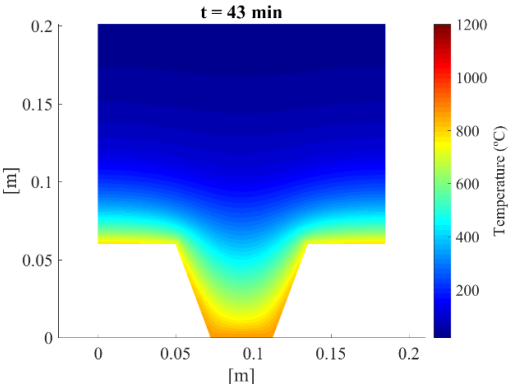


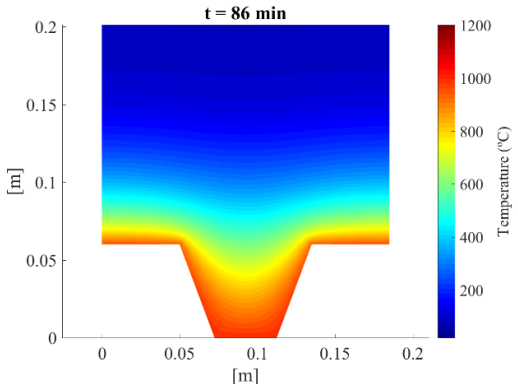
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.2mm

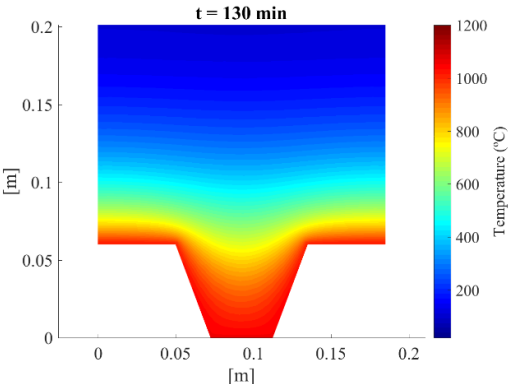


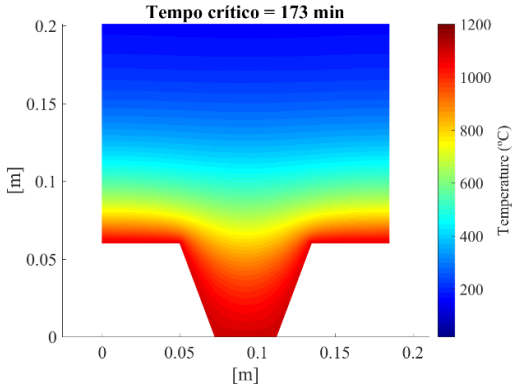


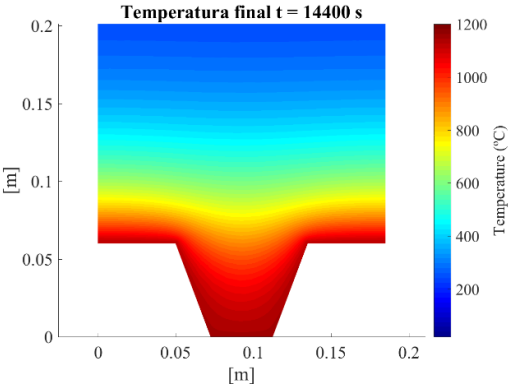






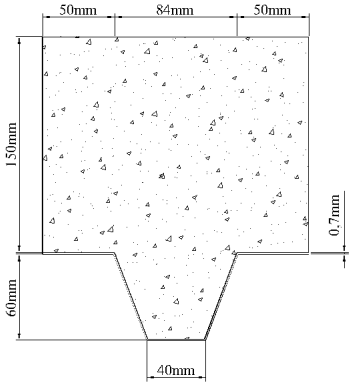






LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.7mm

GEOMETRIA



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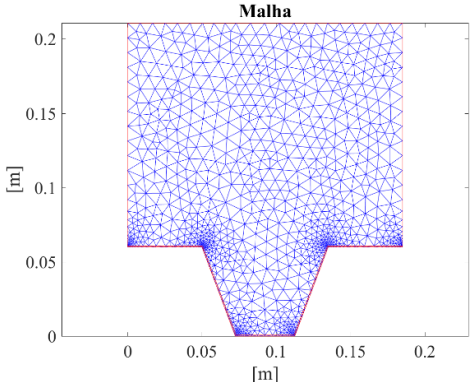
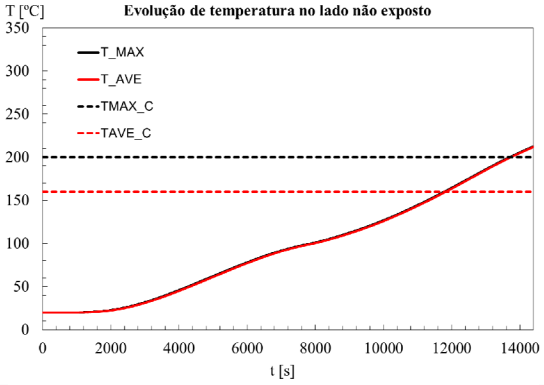
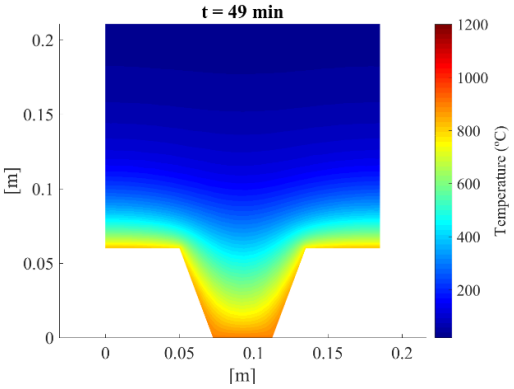
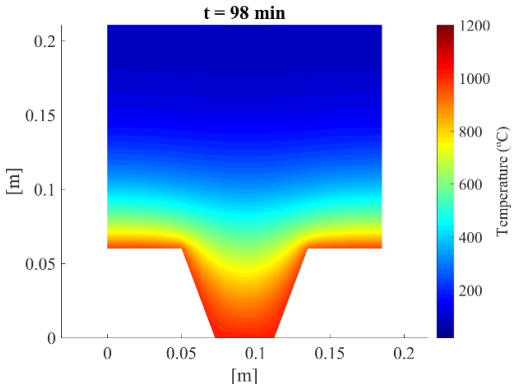
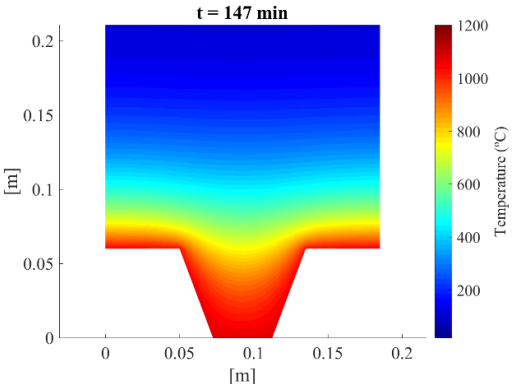
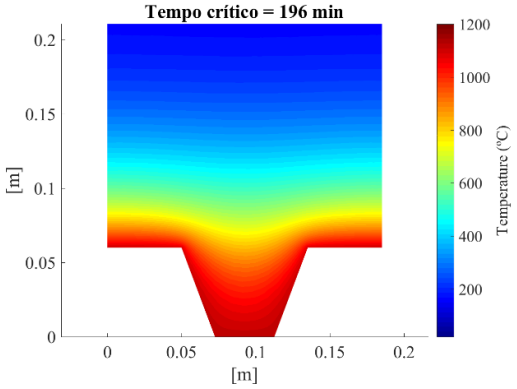


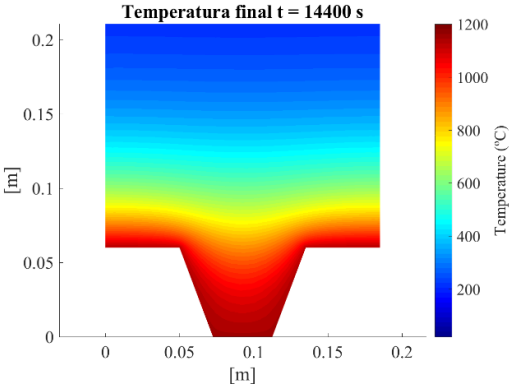




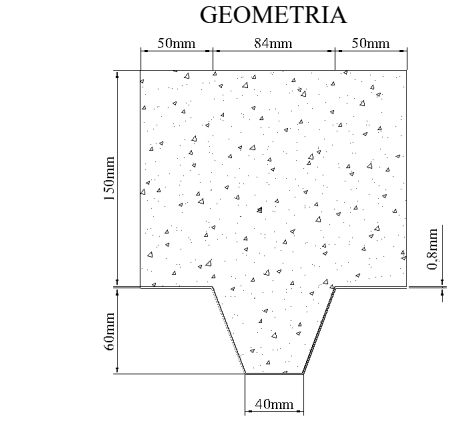


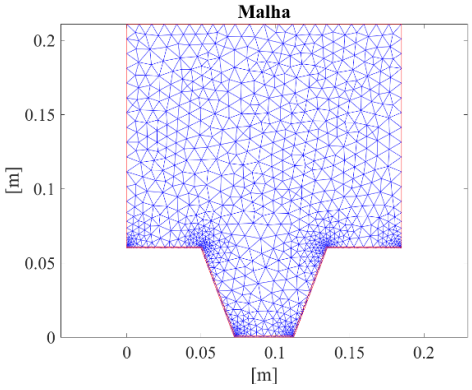


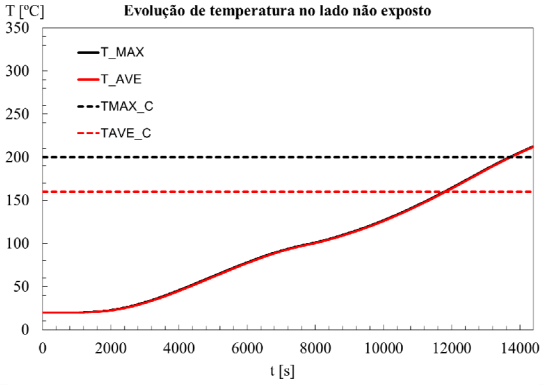


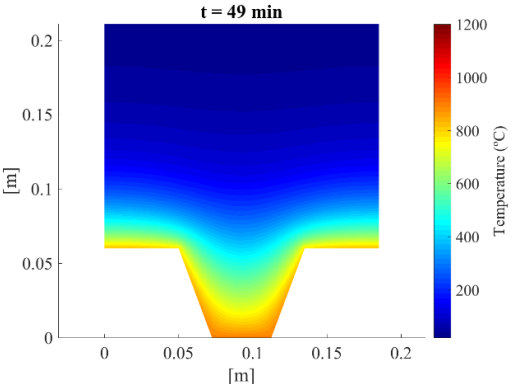


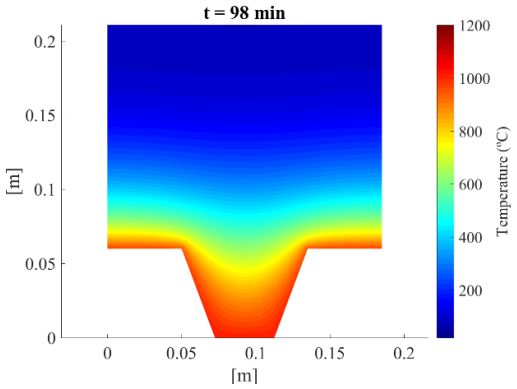
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.8mm

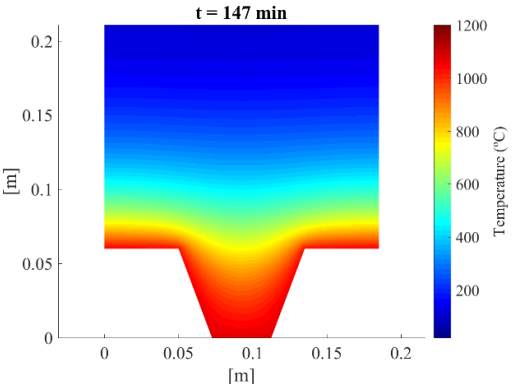


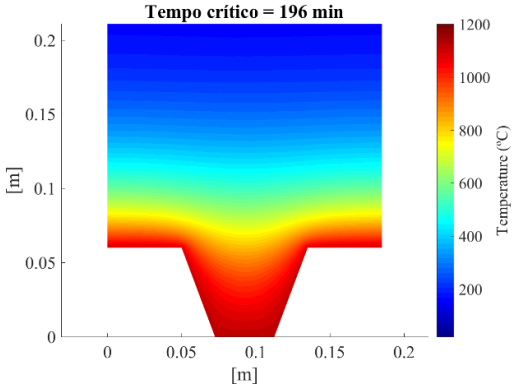


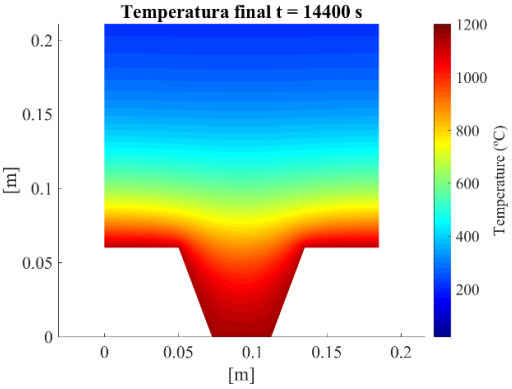




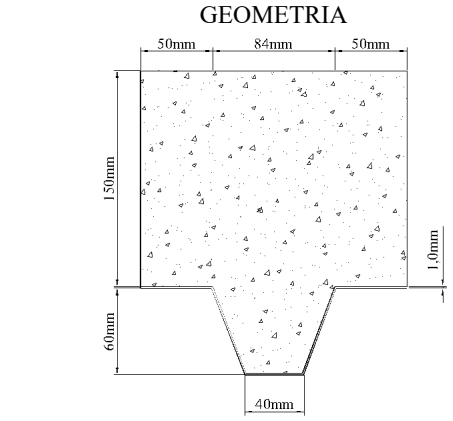


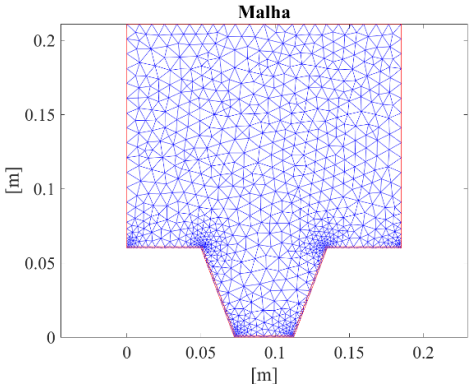


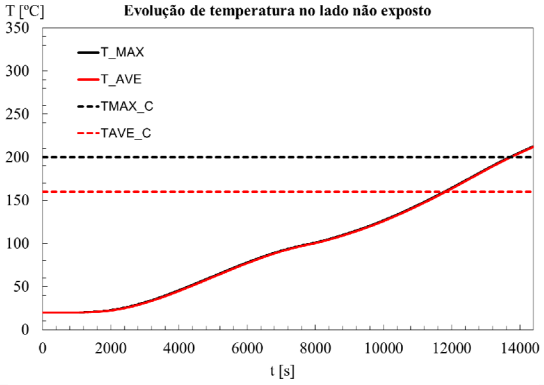


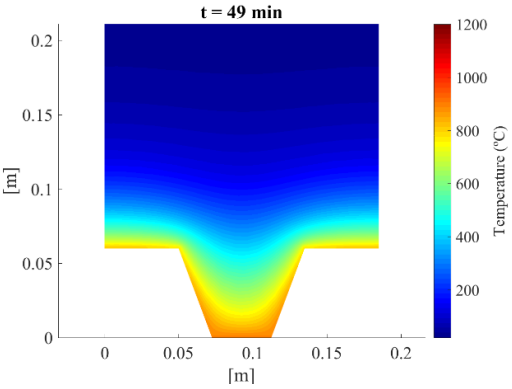


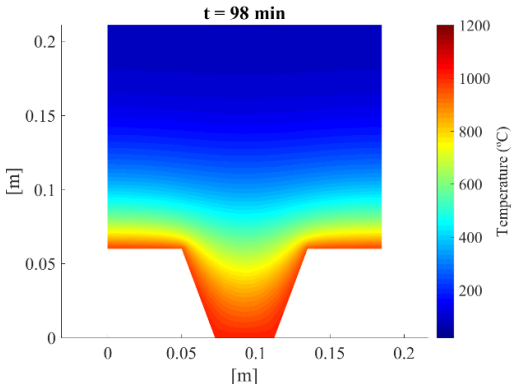
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.0mm

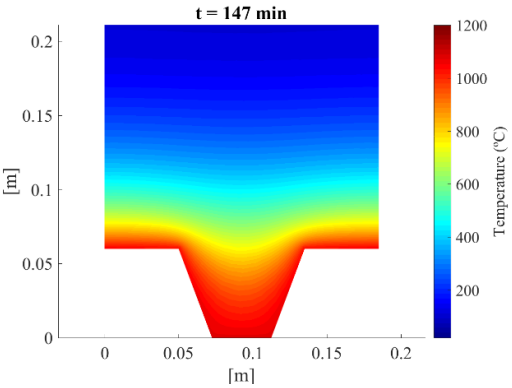


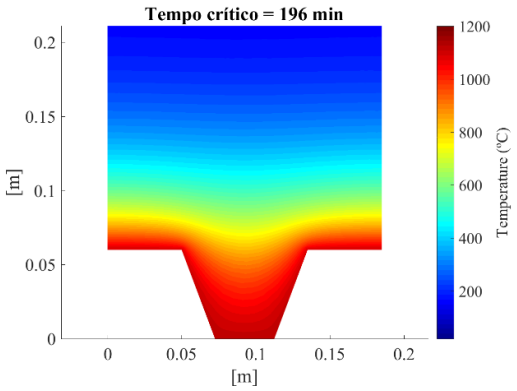


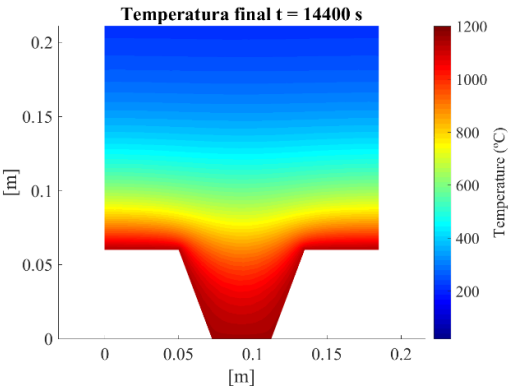




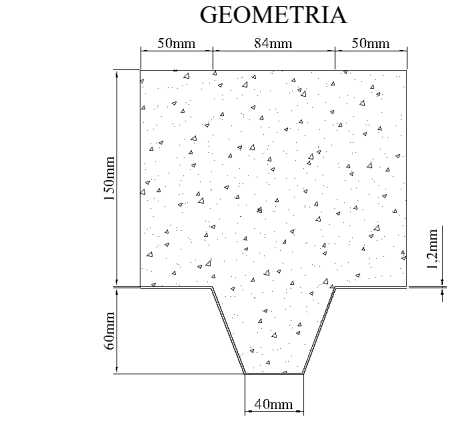


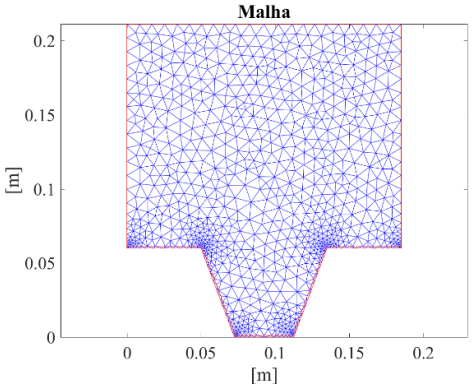


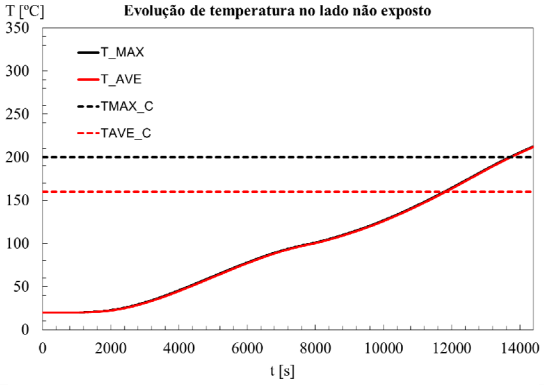


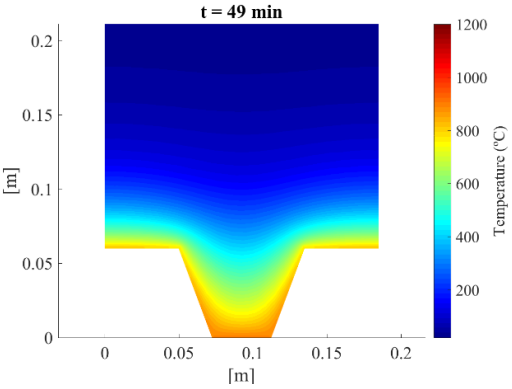


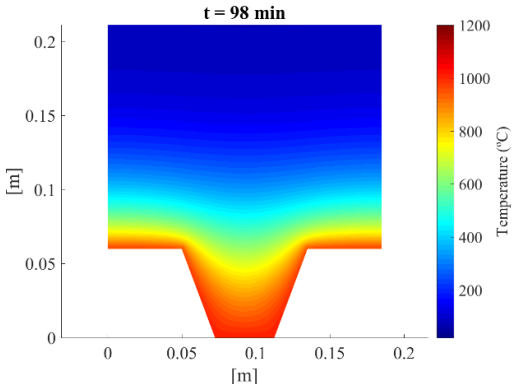
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.2mm

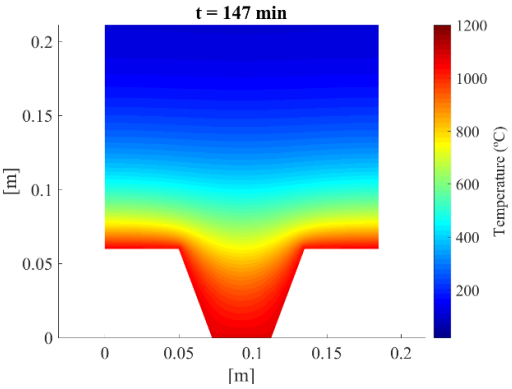


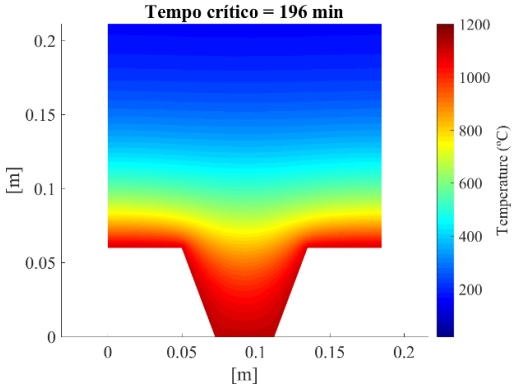


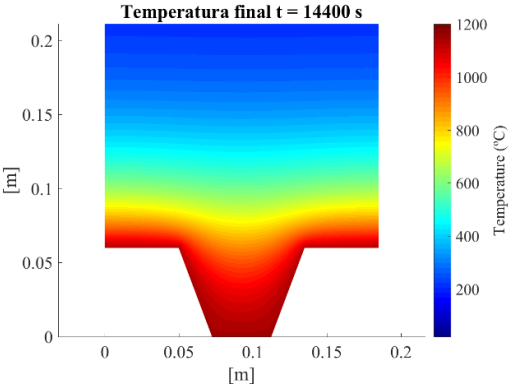






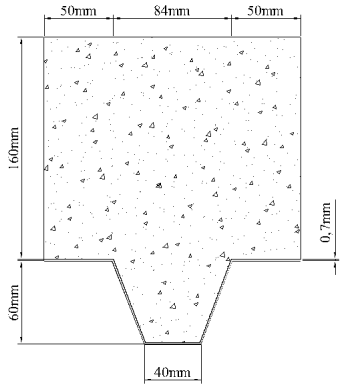


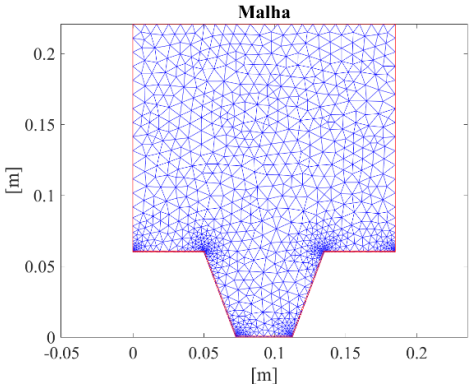


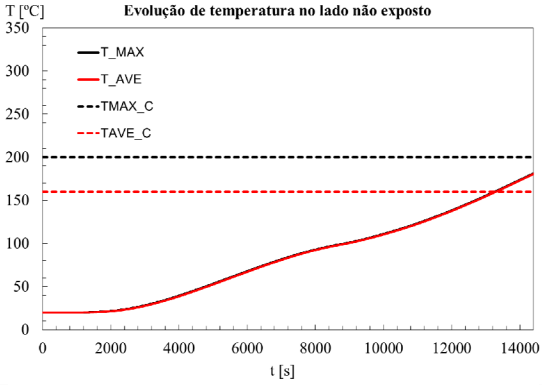


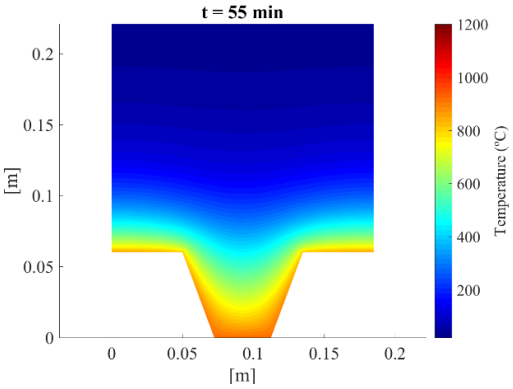
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.7mm

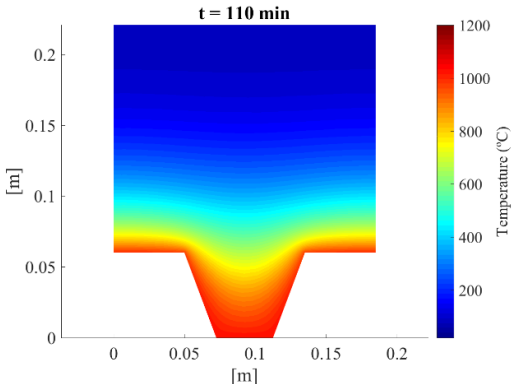
GEOMETRIA

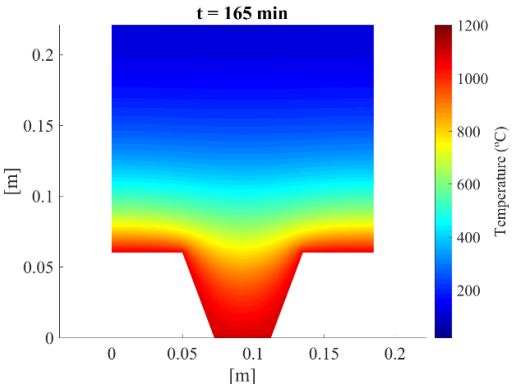


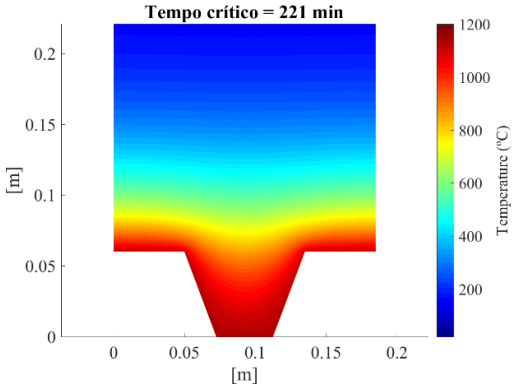


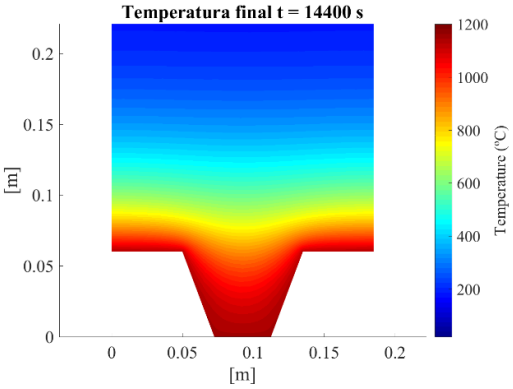






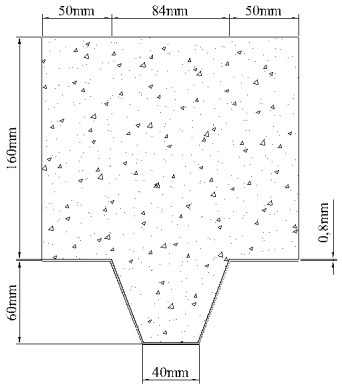


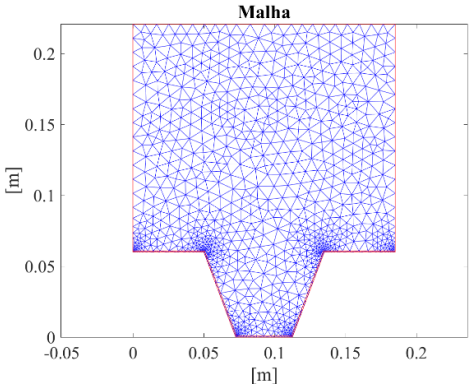


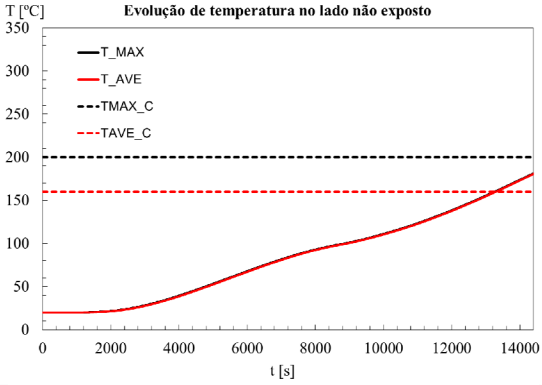


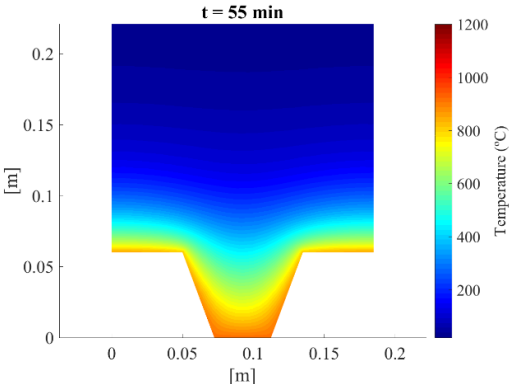
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.8mm

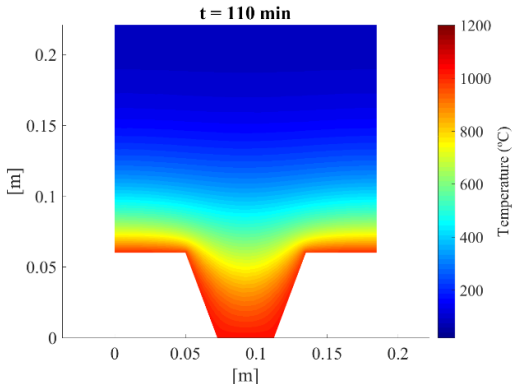
GEOMETRIA

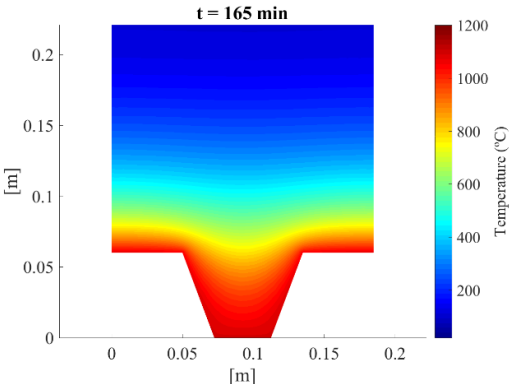


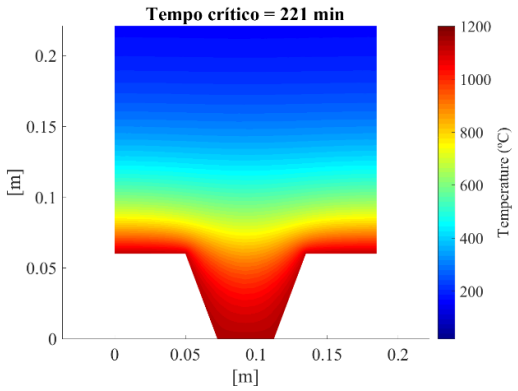


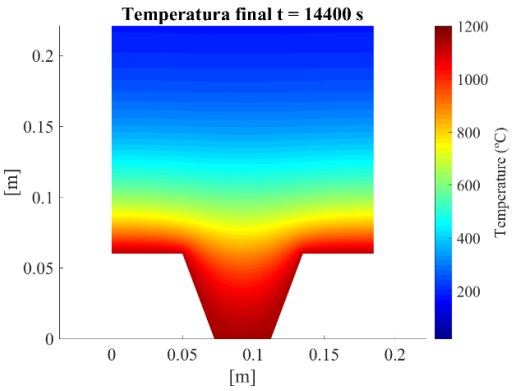




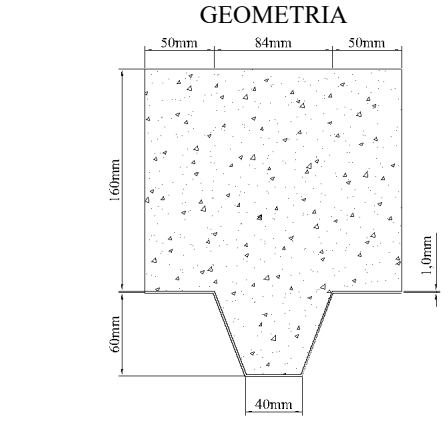


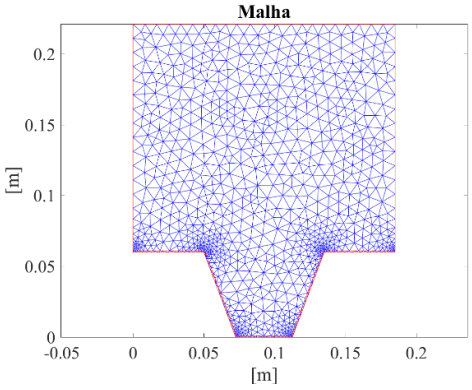


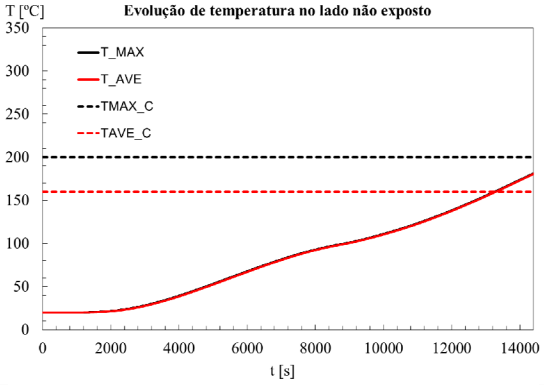


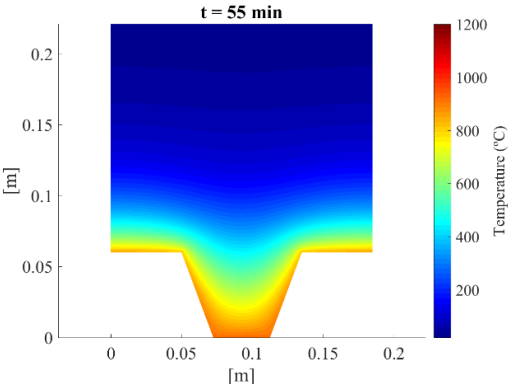


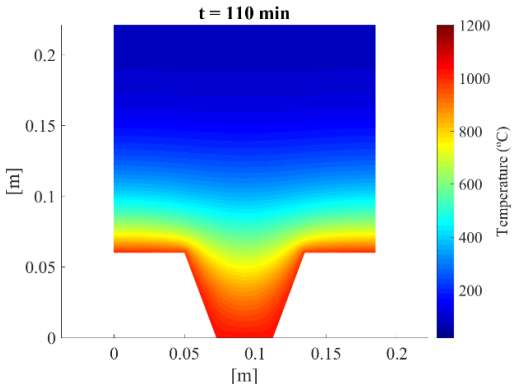
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.0mm

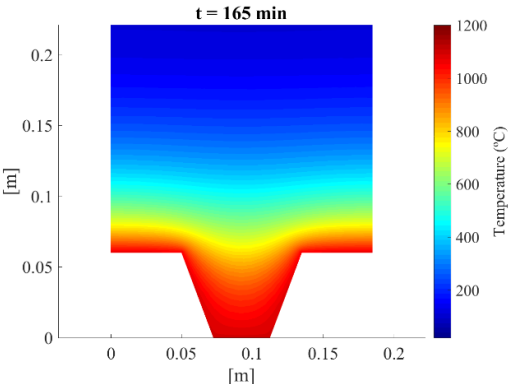


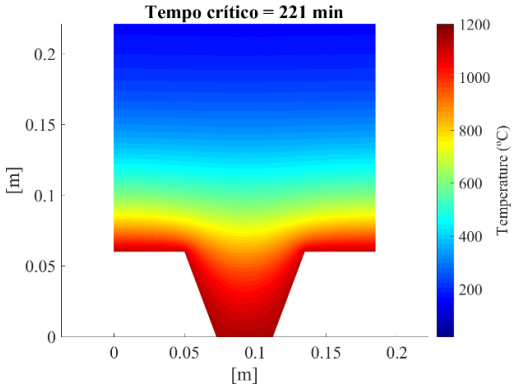


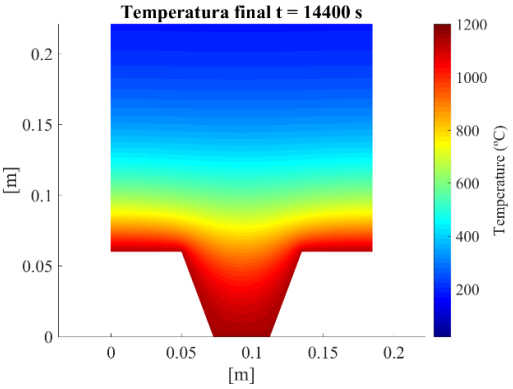






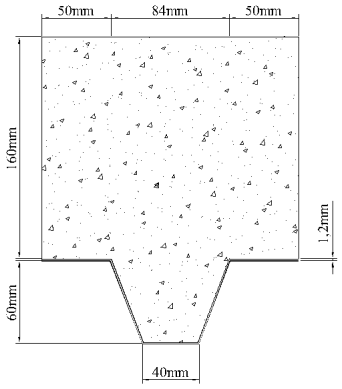


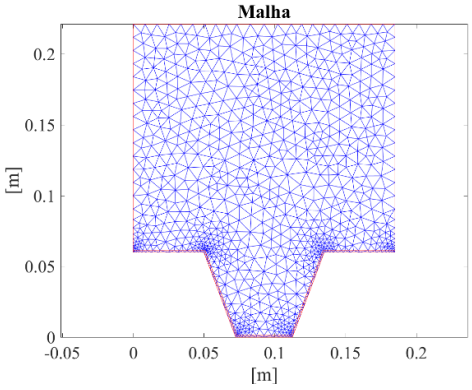


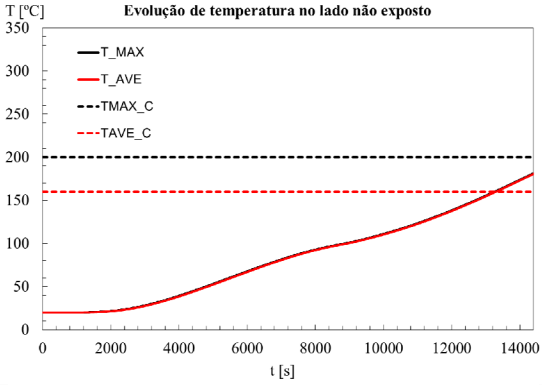


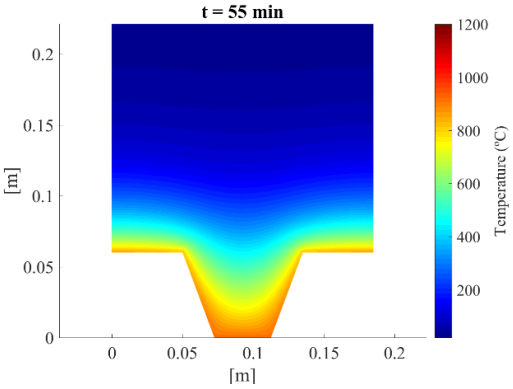
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.2mm

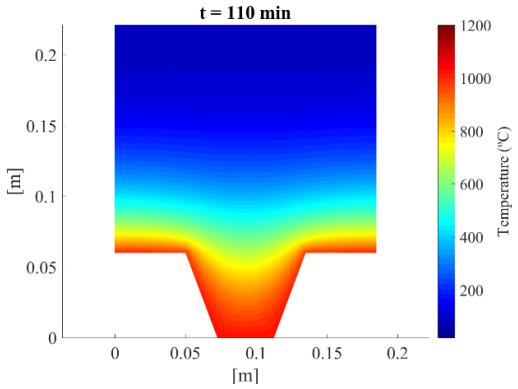
GEOMETRIA

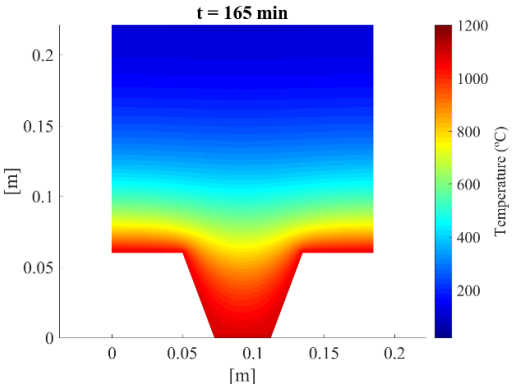


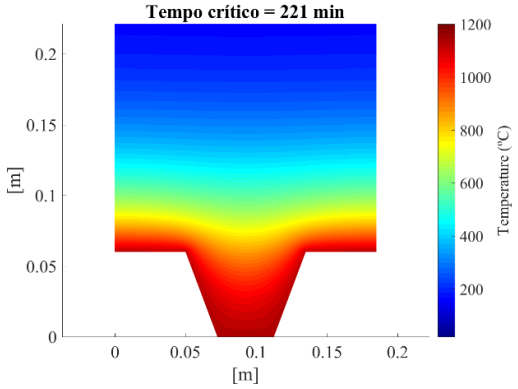


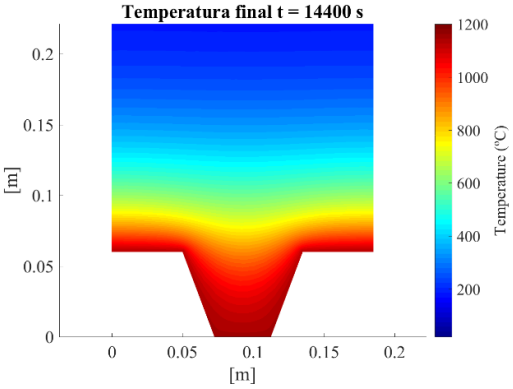




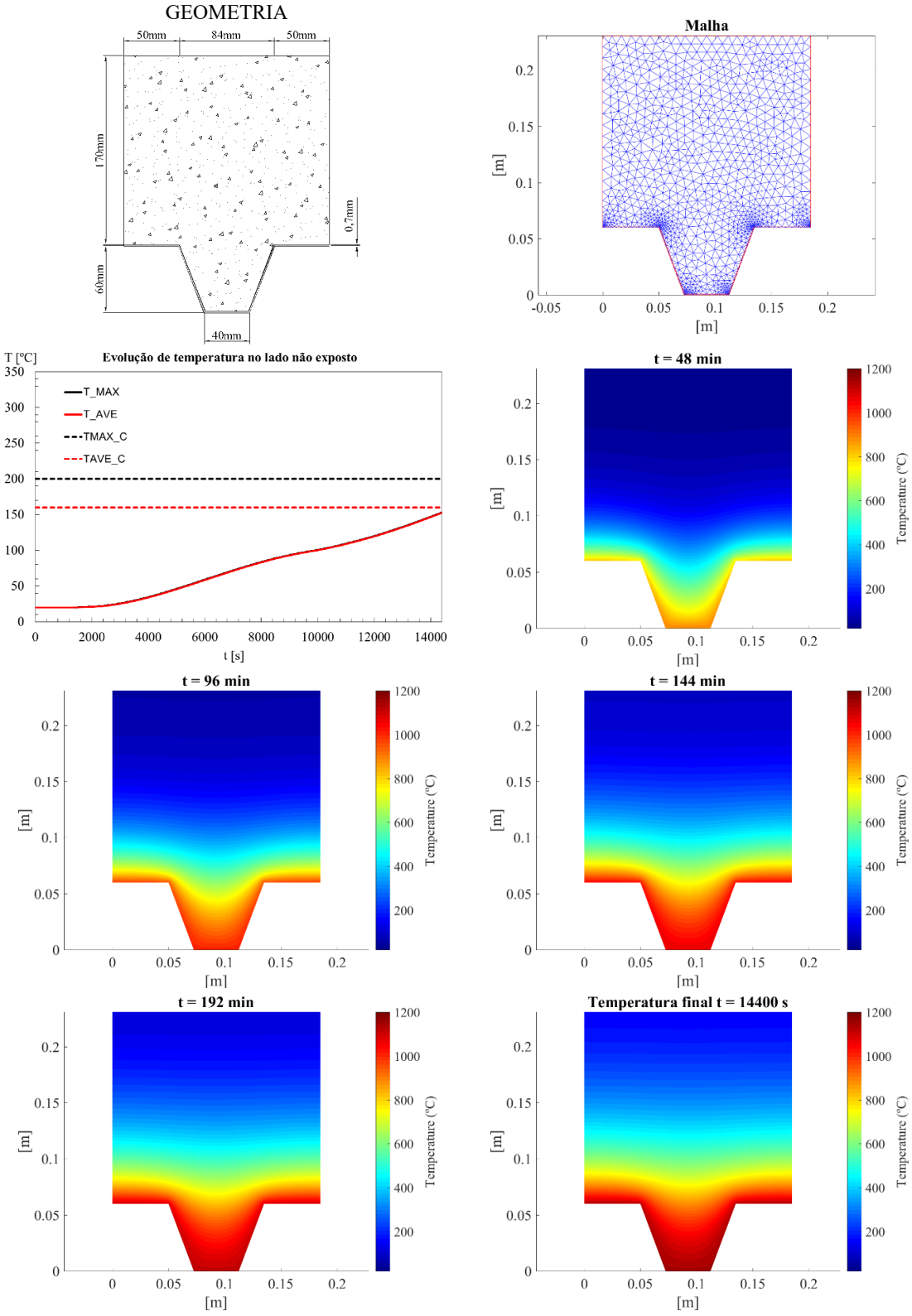








LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.7mm



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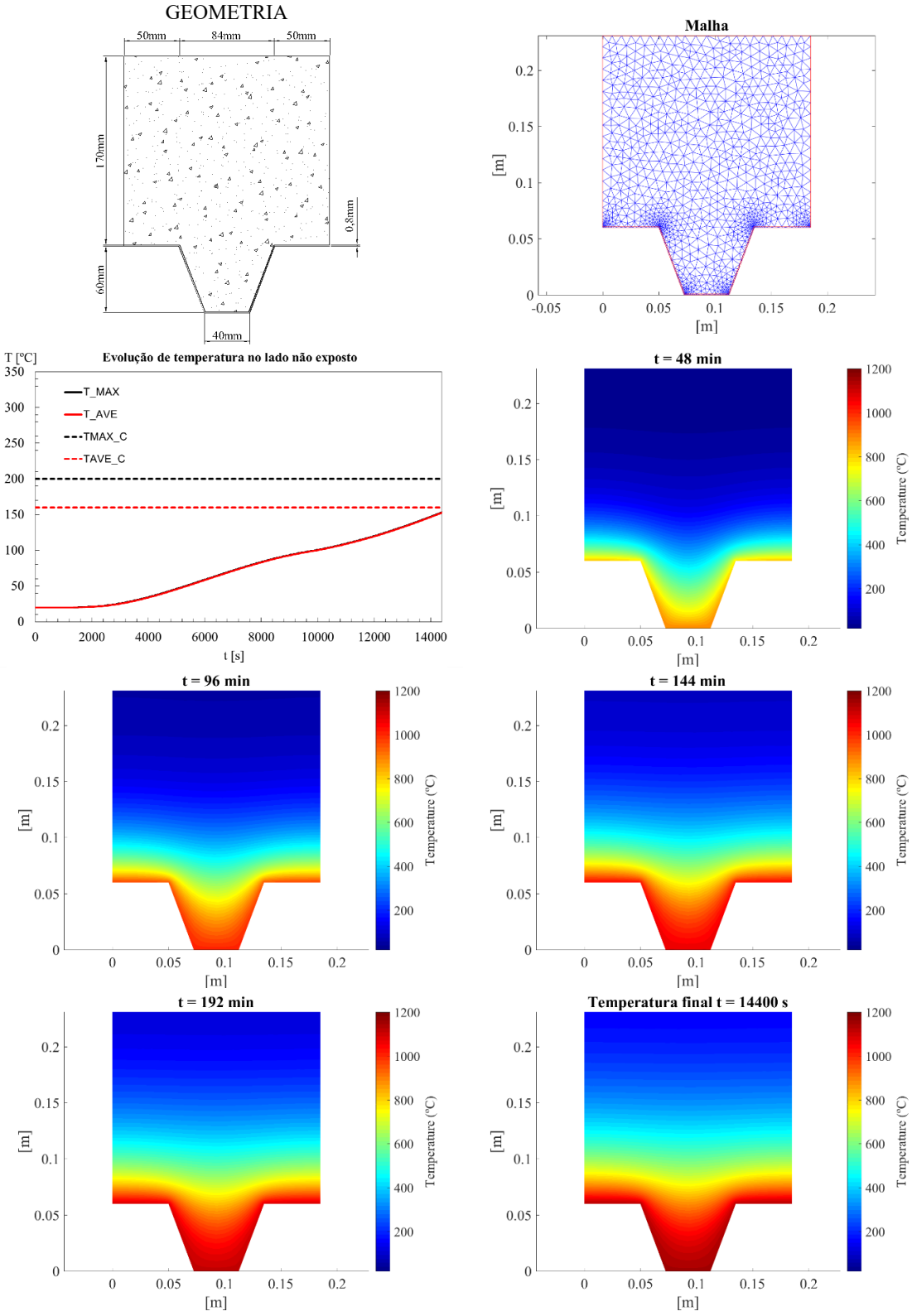
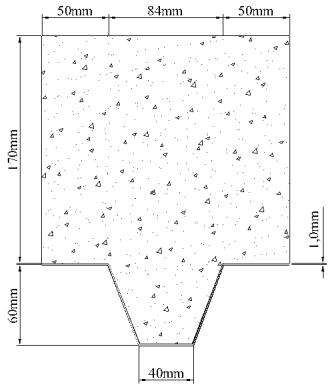
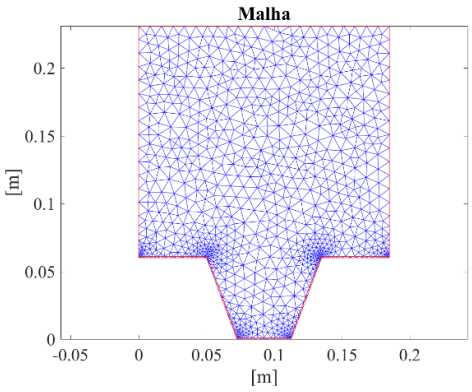
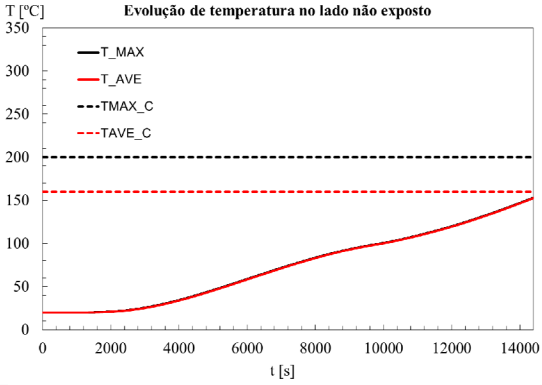


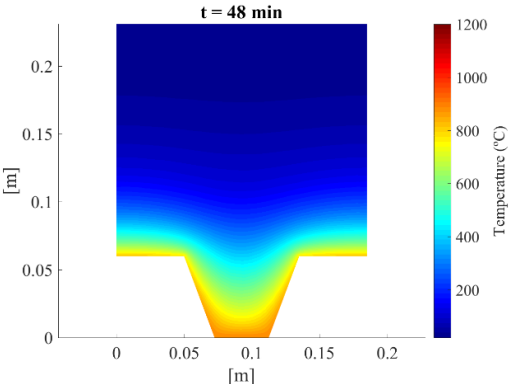
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.0mm

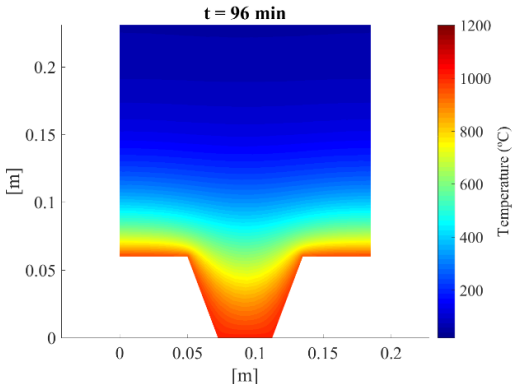
GEOMETRIA

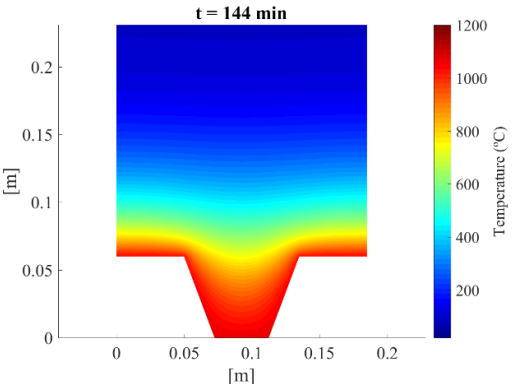


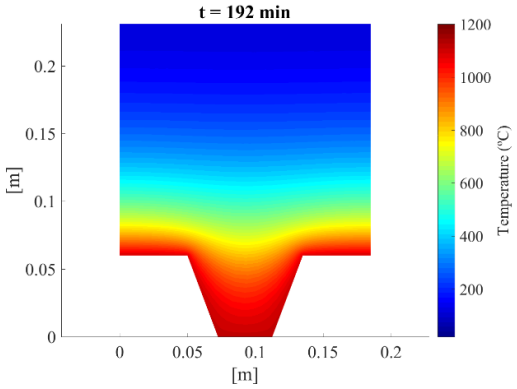


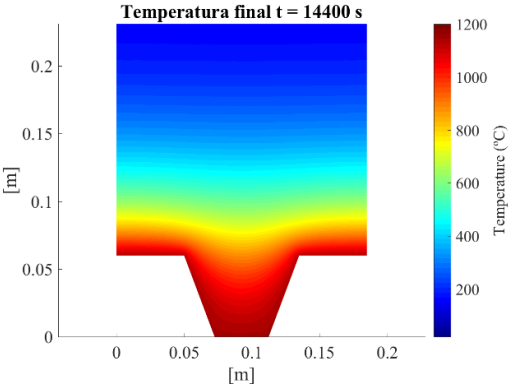




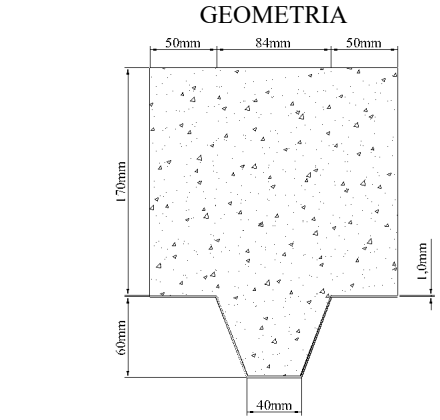


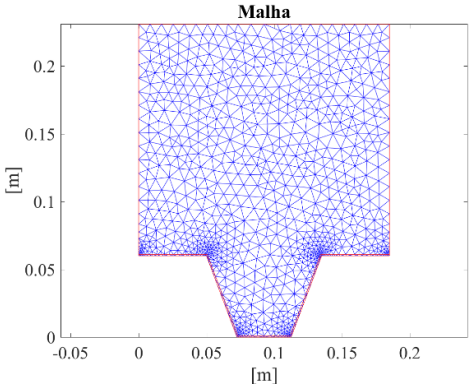


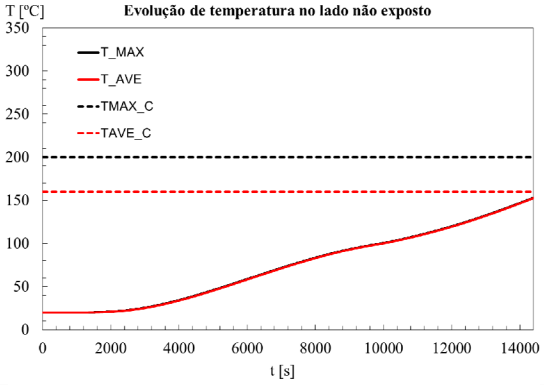


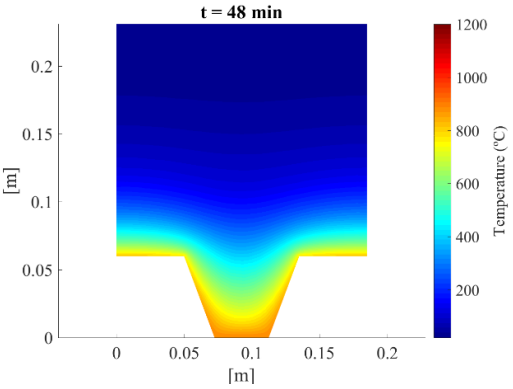


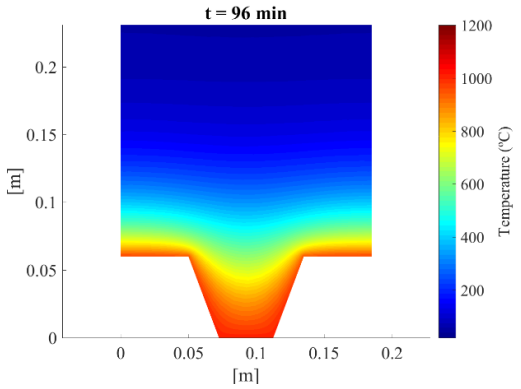
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.2mm

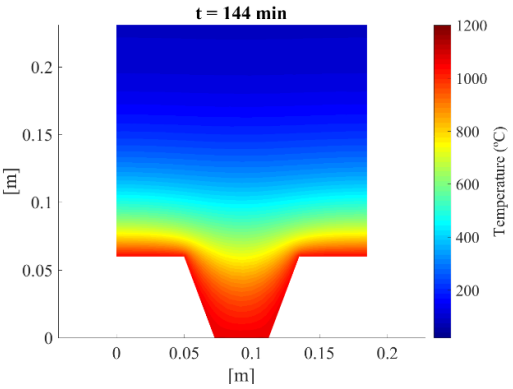


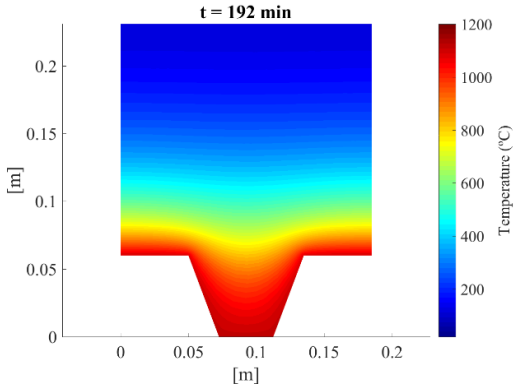


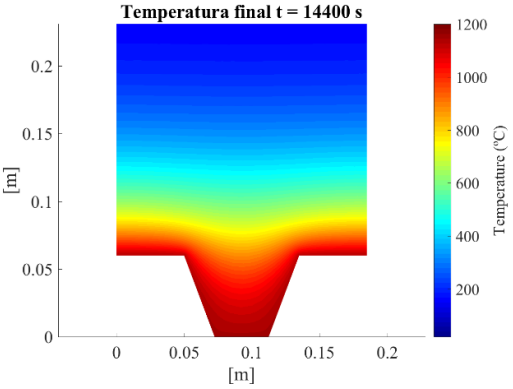










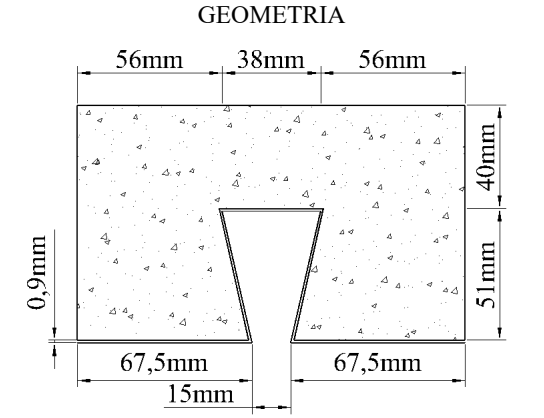


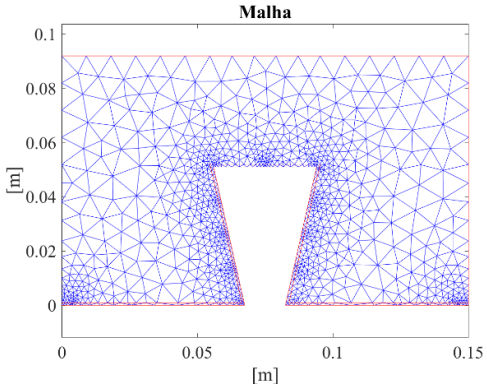
Anexo B

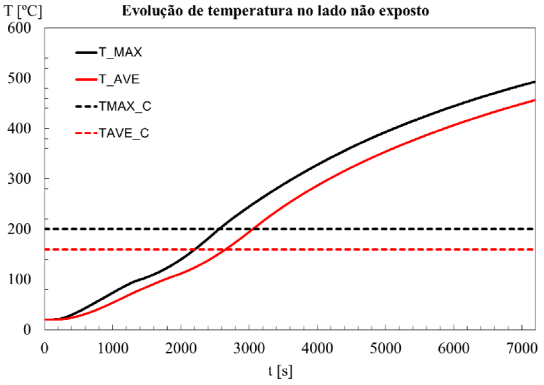
Análise térmica da seção transversal

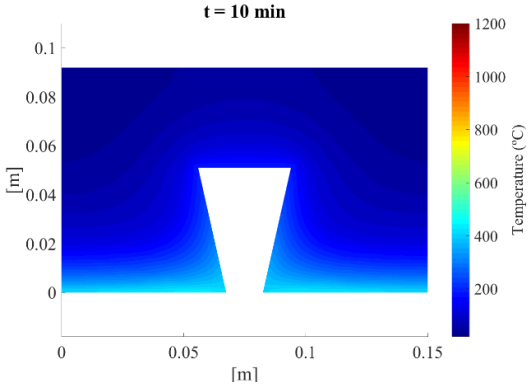
Método avançado de cálculo para lajes reentrantes: Matlab.

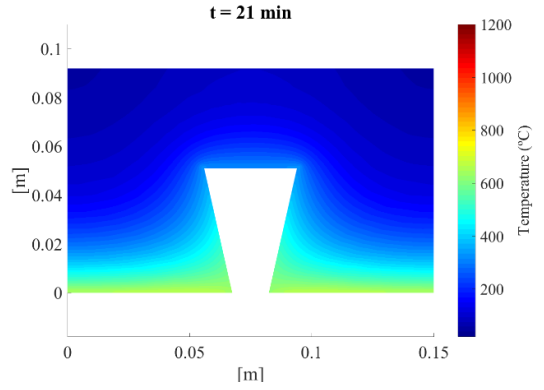
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.9mm

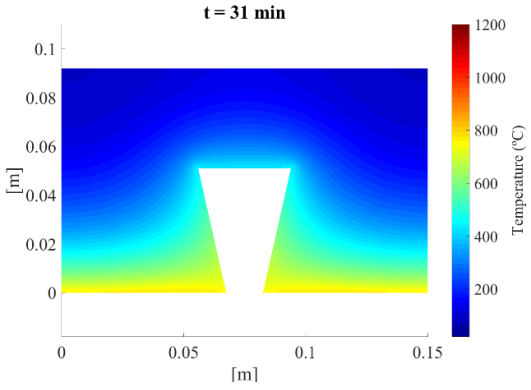


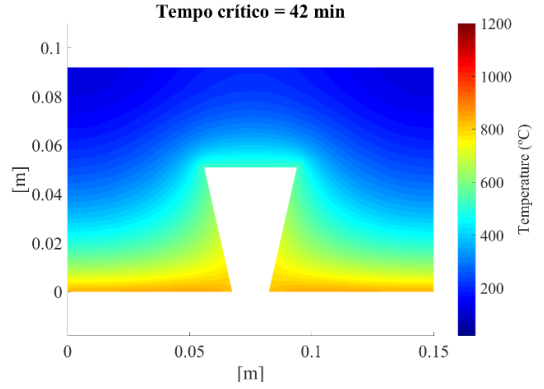


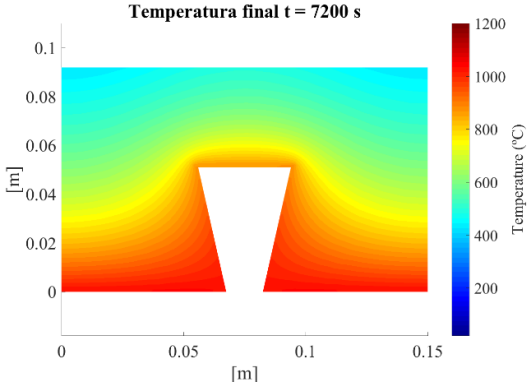




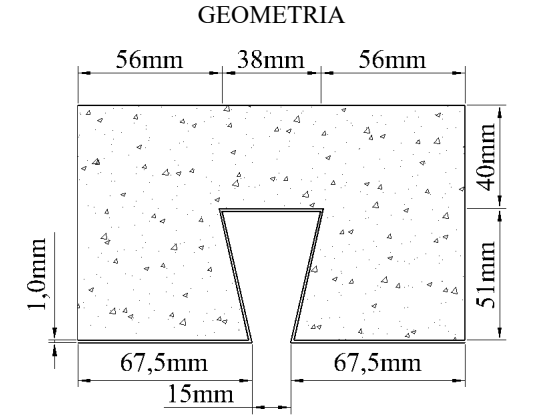


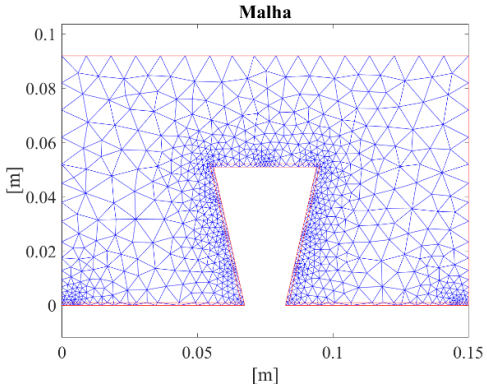


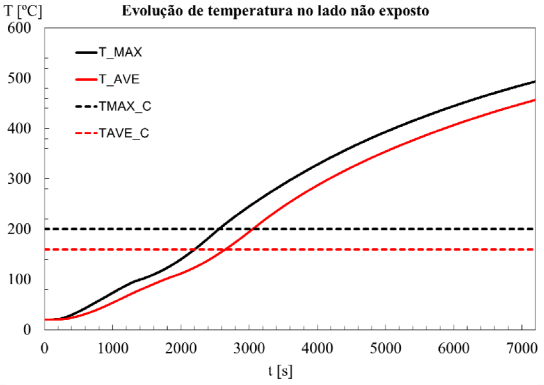


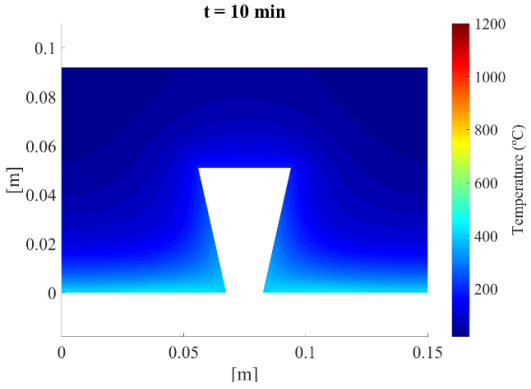


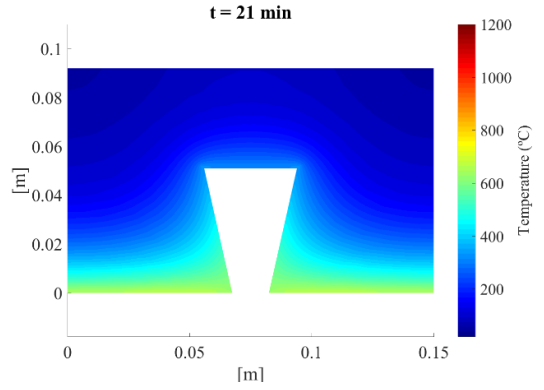
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.0mm

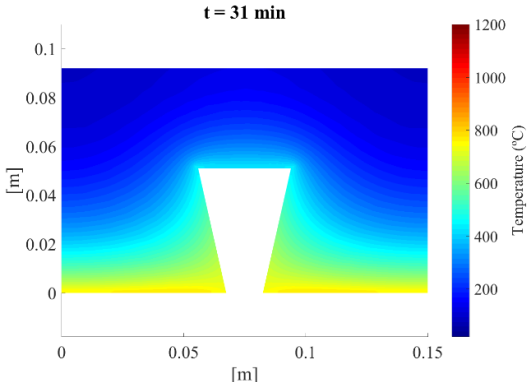


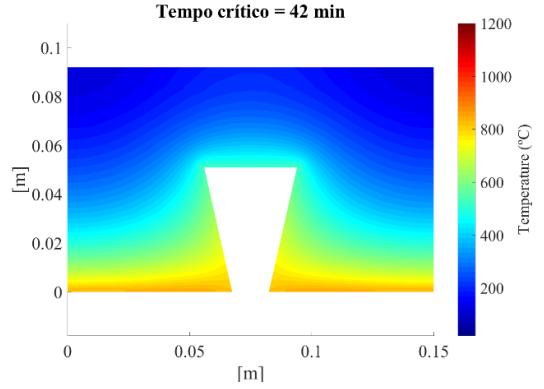


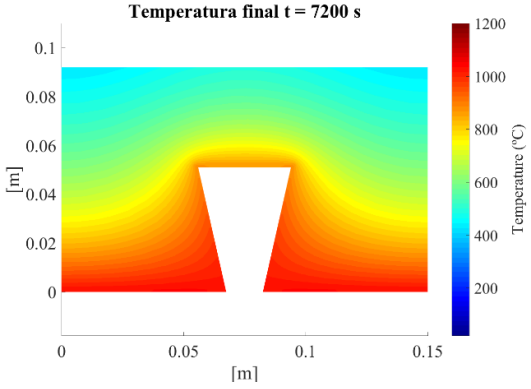




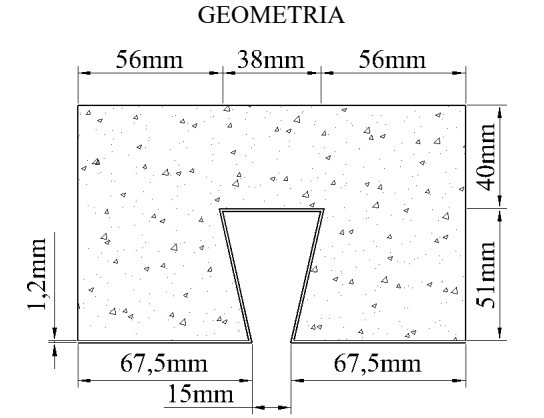


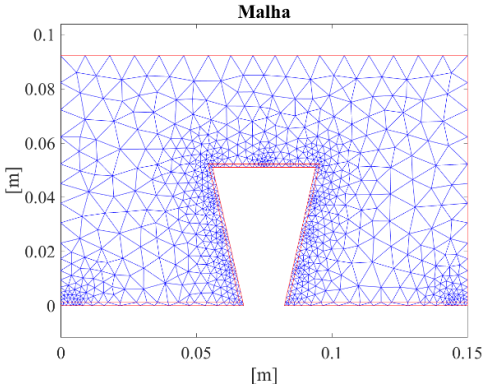


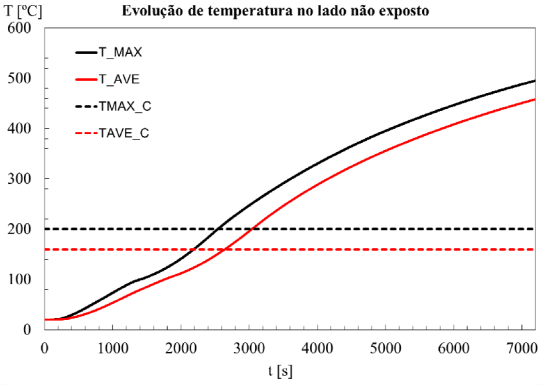


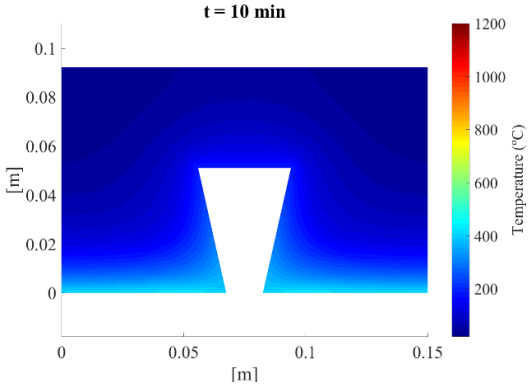


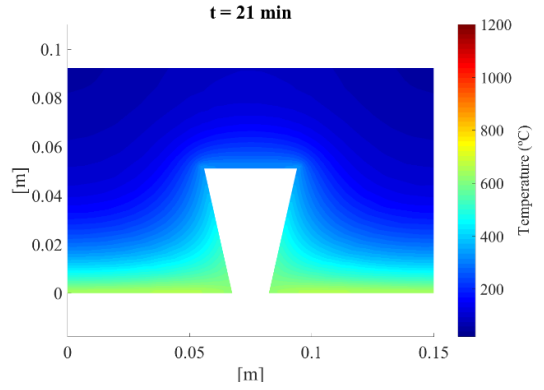
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.2mm

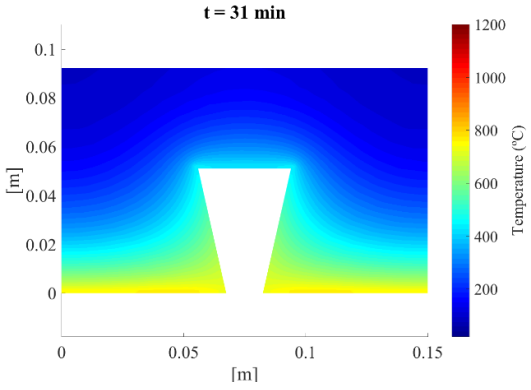


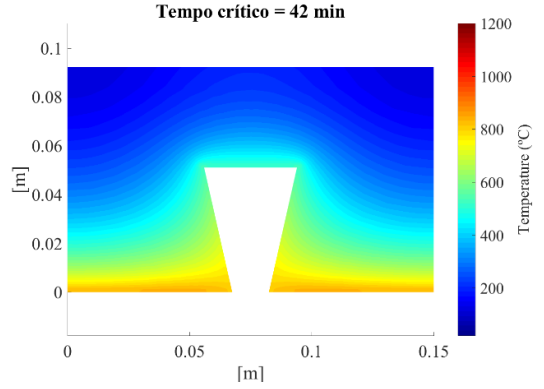


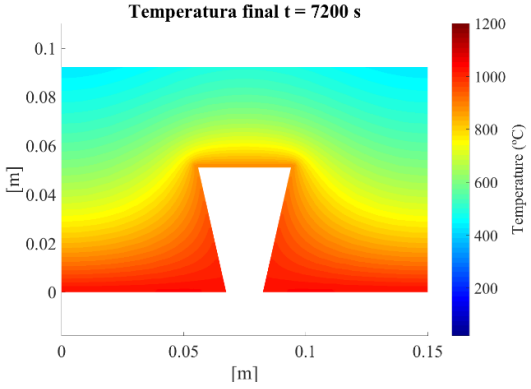




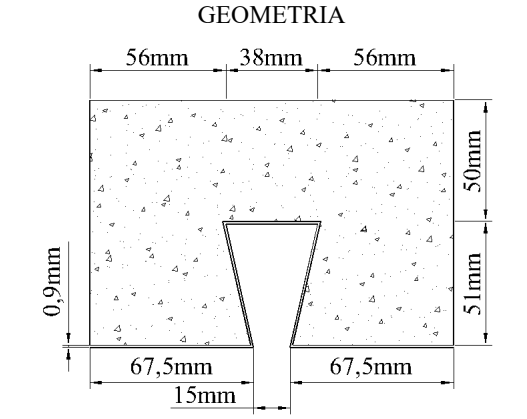


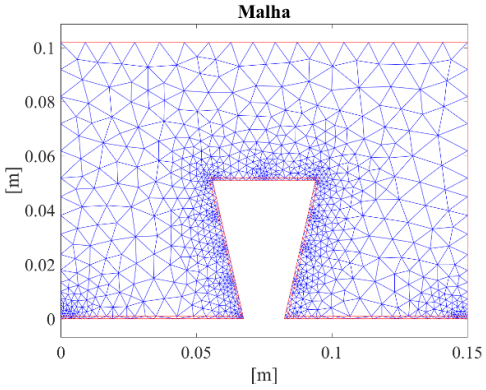


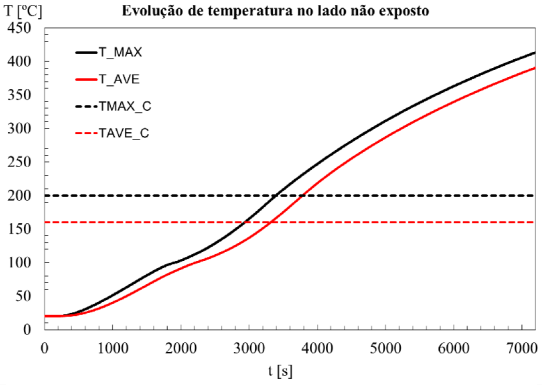


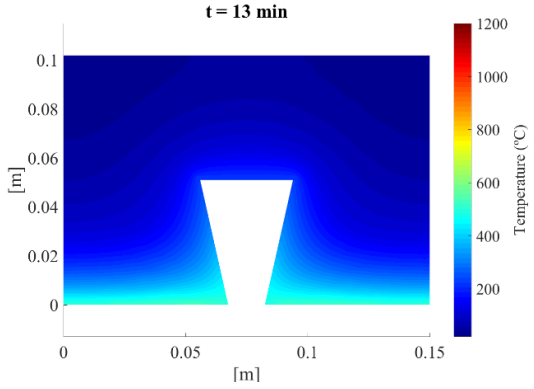


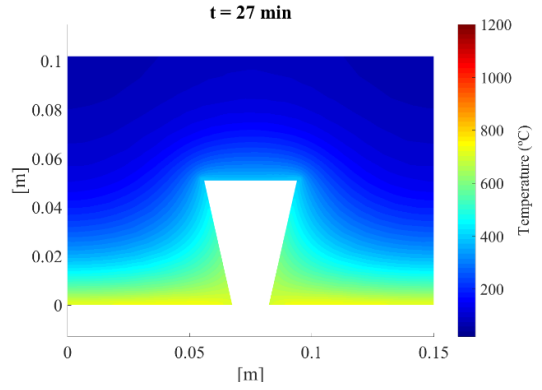
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.9mm

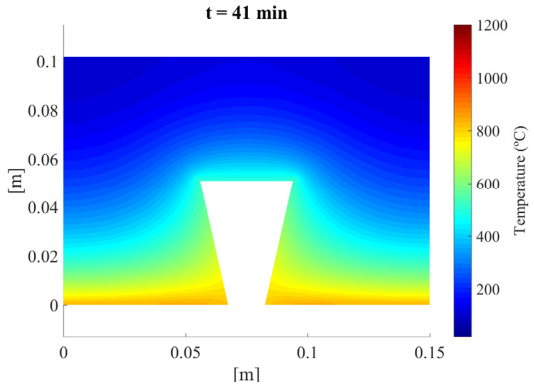


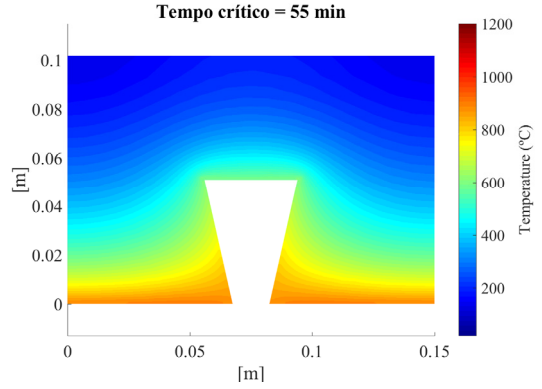


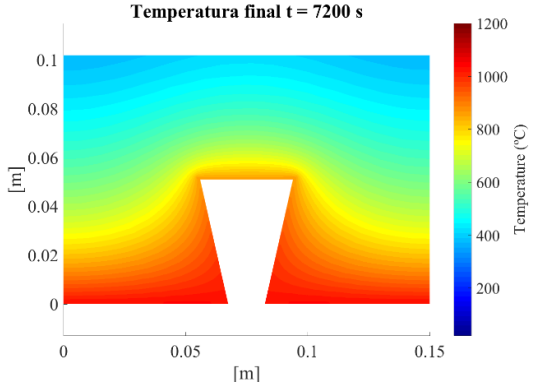




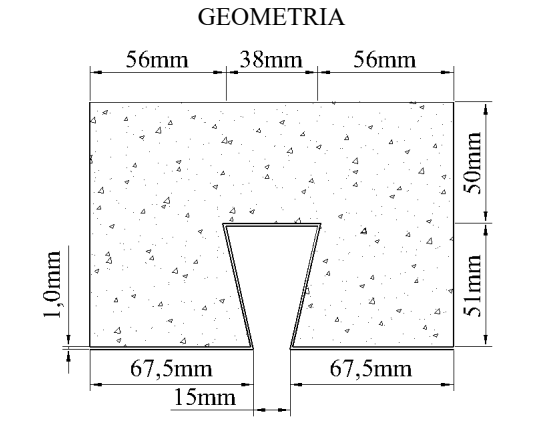


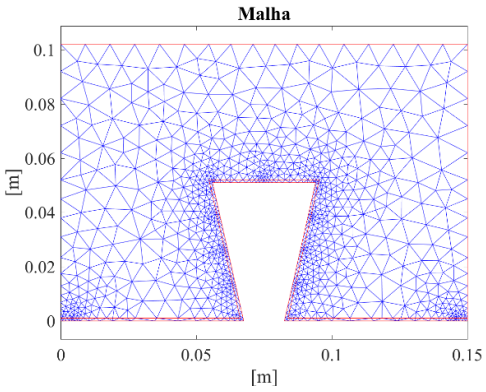


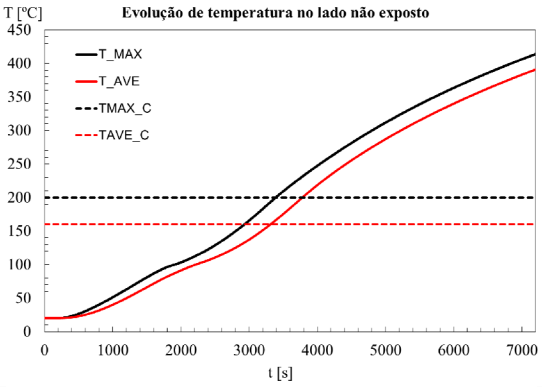


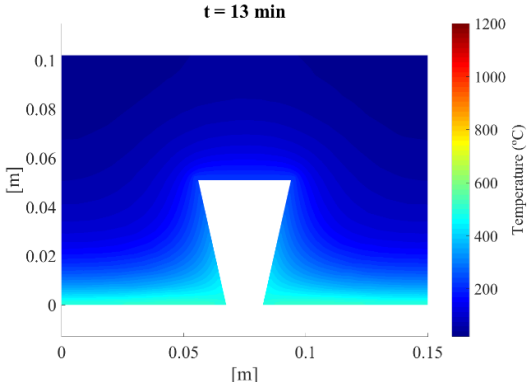


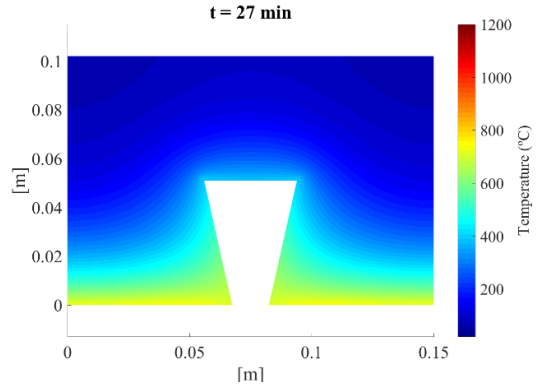
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.0mm

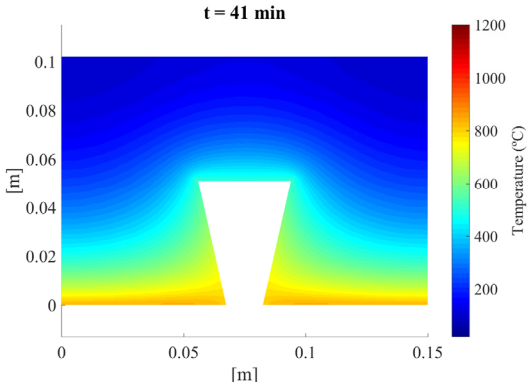


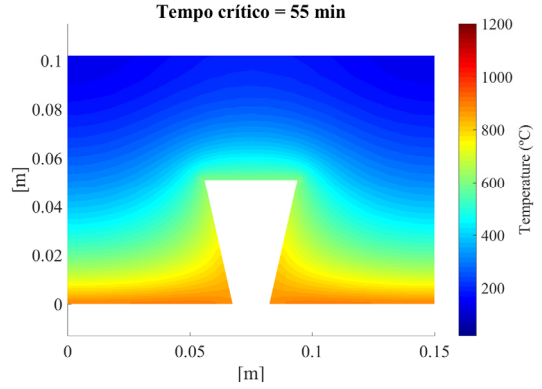


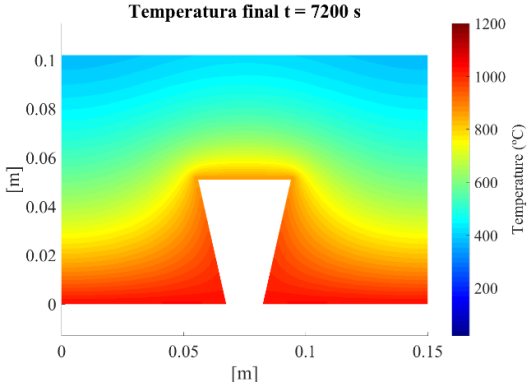




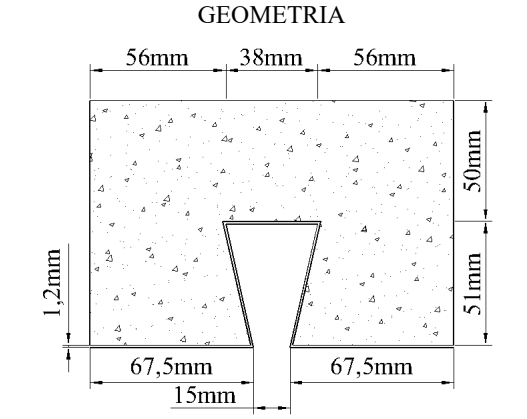


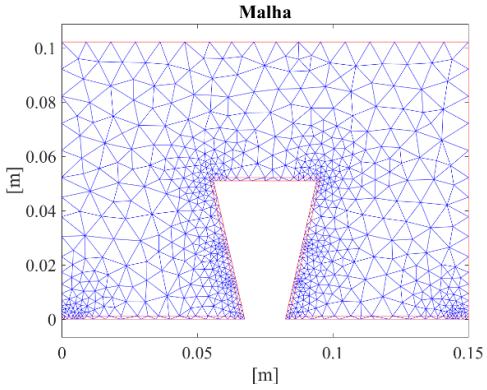


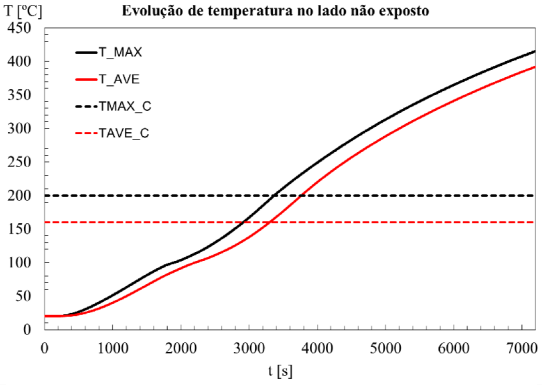


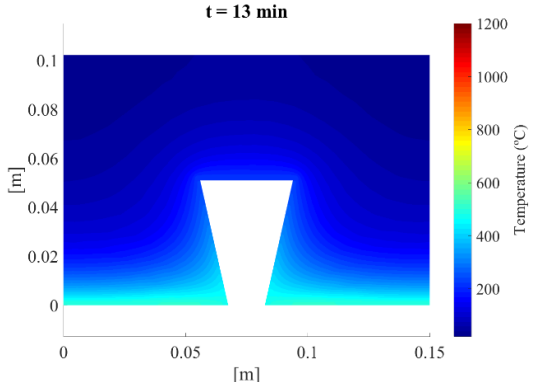


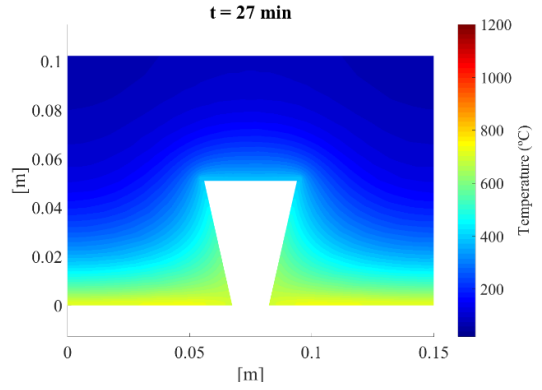
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.2mm

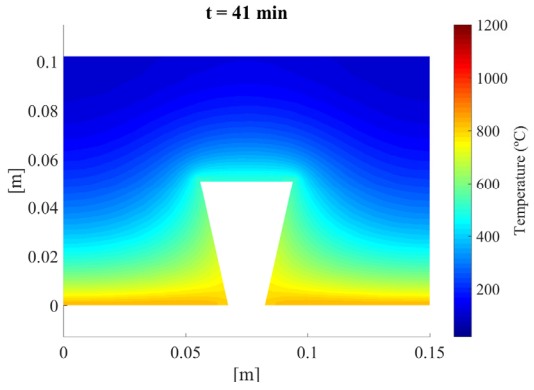


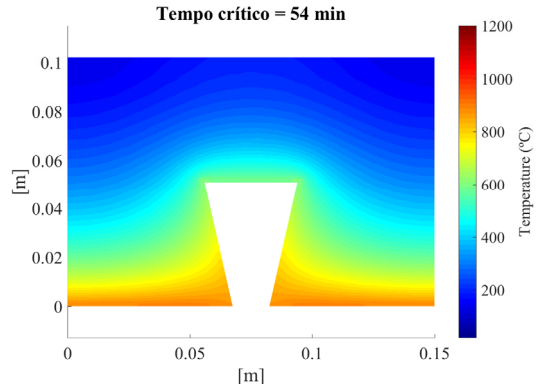


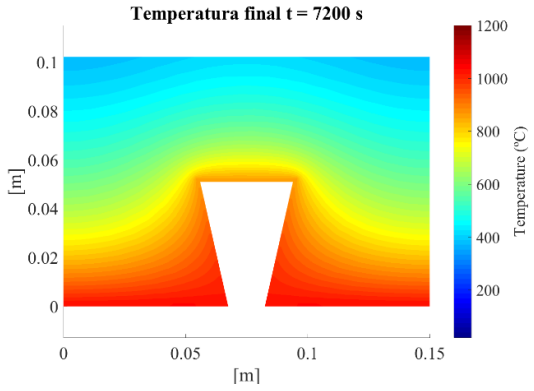




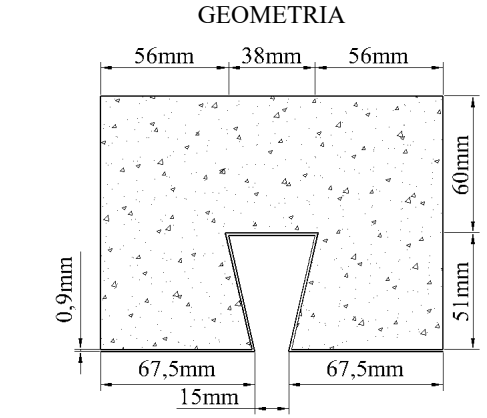


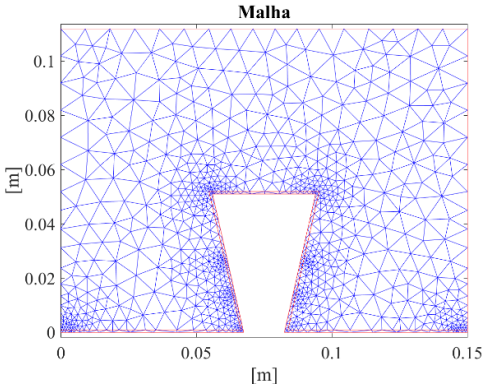


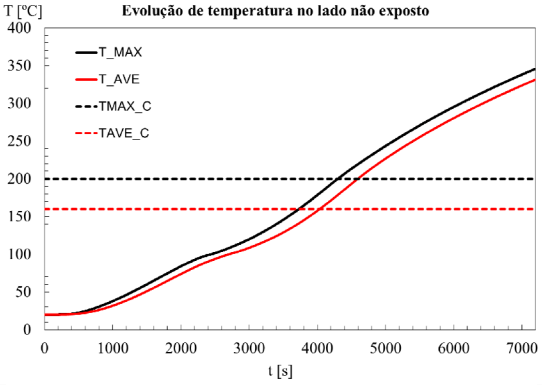


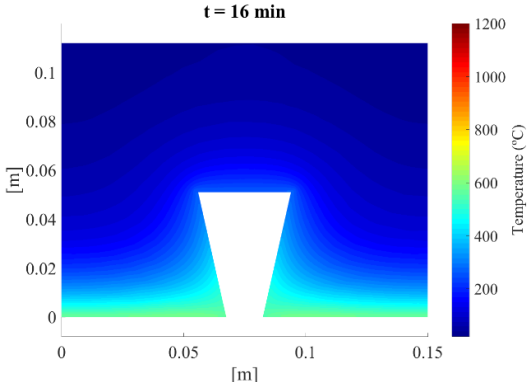


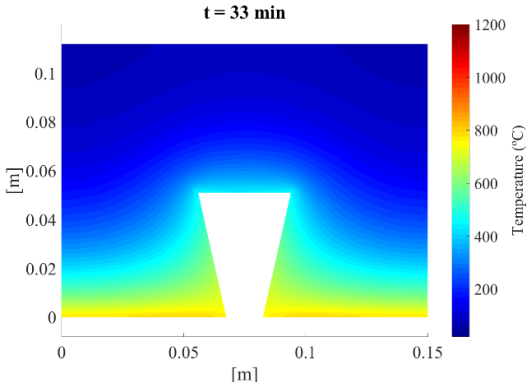
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.9mm

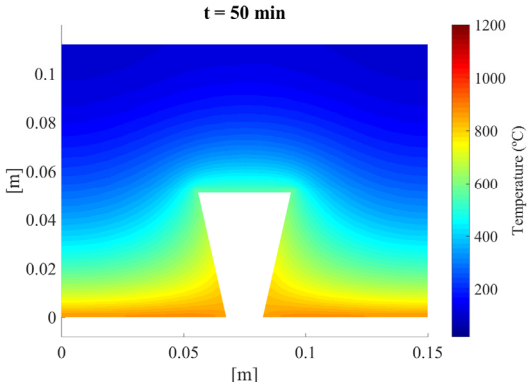


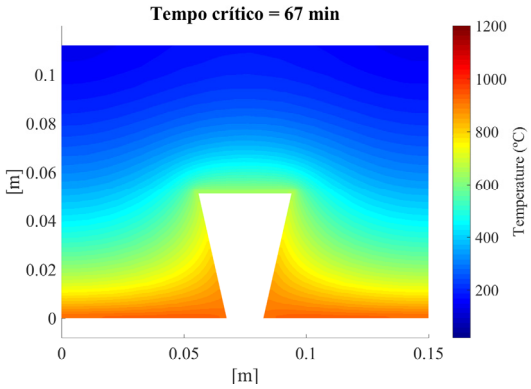


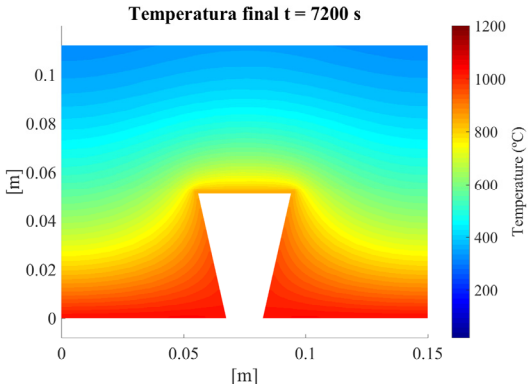




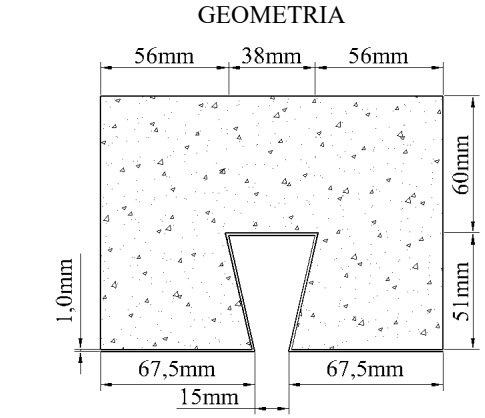


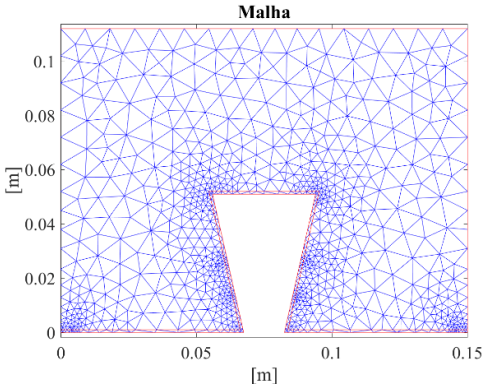


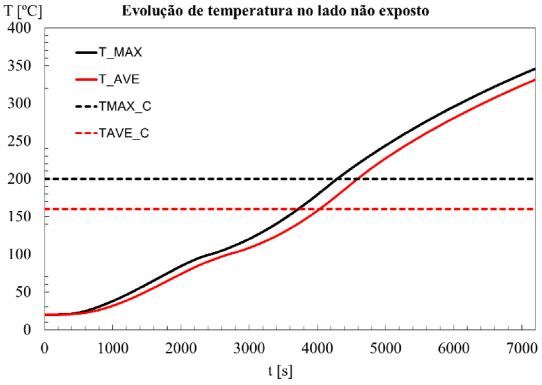


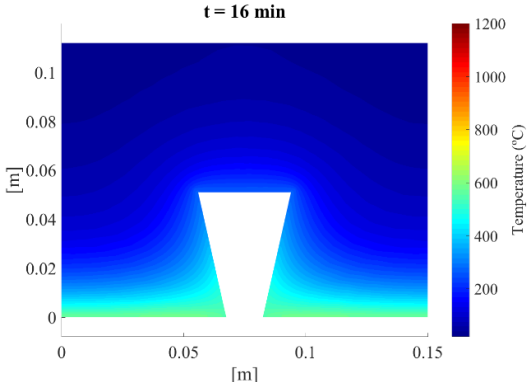


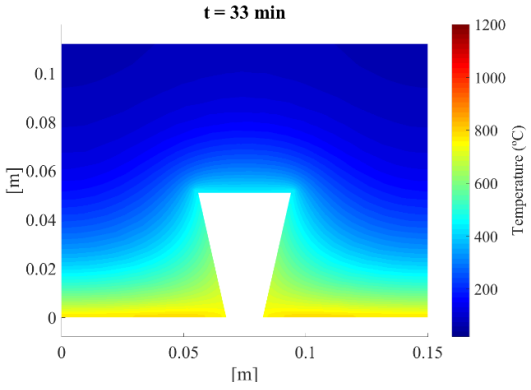
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.0mm

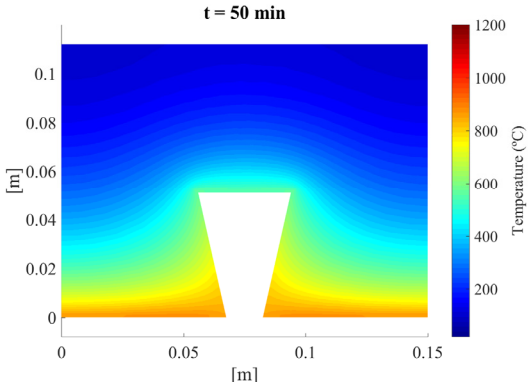


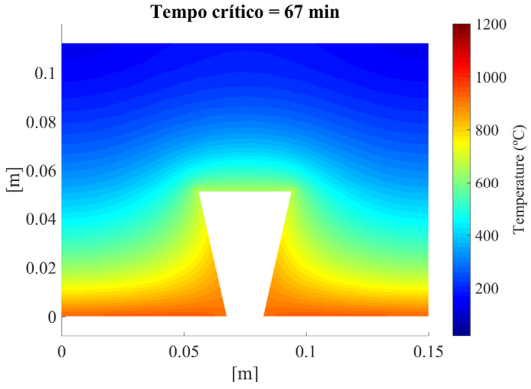


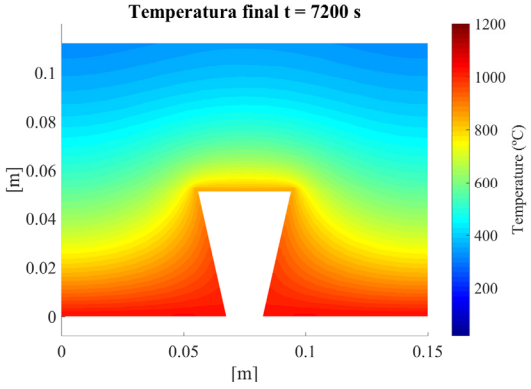




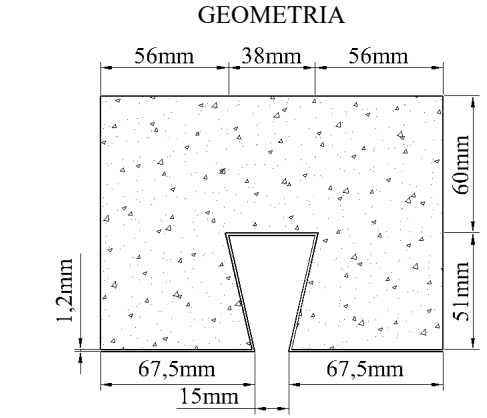


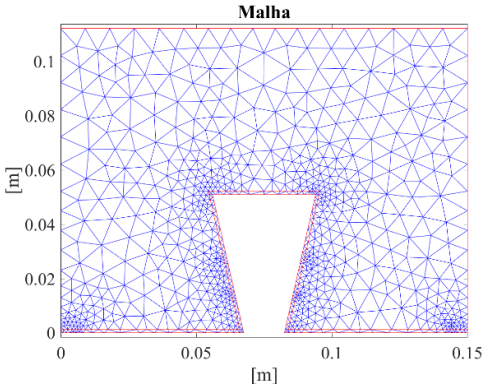


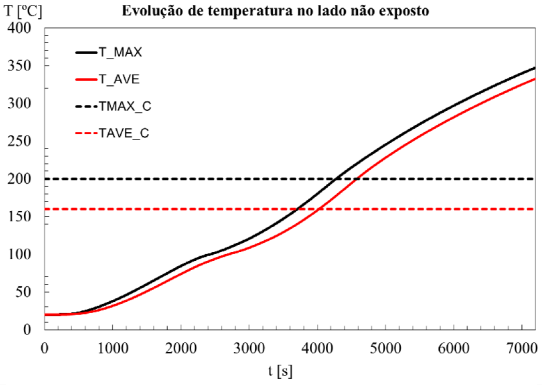


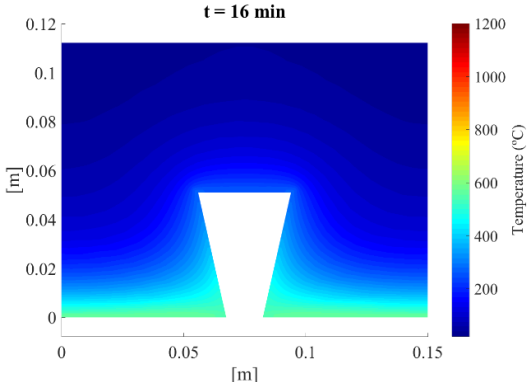


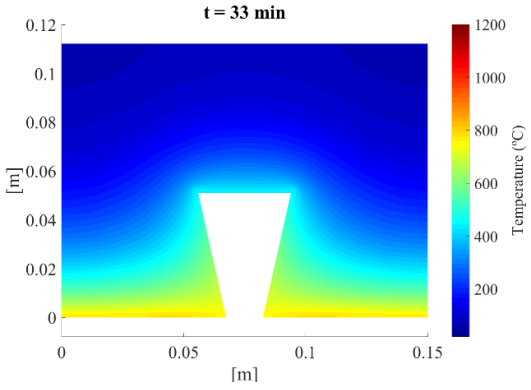
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.2mm

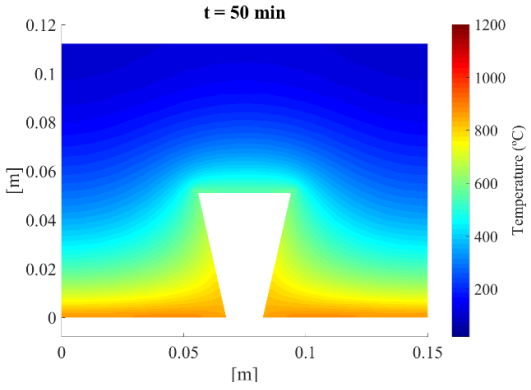


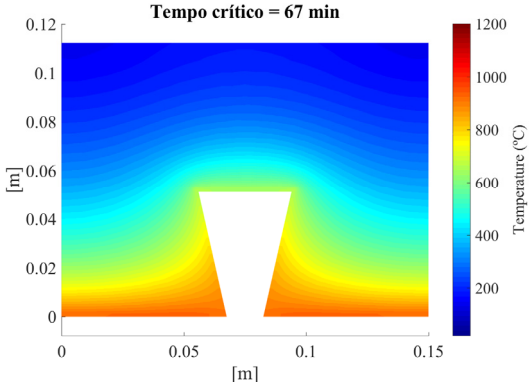


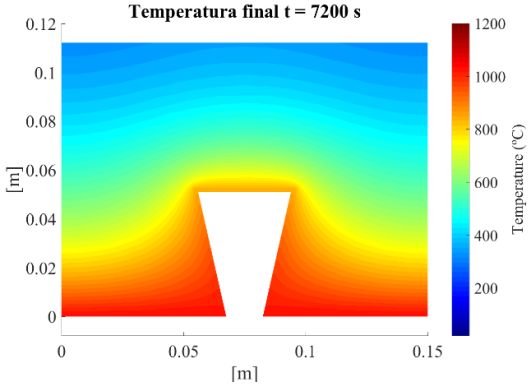




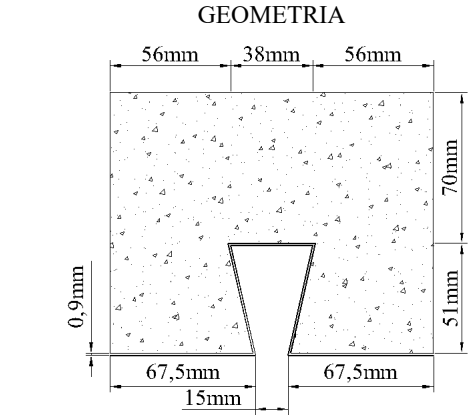


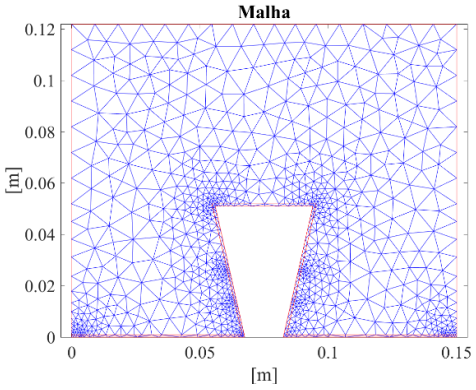


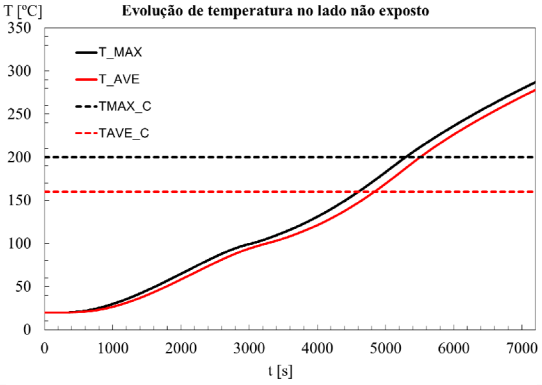


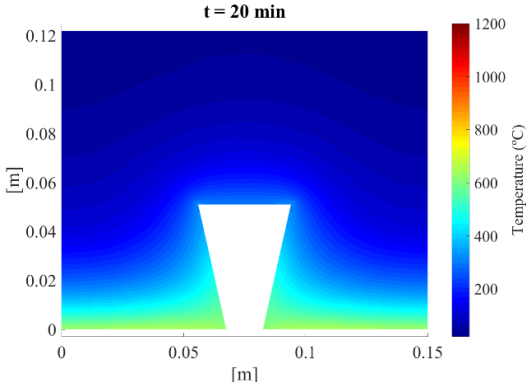


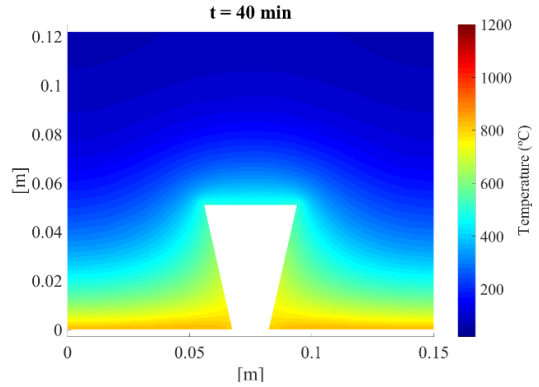
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.9mm

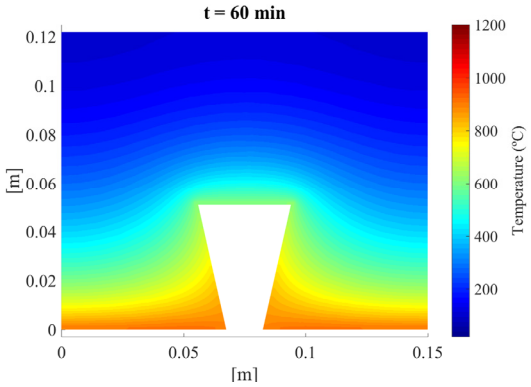


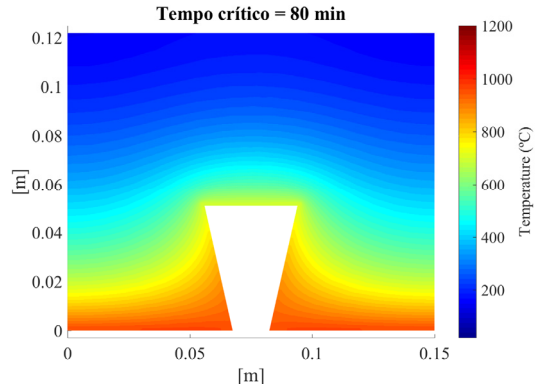


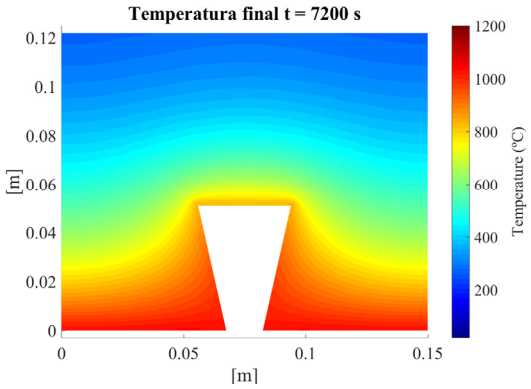




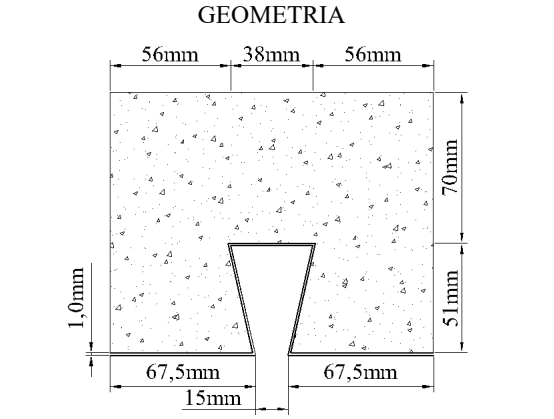


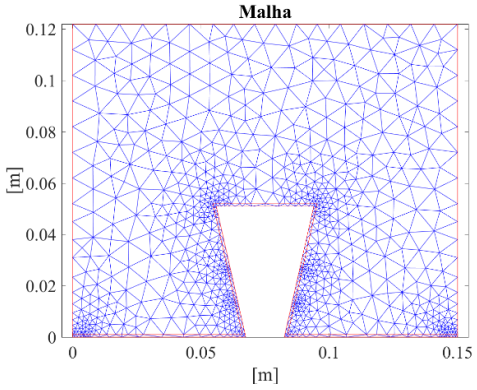


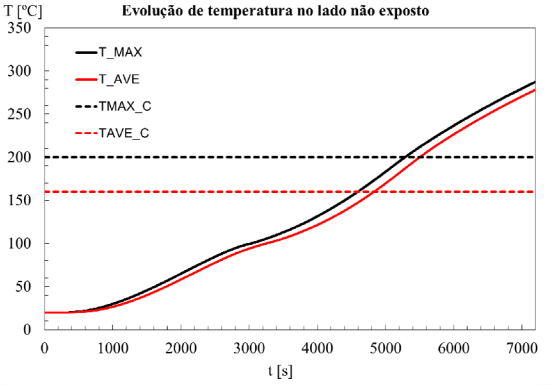


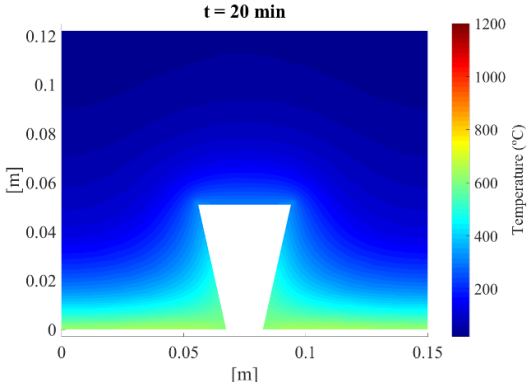


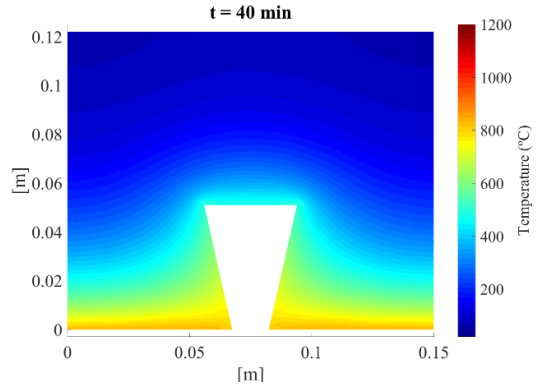
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.0mm

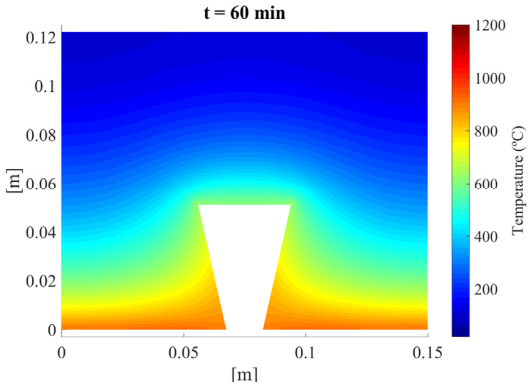


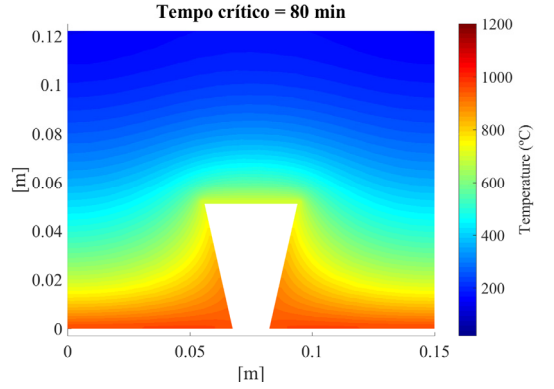


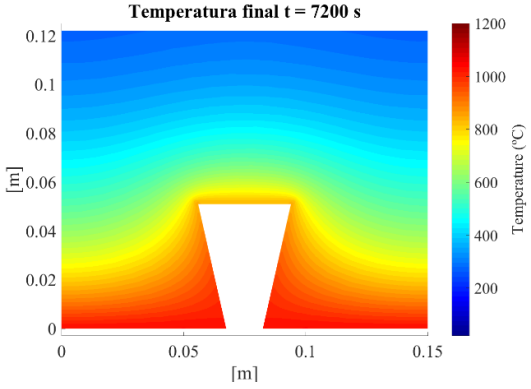




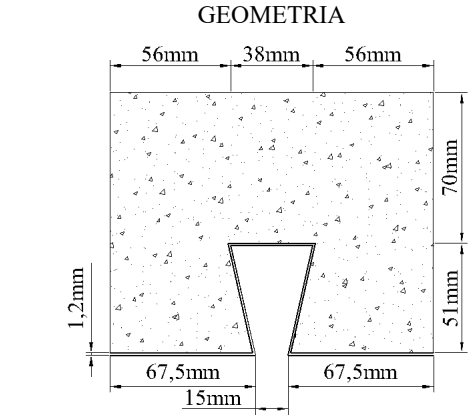


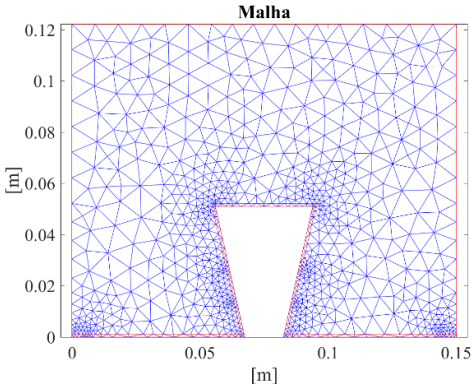


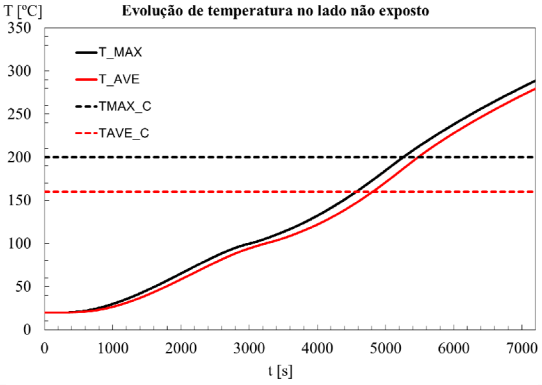


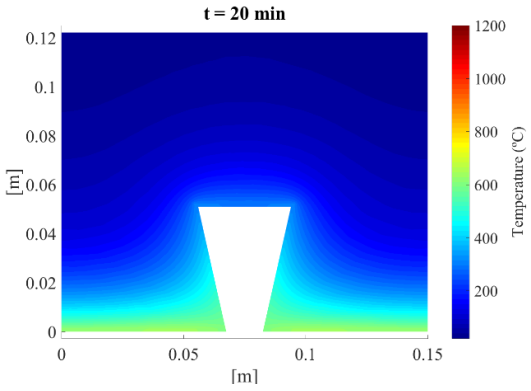


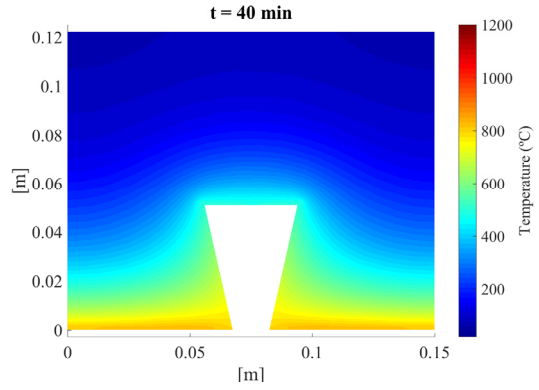
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.2mm

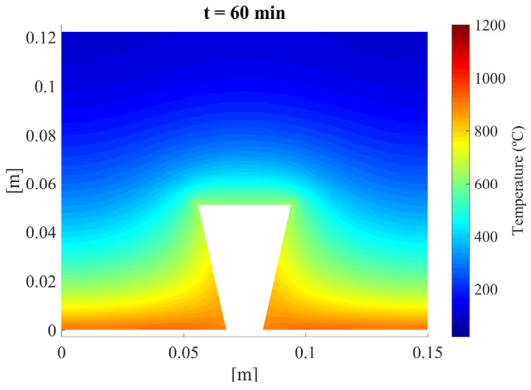


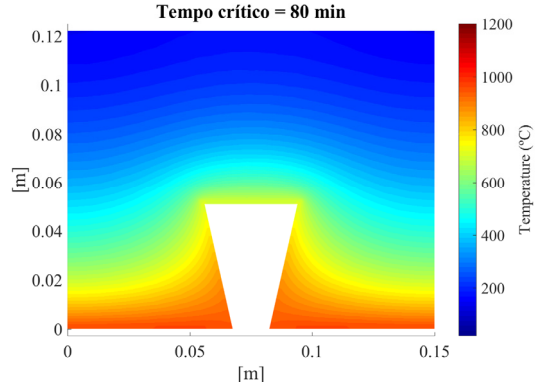


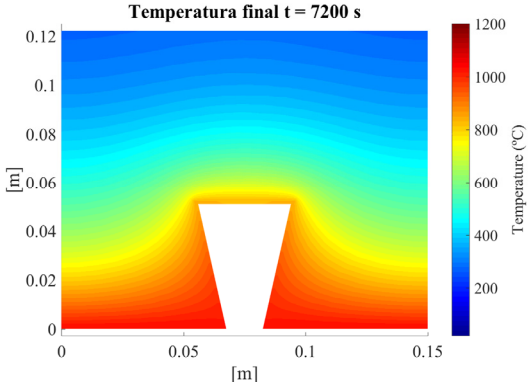




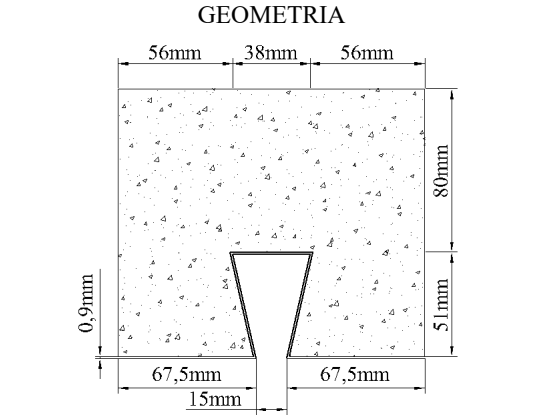


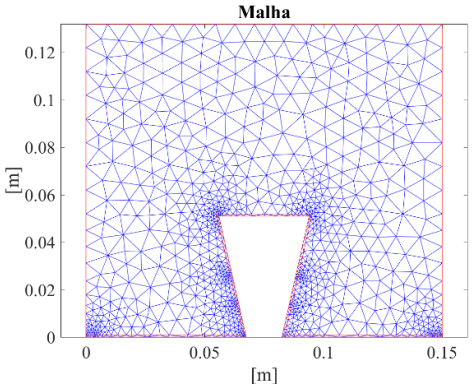


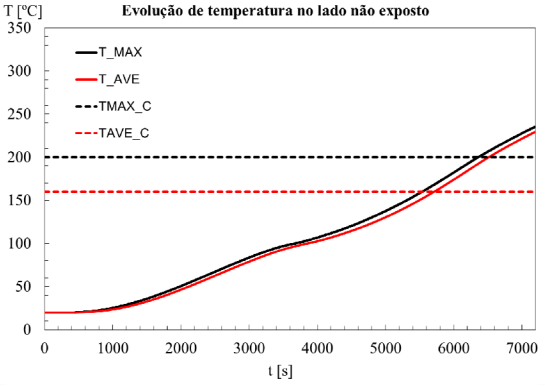


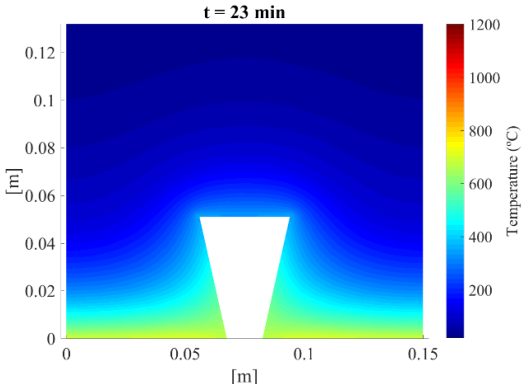


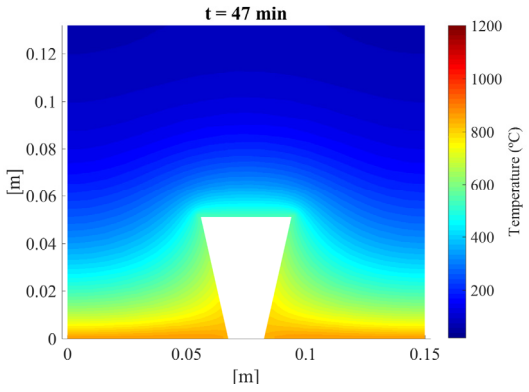
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.9mm

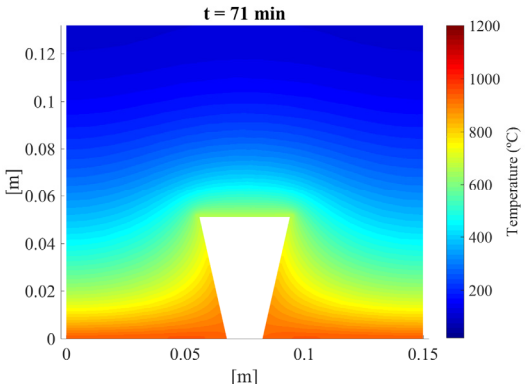


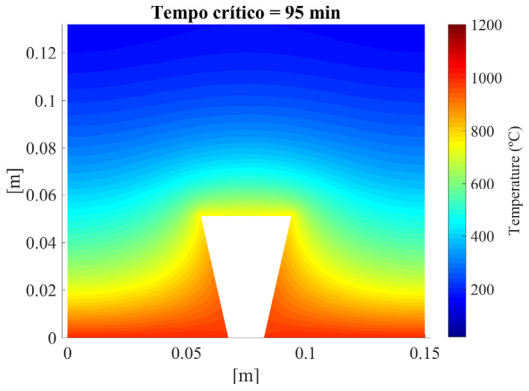


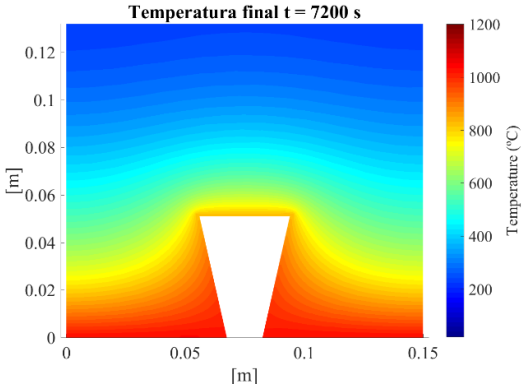




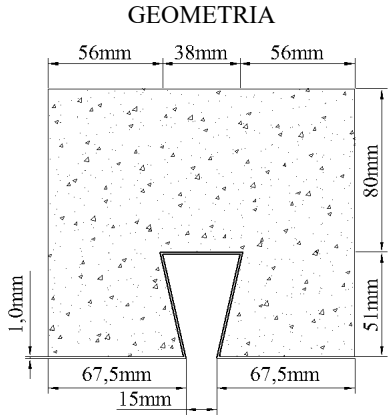


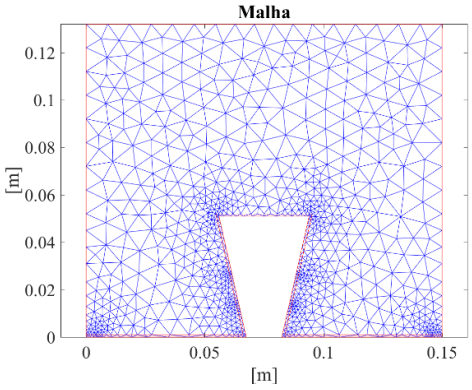


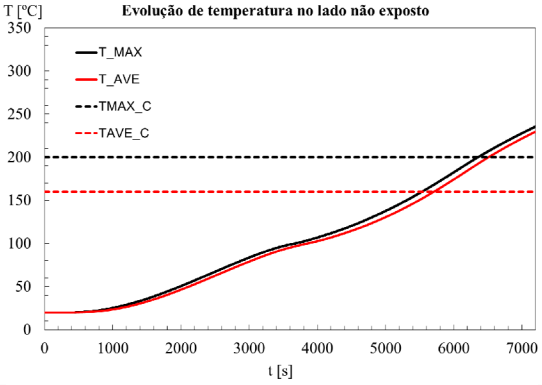


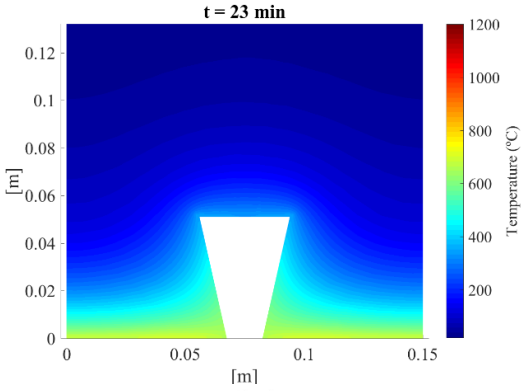


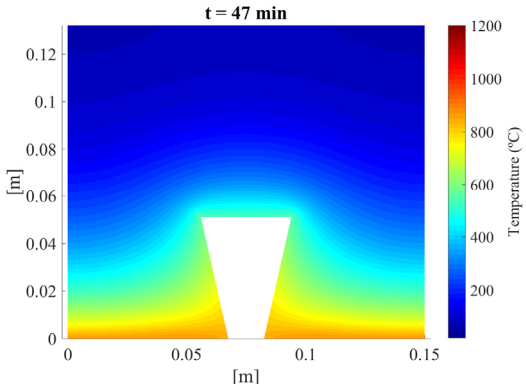
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.0mm

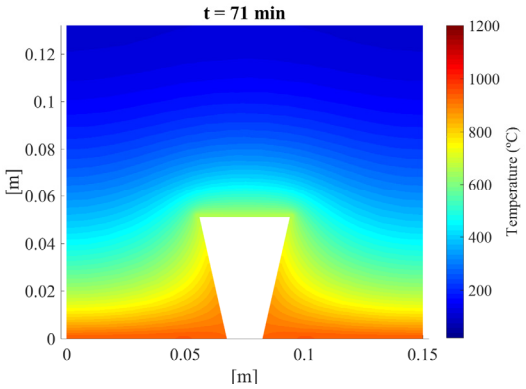


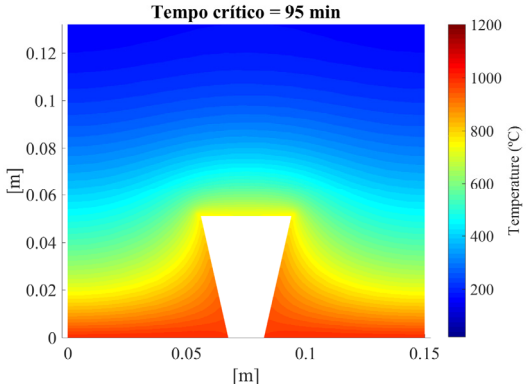


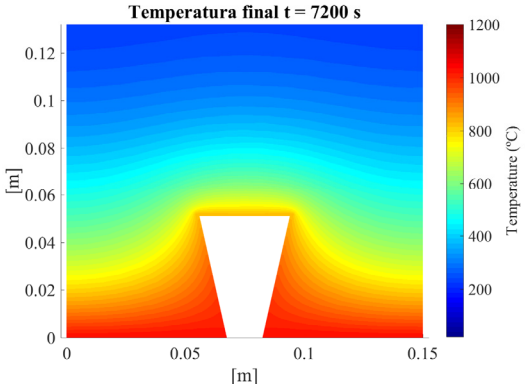




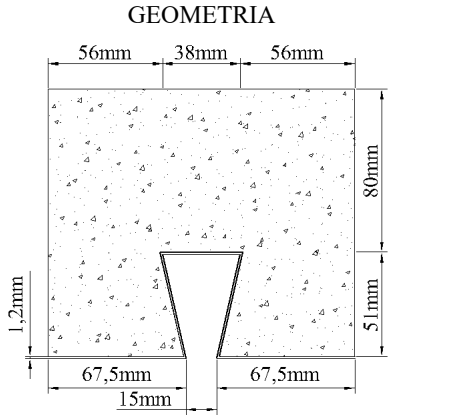


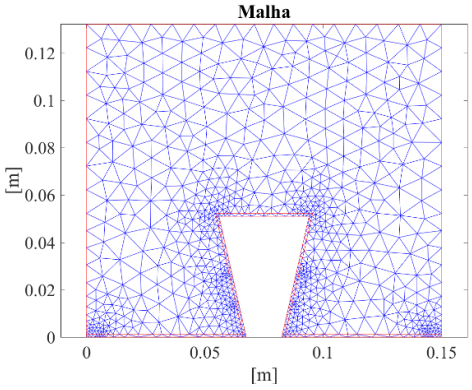


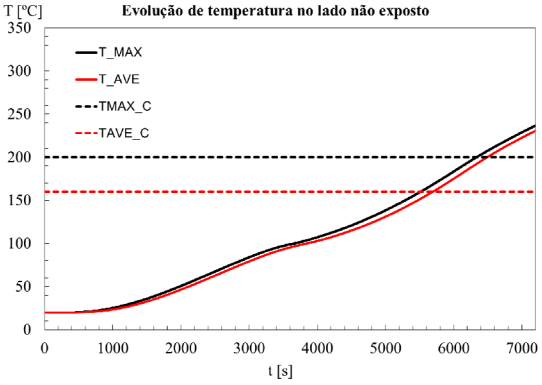


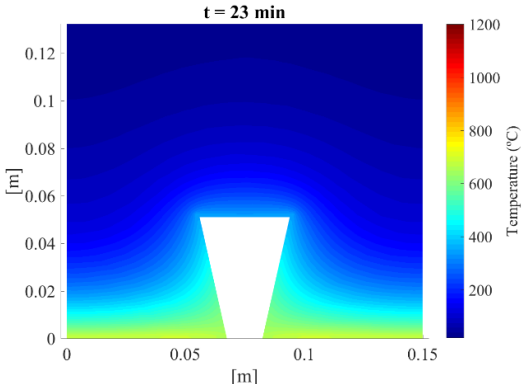


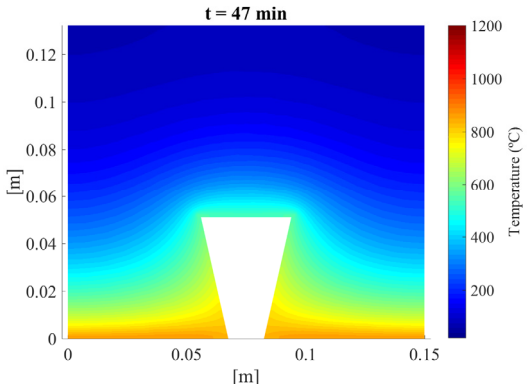
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.2mm

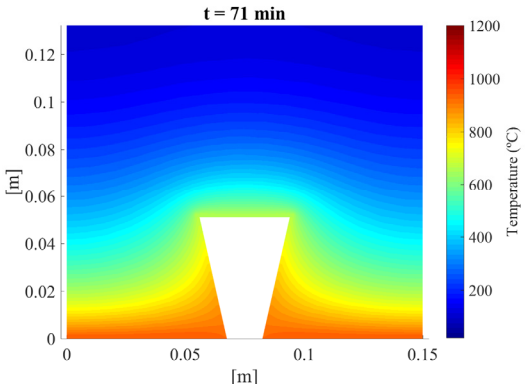


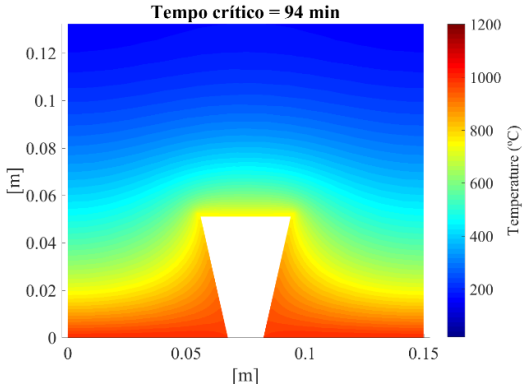


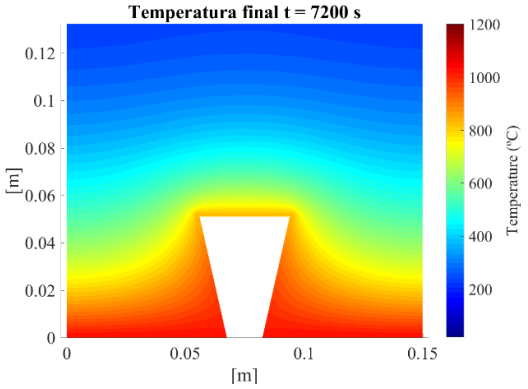






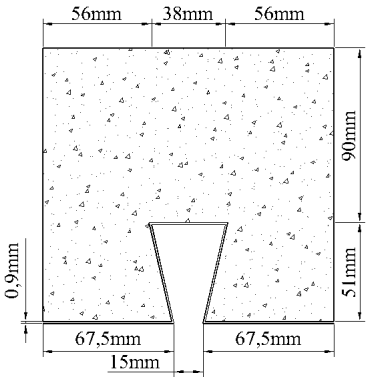


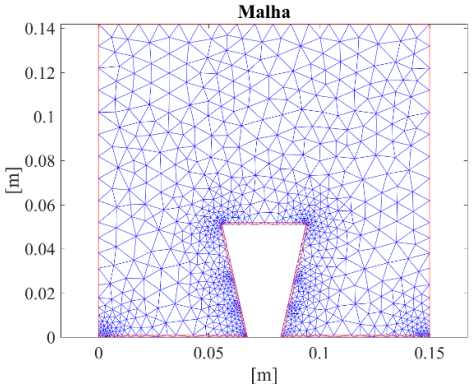


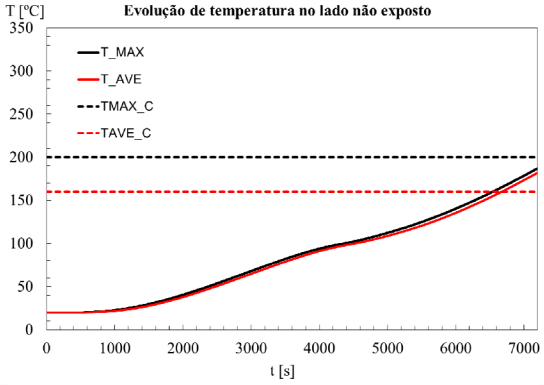


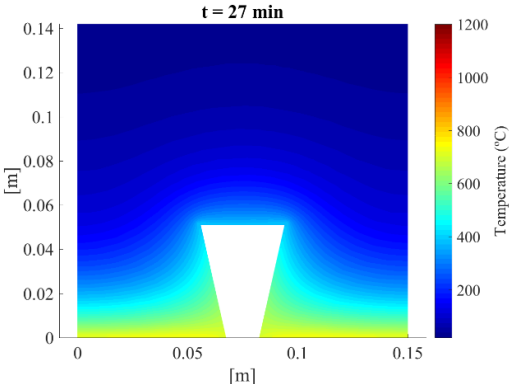
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.9mm

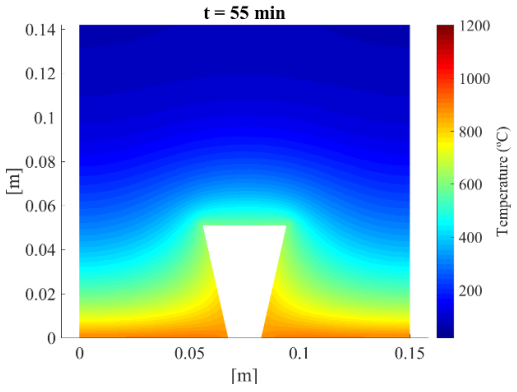
GEOMETRIA

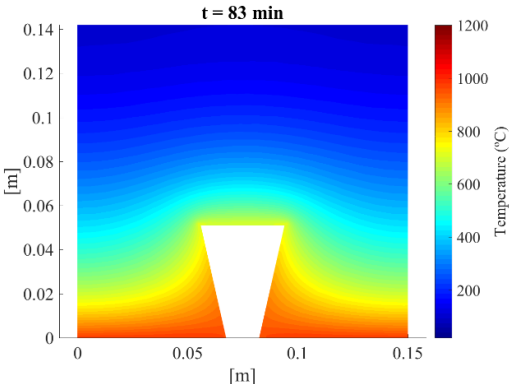


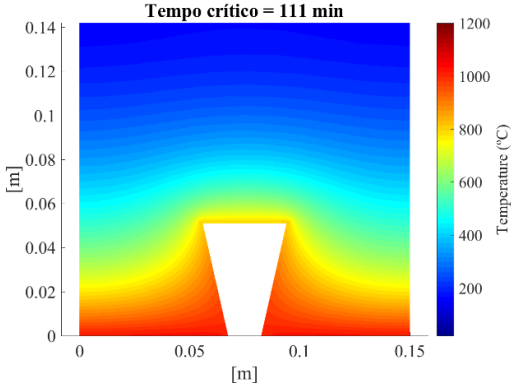


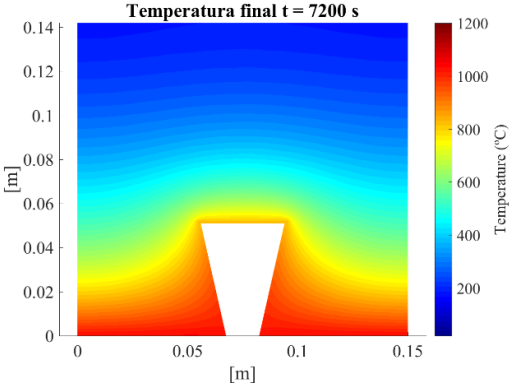




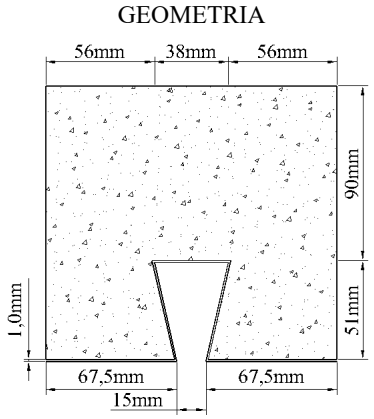


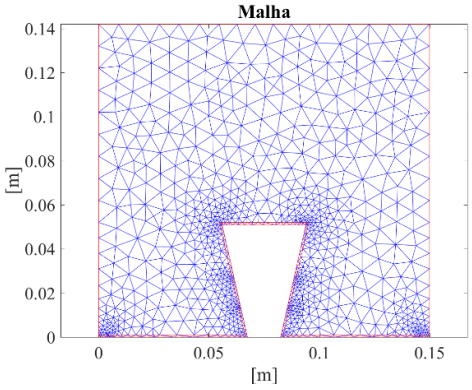


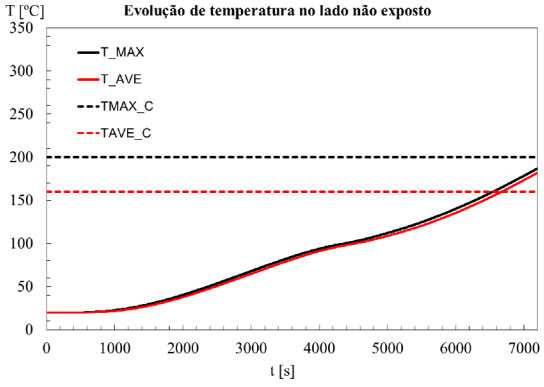


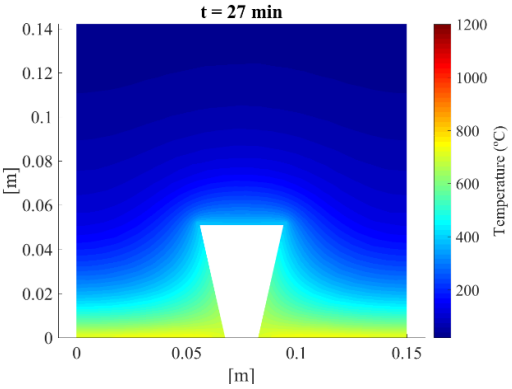


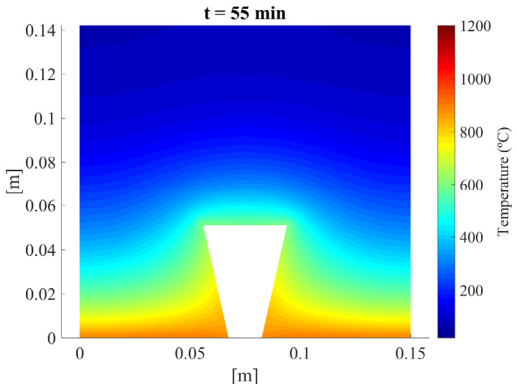
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.0mm

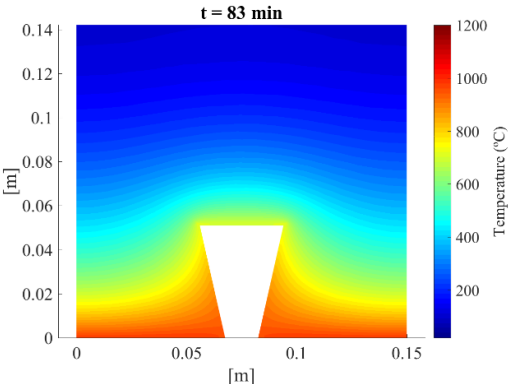


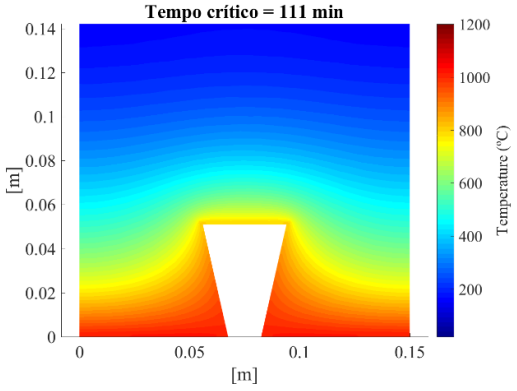


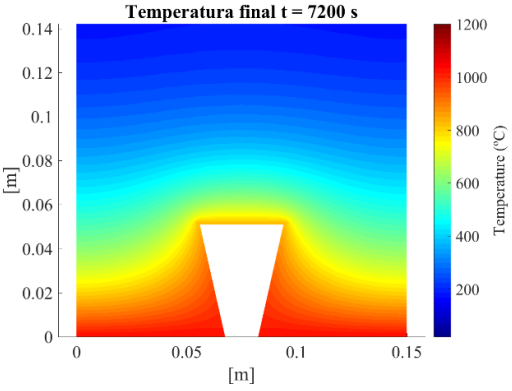




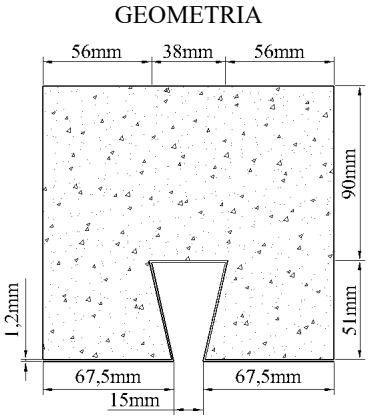


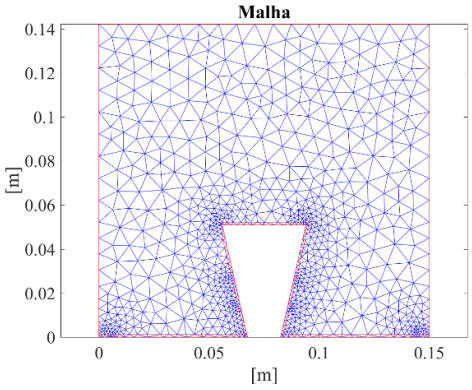


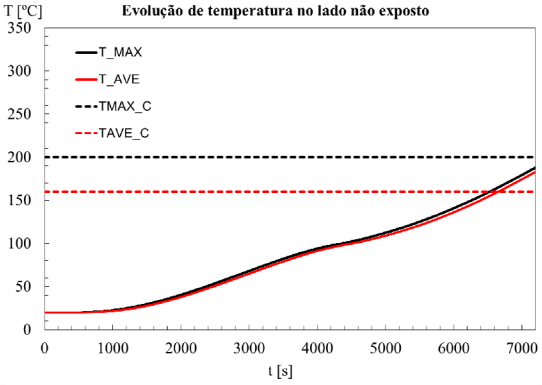


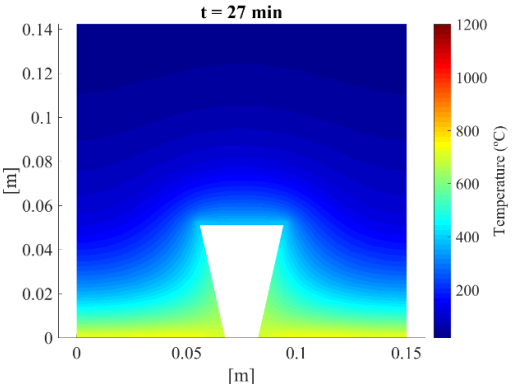


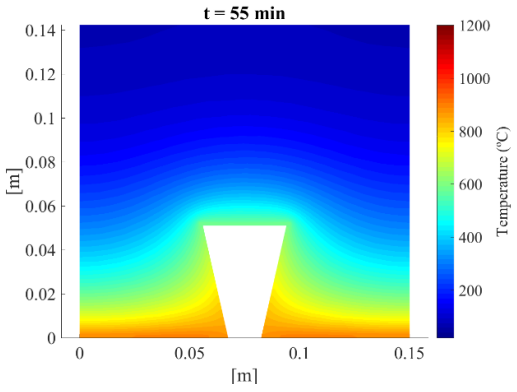
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.2mm

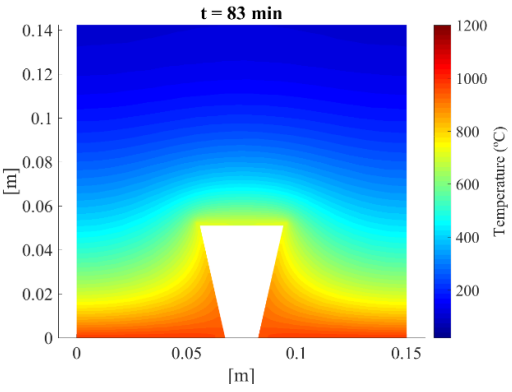


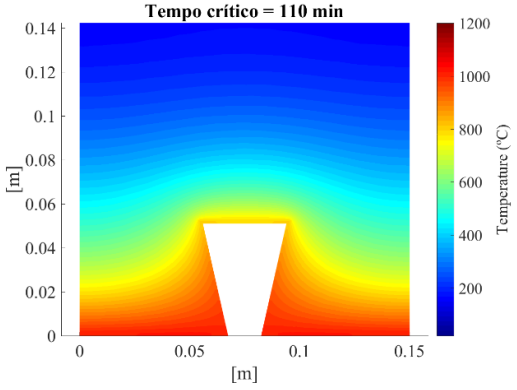


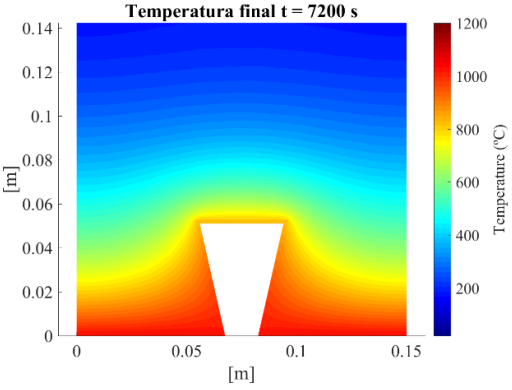




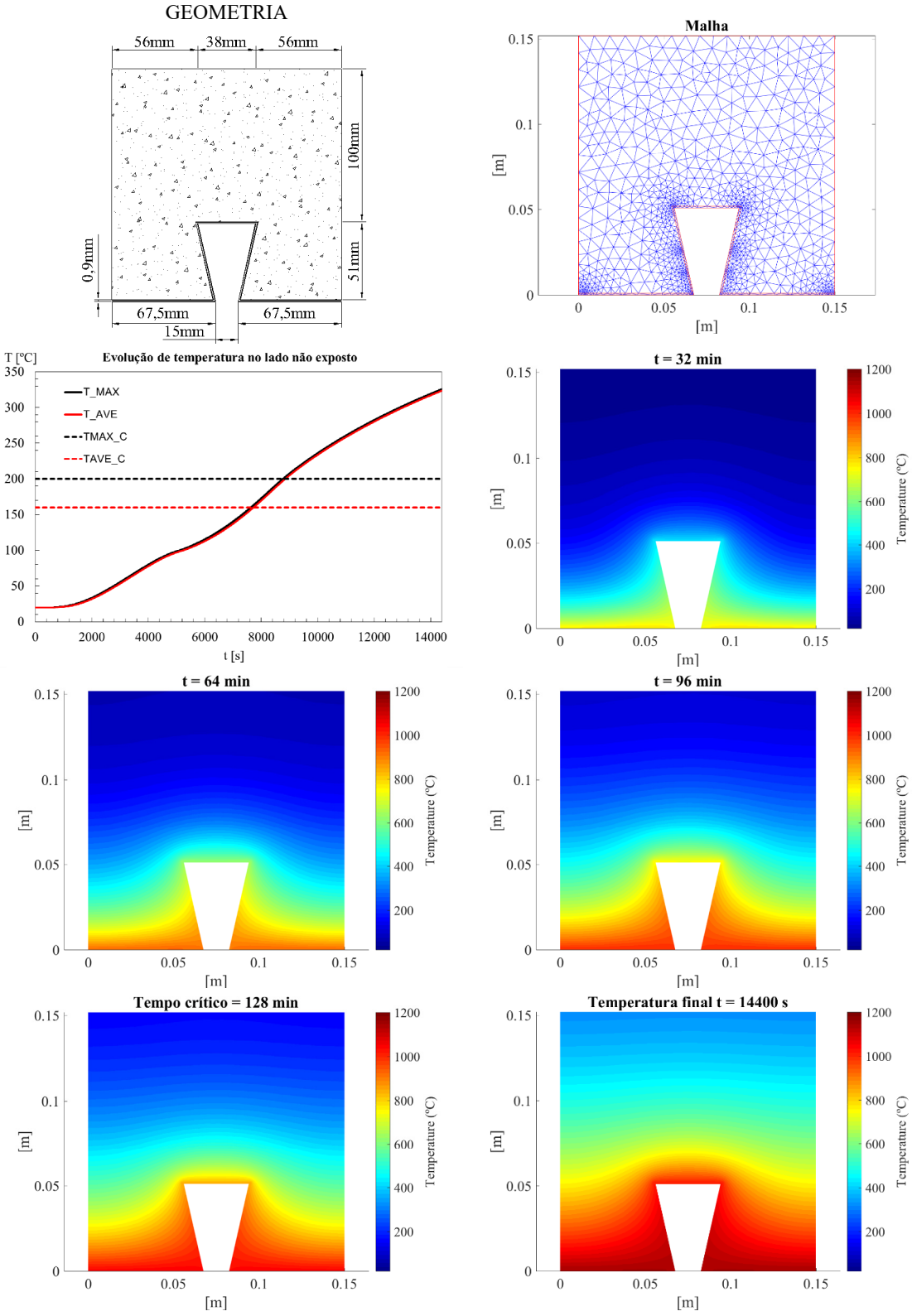




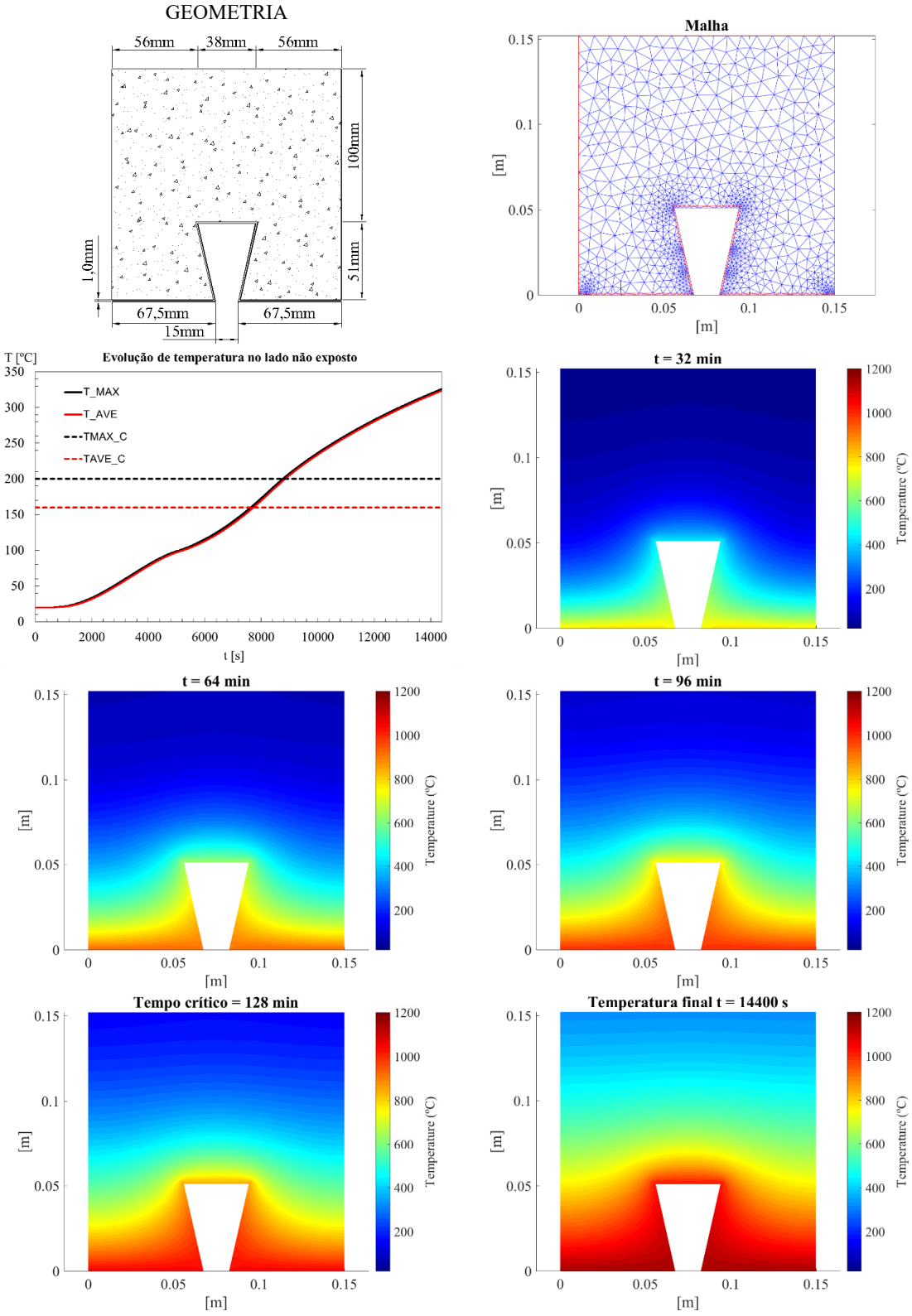




LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.9mm



LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.0mm



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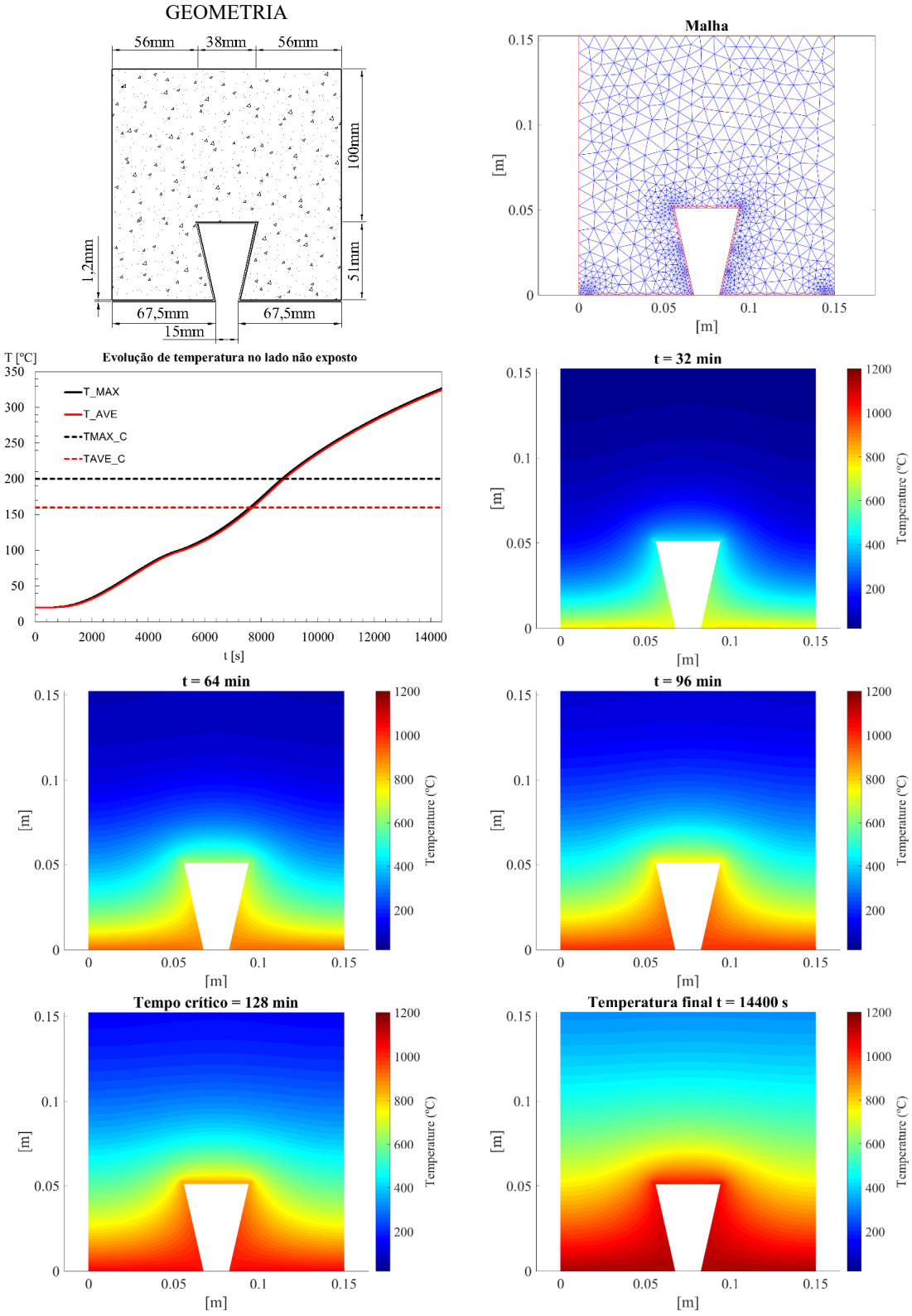
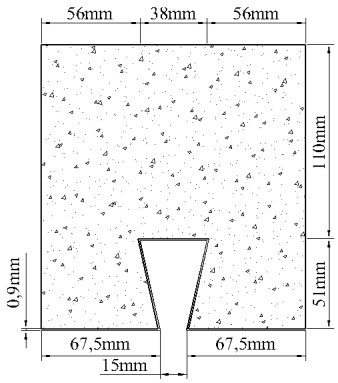
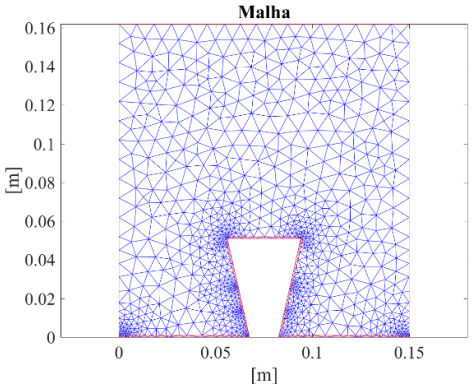
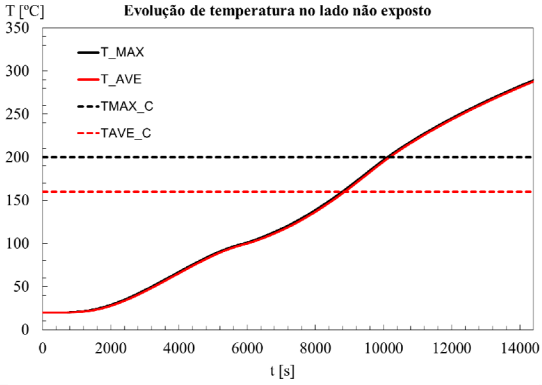


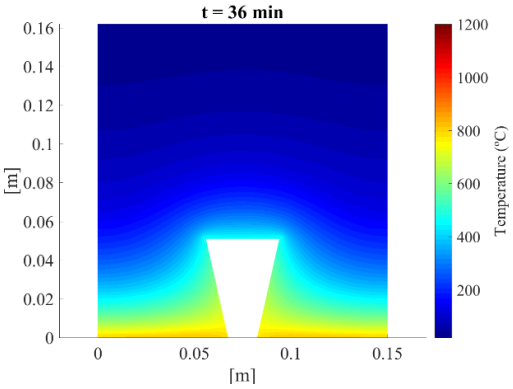
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.9mm

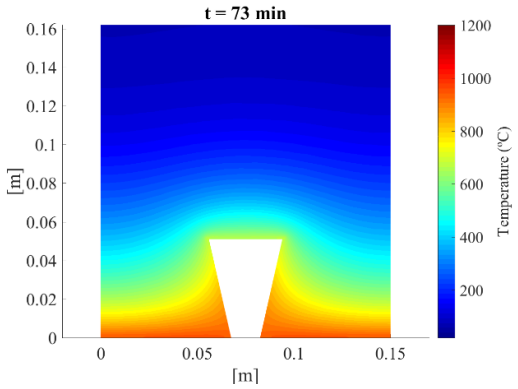
GEOMETRIA

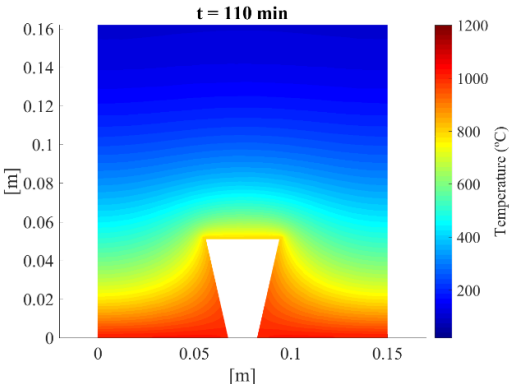


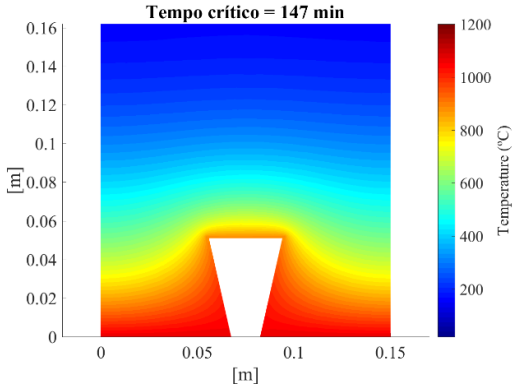


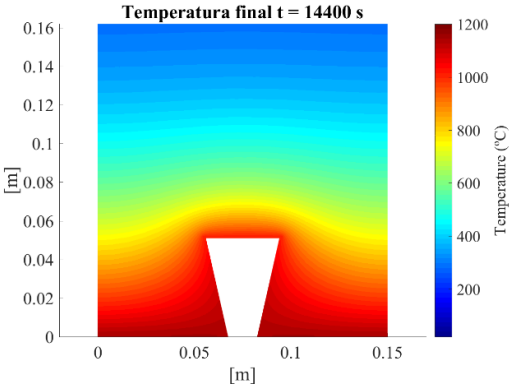






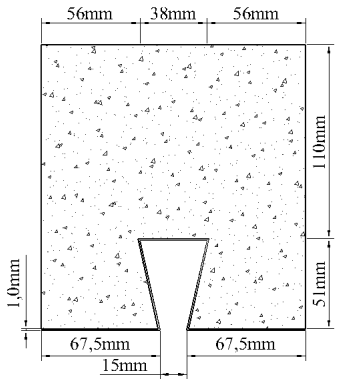


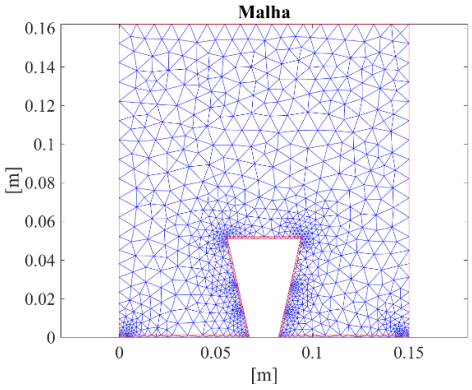


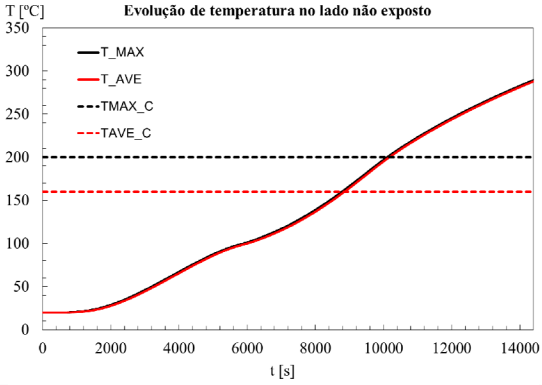


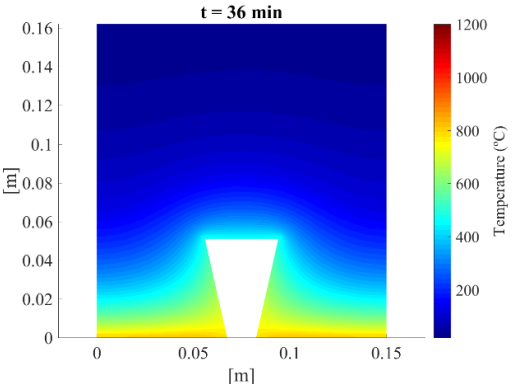
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.0mm

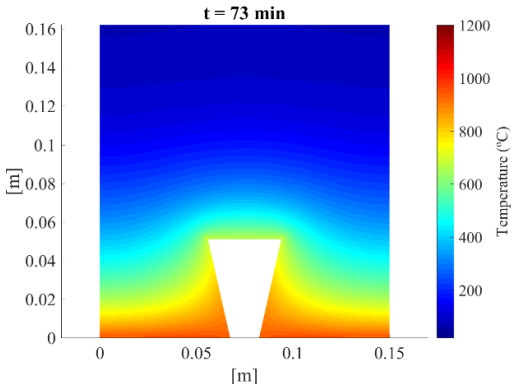
GEOMETRIA

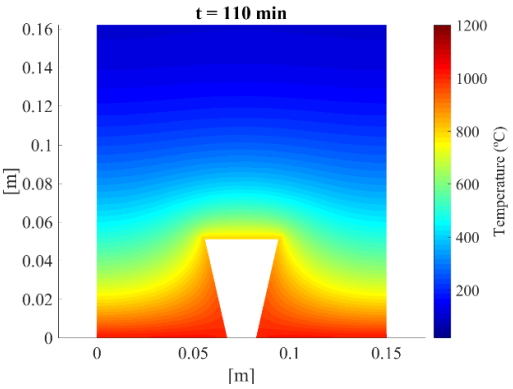


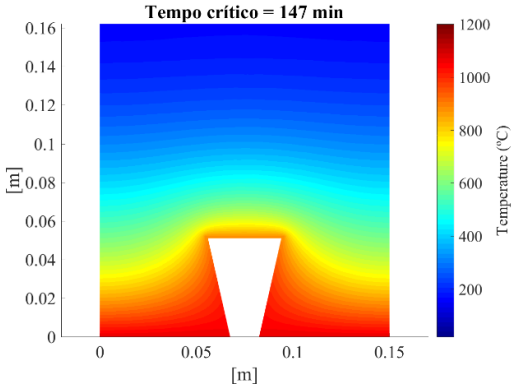


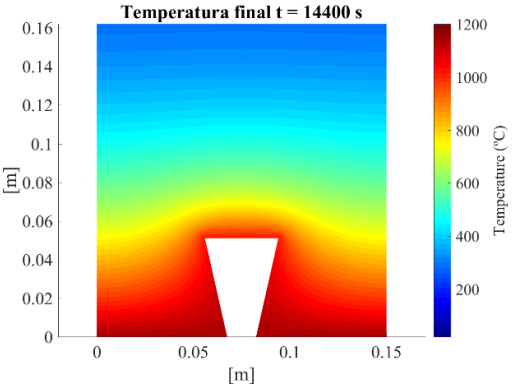






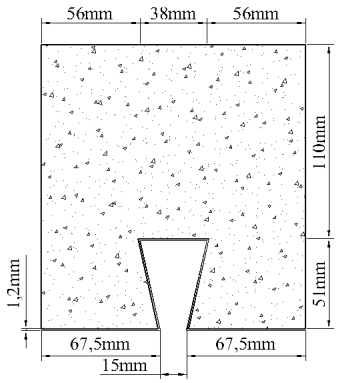


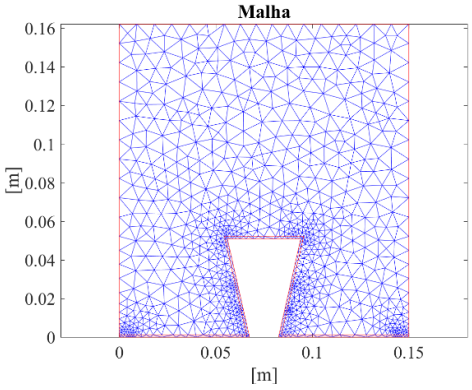


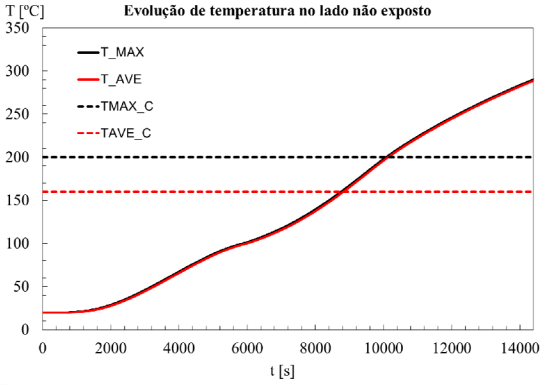


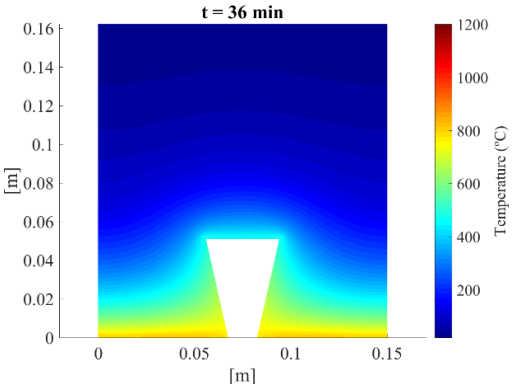
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.2mm

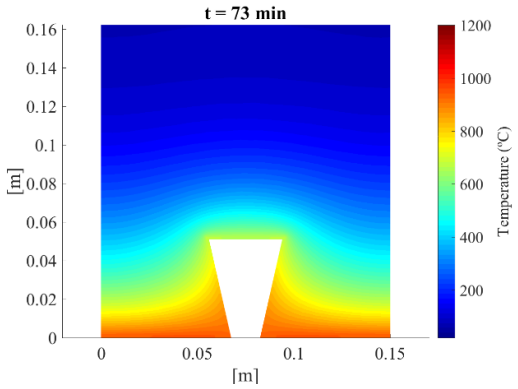
GEOMETRIA

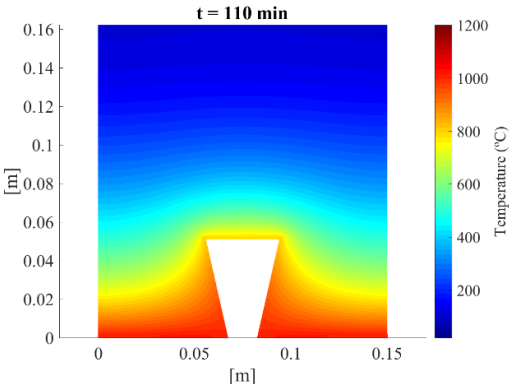


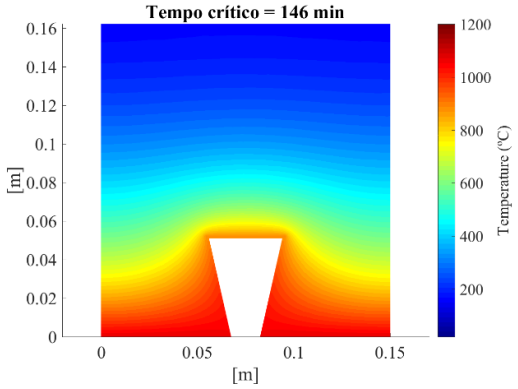


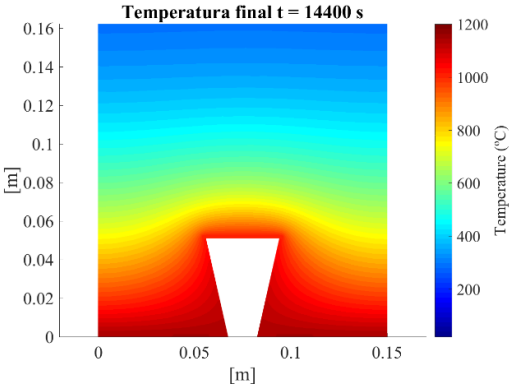




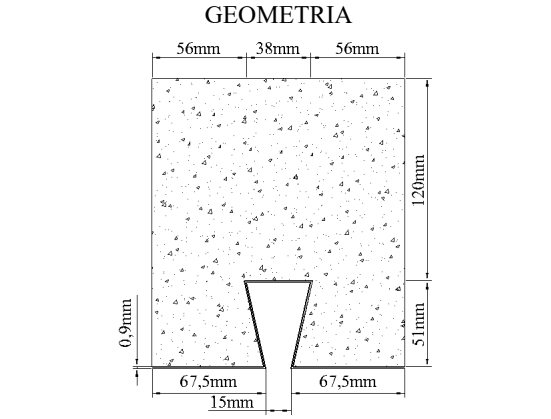


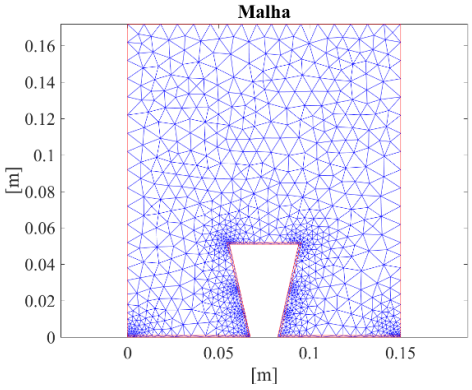


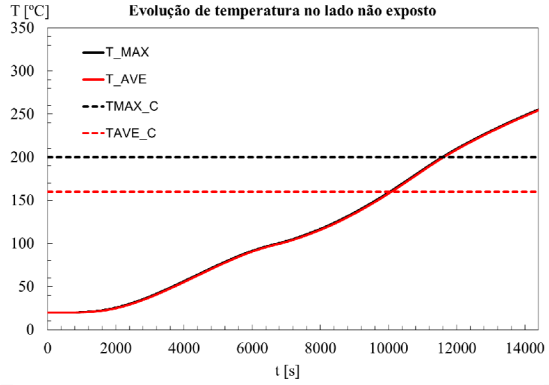


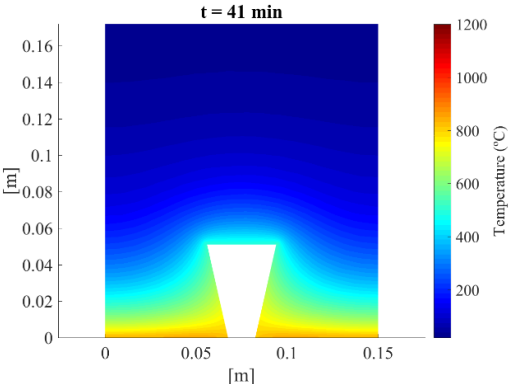


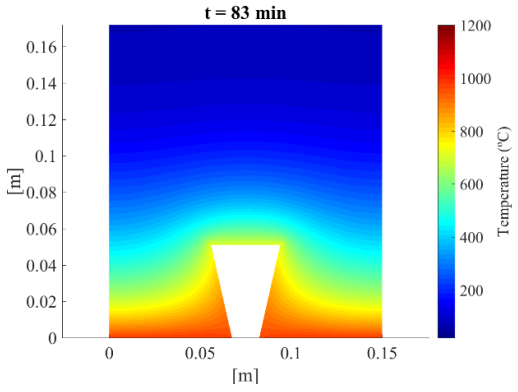
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.9mm

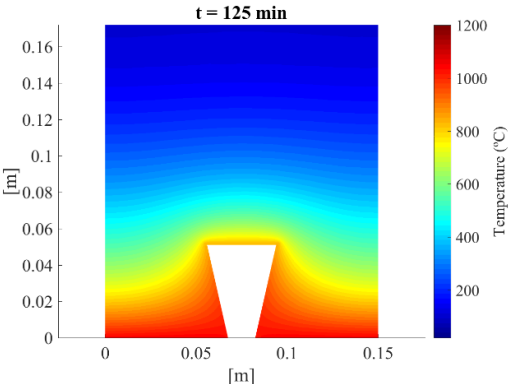


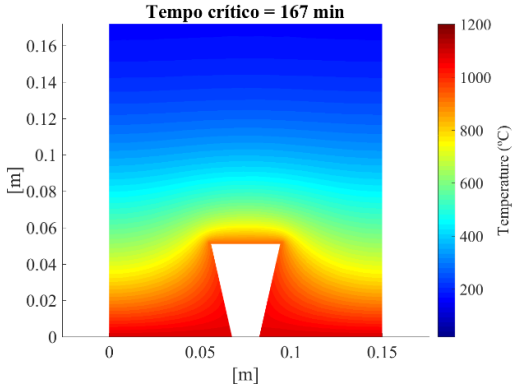


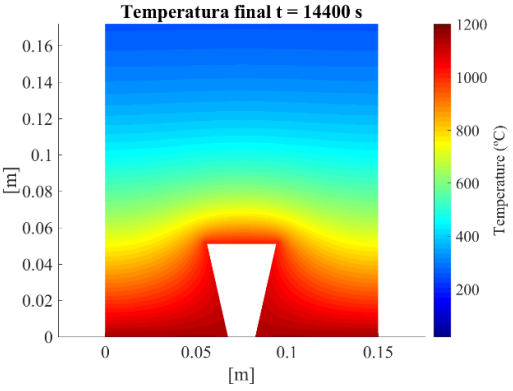






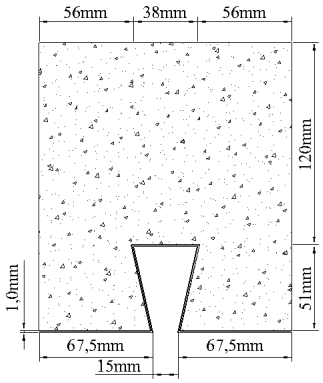


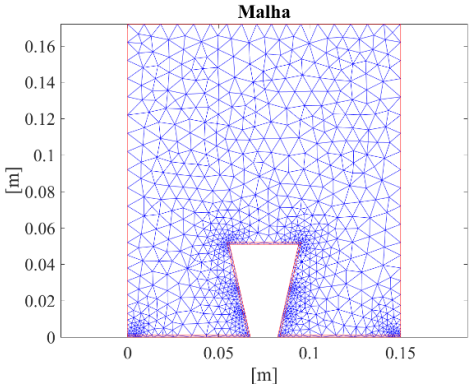


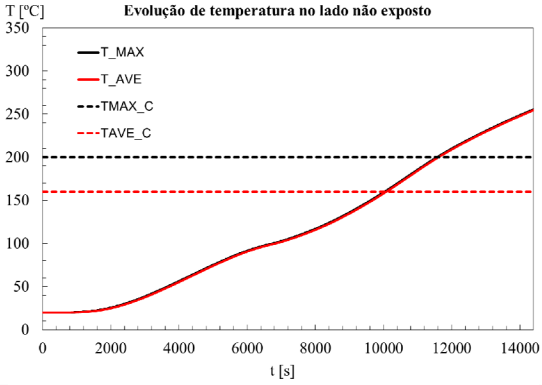


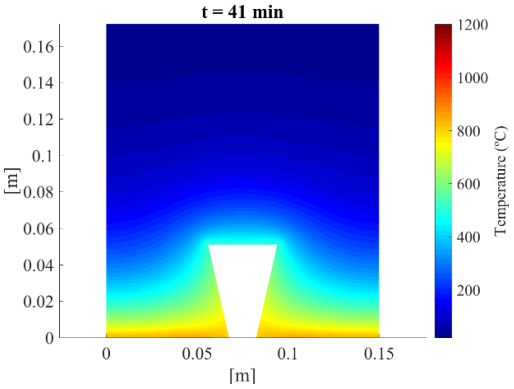
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.0mm

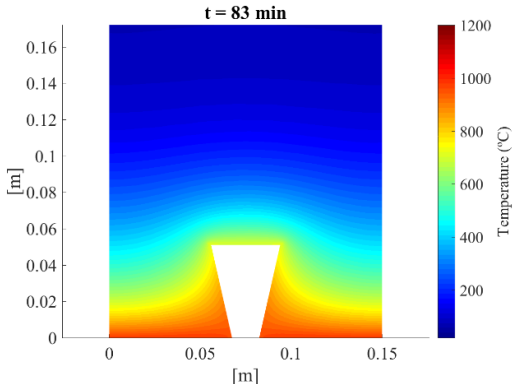
GEOMETRIA

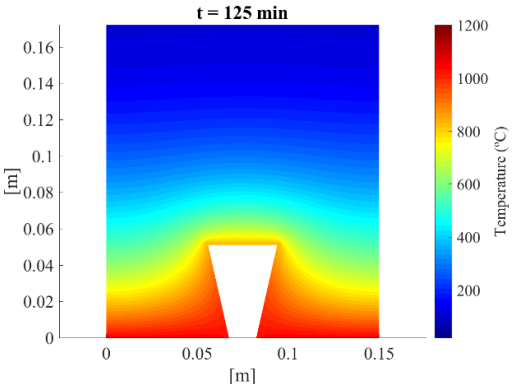


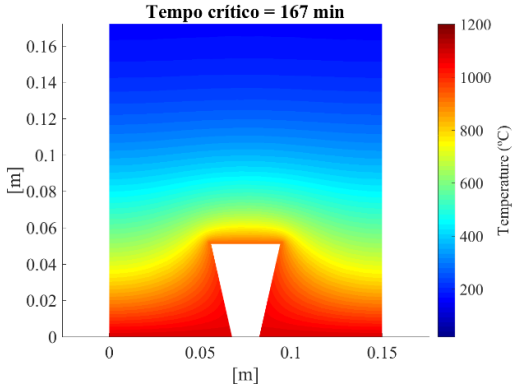


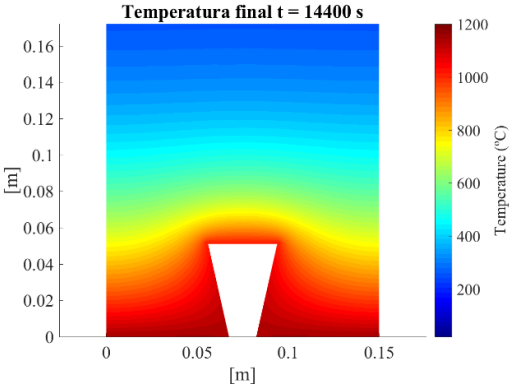






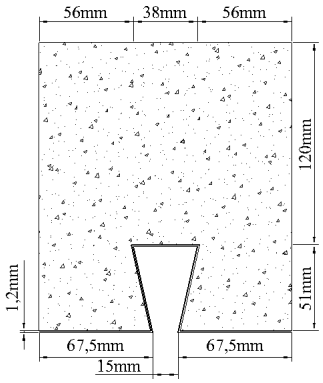


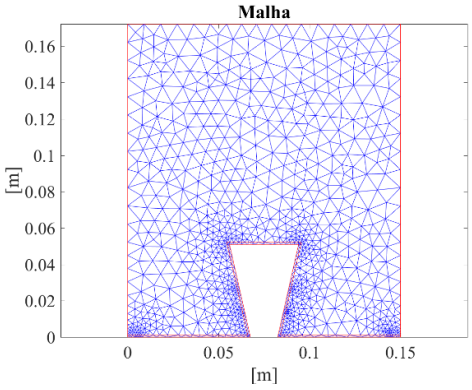


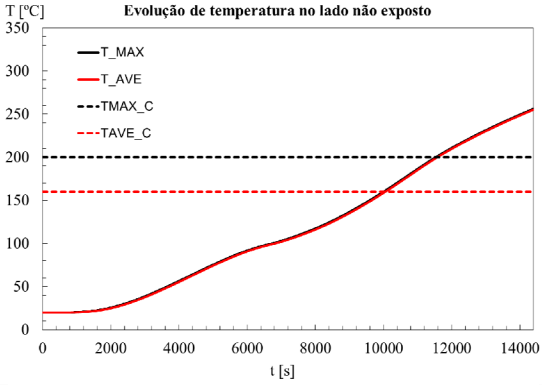


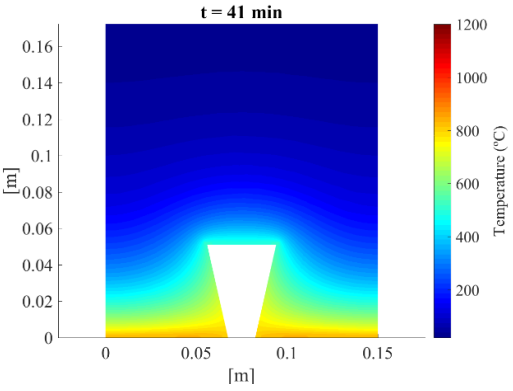
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.2mm

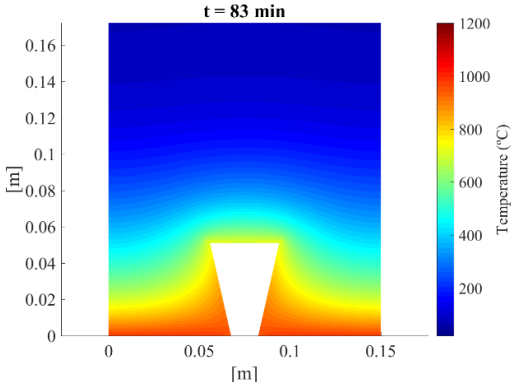
GEOMETRIA

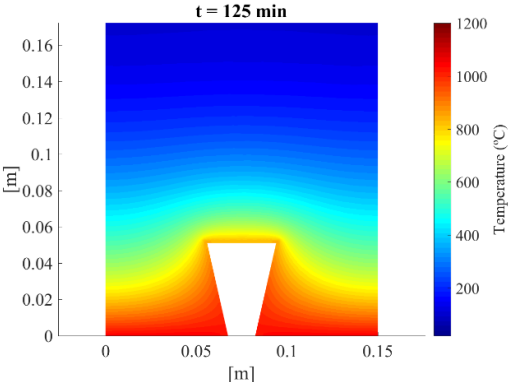


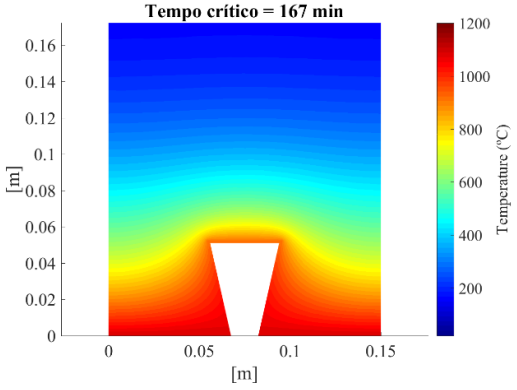


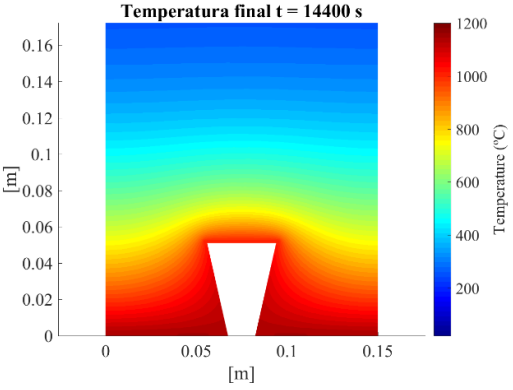




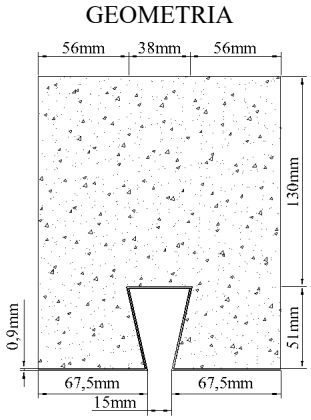


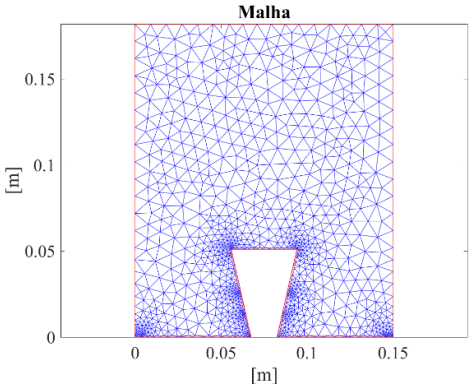


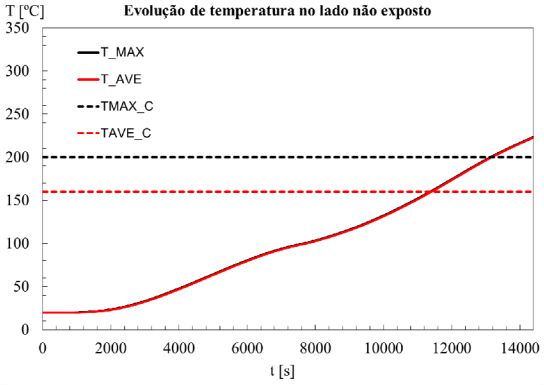


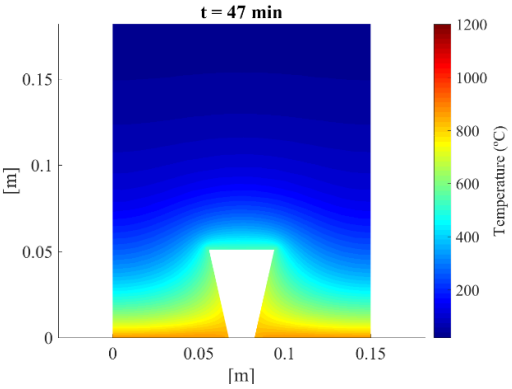


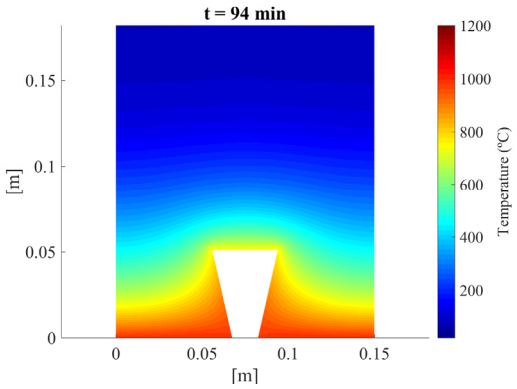
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.9mm

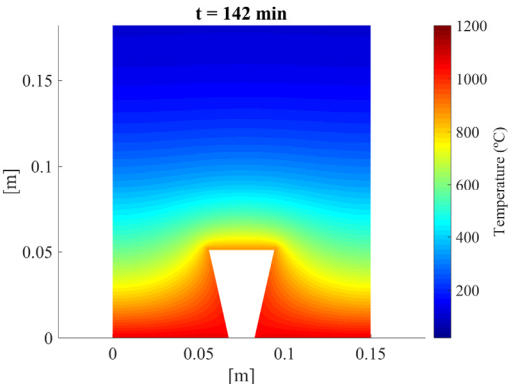


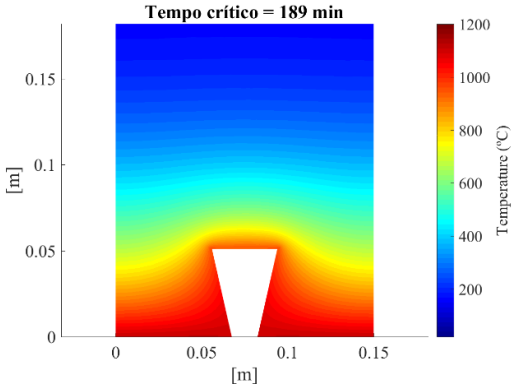


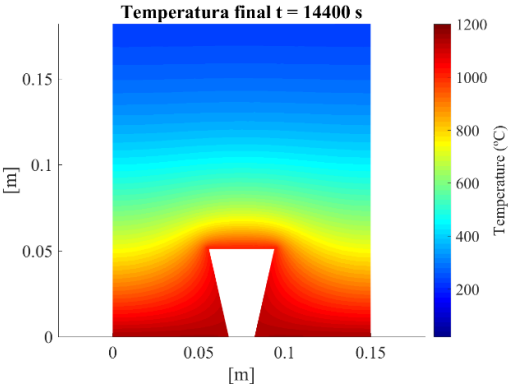




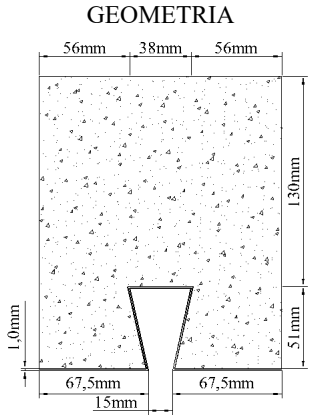


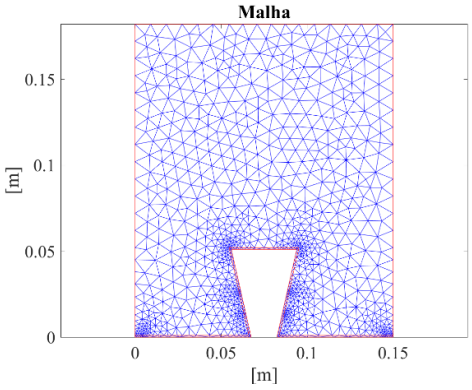


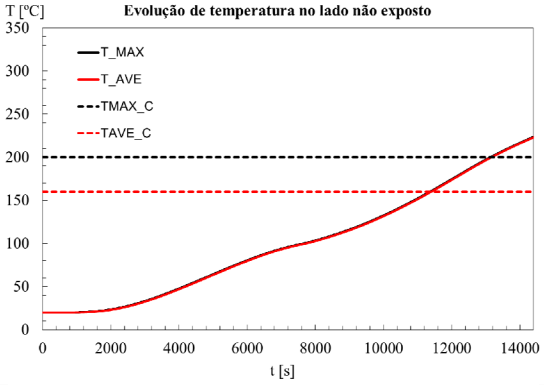


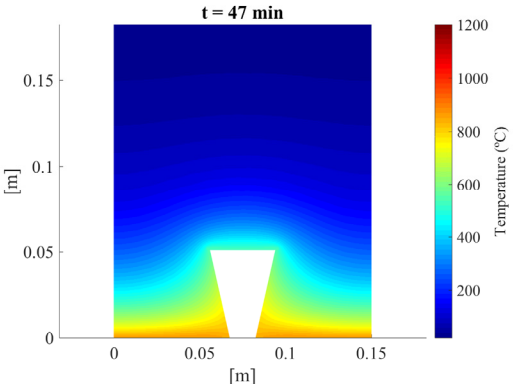


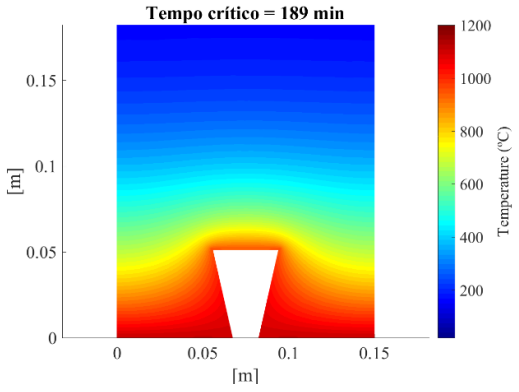
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.0mm

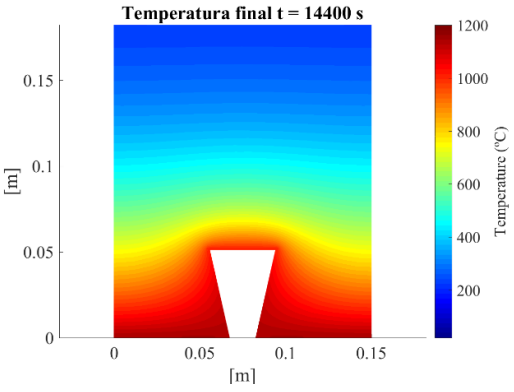


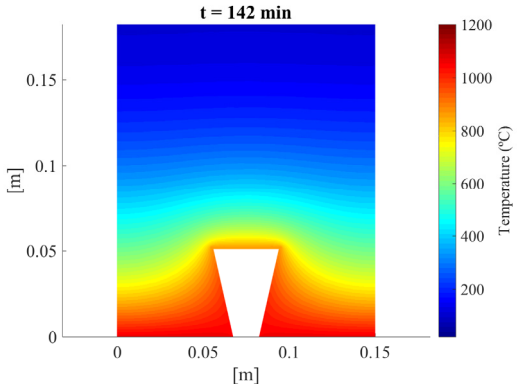


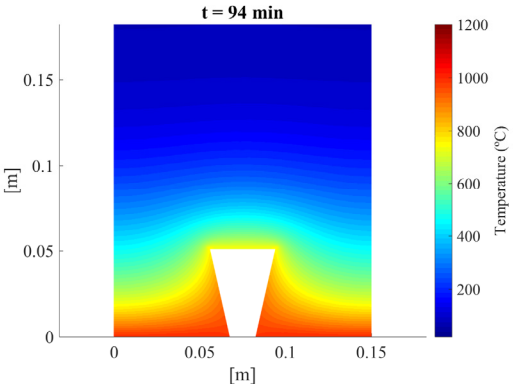




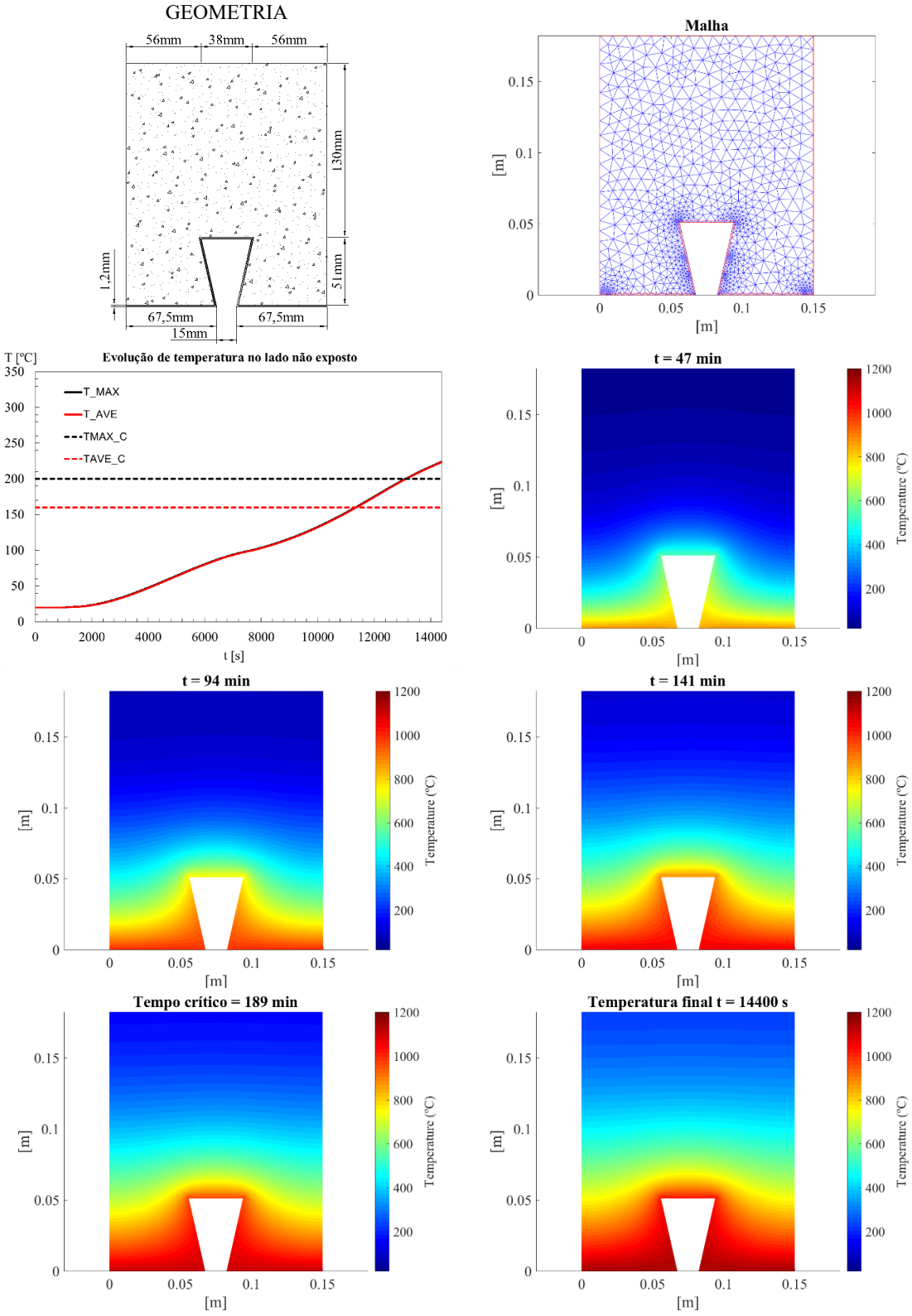




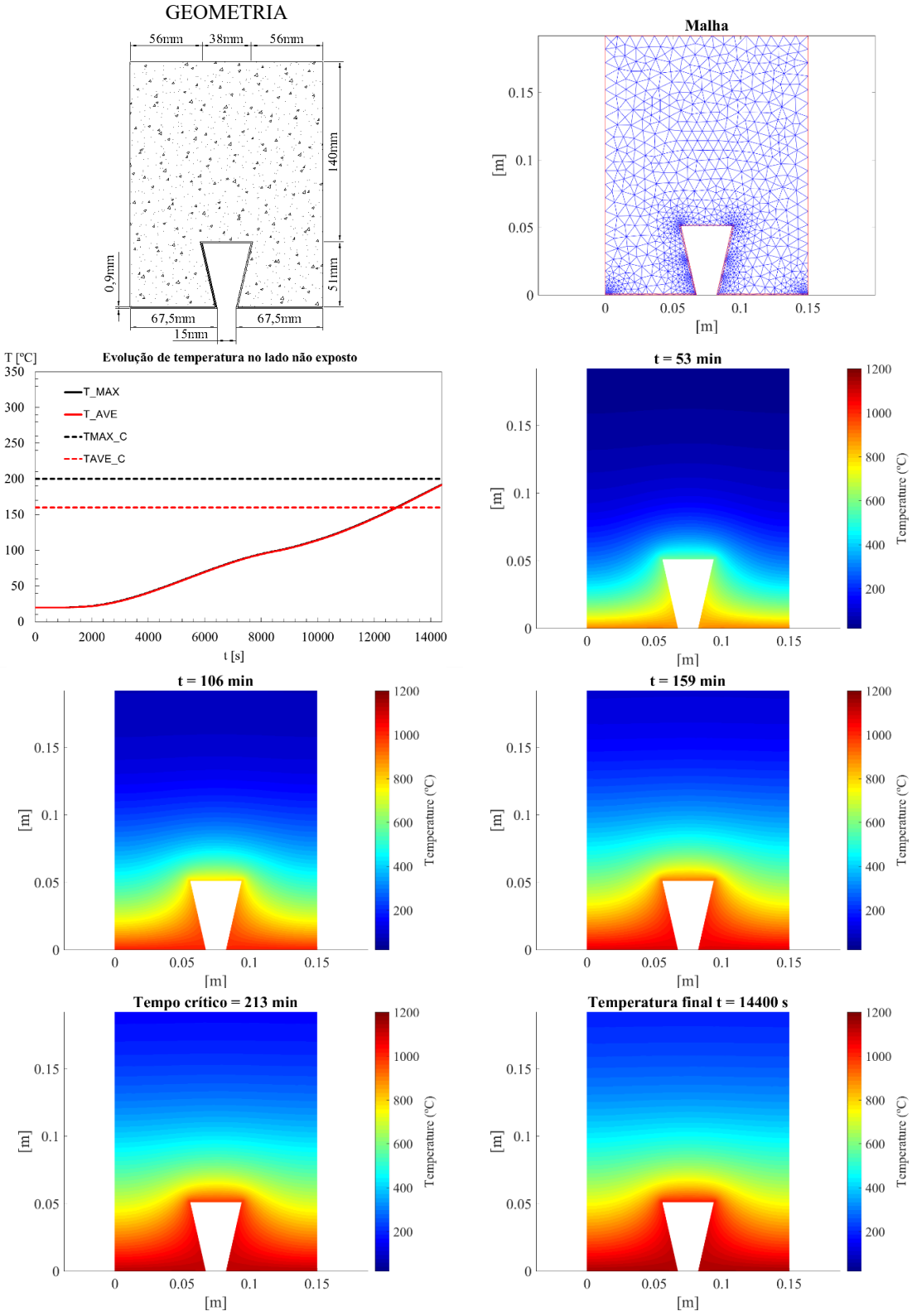




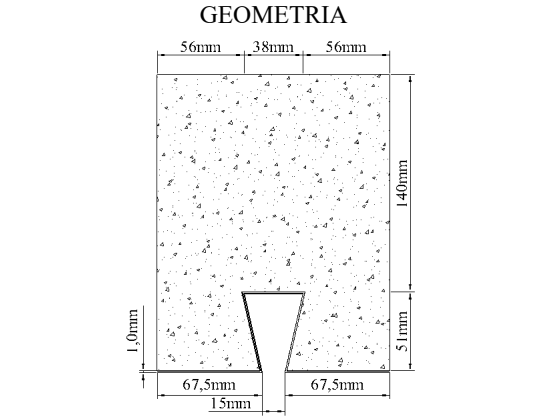
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.2mm

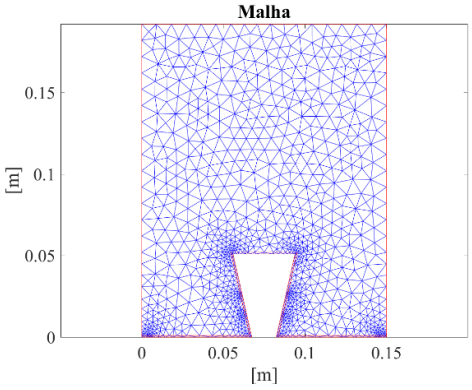


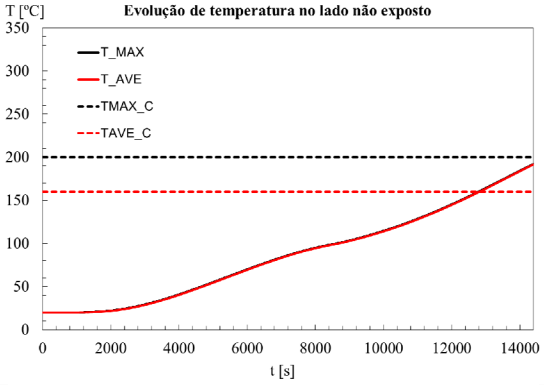
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.9mm

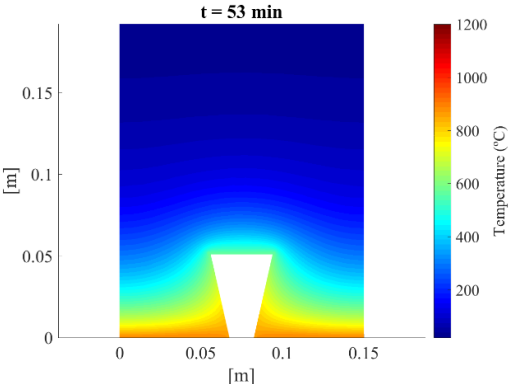


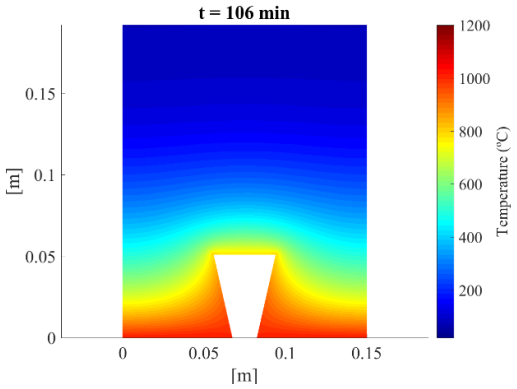
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.0mm

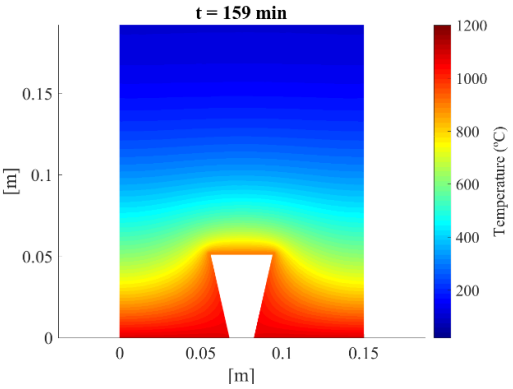


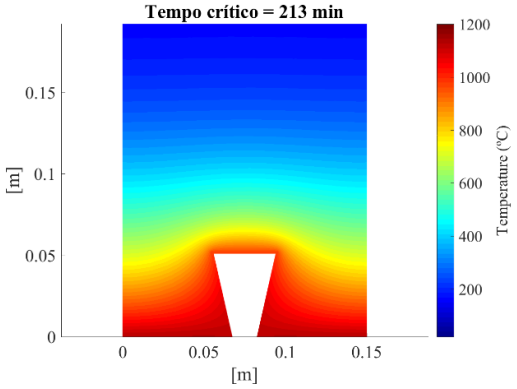


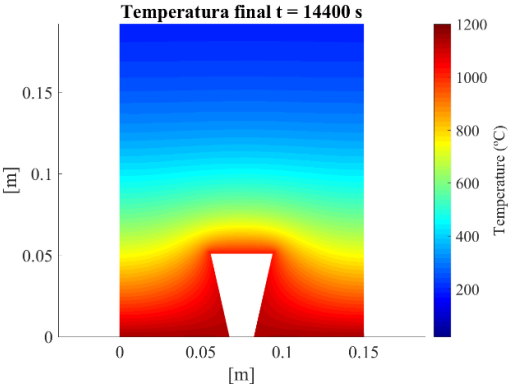




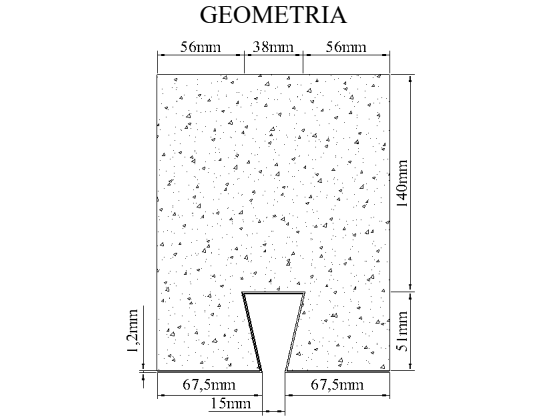


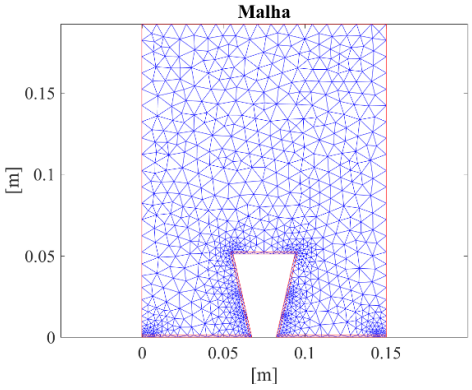


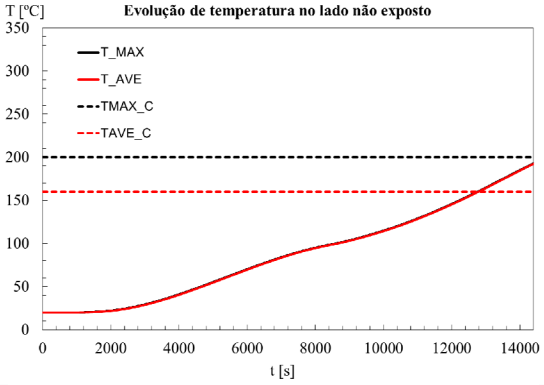


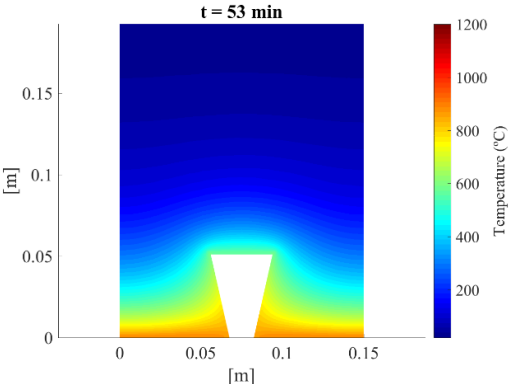


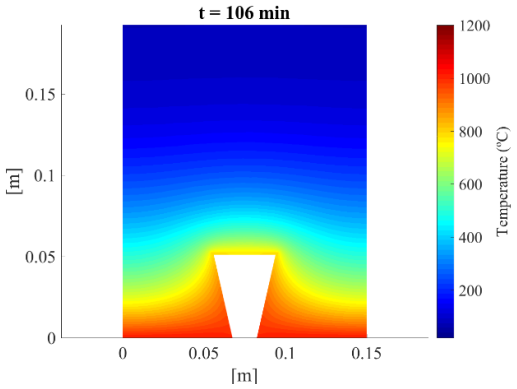
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.2mm

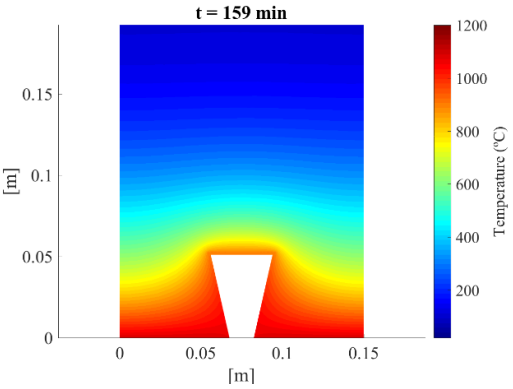


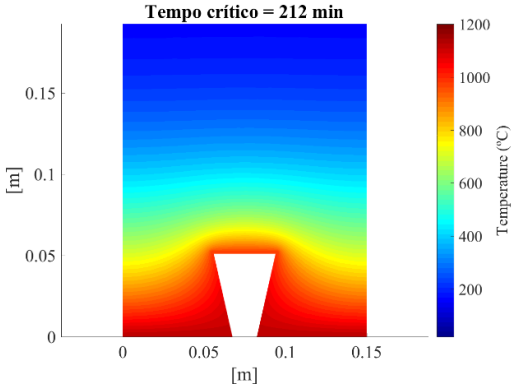


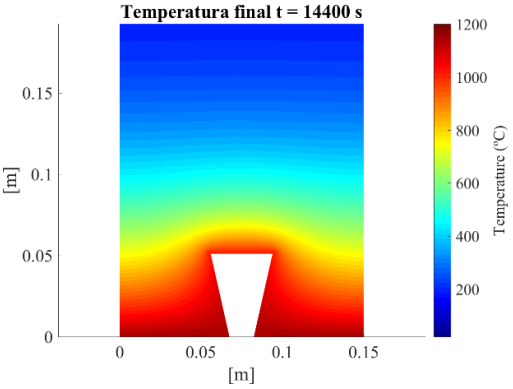






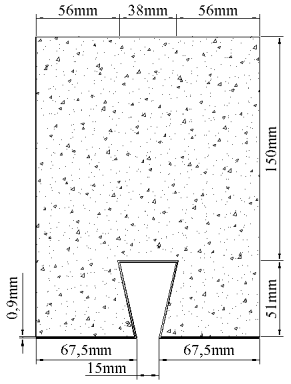


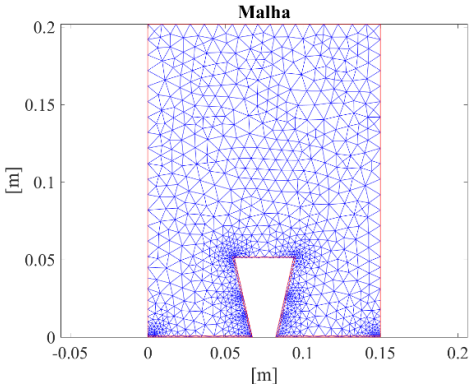


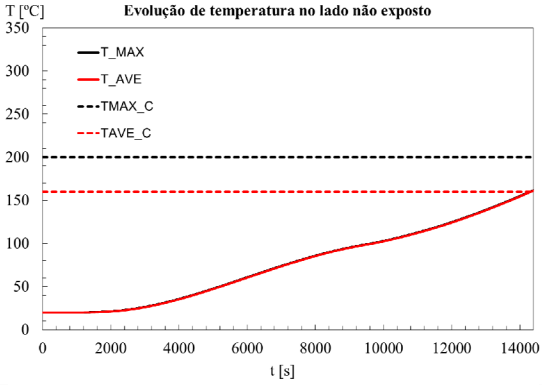


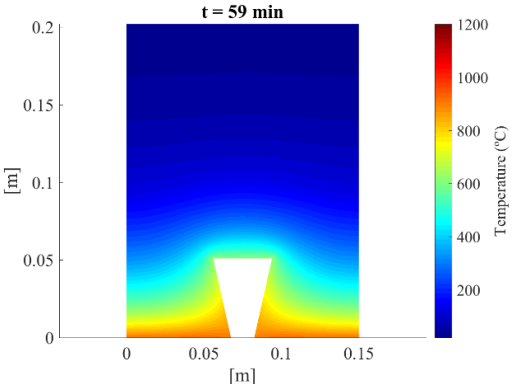
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.9mm

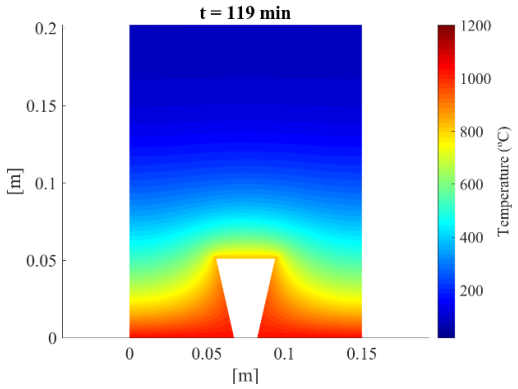
GEOMETRIA

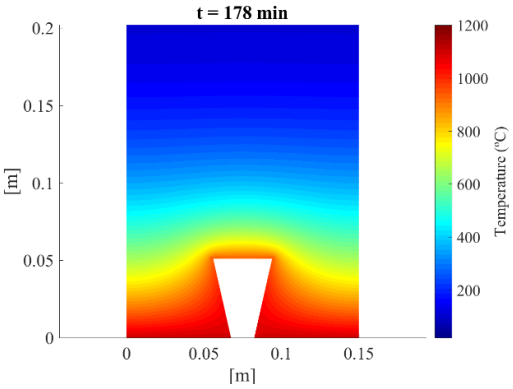


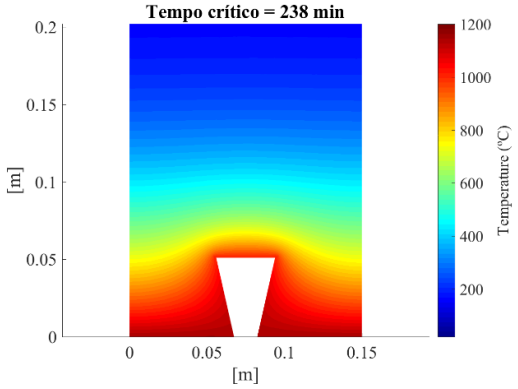


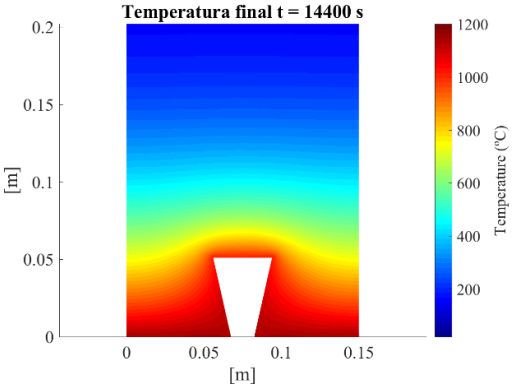




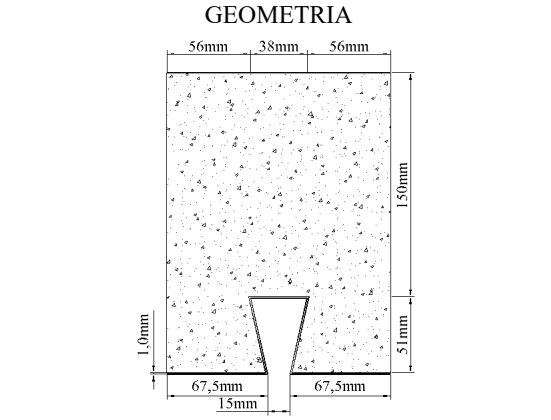


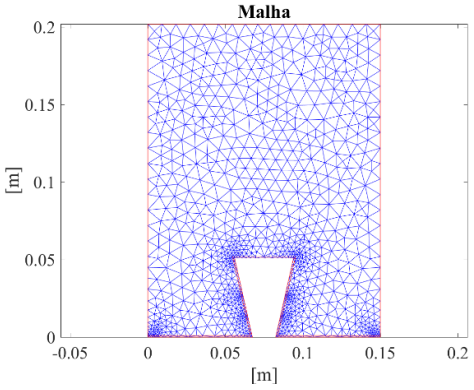


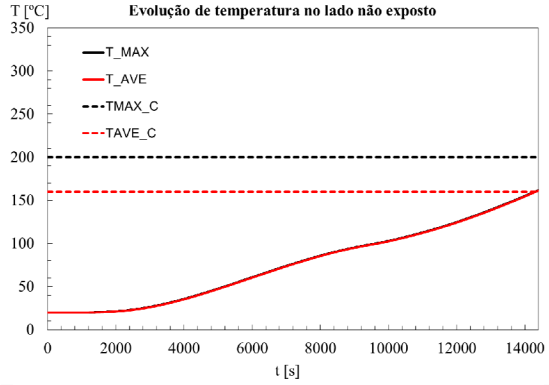


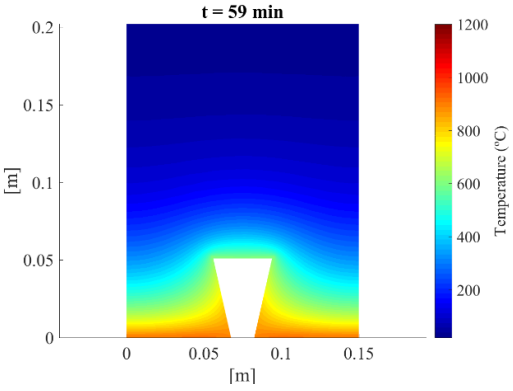


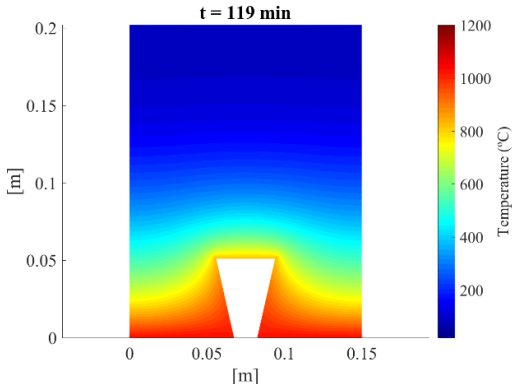
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.0mm

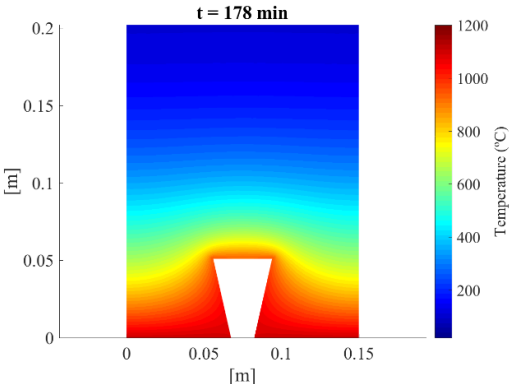


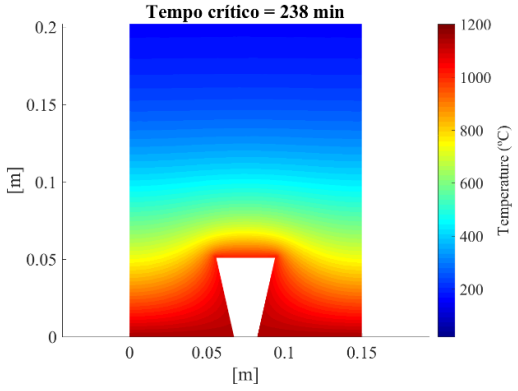


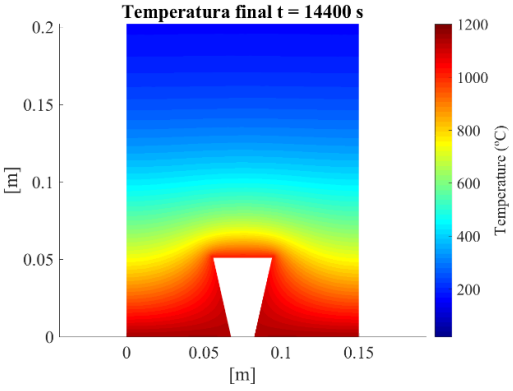




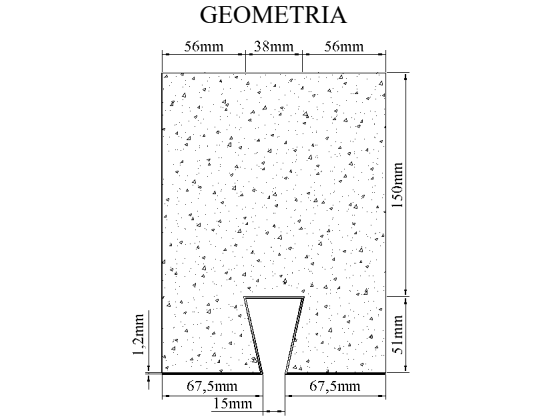


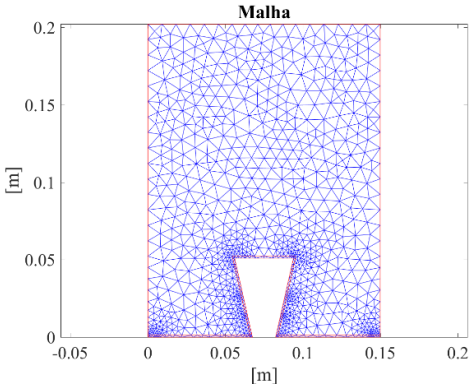


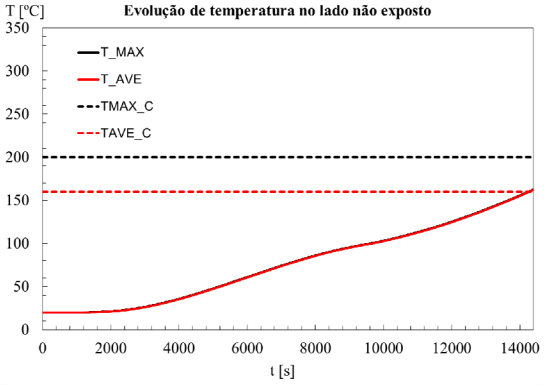


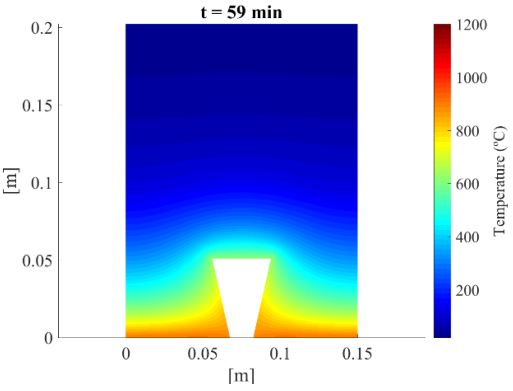


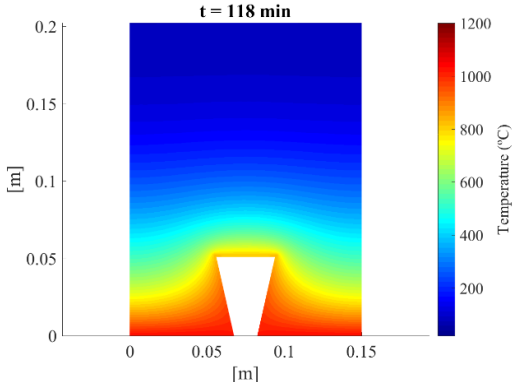
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.2mm

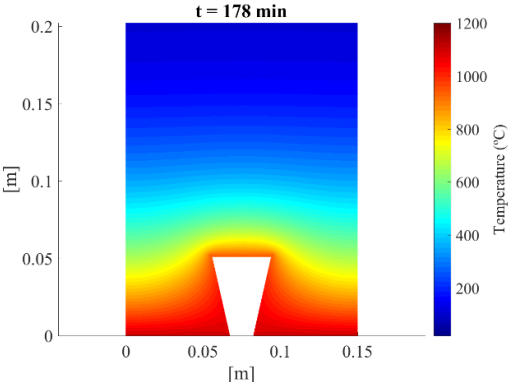


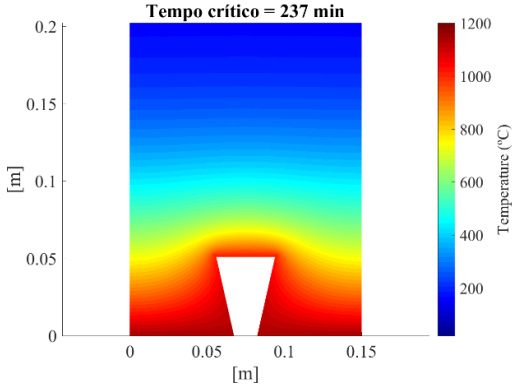


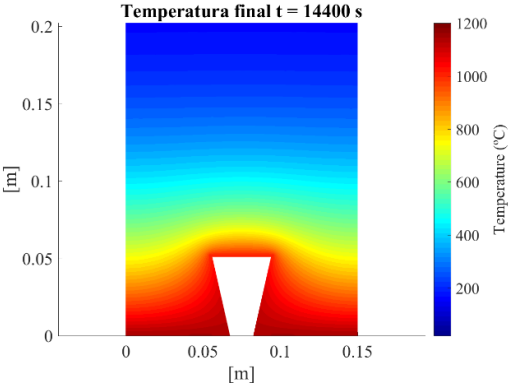






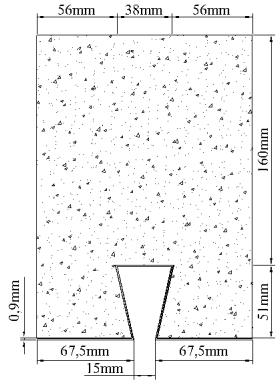


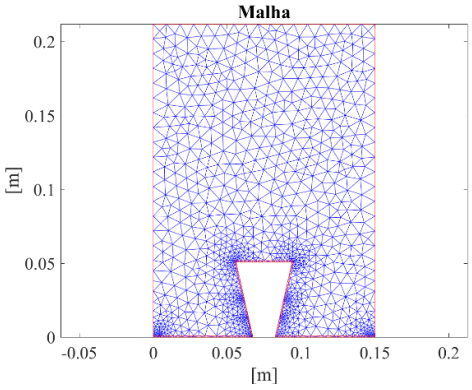


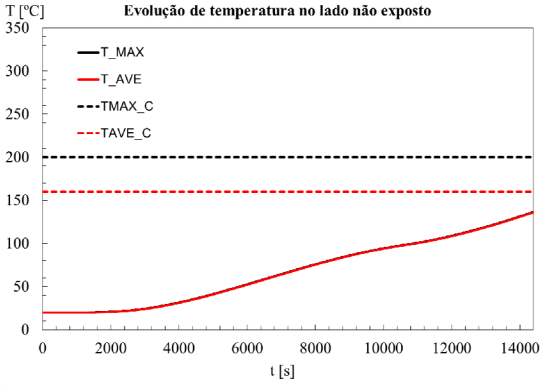


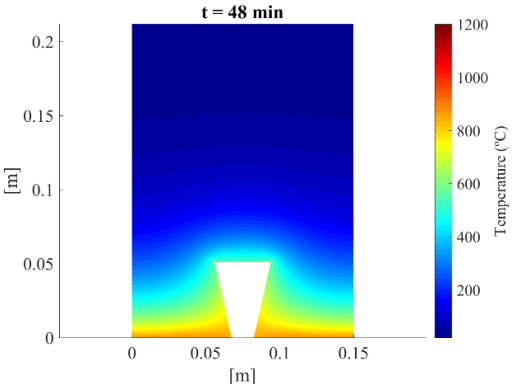
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.9mm

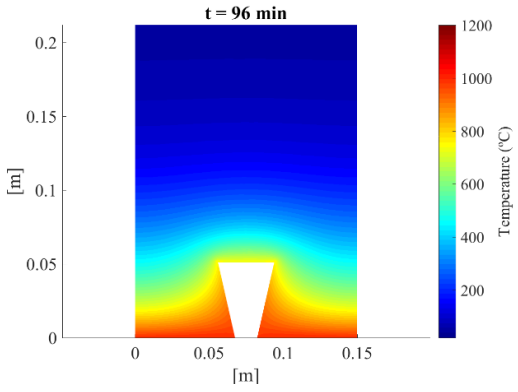
GEOMETRIA

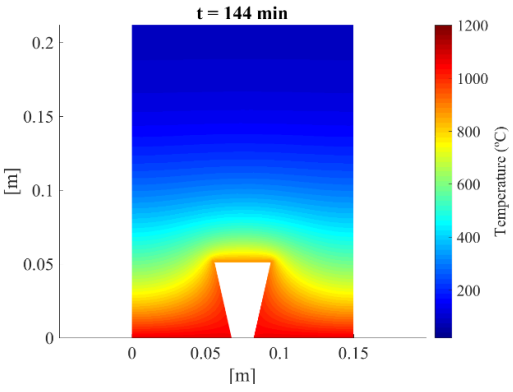


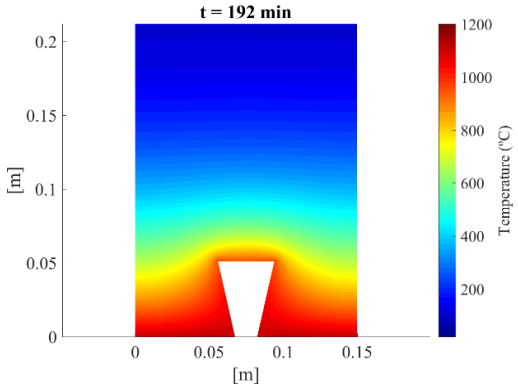


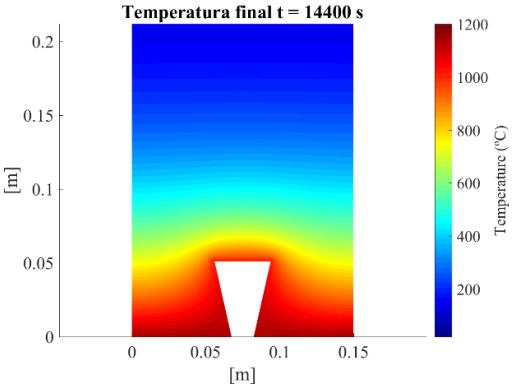






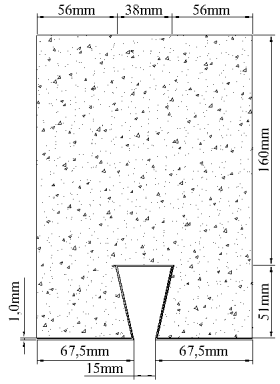


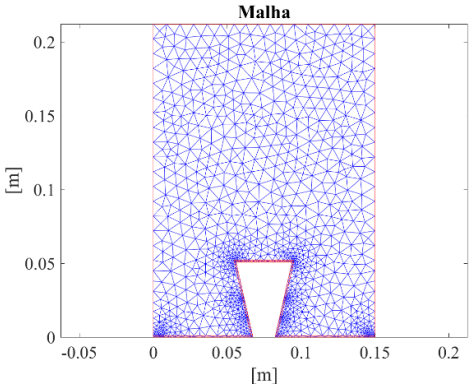


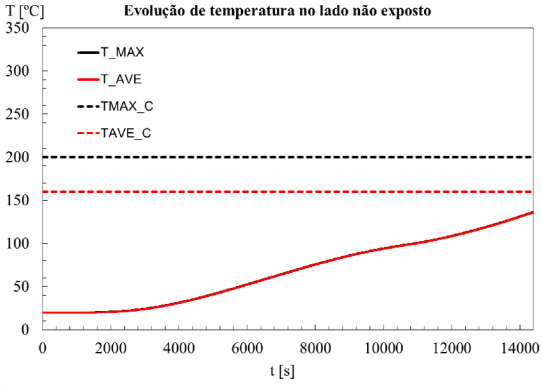


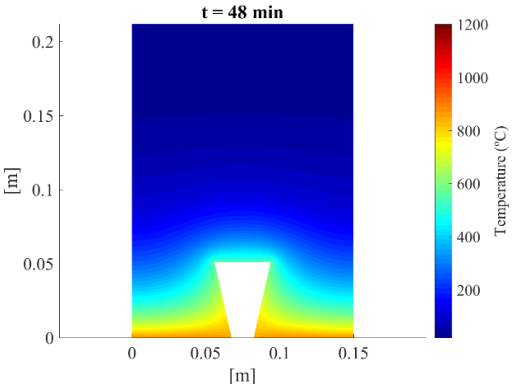
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.0mm

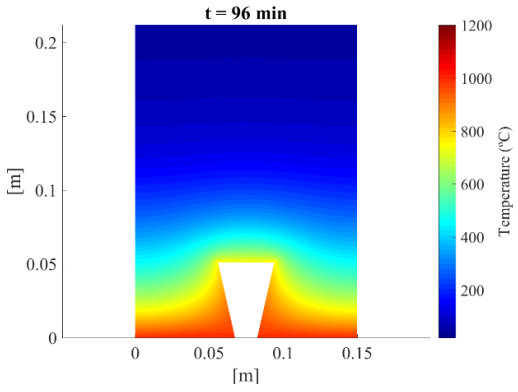
GEOMETRIA

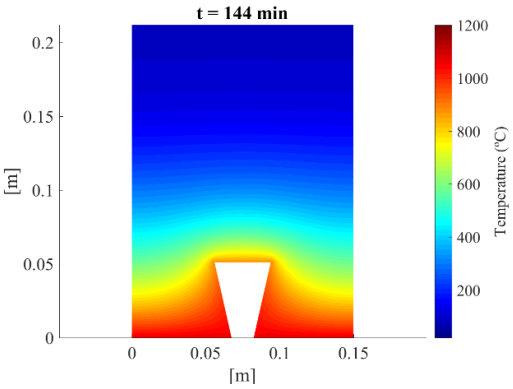


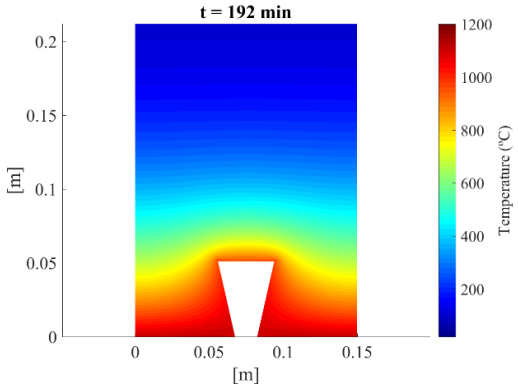


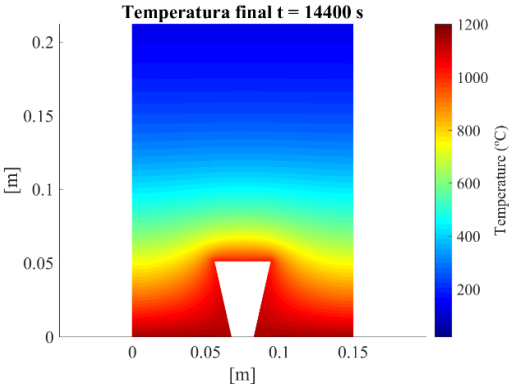




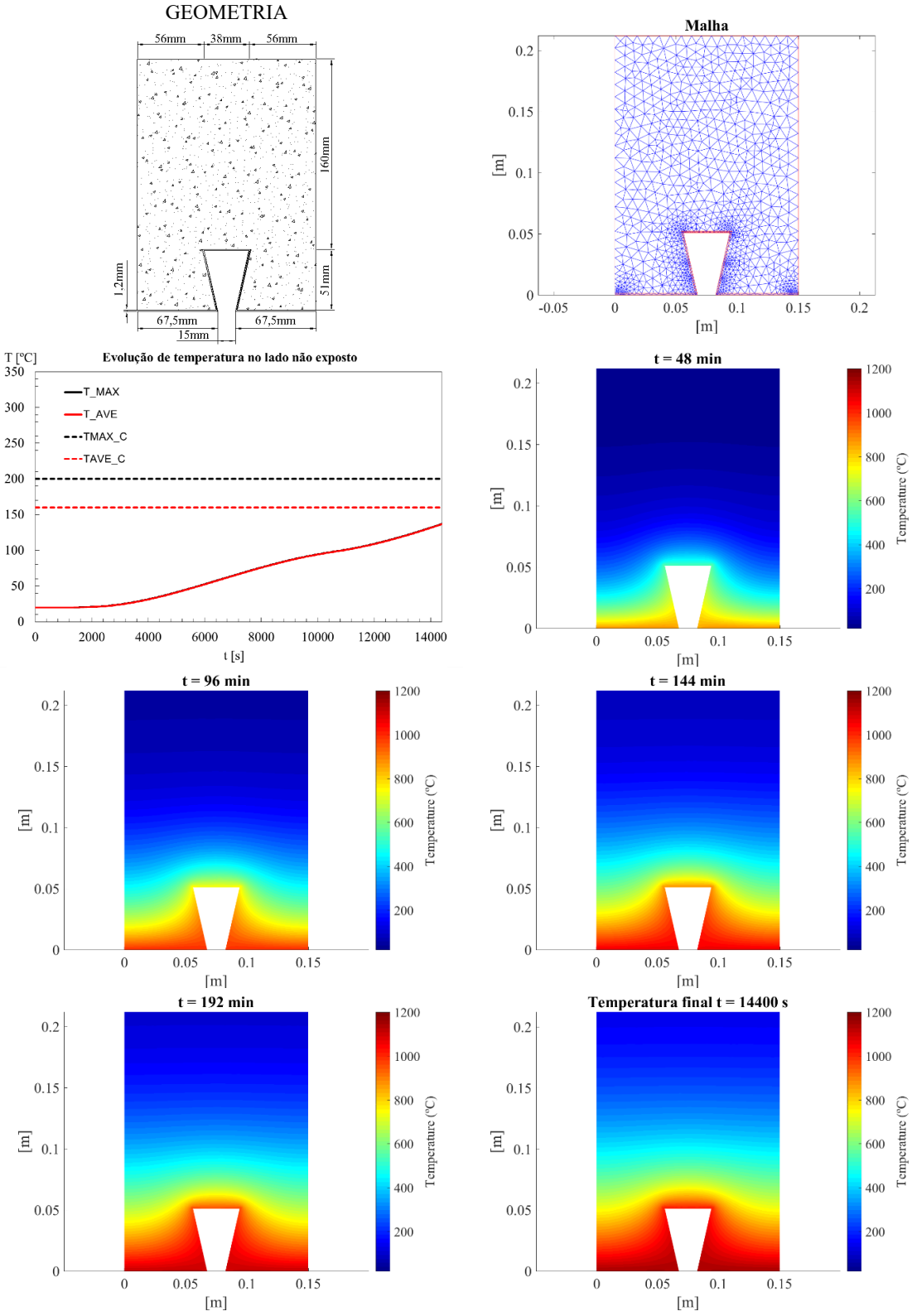






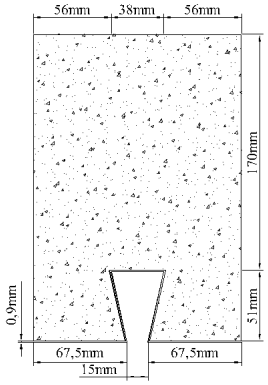


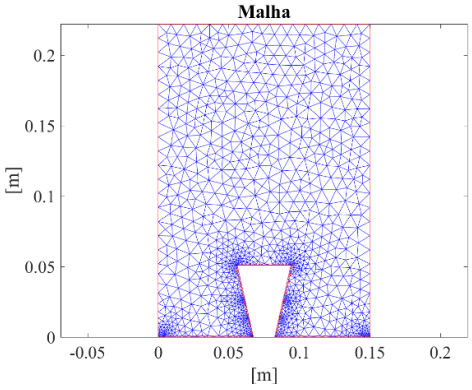
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.2mm

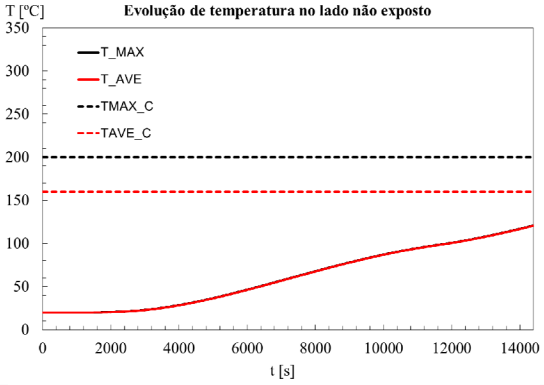


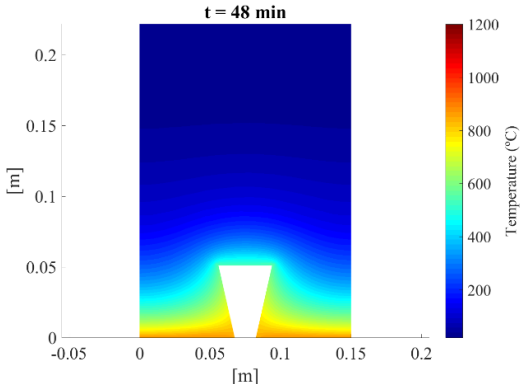
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.9mm

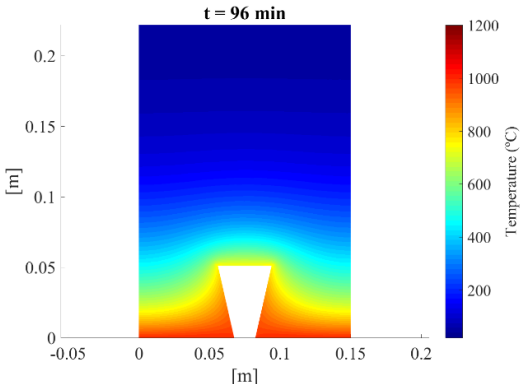
GEOMETRIA

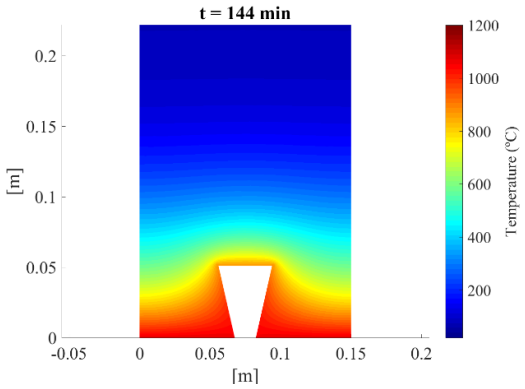


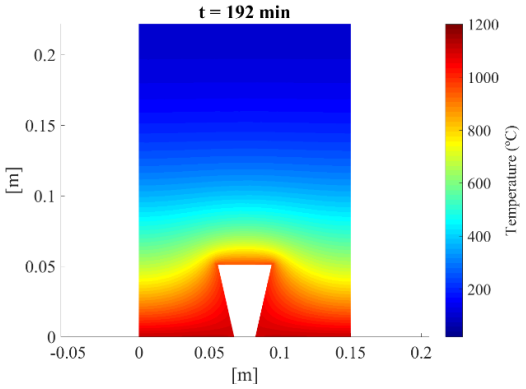


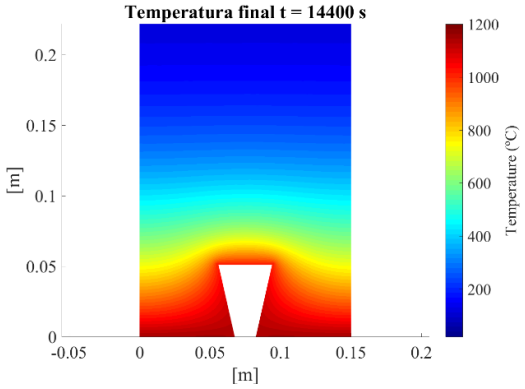




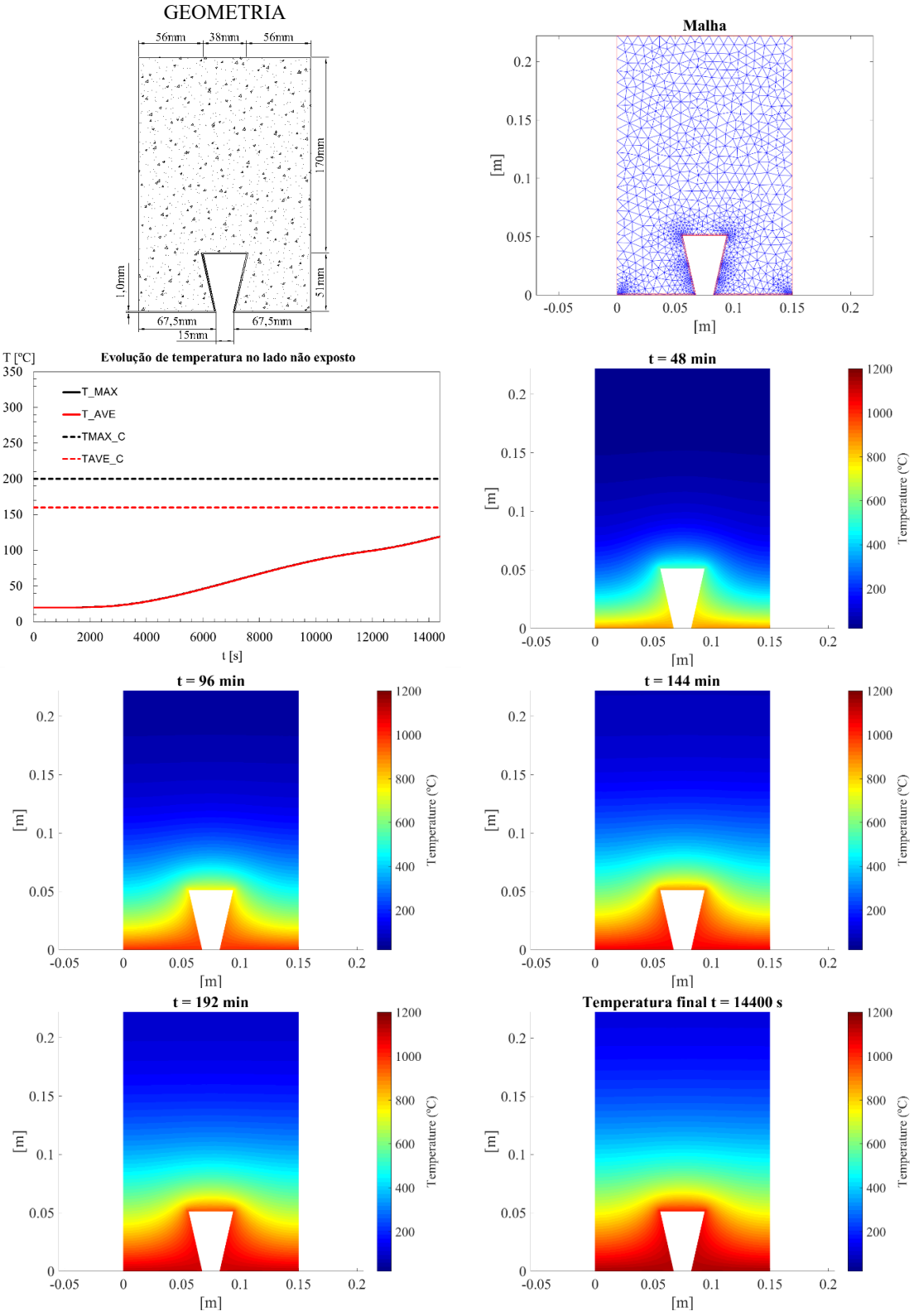




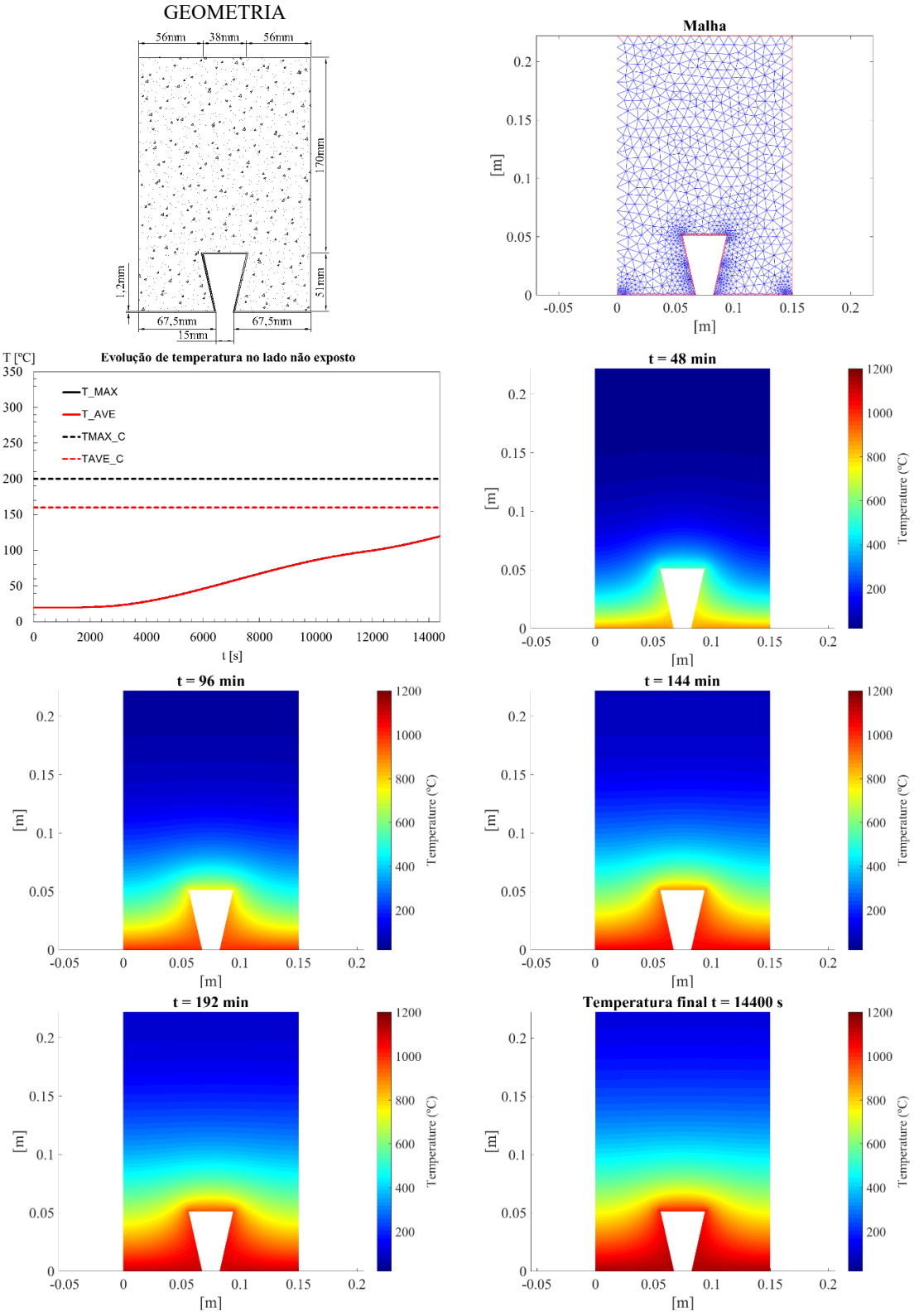




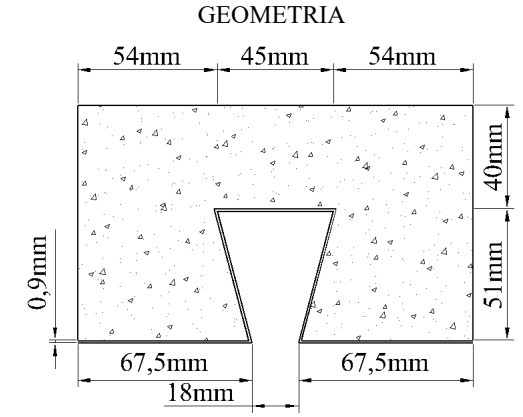
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.0mm

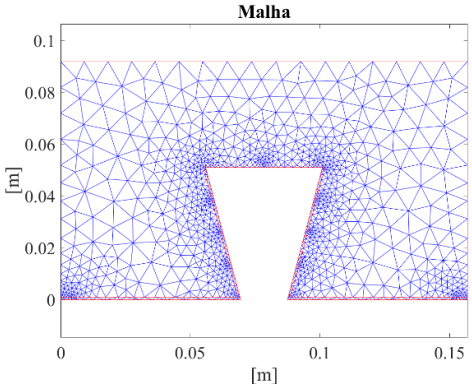


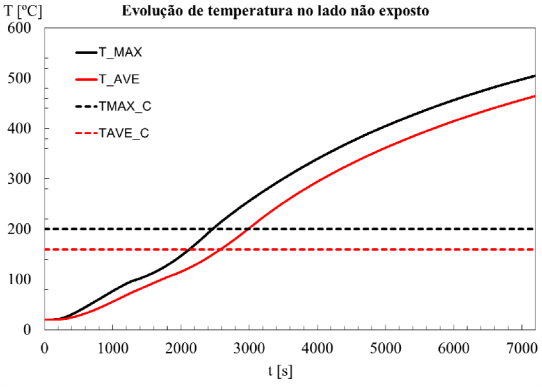
LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.2mm

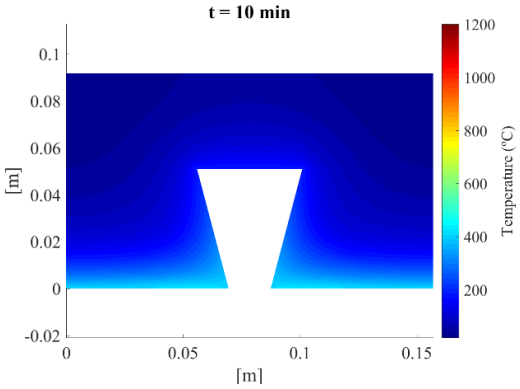


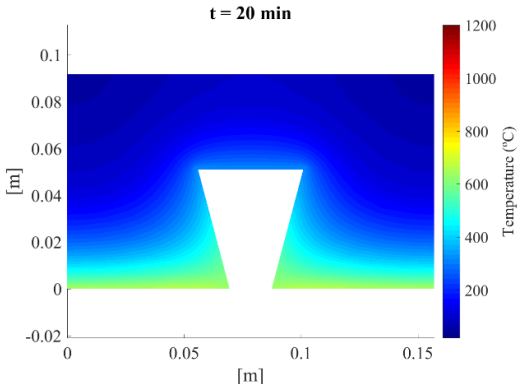
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.9mm

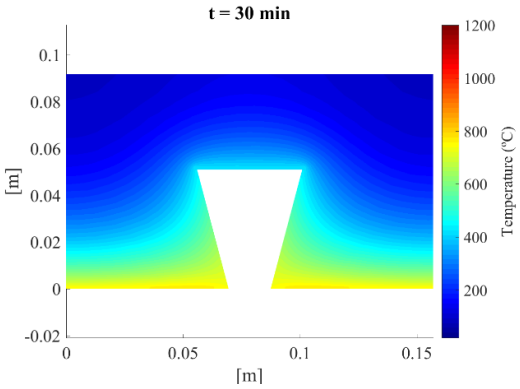


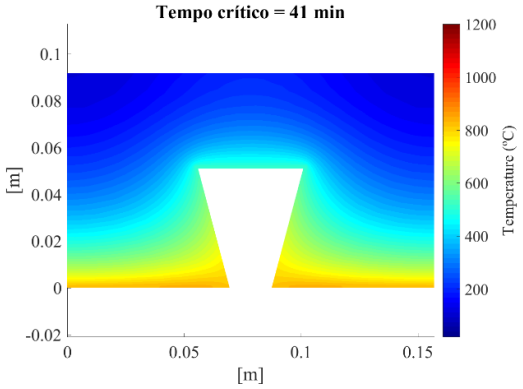


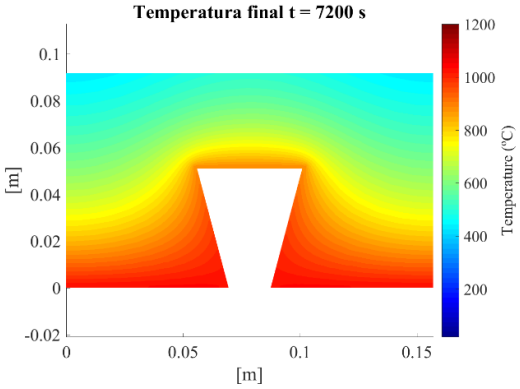




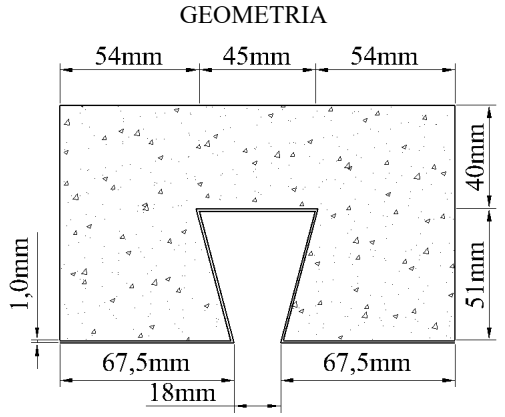


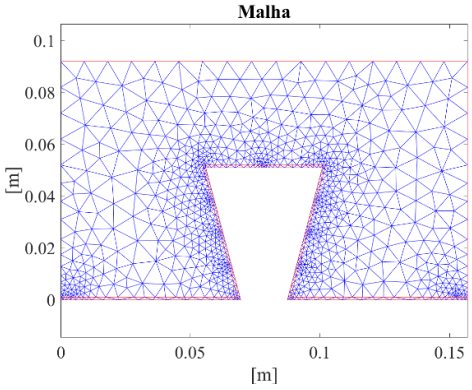


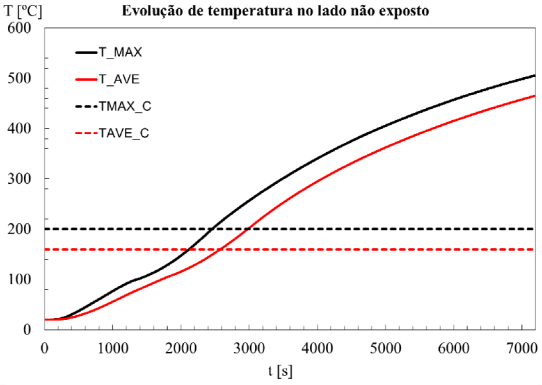


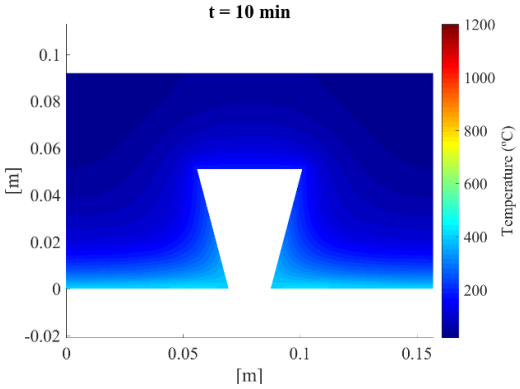


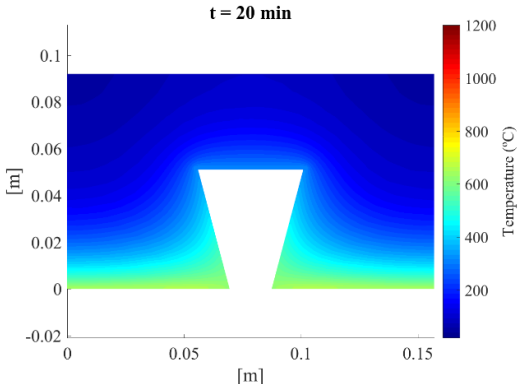
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.0mm

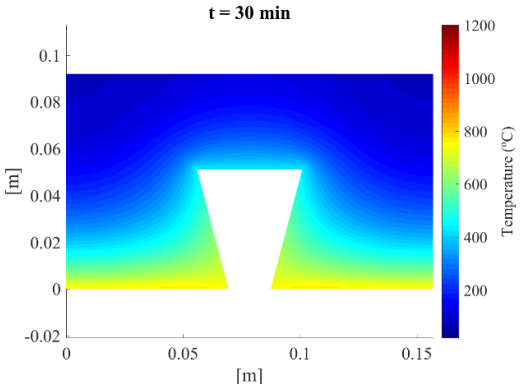


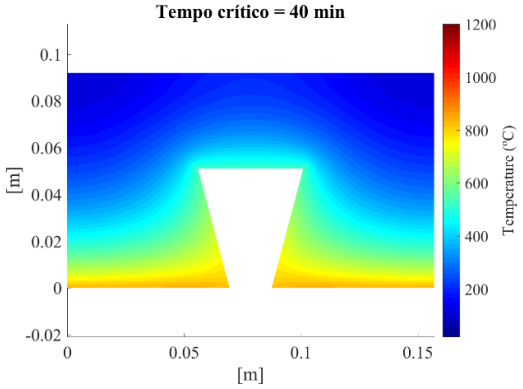


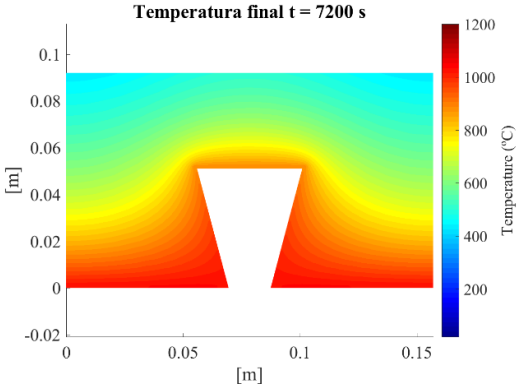




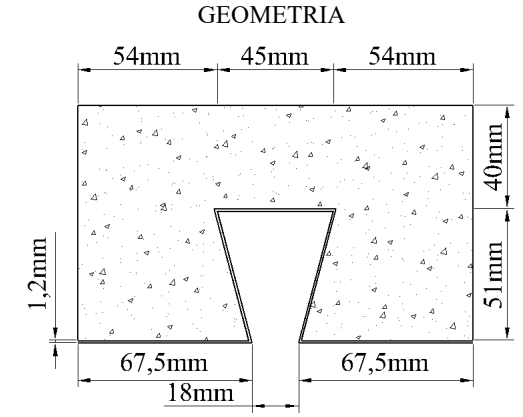


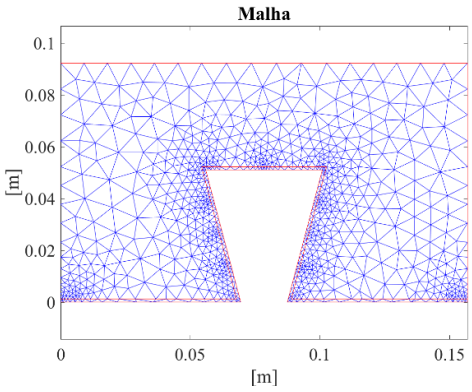


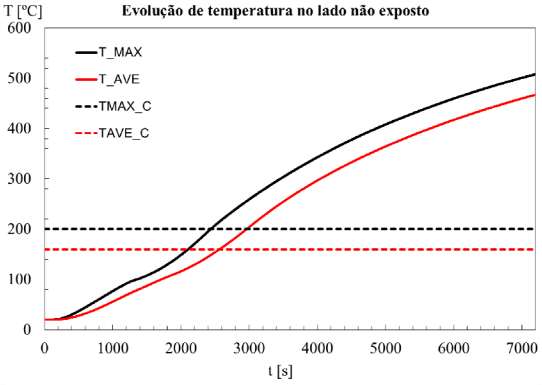


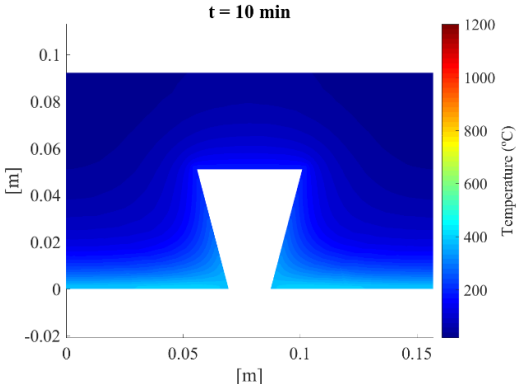


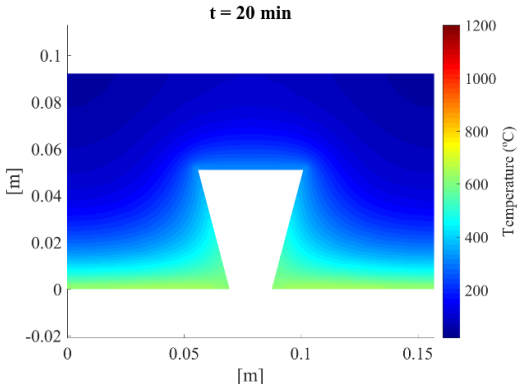
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.2mm

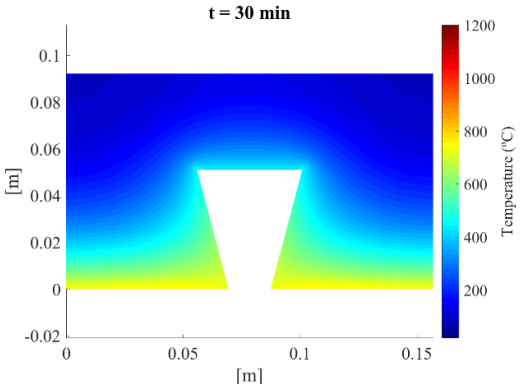


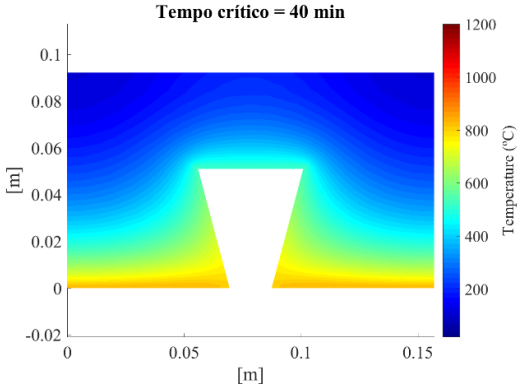


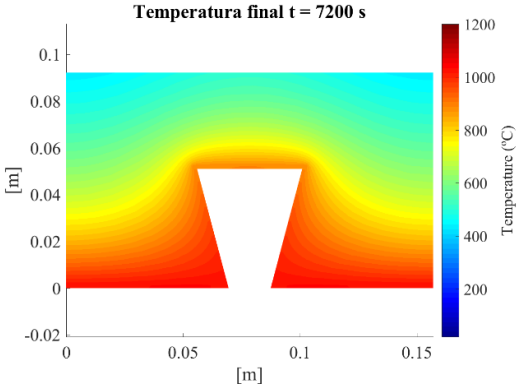




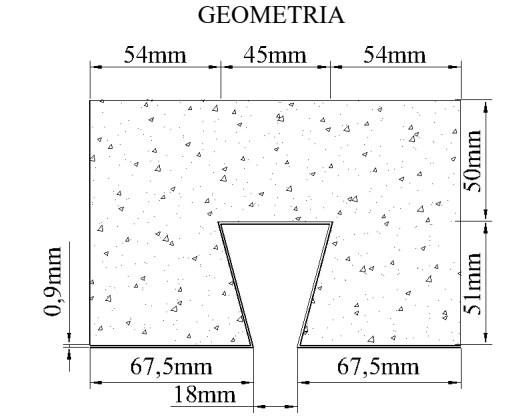


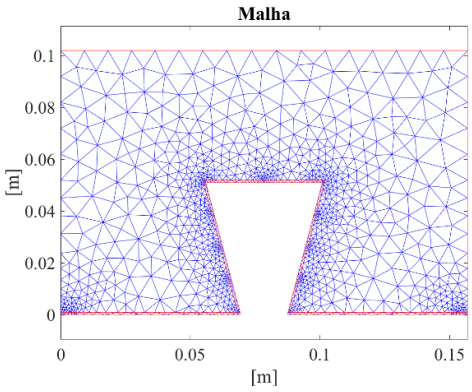


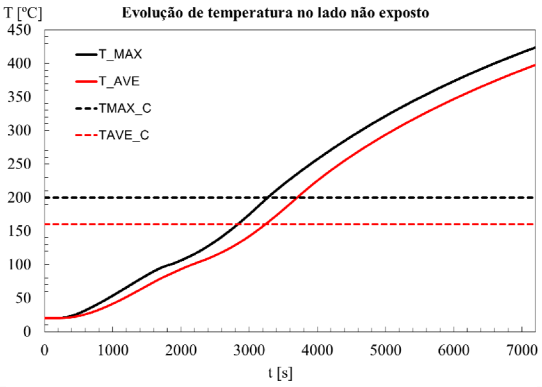


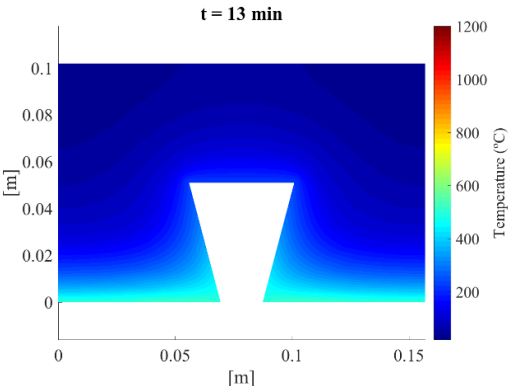


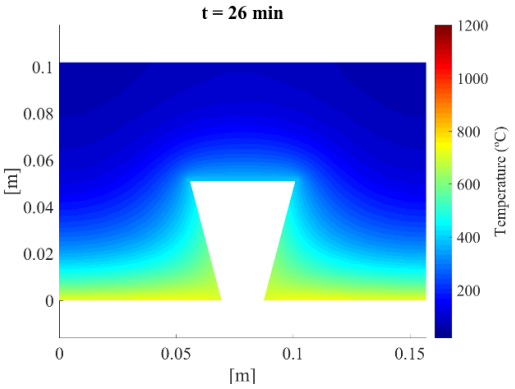
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.9mm

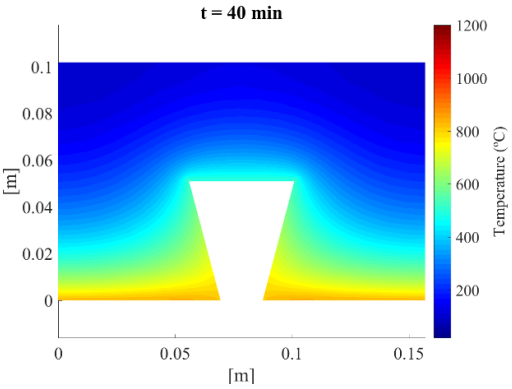


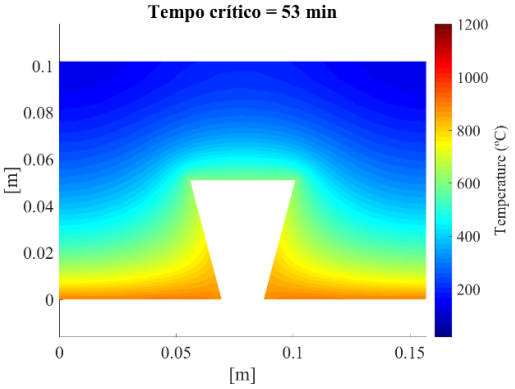


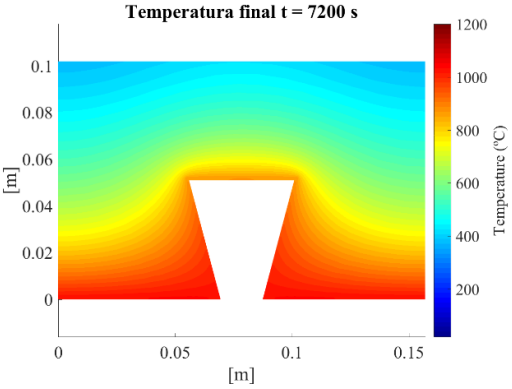




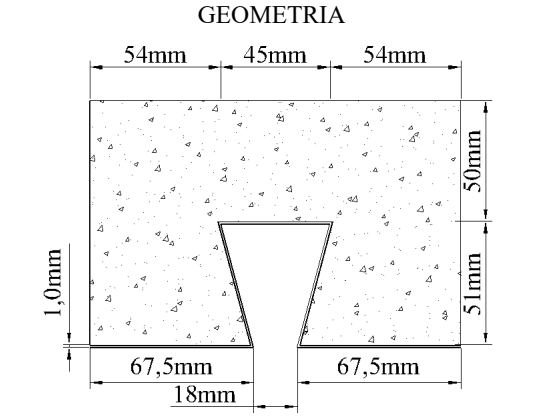


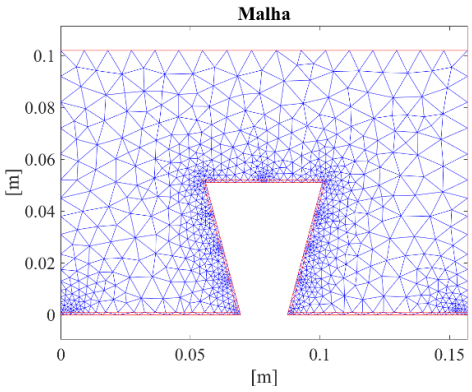


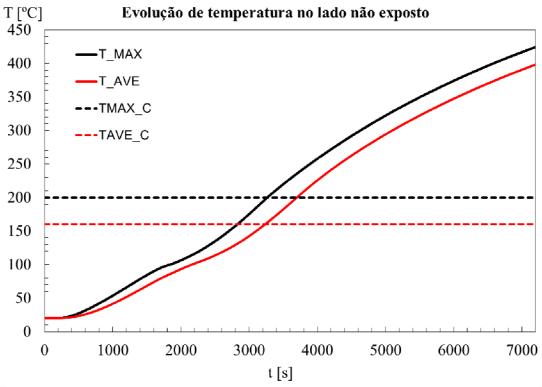


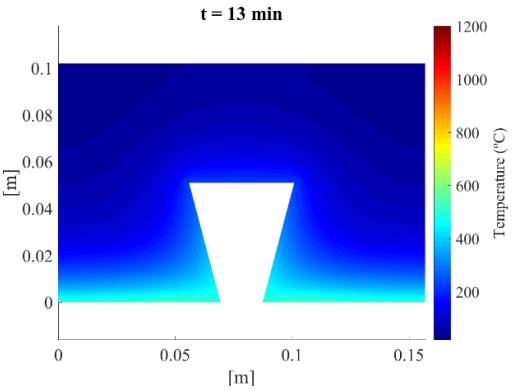


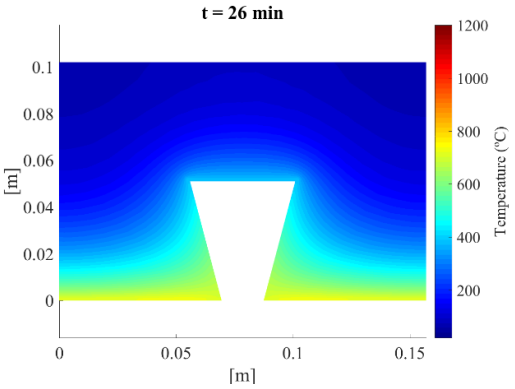
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.0mm

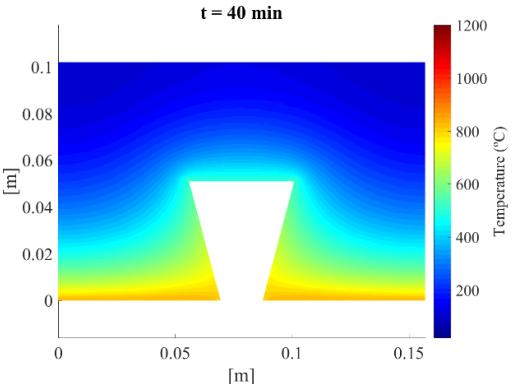


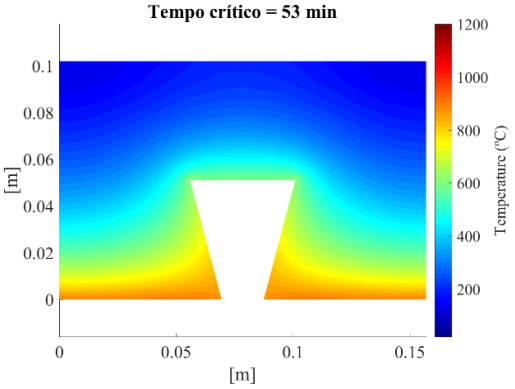


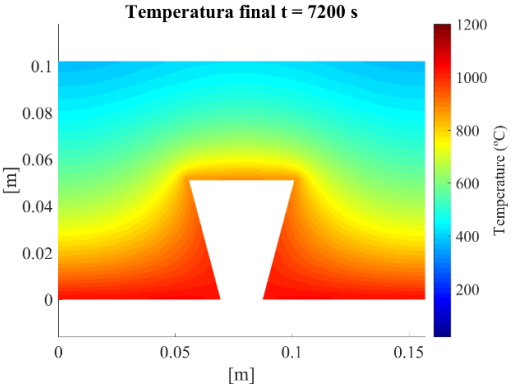




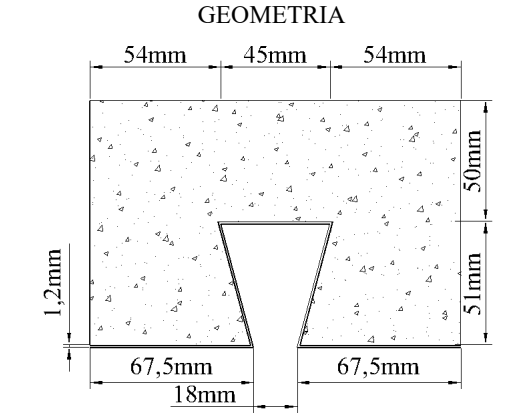


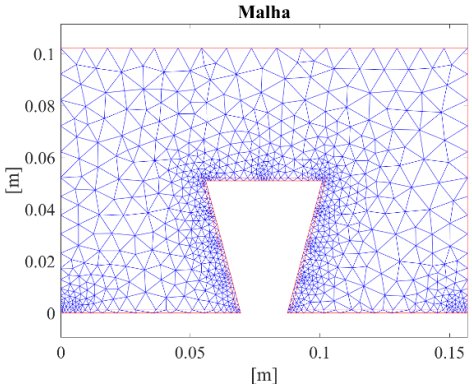


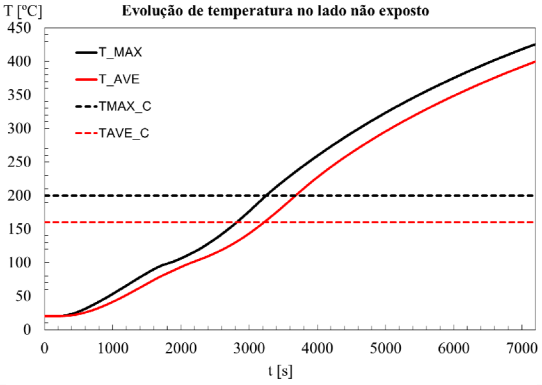


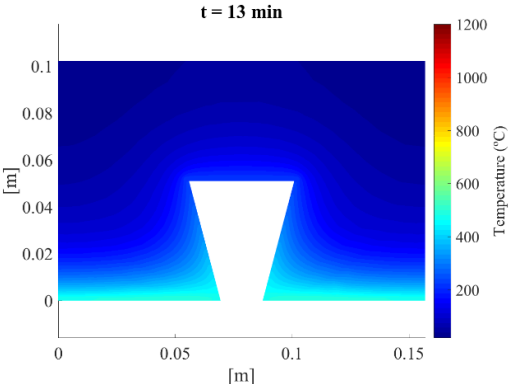


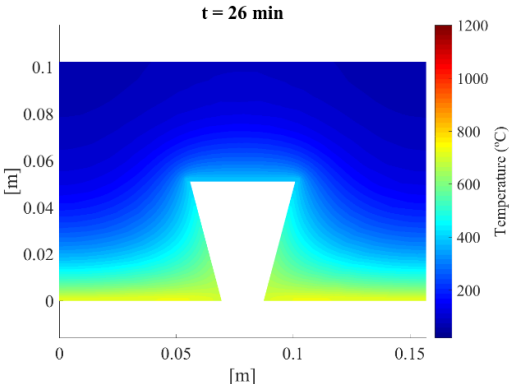
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.2mm

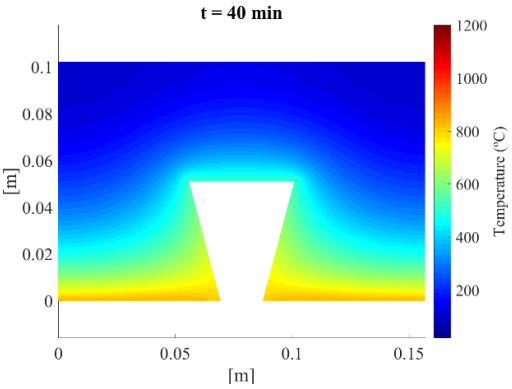


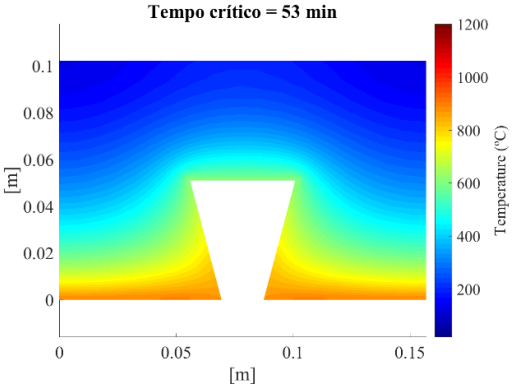


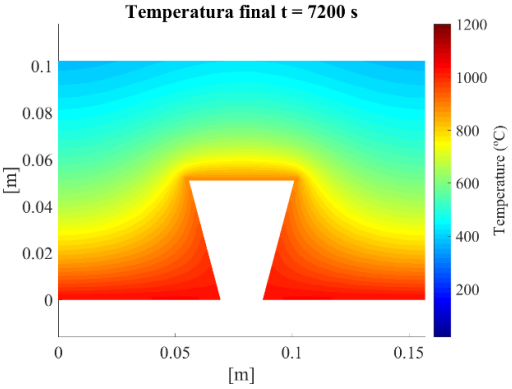




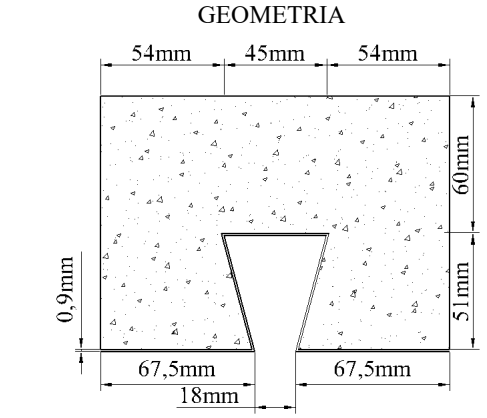


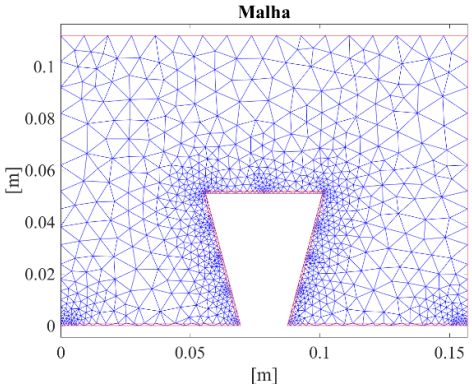


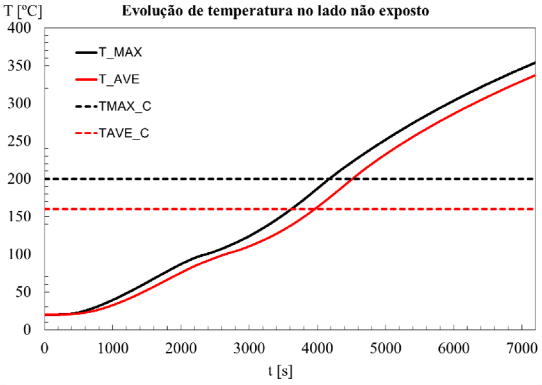


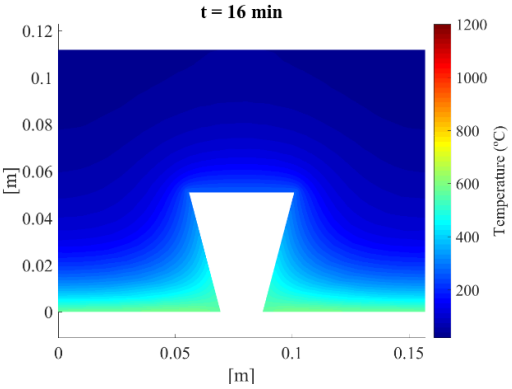


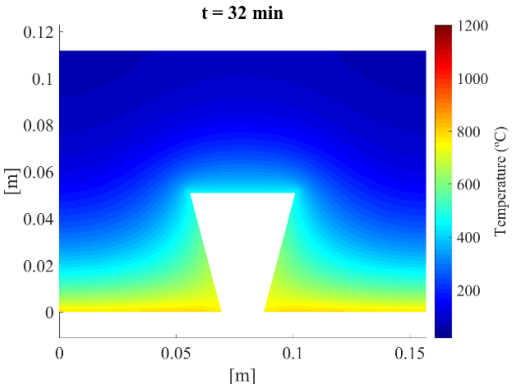
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.9mm

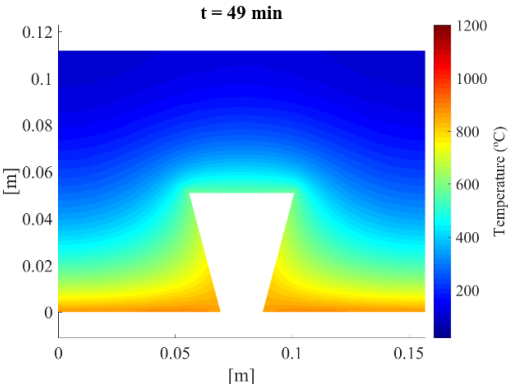


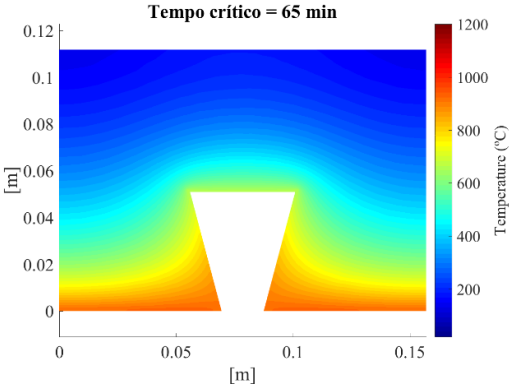


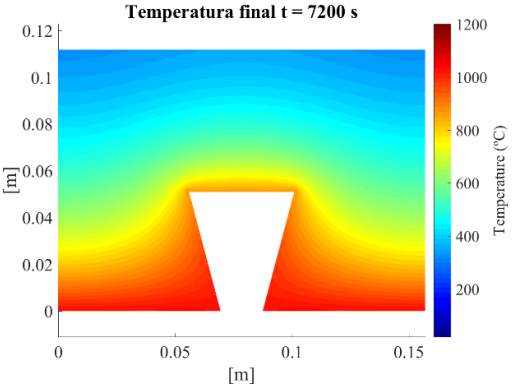




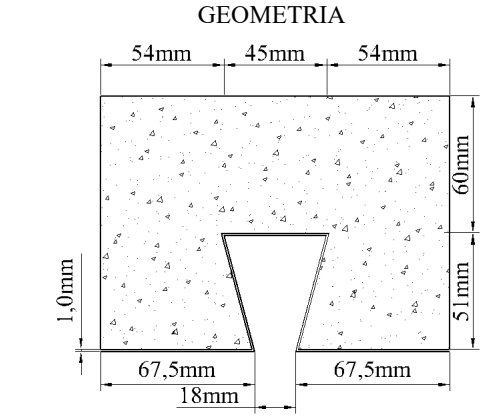


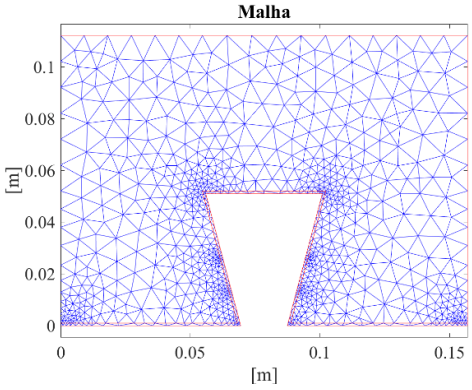


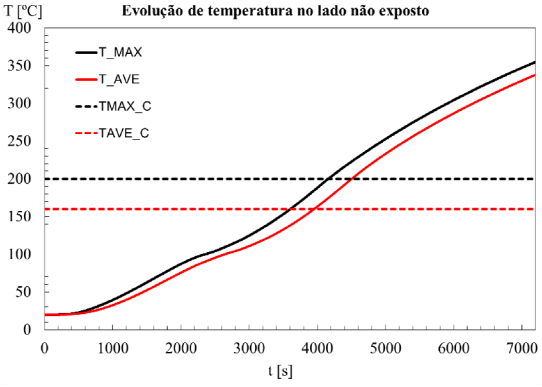


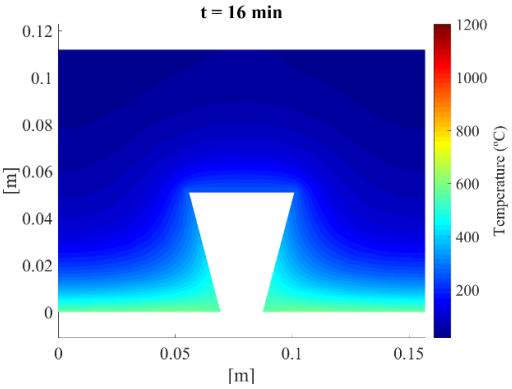


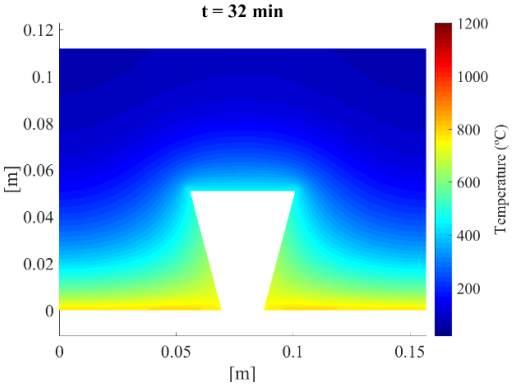
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.0mm

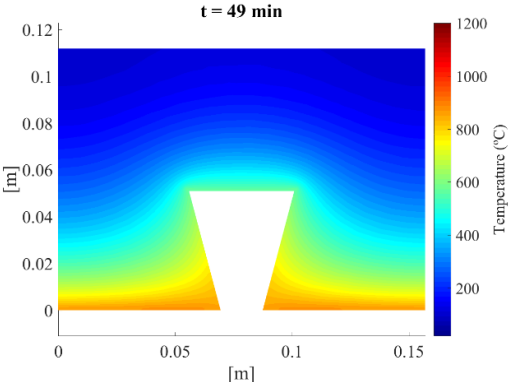


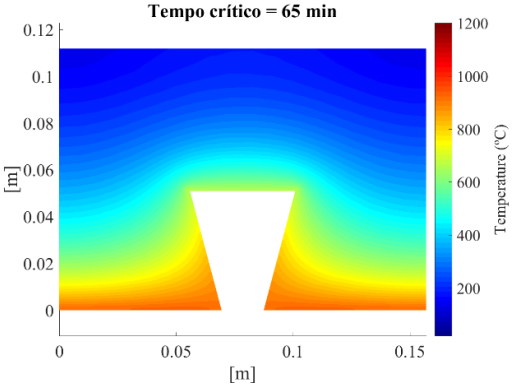


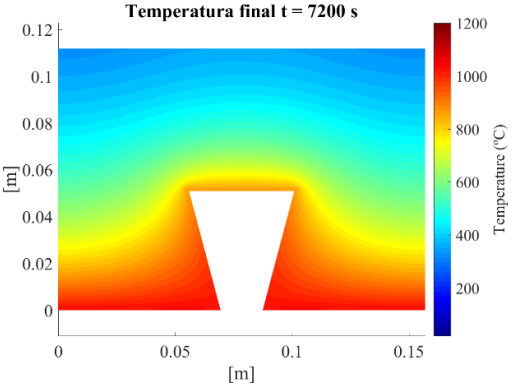




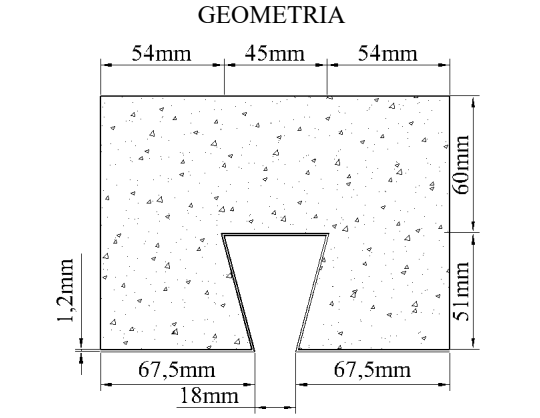


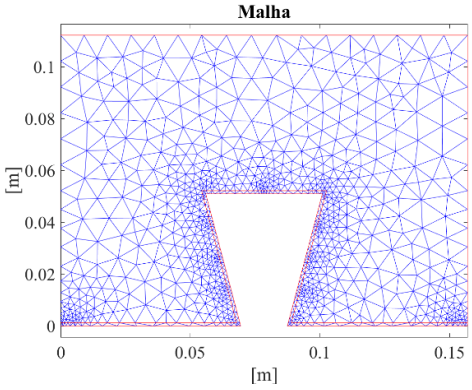


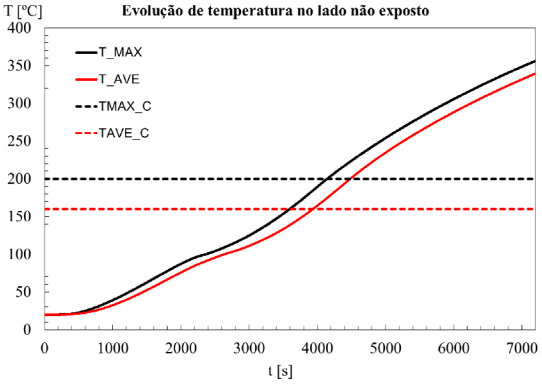


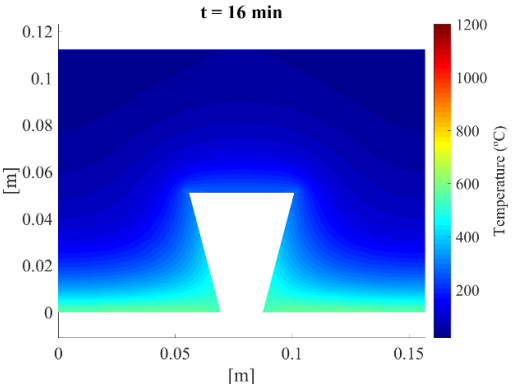


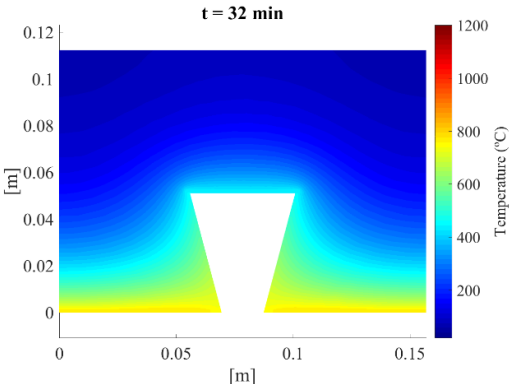
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.2mm

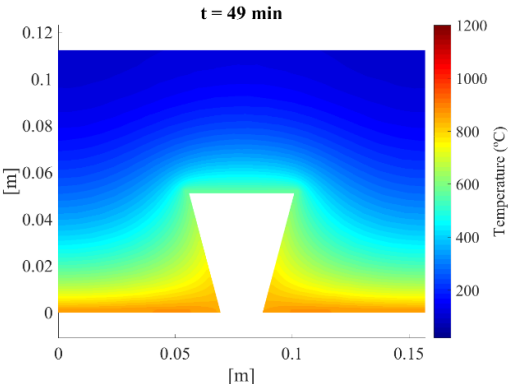


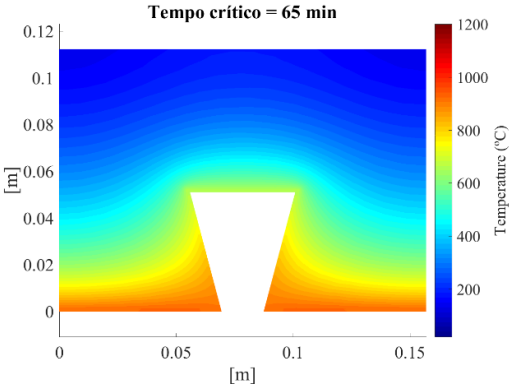


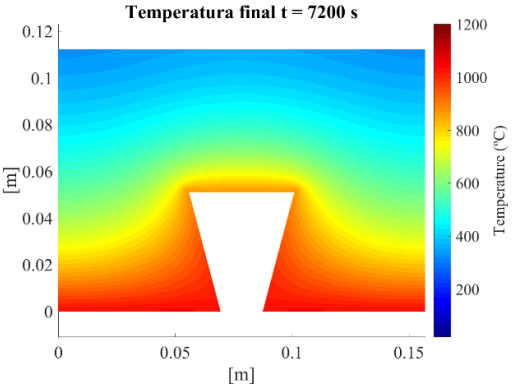




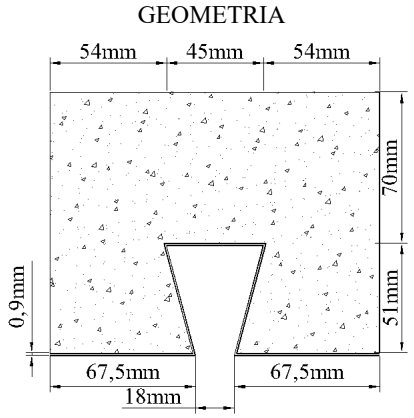


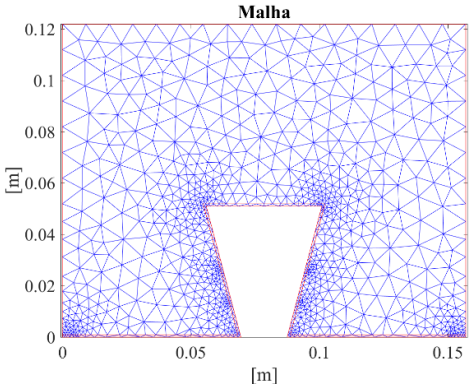


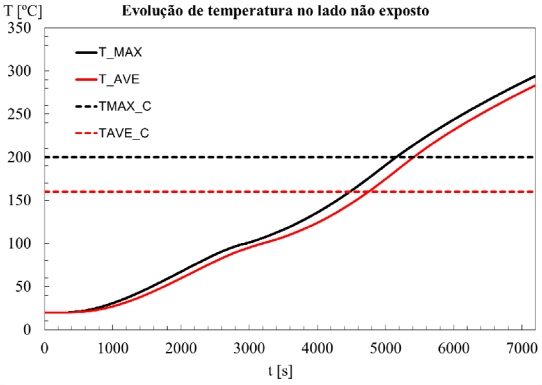


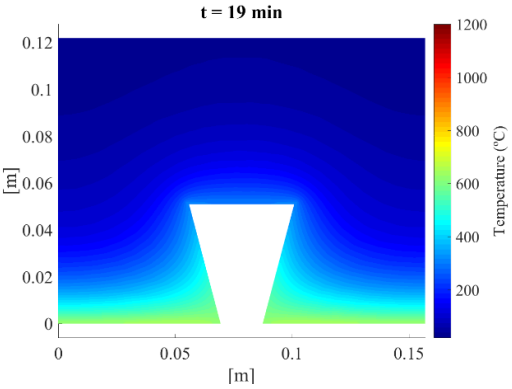


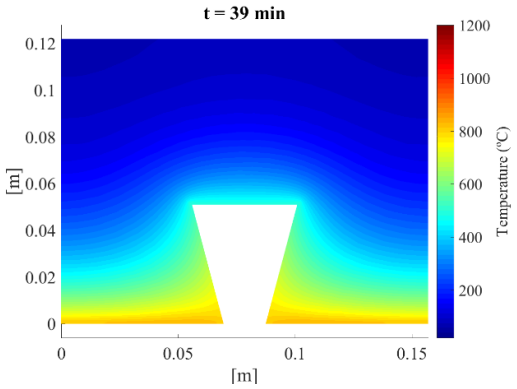
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.9mm

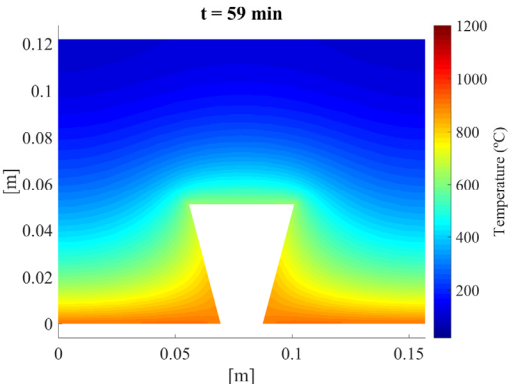


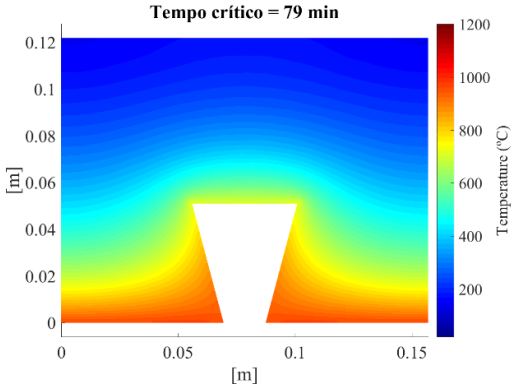


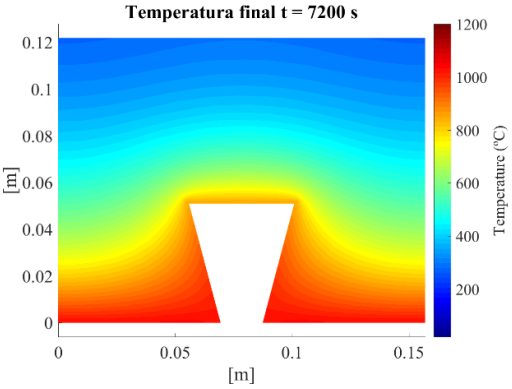




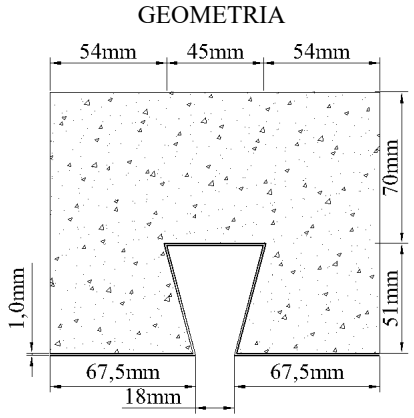


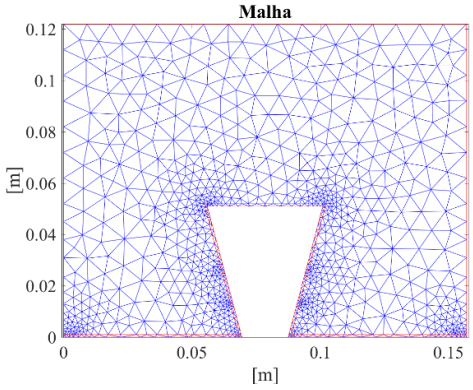


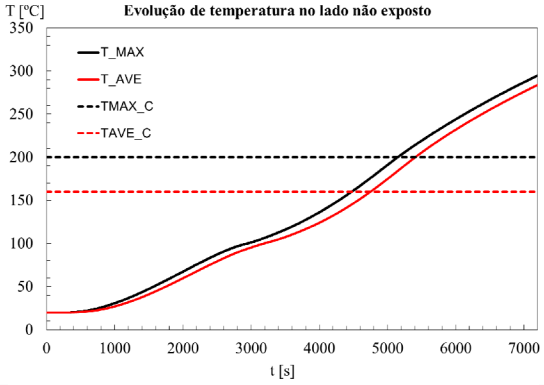


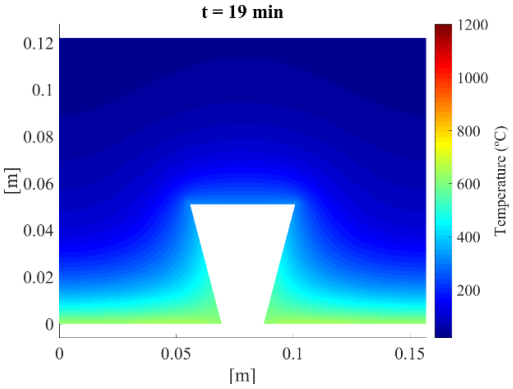


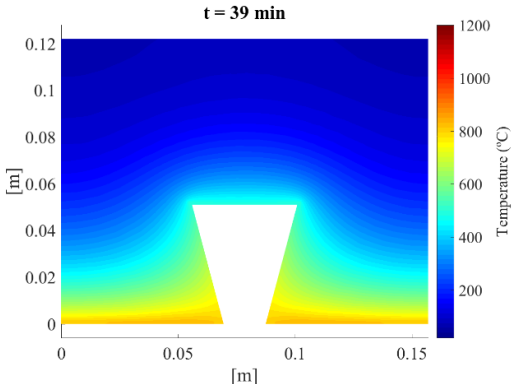
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.0mm

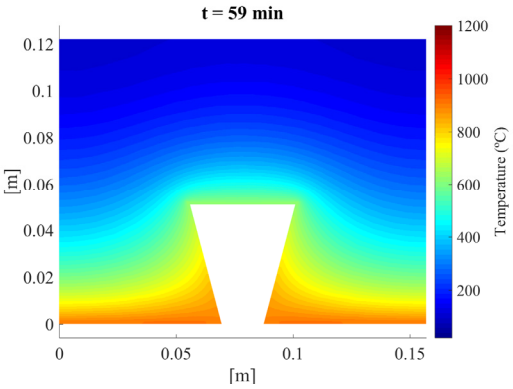


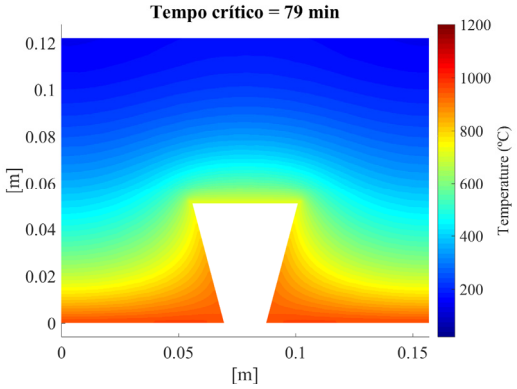


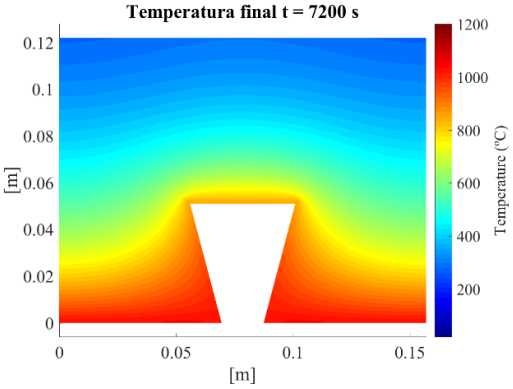




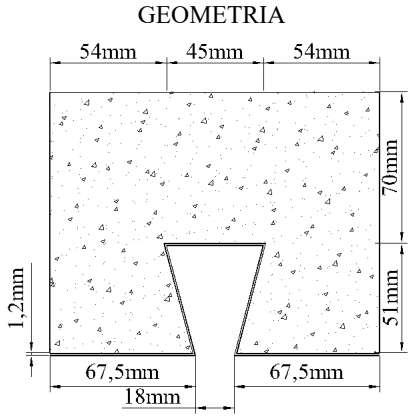


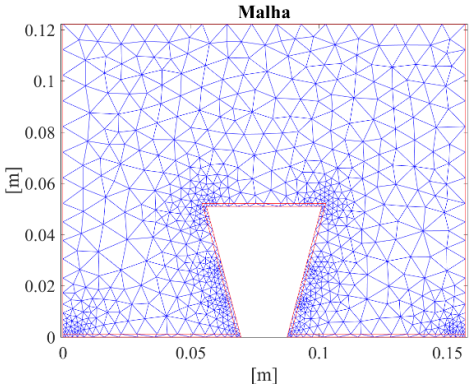


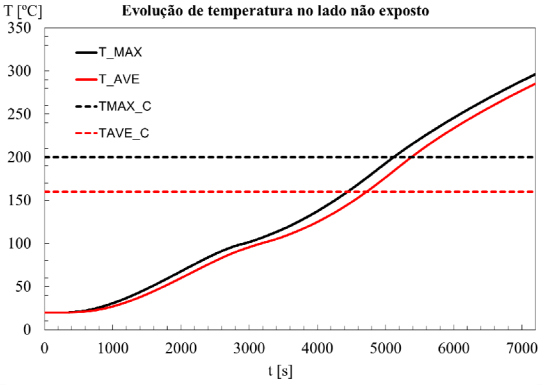


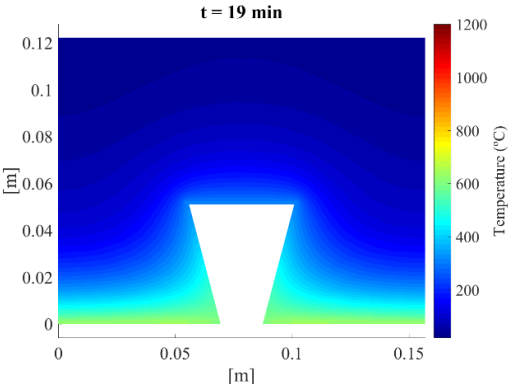


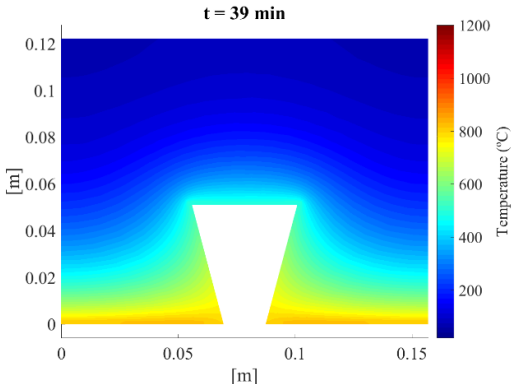
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.2mm

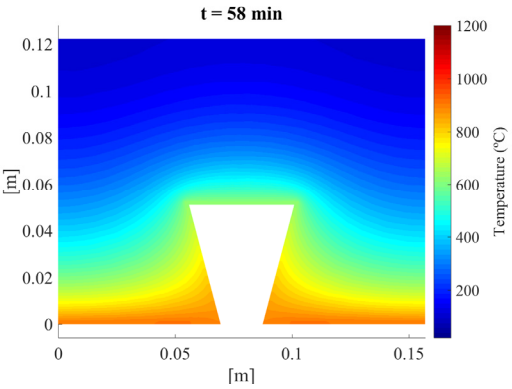


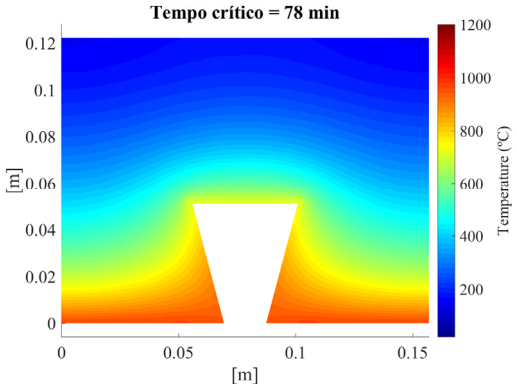


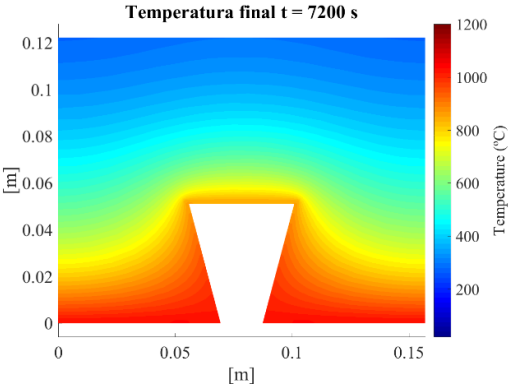




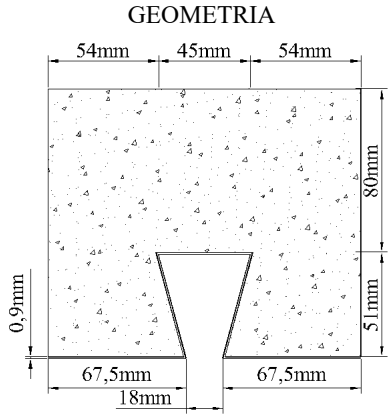


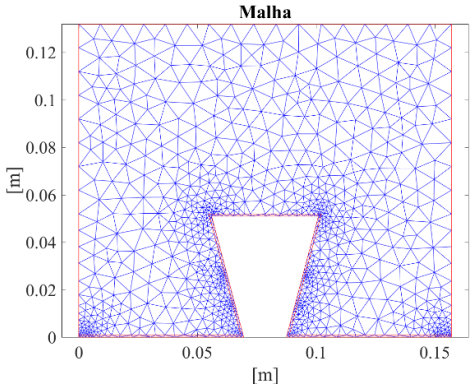


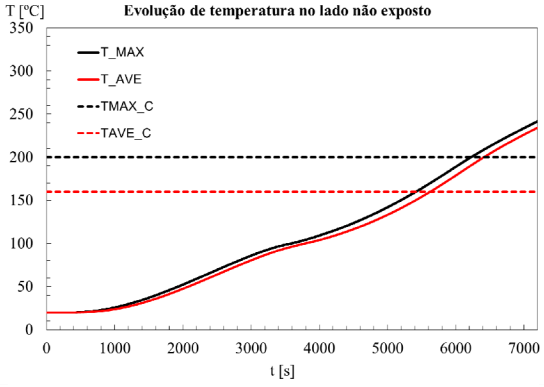


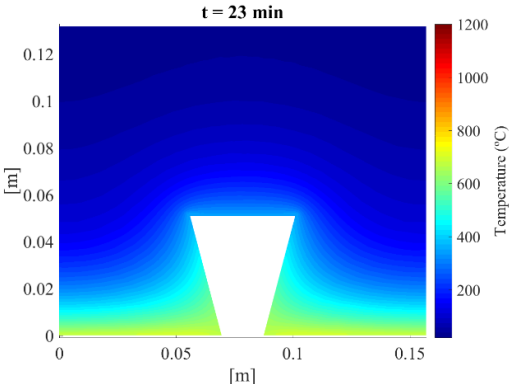


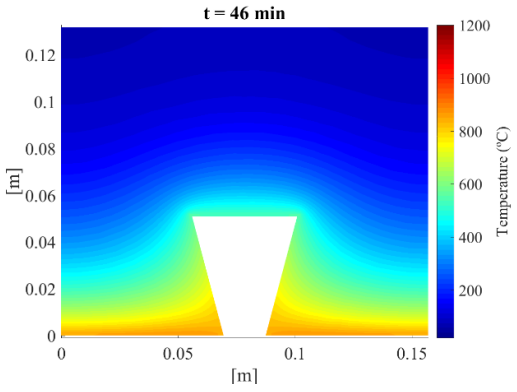
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.9mm

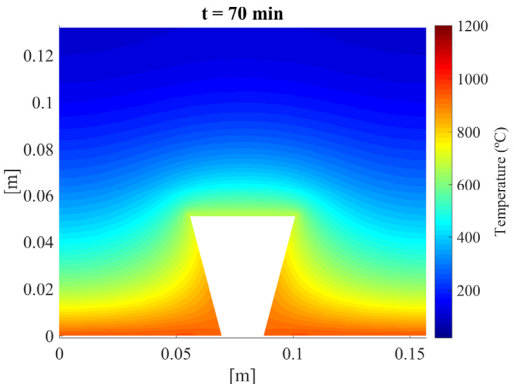


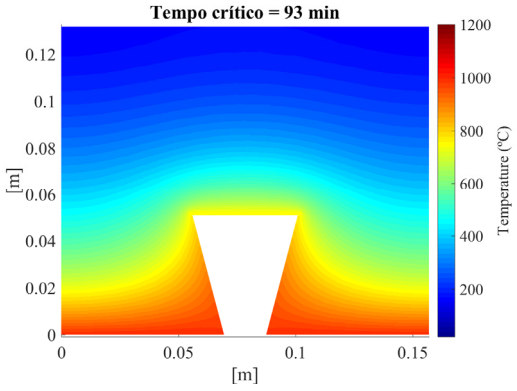


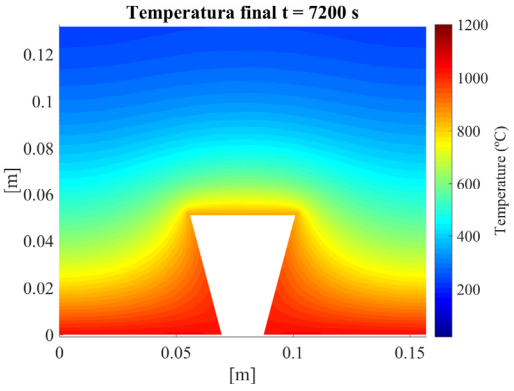




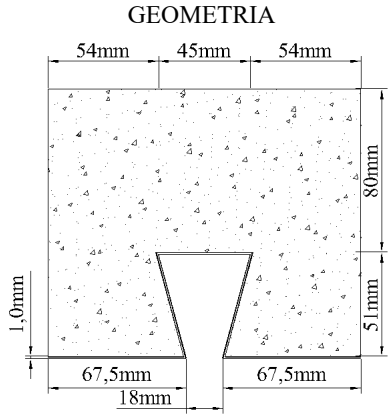


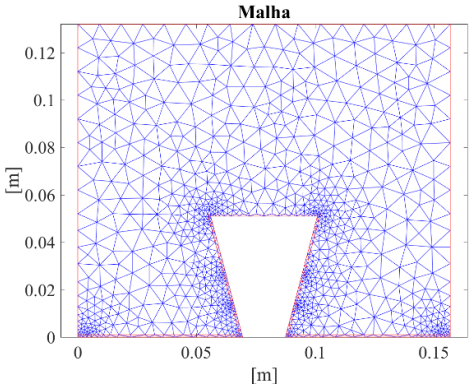


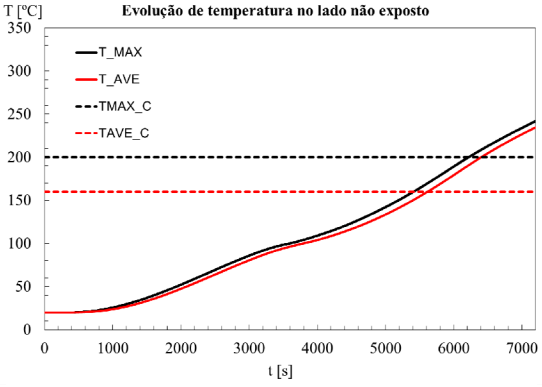


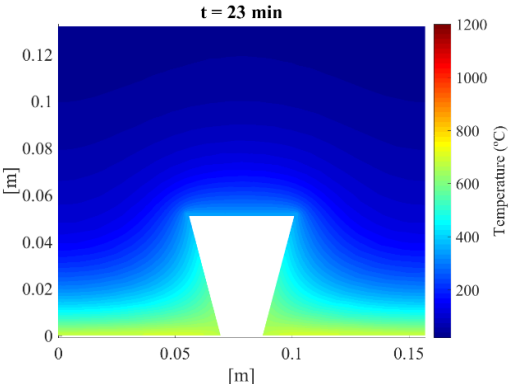


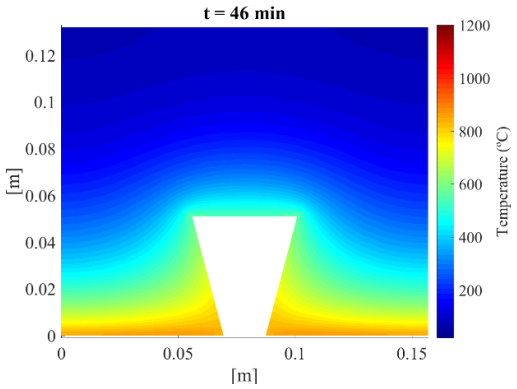
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.0mm

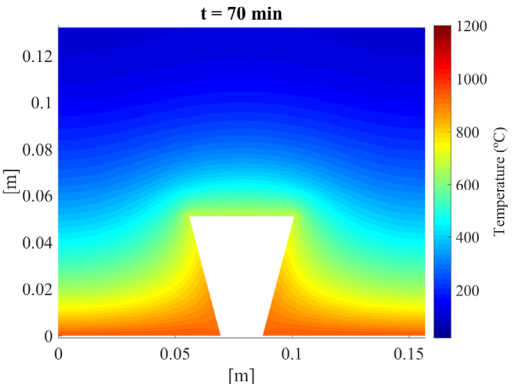


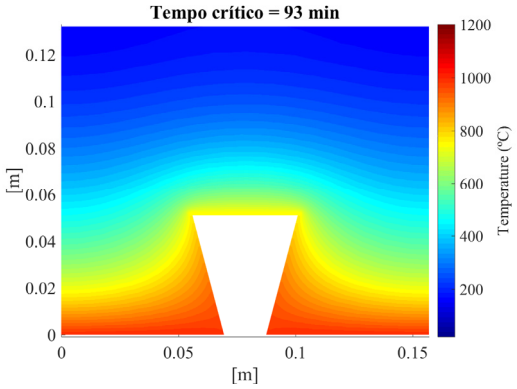


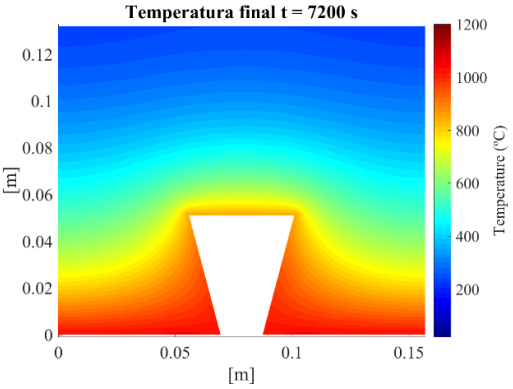




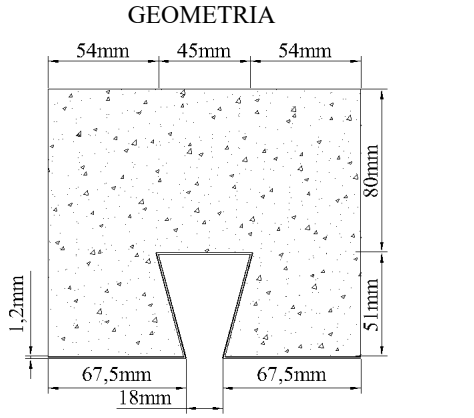


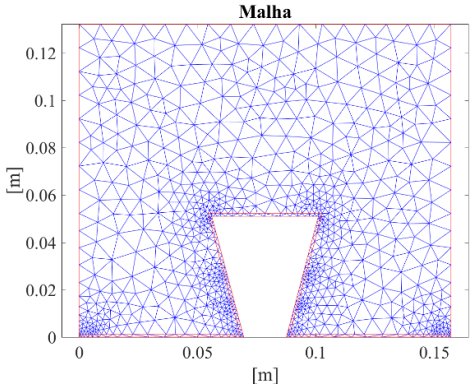


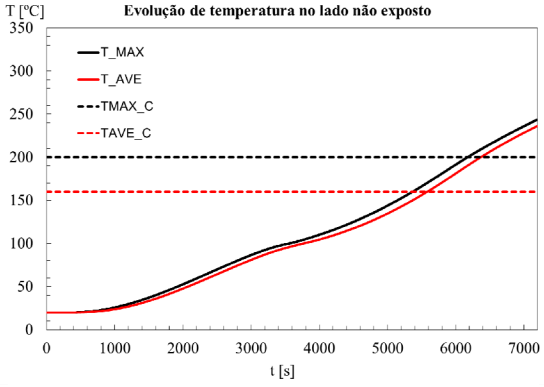


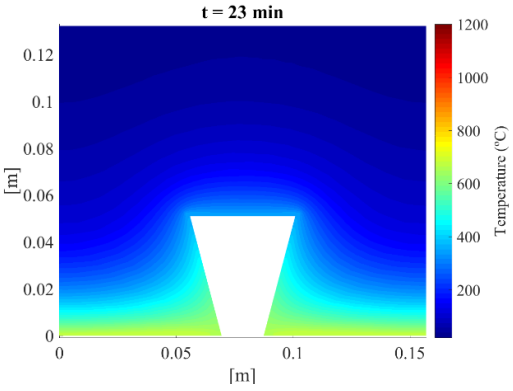


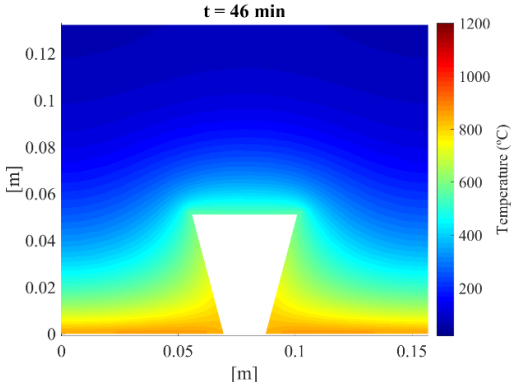
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.2mm

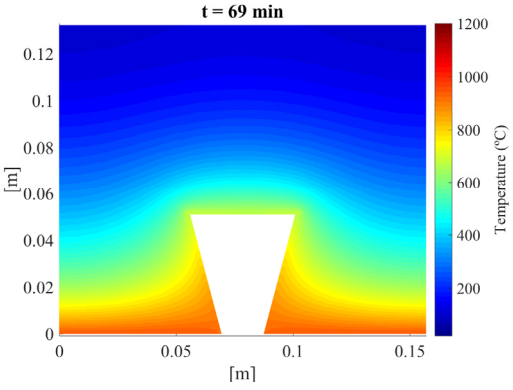


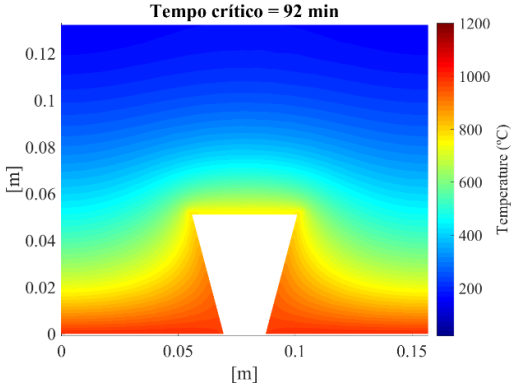


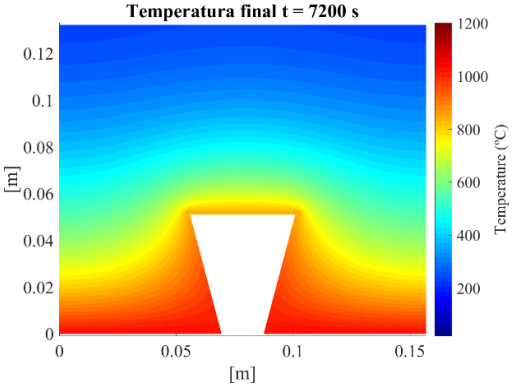




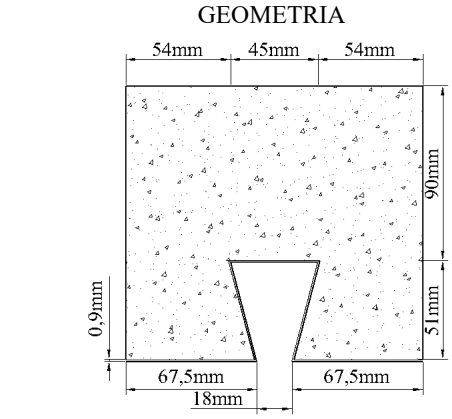


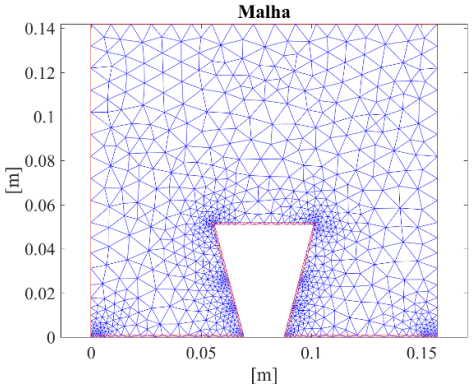


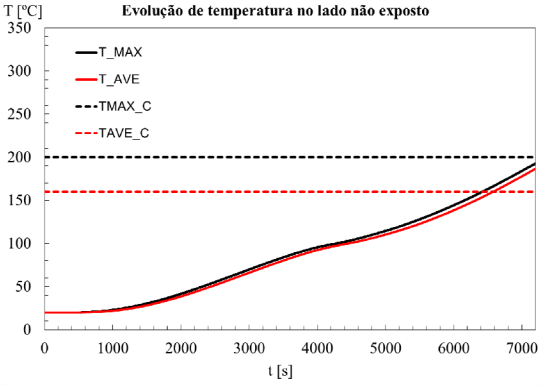


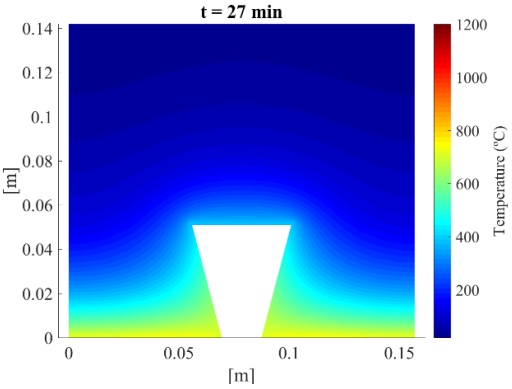


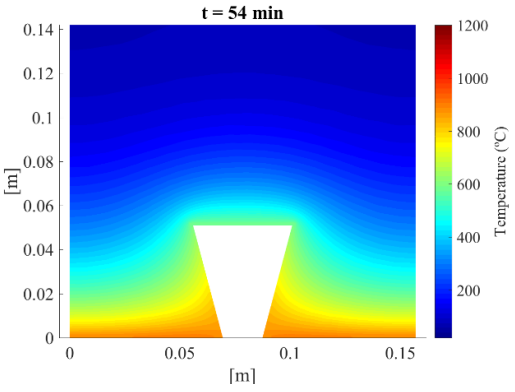
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.9mm

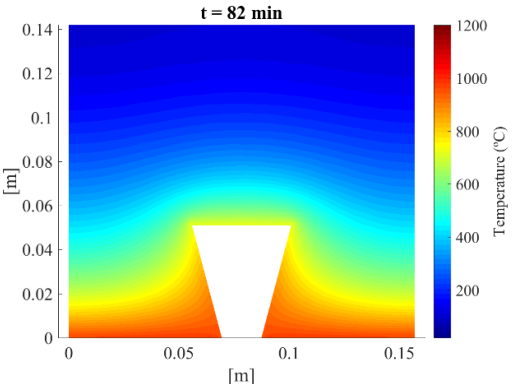


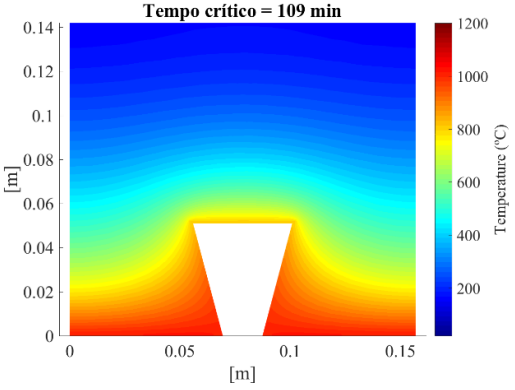


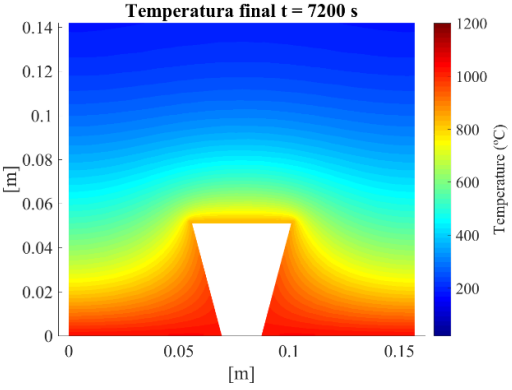




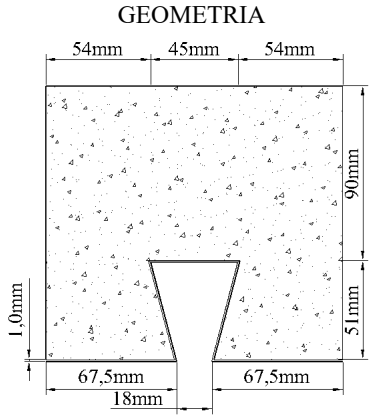


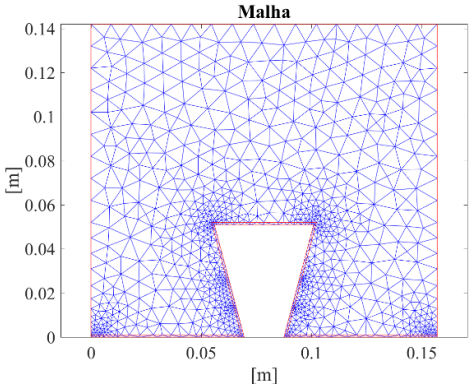


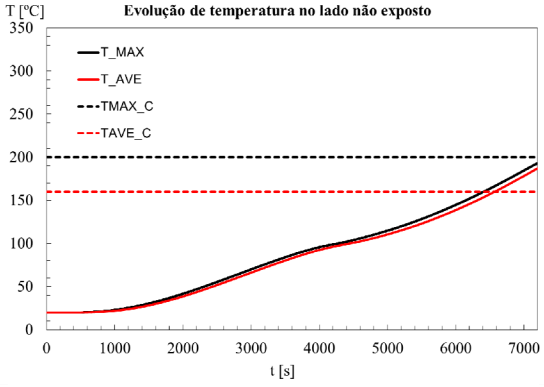


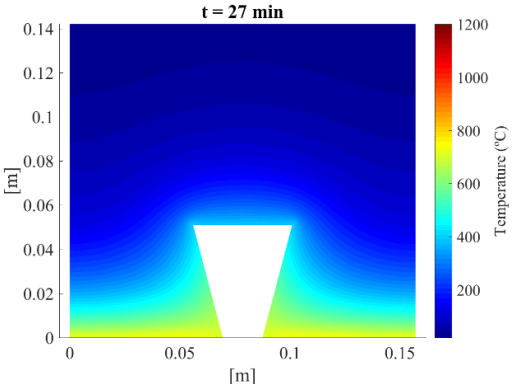


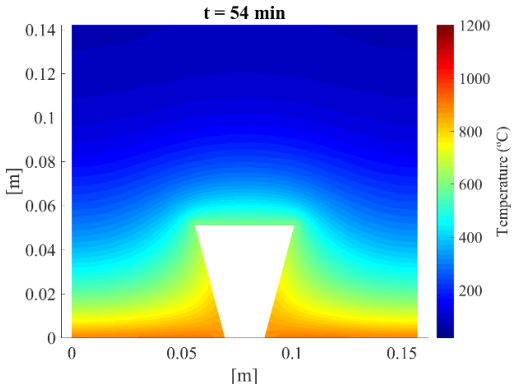
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.0mm

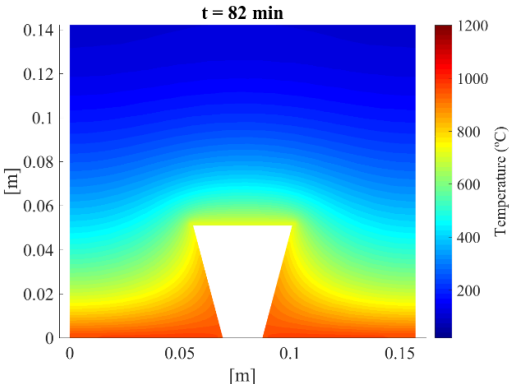


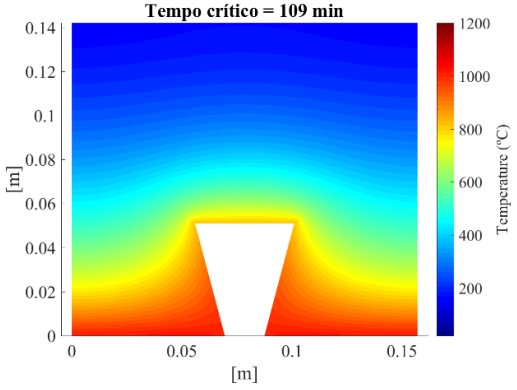


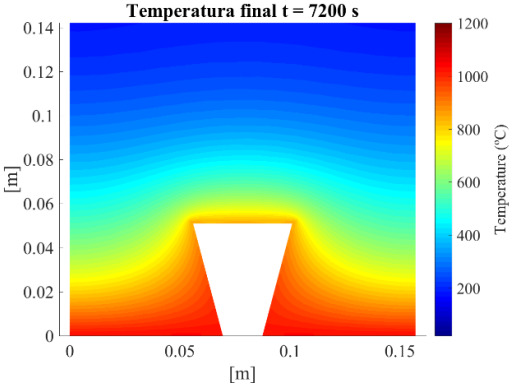




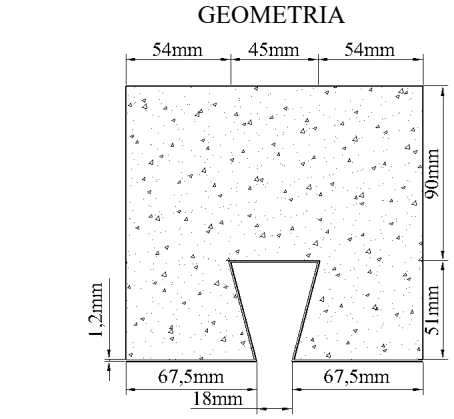


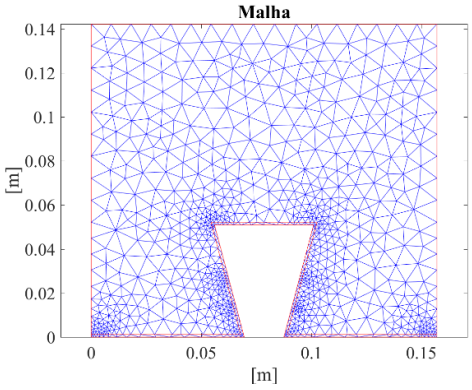


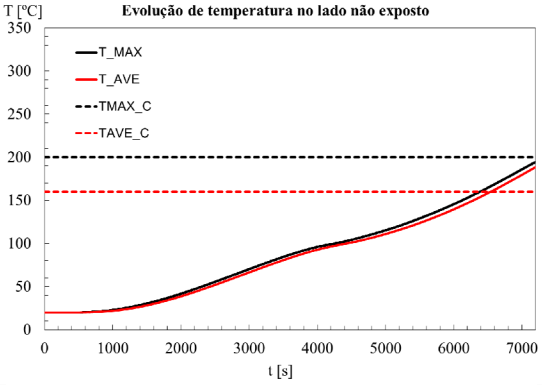


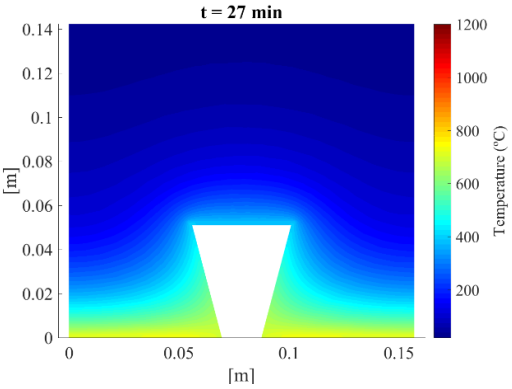


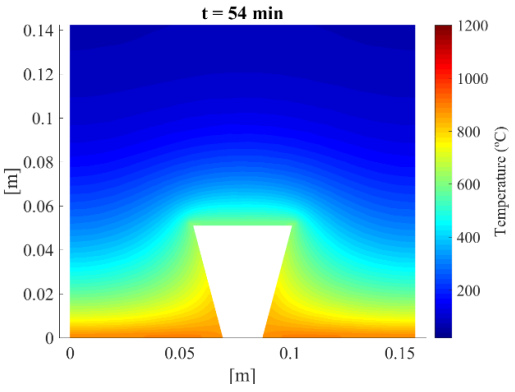
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.2mm

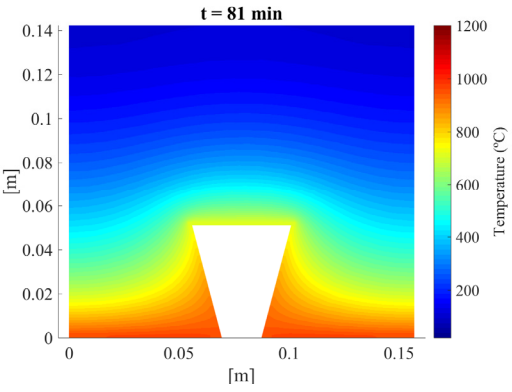


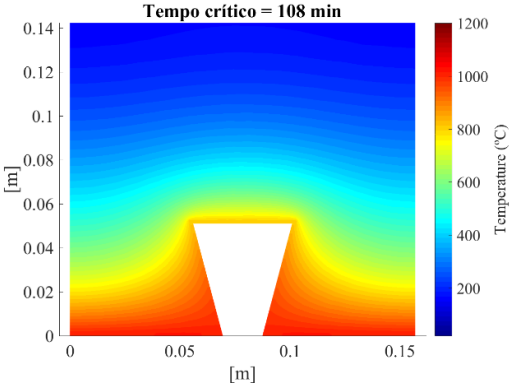


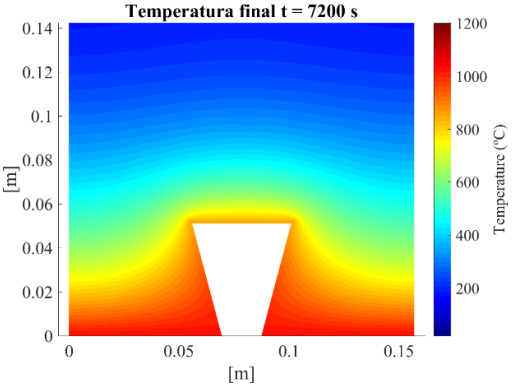




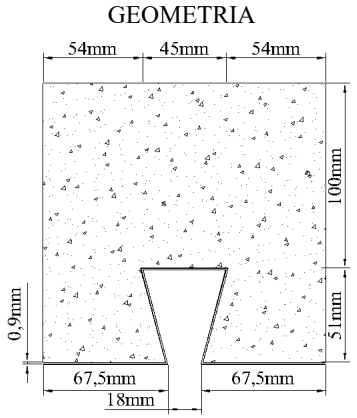


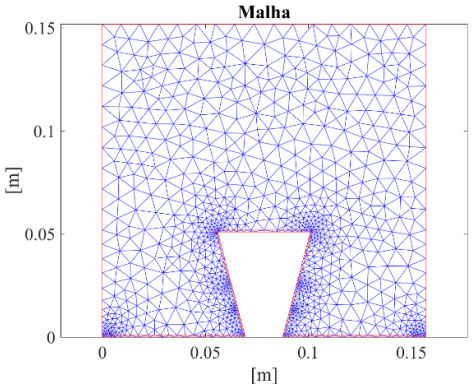


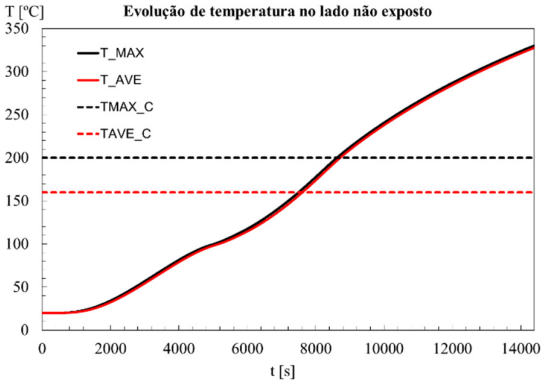


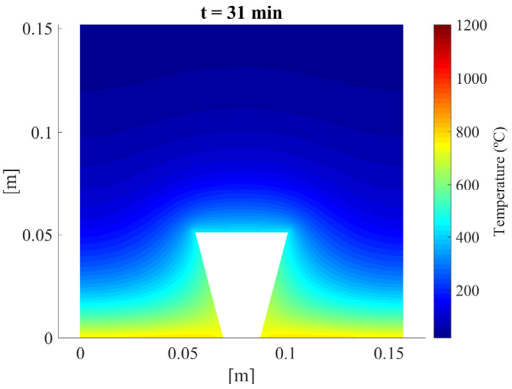


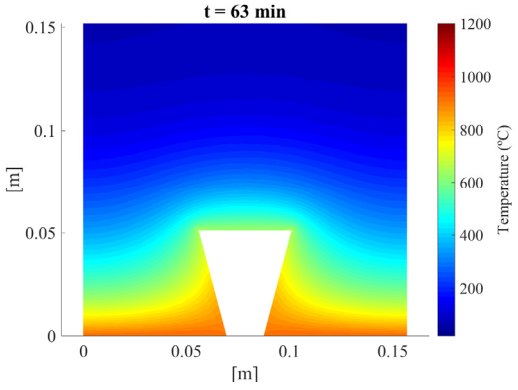
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.9mm

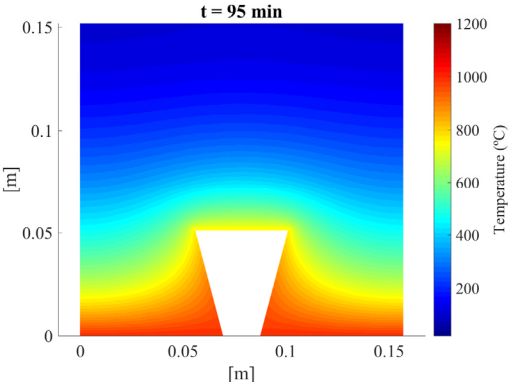


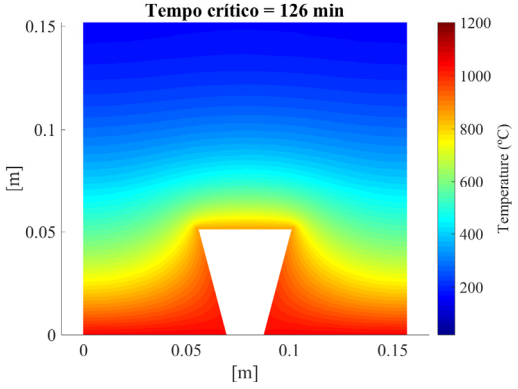


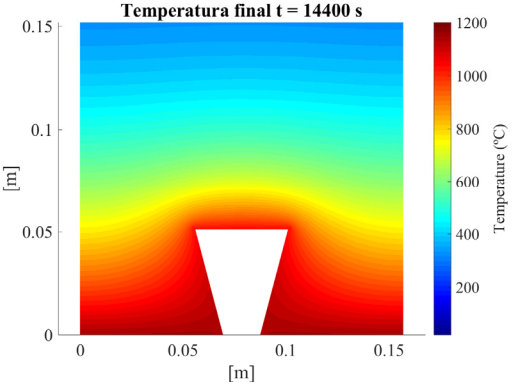




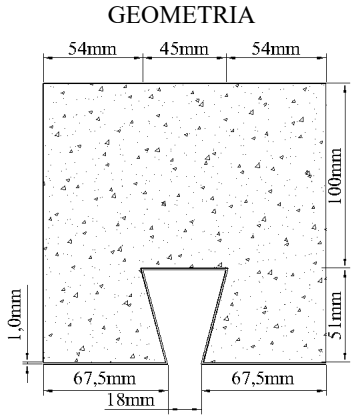


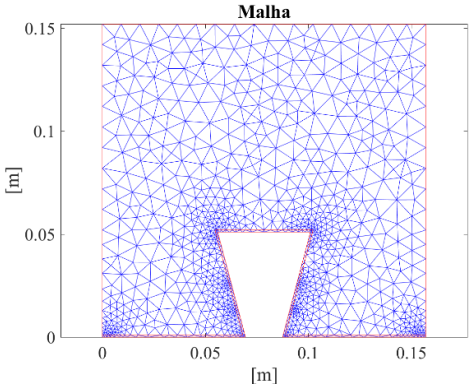


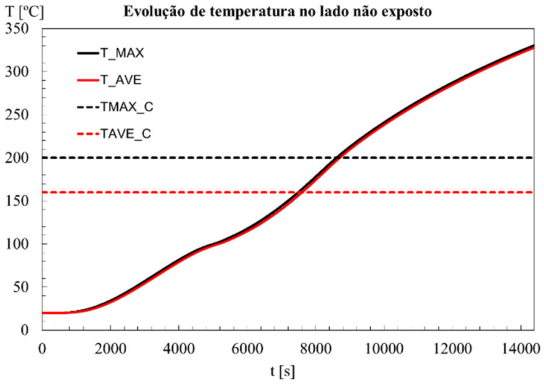


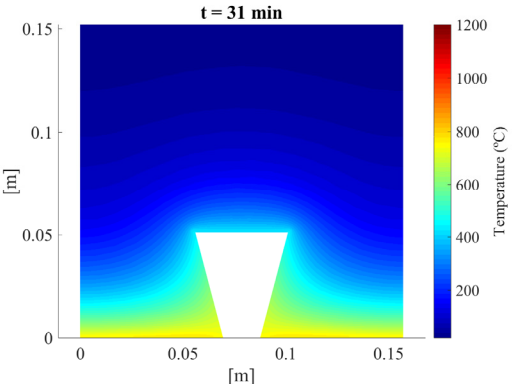


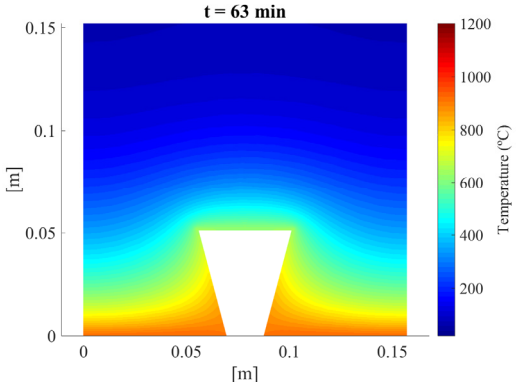
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.0mm

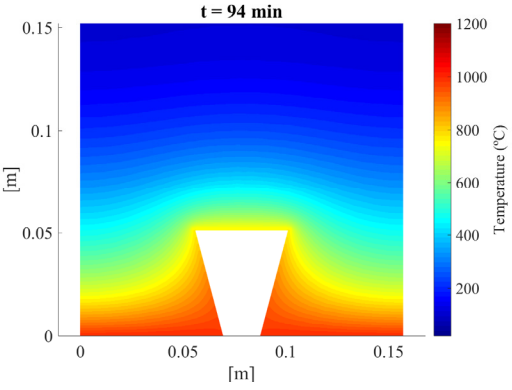


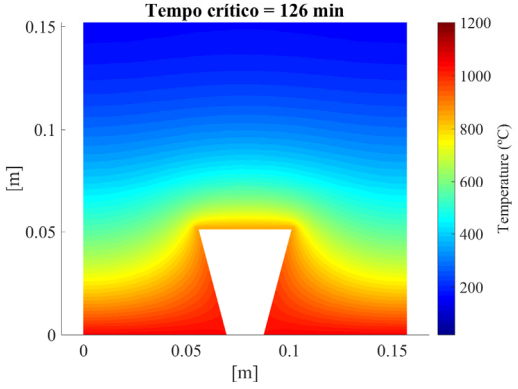


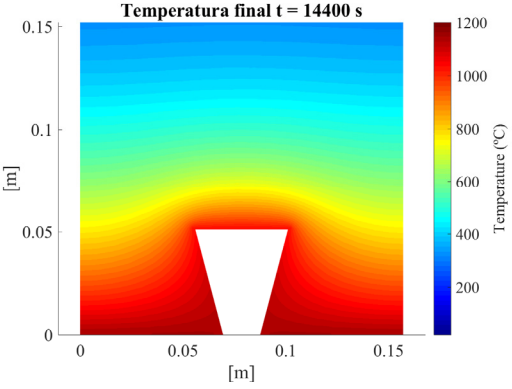






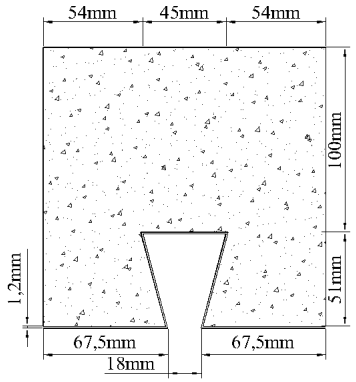


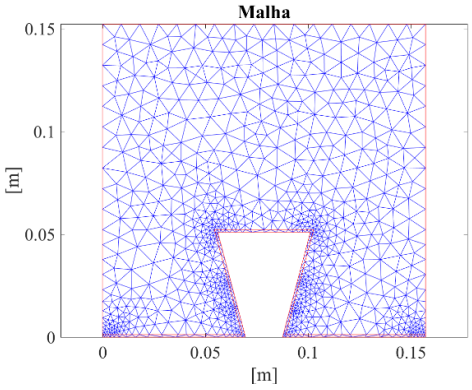


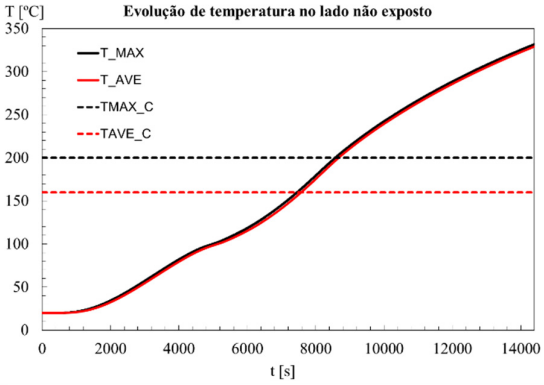


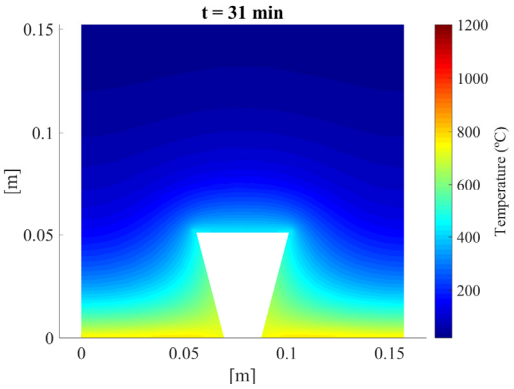
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.2mm

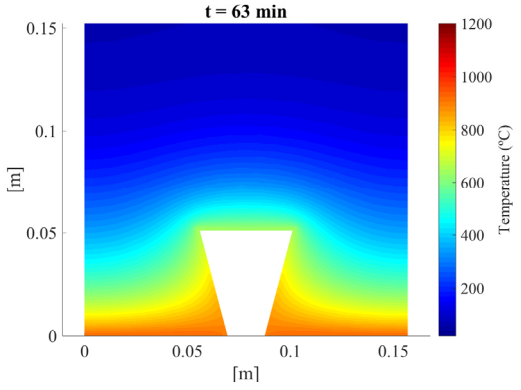
GEOMETRIA

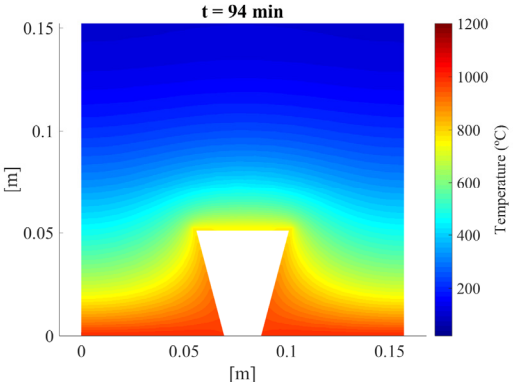


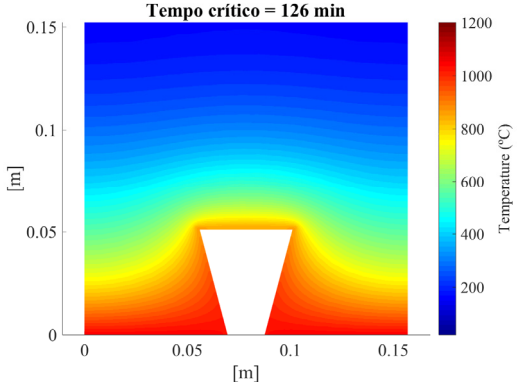


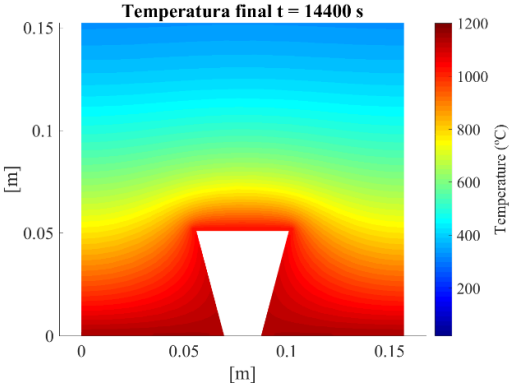




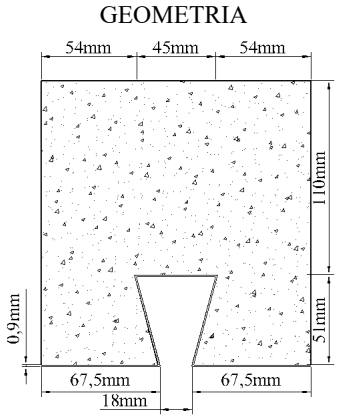


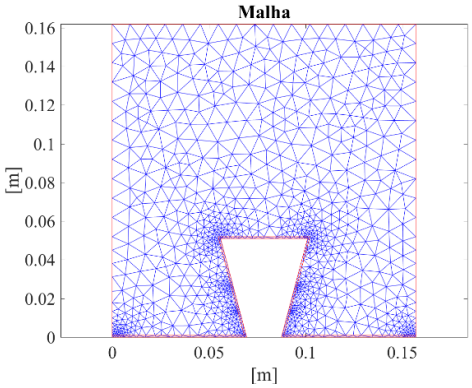


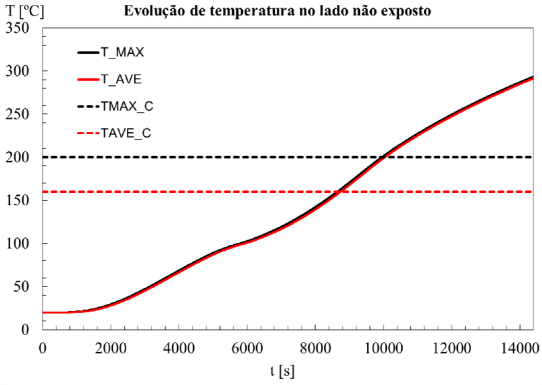


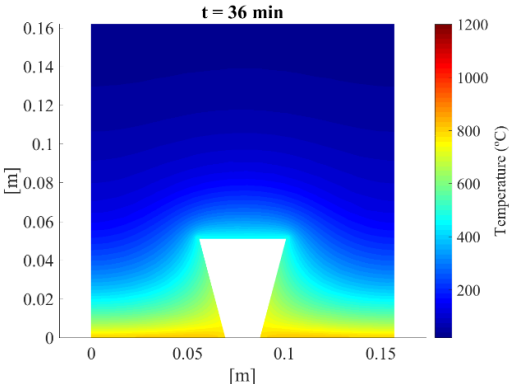


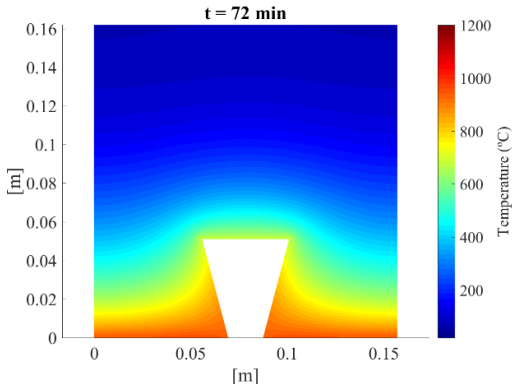
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.9mm

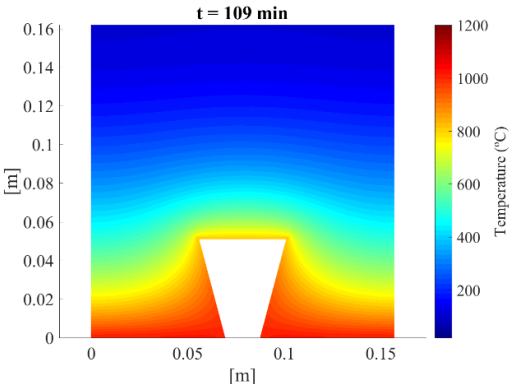


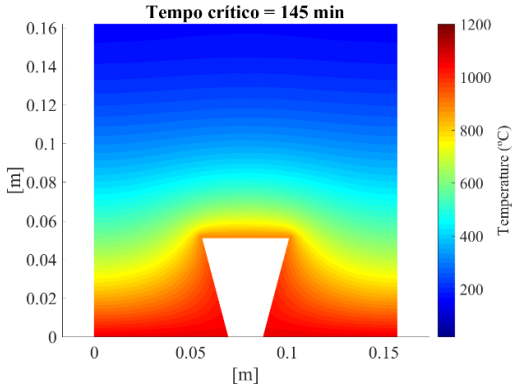


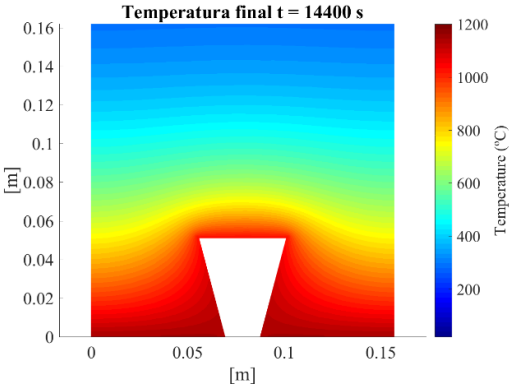




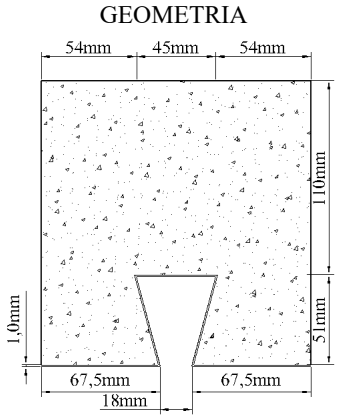


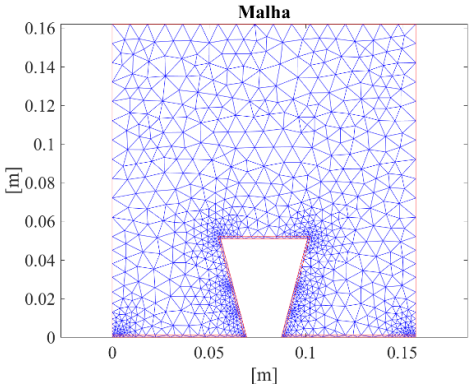


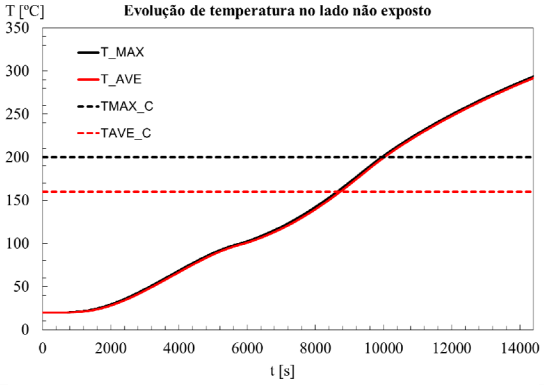


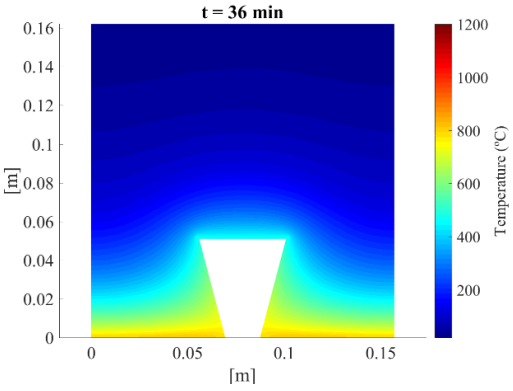


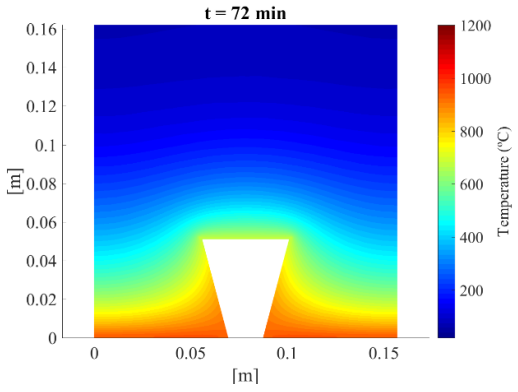
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.0mm

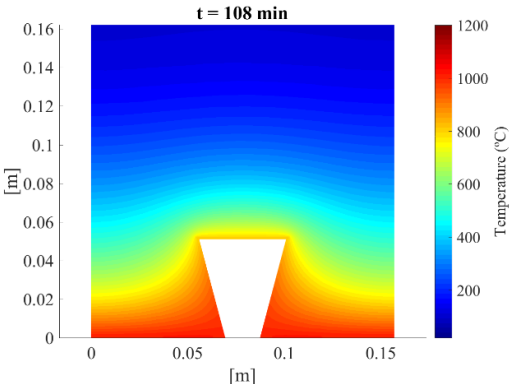


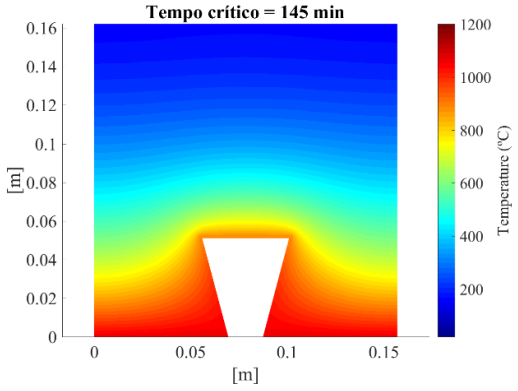


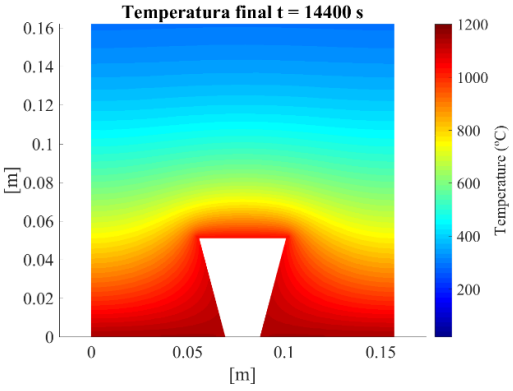




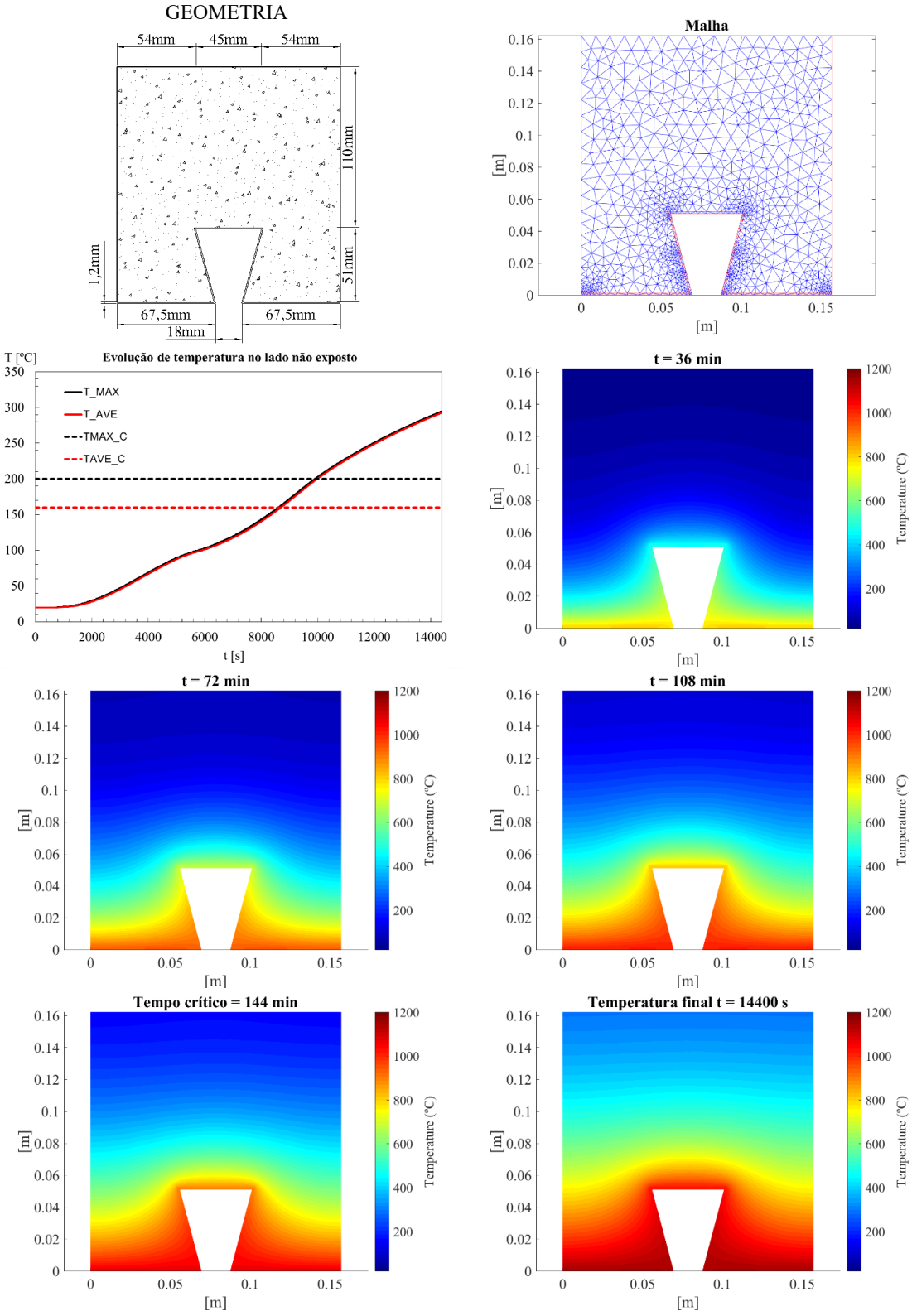








LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.2mm



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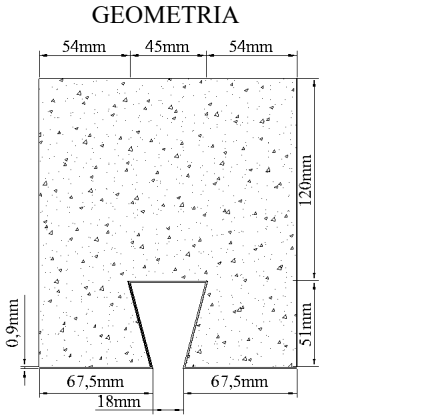
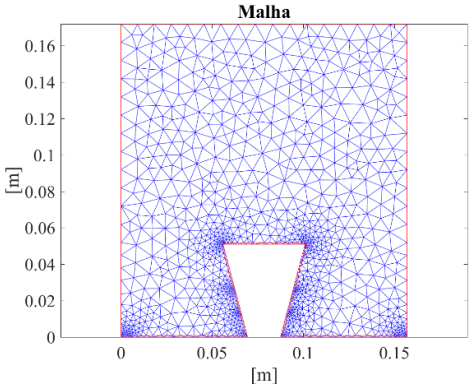
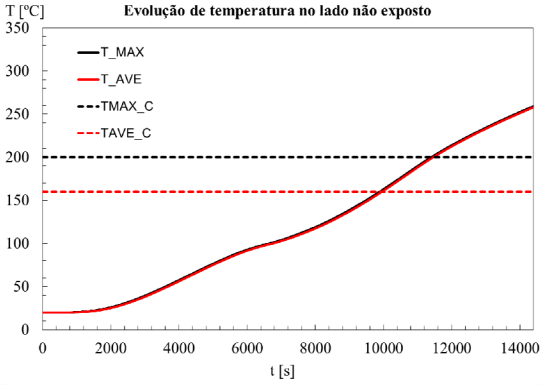
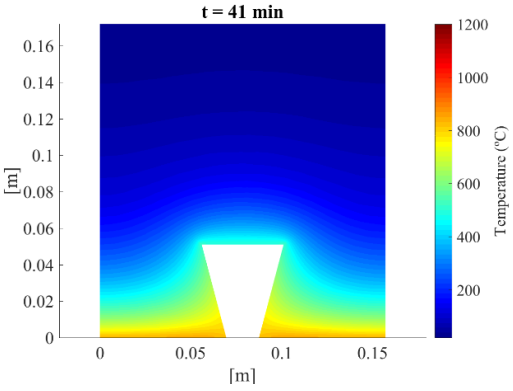
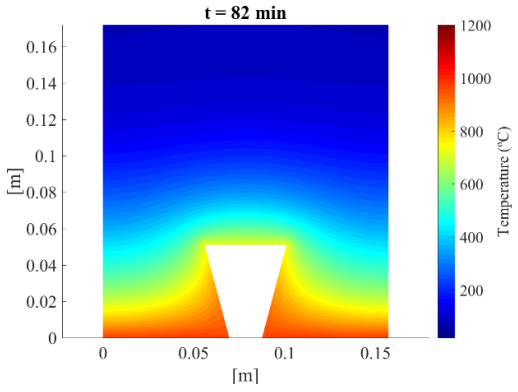
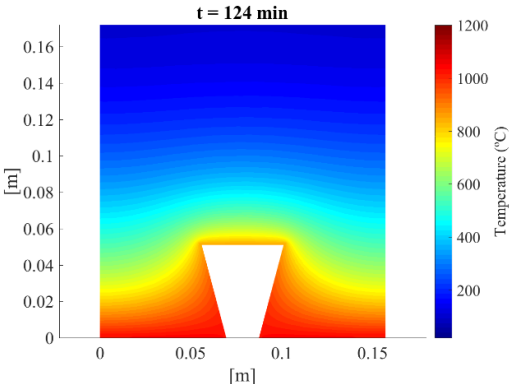


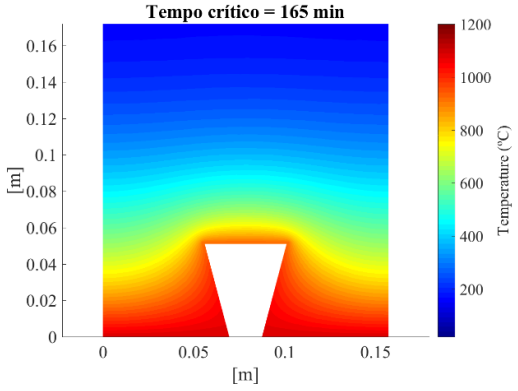


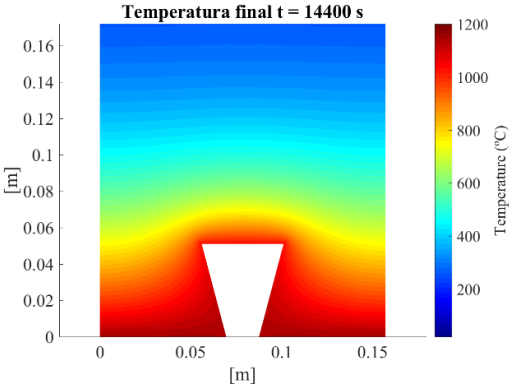




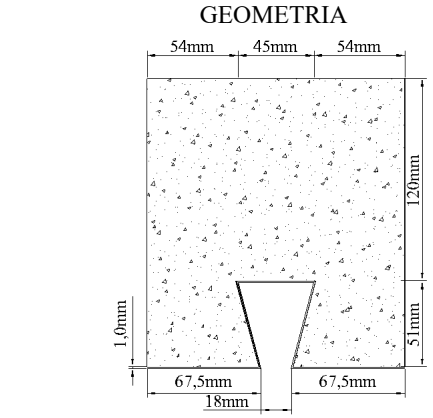


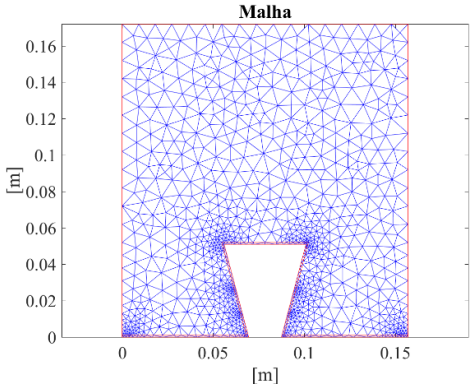


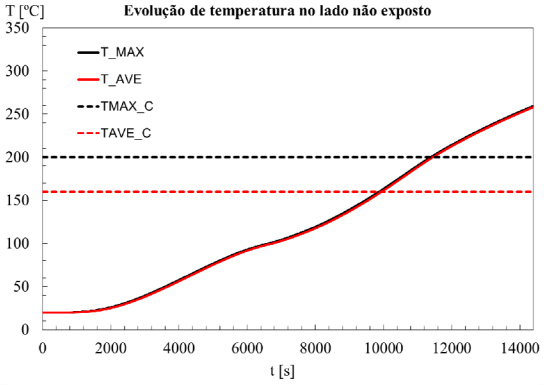


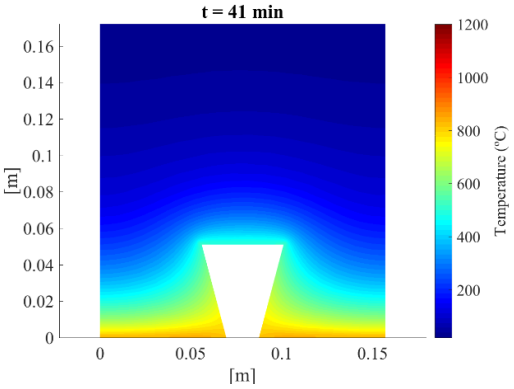


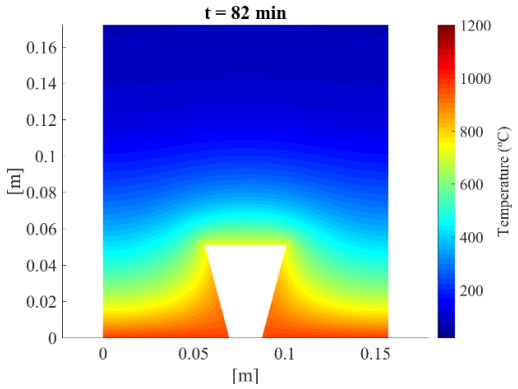
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.0mm

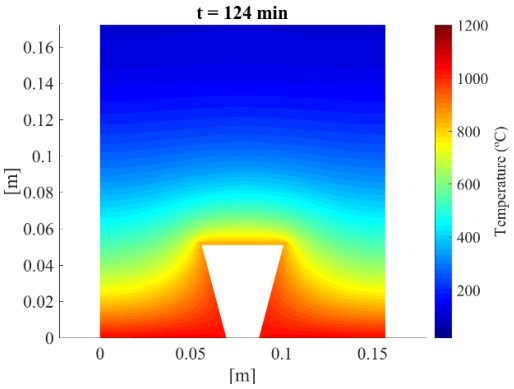


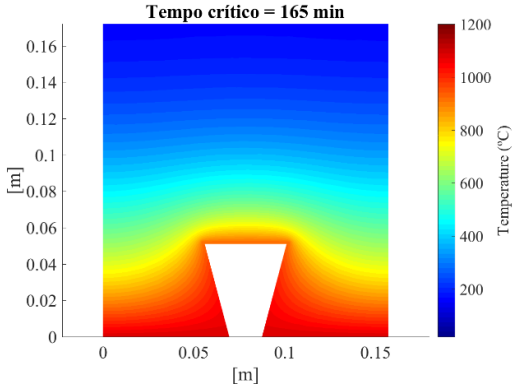


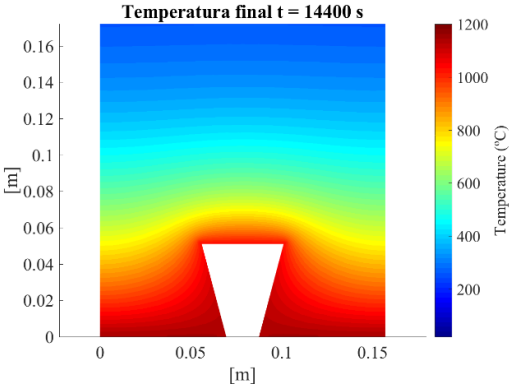




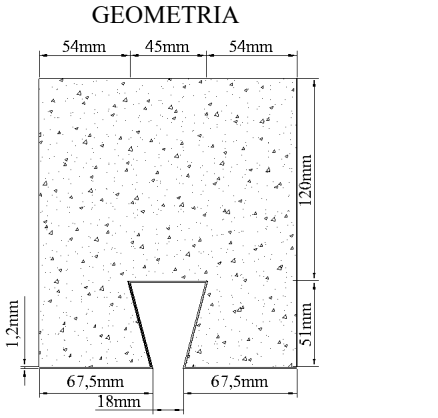


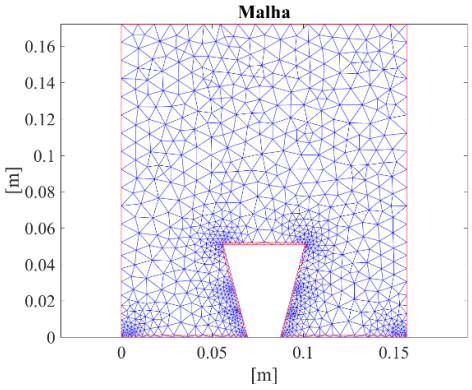


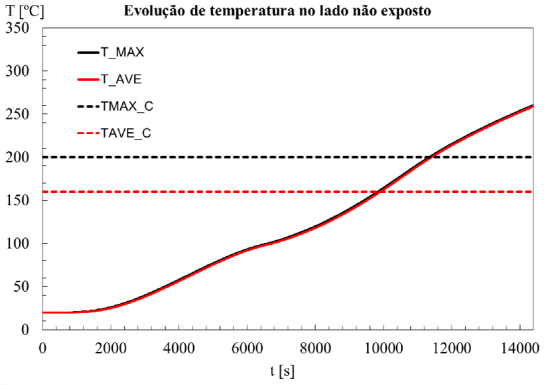


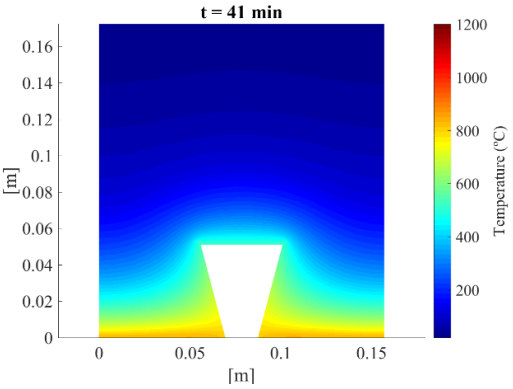


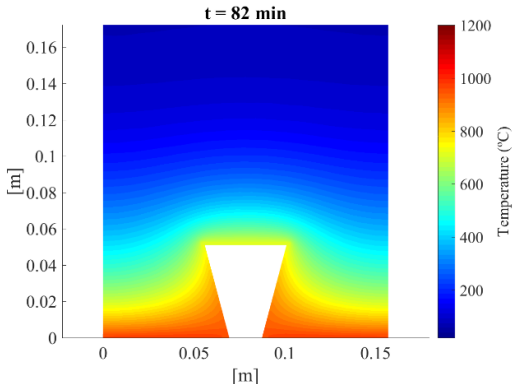
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.2mm

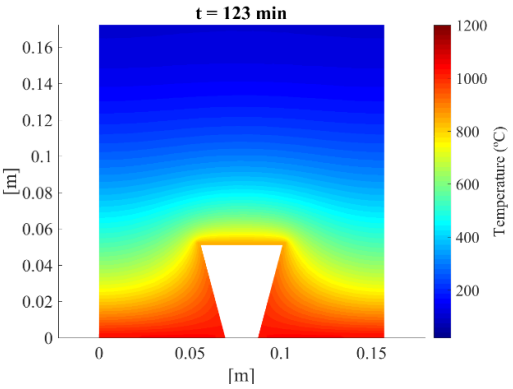


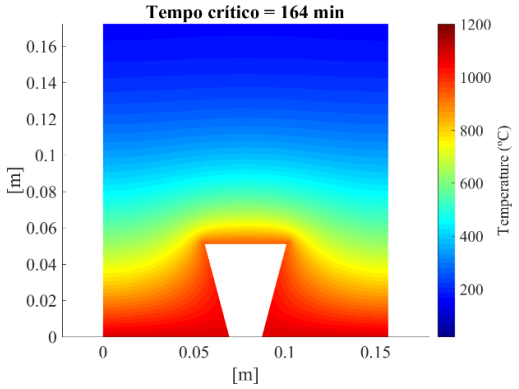


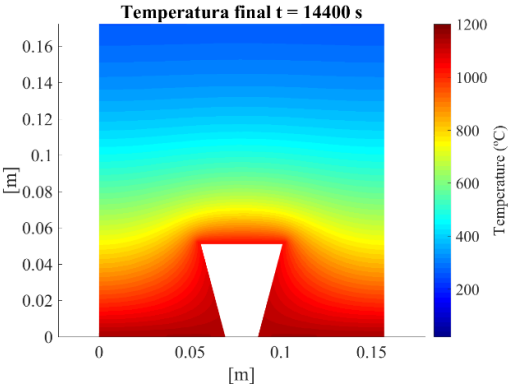




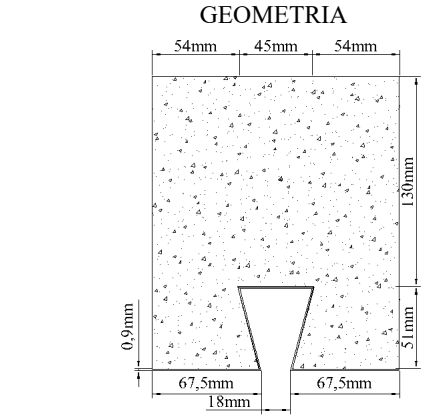


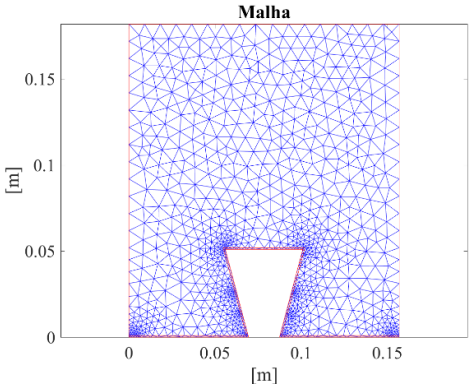


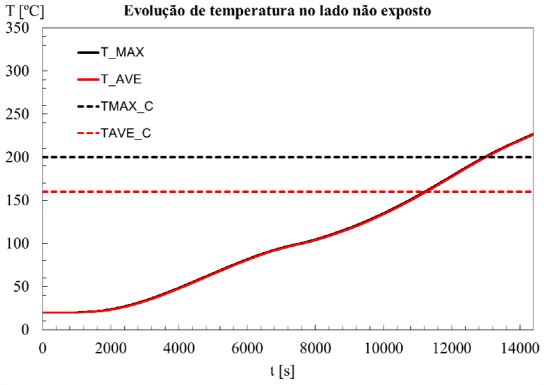


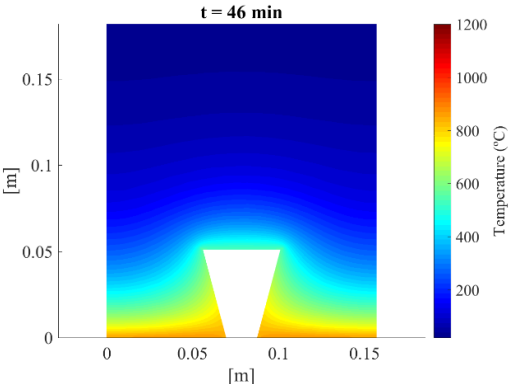


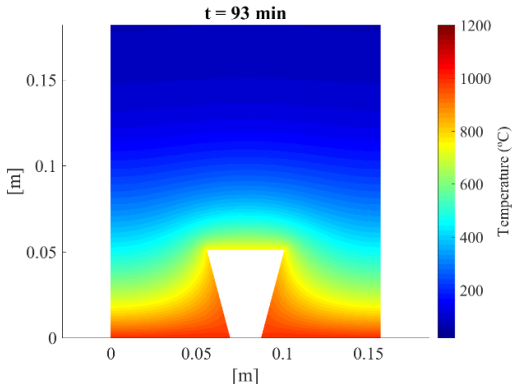
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.9mm

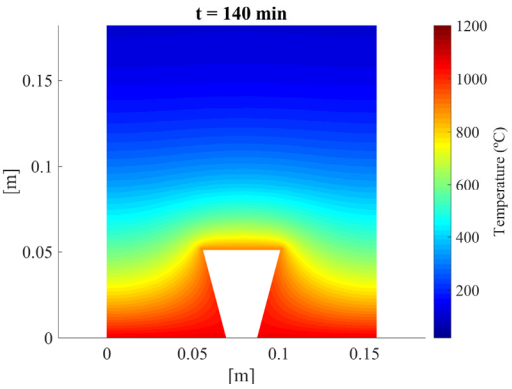


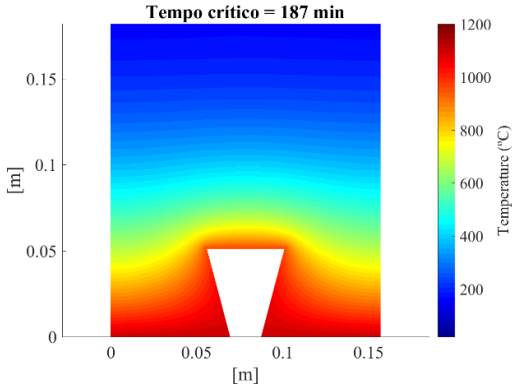


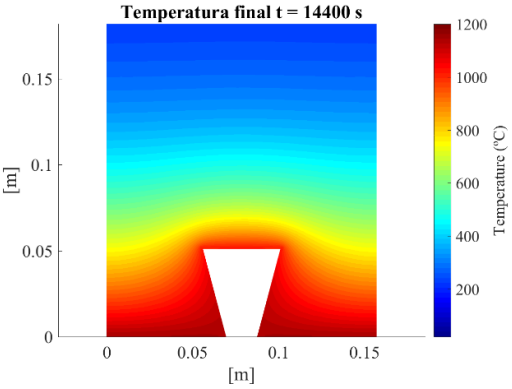




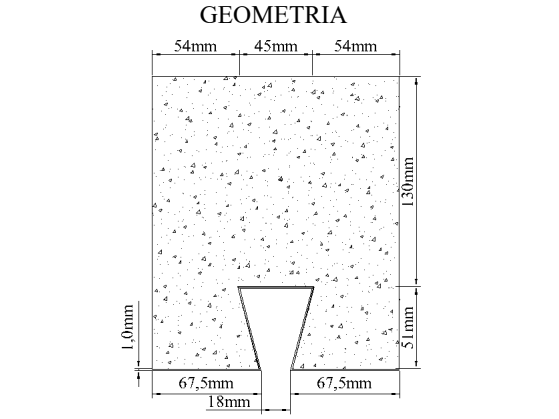


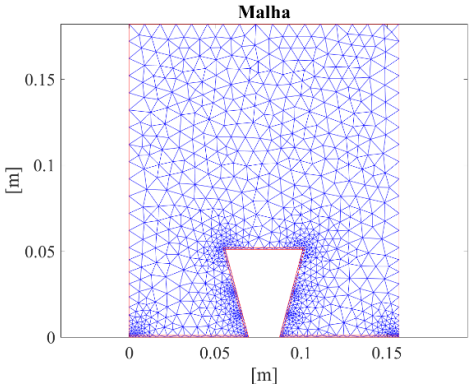


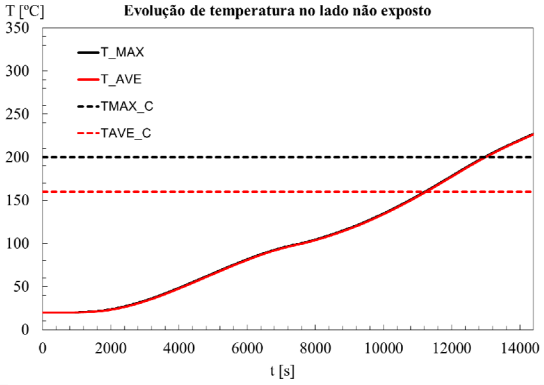


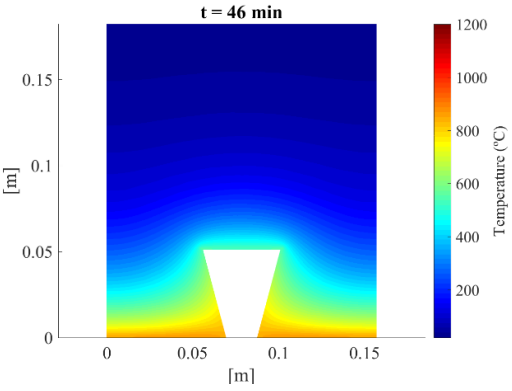


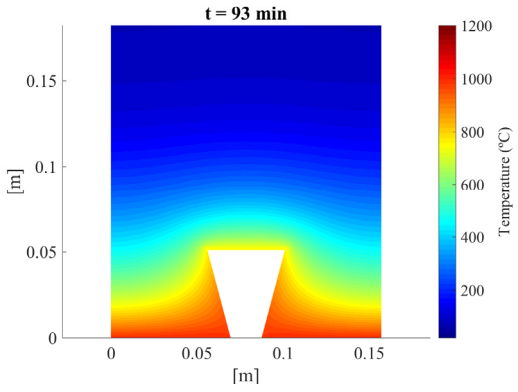
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.0mm

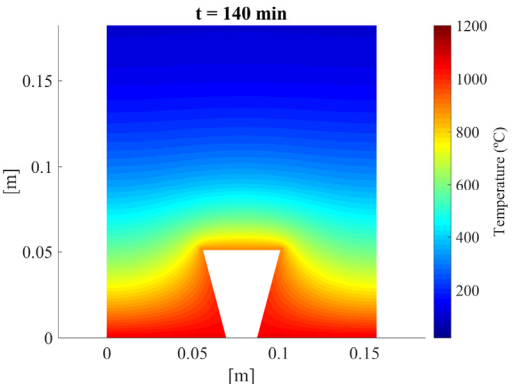


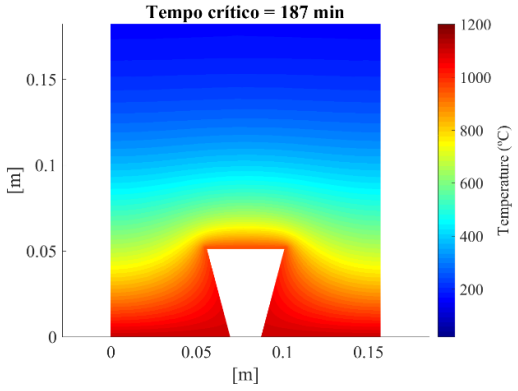


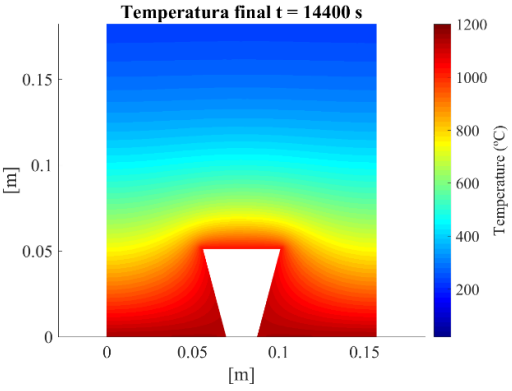




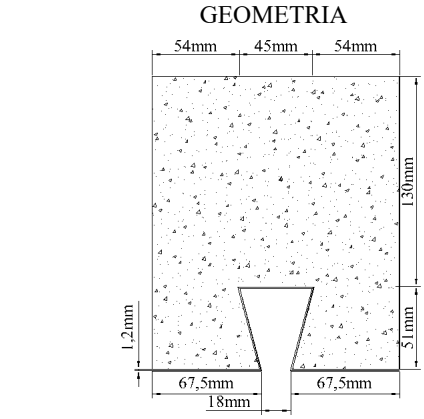


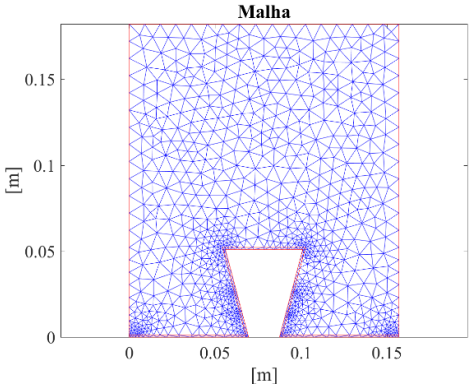


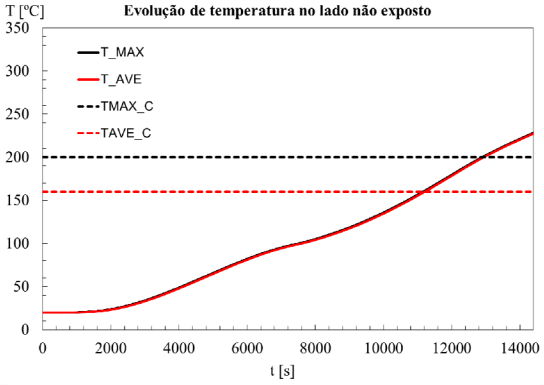


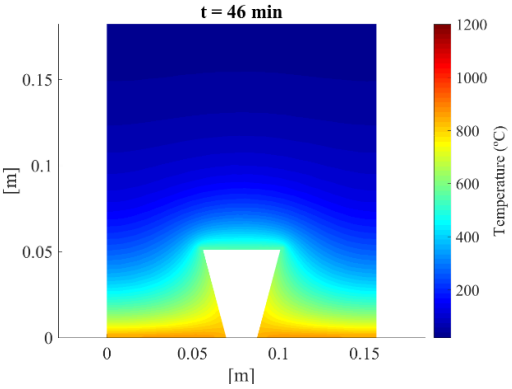


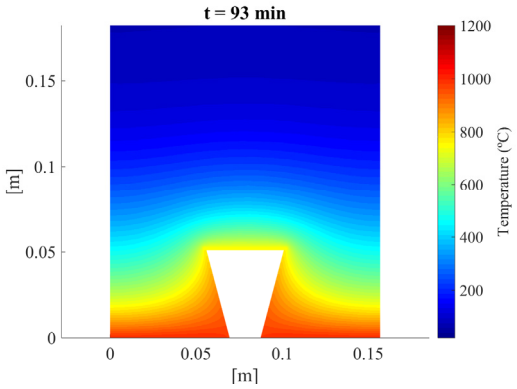
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.2mm

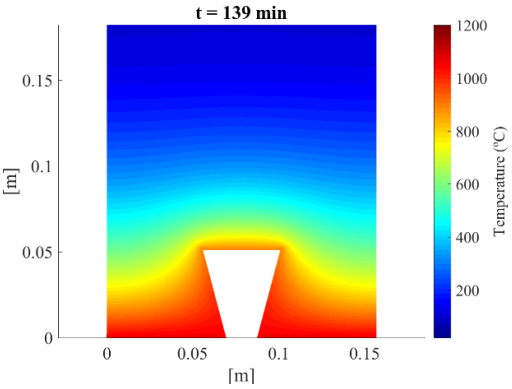


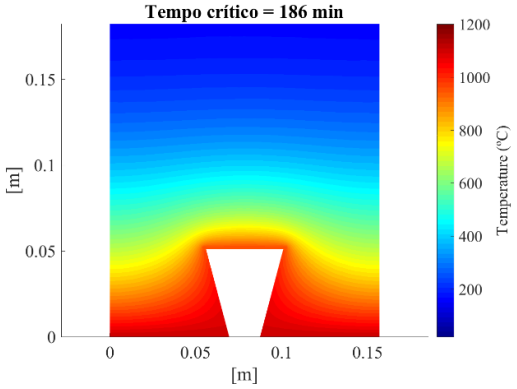


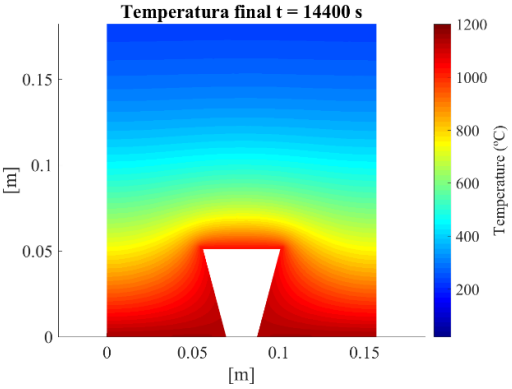




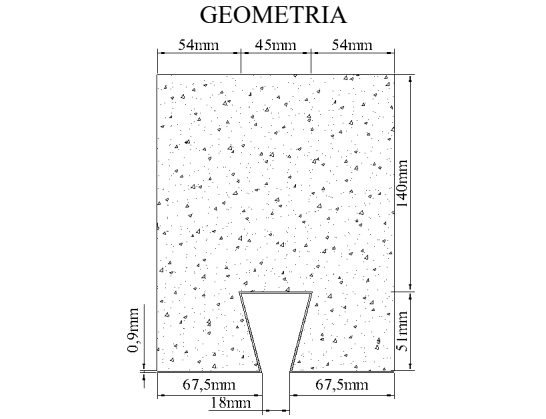


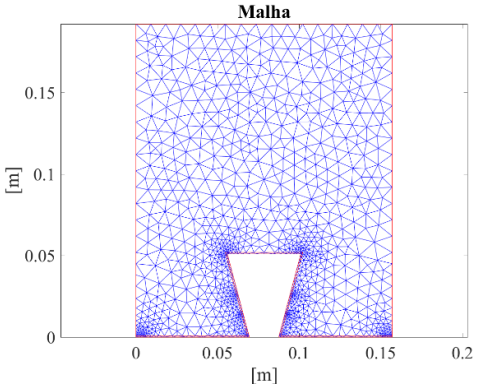


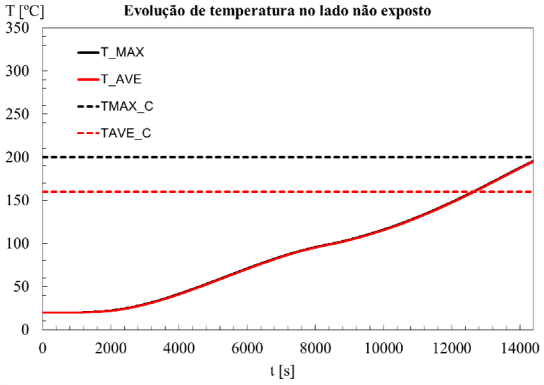


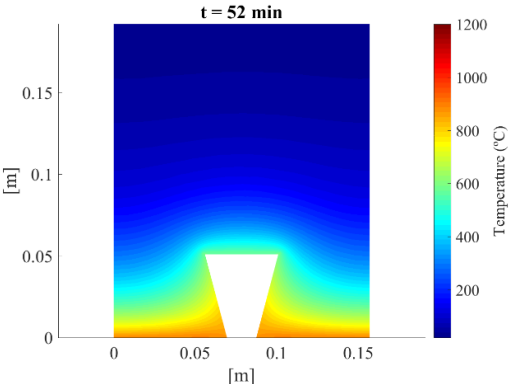


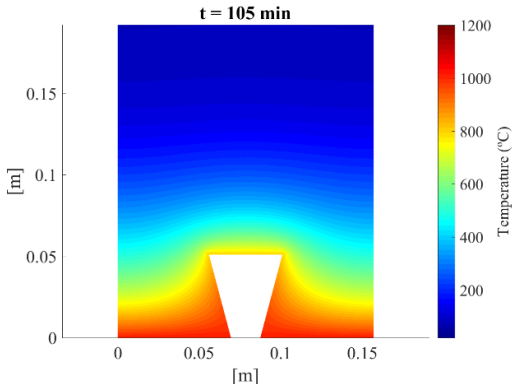
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.9mm

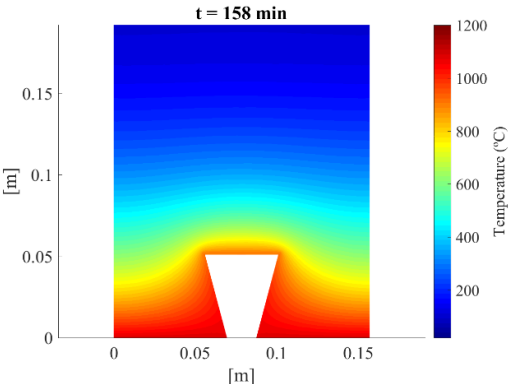


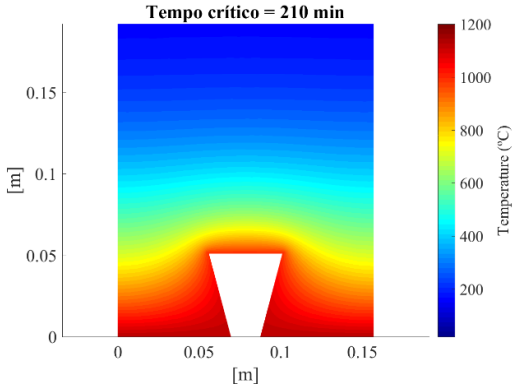


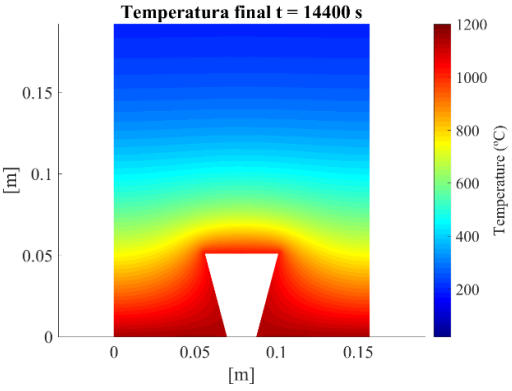




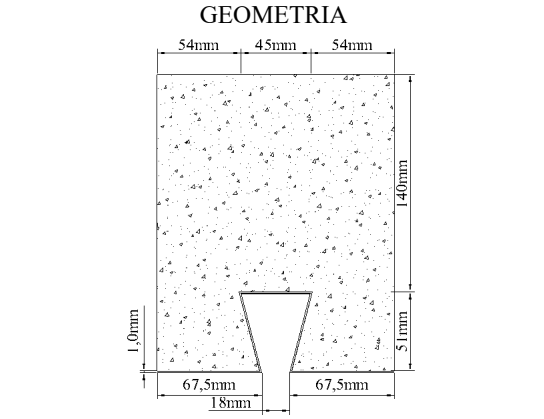


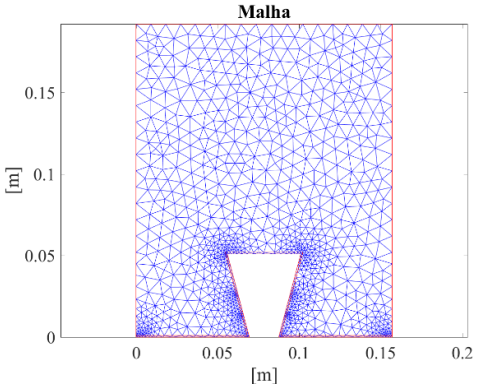


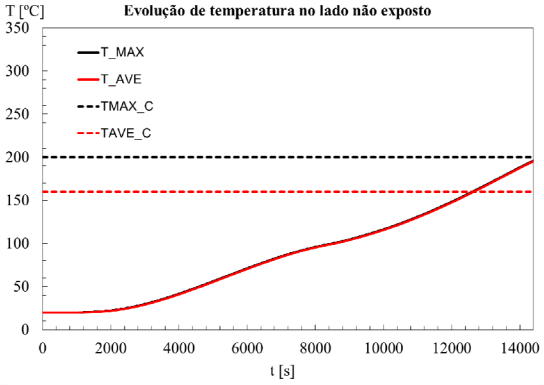


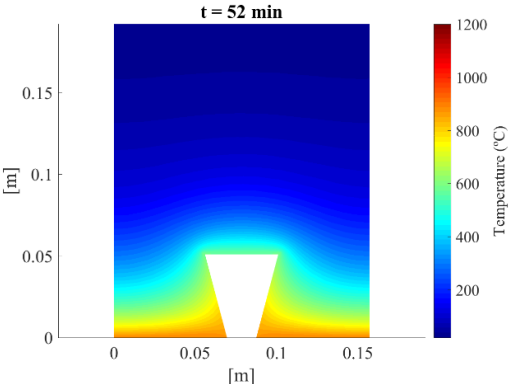


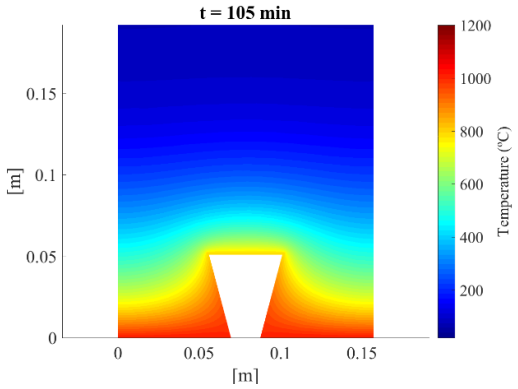
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.0mm

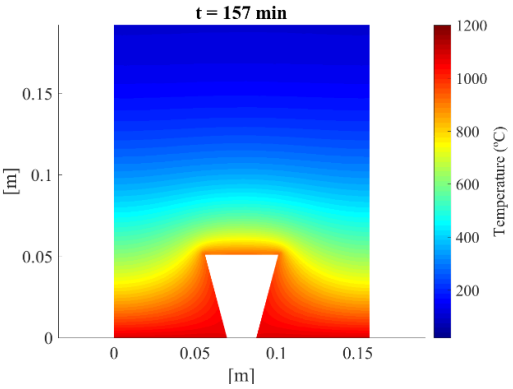


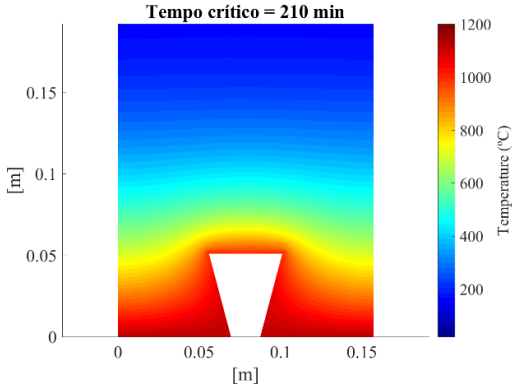


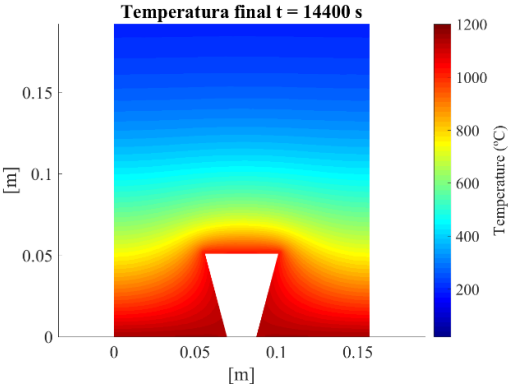




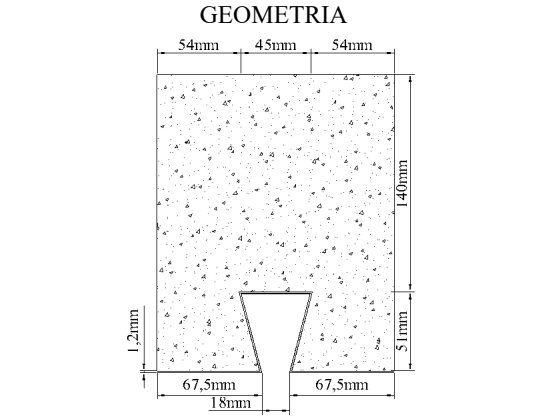


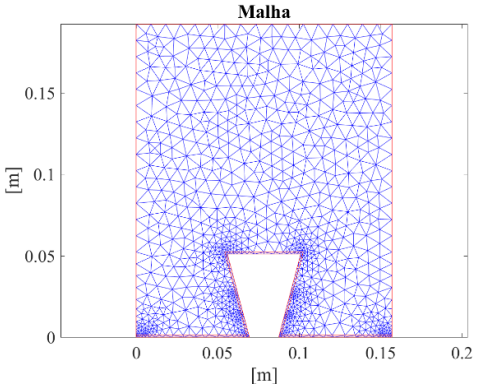


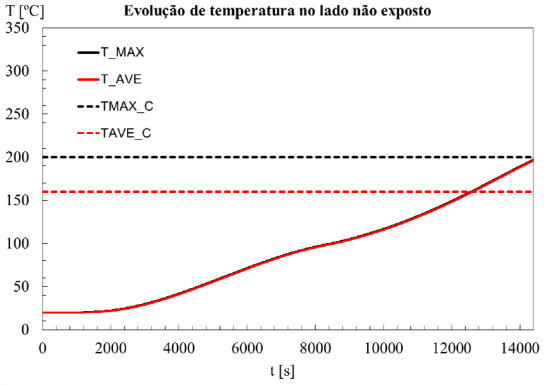


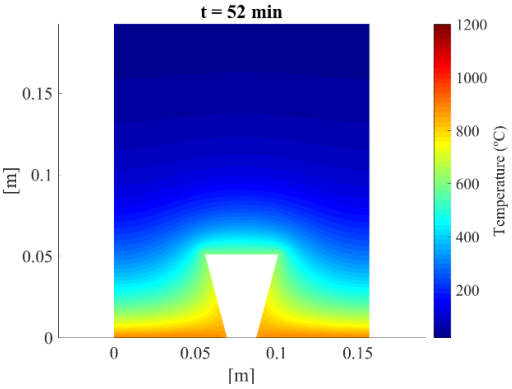


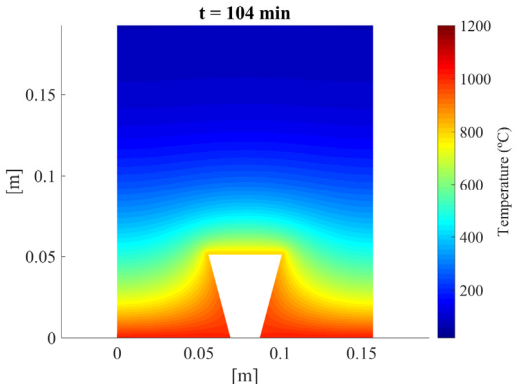
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.2mm

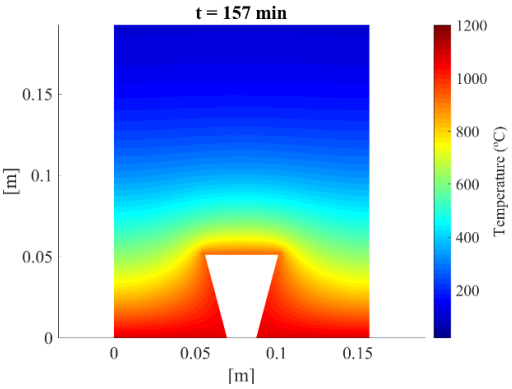


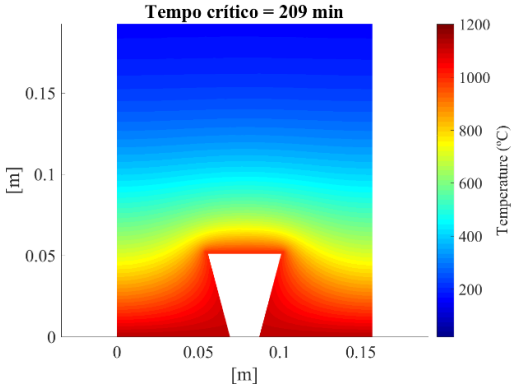


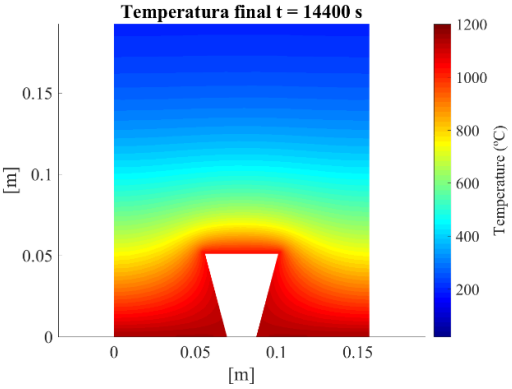




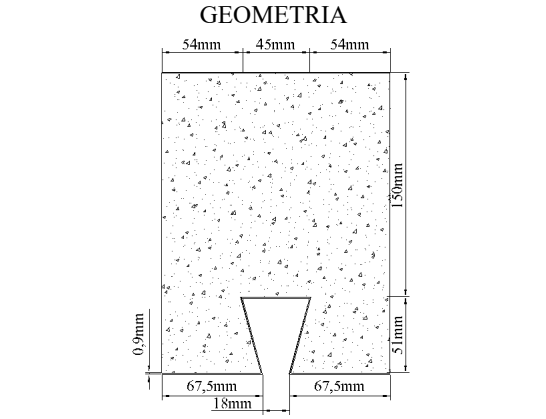


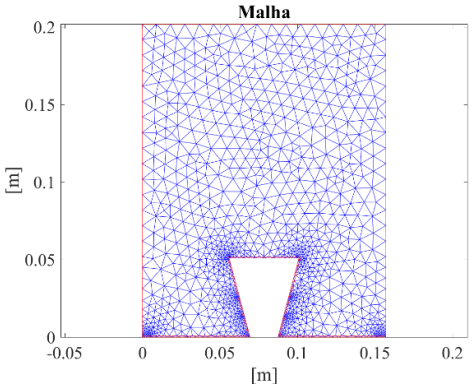


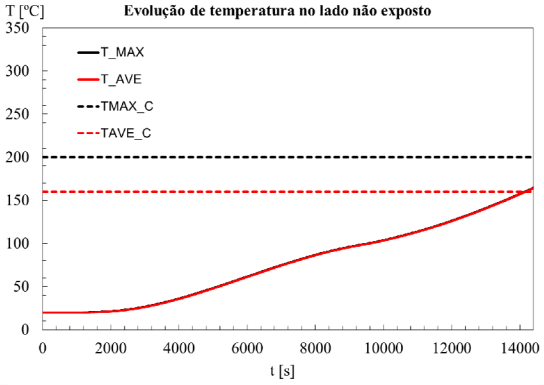


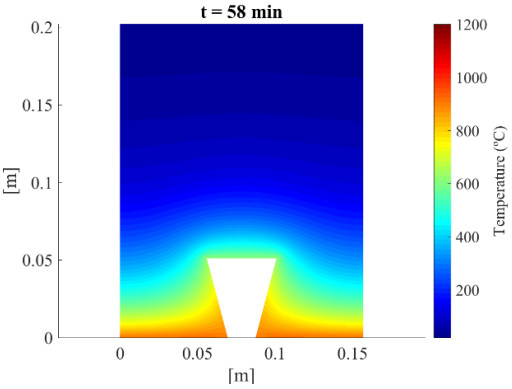


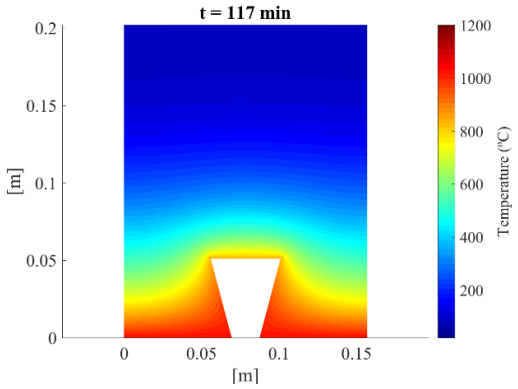
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.9mm

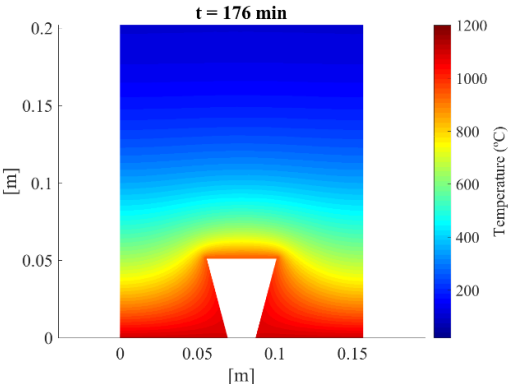


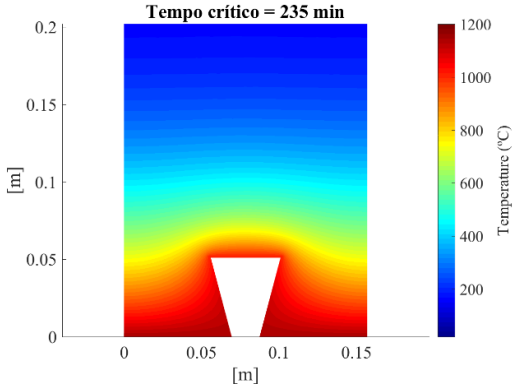


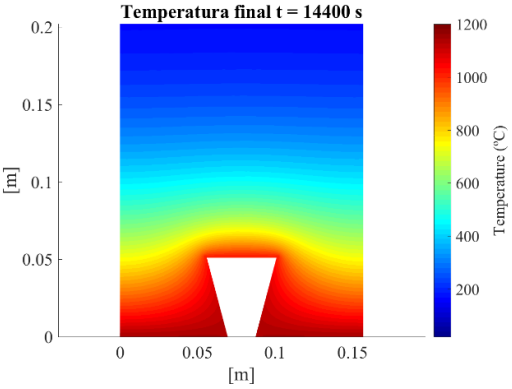




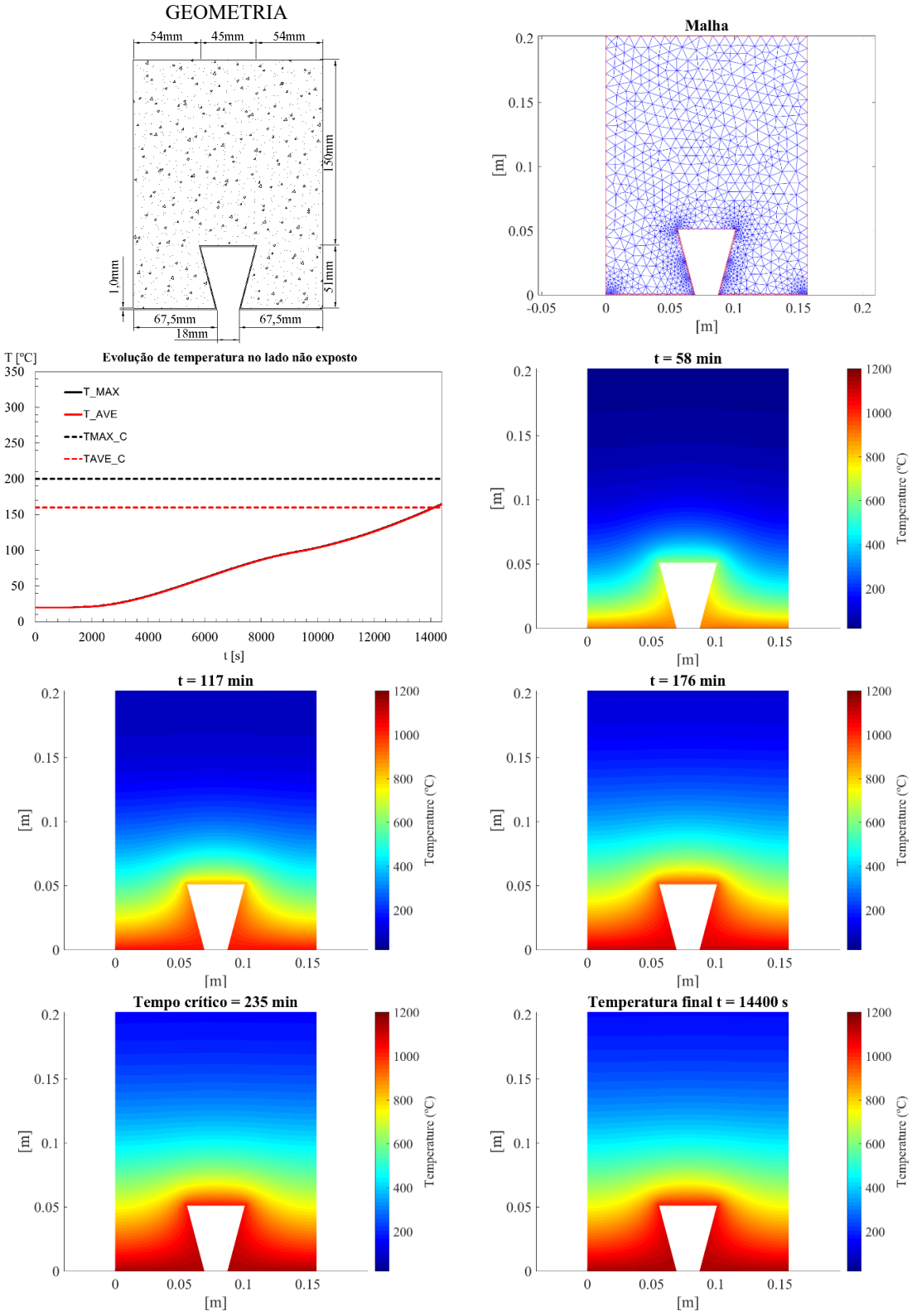




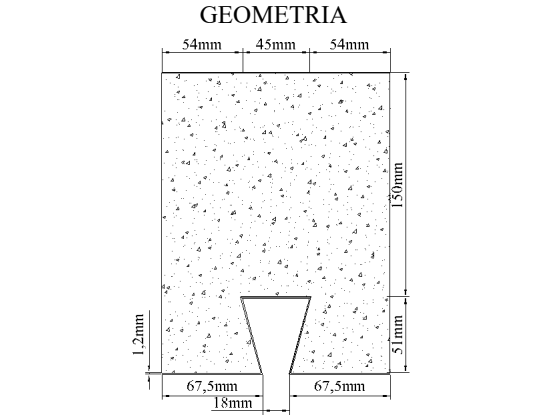


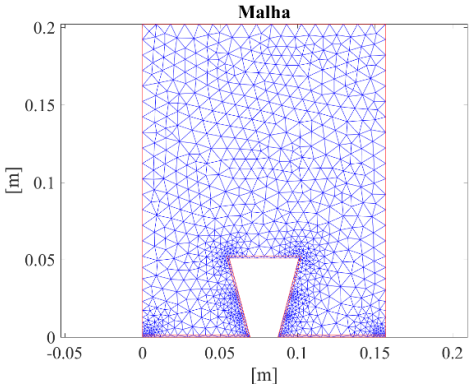


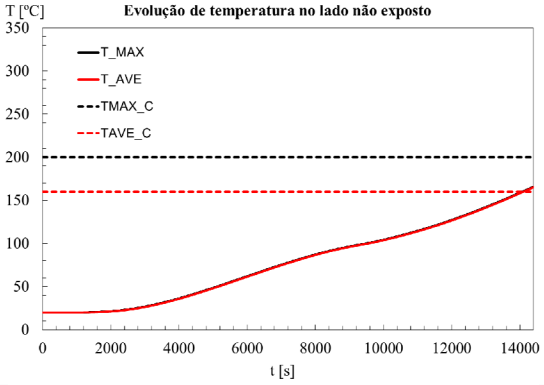
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.0mm

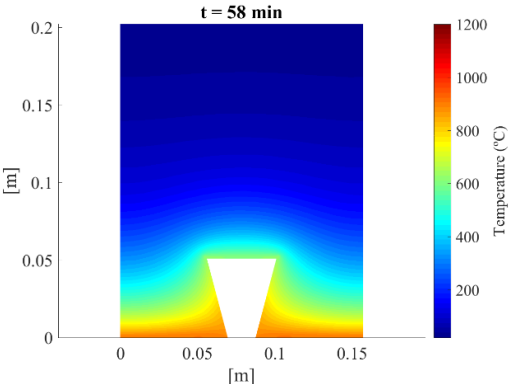


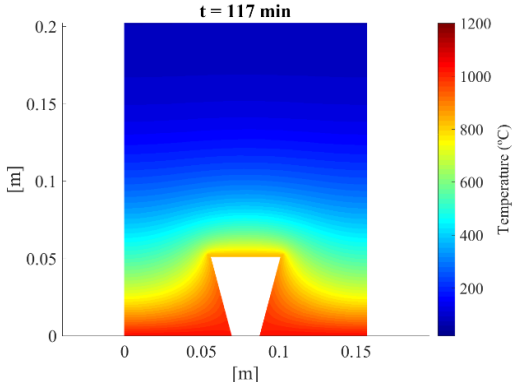
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.2mm

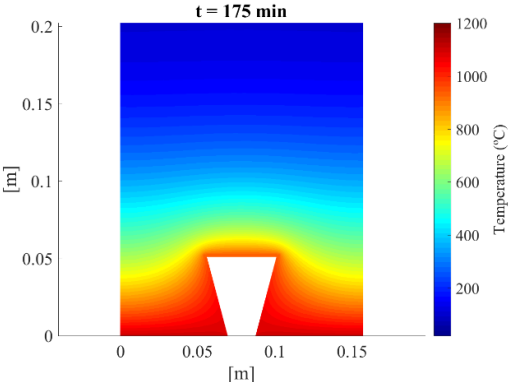


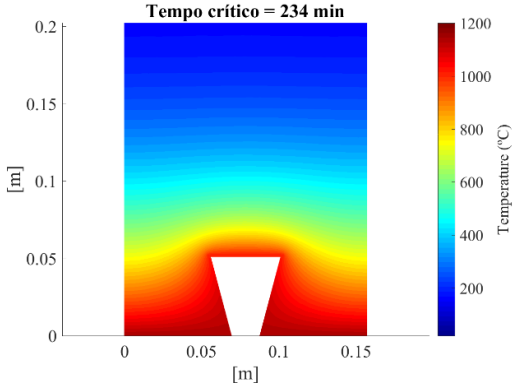


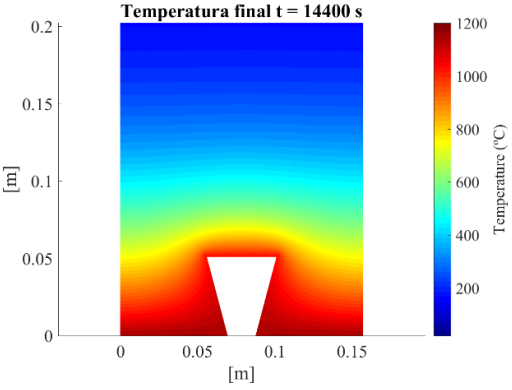




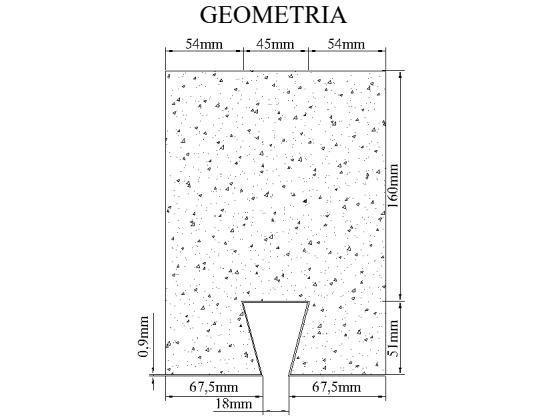


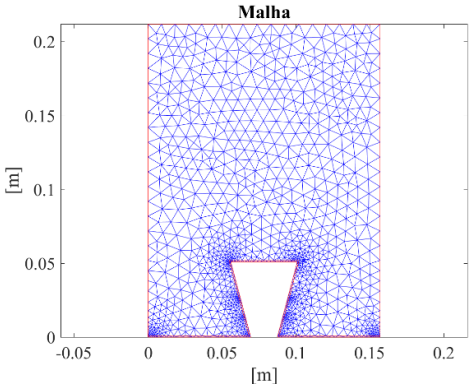


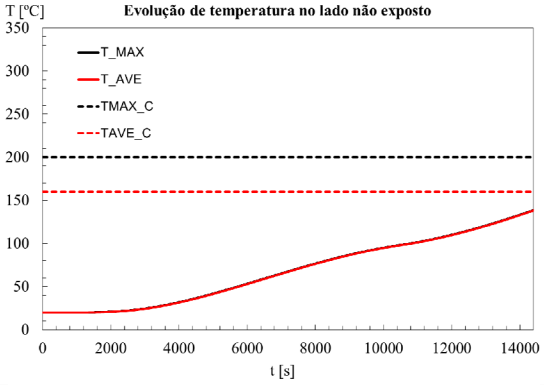


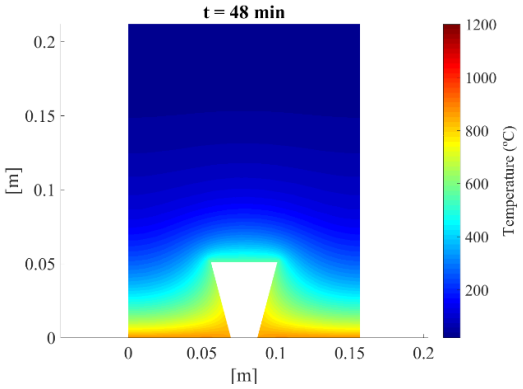


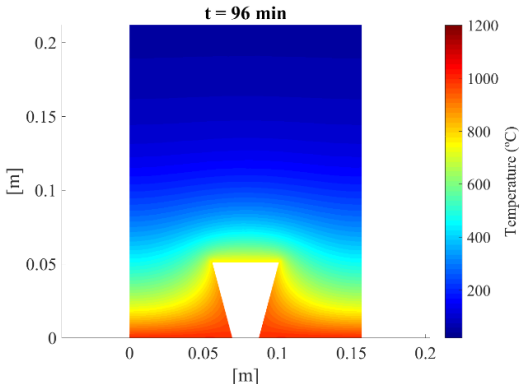
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.9mm

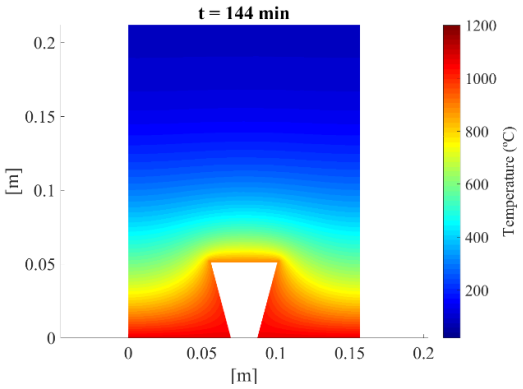


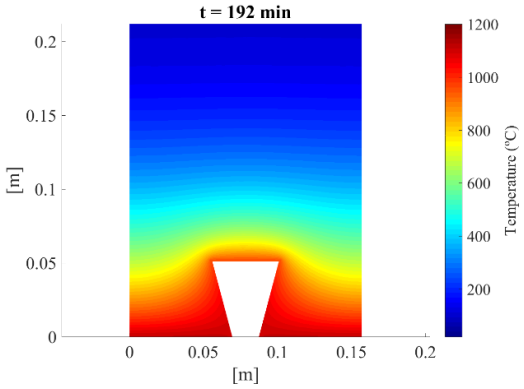


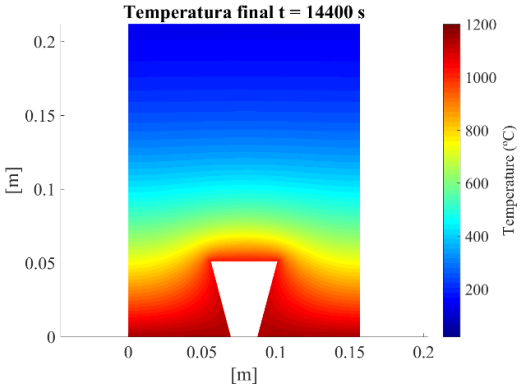




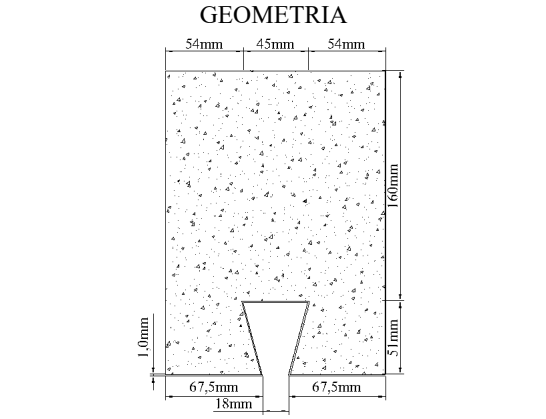


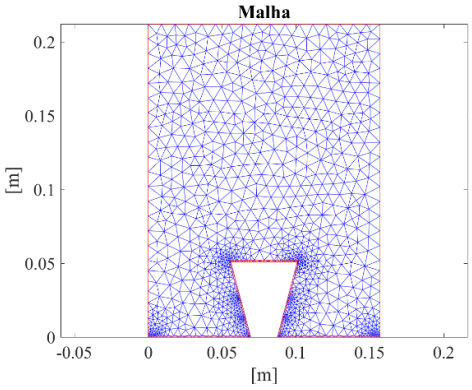


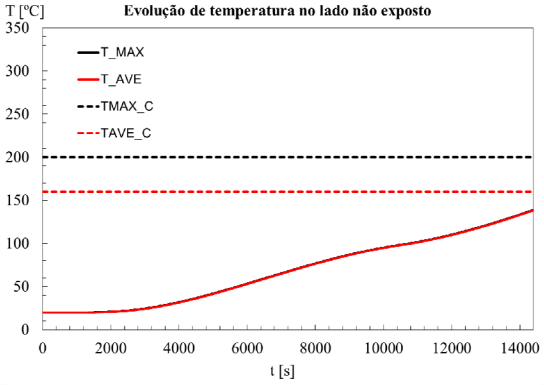


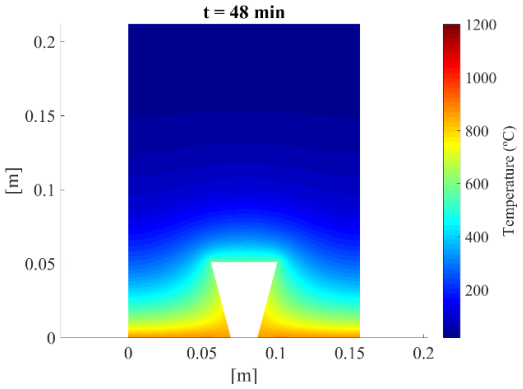


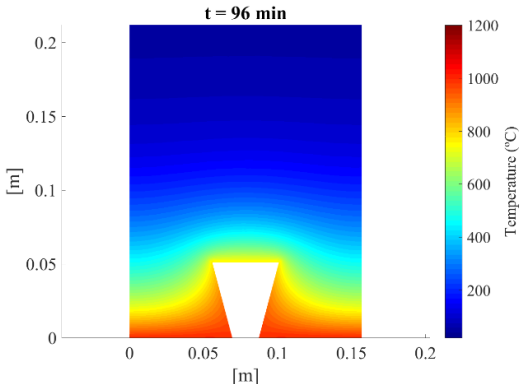
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.0mm

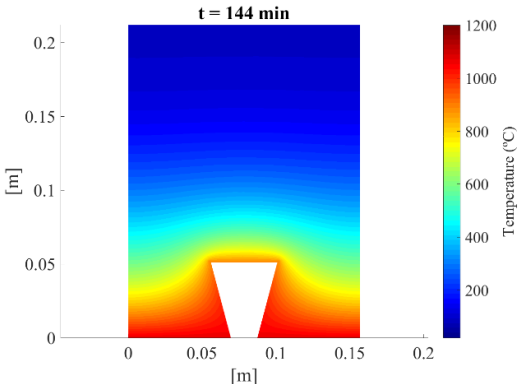


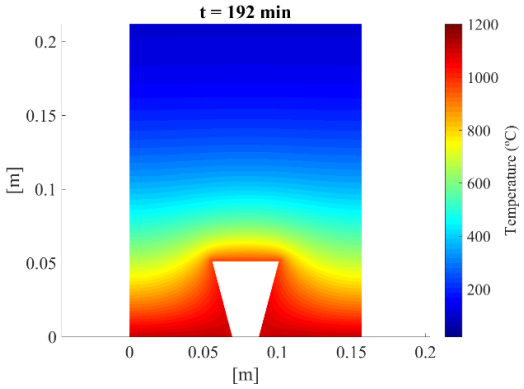


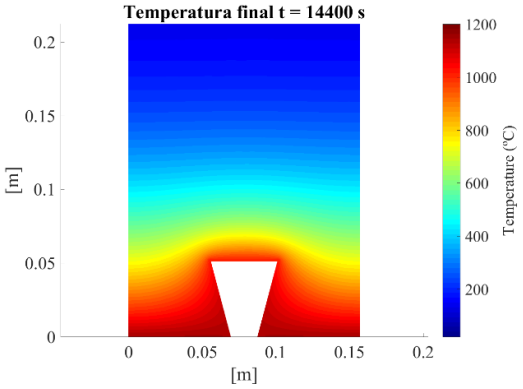




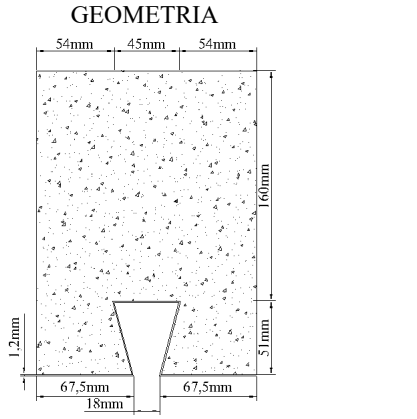


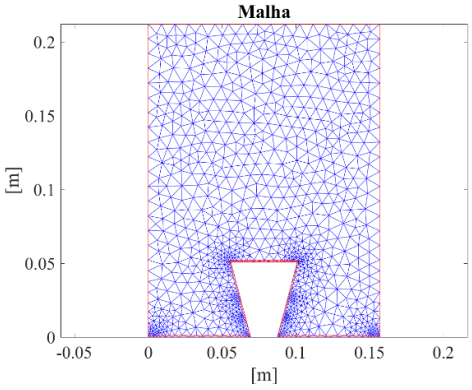


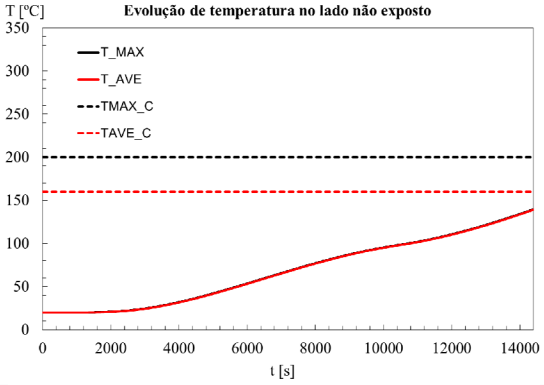


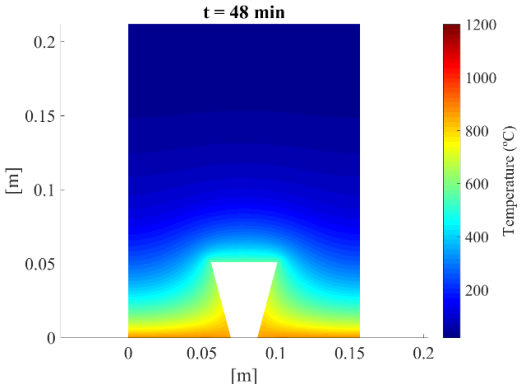


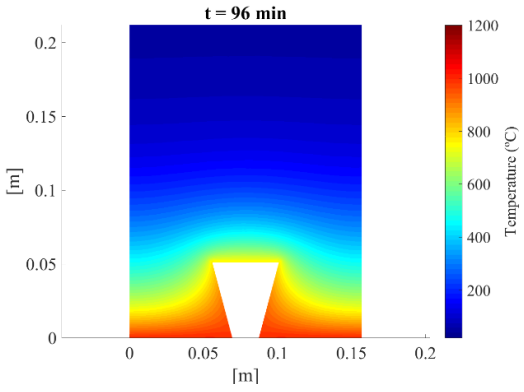
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.2mm

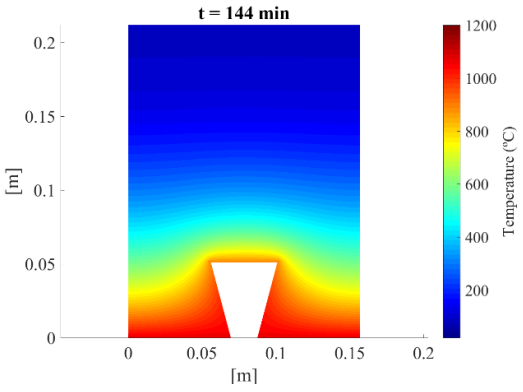


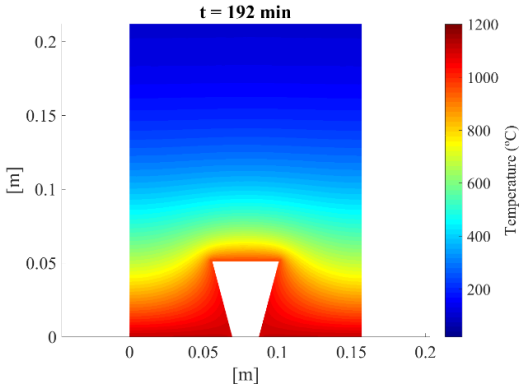


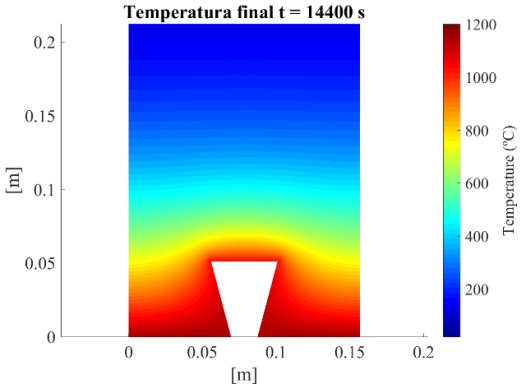




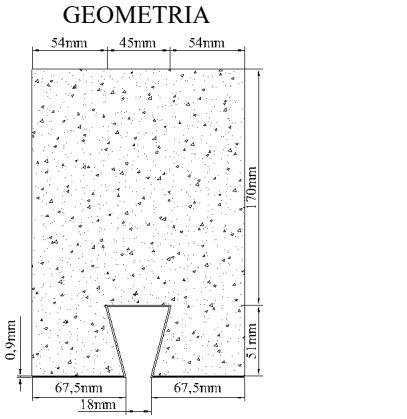


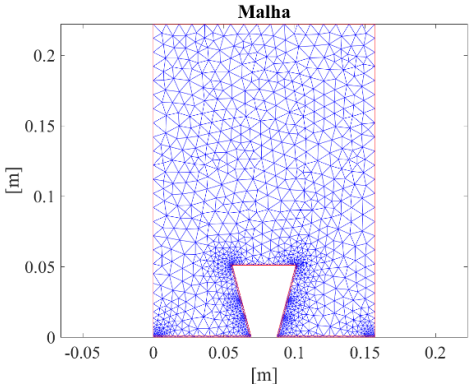


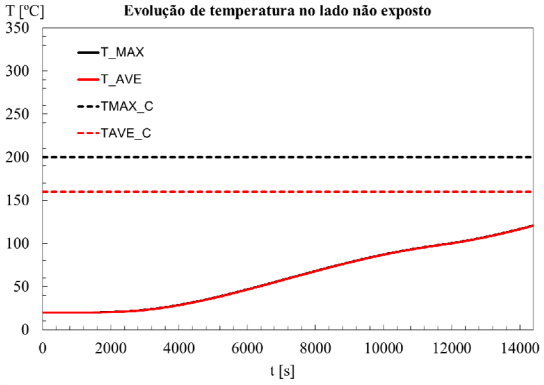


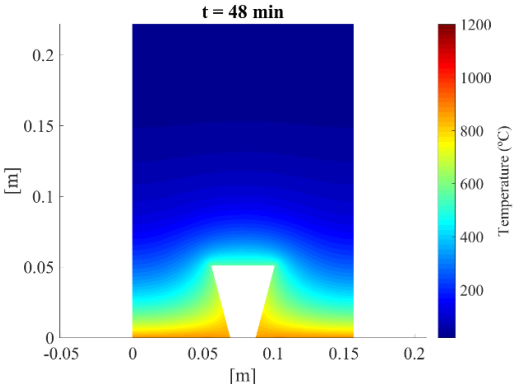


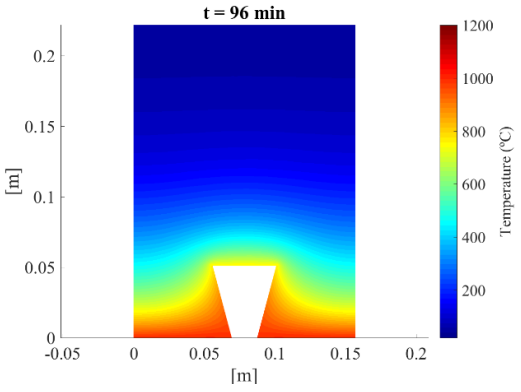
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.9mm

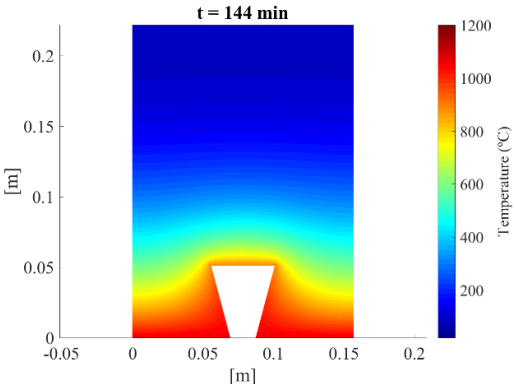


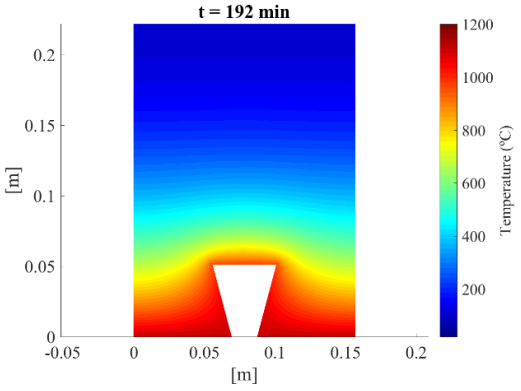


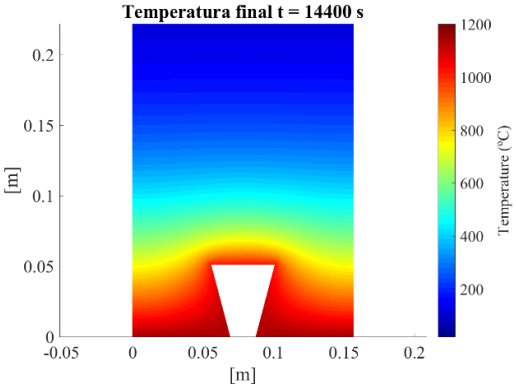




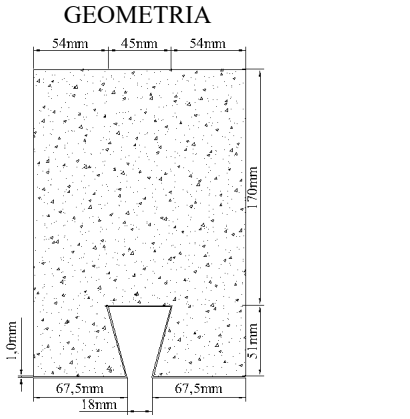


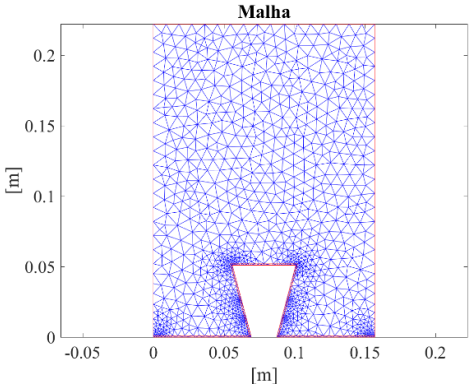


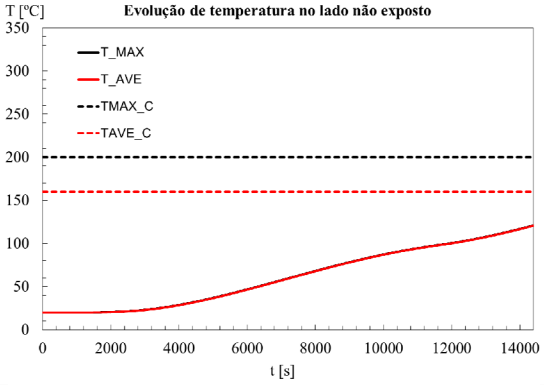


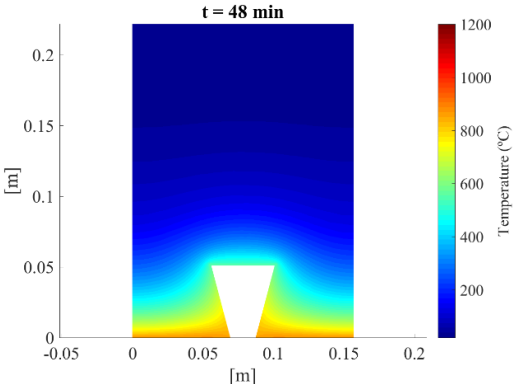


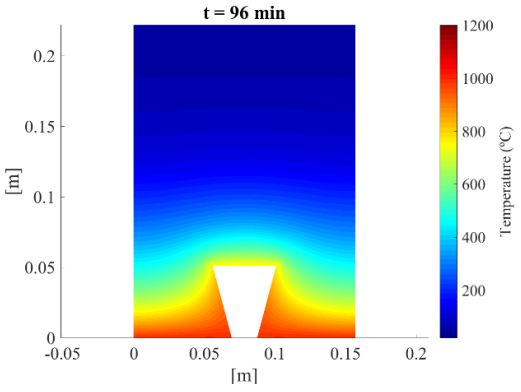
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.0mm

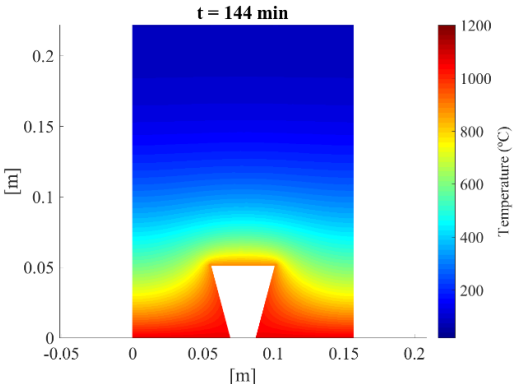


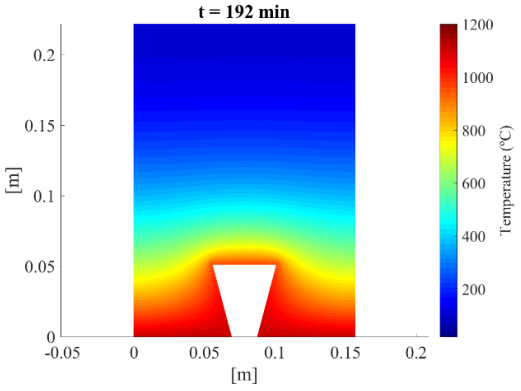


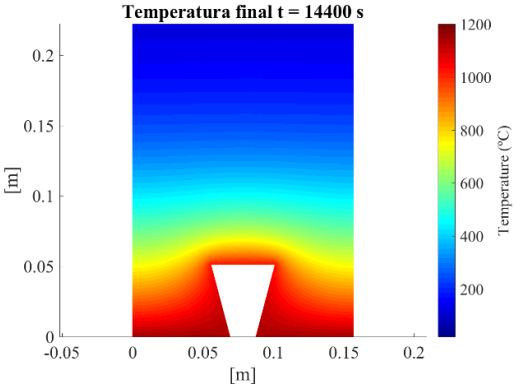




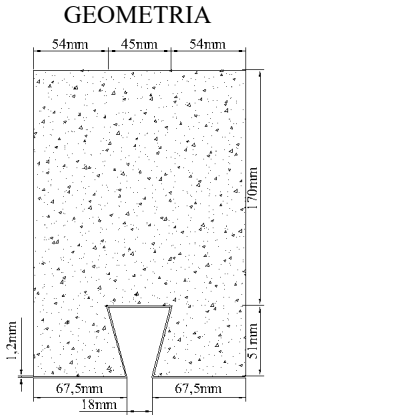


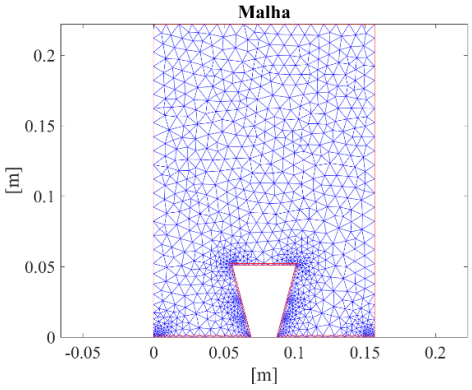


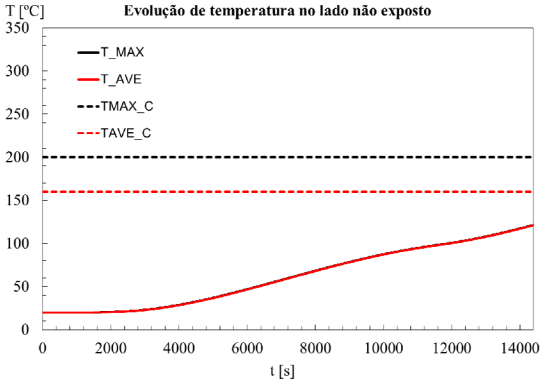


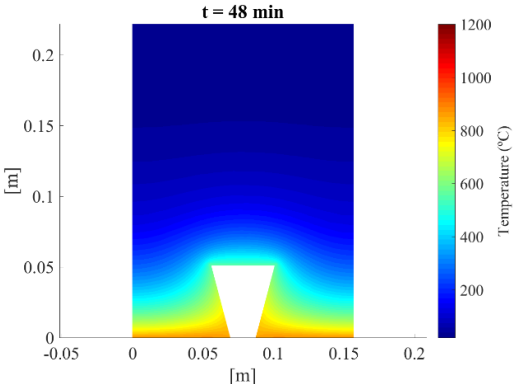


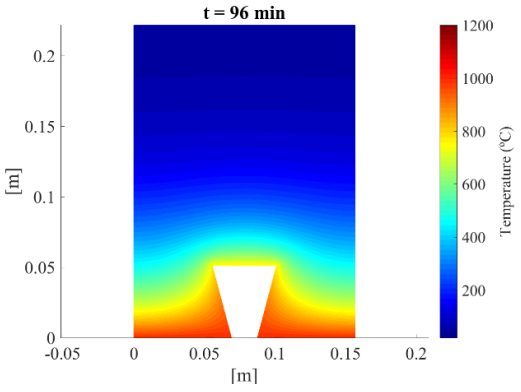
LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.2mm

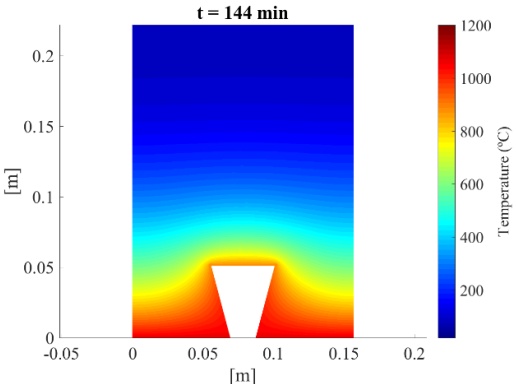


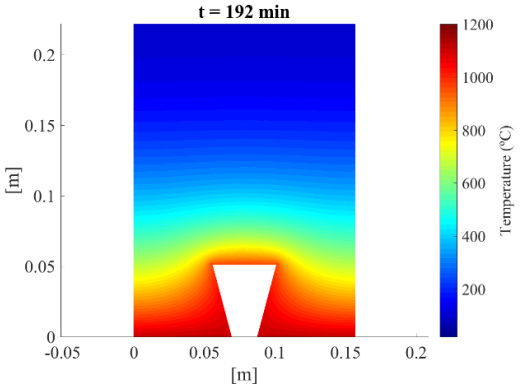


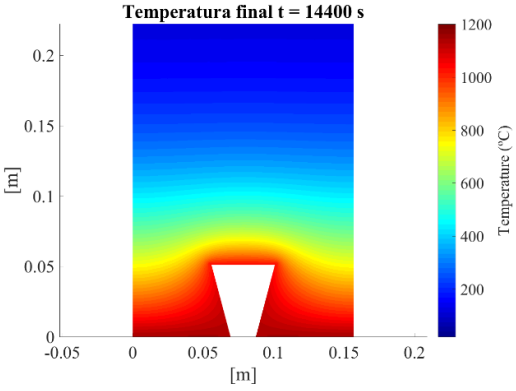












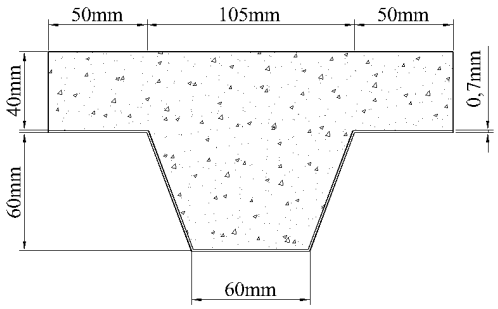
Anexo C

Análise térmica da seção transversal

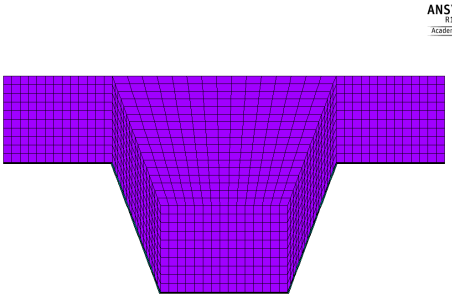
Método avançado de cálculo para lajes trapezoidais: ANSYS.

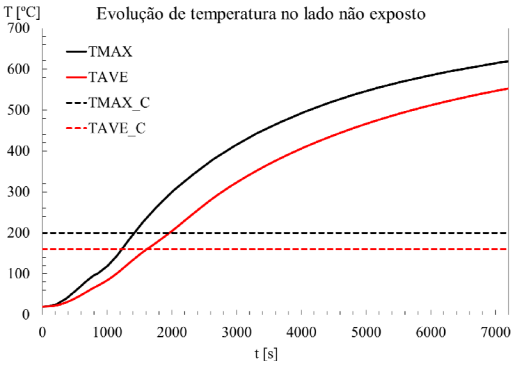
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.7mm

GEOMETRIA

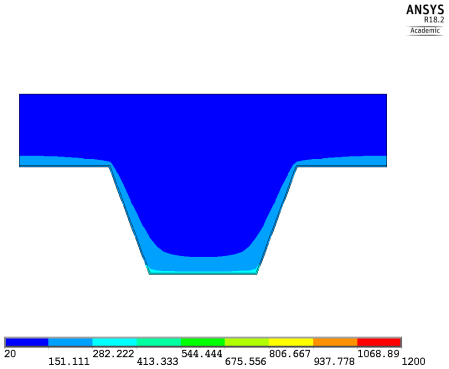


Malha

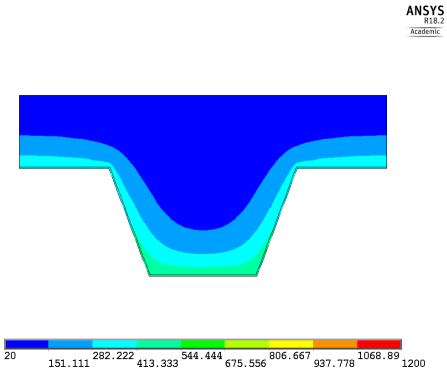




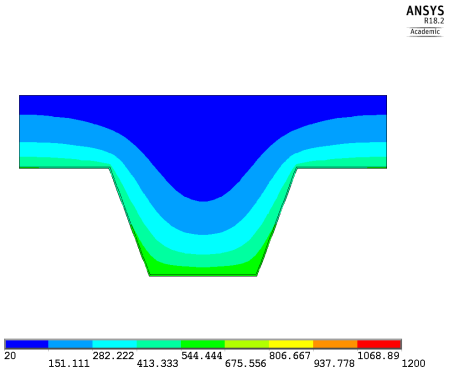
t = 5 min



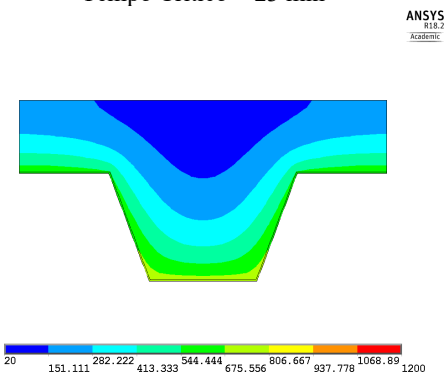
t = 11 min



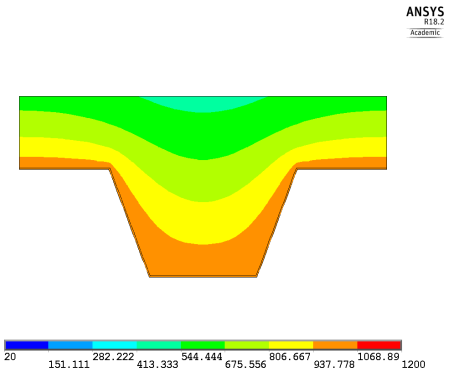
t = 17 min



Tempo Crítico = 23 min

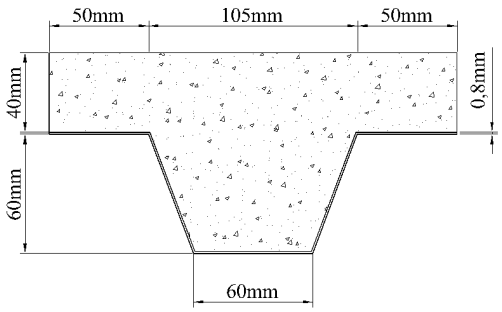


t = 7200s

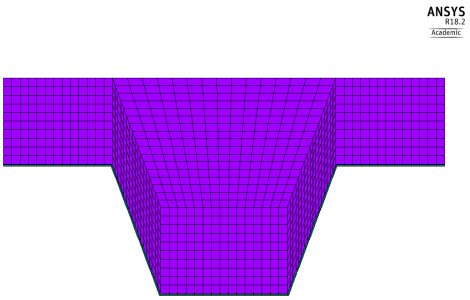


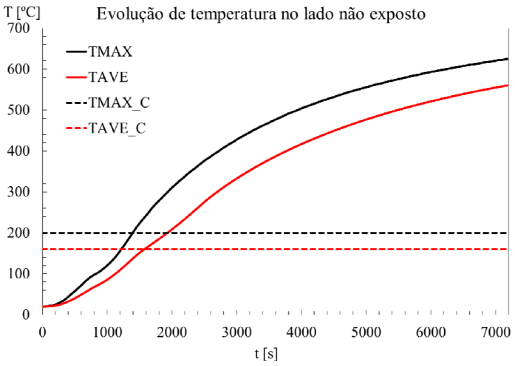
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.8mm

GEOMETRIA

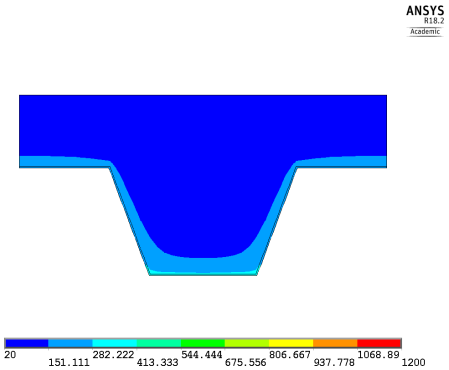


Malha

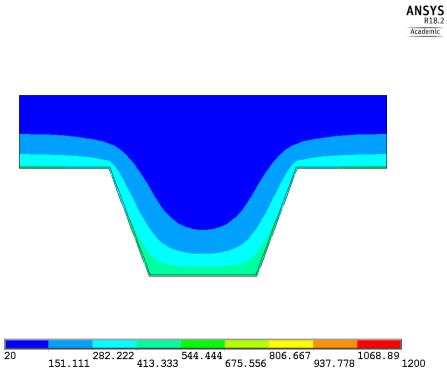




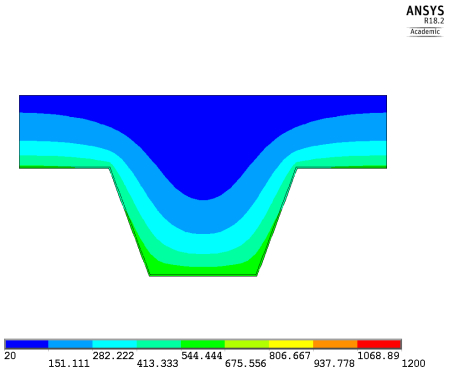
t = 5 min



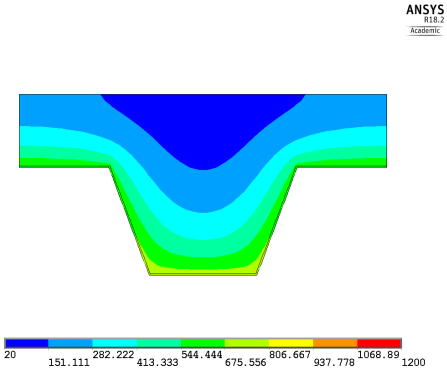
t = 11 min



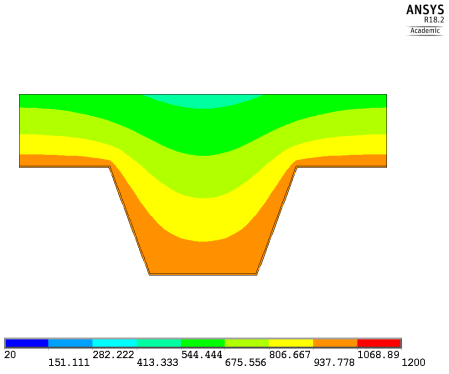
t = 17 min



Tempo Crítico = 23 min

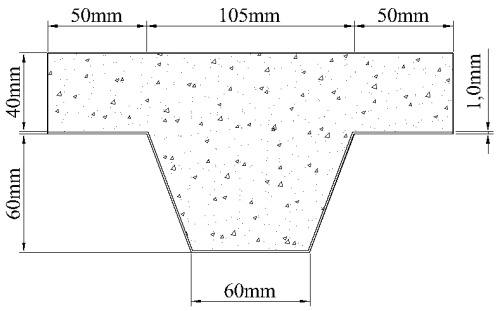


t = 7200s

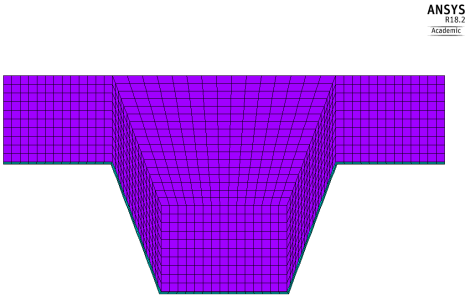


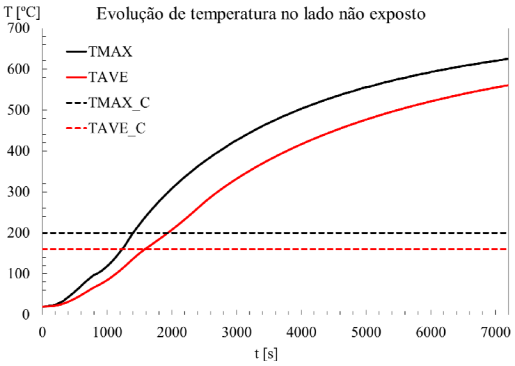
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.0mm

GEOMETRIA

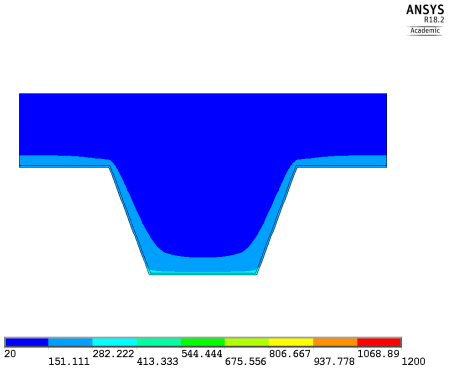


Malha

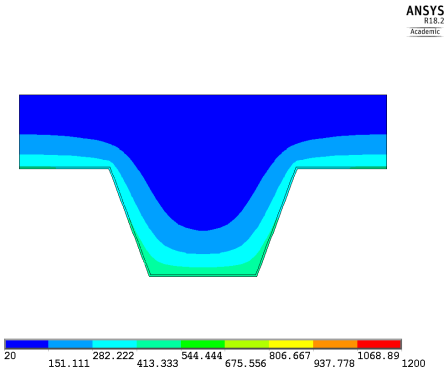




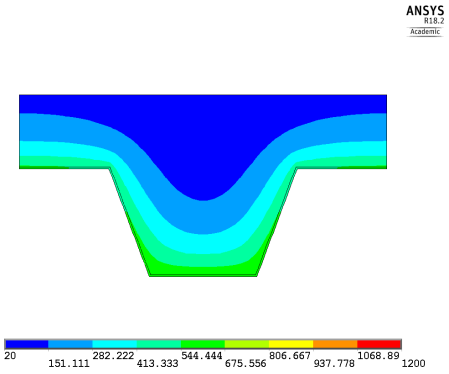
t = 5 min



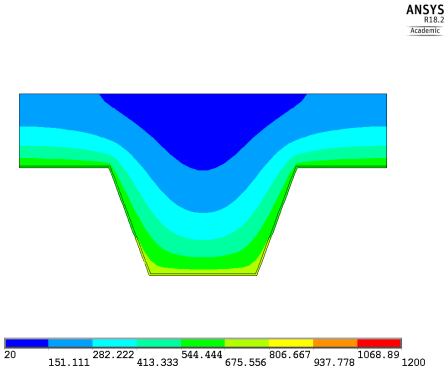
t = 11 min



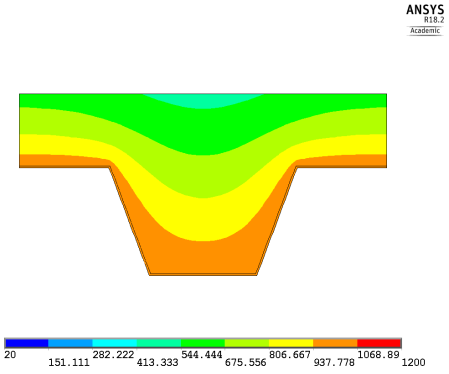
t = 17 min



Tempo Crítico = 23 min

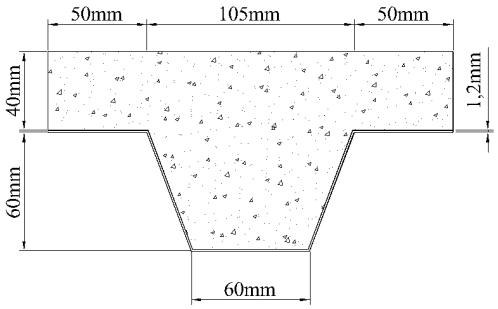


t = 7200s

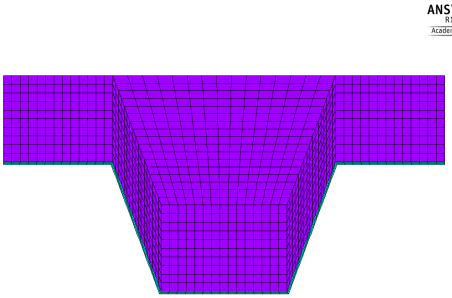


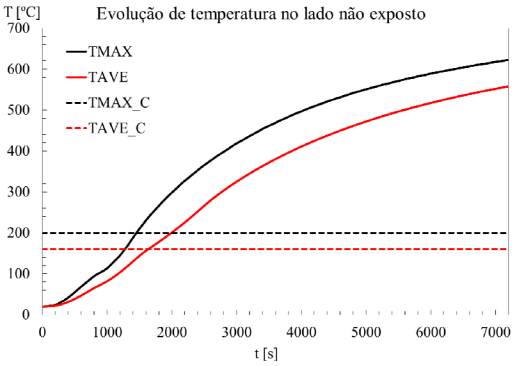
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.2mm

GEOMETRIA

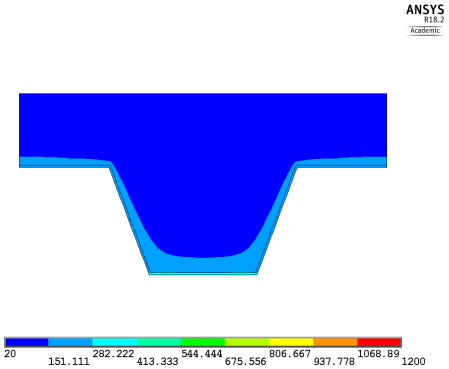


Malha

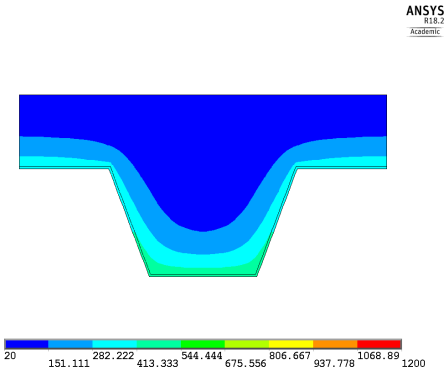




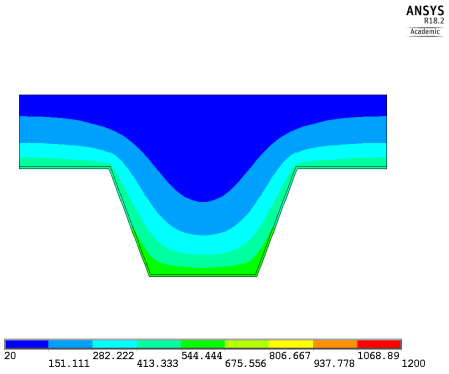
t = 6 min



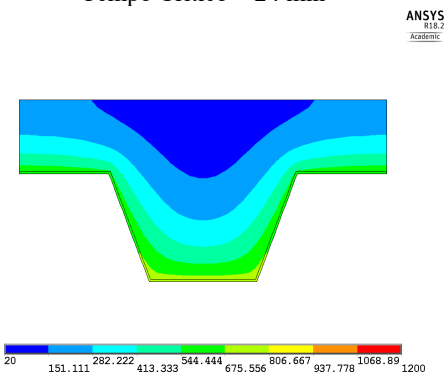
t = 12 min



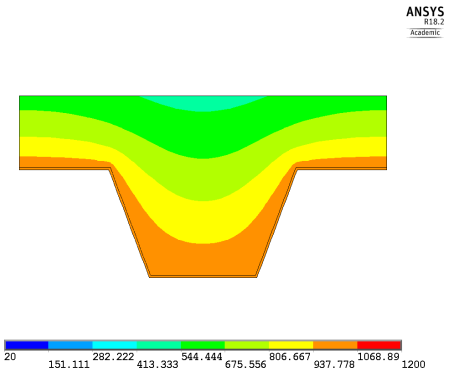
t = 18 min



Tempo Crítico = 24 min

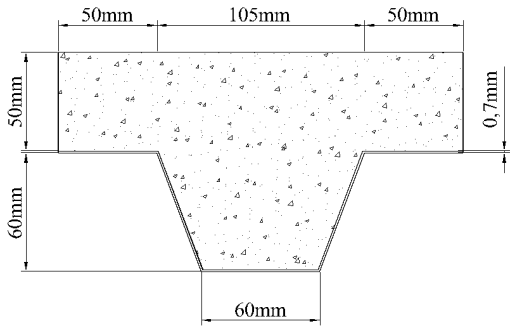


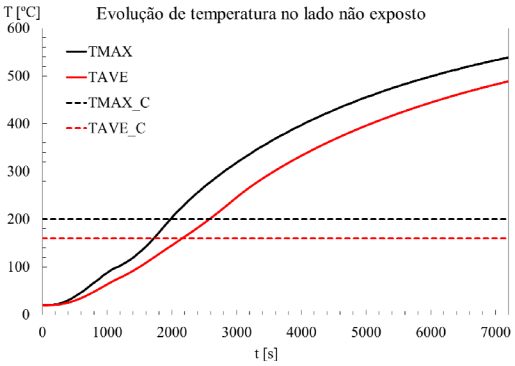
t = 7200s



LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.7mm

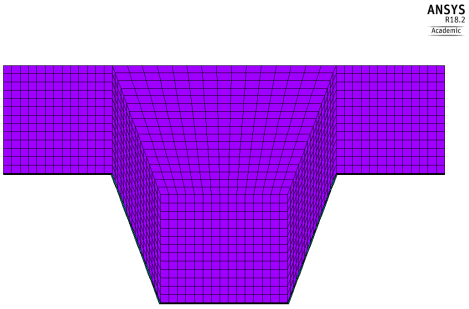
GEOMETRIA



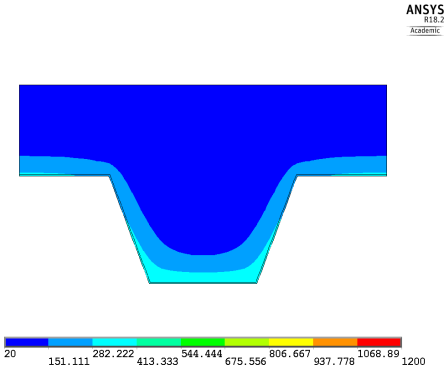


t = 16 min

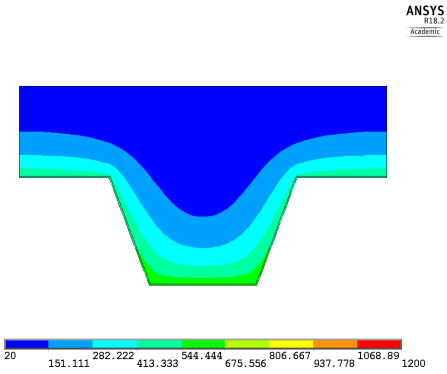
Malha



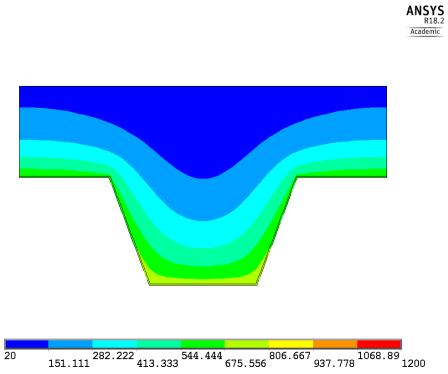
t = 8 min



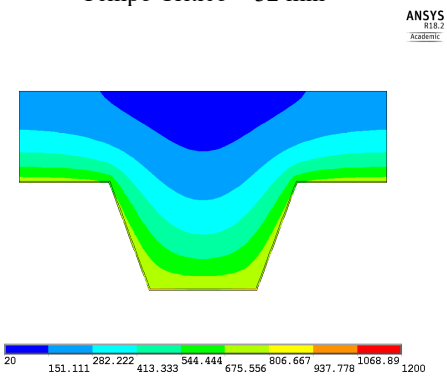
t = 24 min

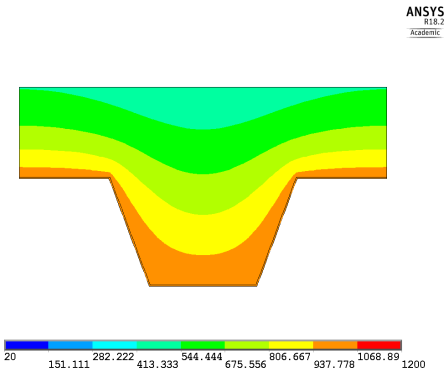


Tempo Crítico = 32 min



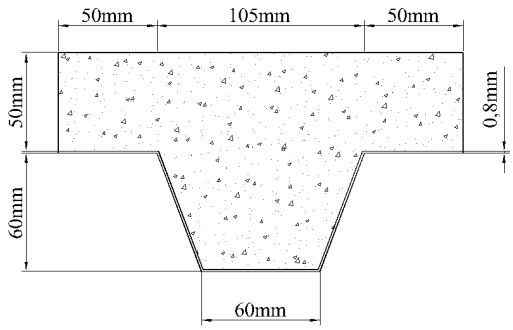
t = 7200s



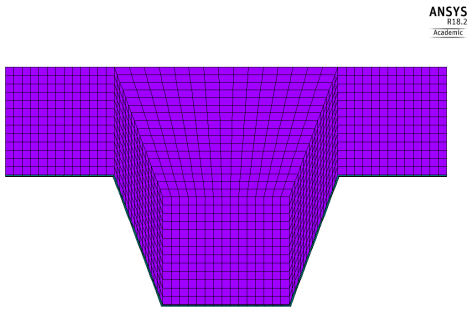


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.8mm

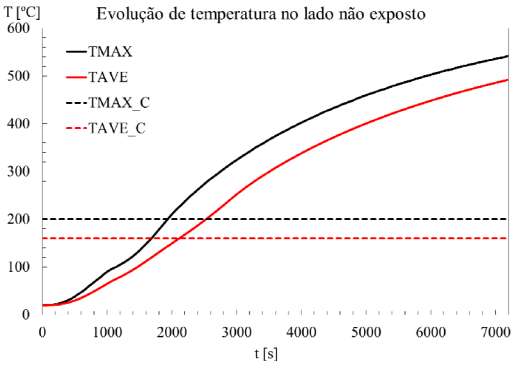
GEOMETRIA



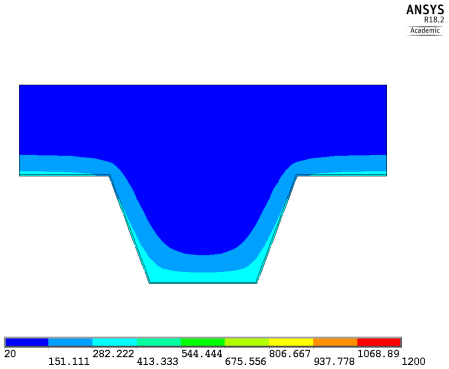
Malha



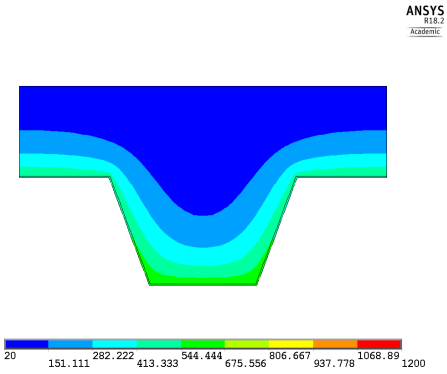
t = 8 min



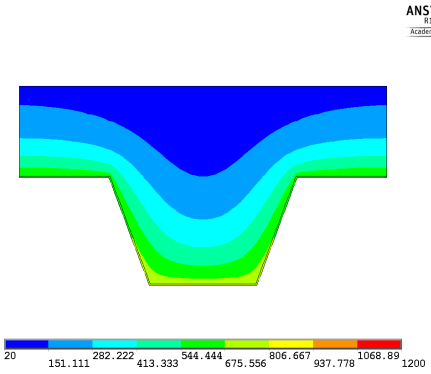
t = 16 min



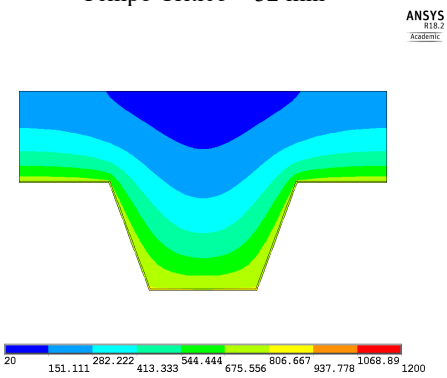
t = 24 min

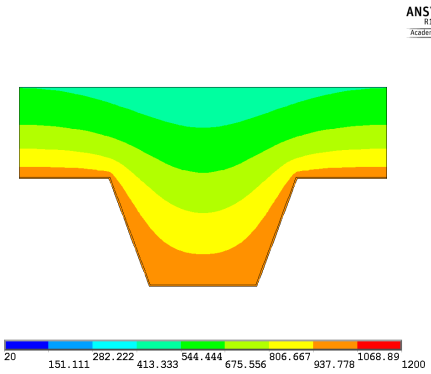


Tempo Crítico = 32 min



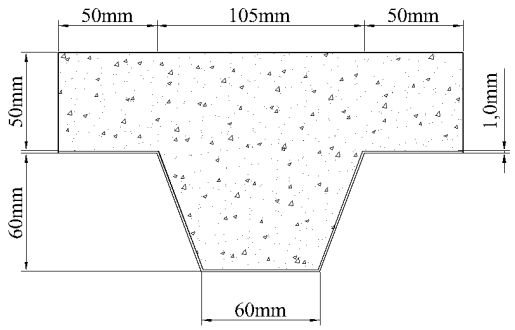
t = 7200s



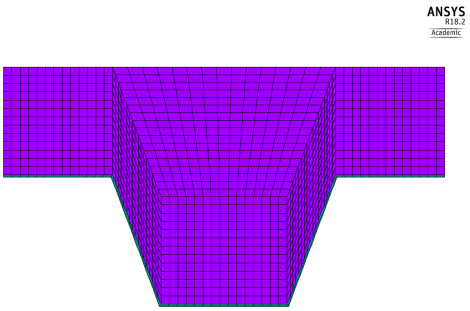


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.0mm

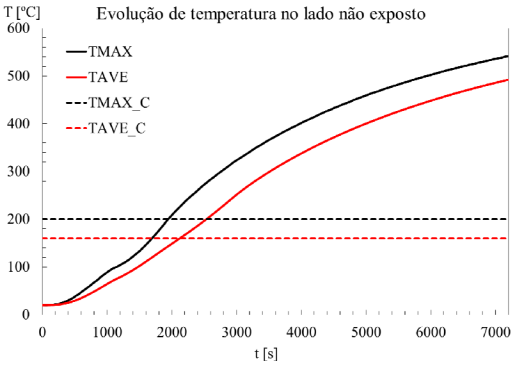
GEOMETRIA



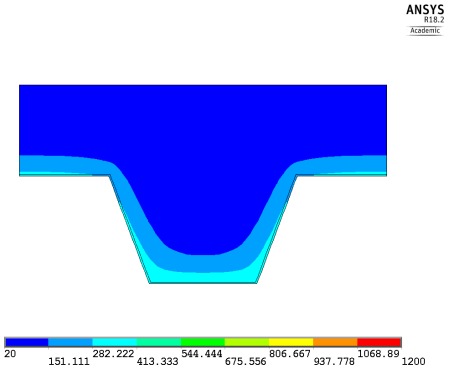
Malha



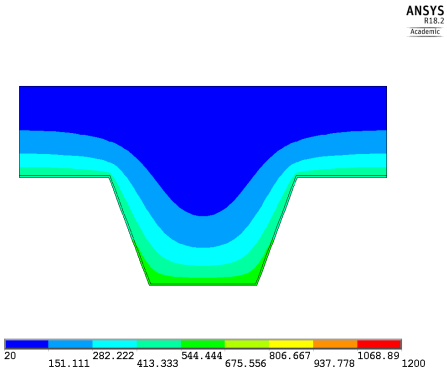
t = 8 min



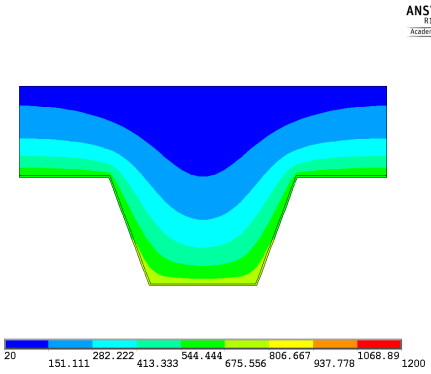
t = 16 min



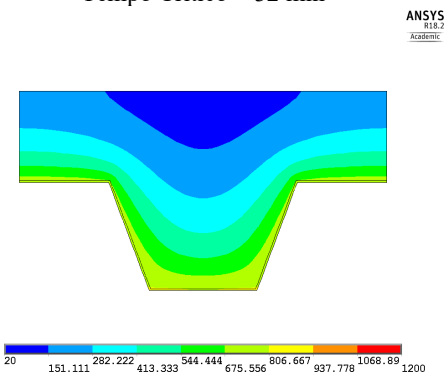
t = 24 min

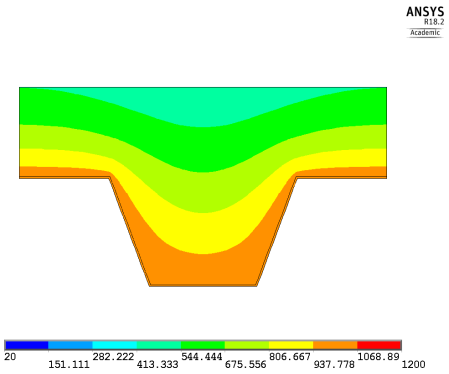


Tempo Crítico = 32 min



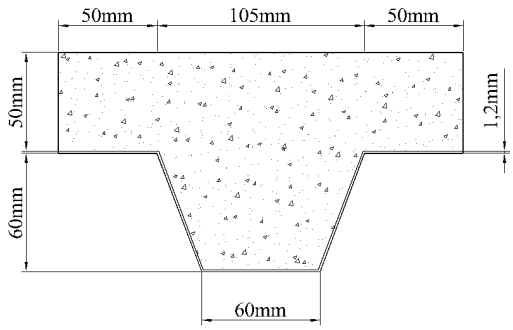
t = 7200s



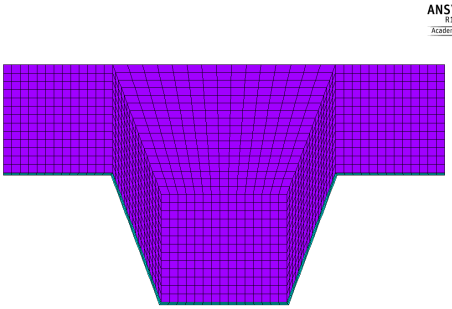


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.2mm

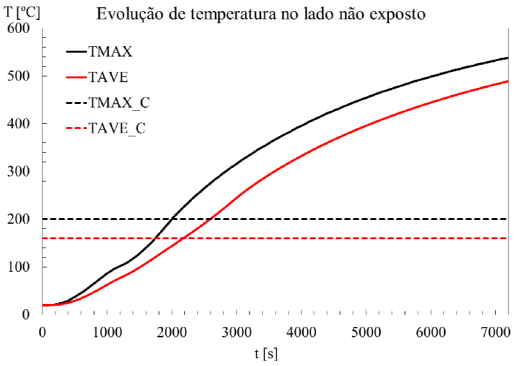
GEOMETRIA



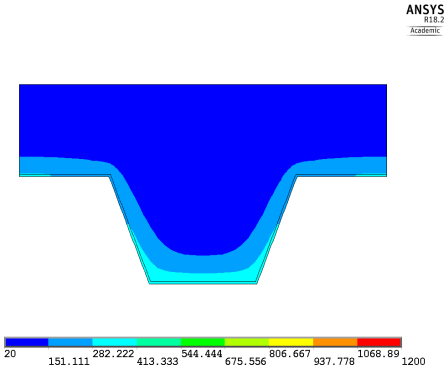
Malha



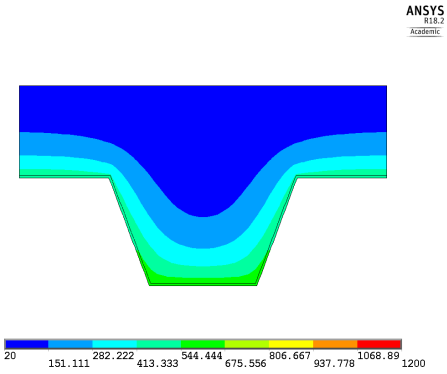
t = 8 min



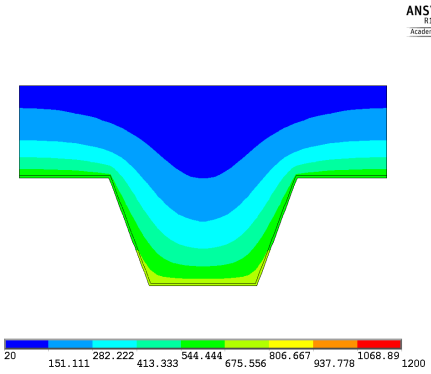
t = 16 min



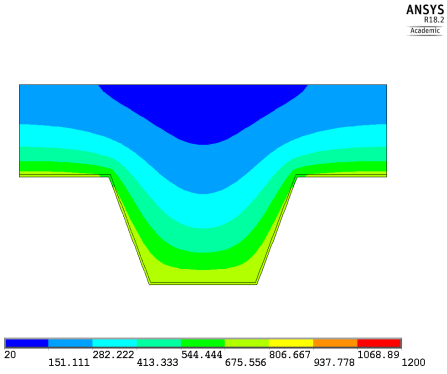
t = 24 min

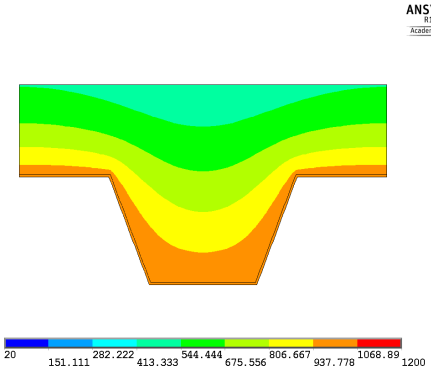


Tempo Crítico = 33 min



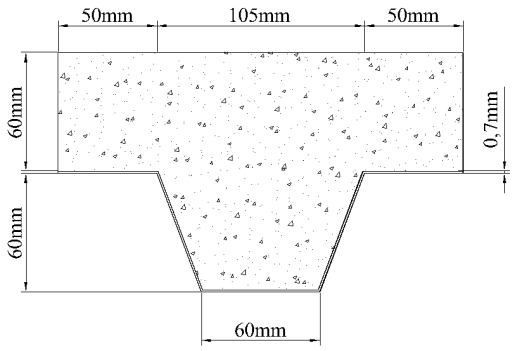
t = 7200s



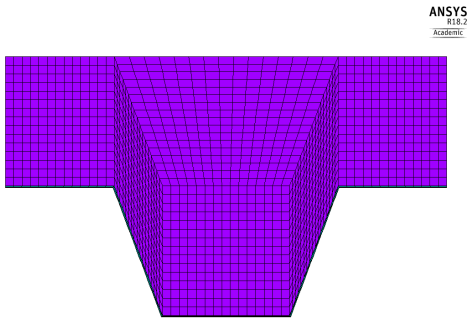


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.7mm

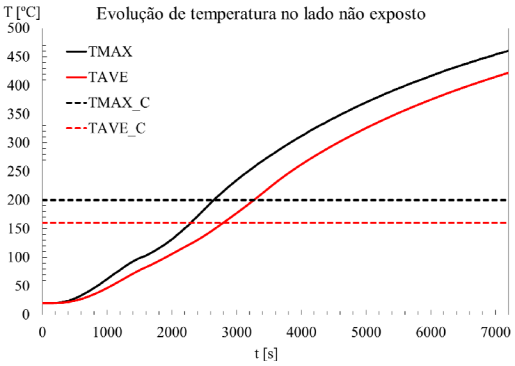
GEOMETRIA



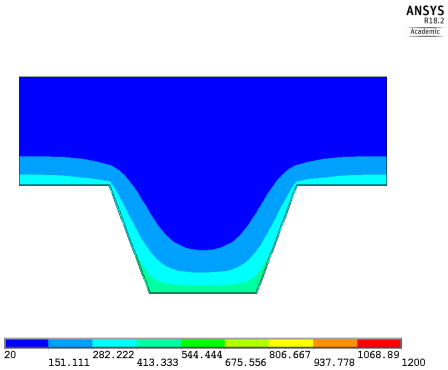
Malha



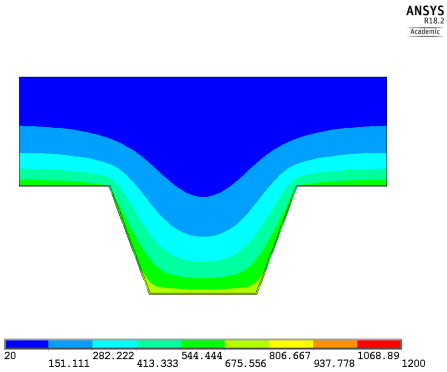
t = 11 min



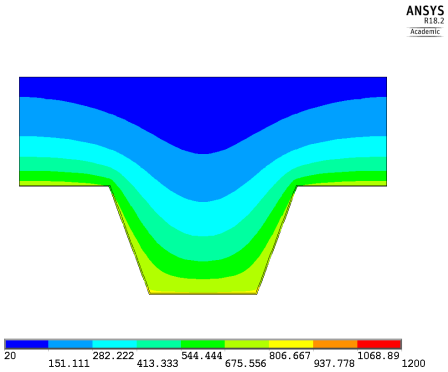
t = 22 min



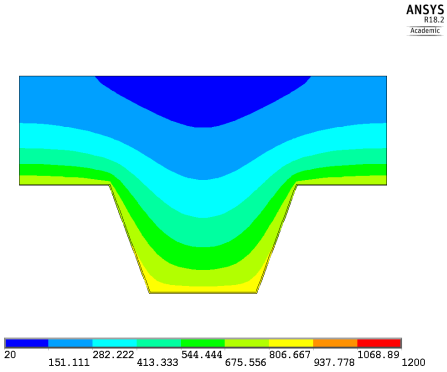
t = 33 min

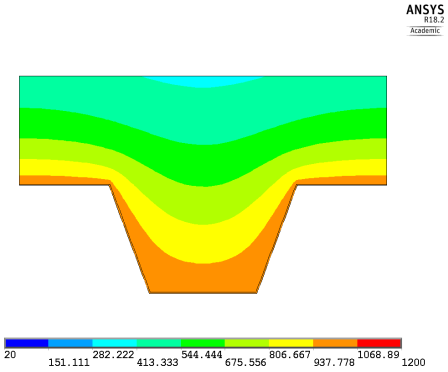


Tempo Crítico = 44 min



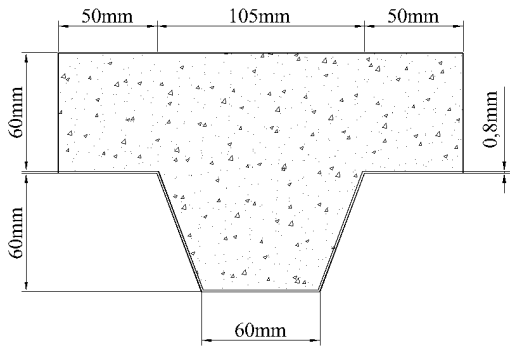
t = 7200s



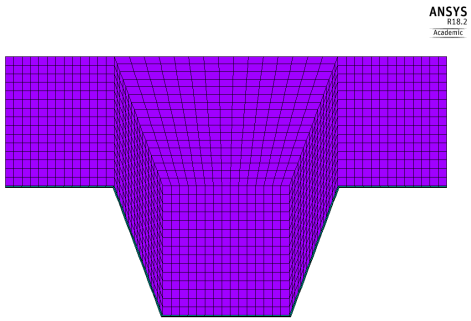


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.8mm

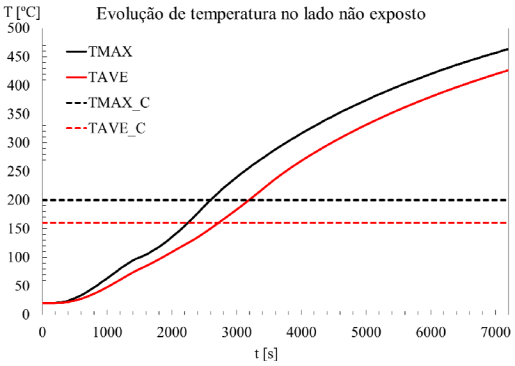
GEOMETRIA



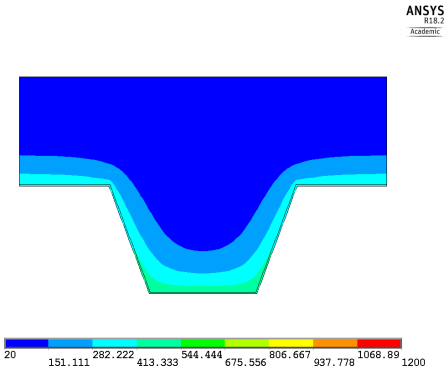
Malha



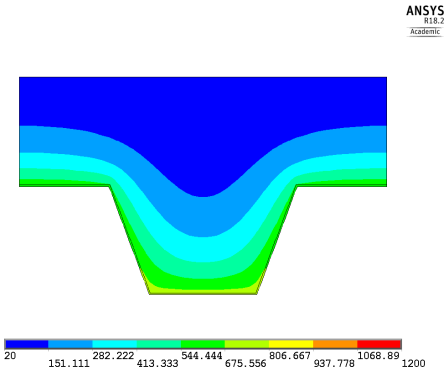
t = 10 min



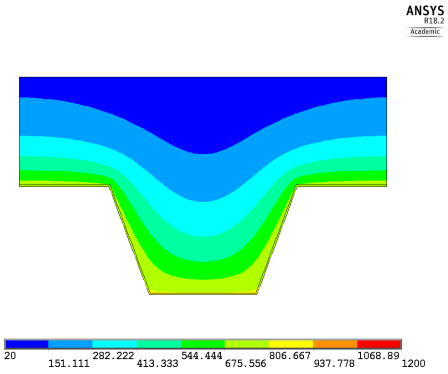
t = 21 min



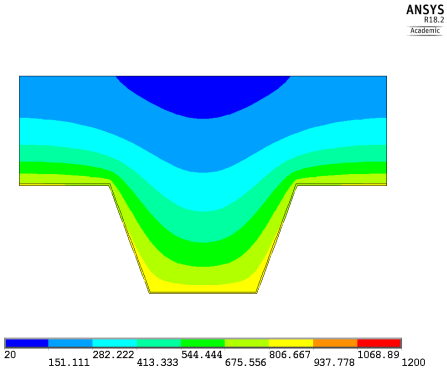
t = 32 min

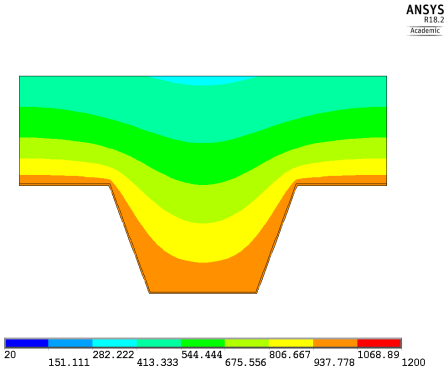


Tempo Crítico = 43 min



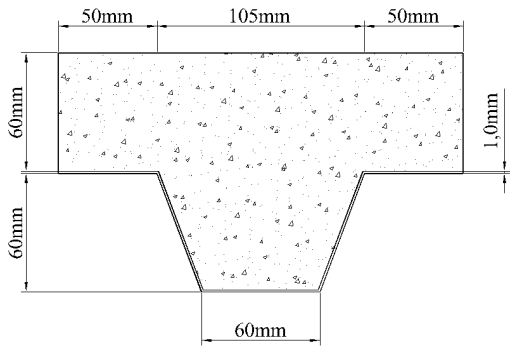
t = 7200s



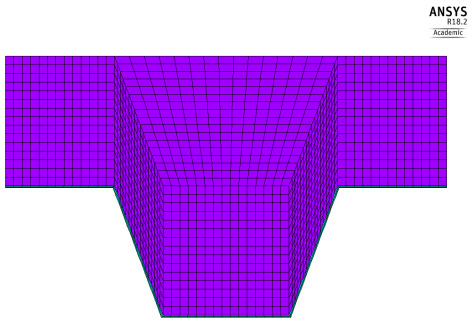


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.0mm

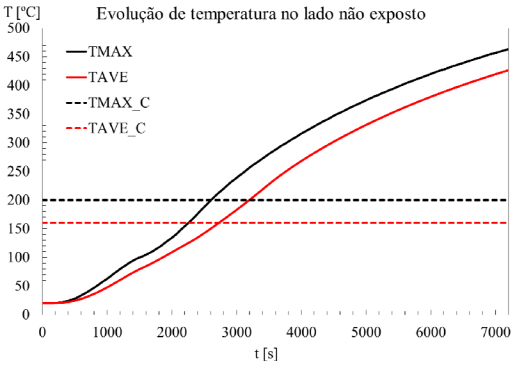
GEOMETRIA



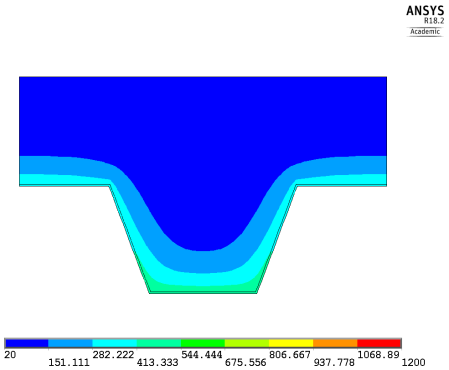
Malha



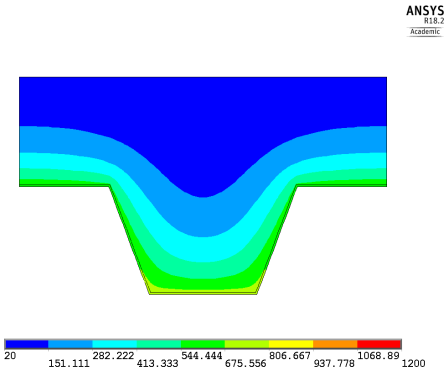
t = 10 min



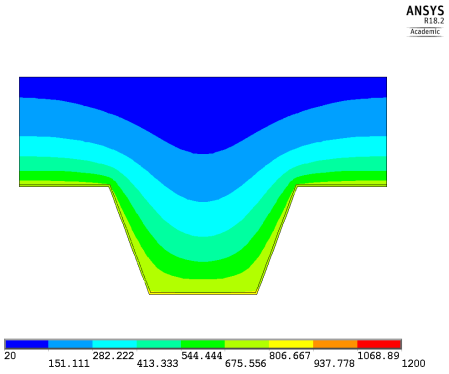
t = 21 min



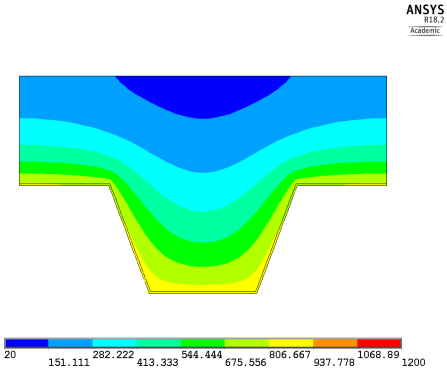
t = 32 min

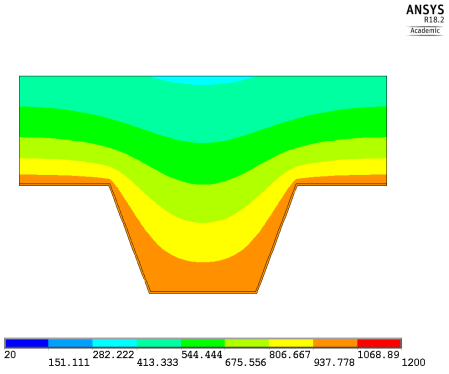


Tempo Crítico = 43 min



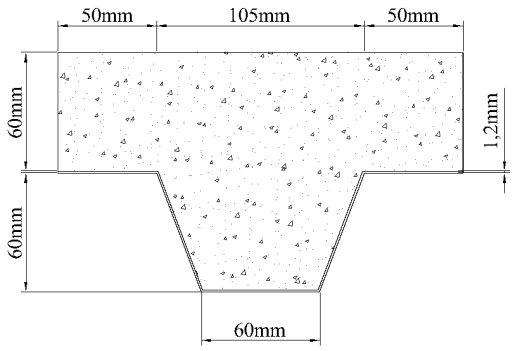
t = 7200s



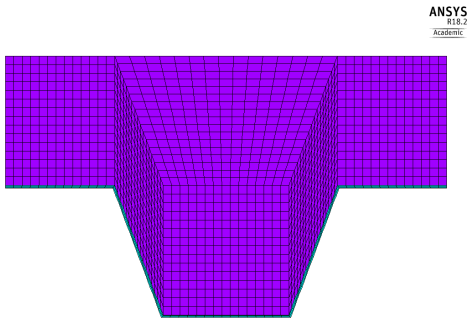


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.2mm

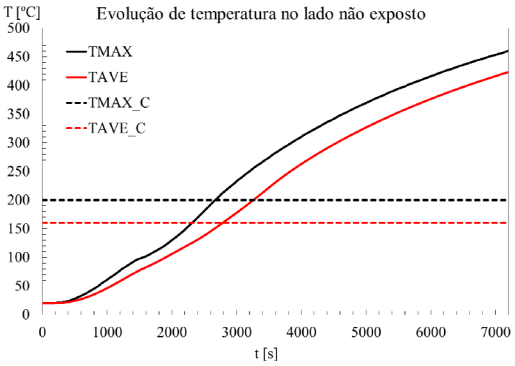
GEOMETRIA



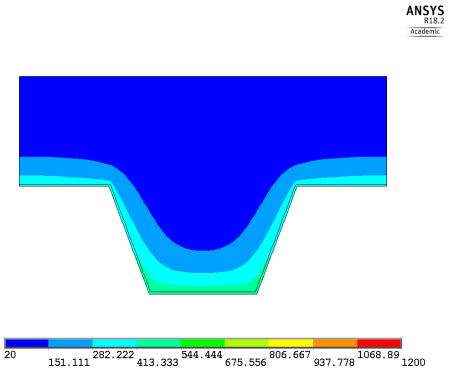
Malha



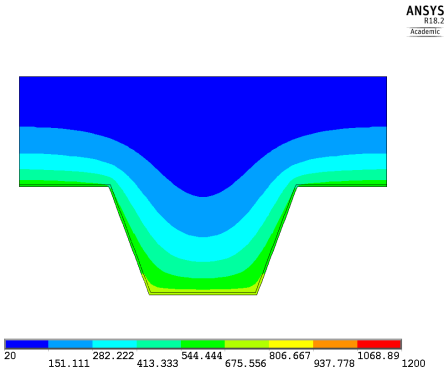
t = 11 min



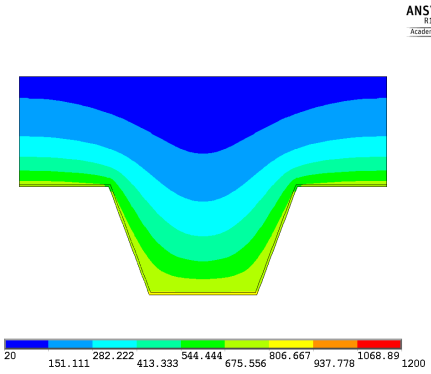
t = 22 min



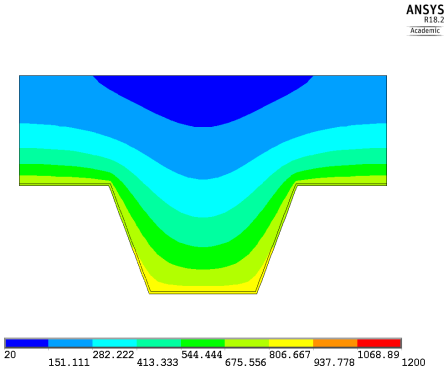
t = 33 min

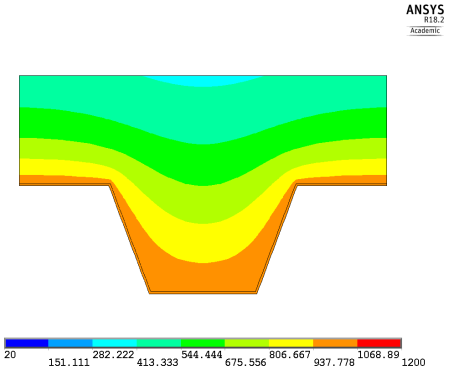


Tempo Crítico = 44 min



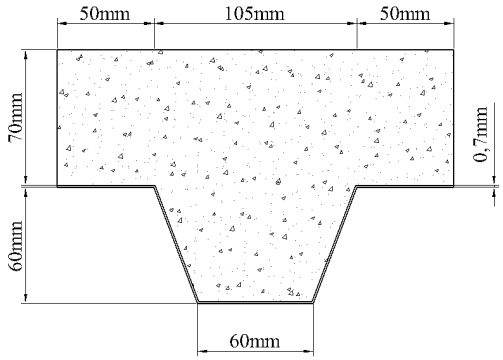
t = 7200s



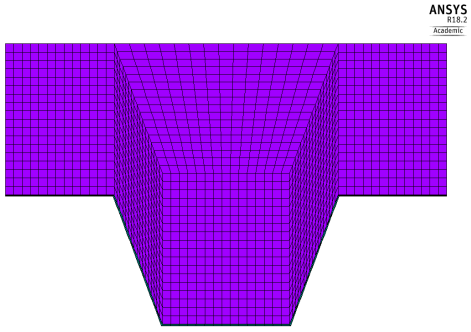


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.7mm

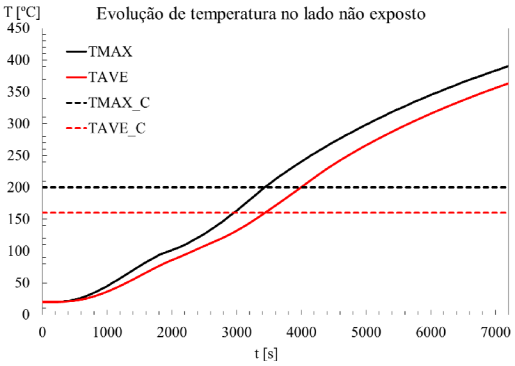
GEOMETRIA



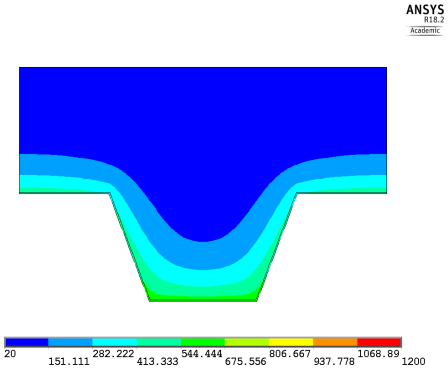
Malha



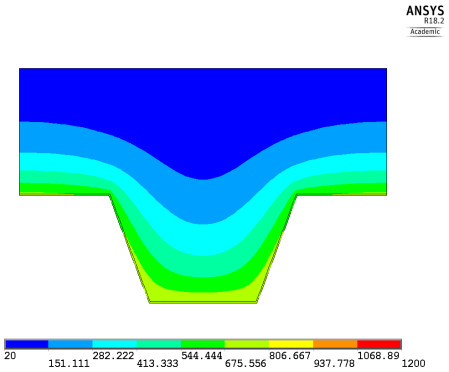
t = 14 min



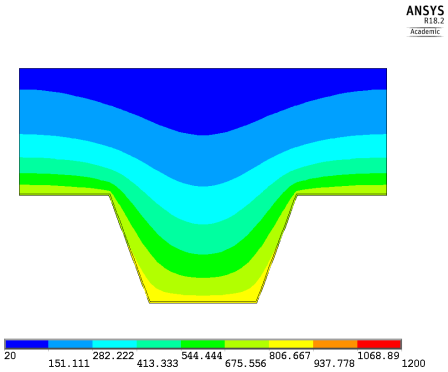
t = 28 min



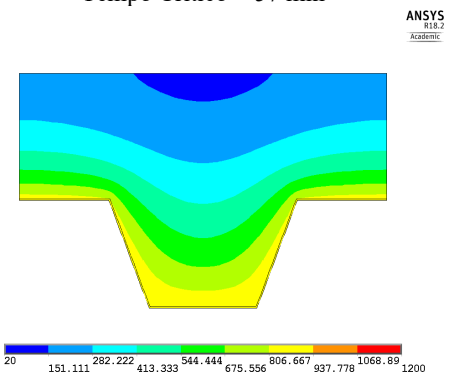
t = 42 min

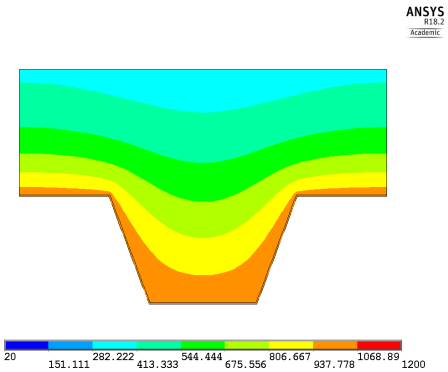


Tempo Crítico = 57 min



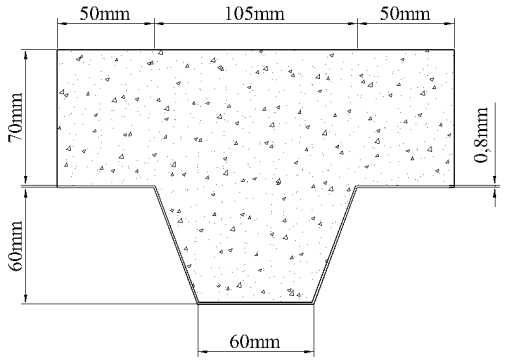
t = 7200s



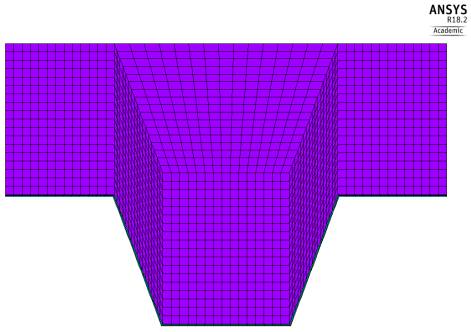


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.8mm

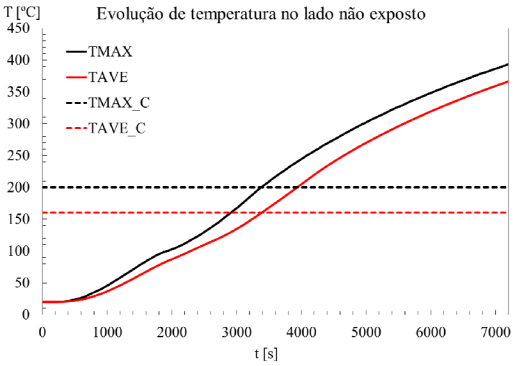
GEOMETRIA



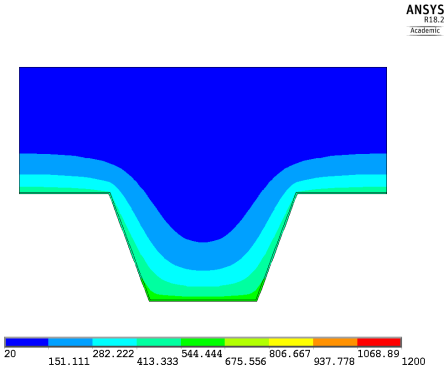
Malha



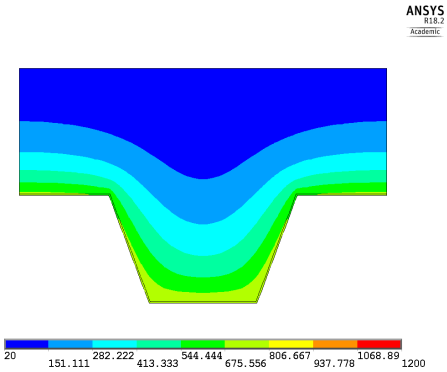
t = 14 min



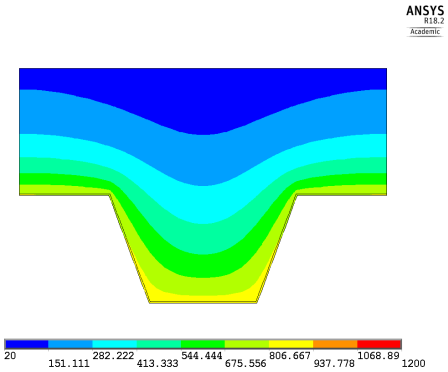
t = 29 min



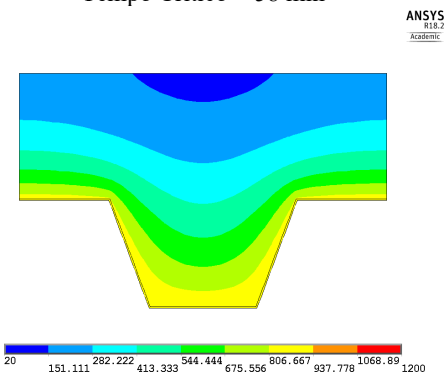
t = 43 min

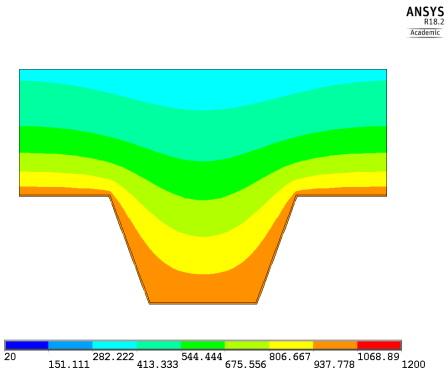


Tempo Crítico = 58 min



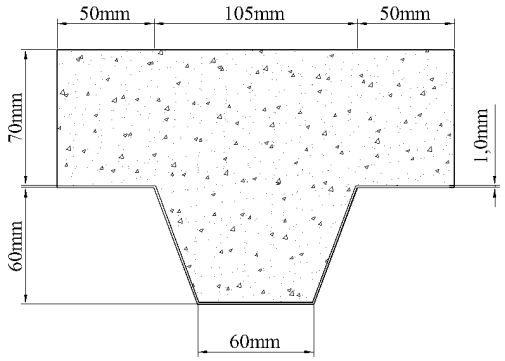
t = 7200s



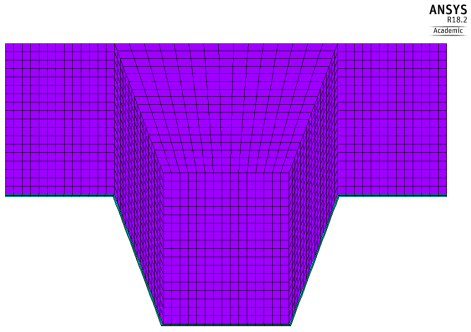


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.0mm

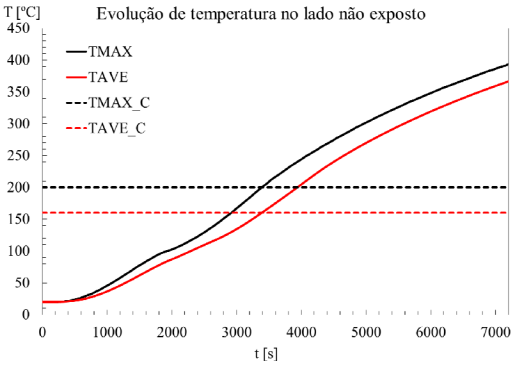
GEOMETRIA



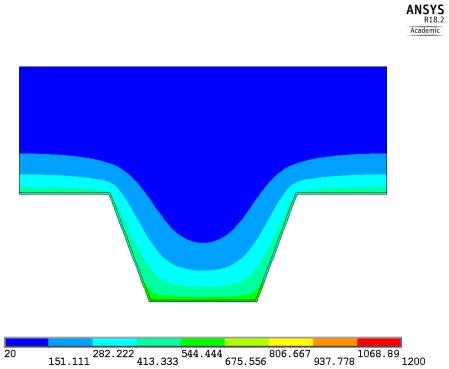
Malha



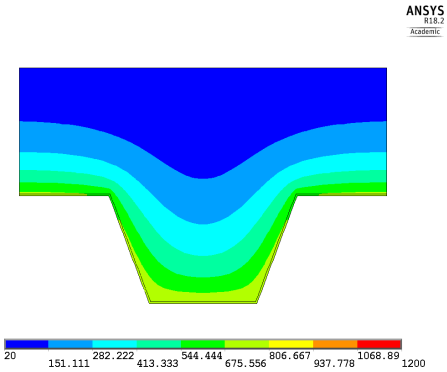
t = 14 min



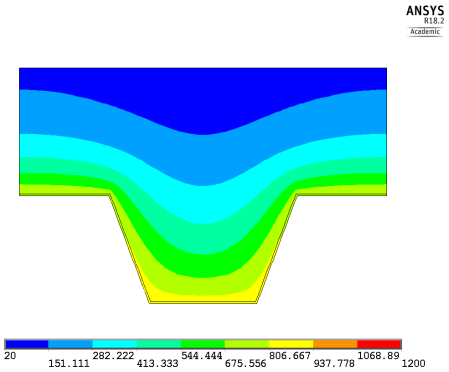
t = 29 min



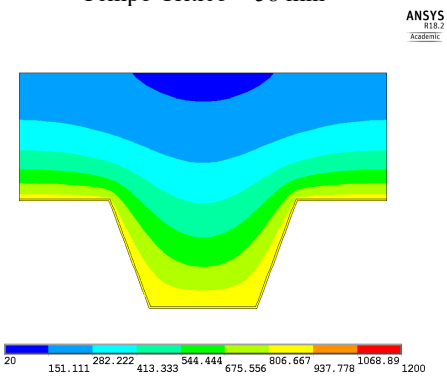
t = 43 min

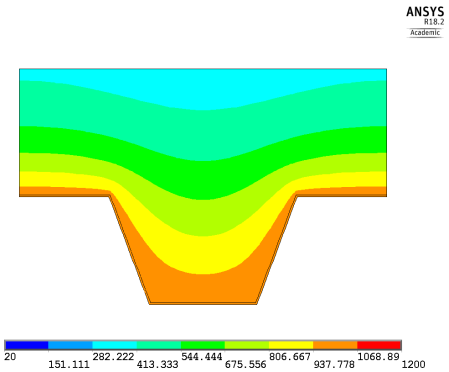


Tempo Crítico = 58 min



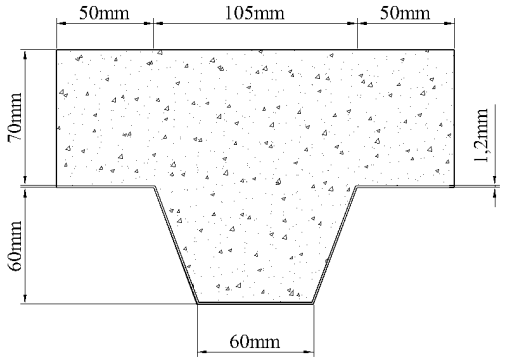
t = 7200s



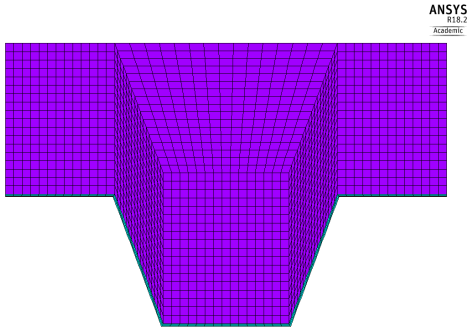


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.2mm

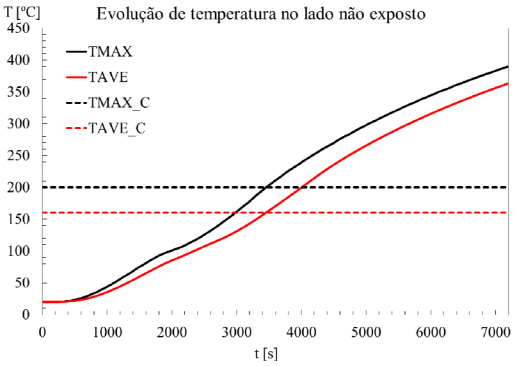
GEOMETRIA



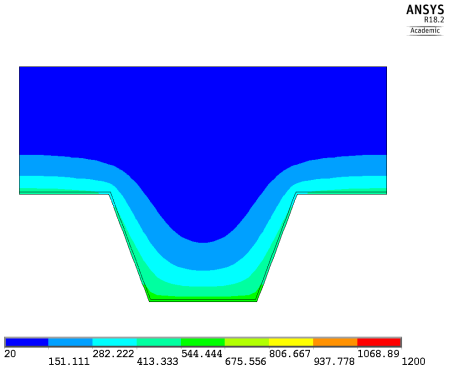
Malha



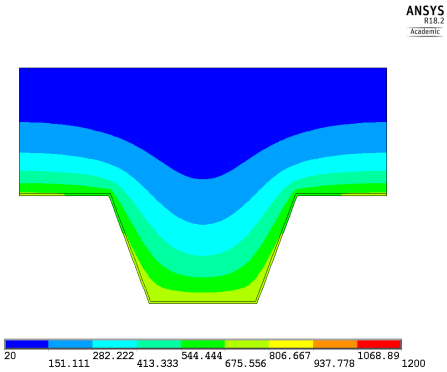
t = 14 min



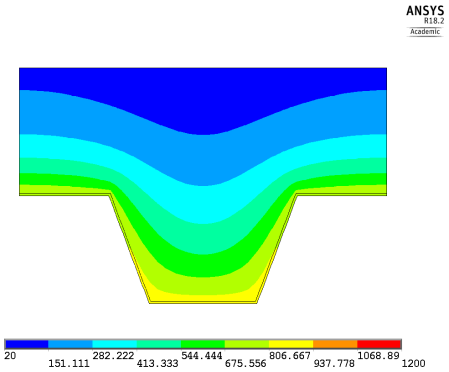
t = 28 min



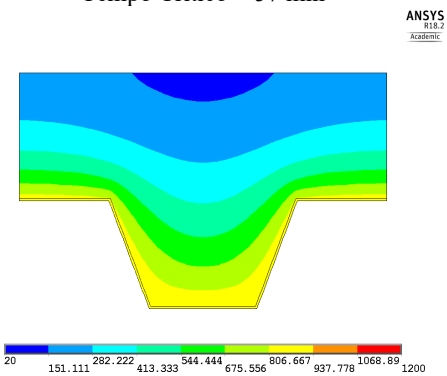
t = 42 min

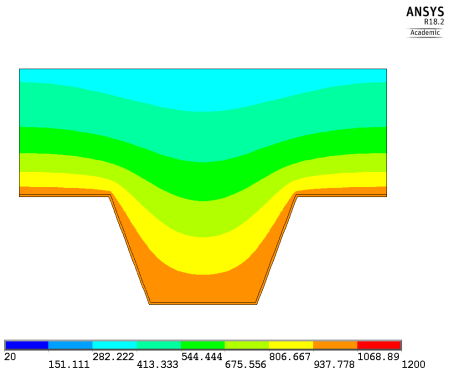


Tempo Crítico = 57 min



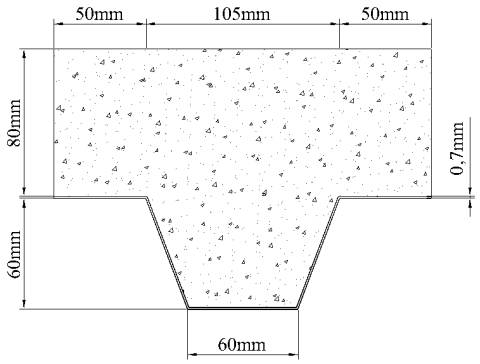
t = 7200s



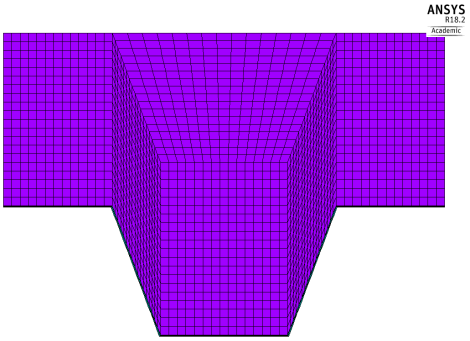


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.7mm

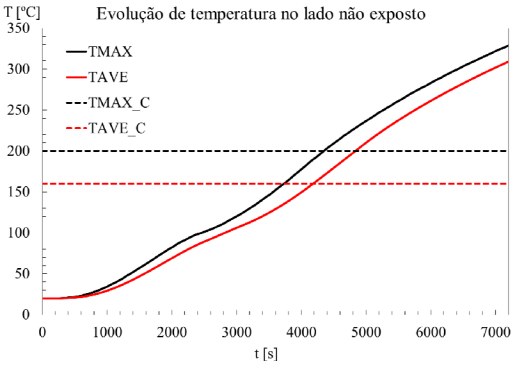
GEOMETRIA



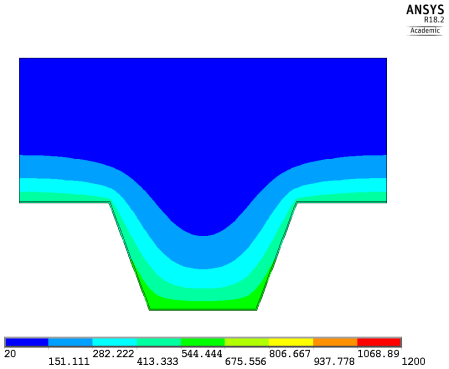
Malha



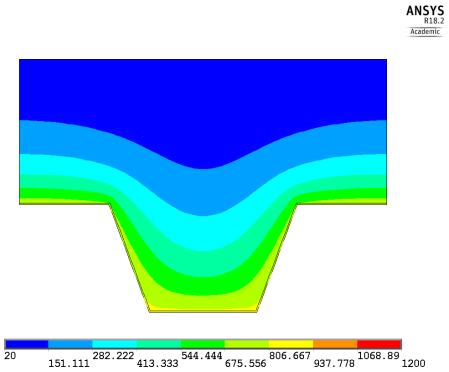
t = 17 min



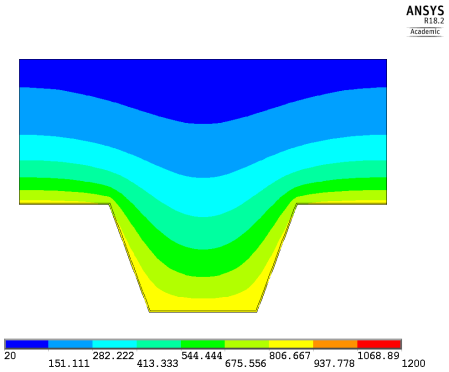
t = 34 min



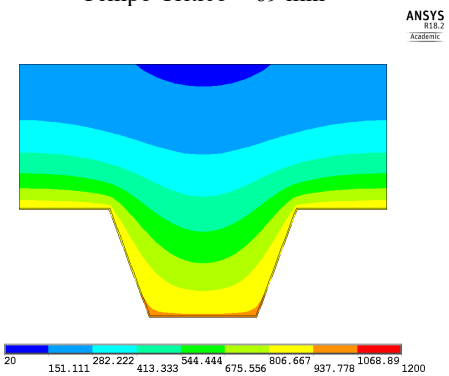
t = 51 min

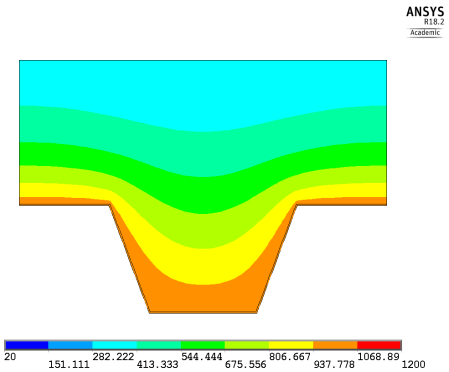


Tempo Crítico = 69 min



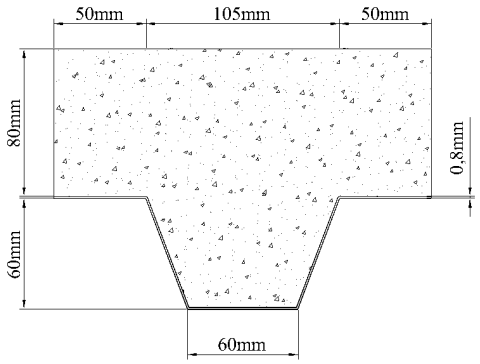
t = 7200s



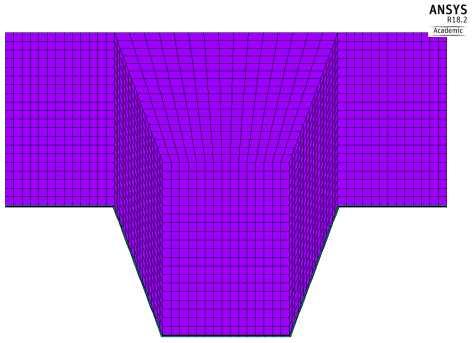


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.8mm

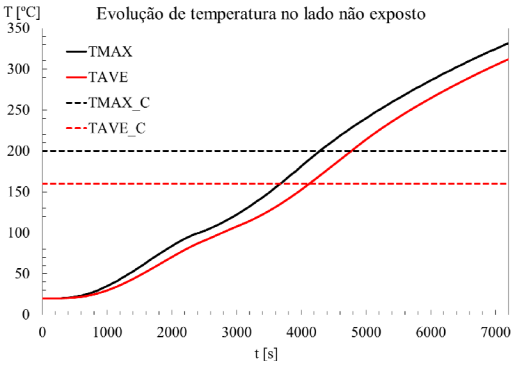
GEOMETRIA



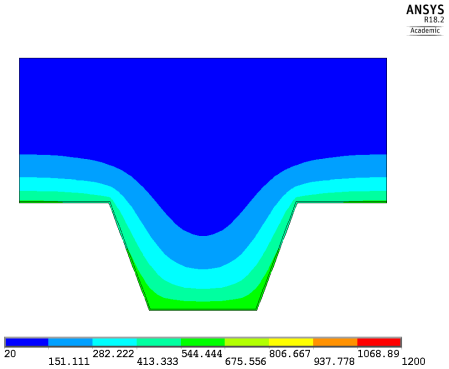
Malha



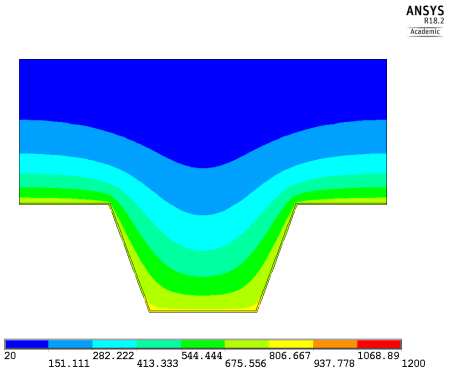
t = 17 min



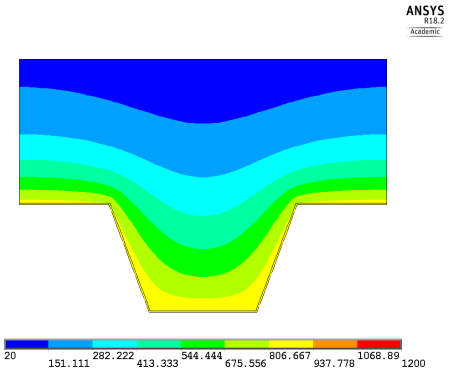
t = 34 min



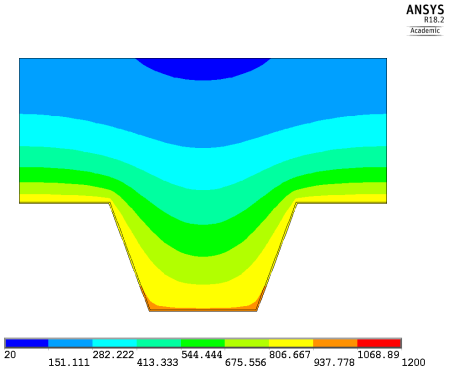
t = 51 min

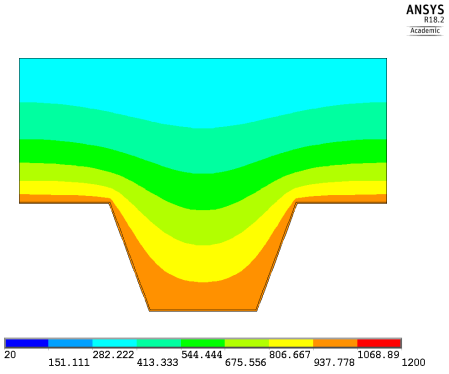


Tempo Crítico = 68 min



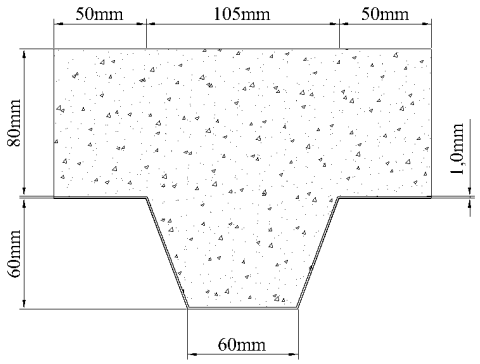
t = 7200s



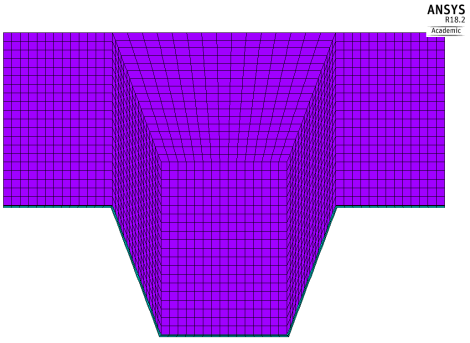


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.0mm

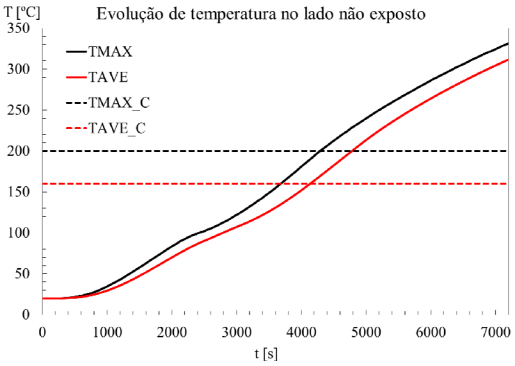
GEOMETRIA



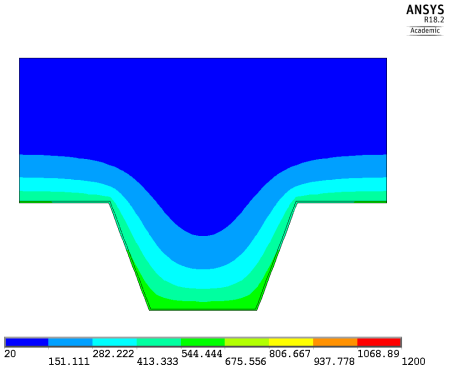
Malha



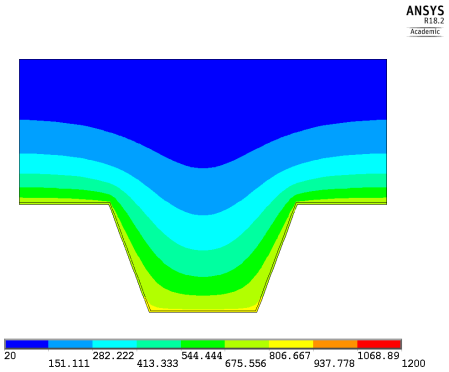
t = 17 min



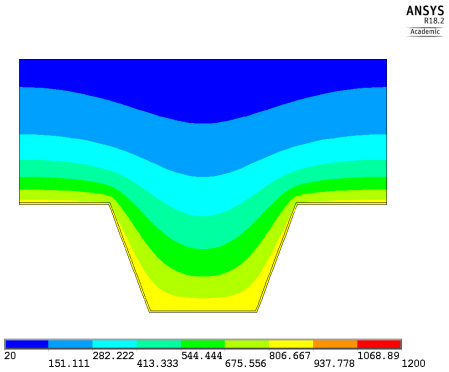
t = 34 min



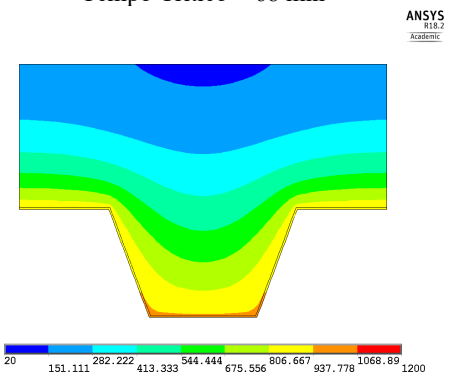
t = 51 min

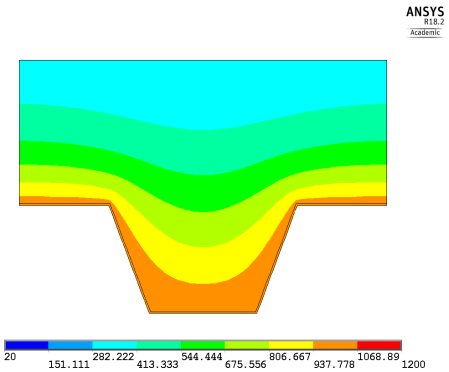


Tempo Crítico = 68 min



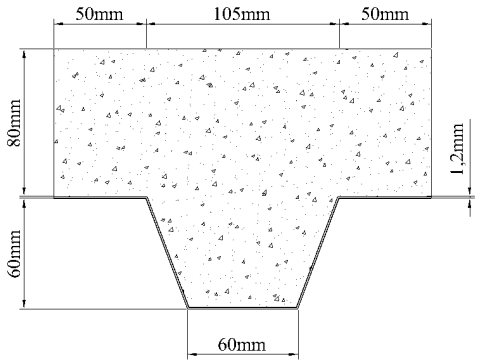
t = 7200s



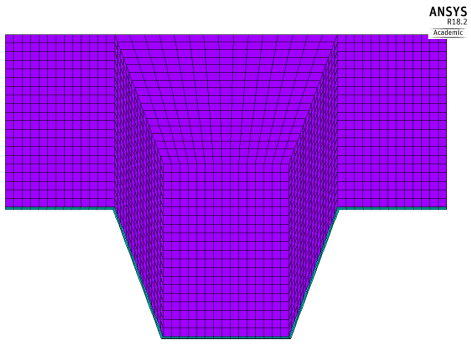


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.2mm

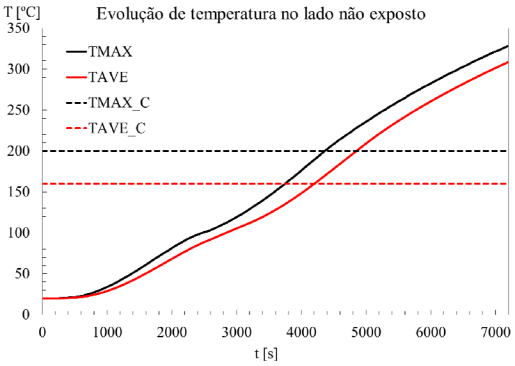
GEOMETRIA



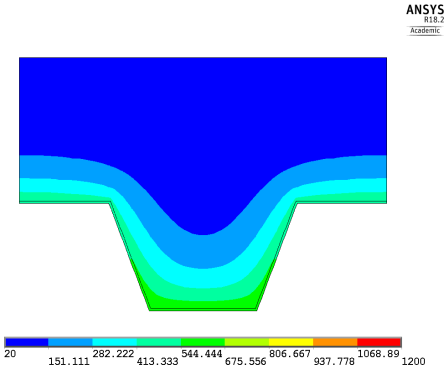
Malha



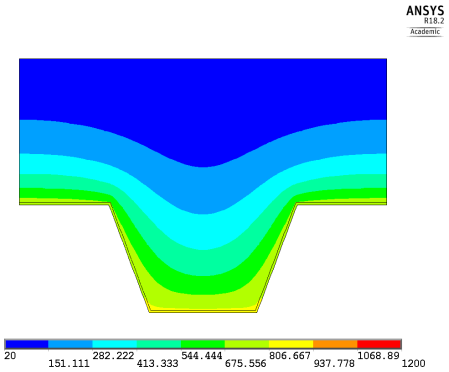
t = 17 min



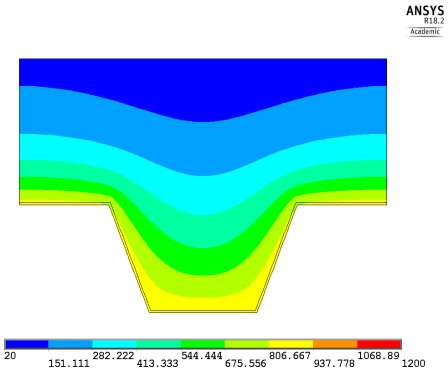
t = 35 min



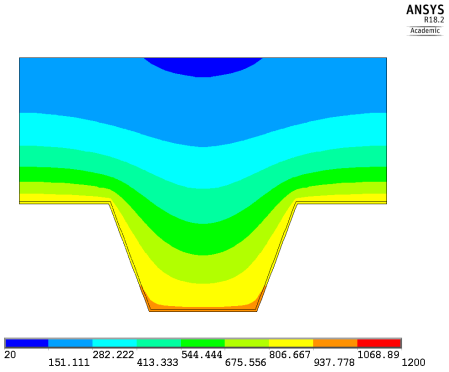
t = 52 min

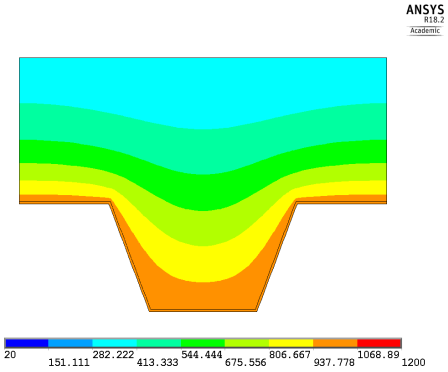


Tempo Crítico = 70 min



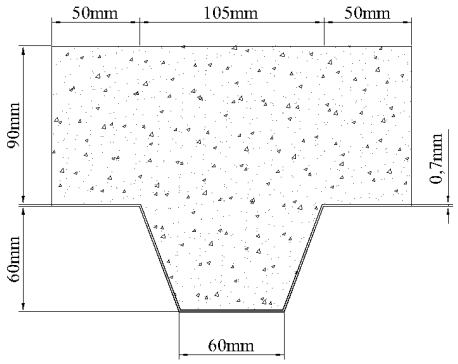
t = 7200s



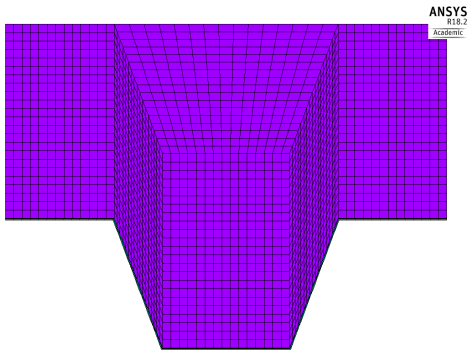


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.7mm

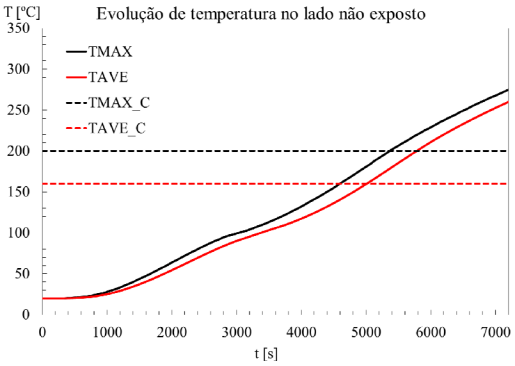
GEOMETRIA



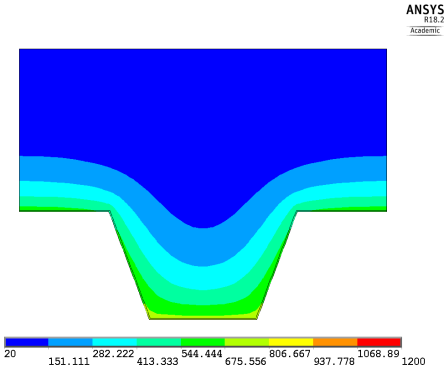
Malha



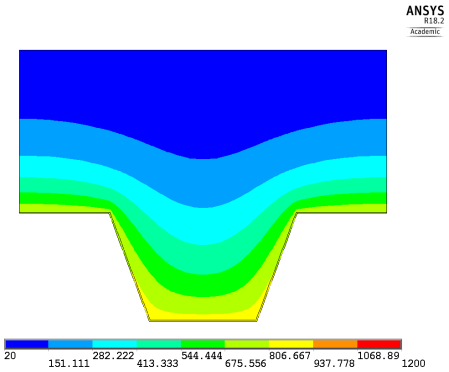
t = 20 min



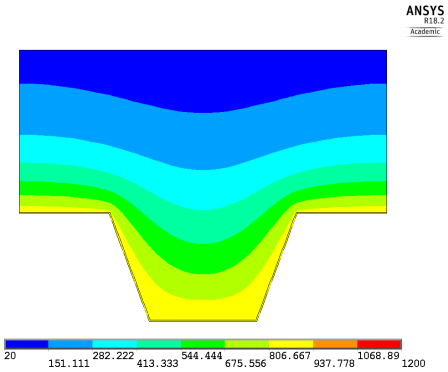
t = 41 min



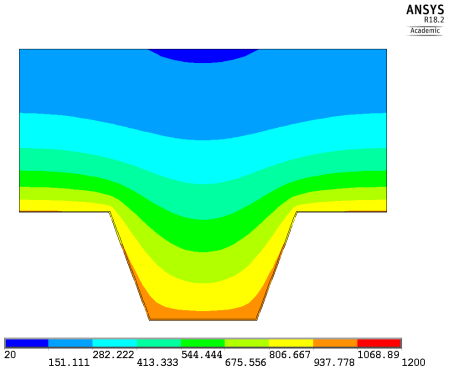
t = 62 min

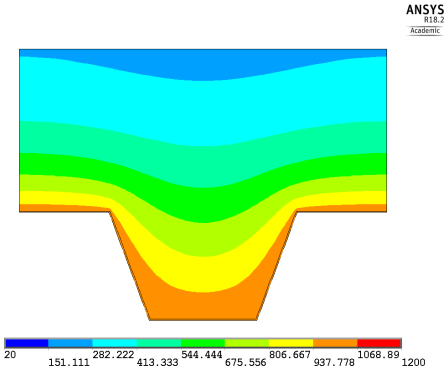


Tempo Crítico = 83 min



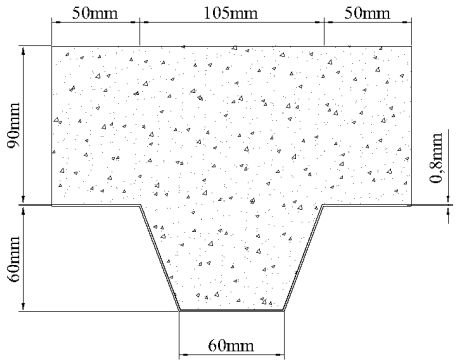
t = 7200s



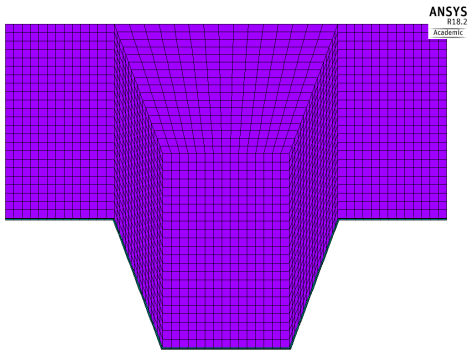


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.8mm

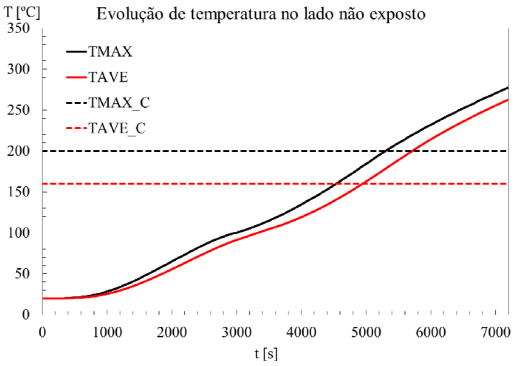
GEOMETRIA



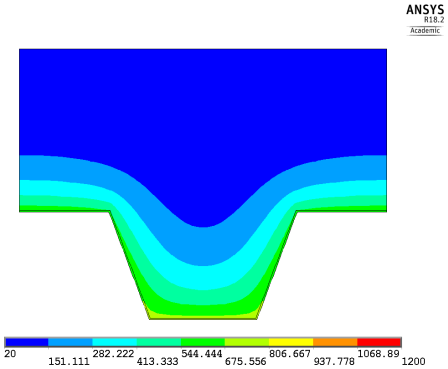
Malha



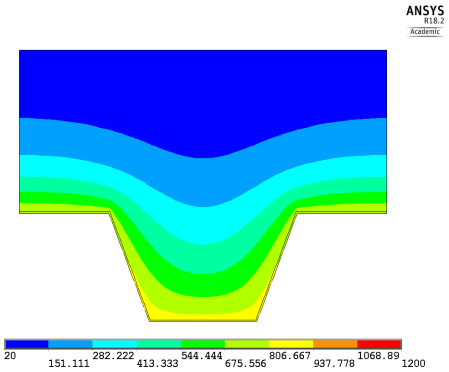
t = 20 min



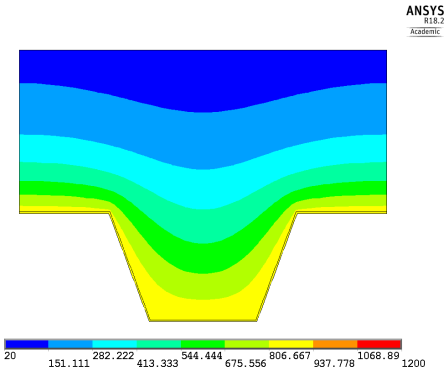
t = 41 min



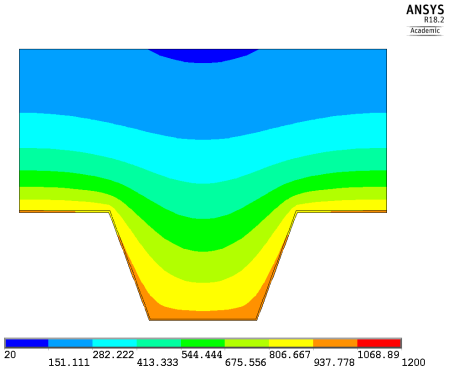
t = 61 min

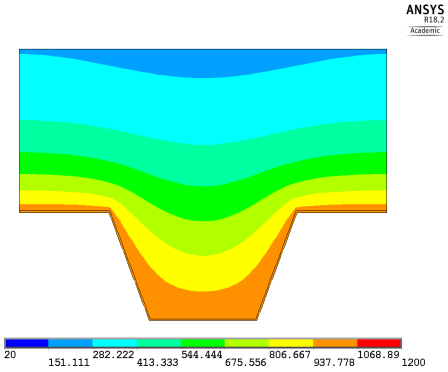


Tempo Crítico = 82 min



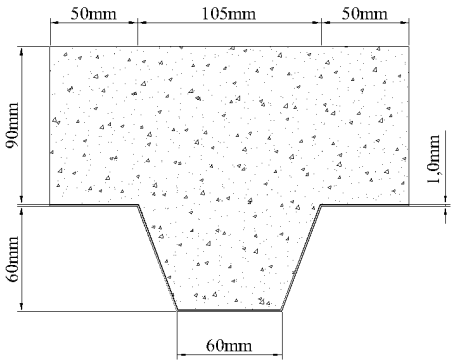
t = 7200s



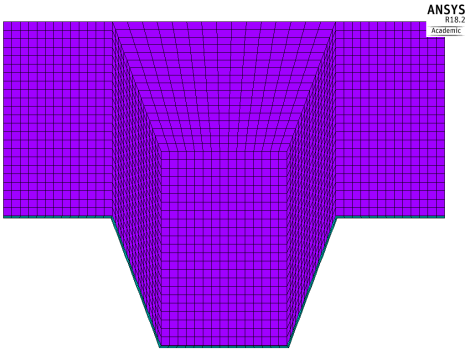


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.0mm

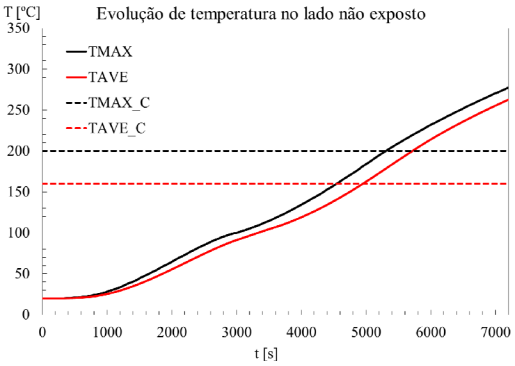
GEOMETRIA



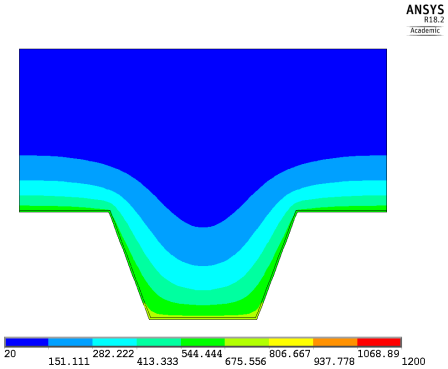
Malha



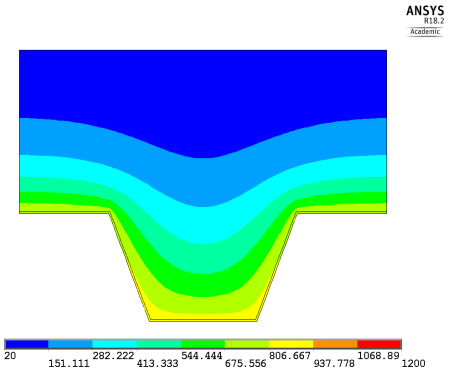
t = 20 min



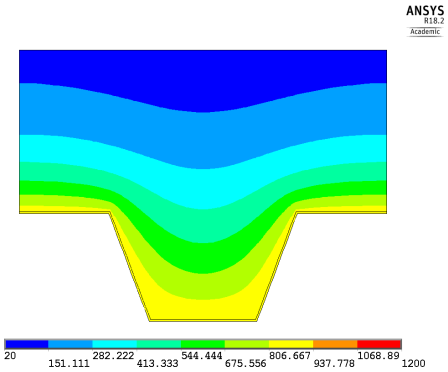
t = 41 min



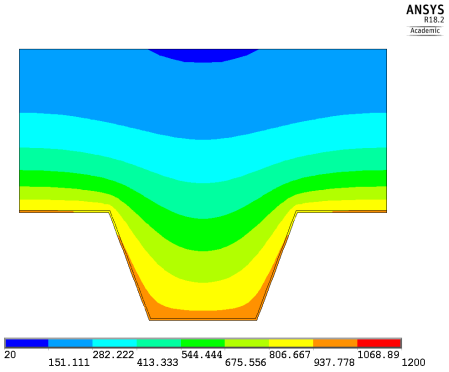
t = 61 min

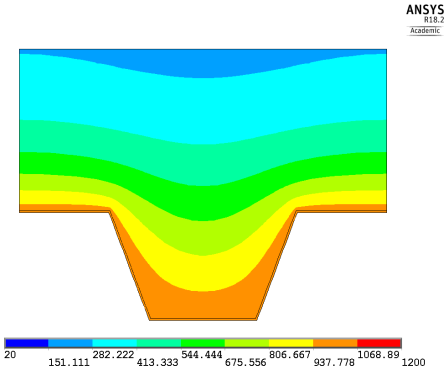


Tempo Crítico = 82 min



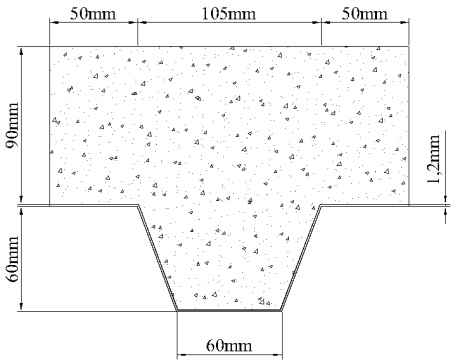
t = 7200s



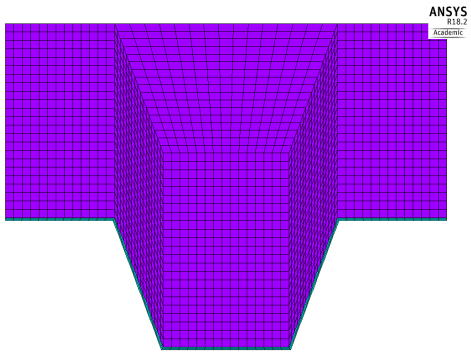


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.2mm

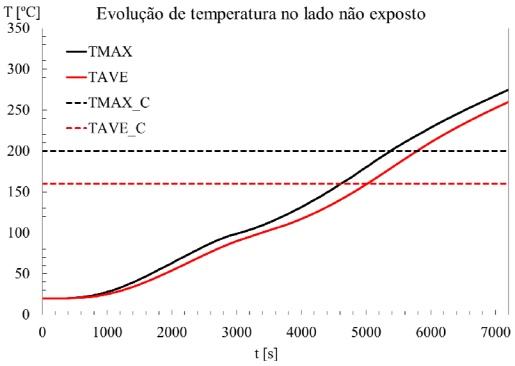
GEOMETRIA



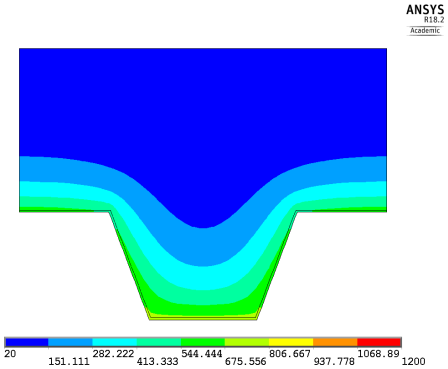
Malha



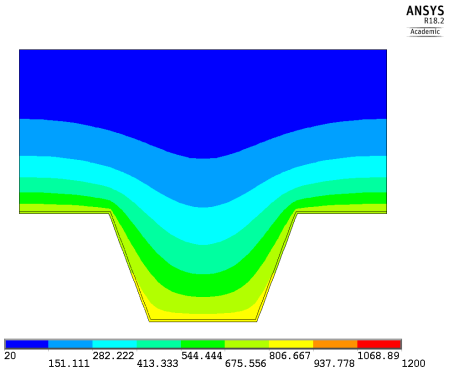
t = 20 min



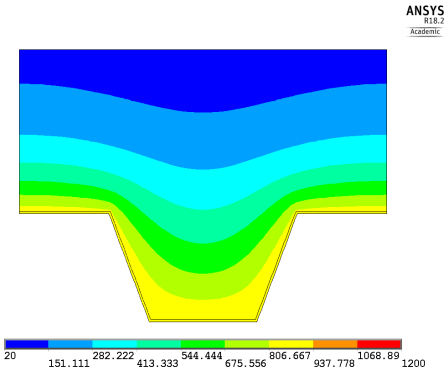
t = 41 min



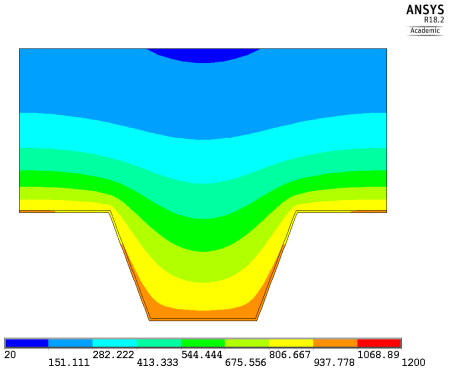
t = 62 min

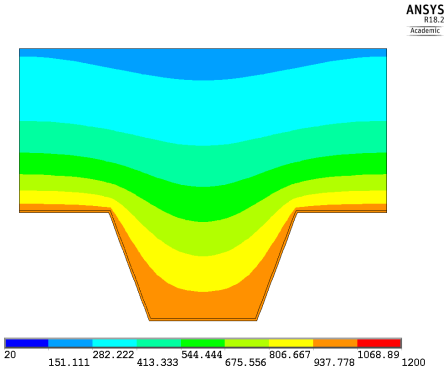


Tempo Crítico = 83 min



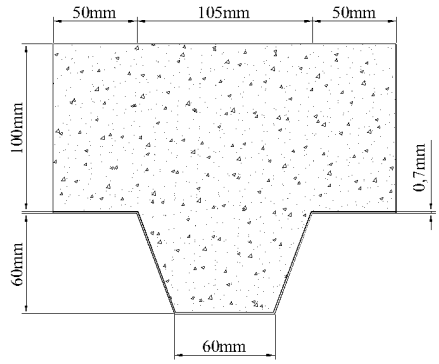
t = 7200s



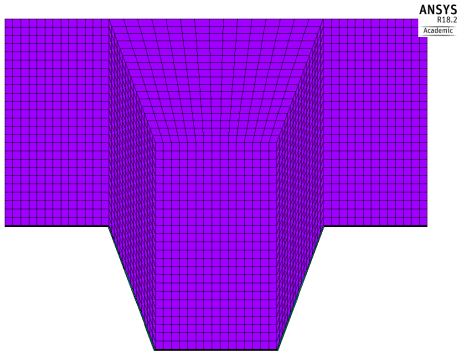


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.7mm

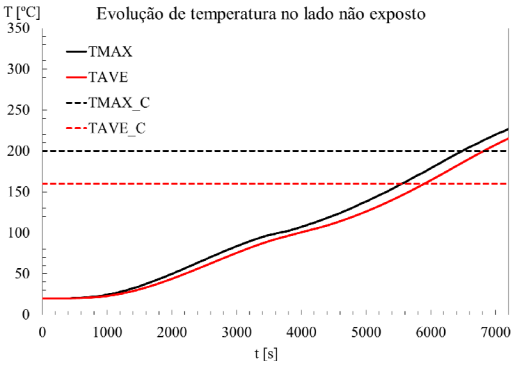
GEOMETRIA



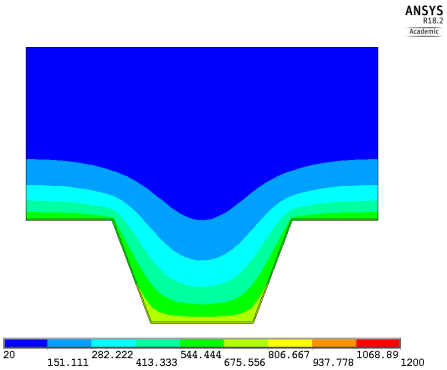
Malha



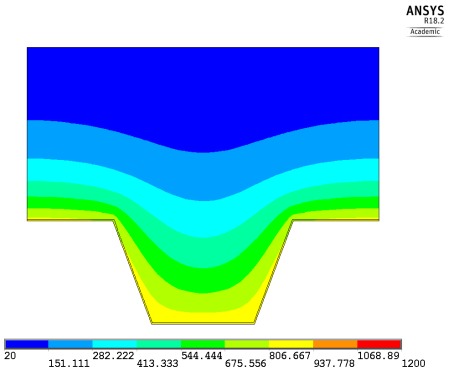
t = 24 min



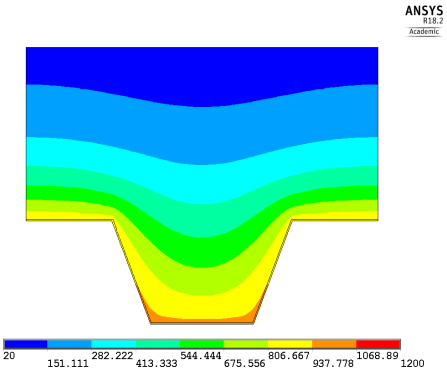
t = 49 min



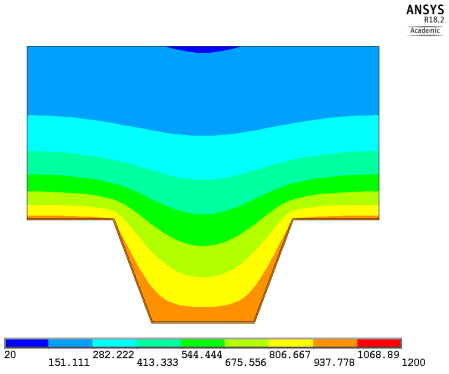
t = 73 min

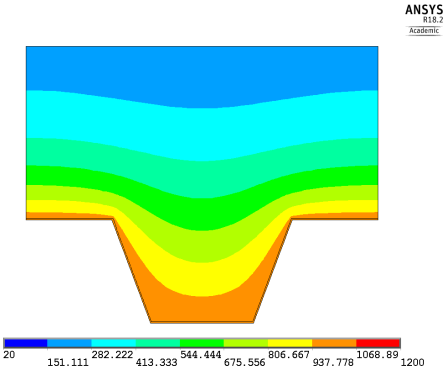


Tempo Crítico = 98 min



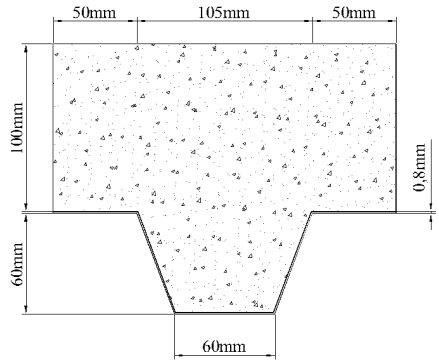
t = 7200s



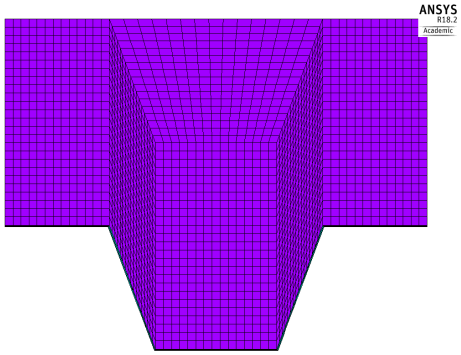


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.8mm

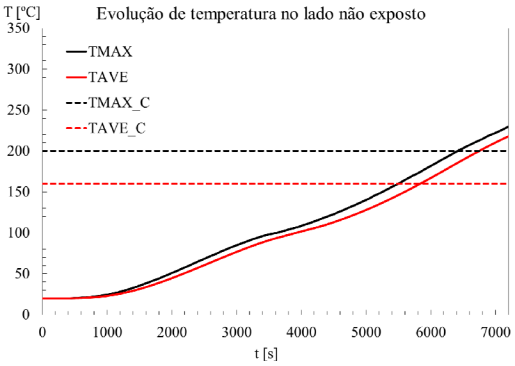
GEOMETRIA



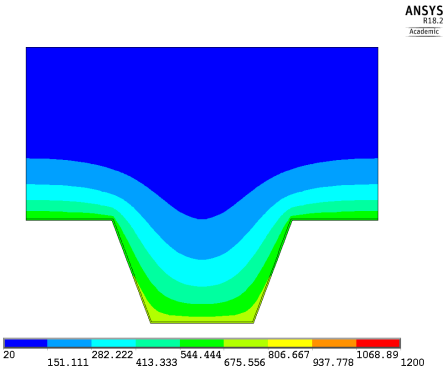
Malha



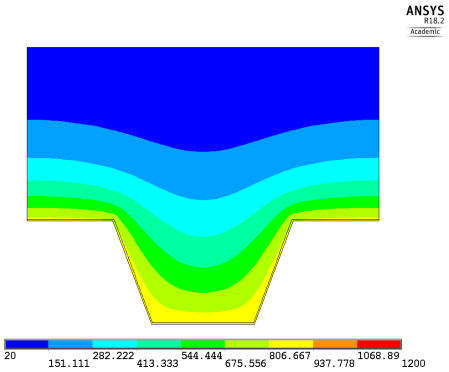
t = 24 min



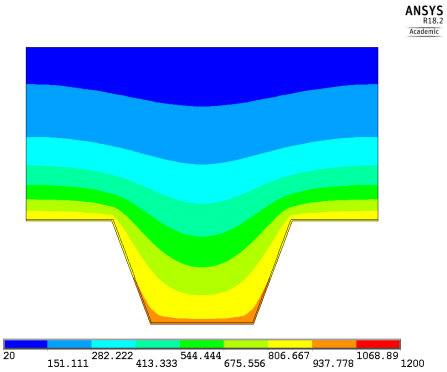
t = 48 min



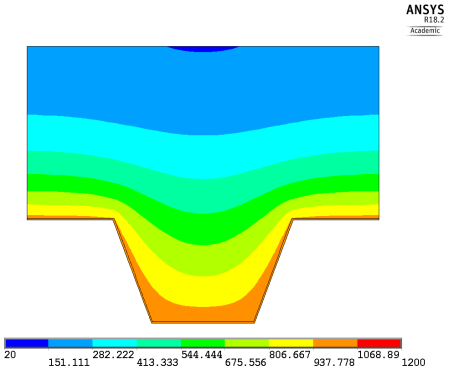
t = 72 min

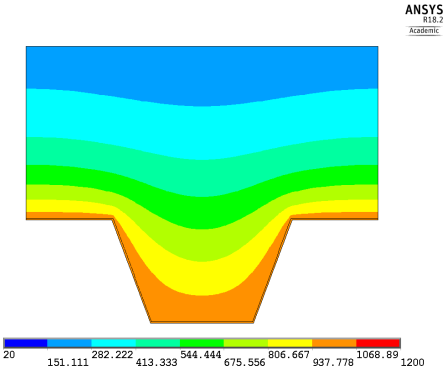


Tempo Crítico = 97 min



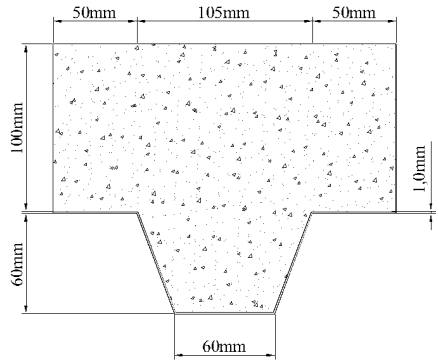
t = 7200s



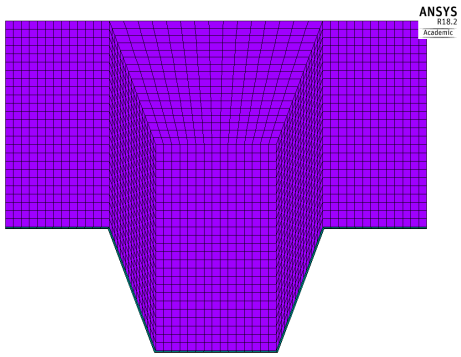


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.0mm

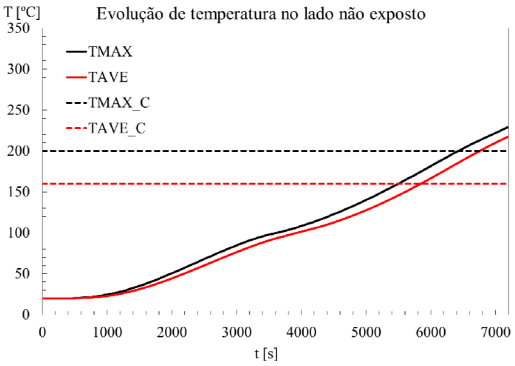
GEOMETRIA



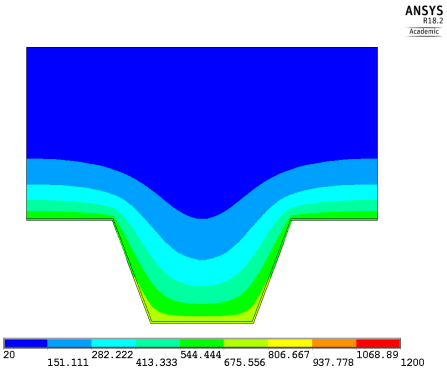
Malha



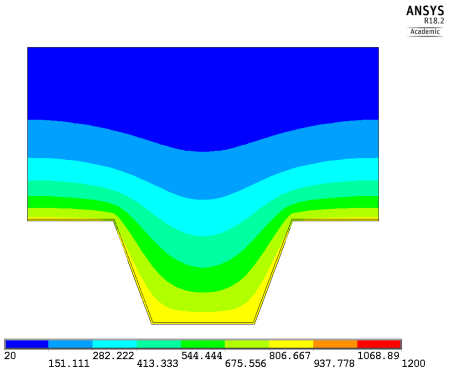
t = 24 min



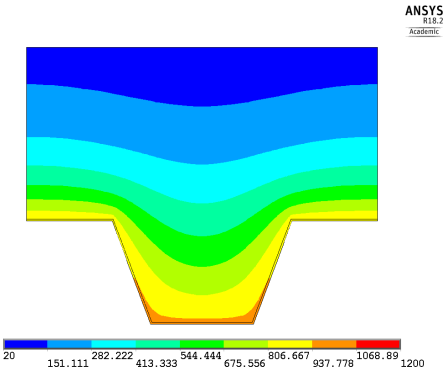
t = 48 min



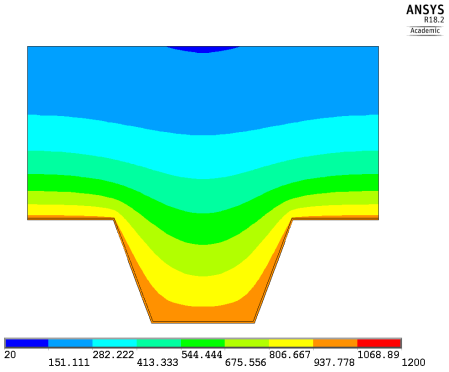
t = 72 min

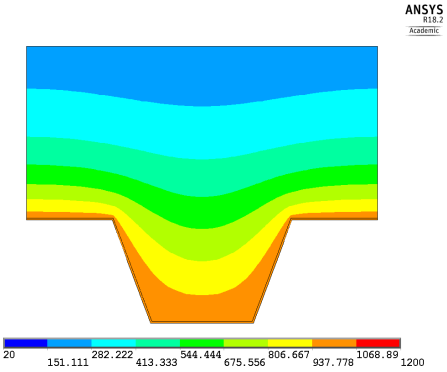


Tempo Crítico = 97 min



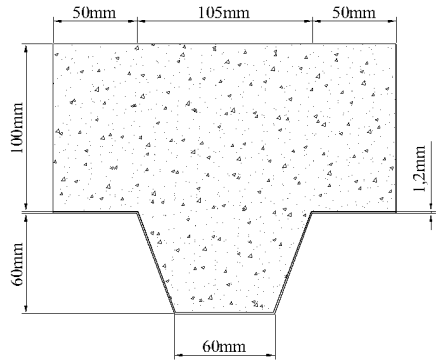
t = 7200s



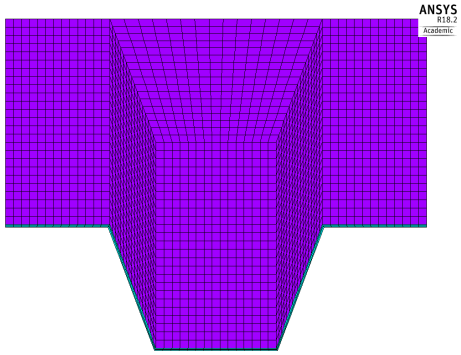


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.2mm

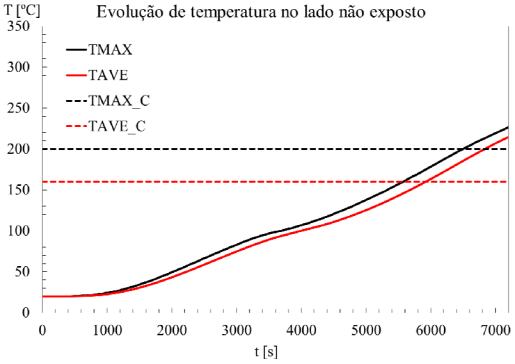
GEOMETRIA



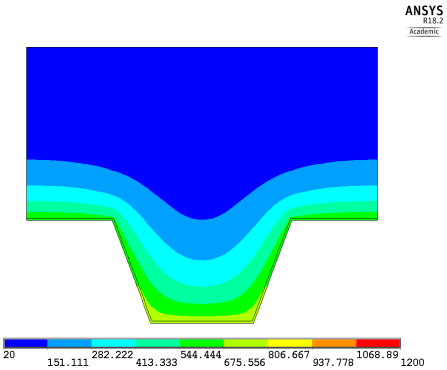
Malha



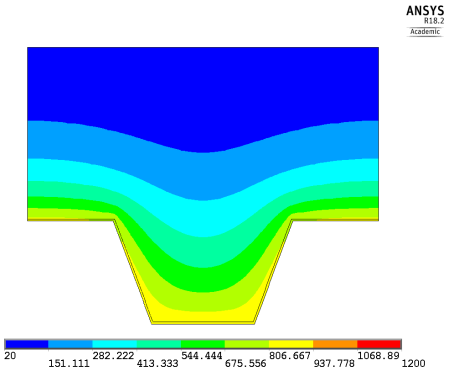
t = 24 min



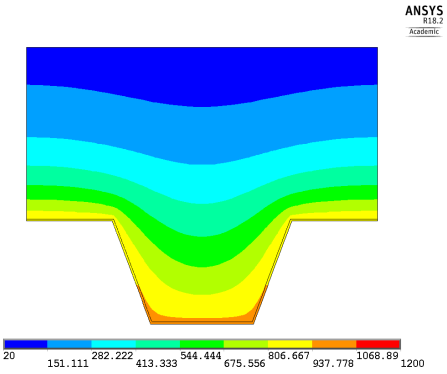
t = 49 min



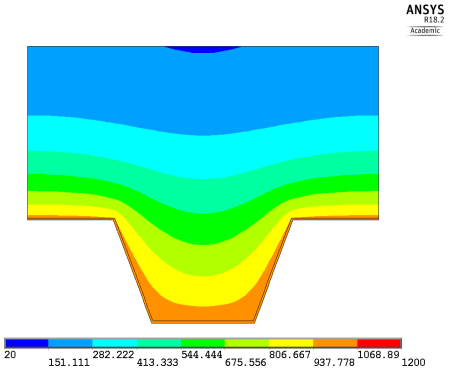
t = 73 min

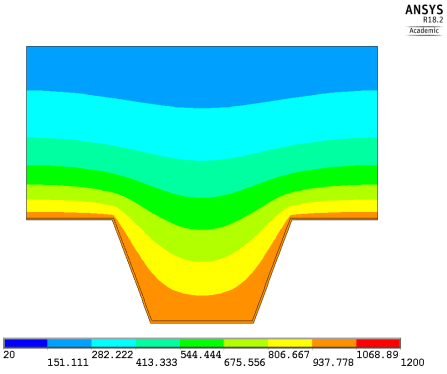


Tempo Crítico = 98 min



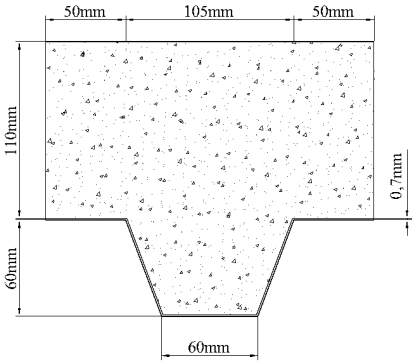
t = 7200s



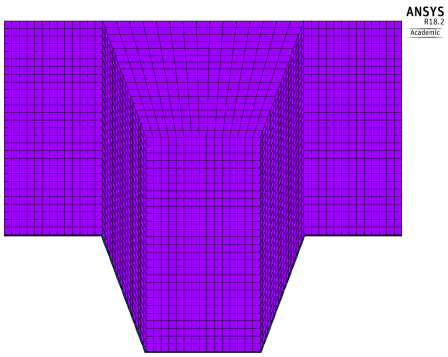


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.7mm

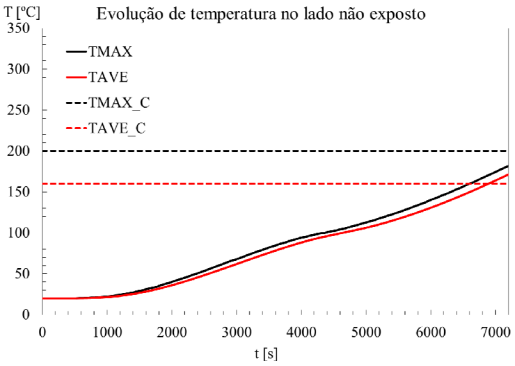
GEOMETRIA



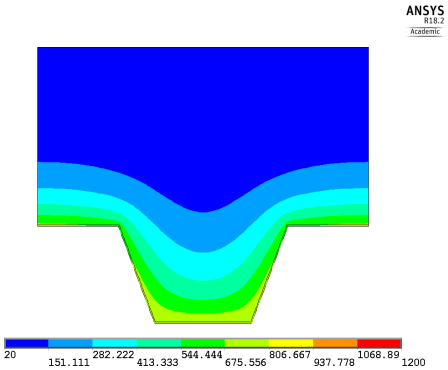
Malha



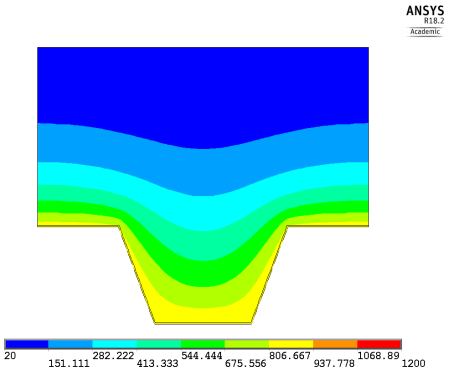
t = 28 min



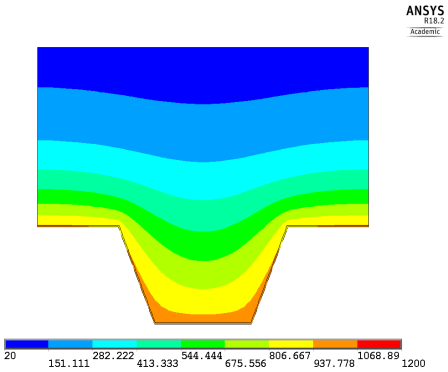
t = 57 min



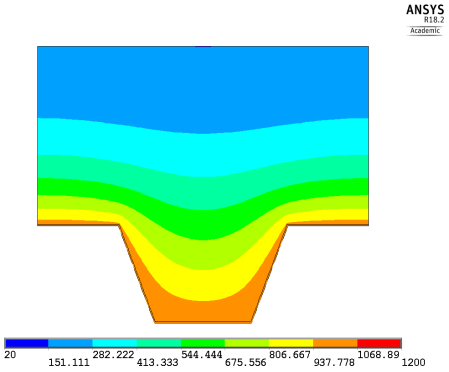
t = 85 min

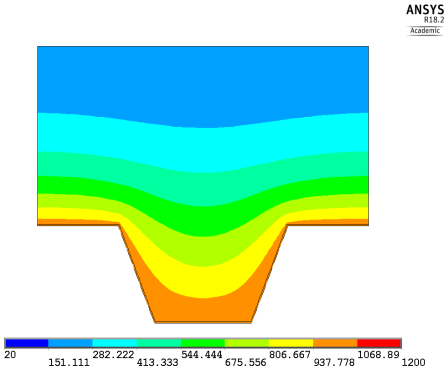


Tempo Crítico = 114 min



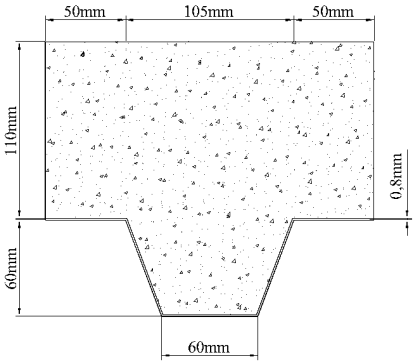
t = 7200s



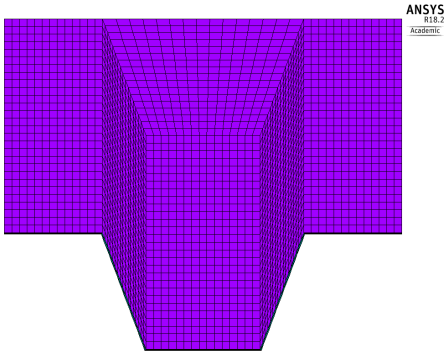


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.8mm

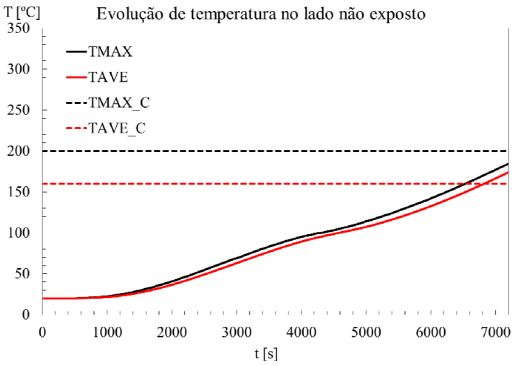
GEOMETRIA



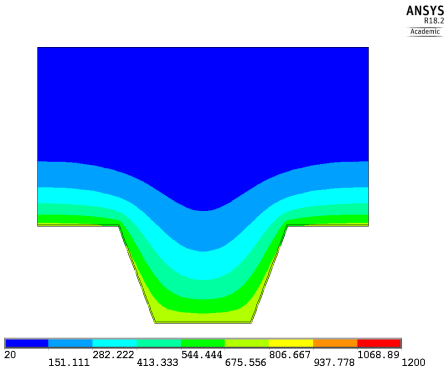
Malha



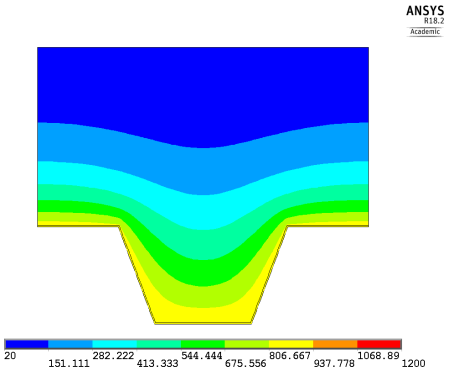
t = 28 min



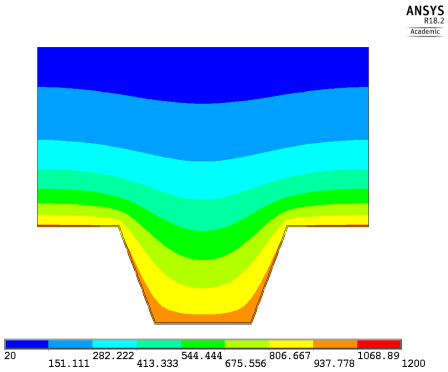
t = 56 min



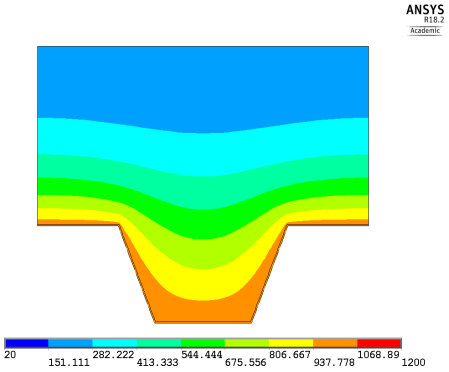
t = 84 min

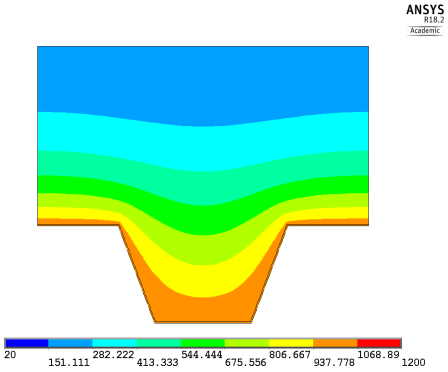


Tempo Crítico = 113 min



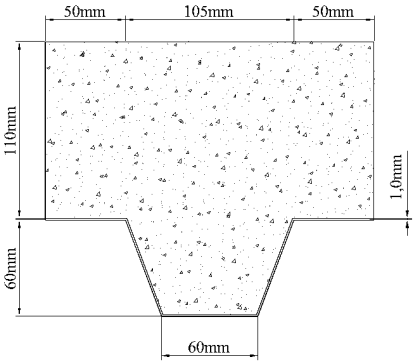
t = 7200s



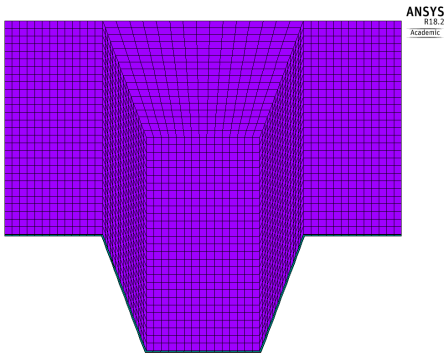


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.0mm

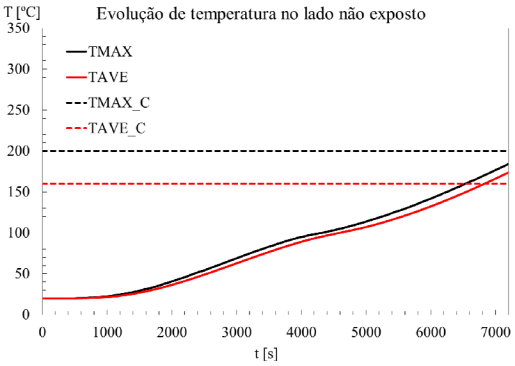
GEOMETRIA



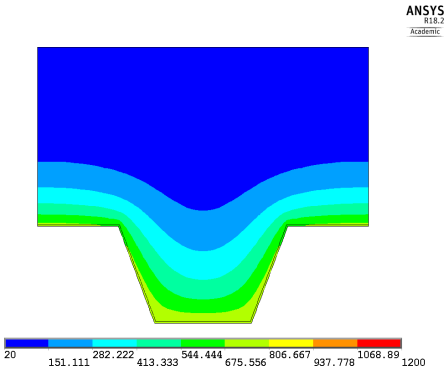
Malha



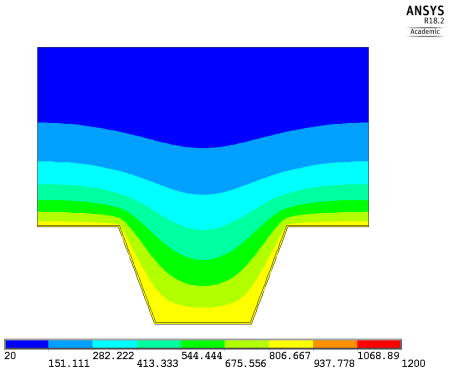
t = 28 min



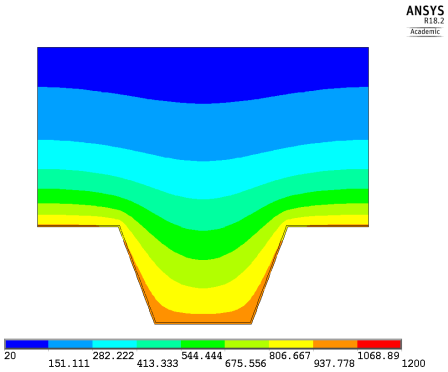
t = 56 min



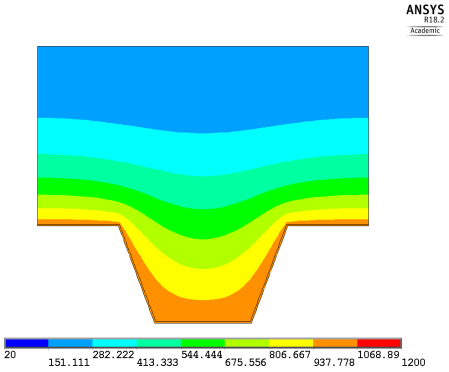
t = 84 min

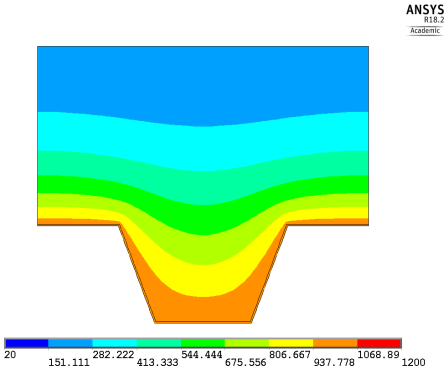


Tempo Crítico = 113 min



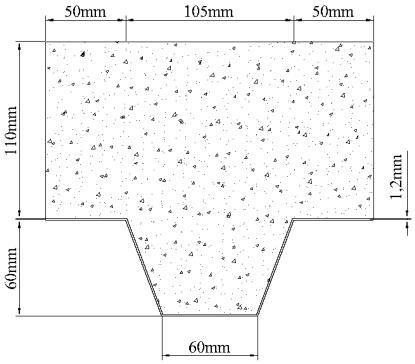
t = 7200s



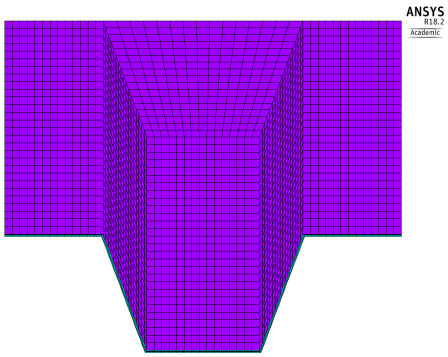


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.2mm

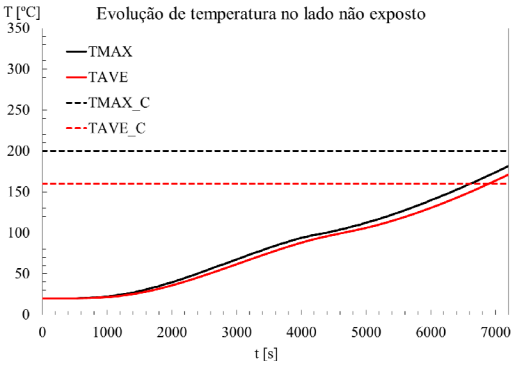
GEOMETRIA



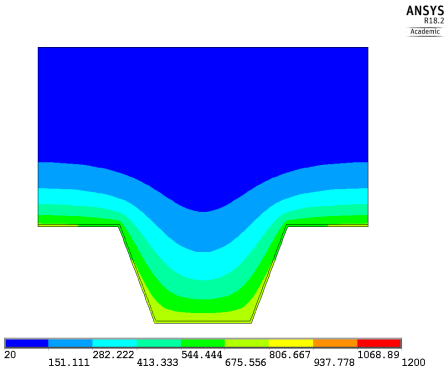
Malha



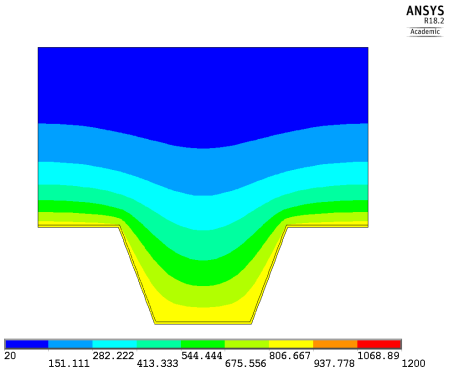
t = 28 min



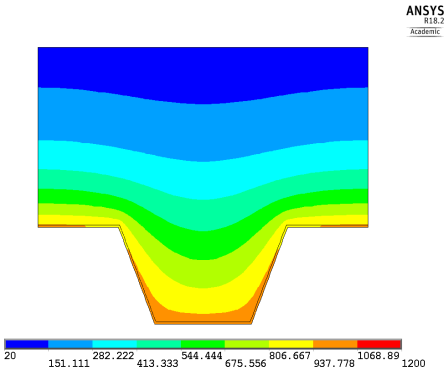
t = 57 min



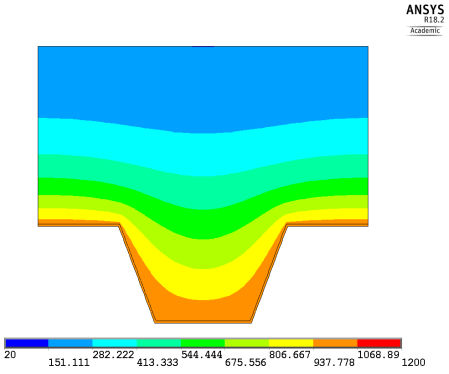
t = 85 min

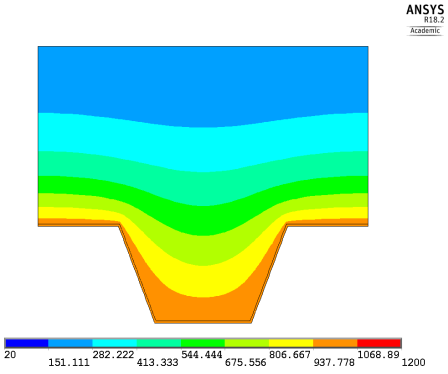


Tempo Crítico = 114 min



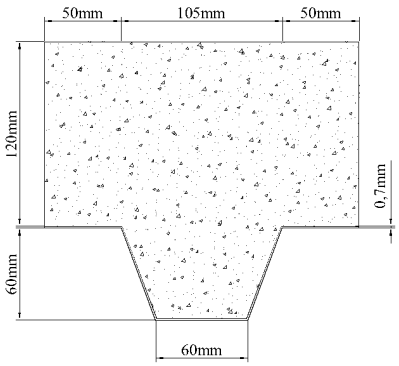
t = 7200s



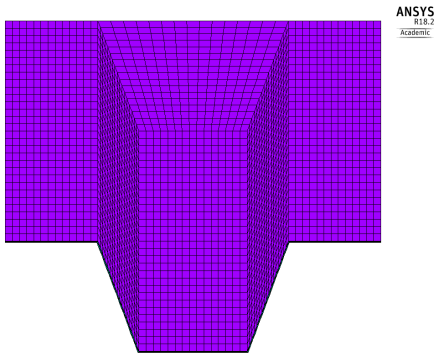


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.7mm

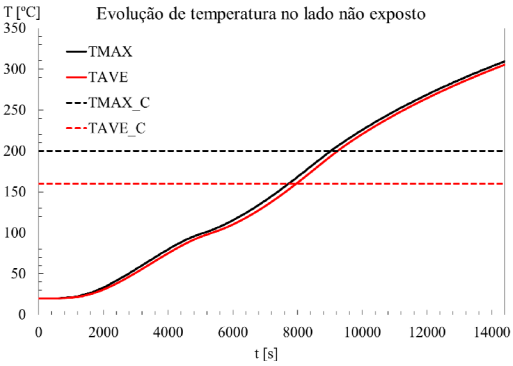
GEOMETRIA



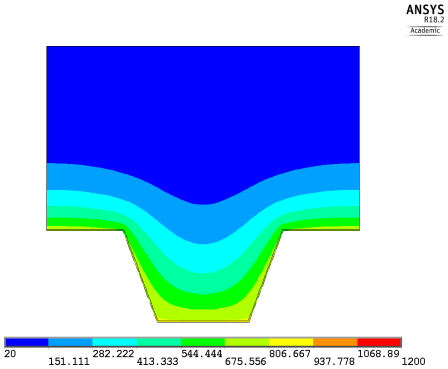
Malha



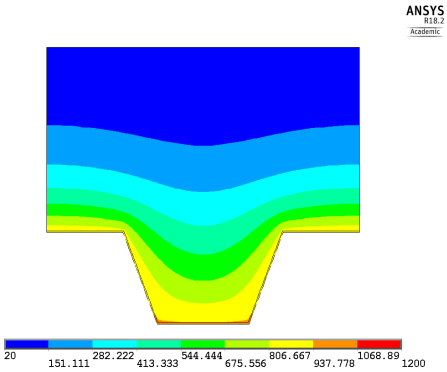
t = 33 min



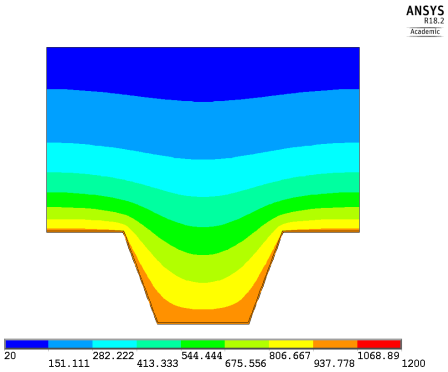
t = 66 min



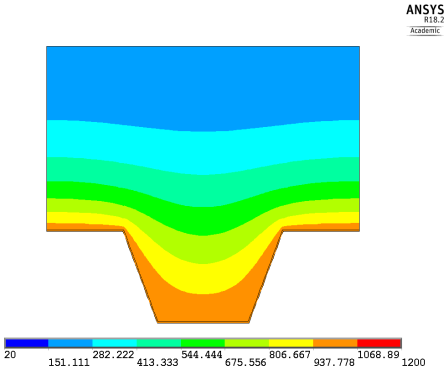
t = 99 min

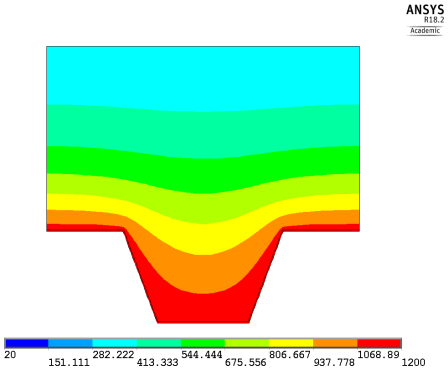


Tempo Crítico = 132 min



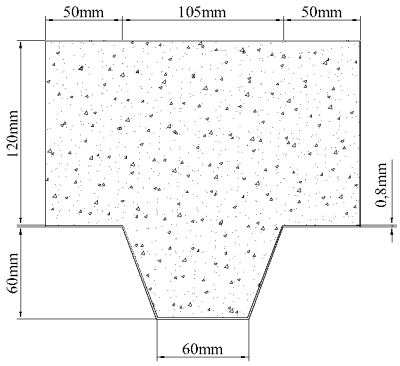
t = 14400s



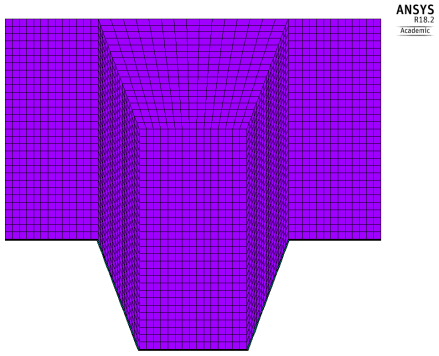


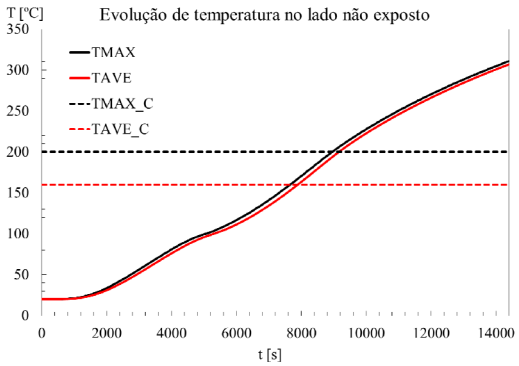
LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.8mm

GEOMETRIA

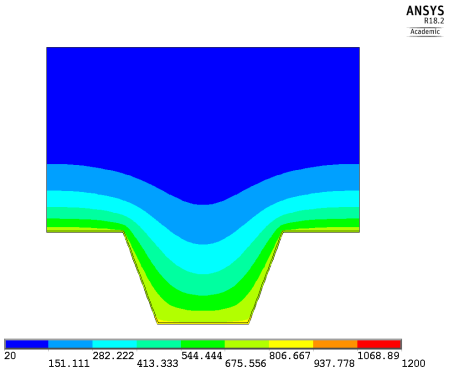


Malha

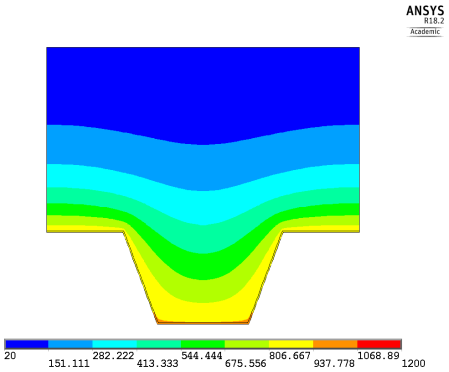




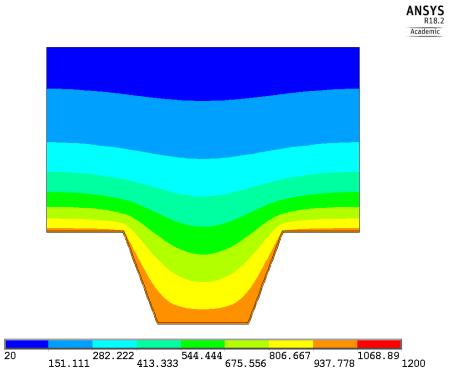
t = 32 min



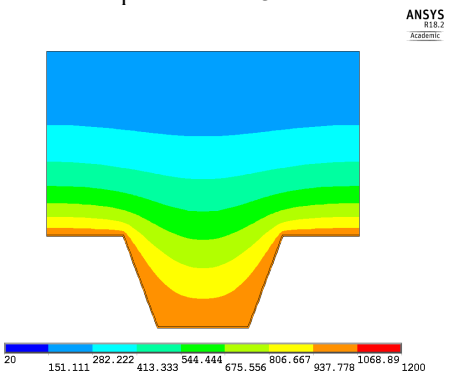
t = 65 min



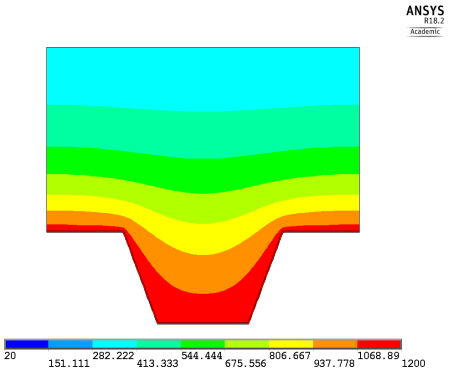
t = 98 min



Tempo Crítico = 131 min

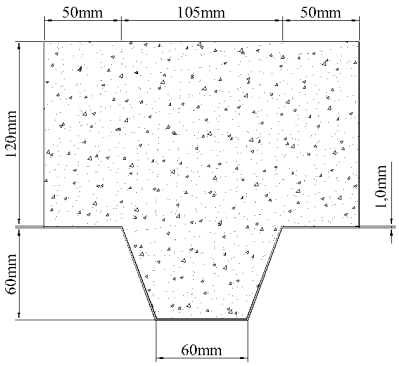


t = 14400s

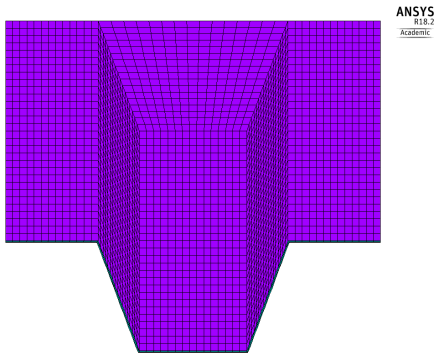


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.0mm

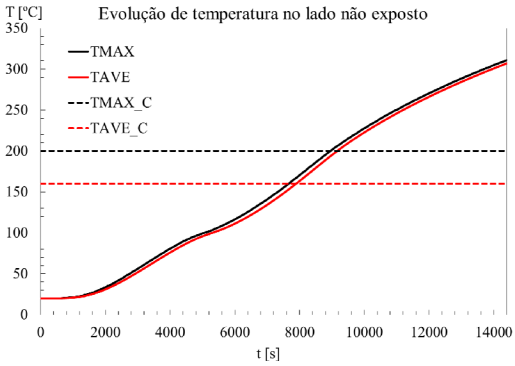
GEOMETRIA



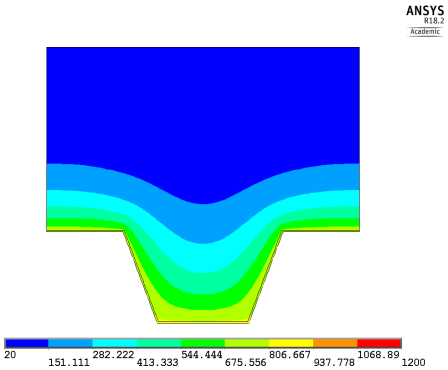
Malha



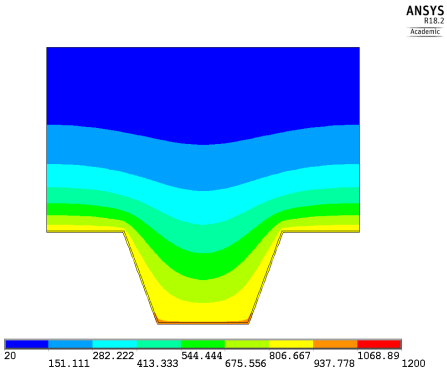
t = 32 min



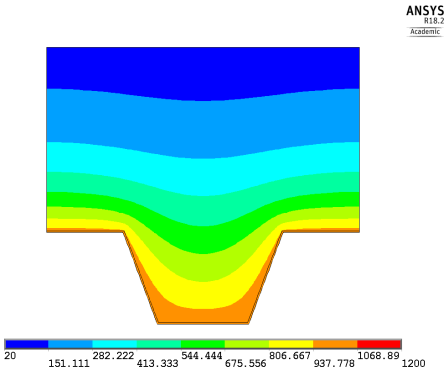
t = 65 min



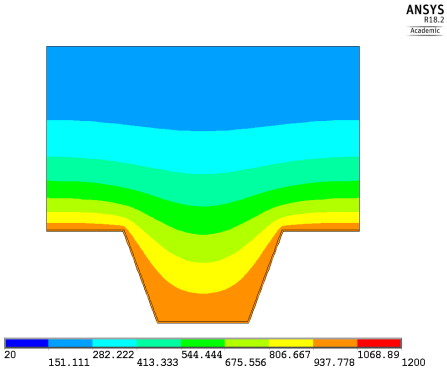
t = 98 min

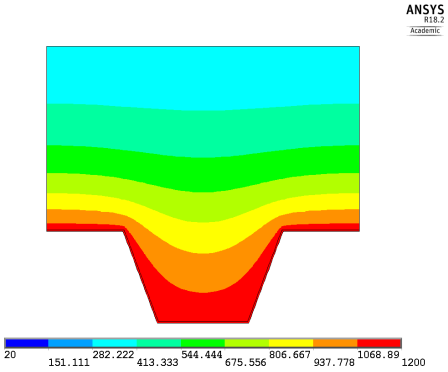


Tempo Crítico = 131 min



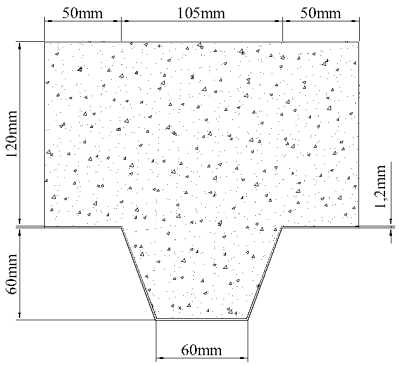
t = 14400s



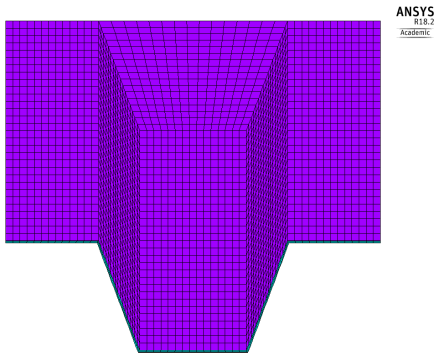


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.2mm

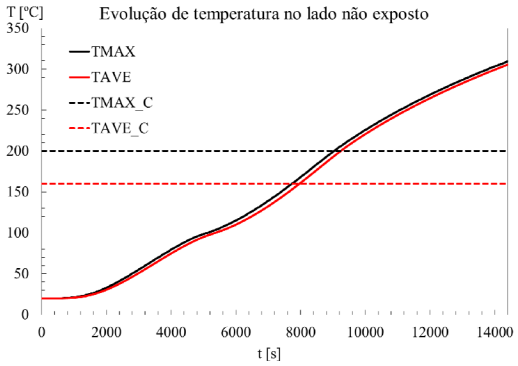
GEOMETRIA



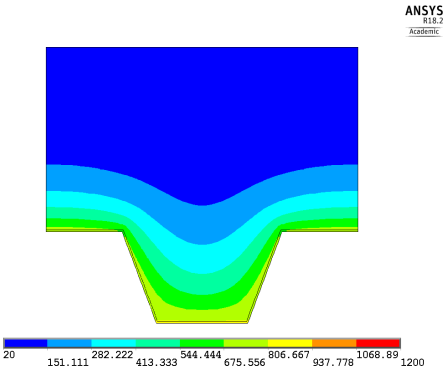
Malha



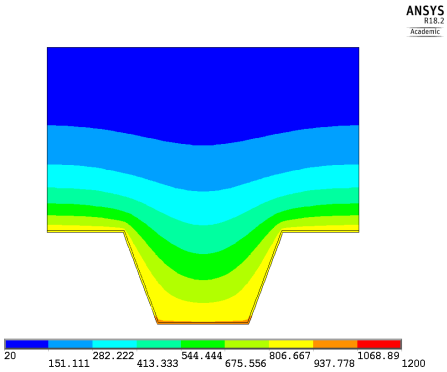
t = 33 min



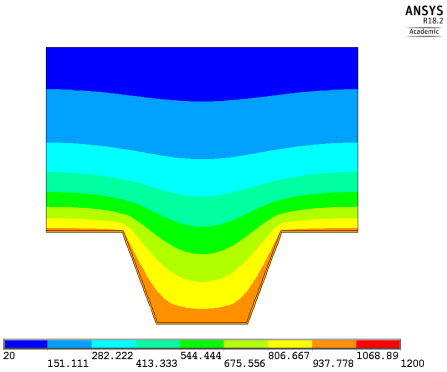
t = 66 min



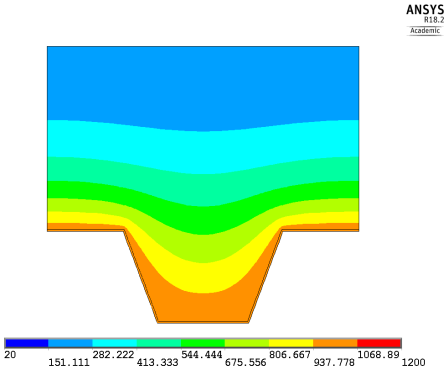
t = 99 min

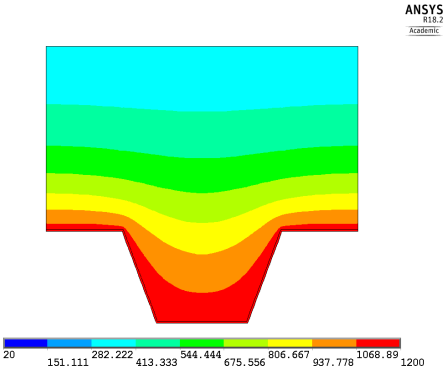


Tempo Crítico = 132 min



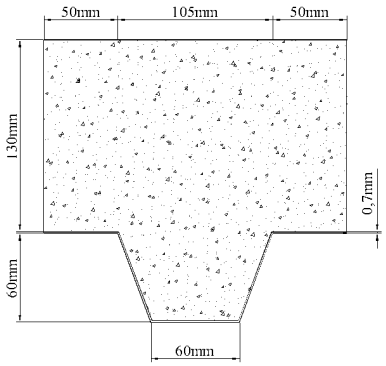
t = 14400s



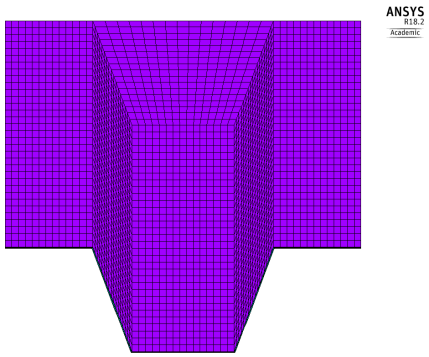


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.7mm

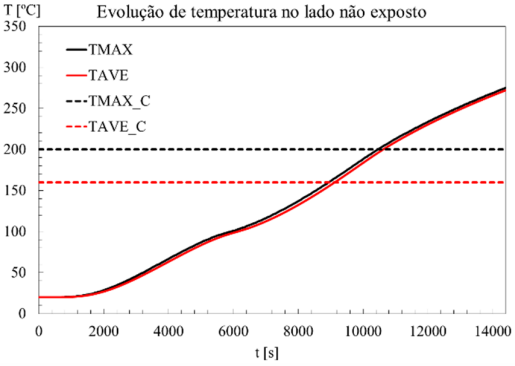
GEOMETRIA



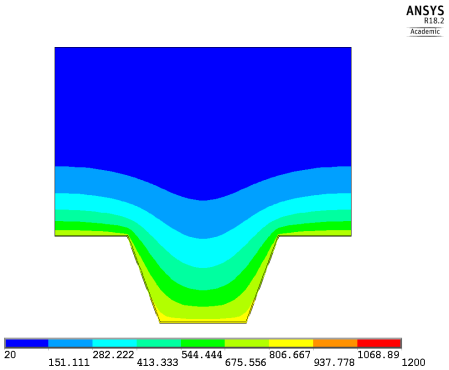
Malha



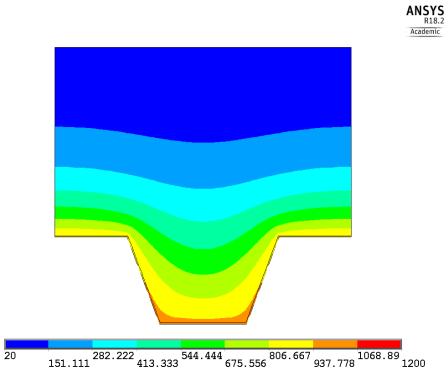
t = 38 min



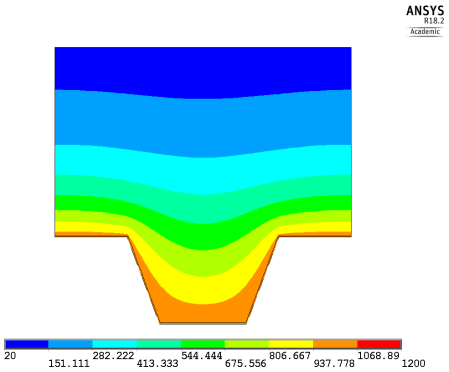
t = 76 min



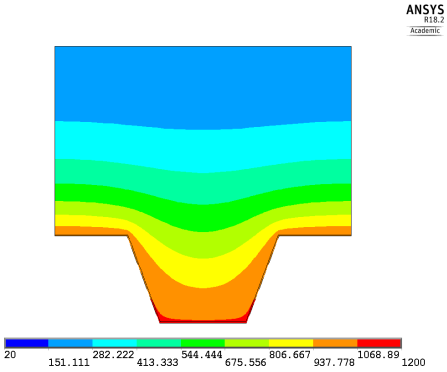
t = 114 min

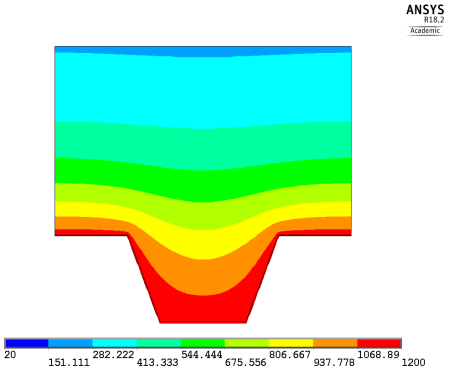


Tempo Crítico = 152 min



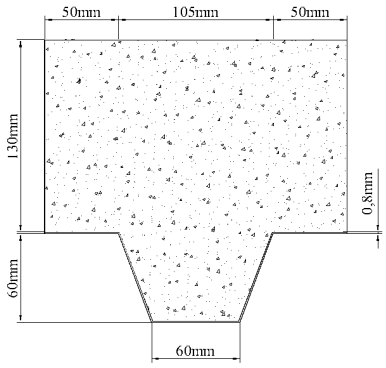
t = 14400s



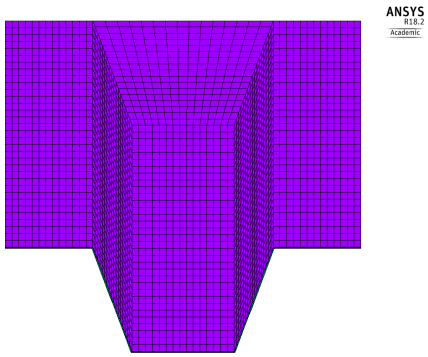


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.8mm

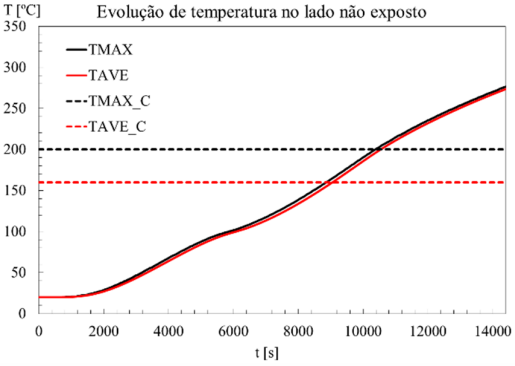
GEOMETRIA



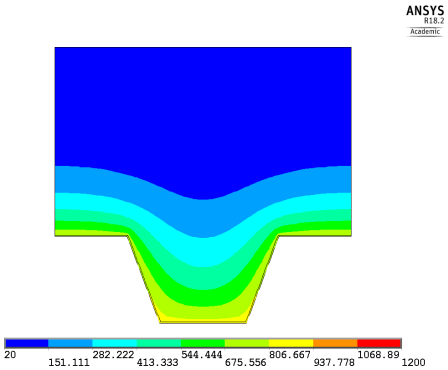
Malha



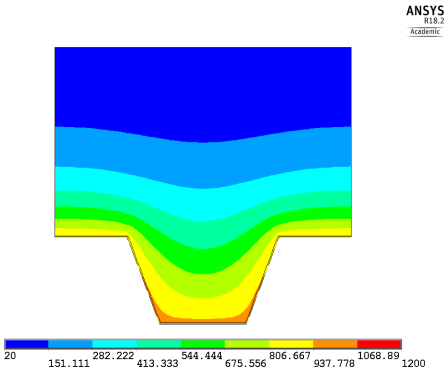
t = 37 min



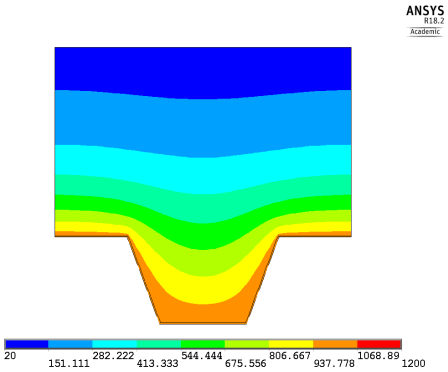
t = 75 min



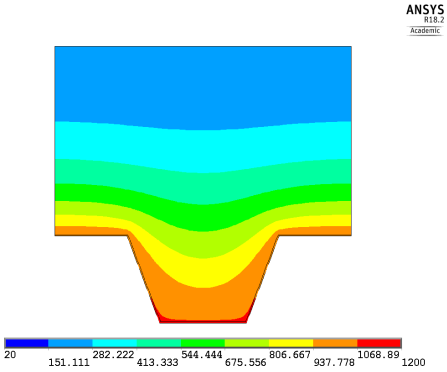
t = 112 min

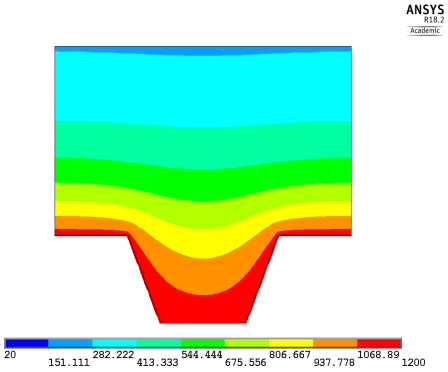


Tempo Crítico = 150 min



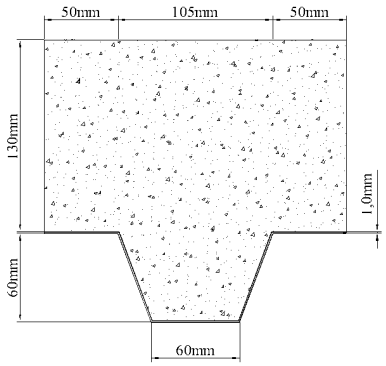
t = 14400s



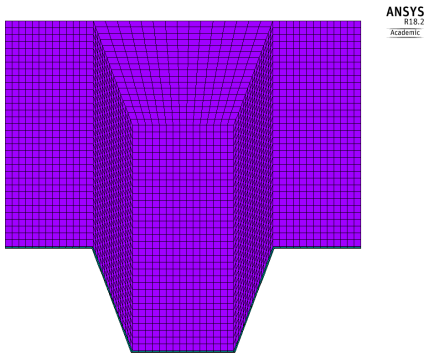


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.0mm

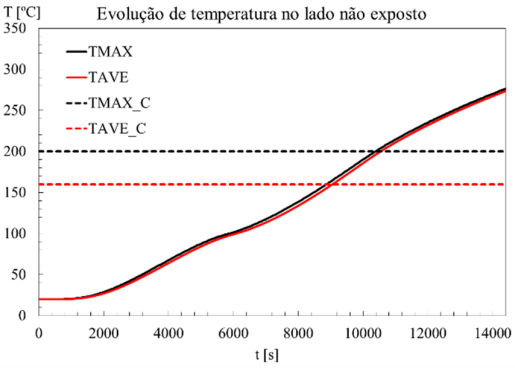
GEOMETRIA



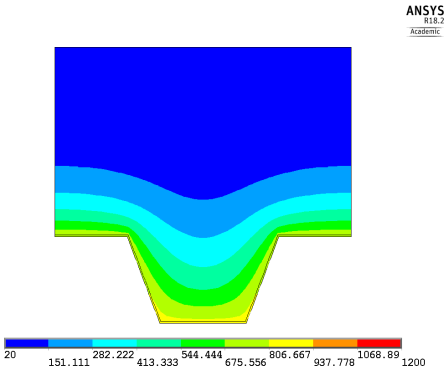
Malha



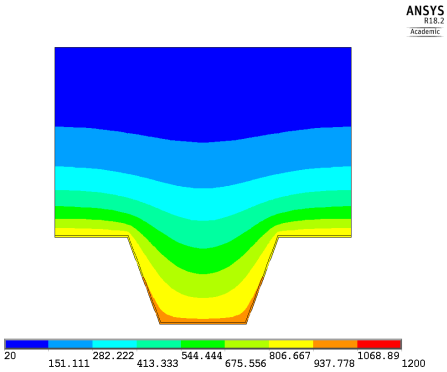
t = 37 min



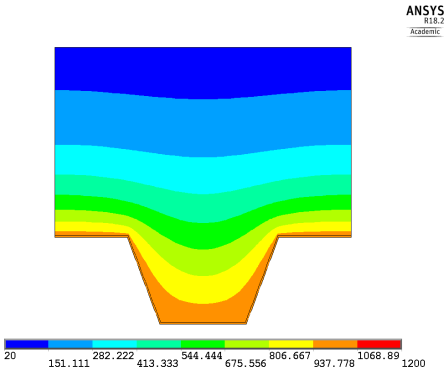
t = 75 min



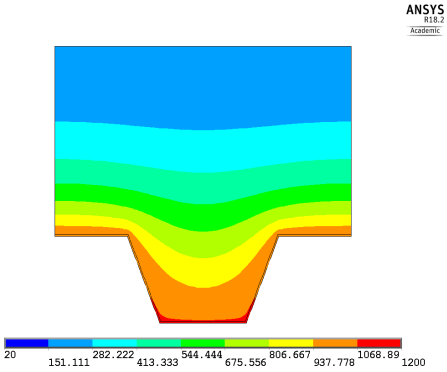
t = 112 min

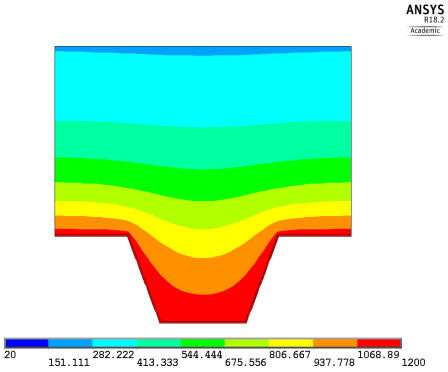


Tempo Crítico = 150 min



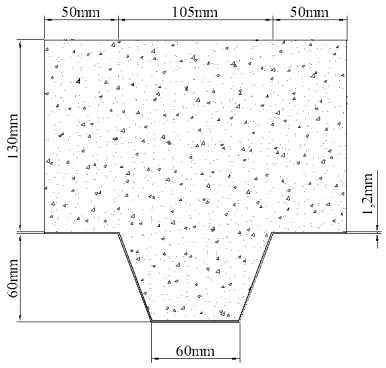
t = 14400s



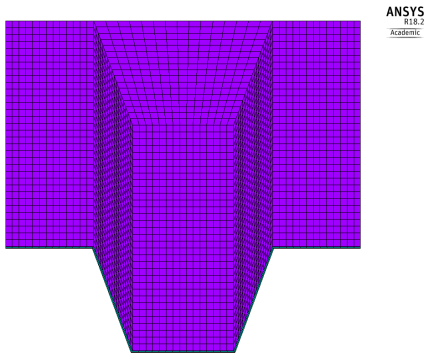


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.2mm

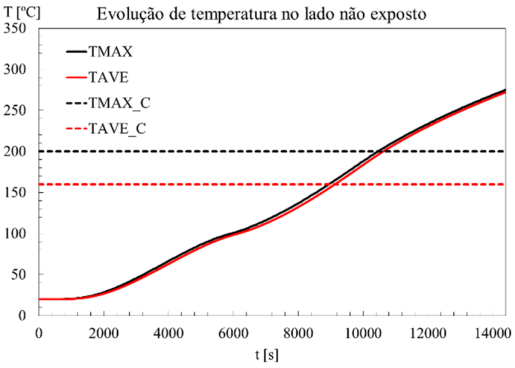
GEOMETRIA



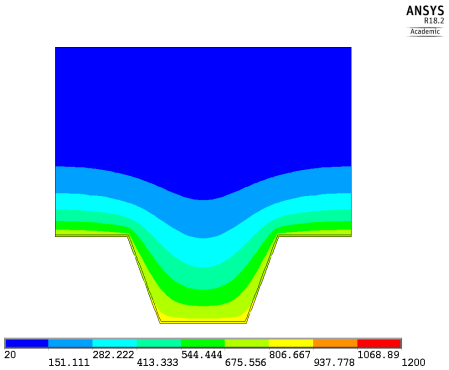
Malha



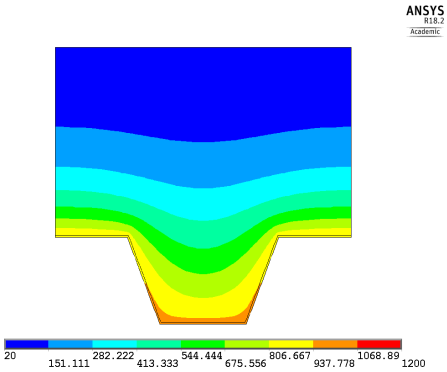
t = 38 min



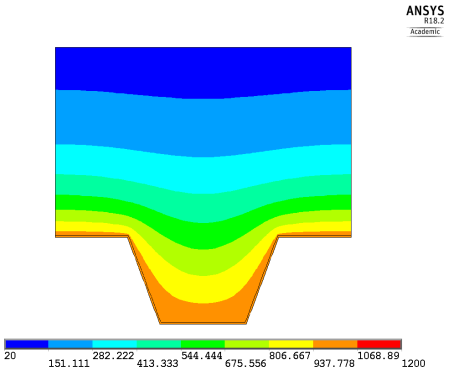
t = 76 min



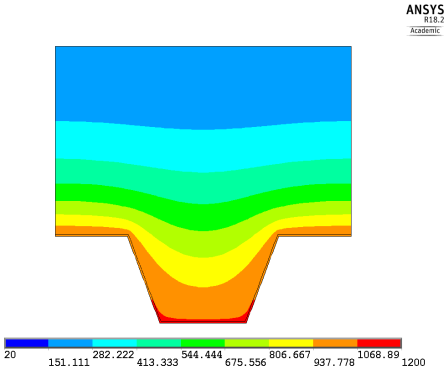
t = 114 min

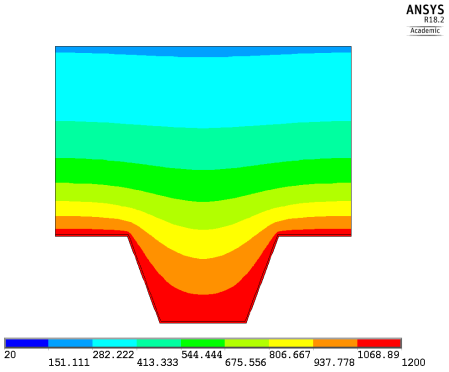


Tempo Crítico = 152 min



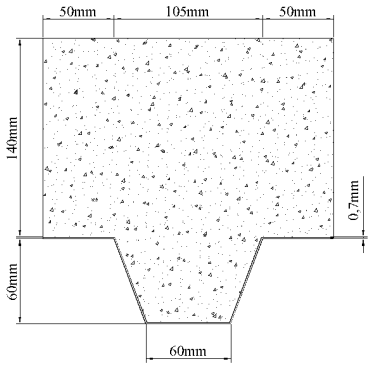
t = 14400s



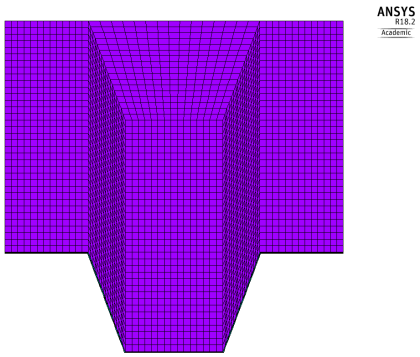


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.7mm

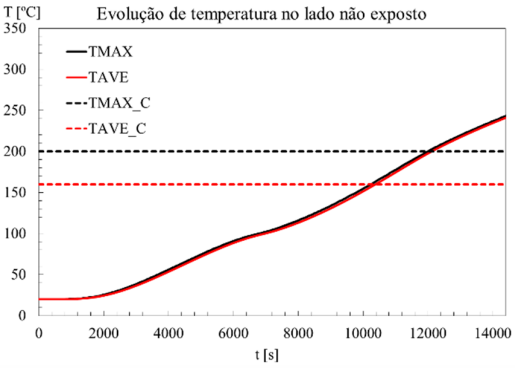
GEOMETRIA



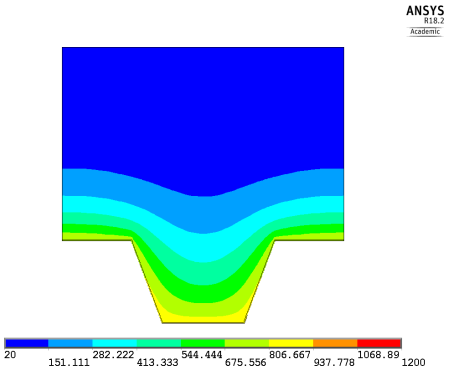
Malha



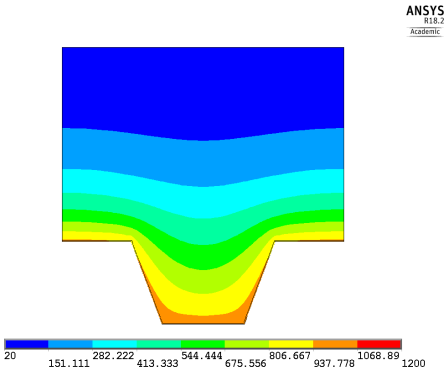
t = 43 min



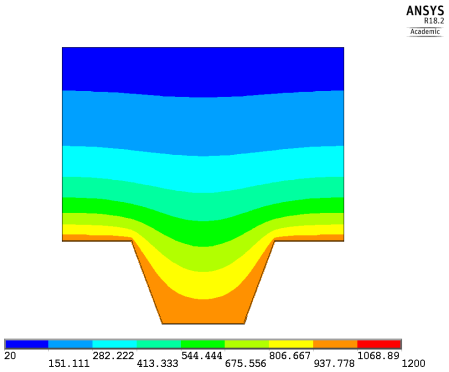
t = 86 min



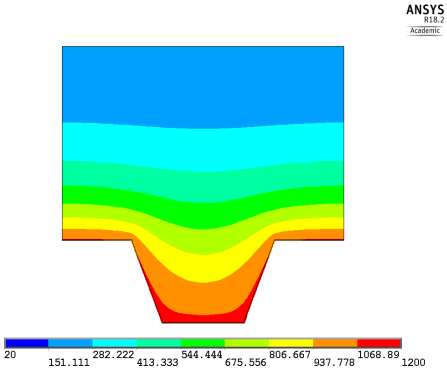
t = 129 min

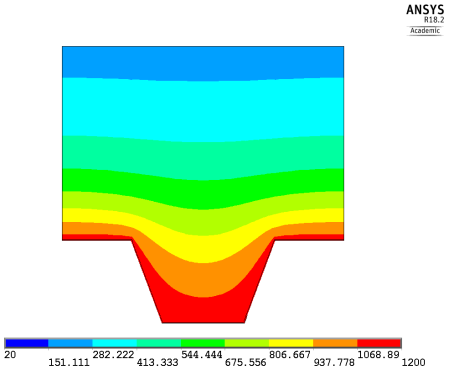


Tempo Crítico = 173 min



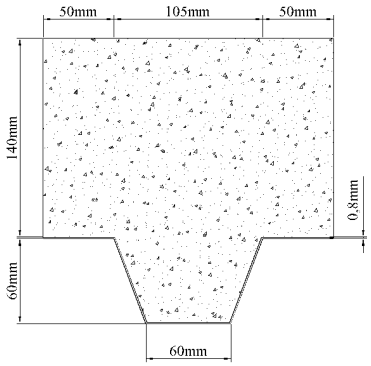
t = 14400s



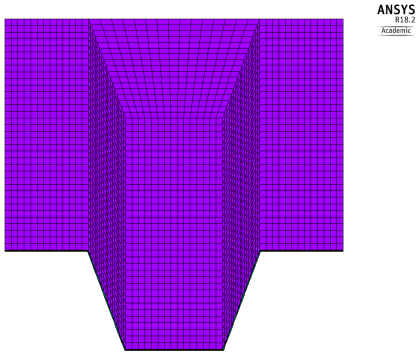


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.8mm

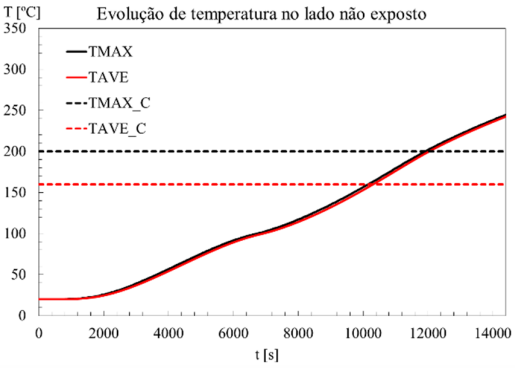
GEOMETRIA



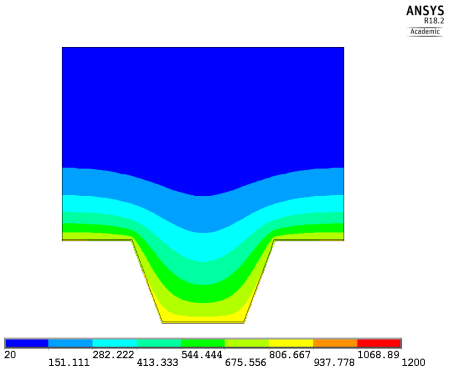
Malha



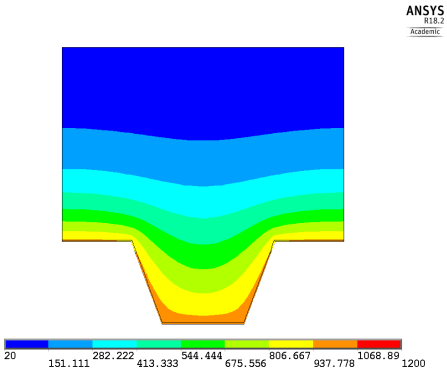
t = 42 min



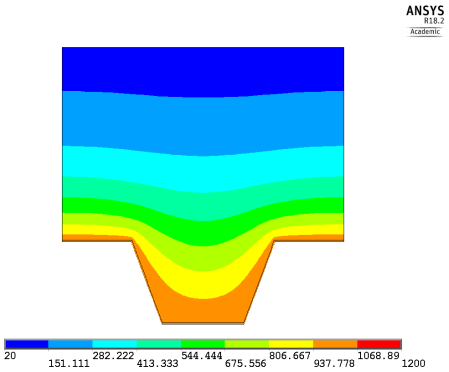
t = 85 min



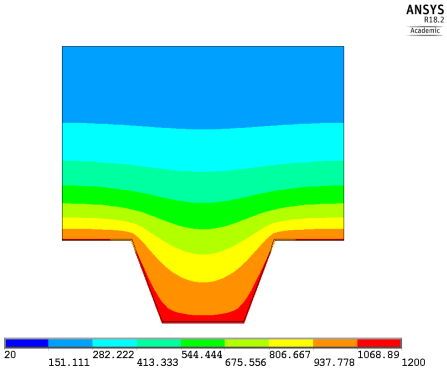
t = 128 min

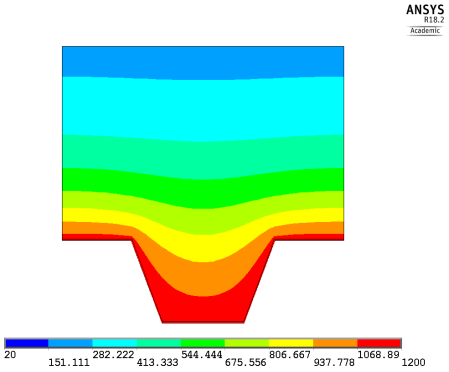


Tempo Crítico = 171 min



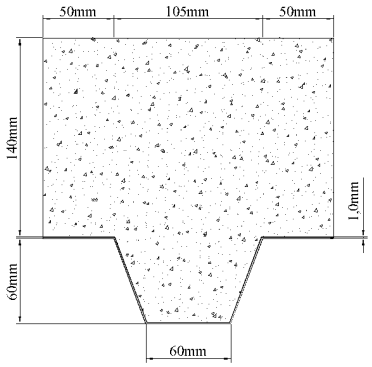
t = 14400s



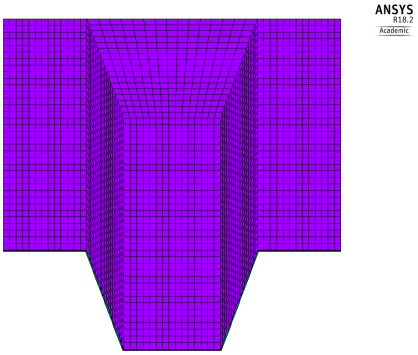


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.0mm

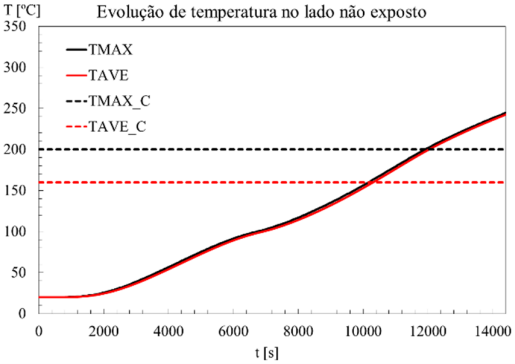
GEOMETRIA



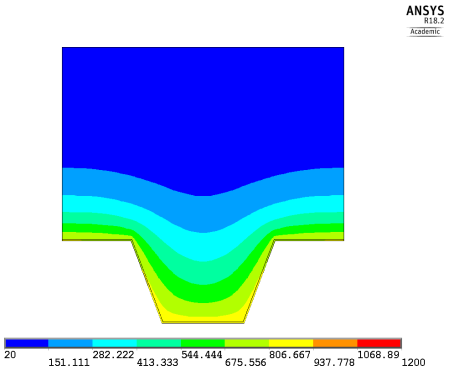
Malha



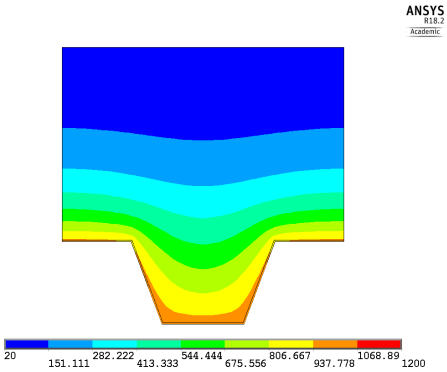
t = 42 min



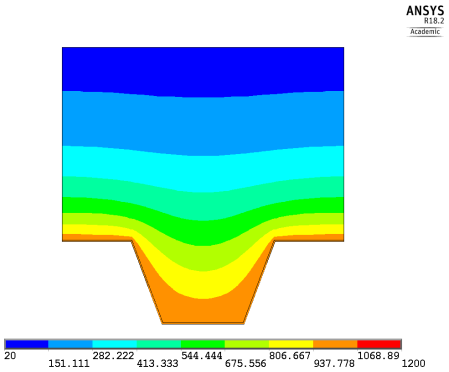
t = 85 min



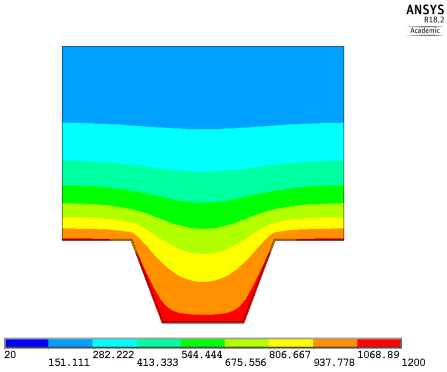
t = 128 min

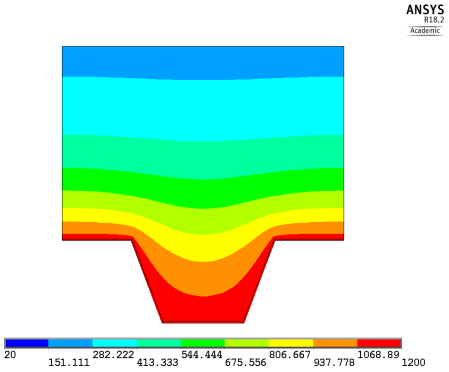


Tempo Crítico = 171 min



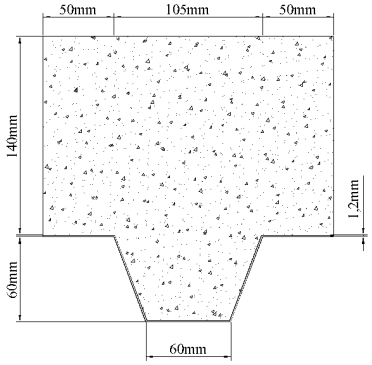
t = 14400s



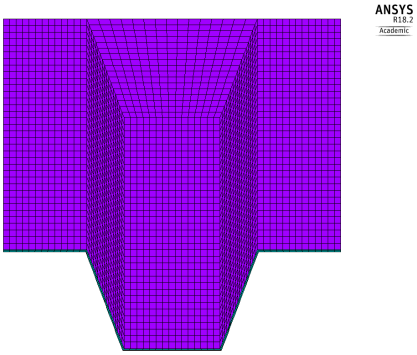


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.2mm

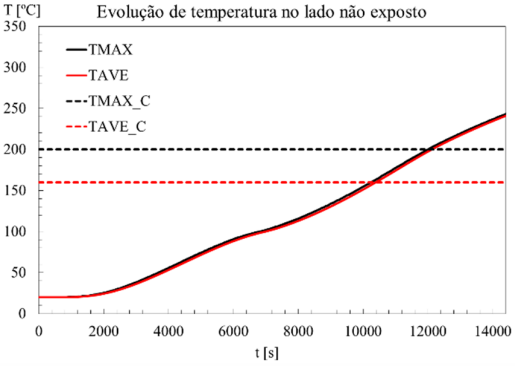
GEOMETRIA



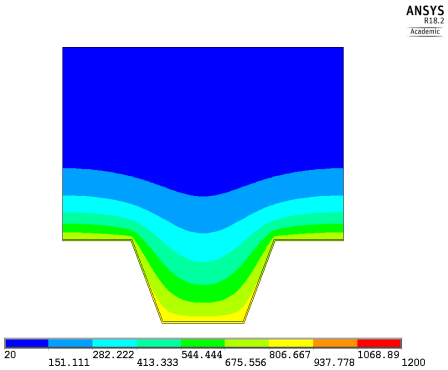
Malha



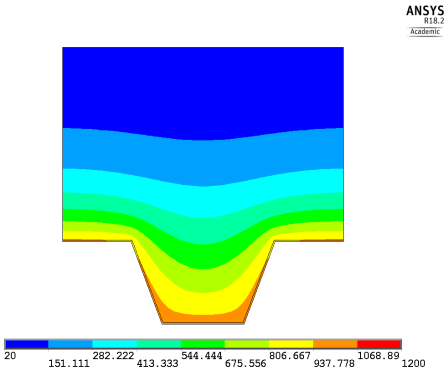
t = 43 min



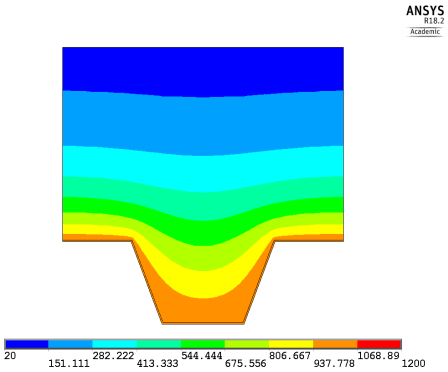
t = 86 min



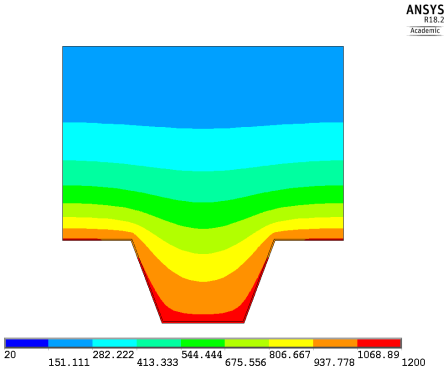
t = 129 min

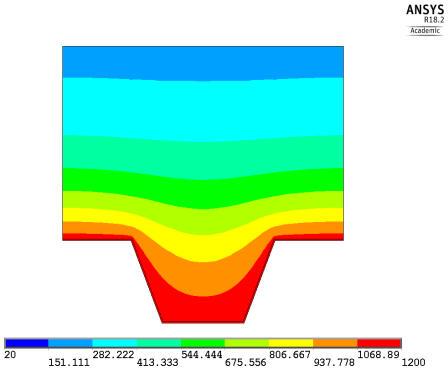


Tempo Crítico = 173 min



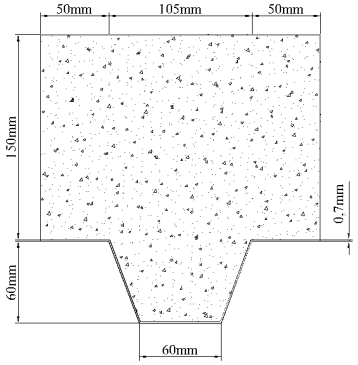
t = 14400s



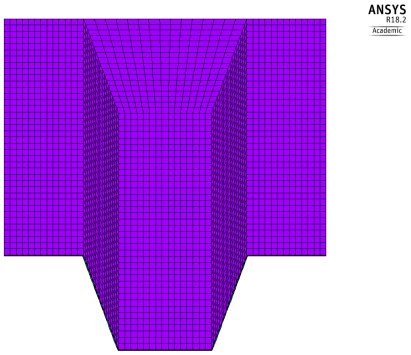


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.7mm

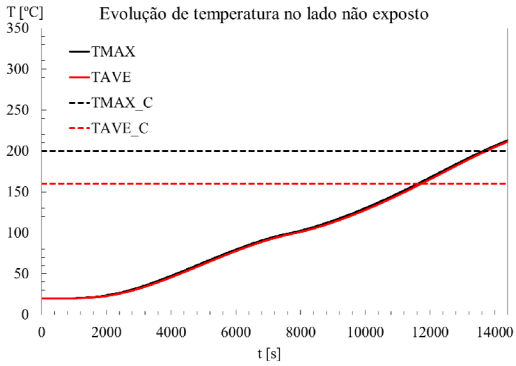
GEOMETRIA



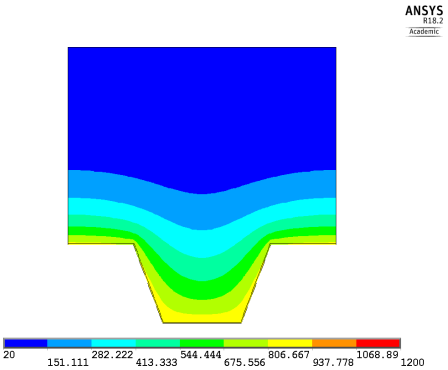
Malha



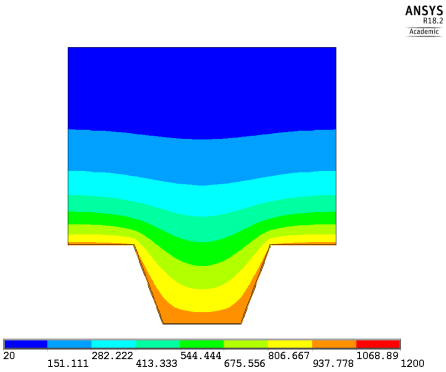
t = 48 min



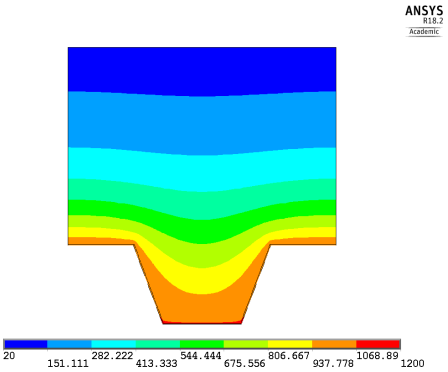
t = 97 min



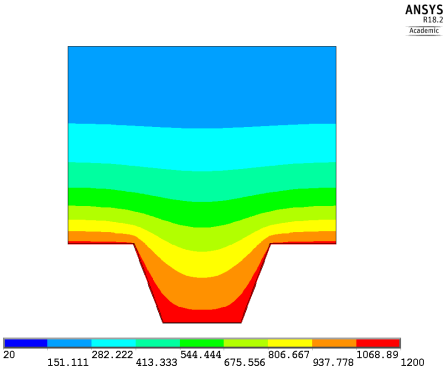
t = 146 min

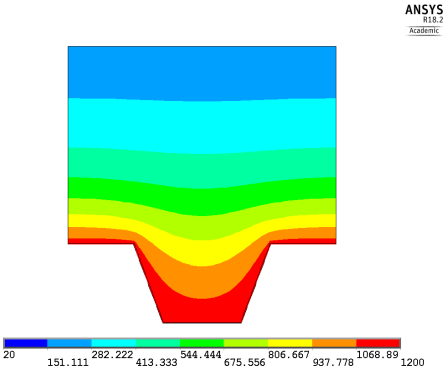


Tempo Crítico = 195 min



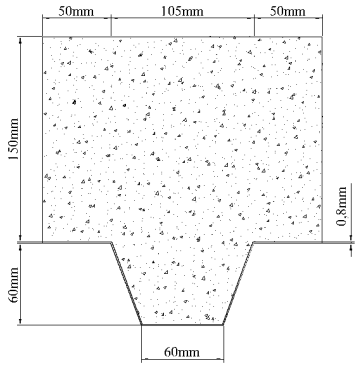
t = 14400s



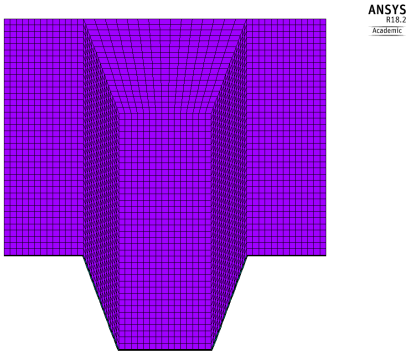


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.8mm

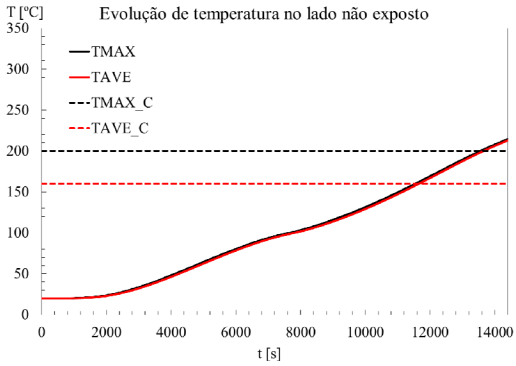
GEOMETRIA



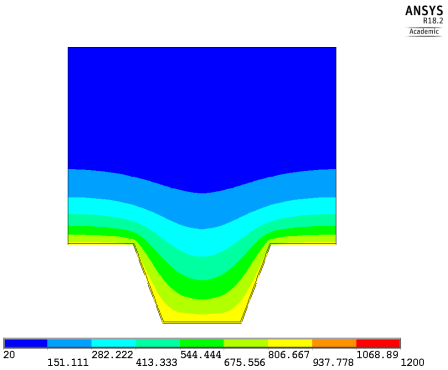
Malha



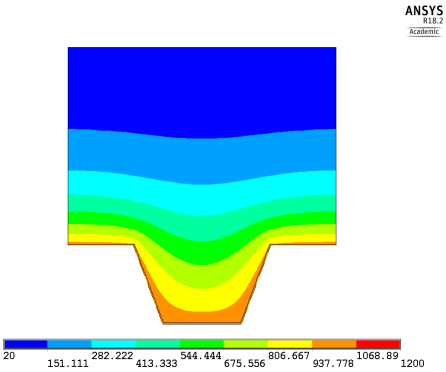
t = 48 min



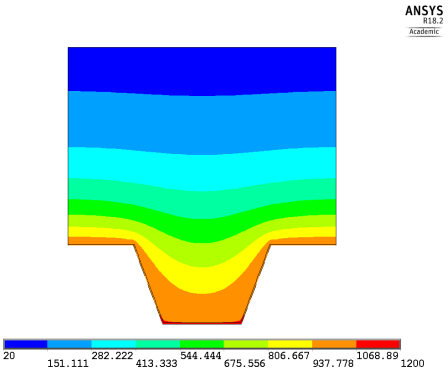
t = 97 min



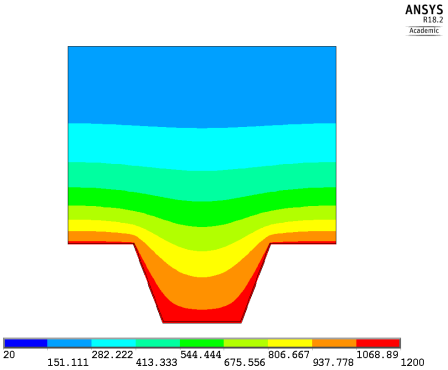
t = 145 min

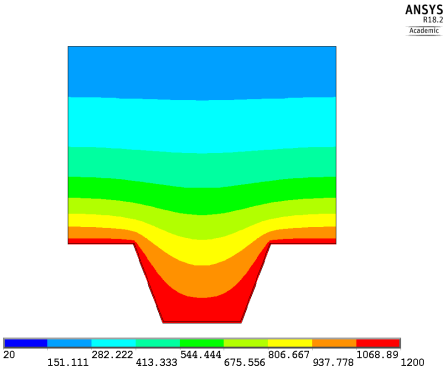


Tempo Crítico = 194 min



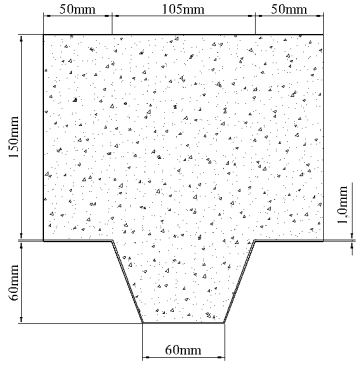
t = 14400s



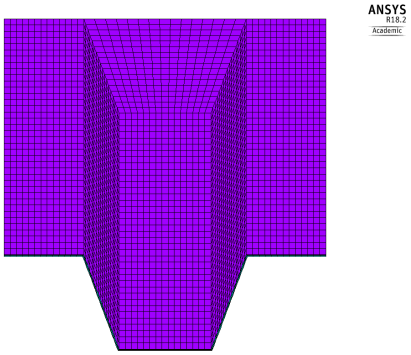


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.0mm

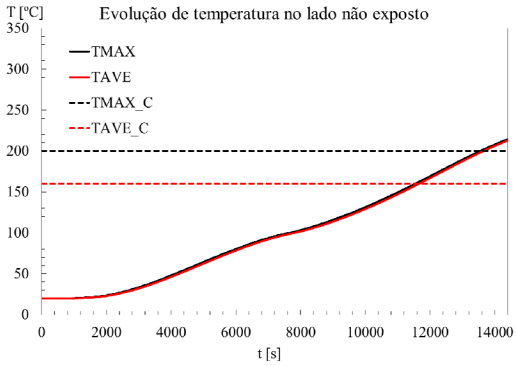
GEOMETRIA



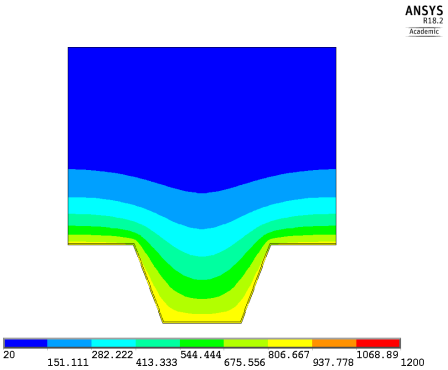
Malha



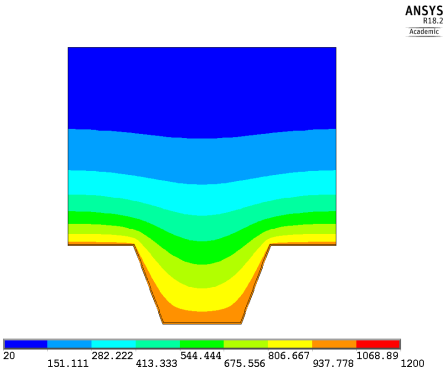
t = 48 min



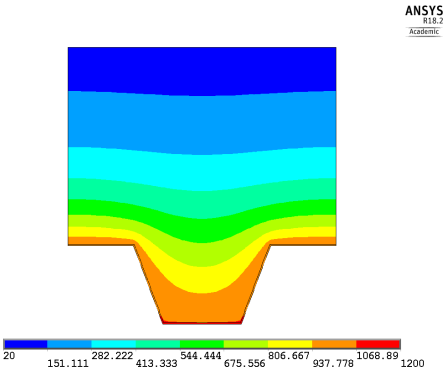
t = 97 min



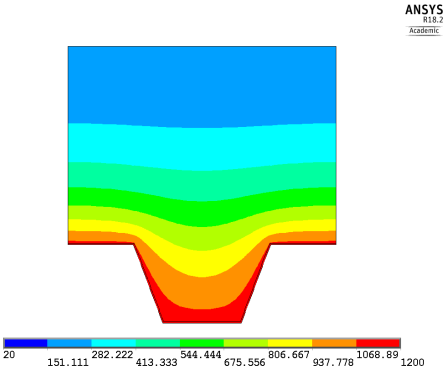
t = 145 min

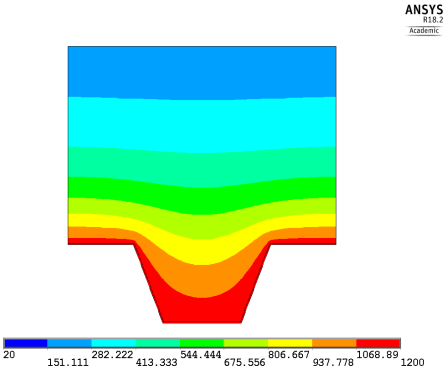


Tempo Crítico = 194 min



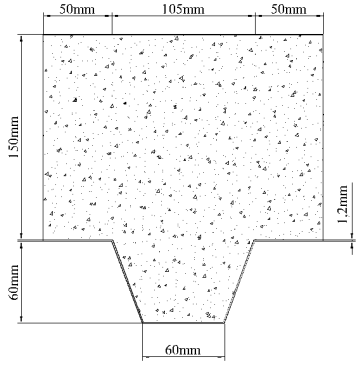
t = 14400s



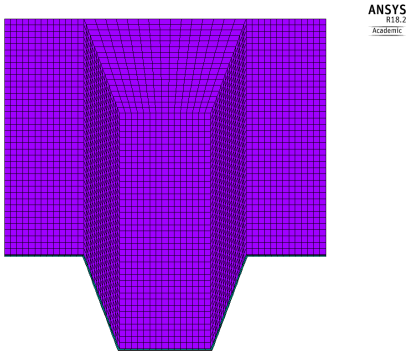


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.2mm

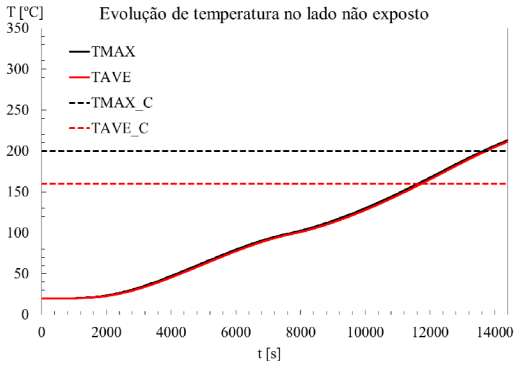
GEOMETRIA



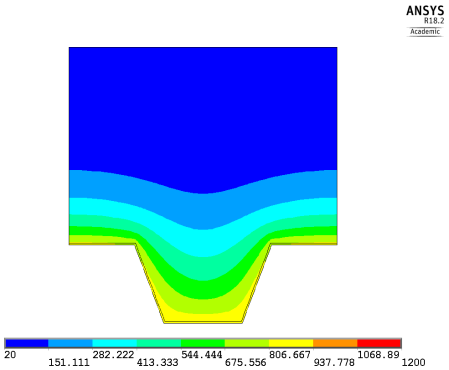
Malha



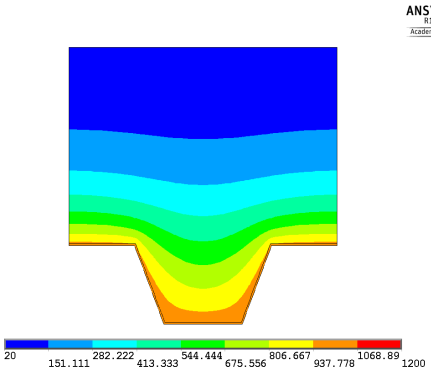
t = 48 min



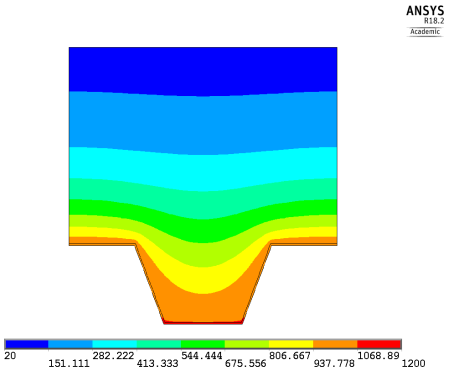
t = 97 min



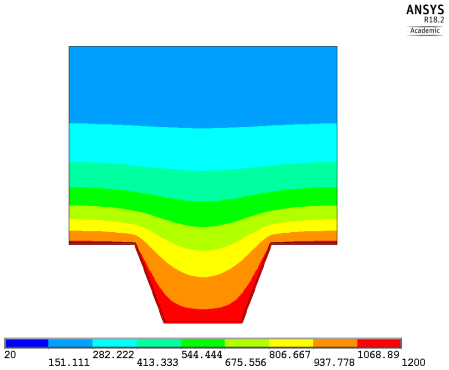
t = 146 min

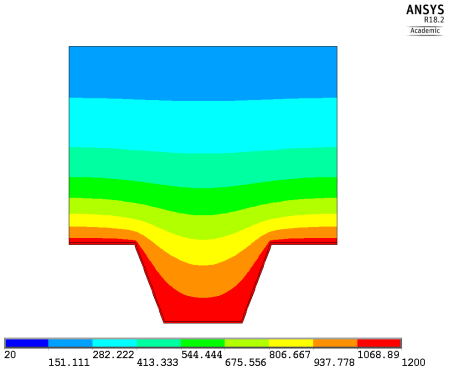


Tempo Crítico = 195 min



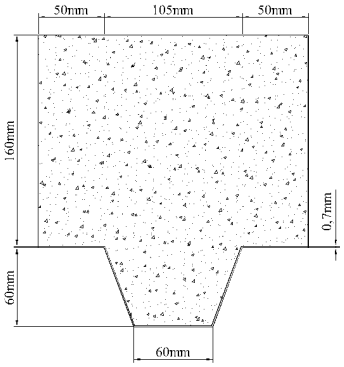
t = 14400s



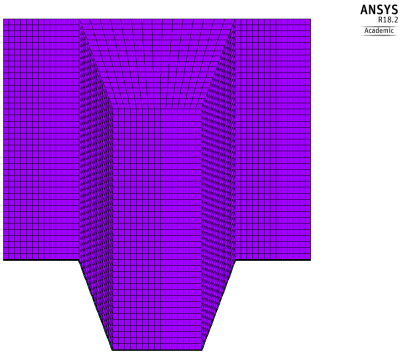


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.7mm

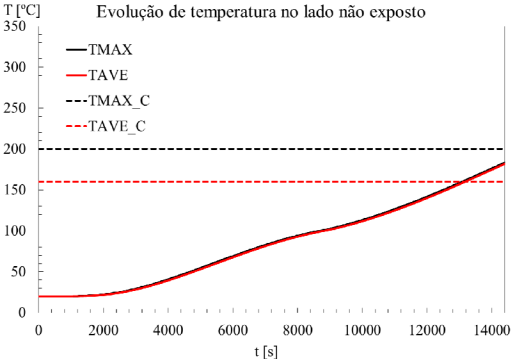
GEOMETRIA



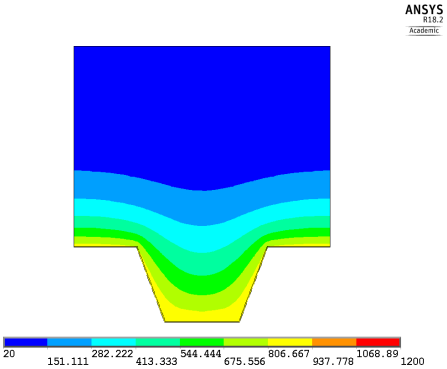
Malha



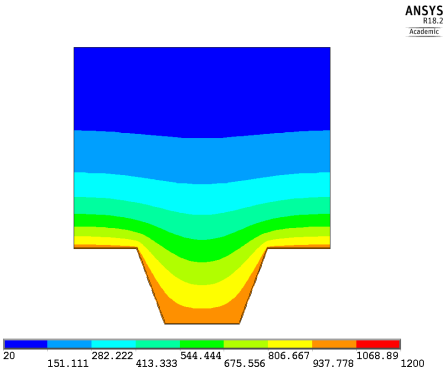
t = 54 min



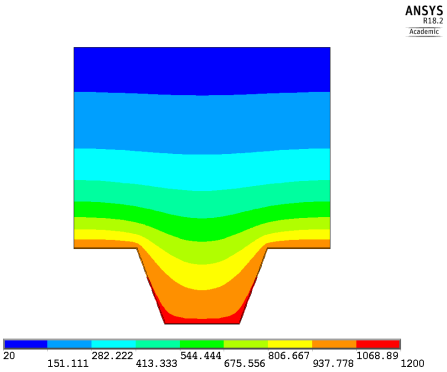
t = 109 min



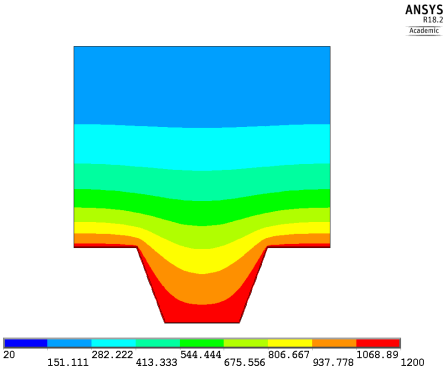
t = 164 min

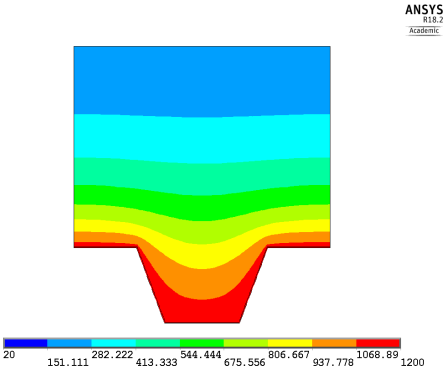


Tempo Crítico = 219 min



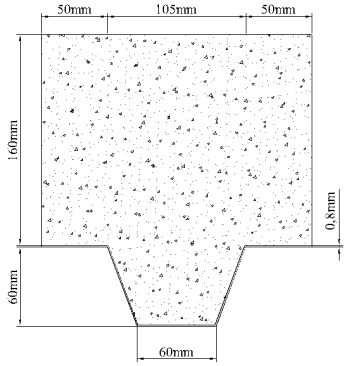
t = 14400s



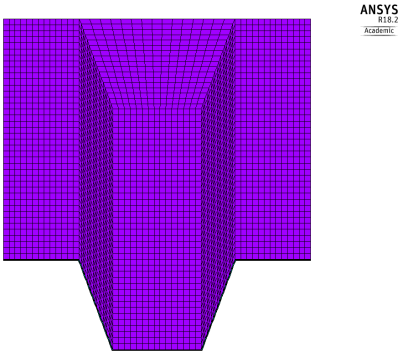


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.8mm

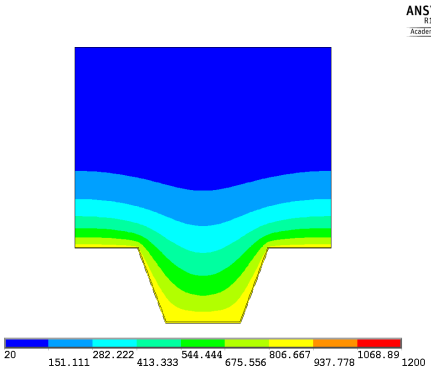
GEOMETRIA



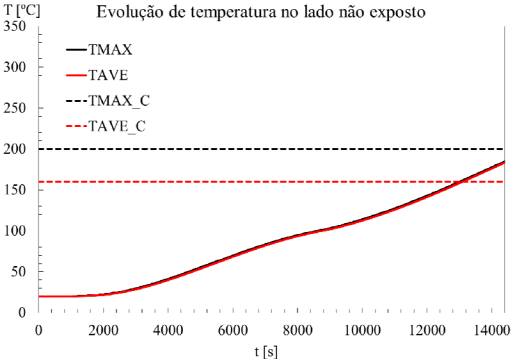
Malha



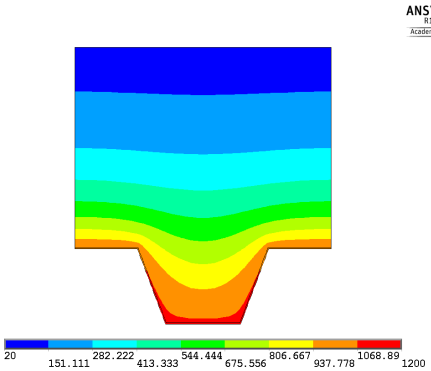
t = 54 min



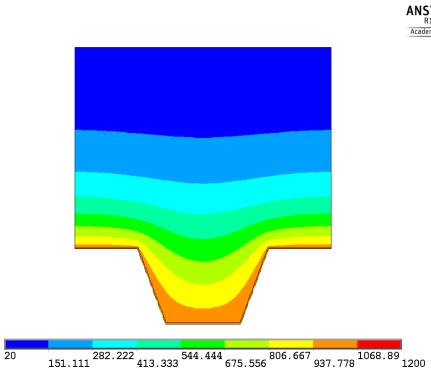
t = 109 min



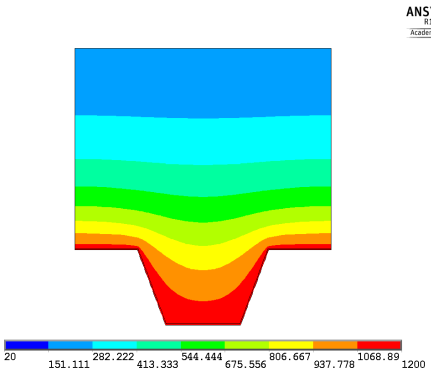
t = 163 min

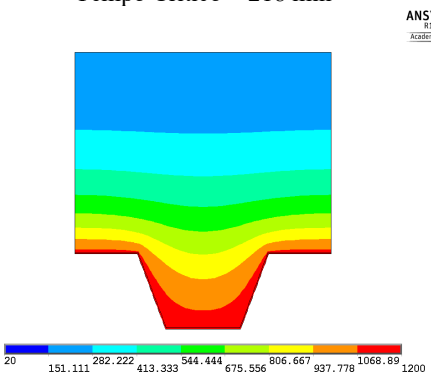


Tempo Crítico = 218 min



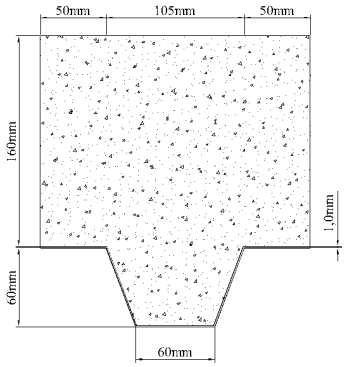
t = 14400s





LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.0mm

GEOMETRIA



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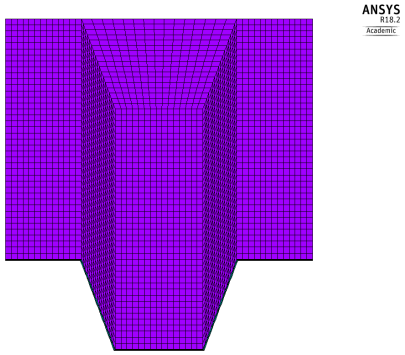
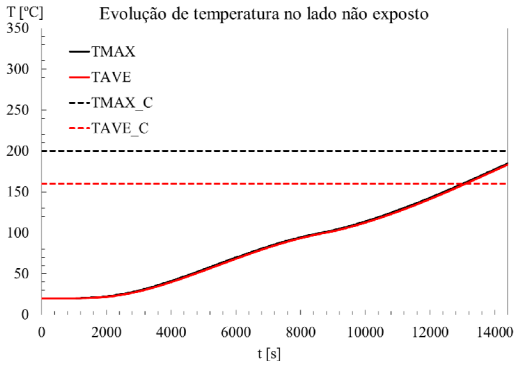
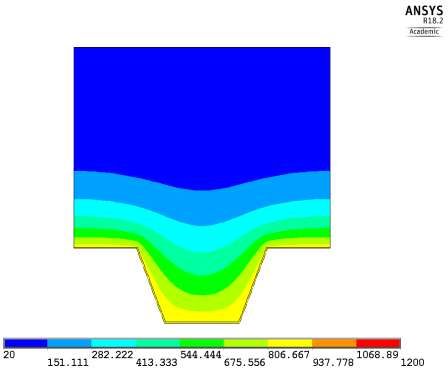


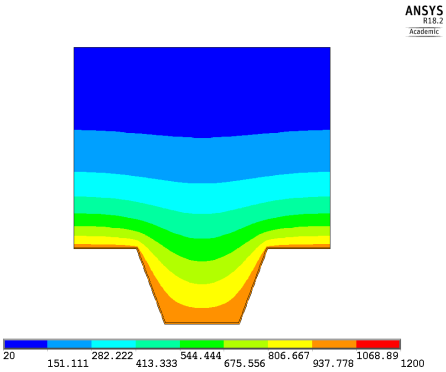
t = 54 min



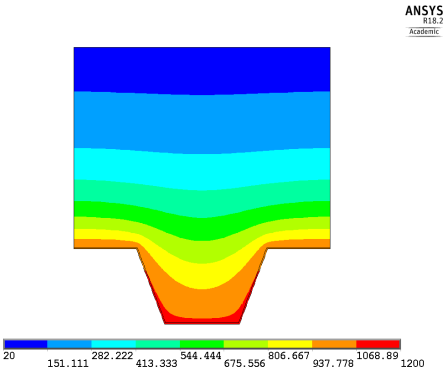
t = 109 min



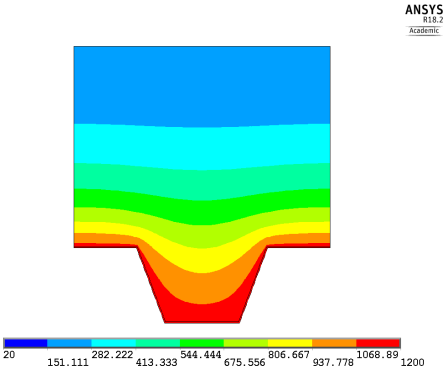
t = 163 min

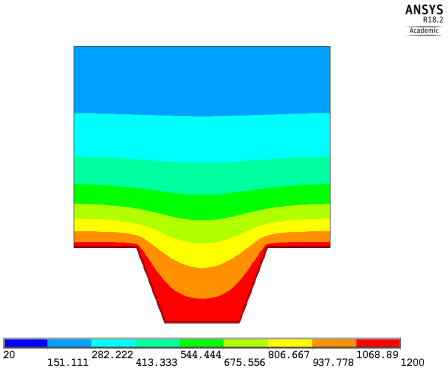


Tempo Crítico = 218 min



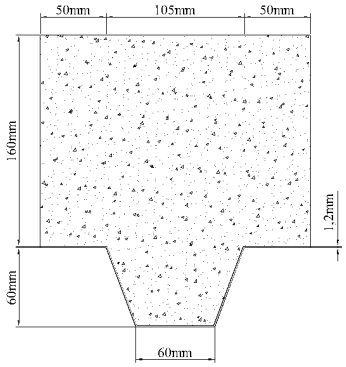
t = 14400s



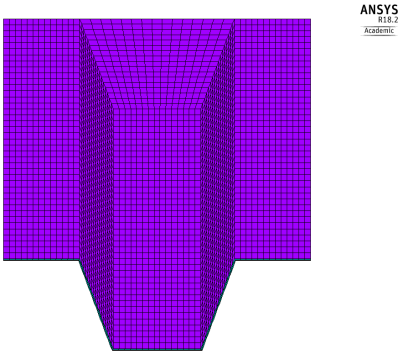


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.2mm

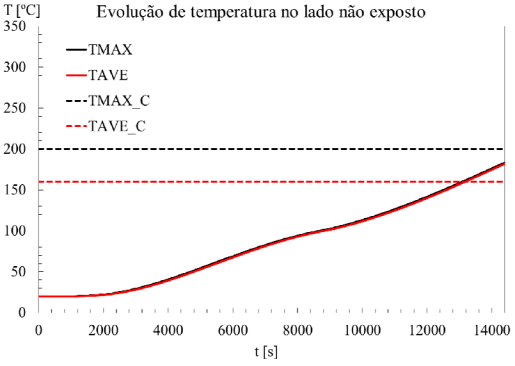
GEOMETRIA



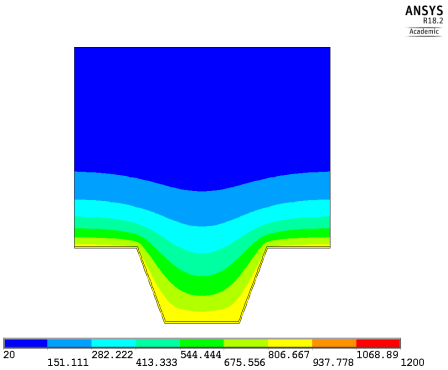
Malha



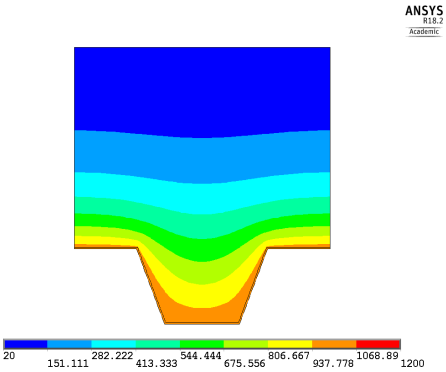
t = 54 min



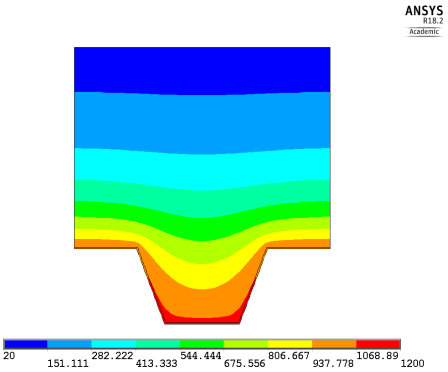
t = 109 min



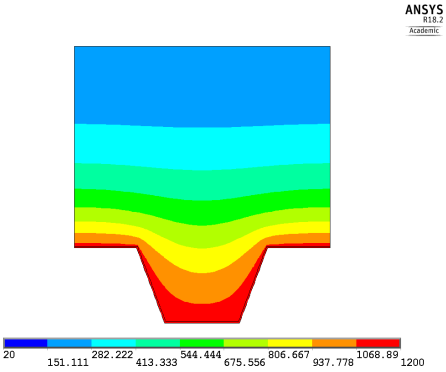
t = 164 min

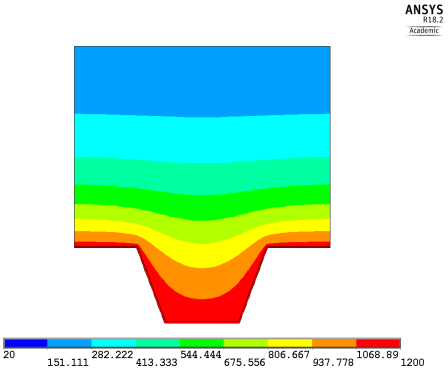


Tempo Crítico = 219 min



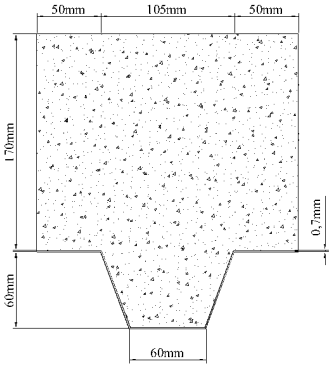
t = 14400s





LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.7mm

GEOMETRIA



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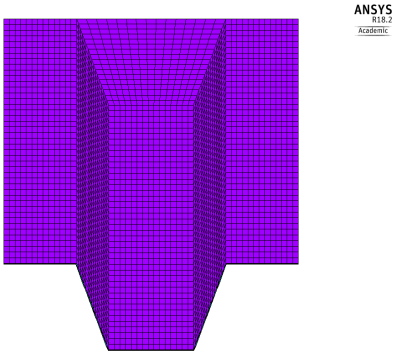
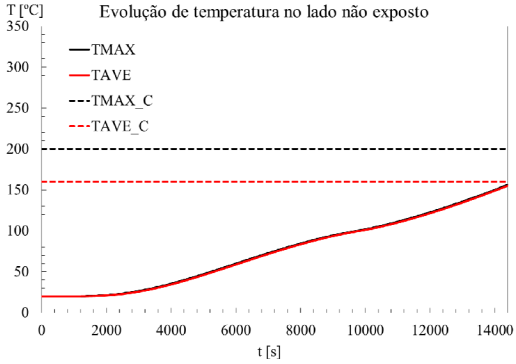
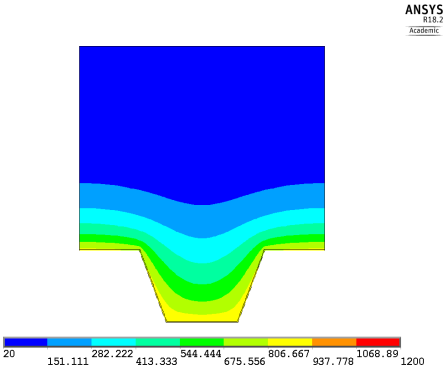


t = 48 min

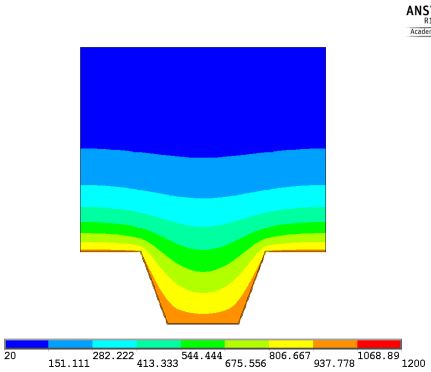


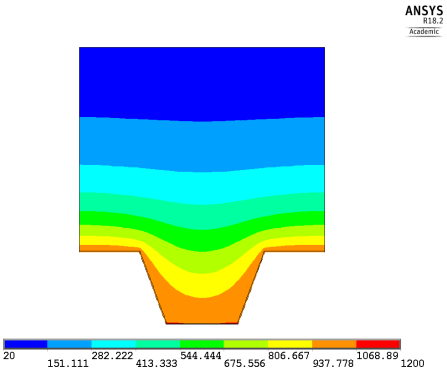
t = 96 min



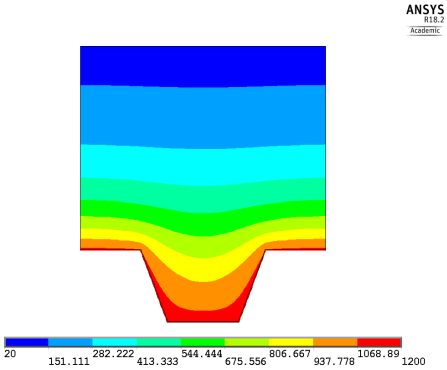
t = 144 min

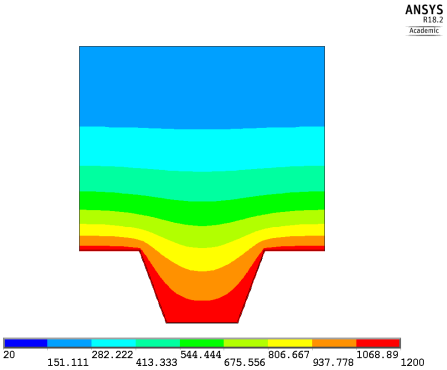
t = 192 min





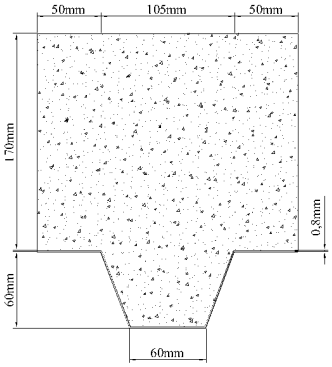
t = 14400s



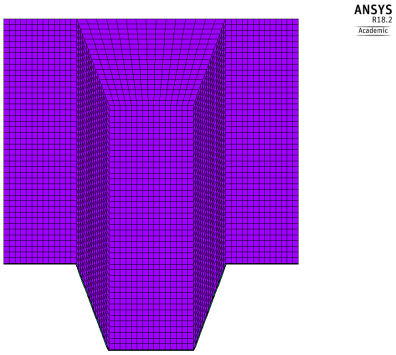


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.8mm

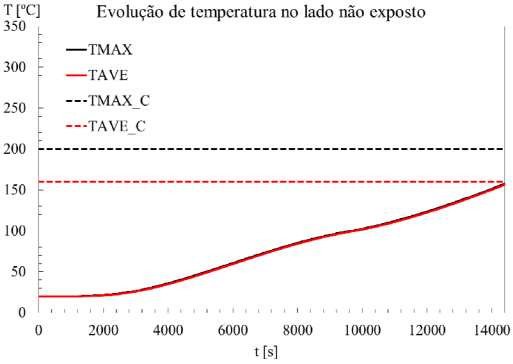
GEOMETRIA



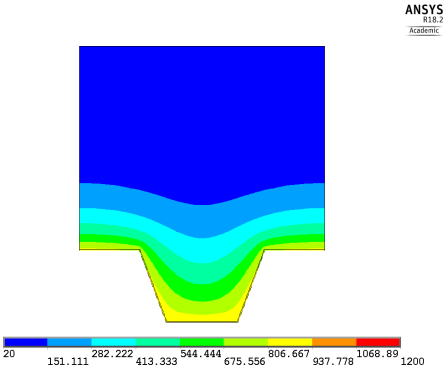
Malha



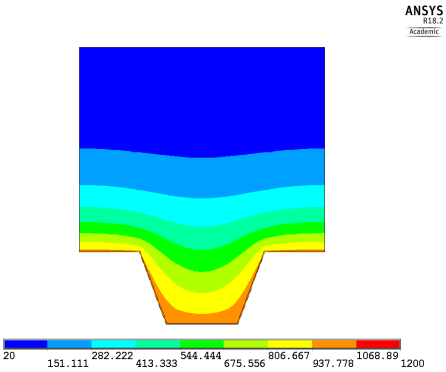
t = 48 min



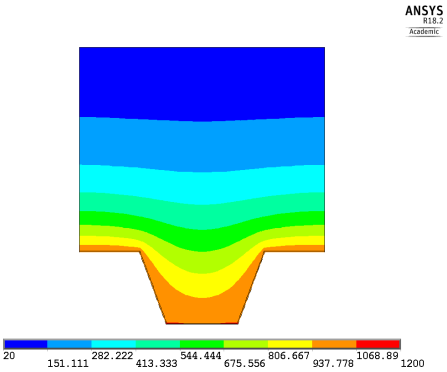
t = 96 min



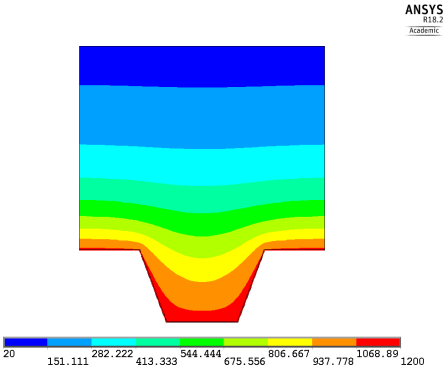
t = 144 min

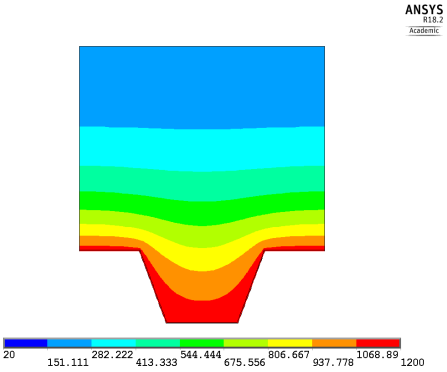


t = 192 min



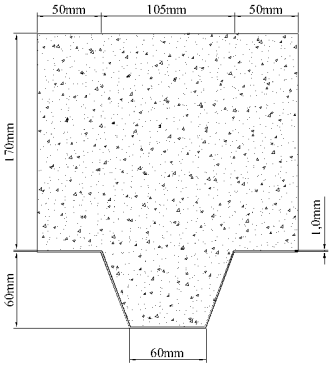
t = 14400s



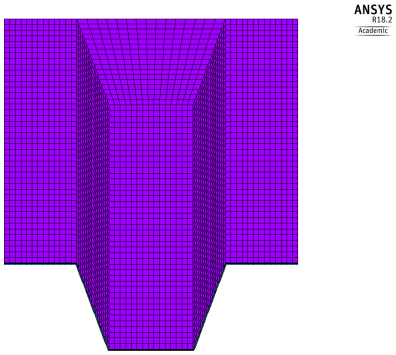


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.0mm

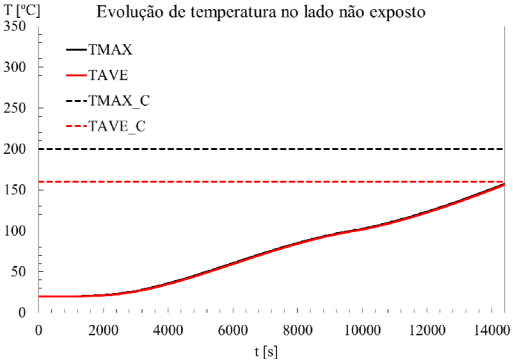
GEOMETRIA



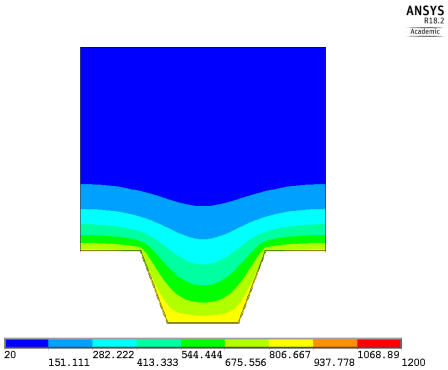
Malha



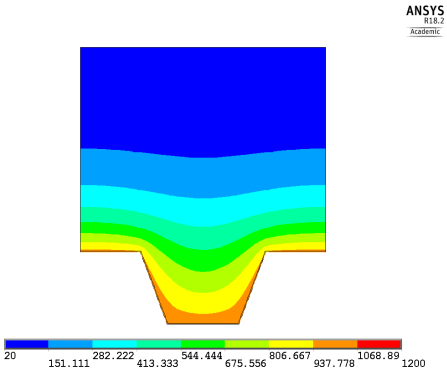
t = 48 min



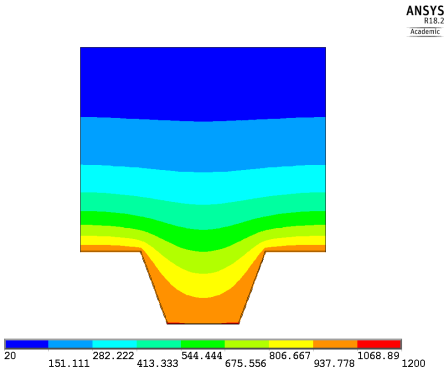
t = 96 min



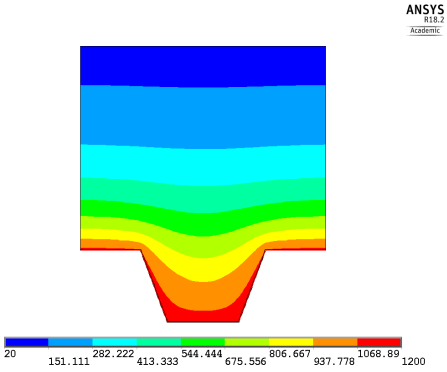
t = 144 min

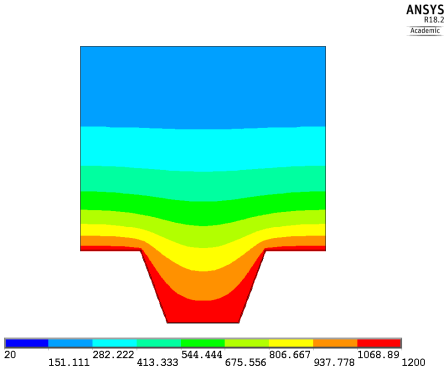


t = 192 min



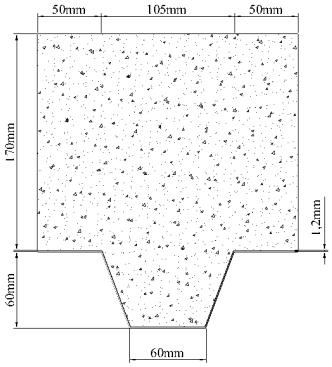
t = 14400s



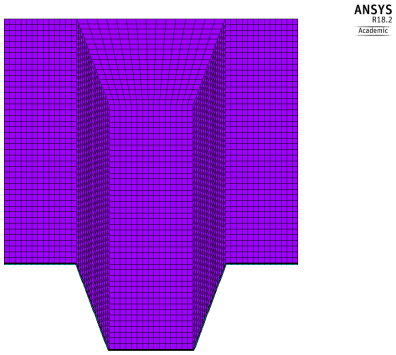


LAJE MISTA TRAPEZOIDAL (L1/L2=105/60mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.2mm

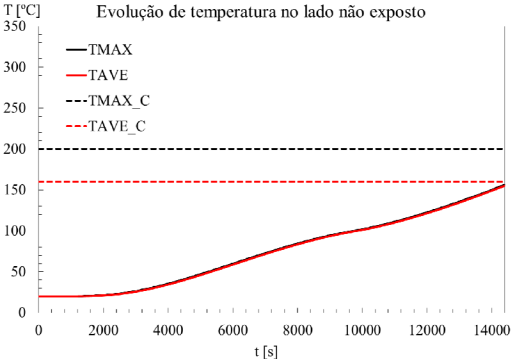
GEOMETRIA



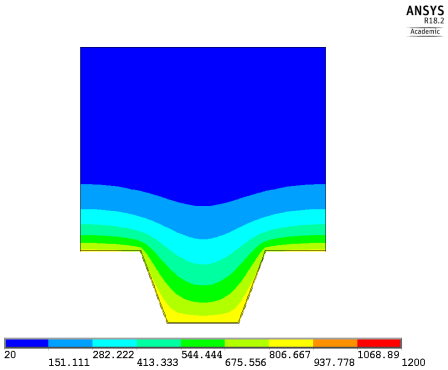
Malha



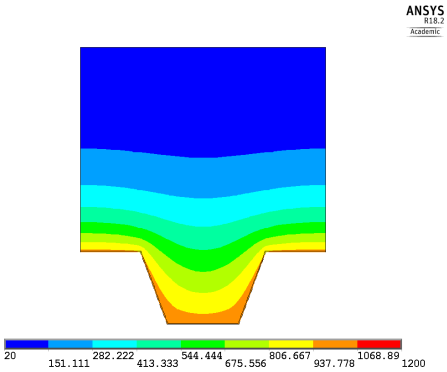
t = 48 min



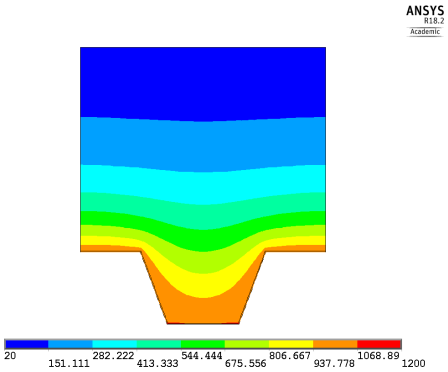
t = 96 min



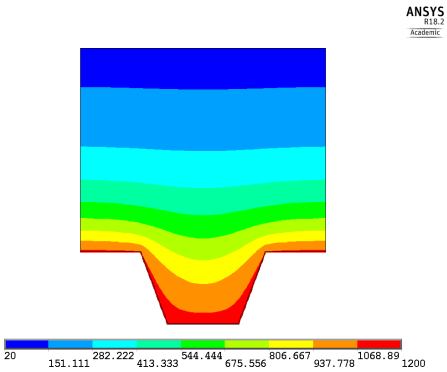
t = 144 min

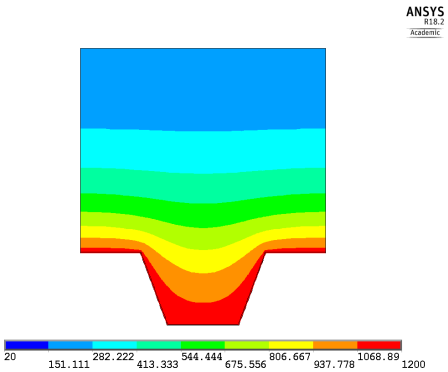


t = 192 min



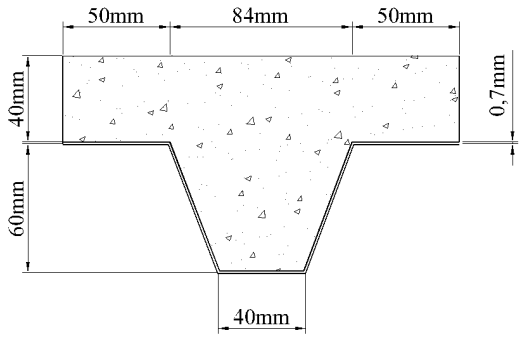
t = 14400s



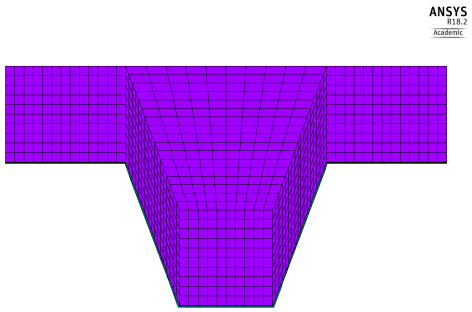


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.7mm

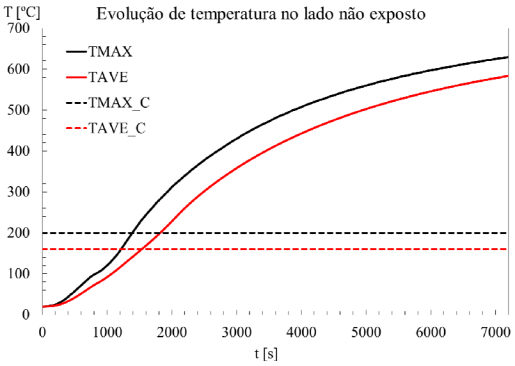
GEOMETRIA



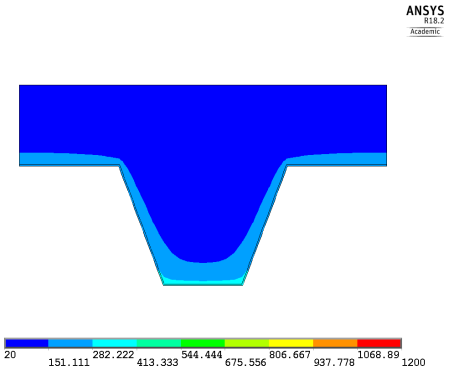
Malha



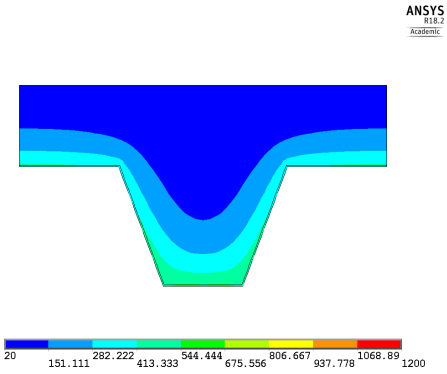
t = 5 min



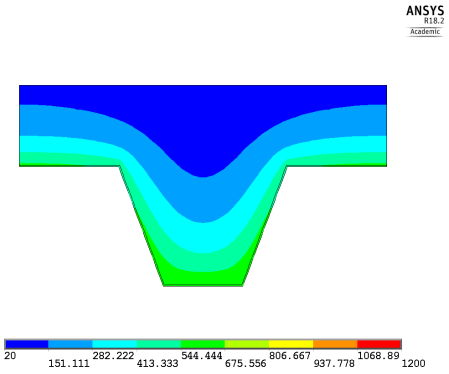
t = 11 min



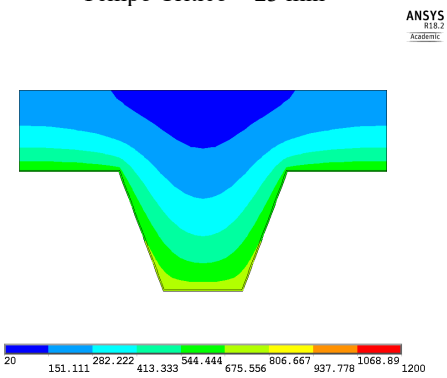
t = 17 min

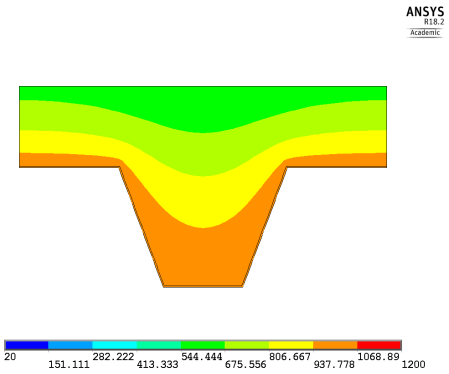


Tempo Crítico = 23 min



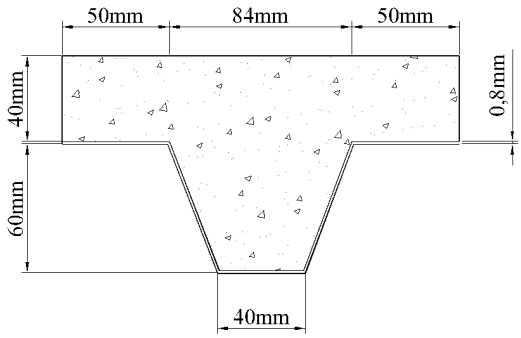
t = 7200s



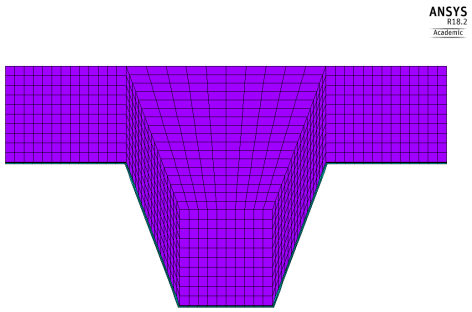


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.8mm

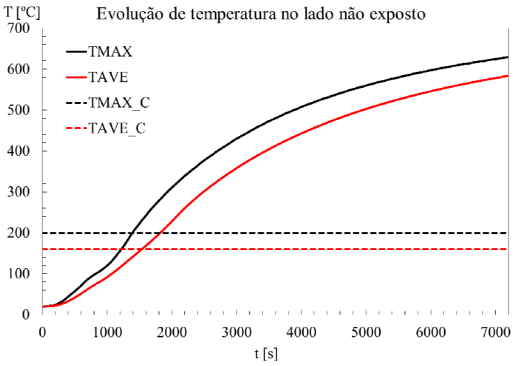
GEOMETRIA



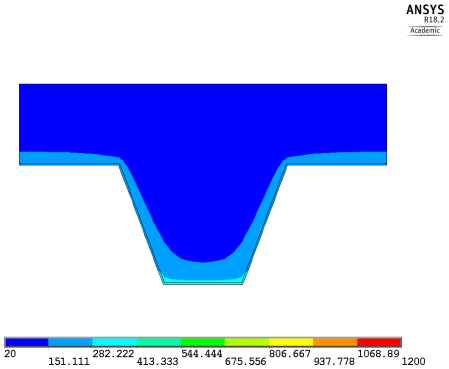
Malha



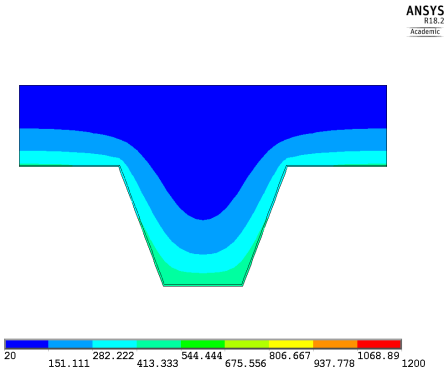
t = 5 min



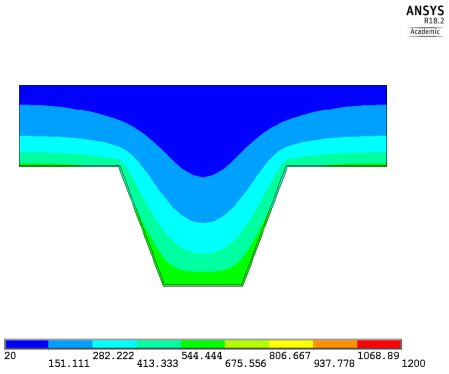
t = 11 min



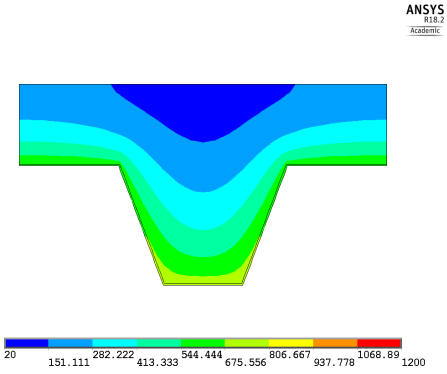
t = 17 min

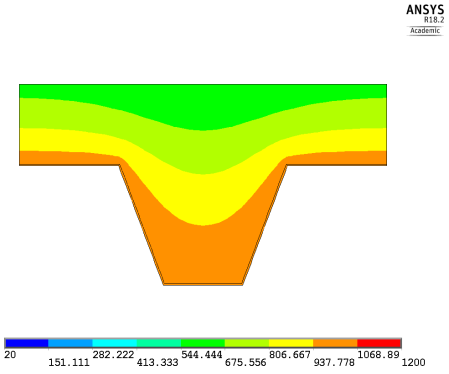


Tempo Crítico = 23 min



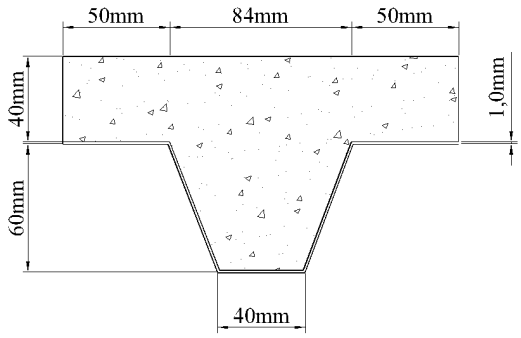
t = 7200s



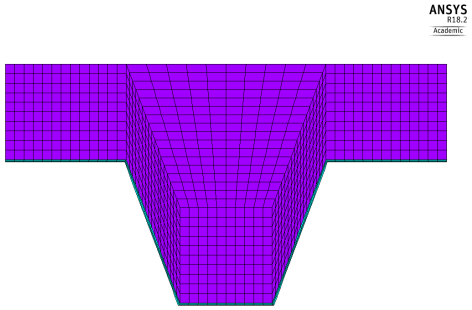


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.0mm

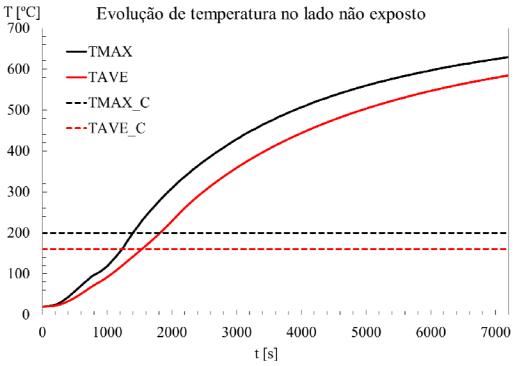
GEOMETRIA



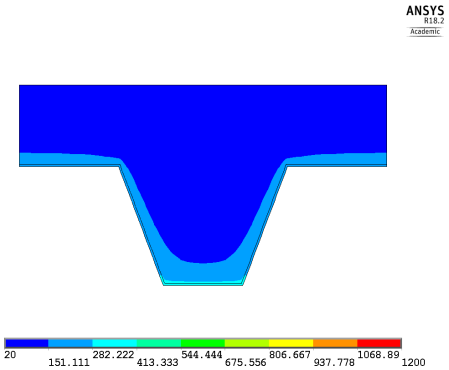
Malha



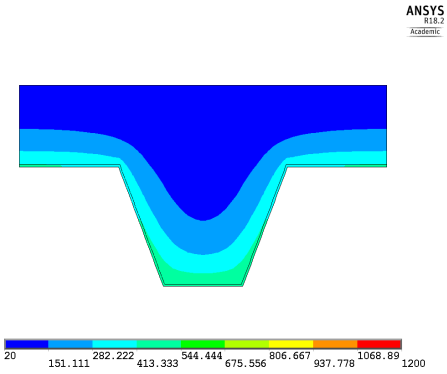
t = 5 min



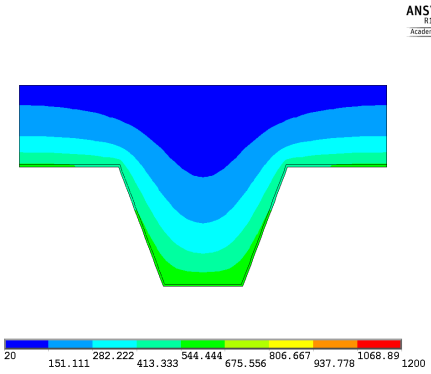
t = 11 min



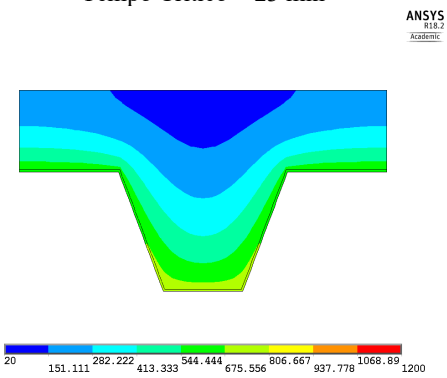
t = 17 min

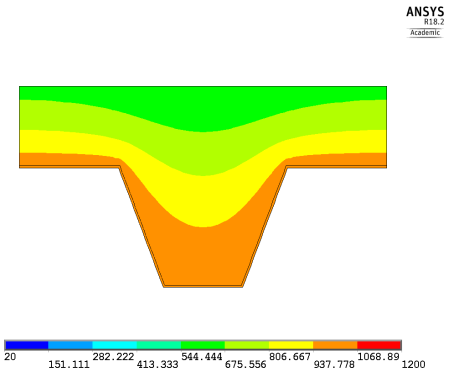


Tempo Crítico = 23 min

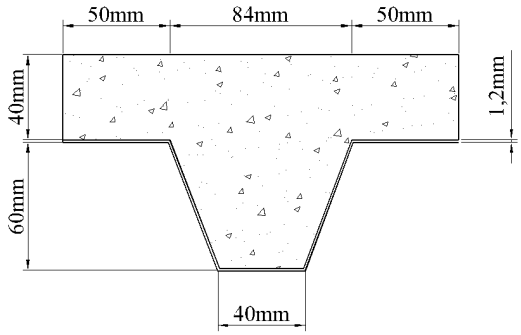


t = 7200s

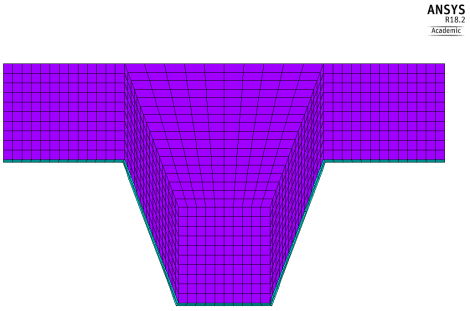


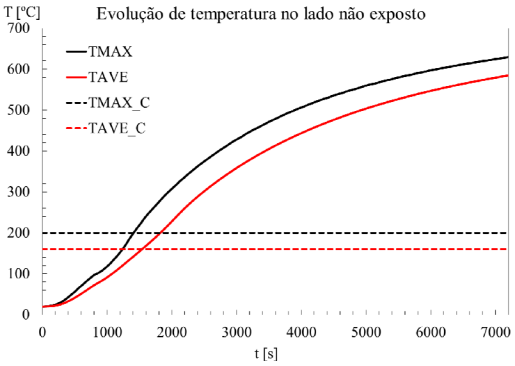


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.2mm

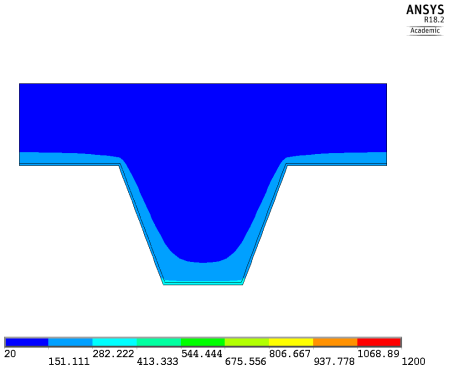


Malha



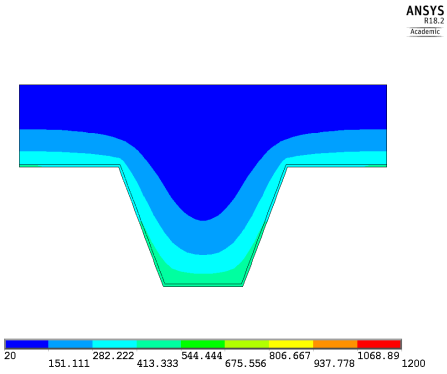


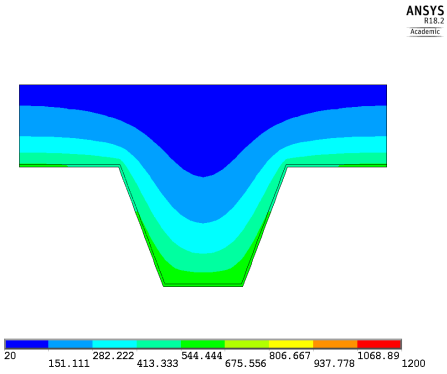
t = 5 min



t = 11 min

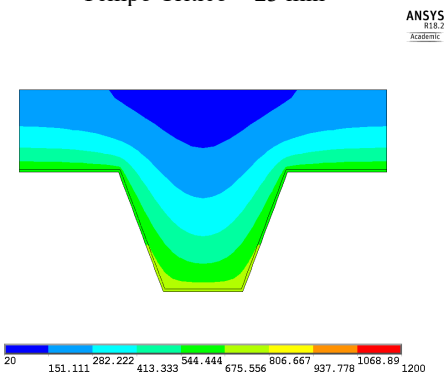
t = 17 min

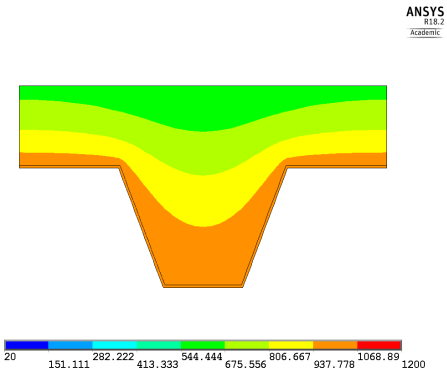




Tempo Crítico = 23 min

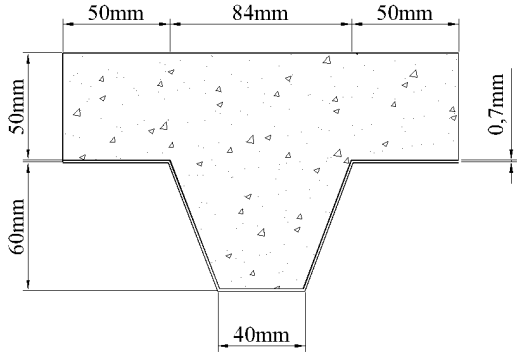
t = 7200s



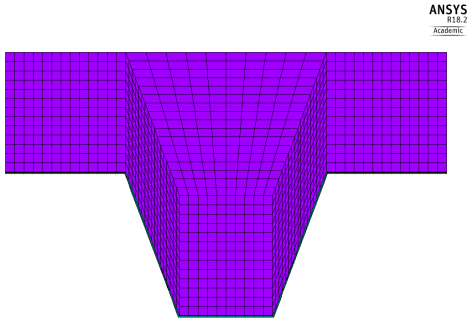


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.7mm

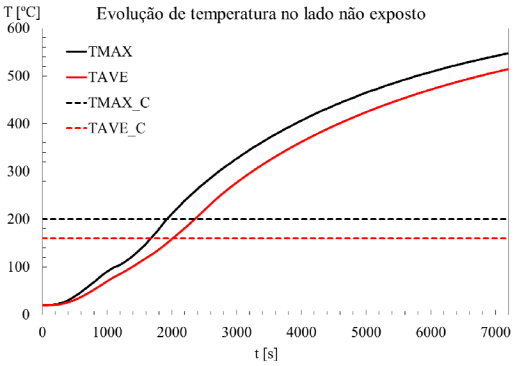
GEOMETRIA



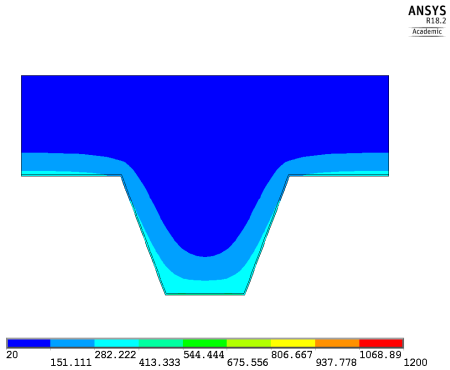
Malha



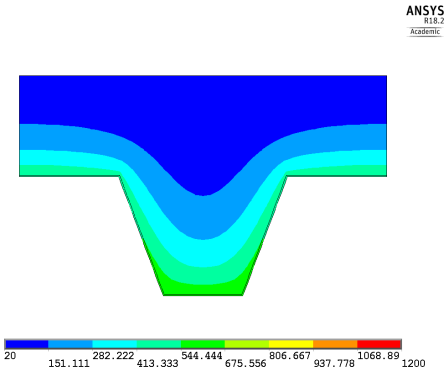
t = 8 min



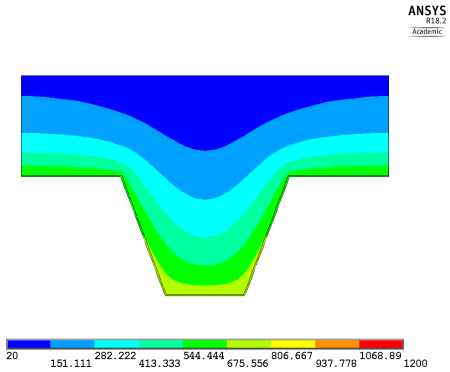
t = 16 min



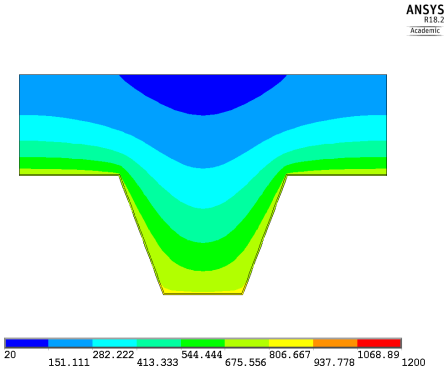
t = 24 min

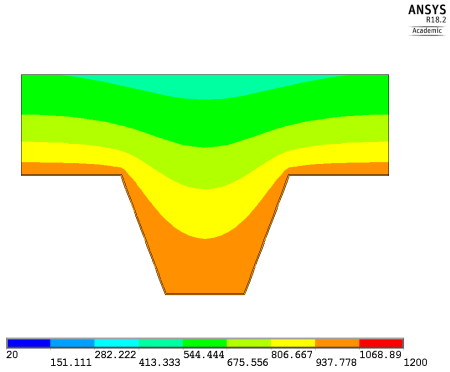


Tempo Crítico = 32 min



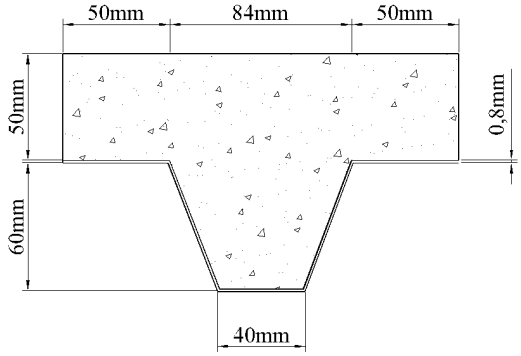
t = 7200s



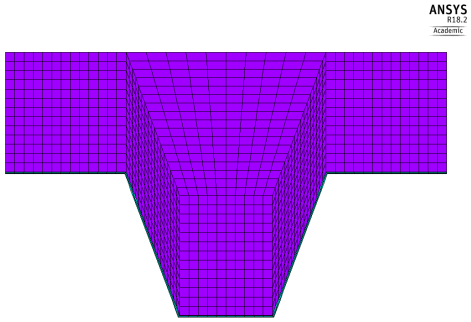


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.8mm

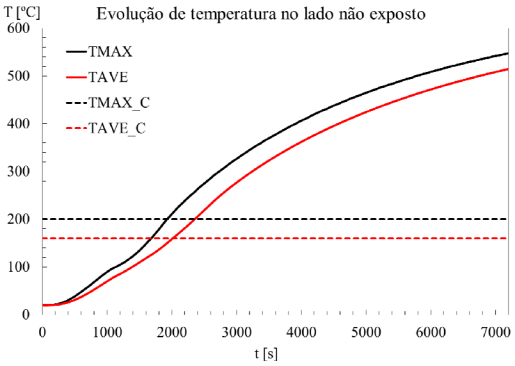
GEOMETRIA



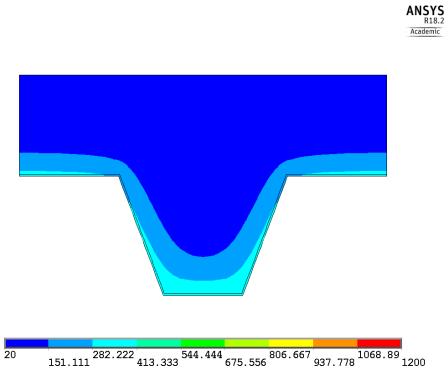
Malha



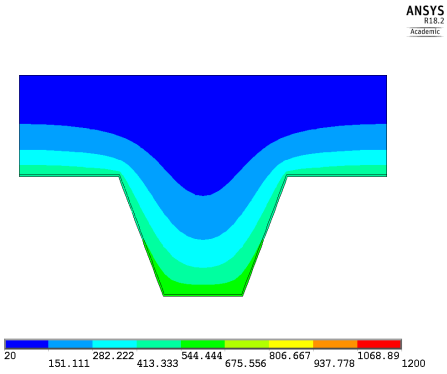
t = 8 min



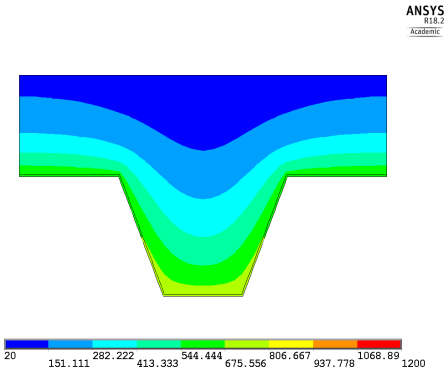
t = 16 min



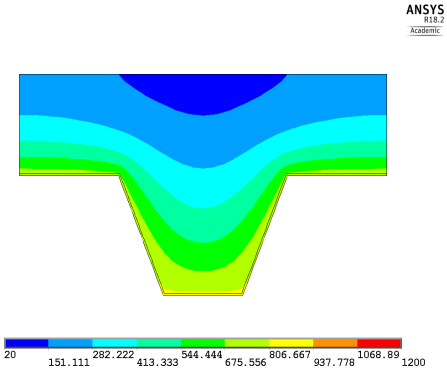
t = 24 min

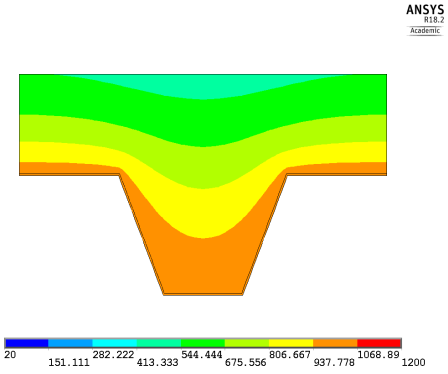


Tempo Crítico = 32 min



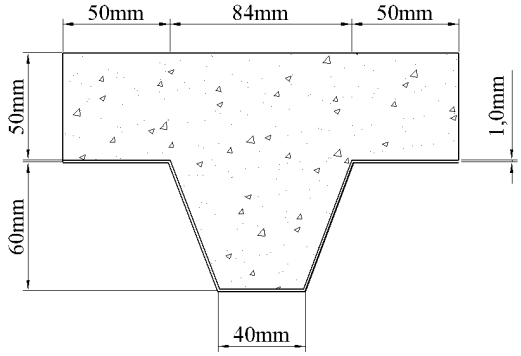
t = 7200s



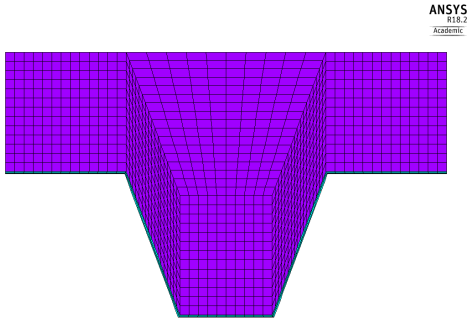


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.0mm

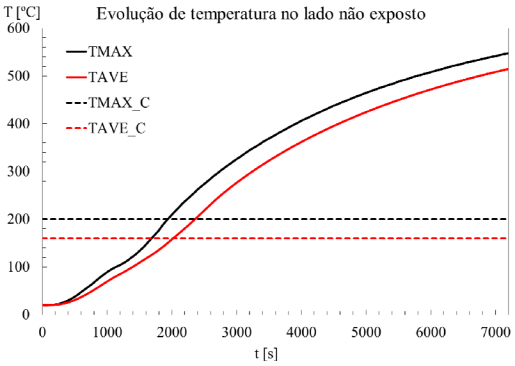
GEOMETRIA



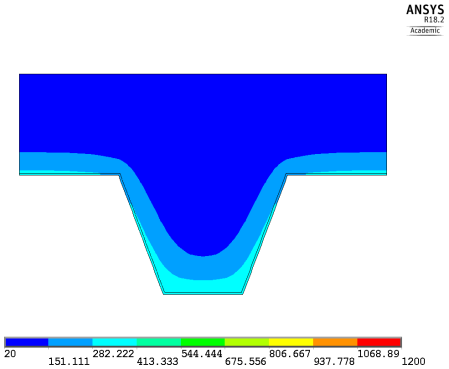
Malha



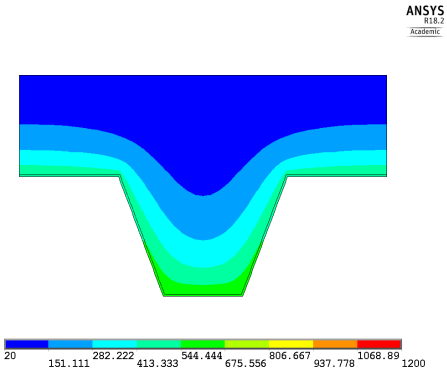
t = 8 min



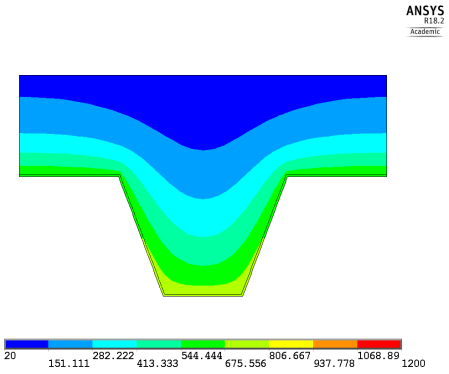
t = 16 min



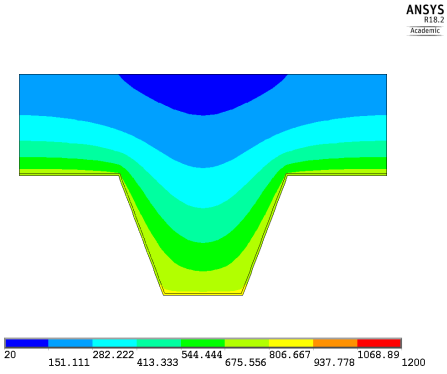
t = 24 min

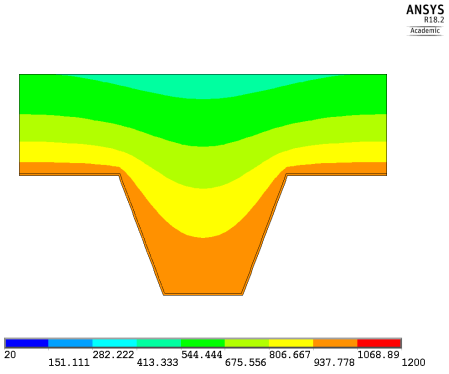


Tempo Crítico = 32 min

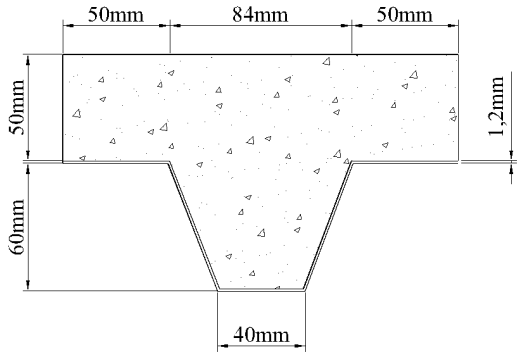


t = 7200s

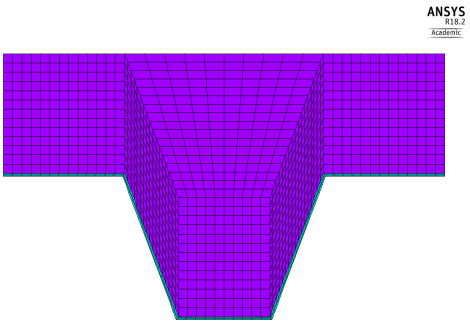


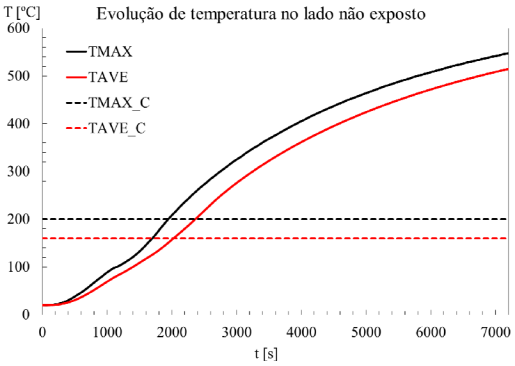


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.2mm

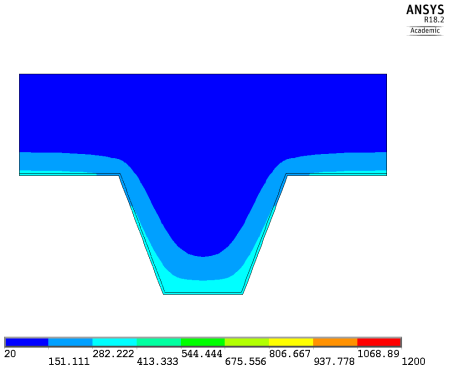


Malha



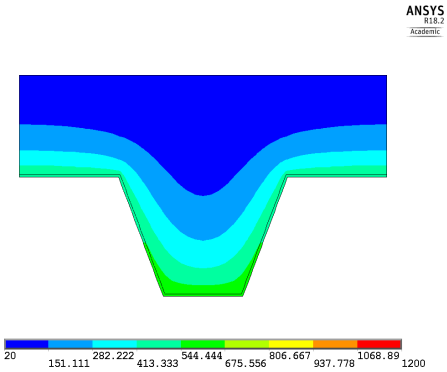


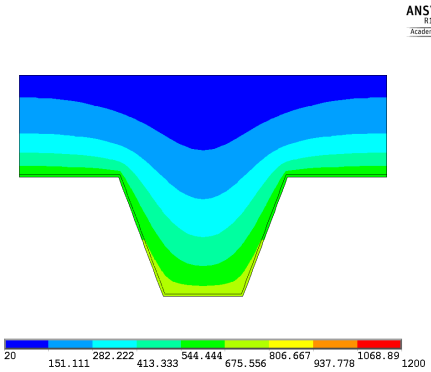
t = 8 min



t = 16 min

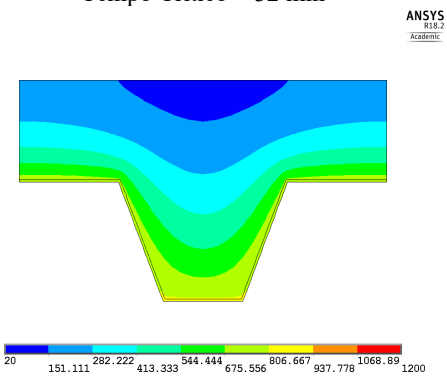
t = 24 min

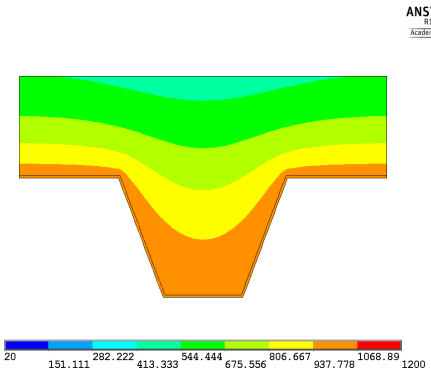




Tempo Crítico = 32 min

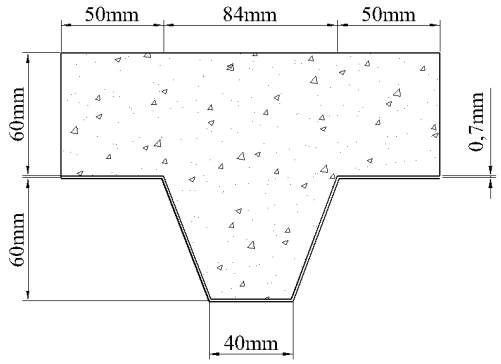
t = 7200s



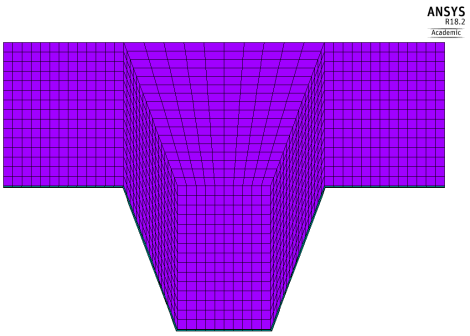


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.7mm

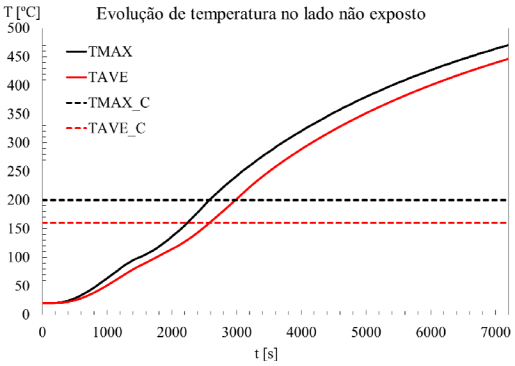
GEOMETRIA



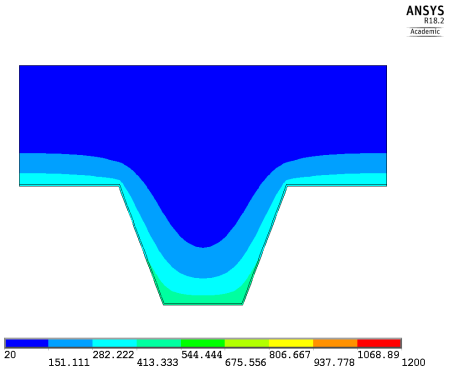
Malha



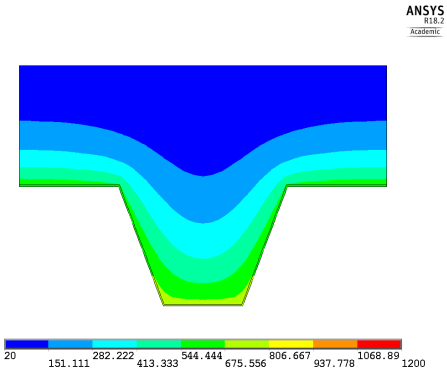
t = 10 min



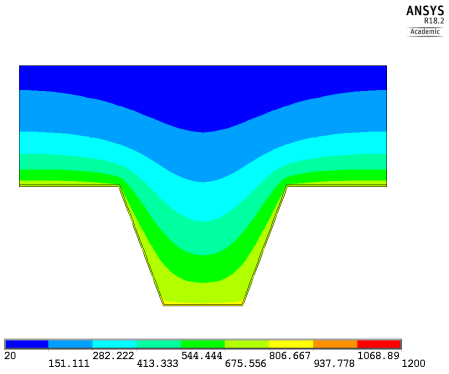
t = 21 min



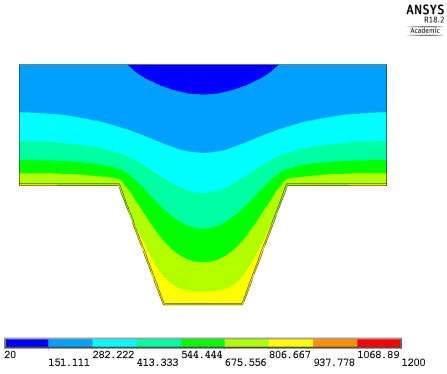
t = 31 min

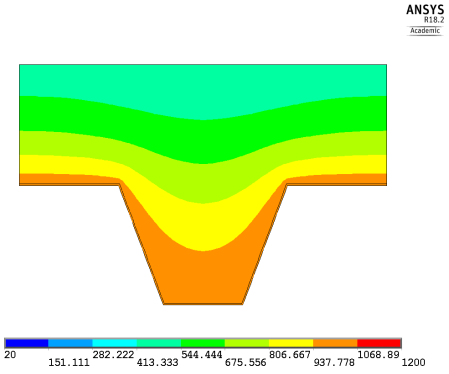


Tempo Crítico = 42 min



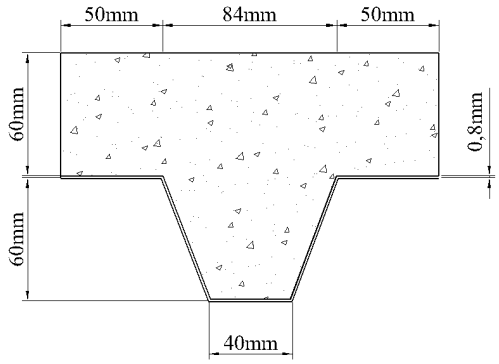
t = 7200s



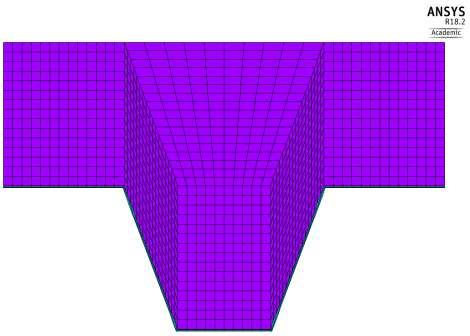


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.8mm

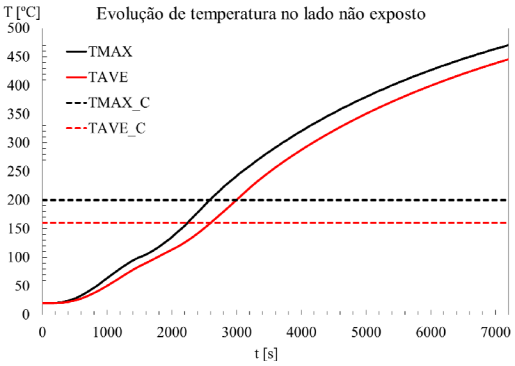
GEOMETRIA



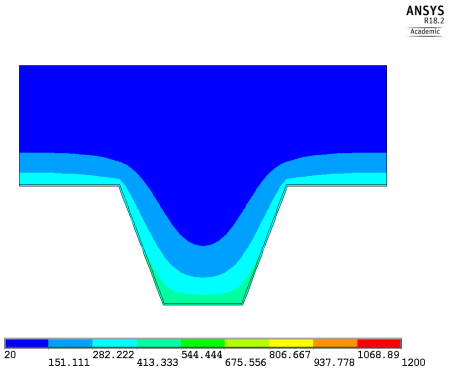
Malha



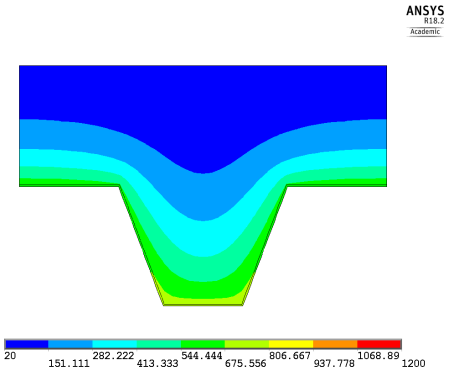
t = 10 min



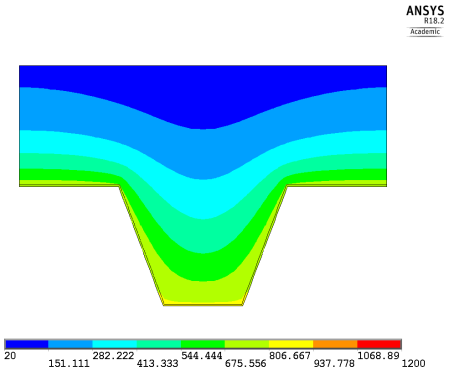
t = 21 min



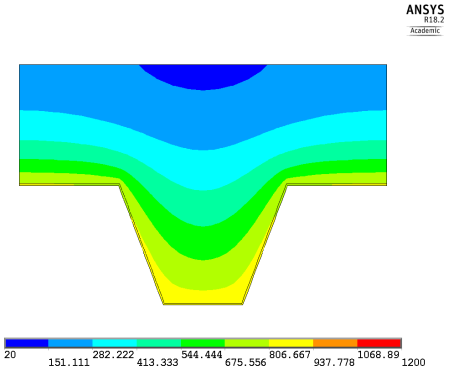
t = 32 min

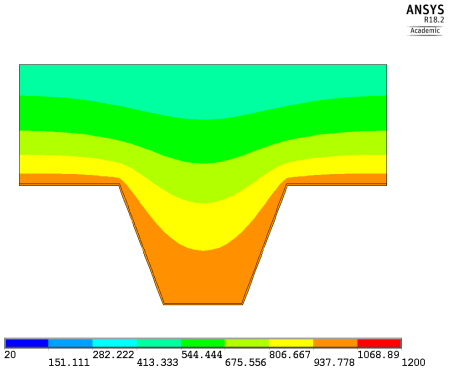


Tempo Crítico = 43 min



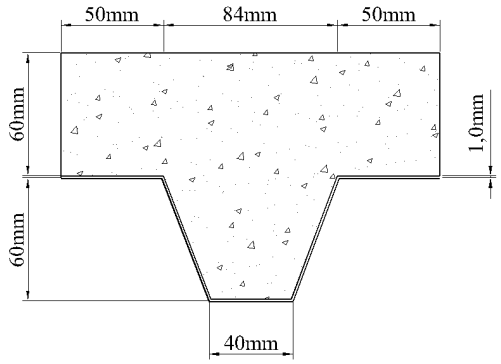
t = 7200s



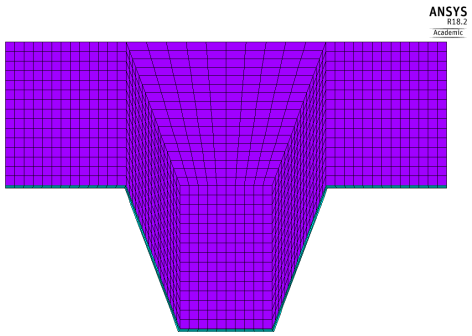


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.0mm

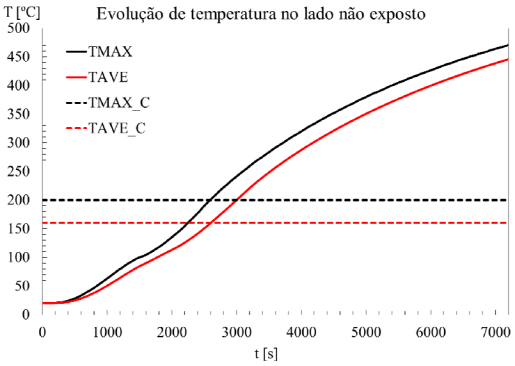
GEOMETRIA



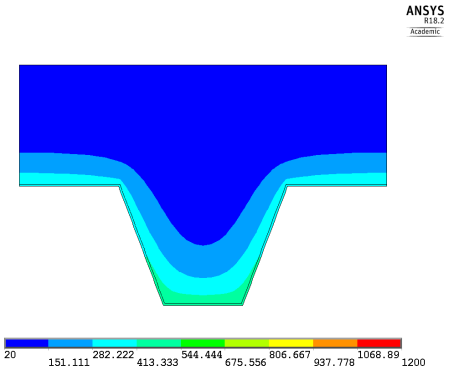
Malha



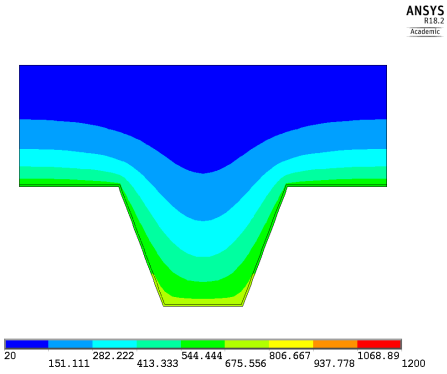
t = 10 min



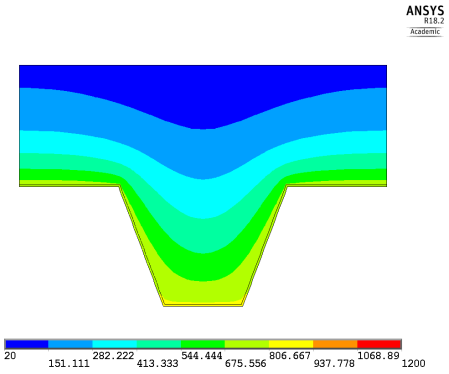
t = 21 min



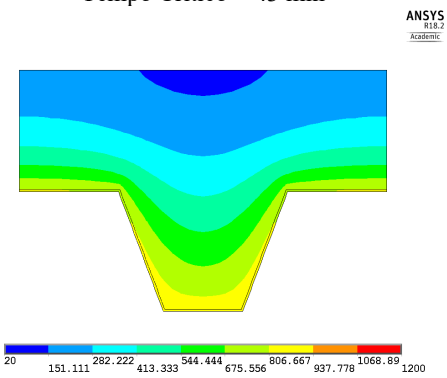
t = 32 min

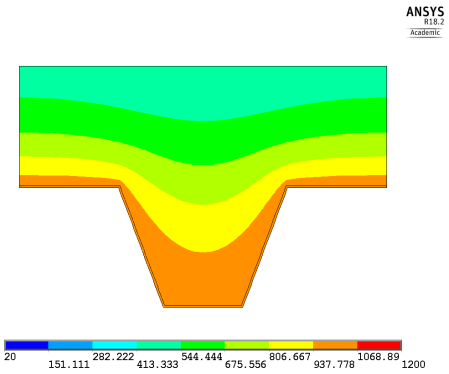


Tempo Crítico = 43 min

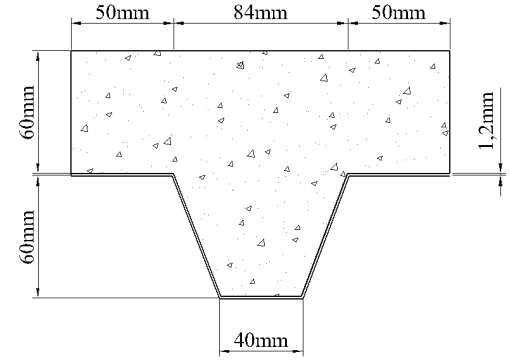


t = 7200s

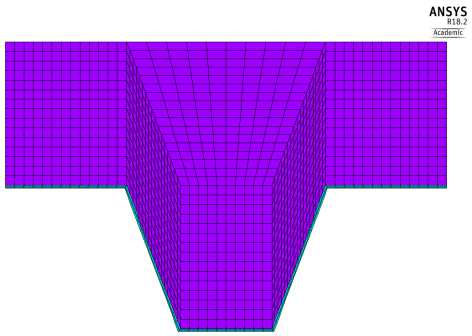




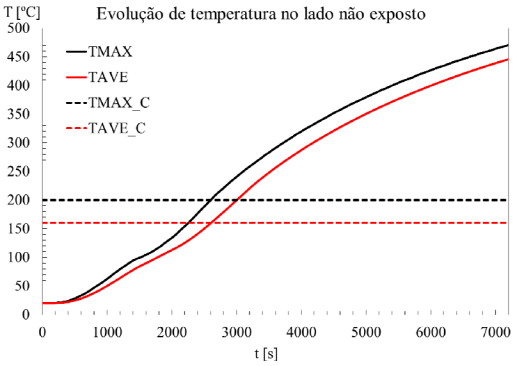
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.2mm



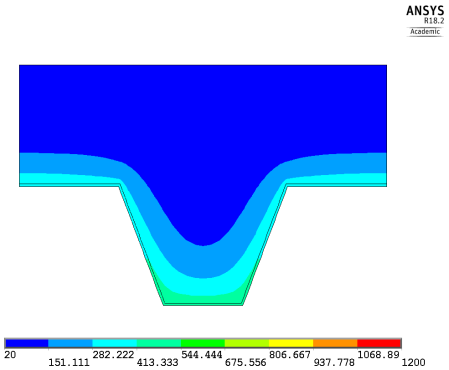
Malha



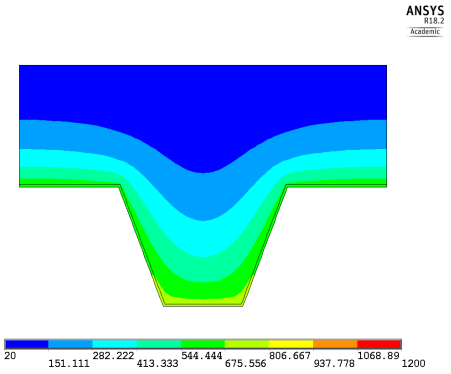
t = 10 min



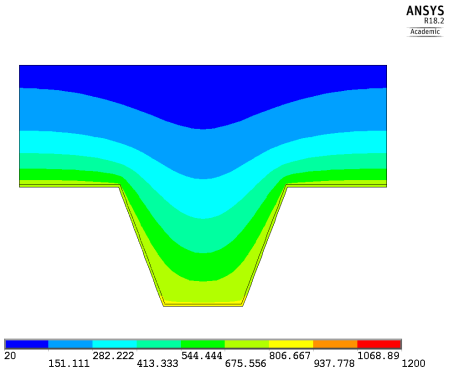
t = 21 min



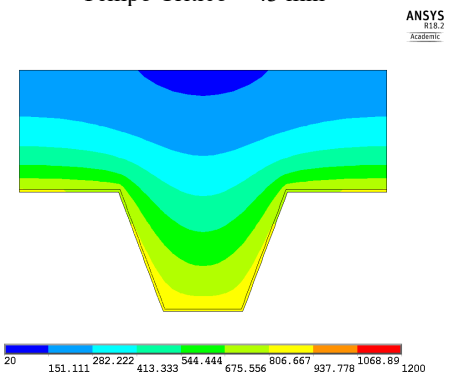
t = 32 min

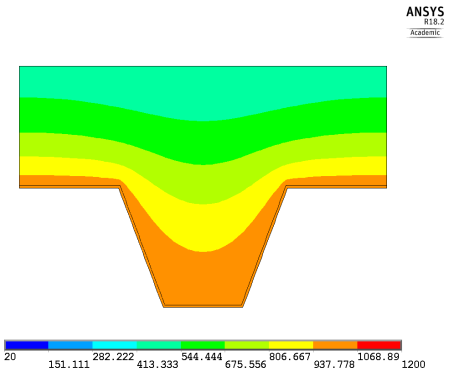


Tempo Crítico = 43 min



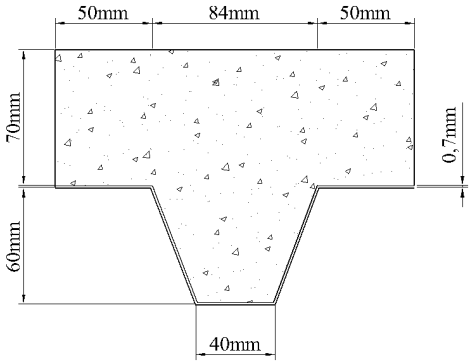
t = 7200s



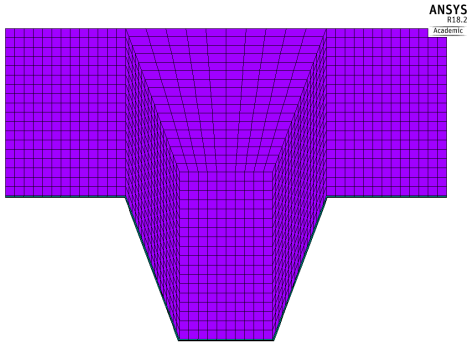


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.7mm

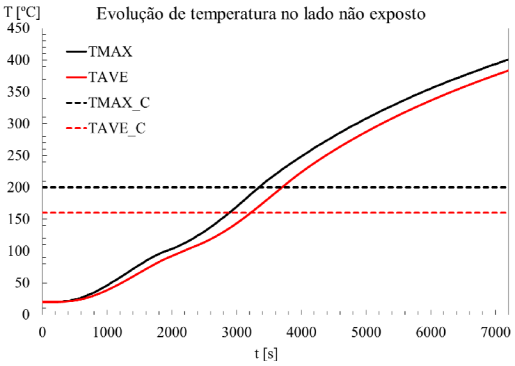
GEOMETRIA



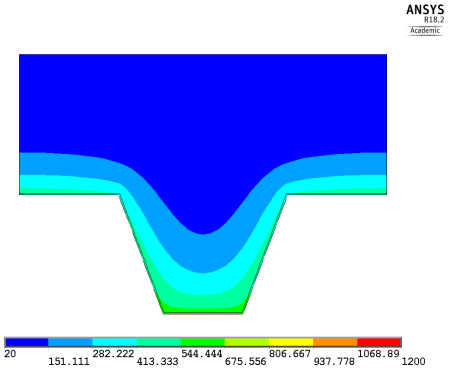
Malha



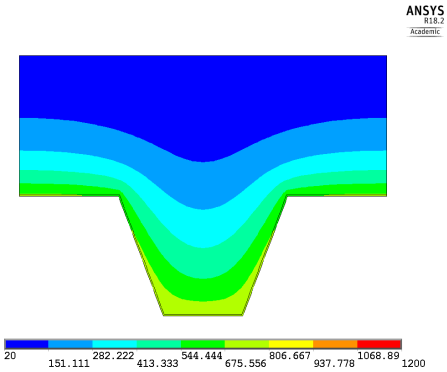
t = 13 min



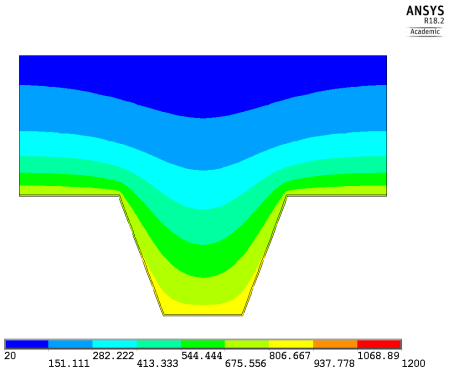
t = 23 min



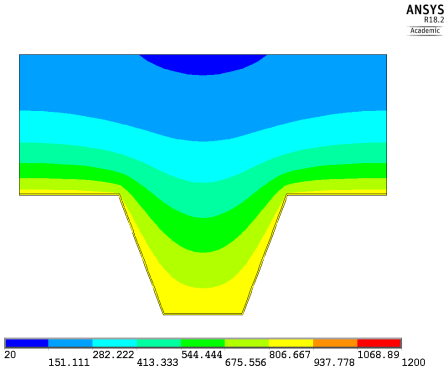
t = 59 min

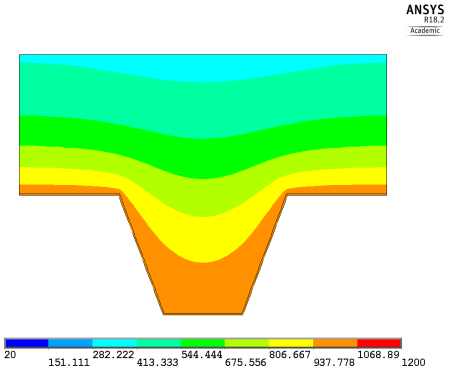


Tempo Crítico = 53 min



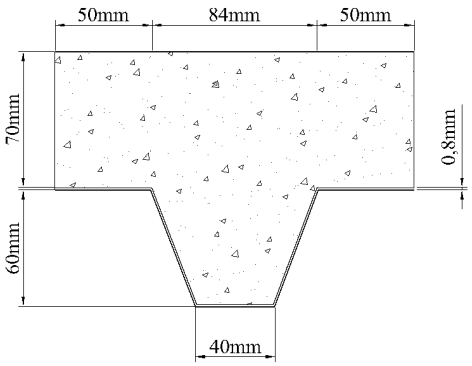
t = 7200s



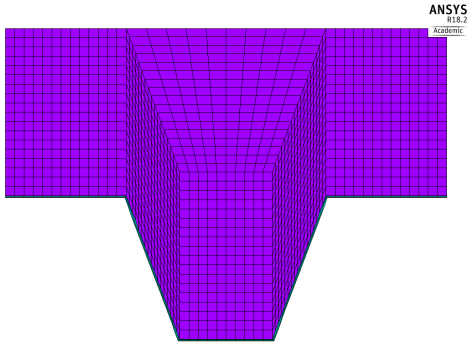


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.8mm

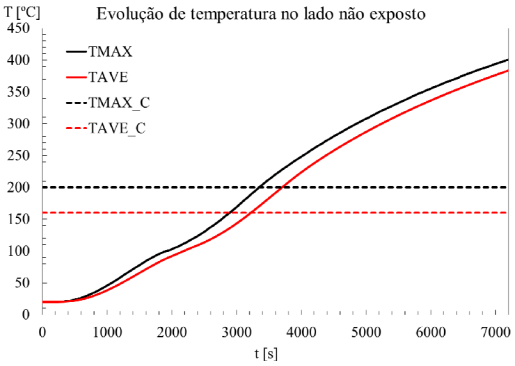
GEOMETRIA



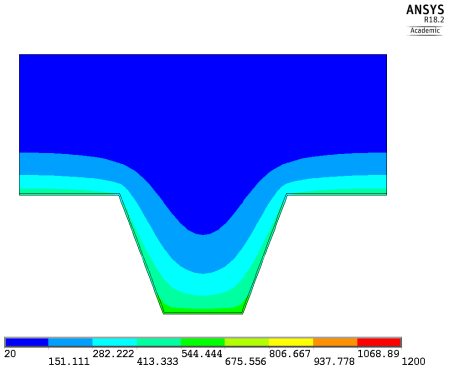
Malha



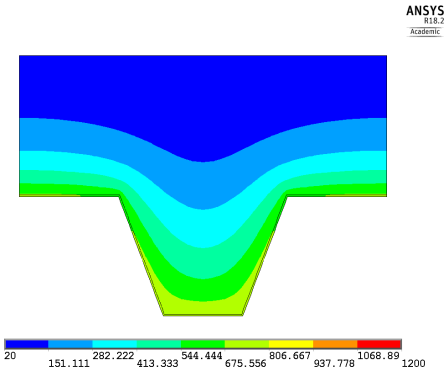
t = 13 min



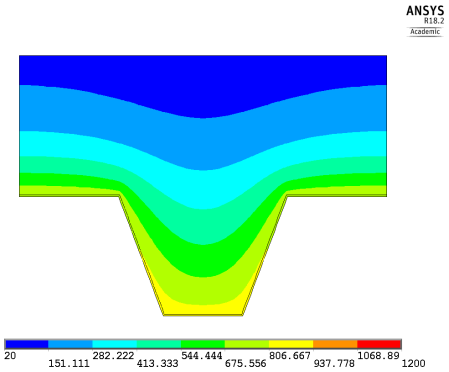
t = 23 min



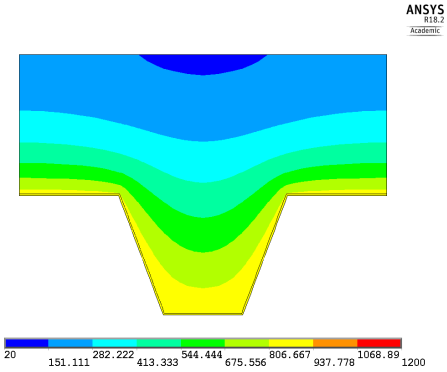
t = 59 min

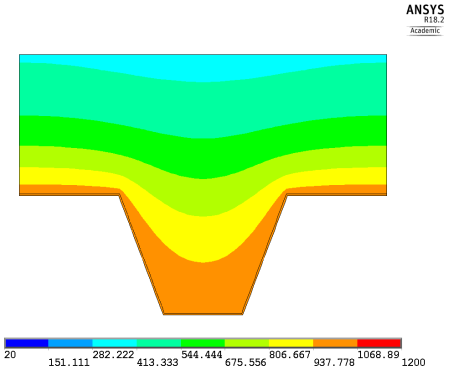


Tempo Crítico = 53 min



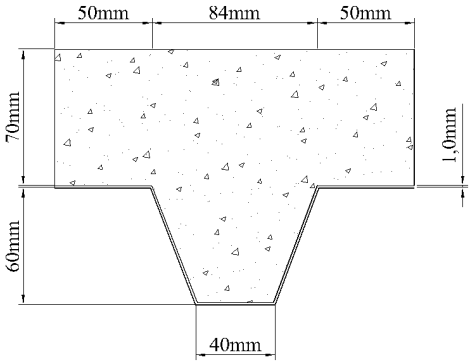
t = 7200s



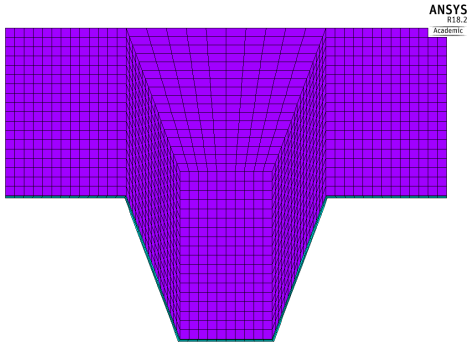


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.0mm

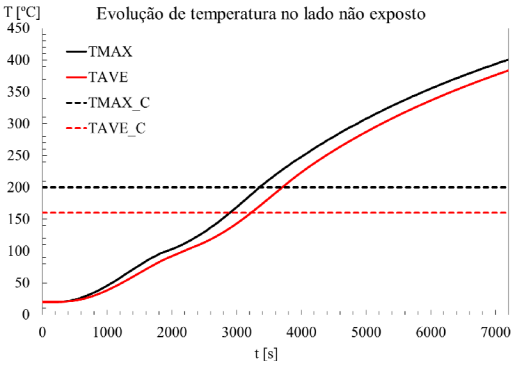
GEOMETRIA



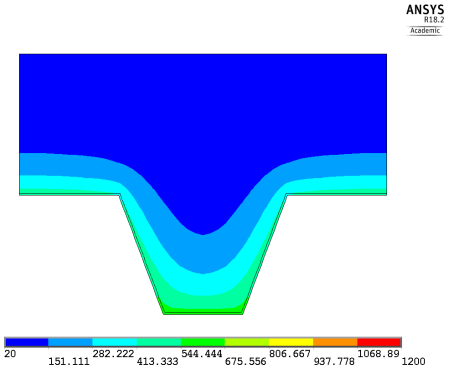
Malha



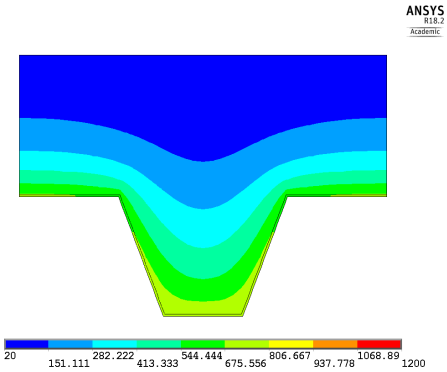
t = 13 min



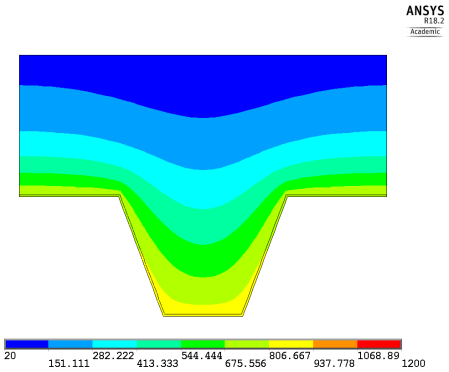
t = 23 min



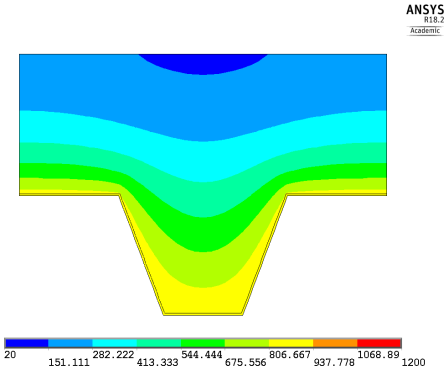
t = 59 min

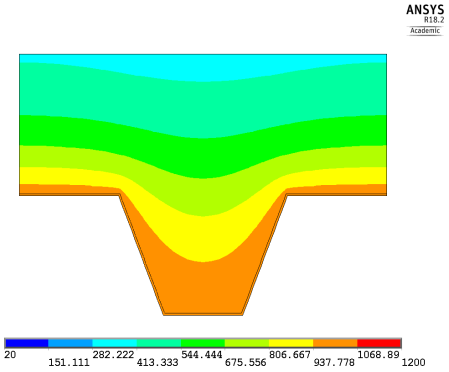


Tempo Crítico = 53 min



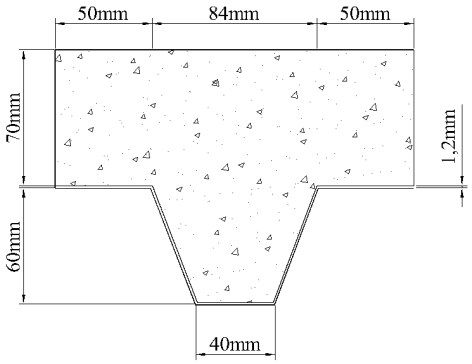
t = 7200s



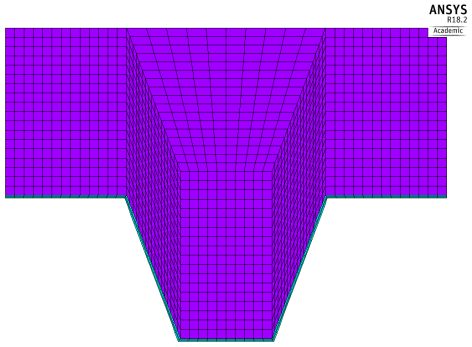


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.2mm

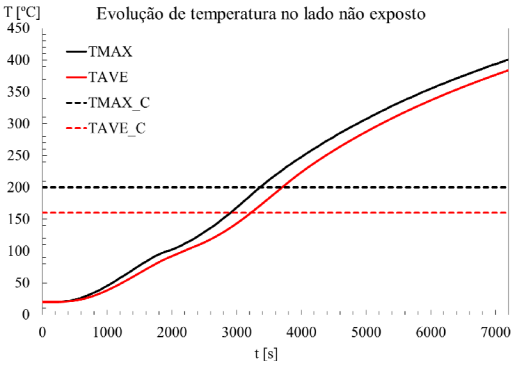
GEOMETRIA



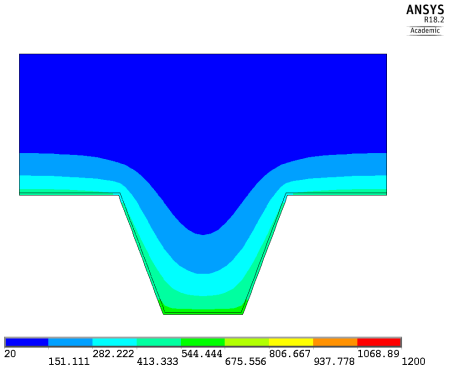
Malha



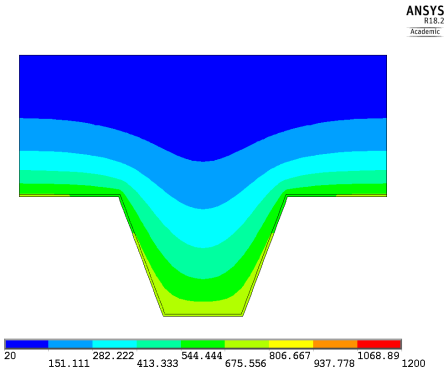
t = 13 min



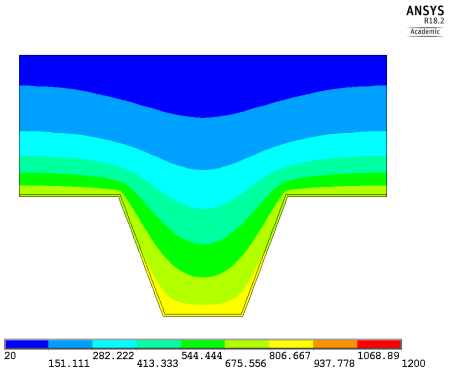
t = 23 min



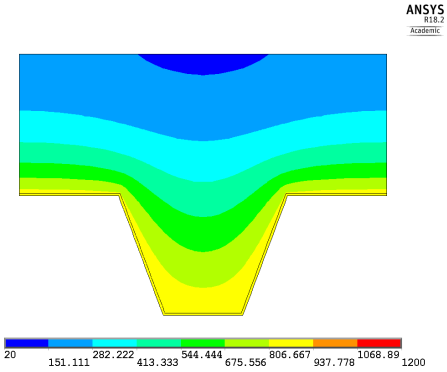
t = 59 min

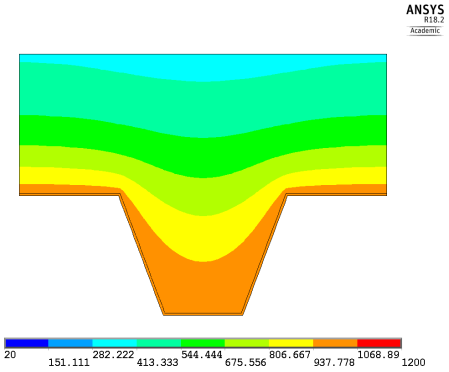


Tempo Crítico = 53 min



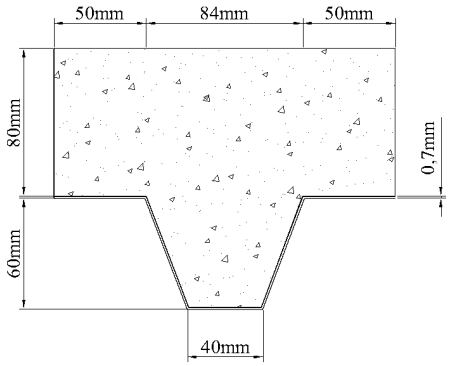
t = 7200s



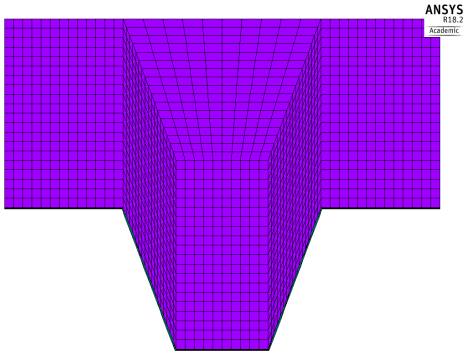


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.7mm

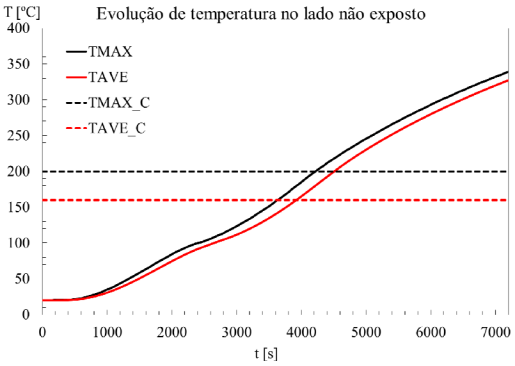
GEOMETRIA



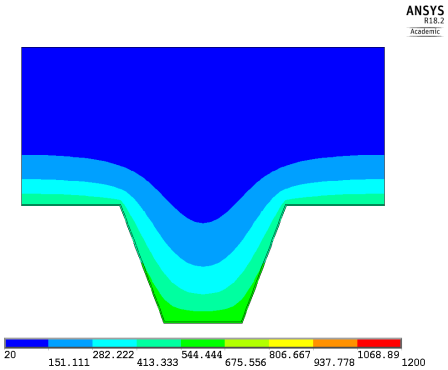
Malha



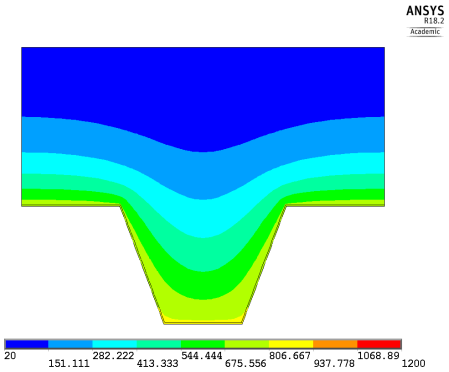
t = 16 min



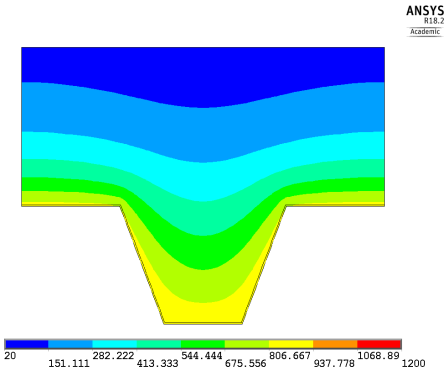
t = 38 min



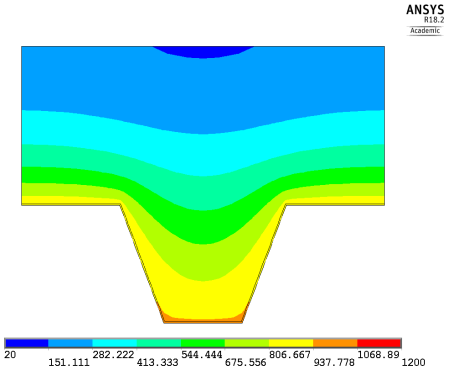
t = 42 min

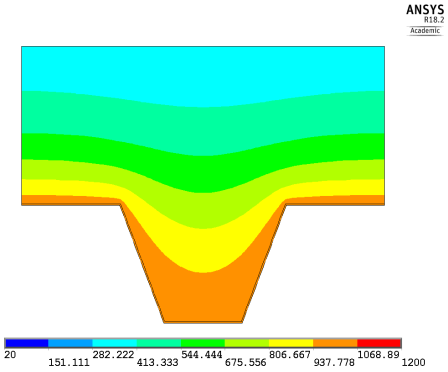


Tempo Crítico = 65 min



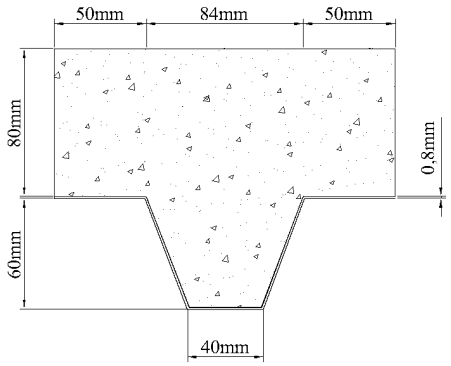
t = 7200s



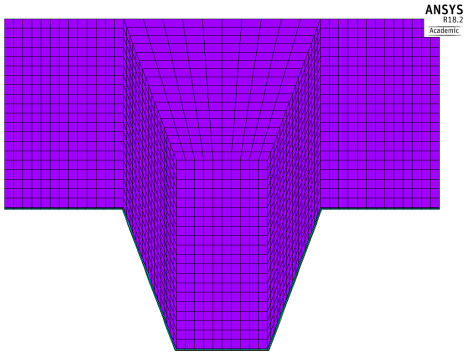


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.8mm

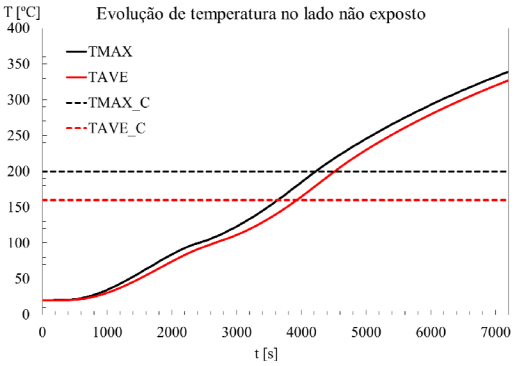
GEOMETRIA



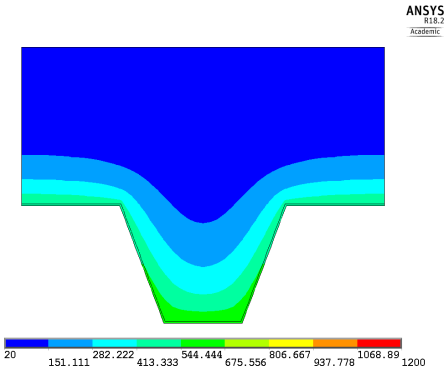
Malha



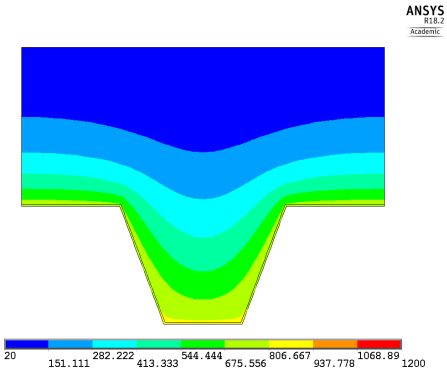
t = 16 min



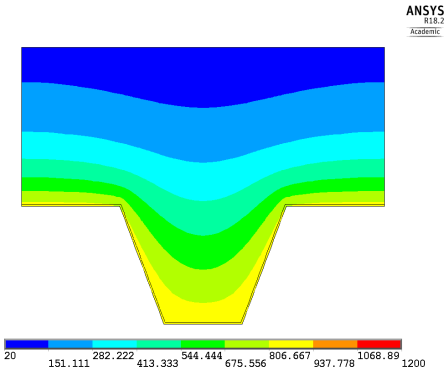
t = 38 min



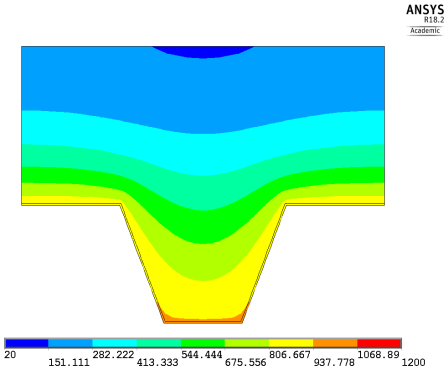
t = 42 min

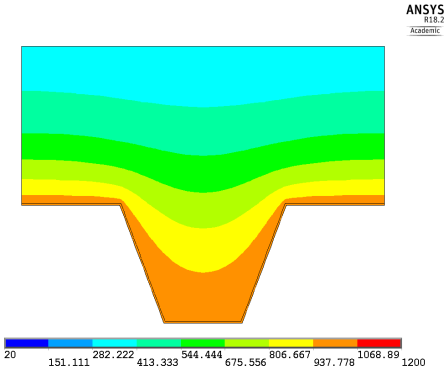


Tempo Crítico = 65 min



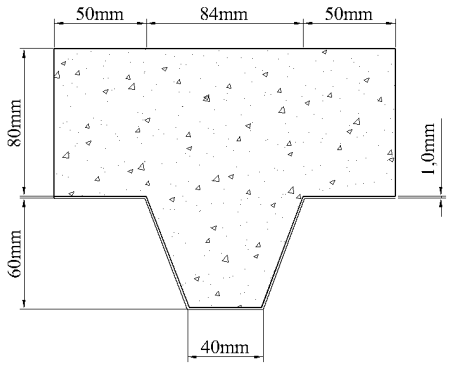
t = 7200s



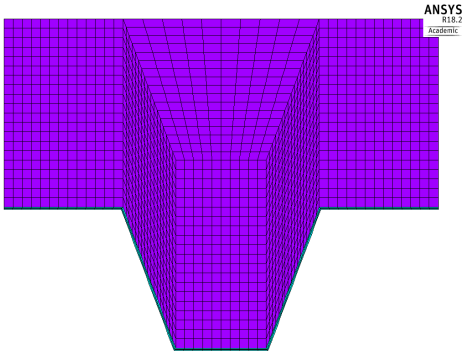


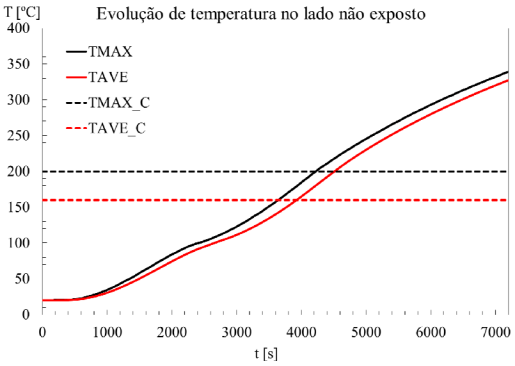
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.0mm

GEOMETRIA

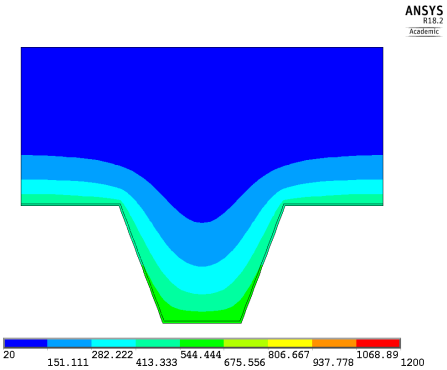


Malha



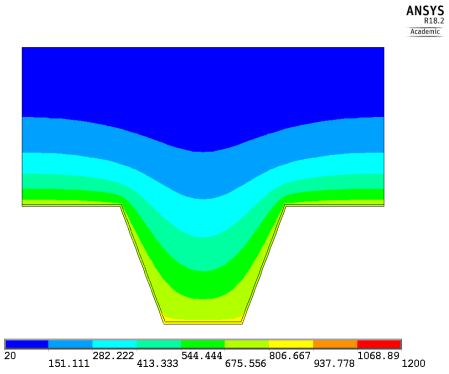


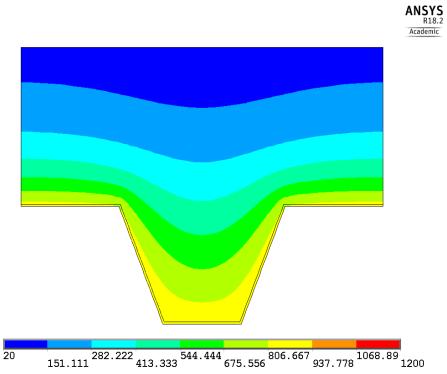
t = 16 min



t = 38 min

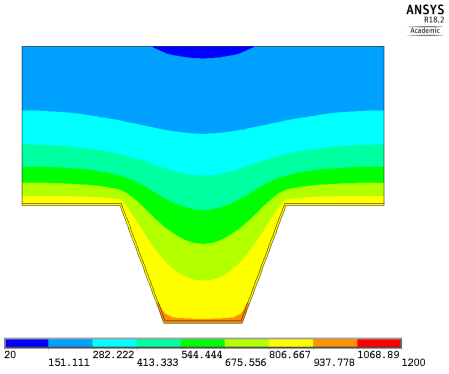
t = 42 min

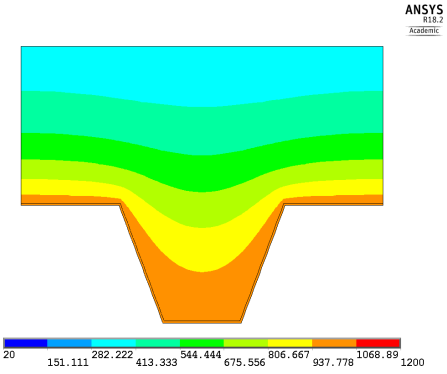




Tempo Crítico = 65 min

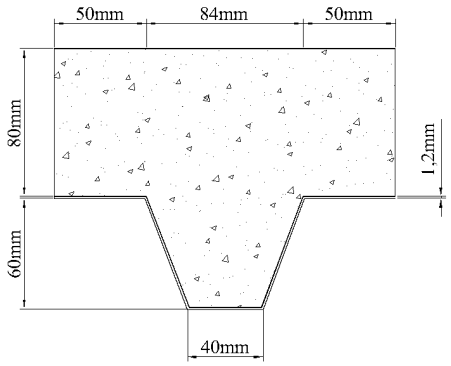
t = 7200s



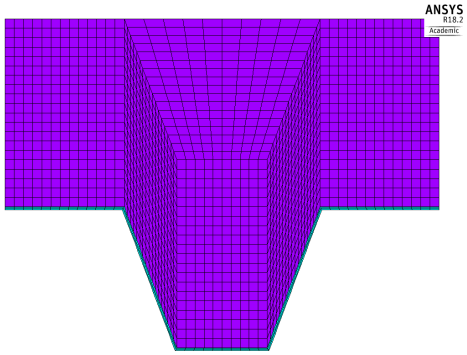


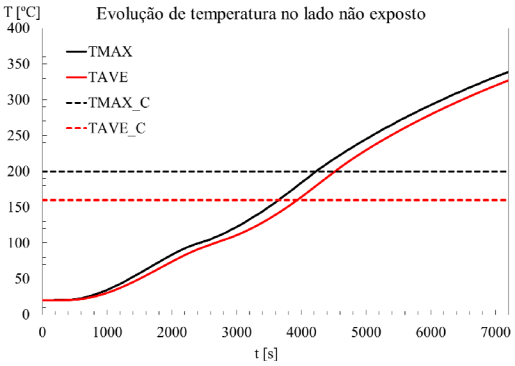
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.2mm

GEOMETRIA

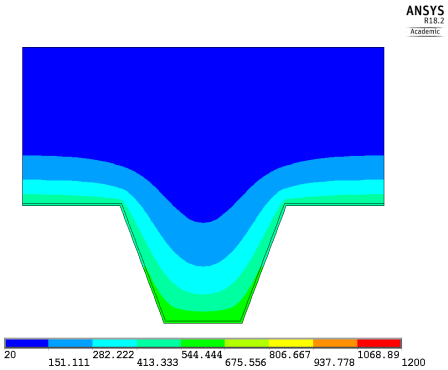


Malha

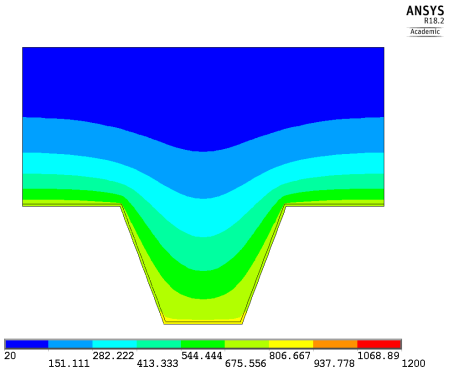




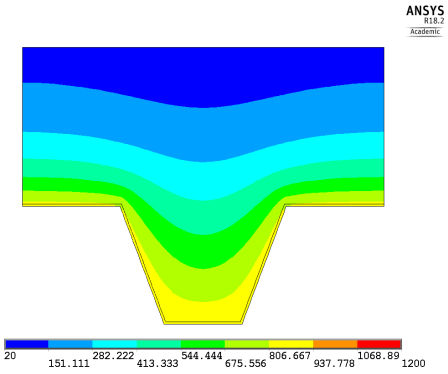
t = 16 min



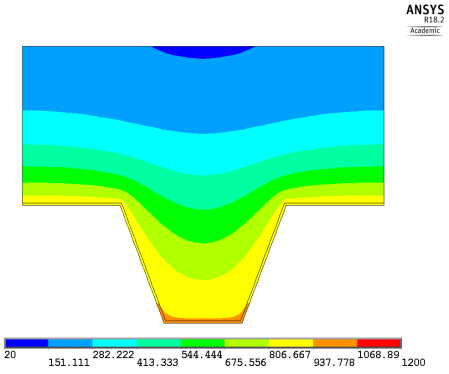
t = 38 min



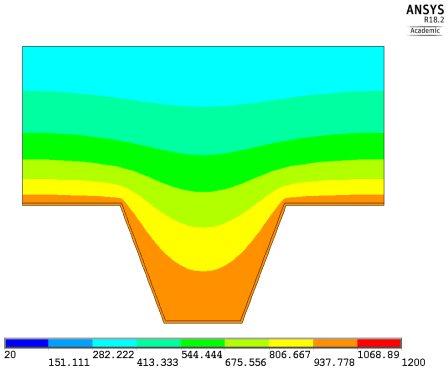
t = 42 min



Tempo Crítico = 65 min

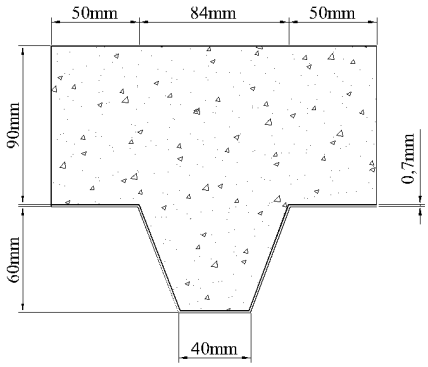


t = 7200s

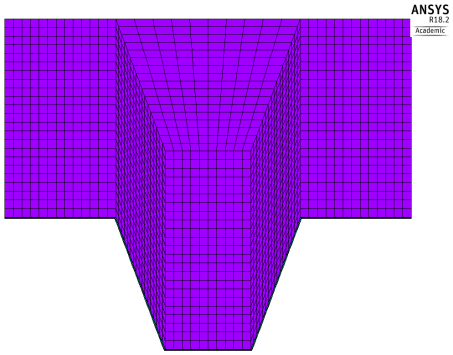


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.7mm

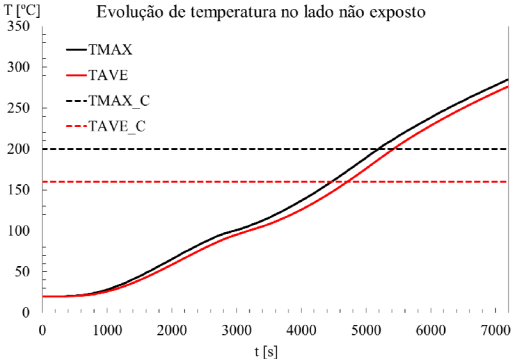
GEOMETRIA



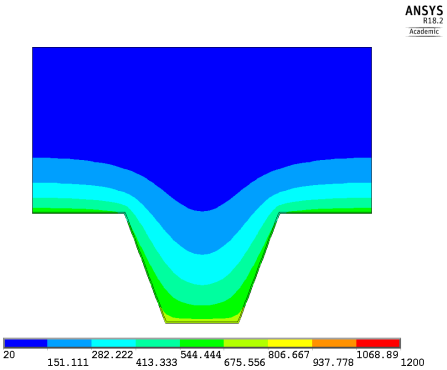
Malha



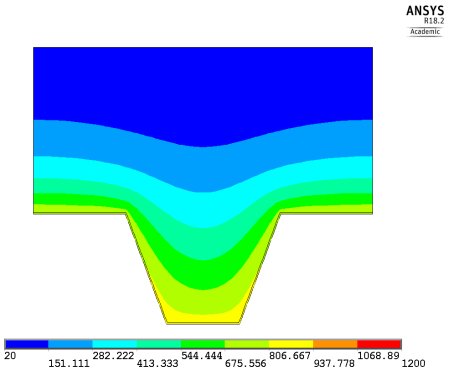
t = 19 min



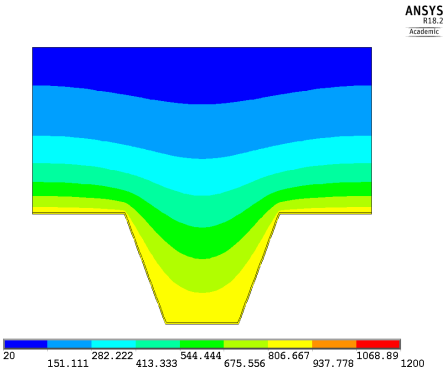
t = 39 min



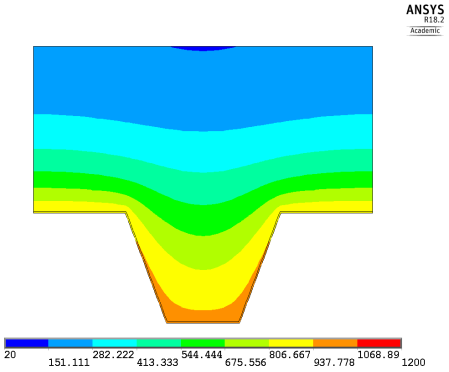
t = 58 min

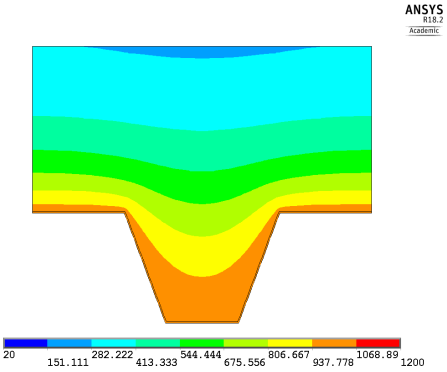


Tempo Crítico = 78 min



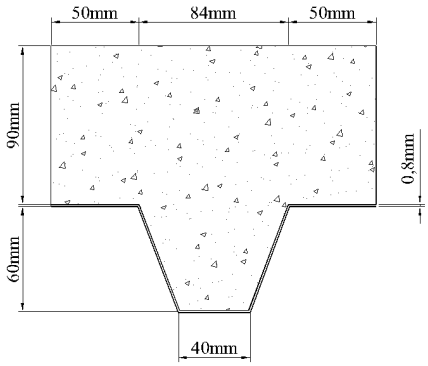
t = 7200s



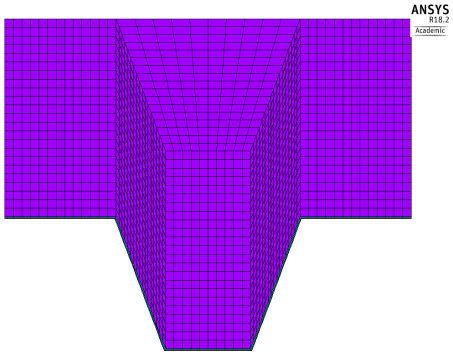


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.8mm

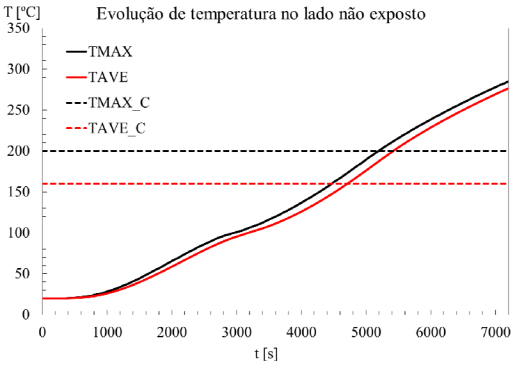
GEOMETRIA



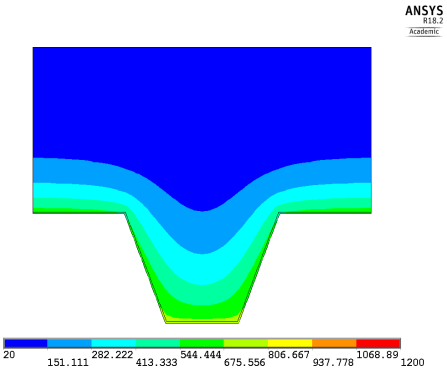
Malha



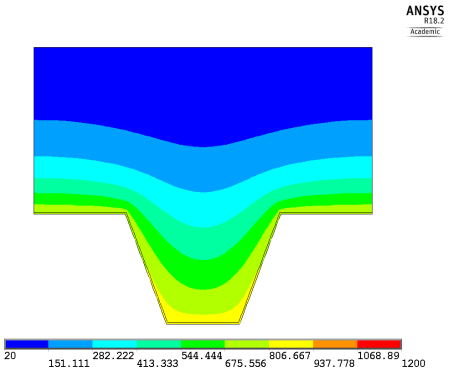
t = 19 min



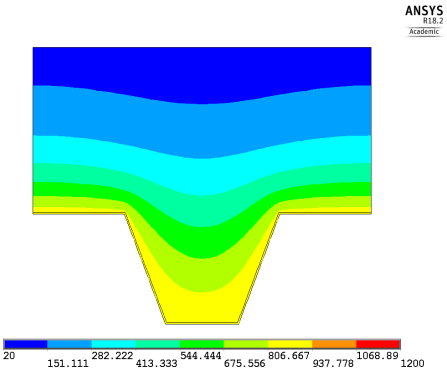
t = 39 min



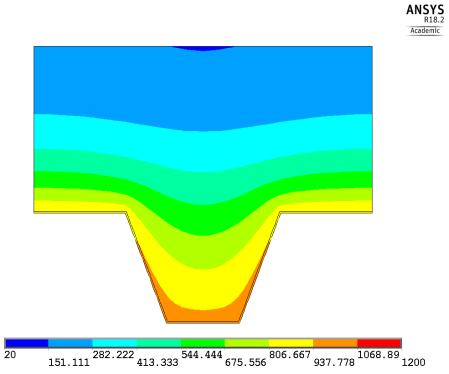
t = 58 min

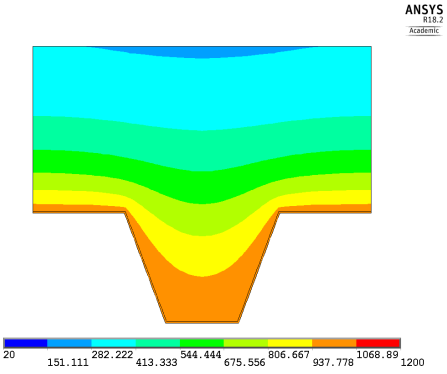


Tempo Crítico = 78 min



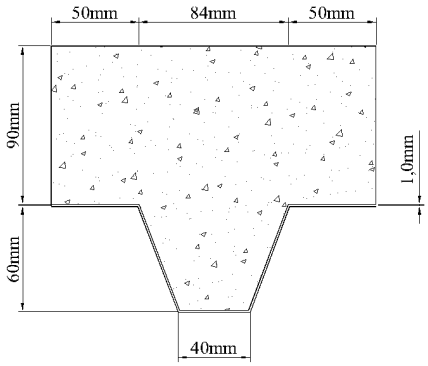
t = 7200s



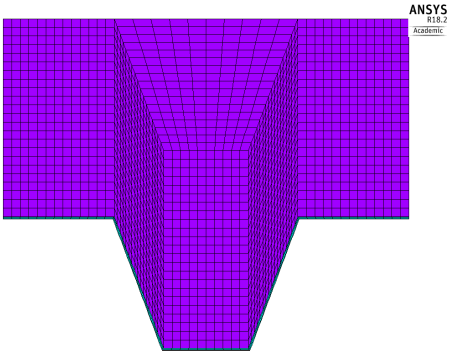


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.0mm

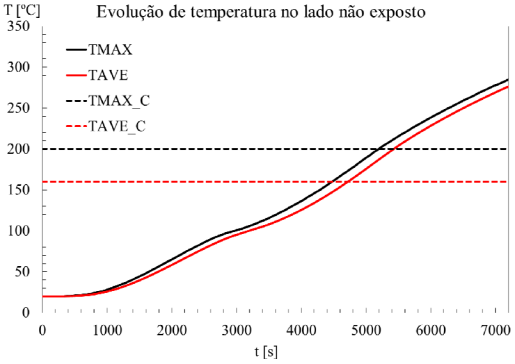
GEOMETRIA



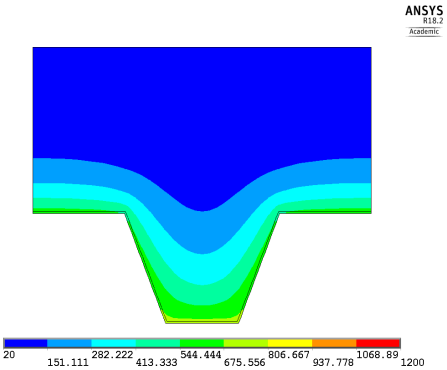
Malha



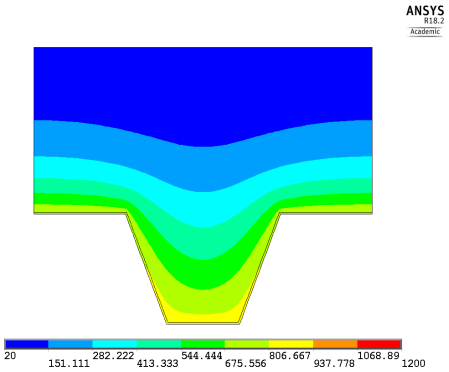
t = 19 min



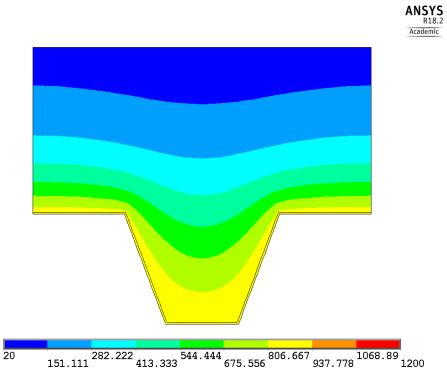
t = 39 min



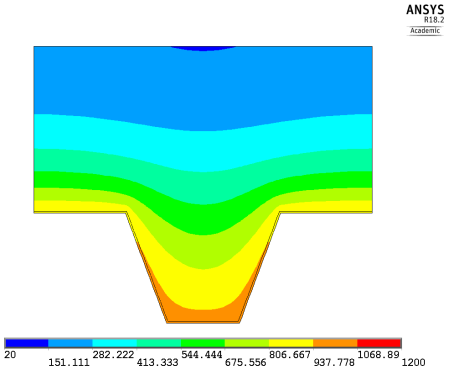
t = 58 min

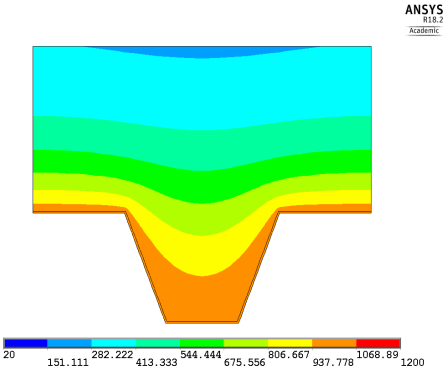


Tempo Crítico = 78 min



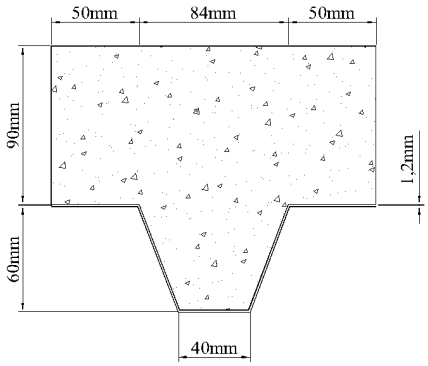
t = 7200s



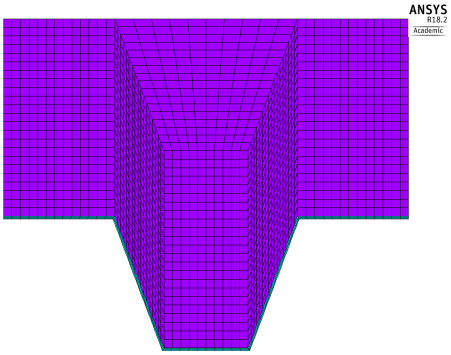


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.2mm

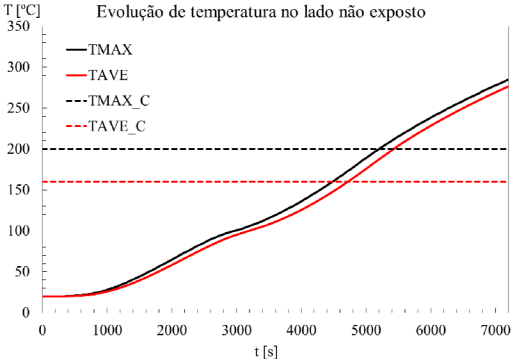
GEOMETRIA



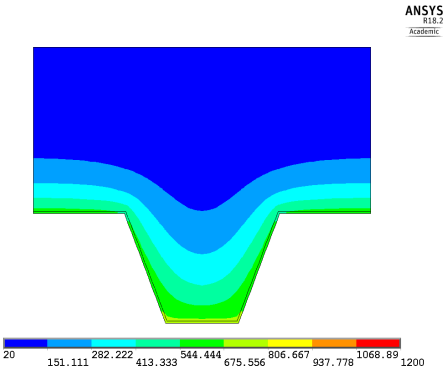
Malha



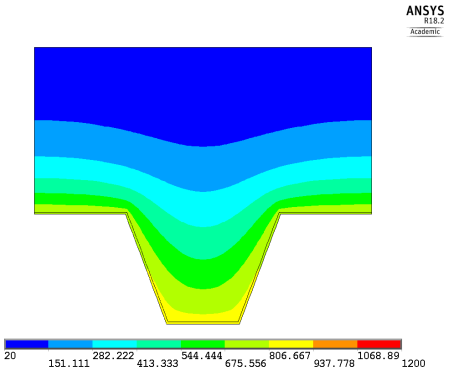
t = 19 min



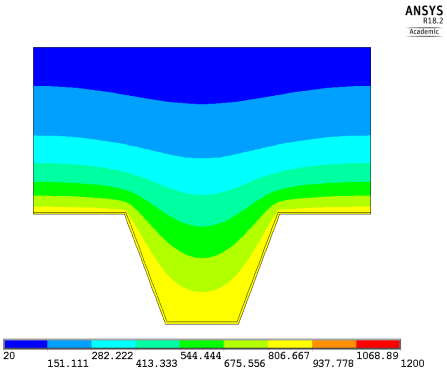
t = 39 min



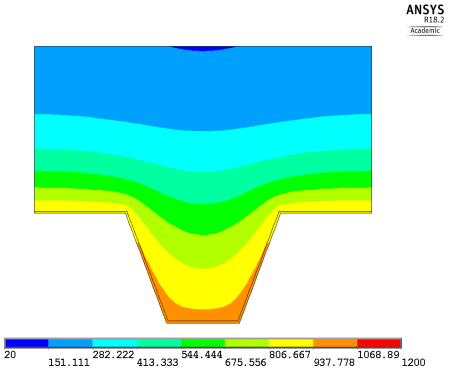
t = 58 min

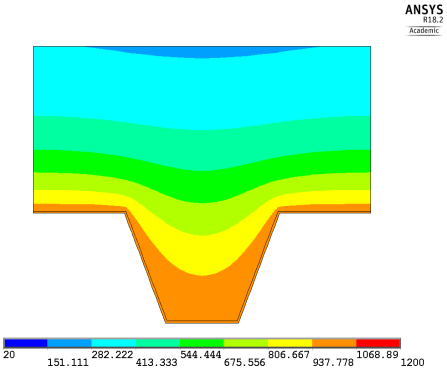


Tempo Crítico = 78 min



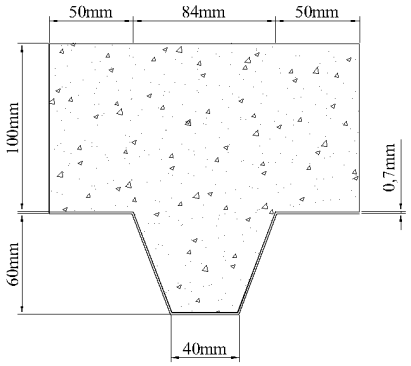
t = 7200s



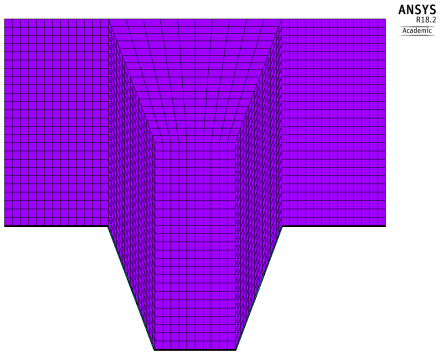


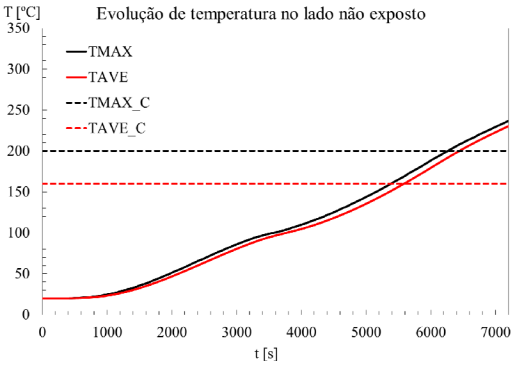
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.7mm

GEOMETRIA

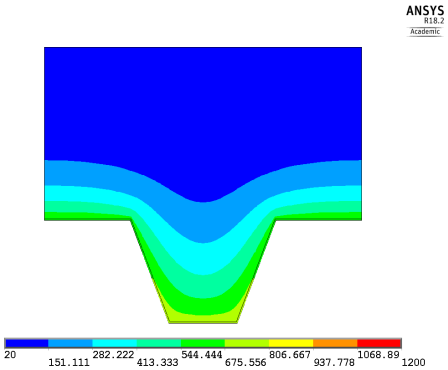


Malha



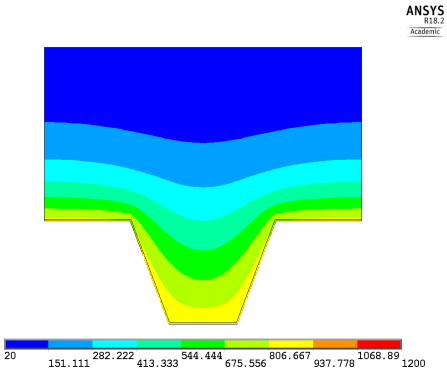


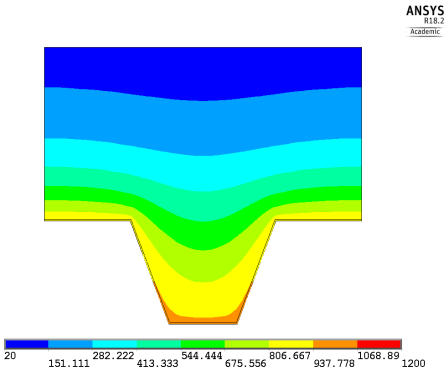
t = 23 min



t = 46 min

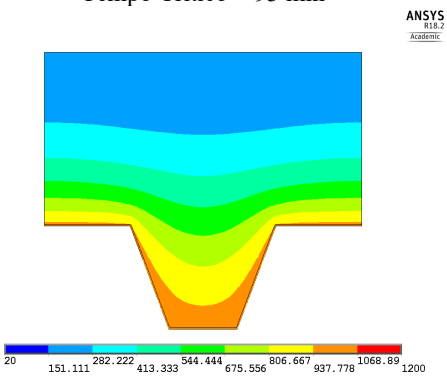
t = 69 min

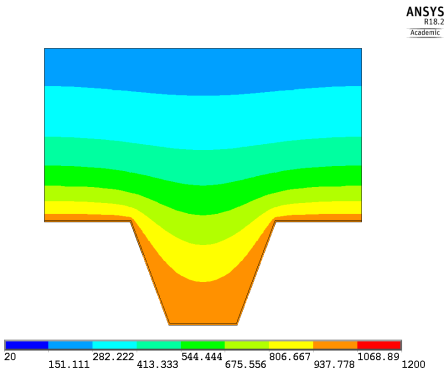




Tempo Crítico = 93 min

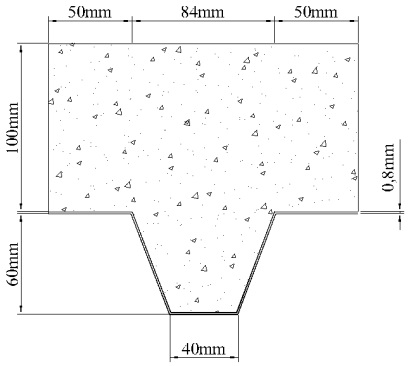
t = 7200s



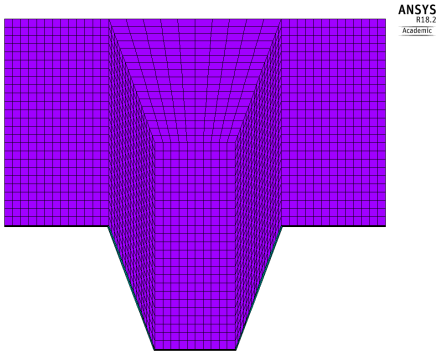


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.8mm

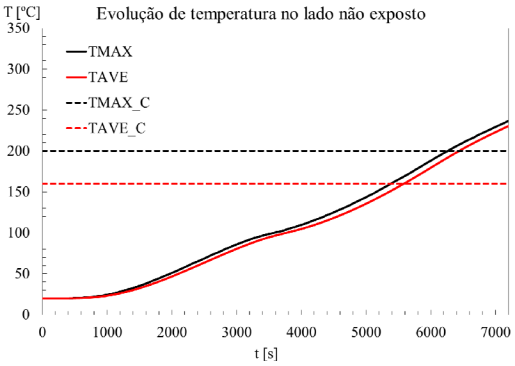
GEOMETRIA



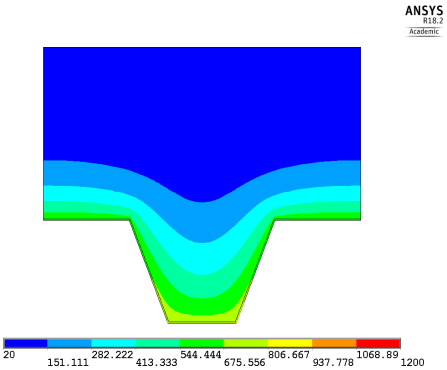
Malha



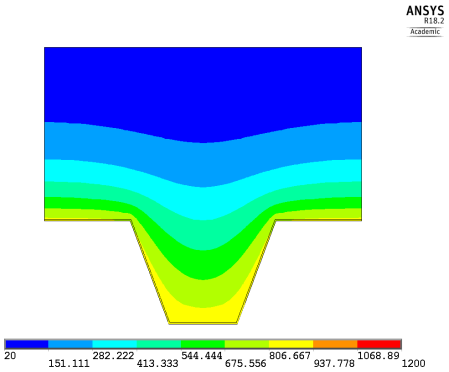
t = 23 min



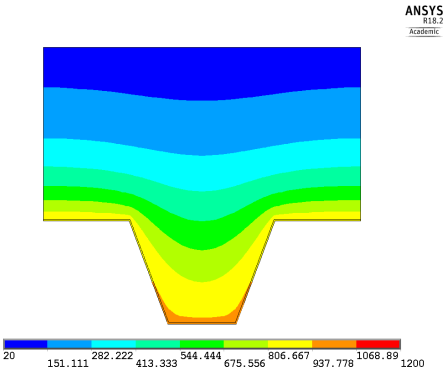
t = 46 min



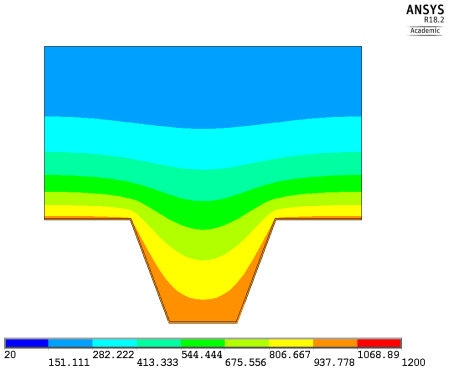
t = 69 min

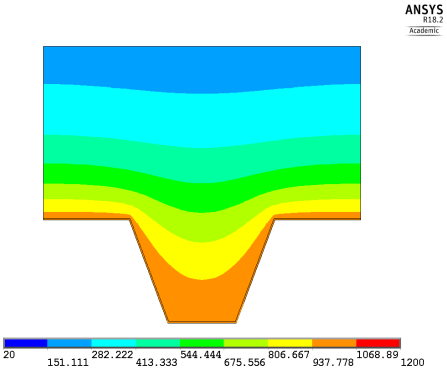


Tempo Crítico = 93 min



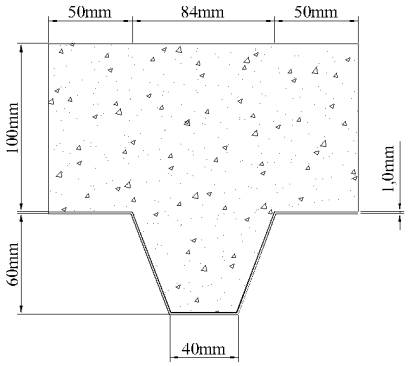
t = 7200s



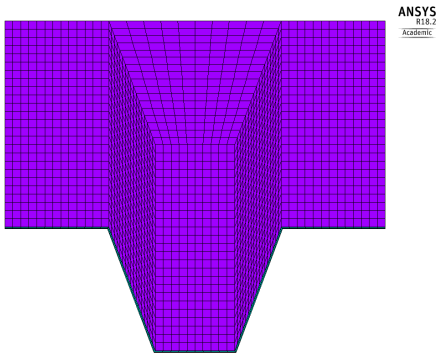


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.0mm

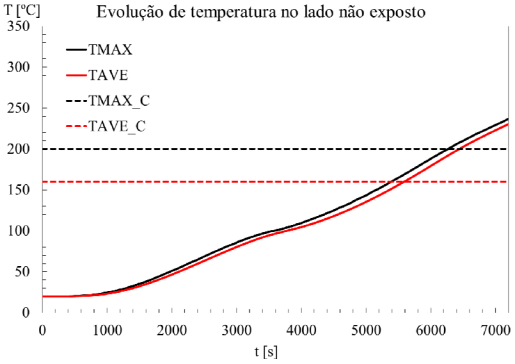
GEOMETRIA



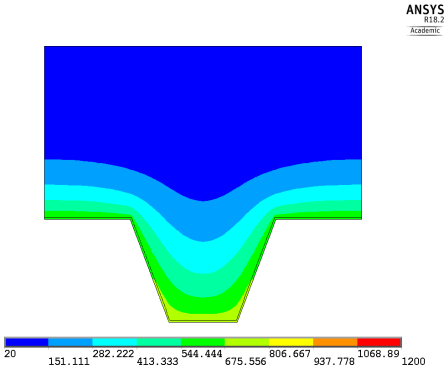
Malha



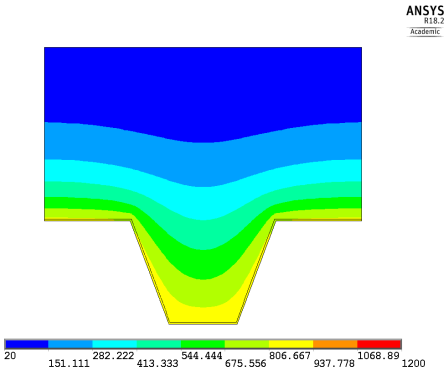
t = 23 min



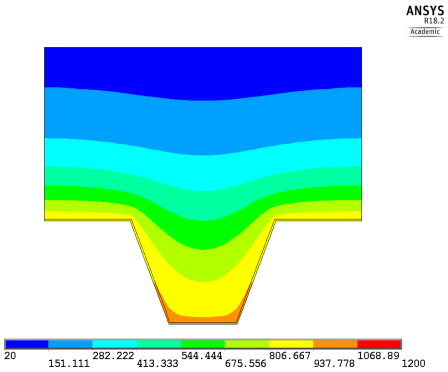
t = 46 min



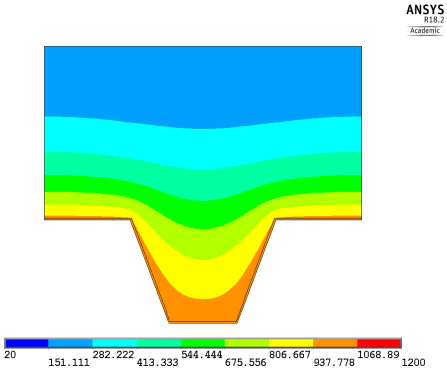
t = 69 min

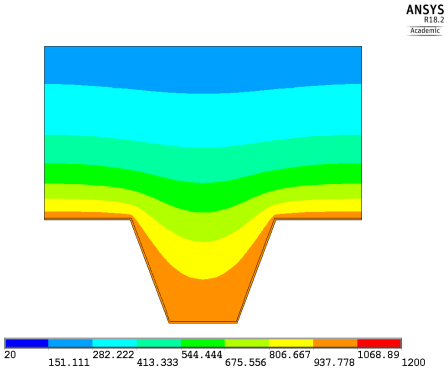


Tempo Crítico = 93 min



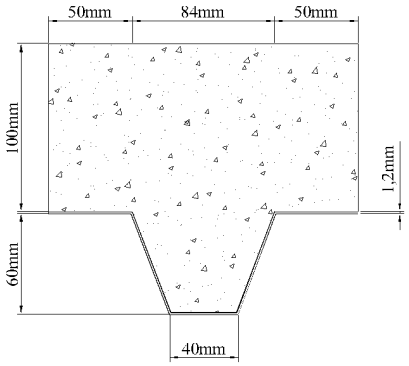
t = 7200s



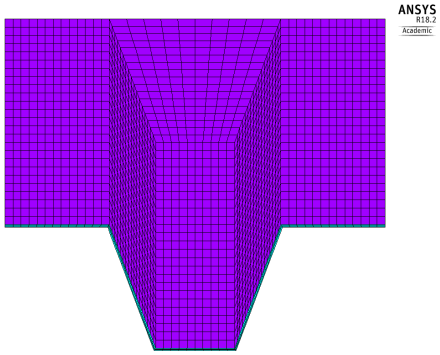


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.2mm

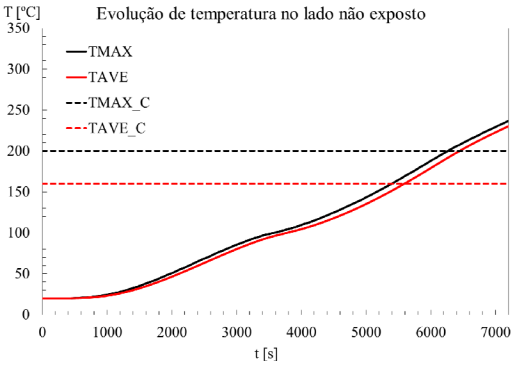
GEOMETRIA



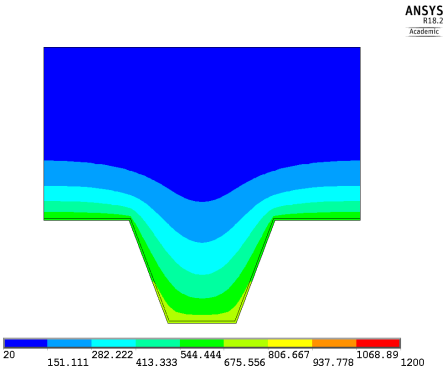
Malha



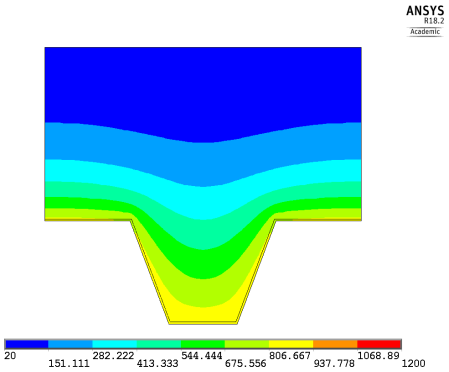
t = 23 min



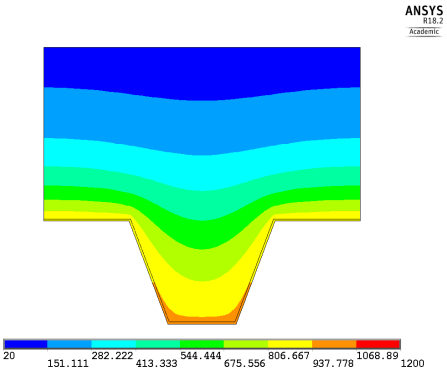
t = 46 min



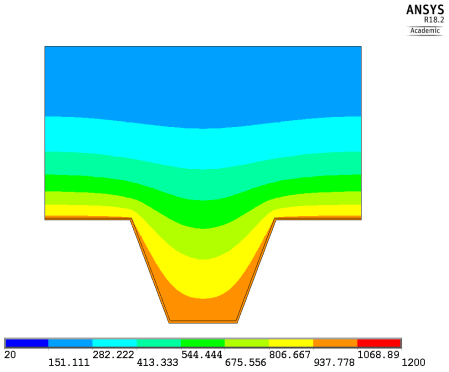
t = 69 min

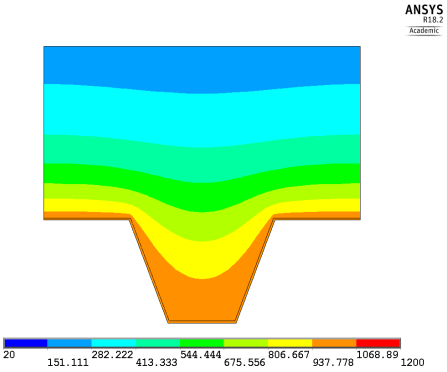


Tempo Crítico = 93 min



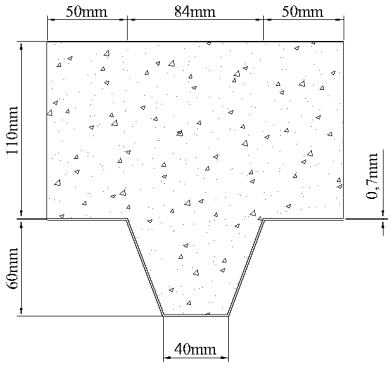
t = 7200s



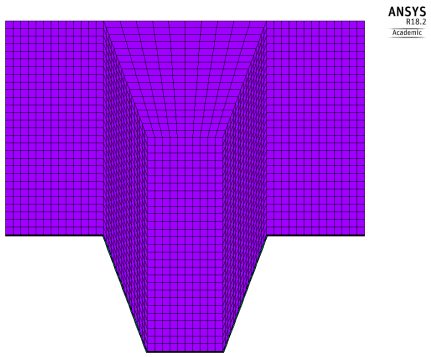


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.7mm

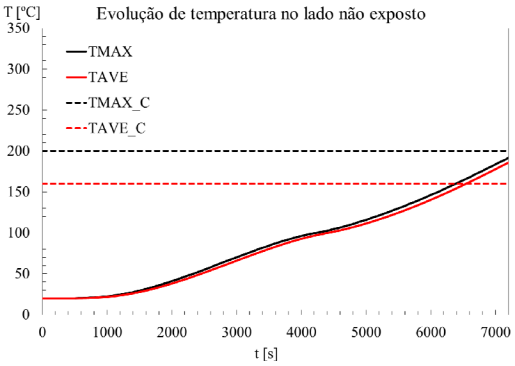
GEOMETRIA



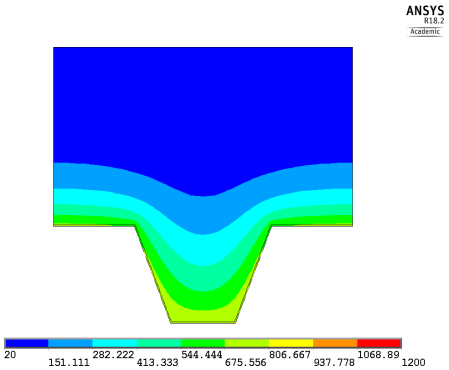
Malha



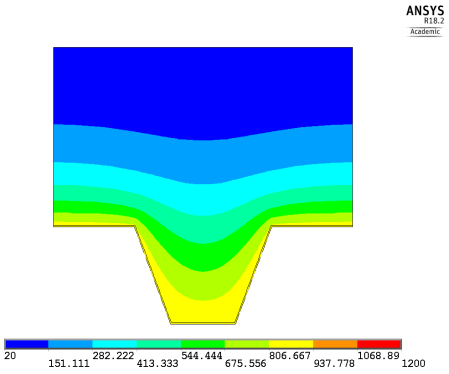
t = 27 min



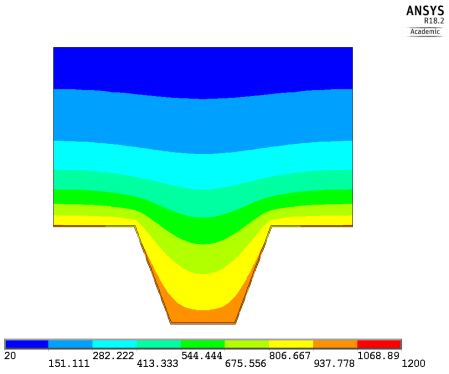
t = 54 min



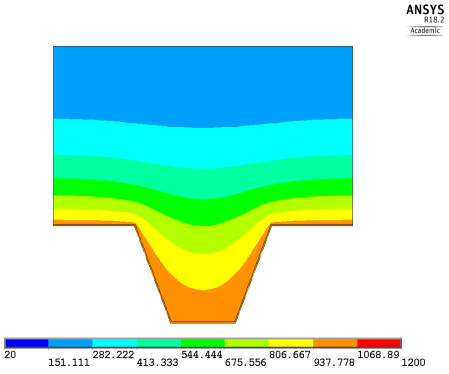
t = 81 min

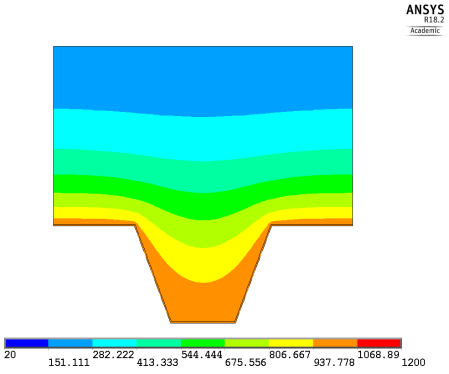


Tempo Crítico = 109 min



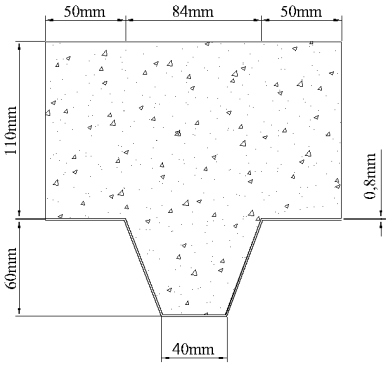
t = 7200s



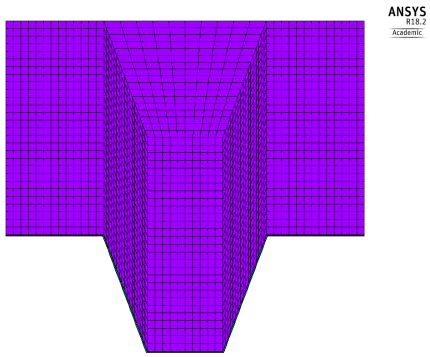


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.8mm

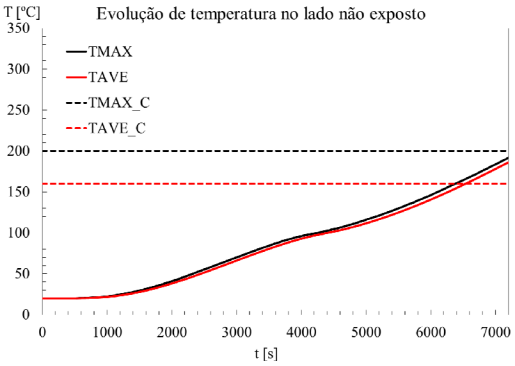
GEOMETRIA



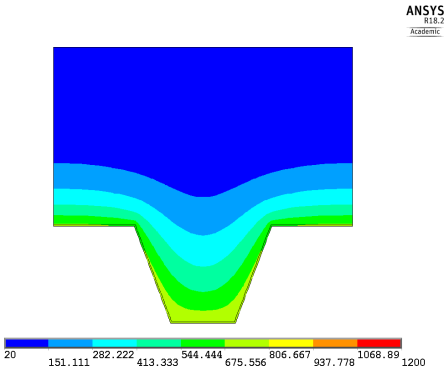
Malha



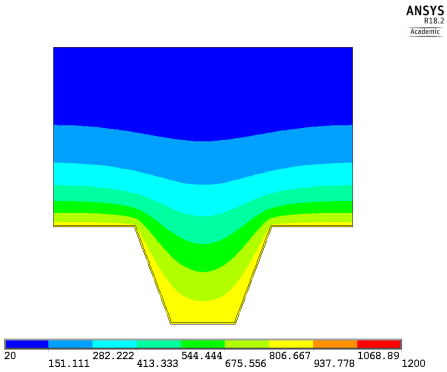
t = 27 min



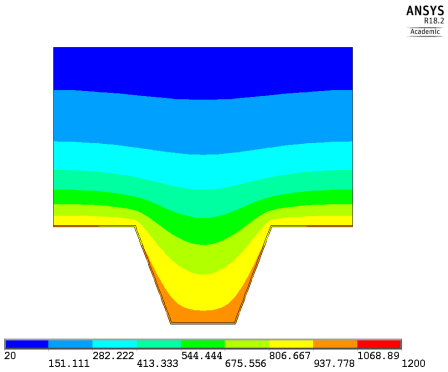
t = 54 min



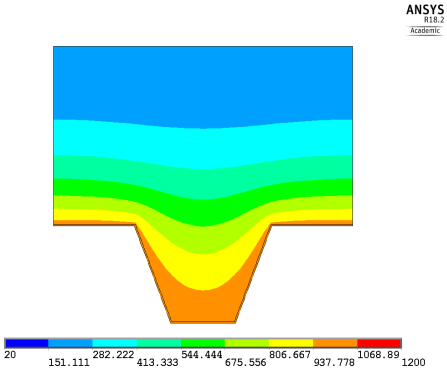
t = 81 min

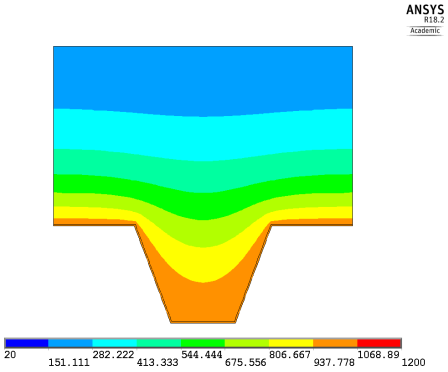


Tempo Crítico = 108 min



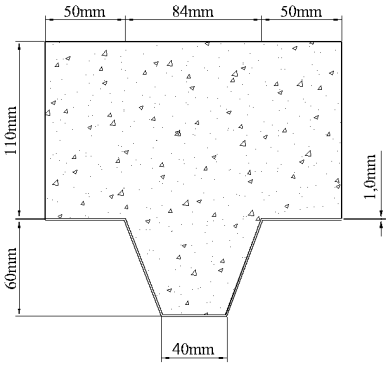
t = 7200s



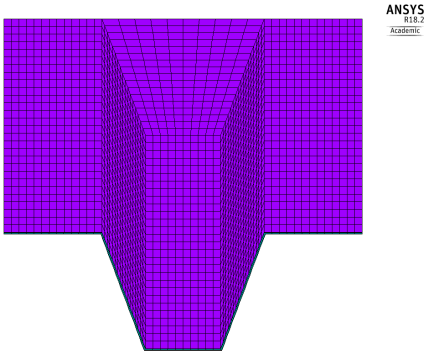


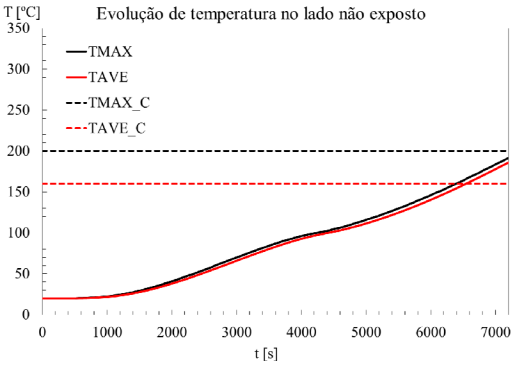
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.0mm

GEOMETRIA

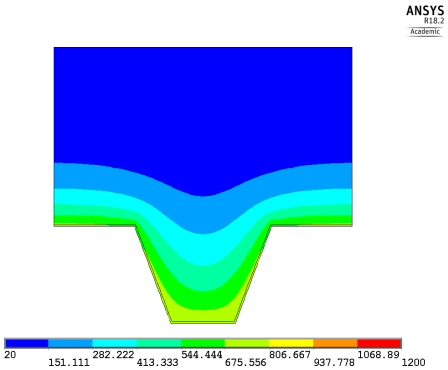


Malha



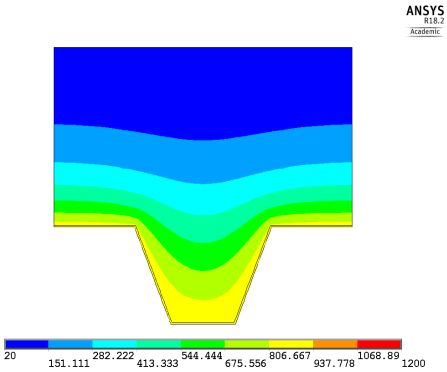


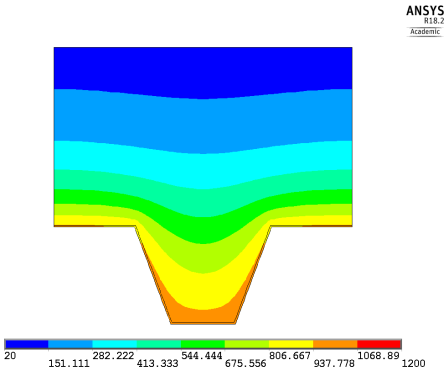
t = 27 min



t = 54 min

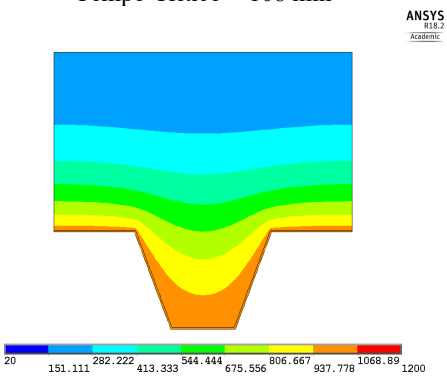
t = 81 min

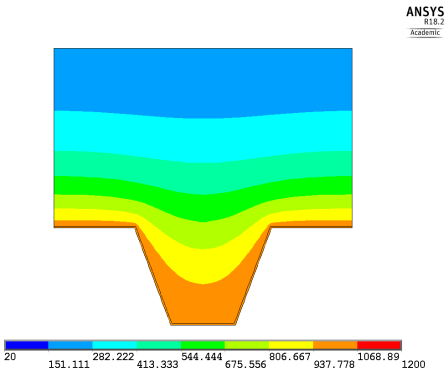




Tempo Crítico = 108 min

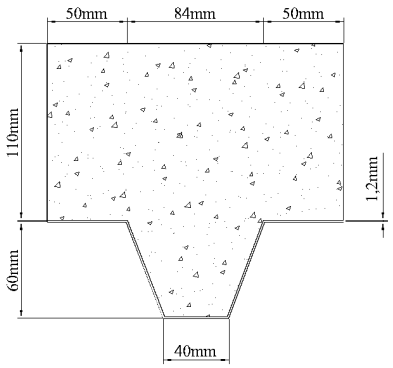
t = 14400s



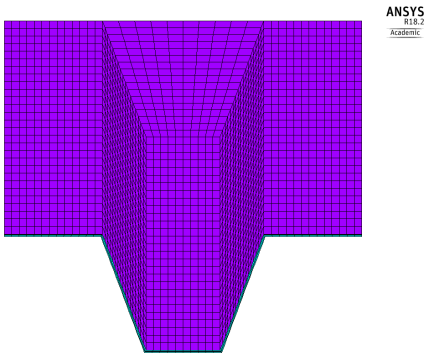


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.2mm

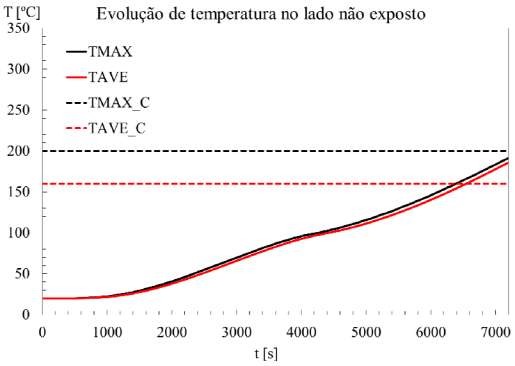
GEOMETRIA



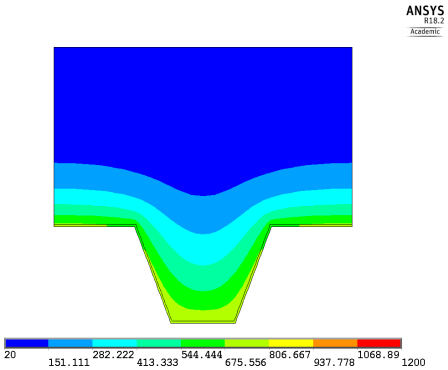
Malha



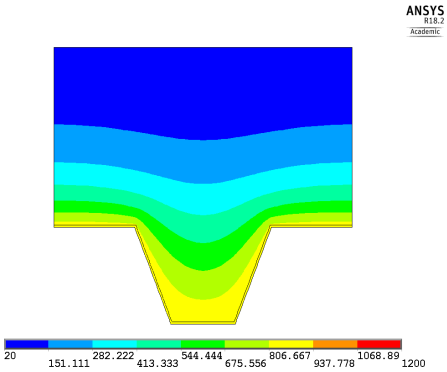
t = 27 min



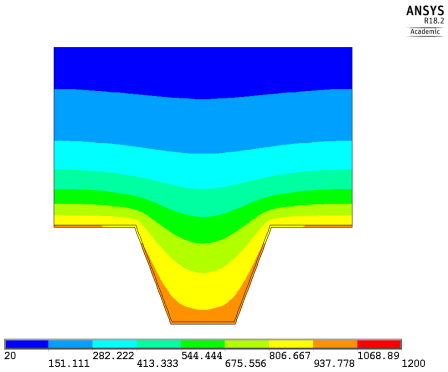
t = 54 min



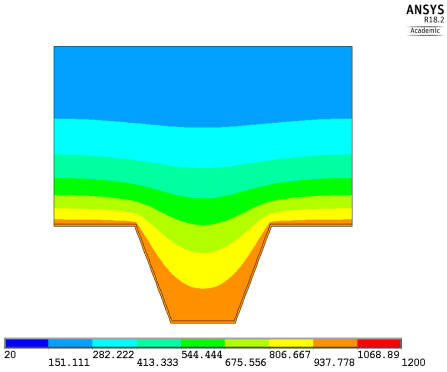
t = 81 min

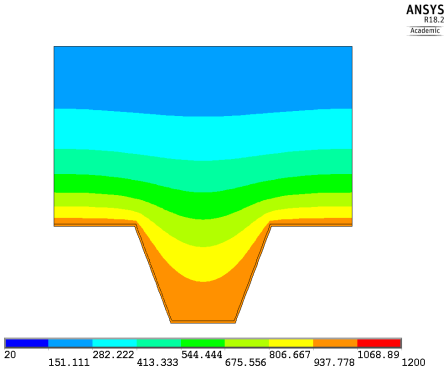


Tempo Crítico = 108 min



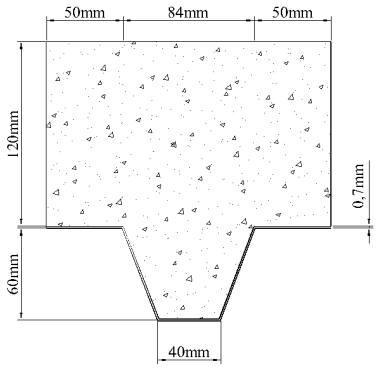
t = 14400s



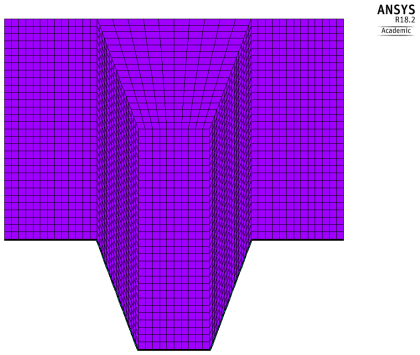


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.7mm

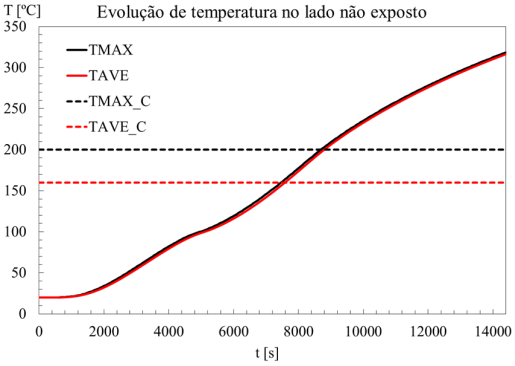
GEOMETRIA



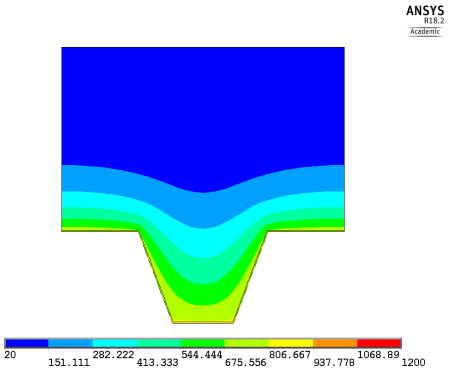
Malha



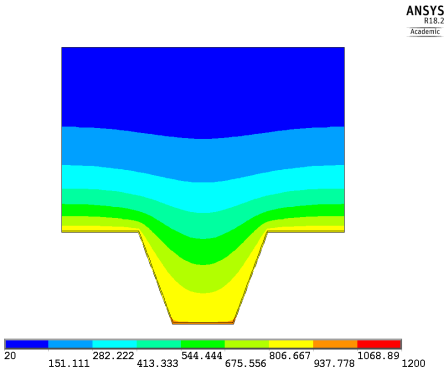
t = 31 min



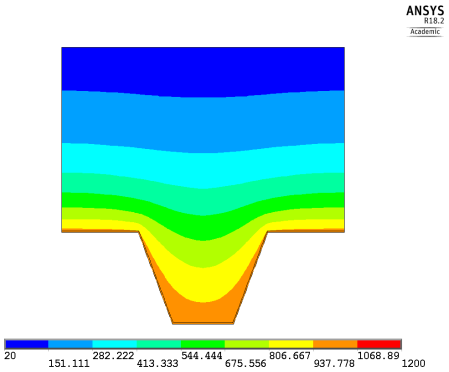
t = 63 min



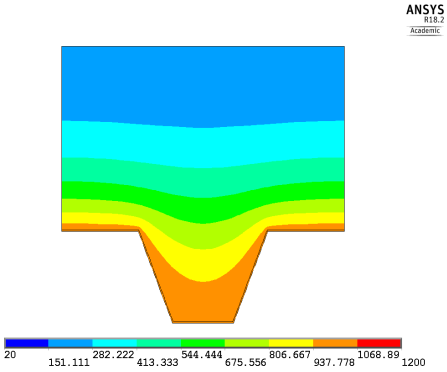
t = 94 min

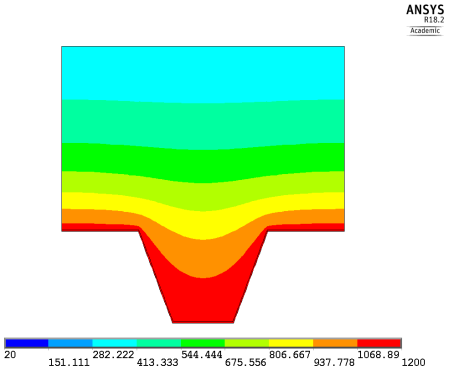


Tempo Crítico = 126 min



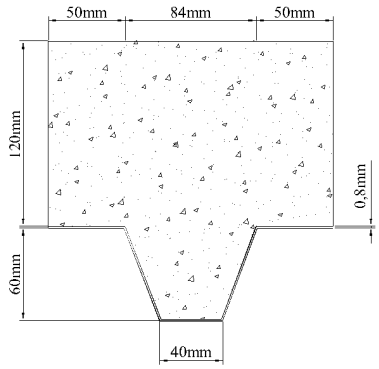
t = 14400s



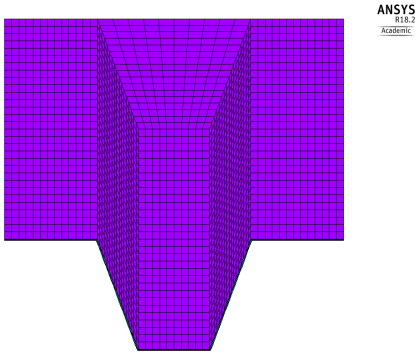


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.8mm

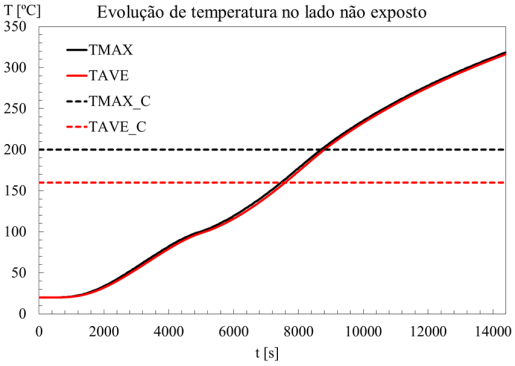
GEOMETRIA



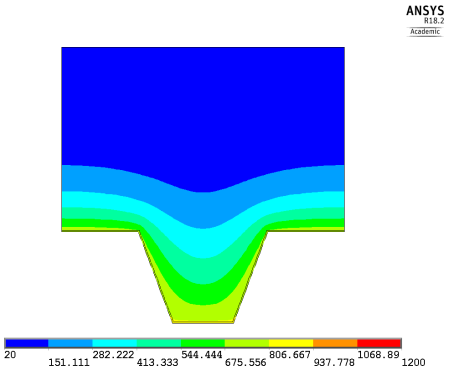
Malha



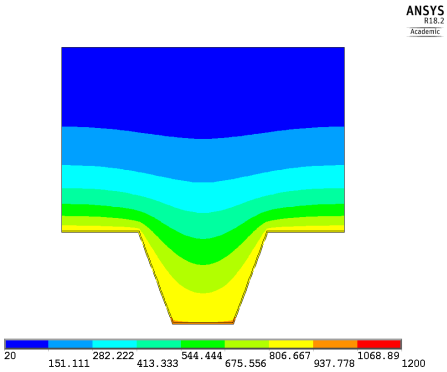
t = 31 min



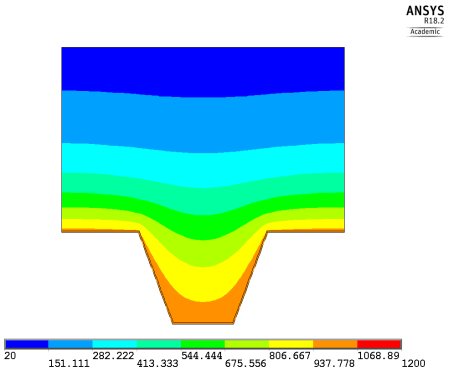
t = 63 min



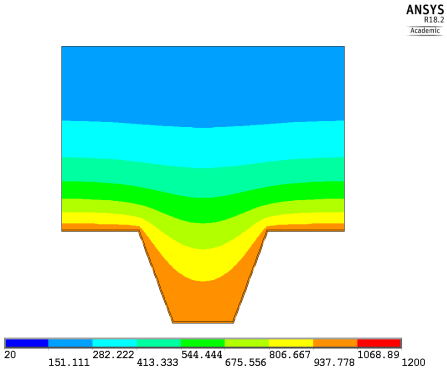
t = 94 min

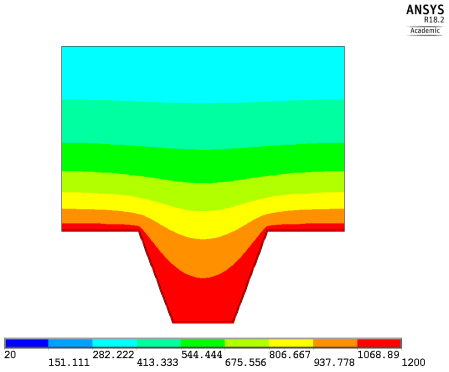


Tempo Crítico = 126 min



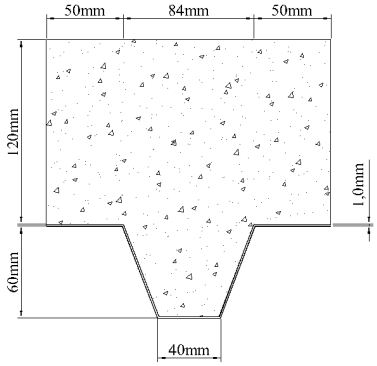
t = 14400s



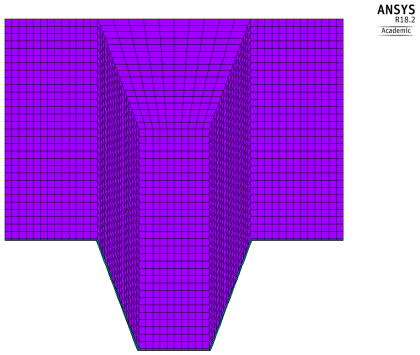


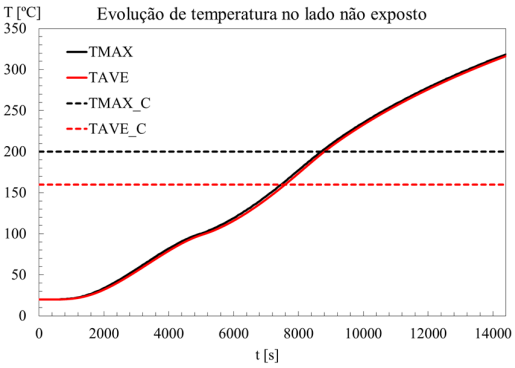
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.0mm

GEOMETRIA

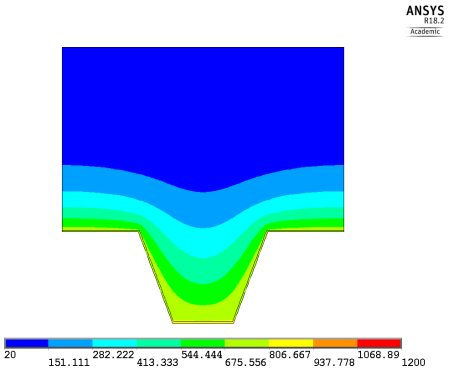


Malha



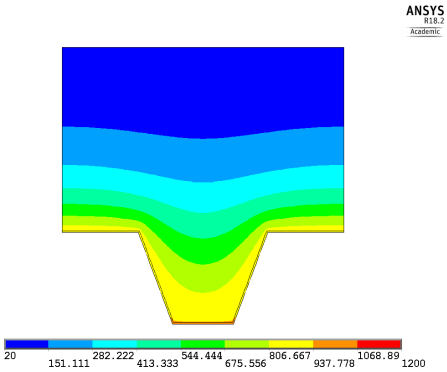


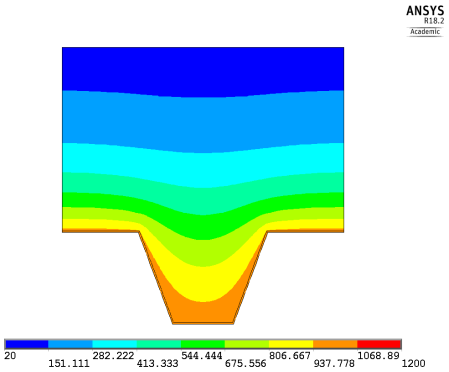
t = 31 min



t = 63 min

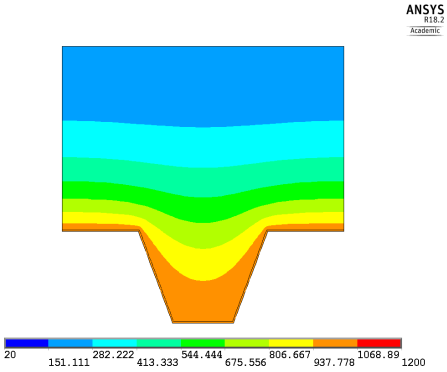
t = 94 min

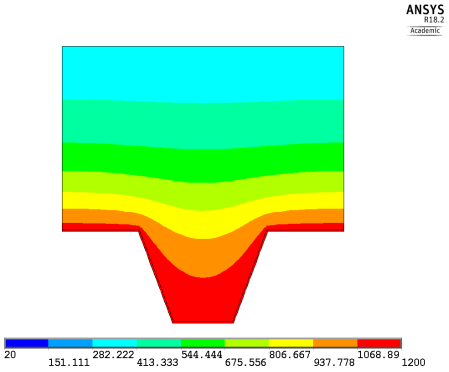




Tempo Crítico = 126 min

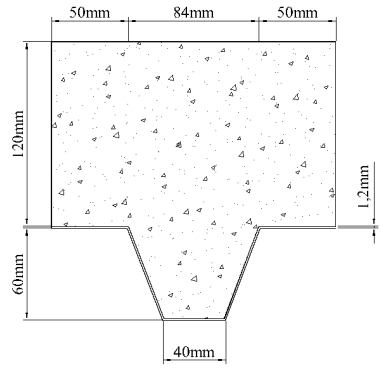
t = 14400s





LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.2mm

GEOMETRIA



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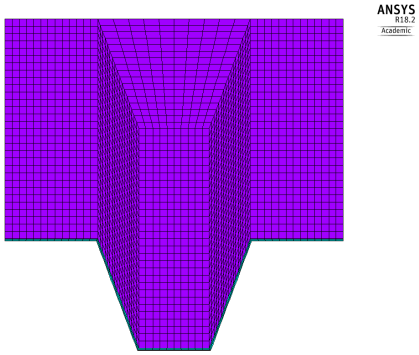
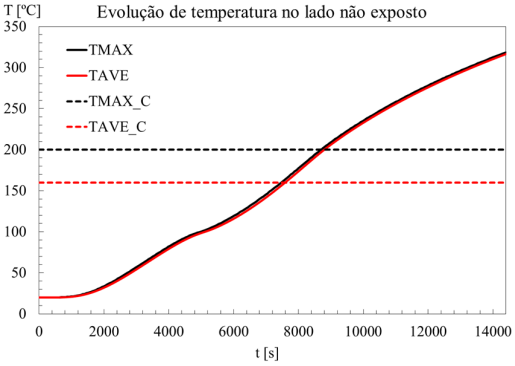
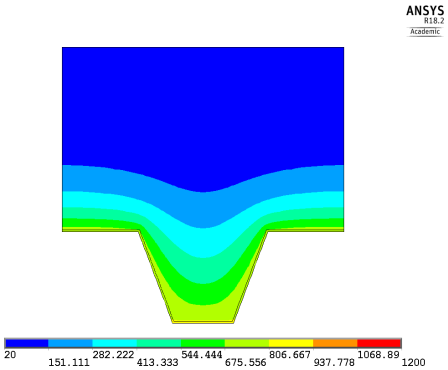


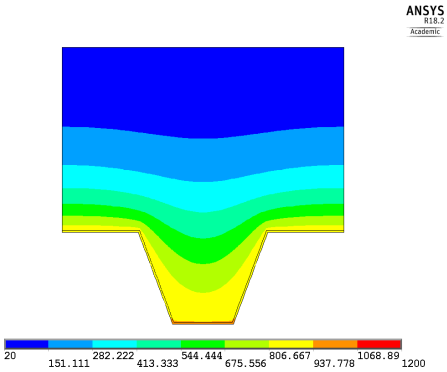
t = 31 min



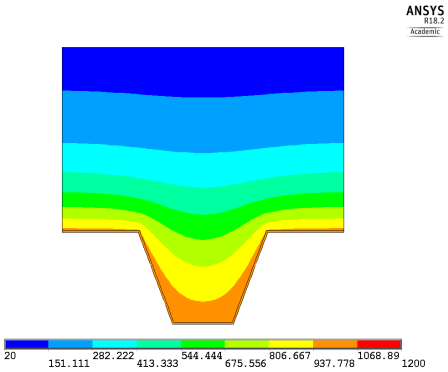
t = 63 min



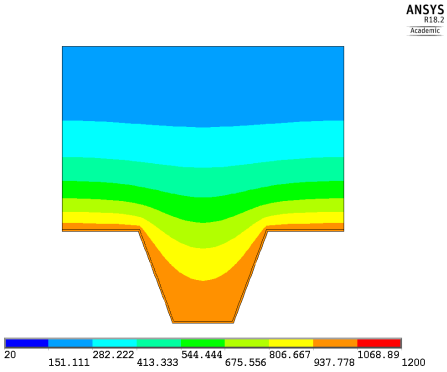
t = 94 min

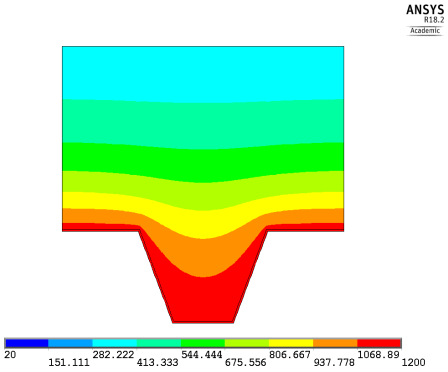


Tempo Crítico = 126 min



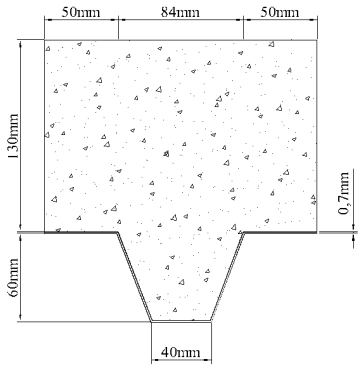
t = 14400s





LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.7mm

GEOMETRIA



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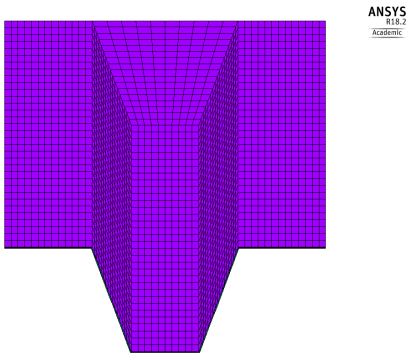
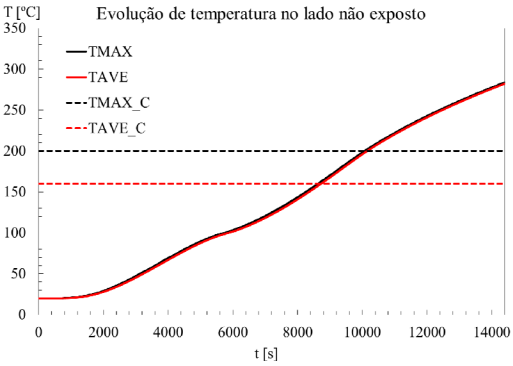
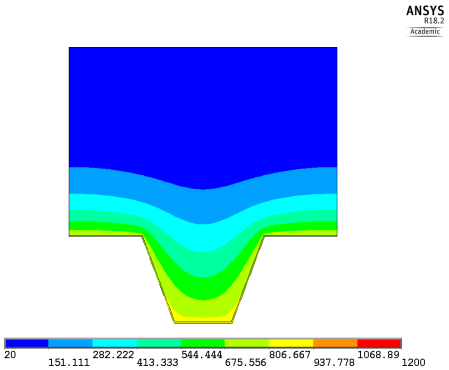


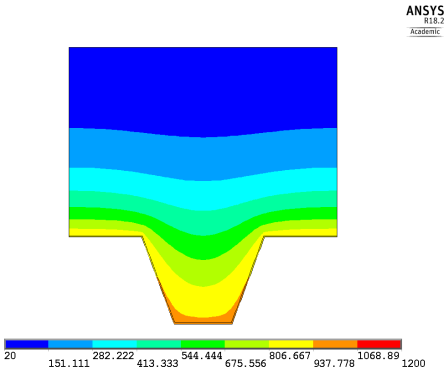
t = 36 min



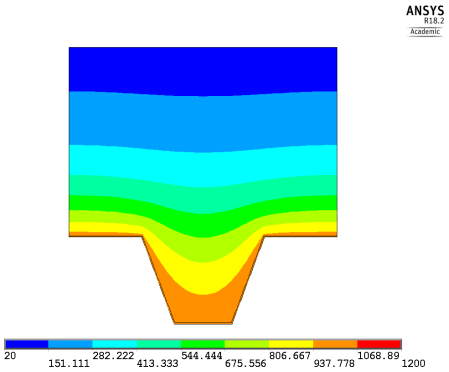
t = 72 min



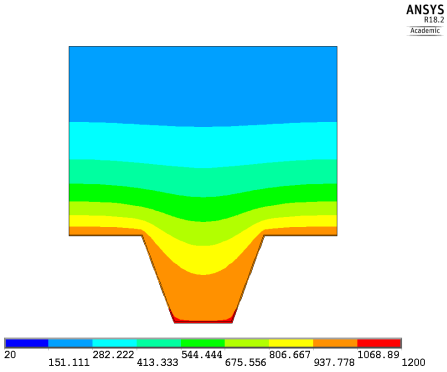
t = 108 min

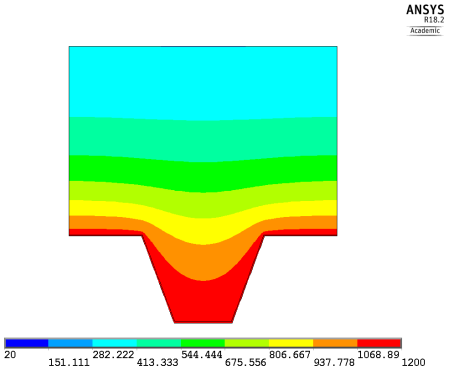


Tempo Crítico = 145 min



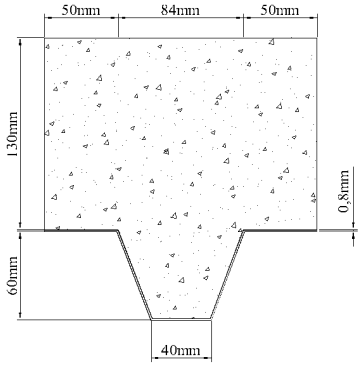
t = 14400s



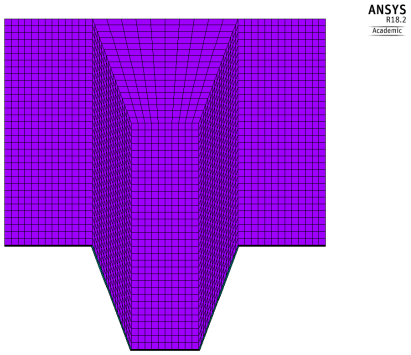


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.8mm

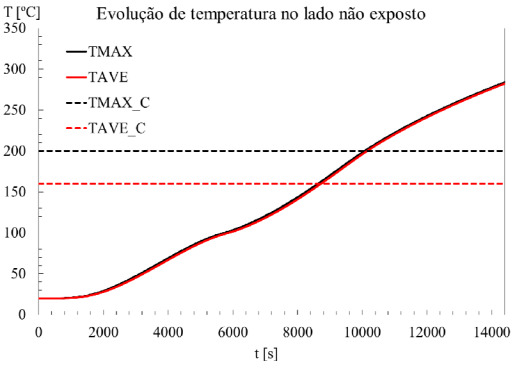
GEOMETRIA



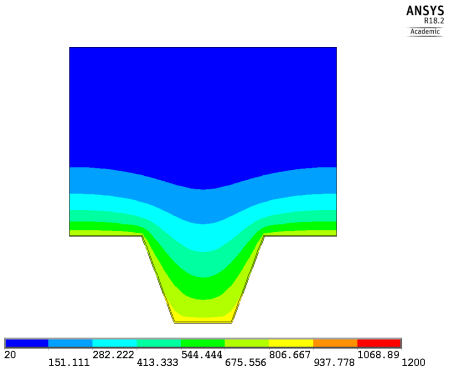
Malha



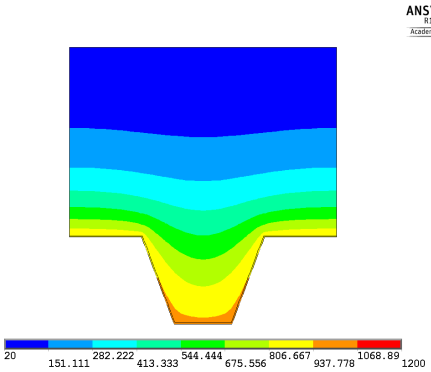
t = 36 min



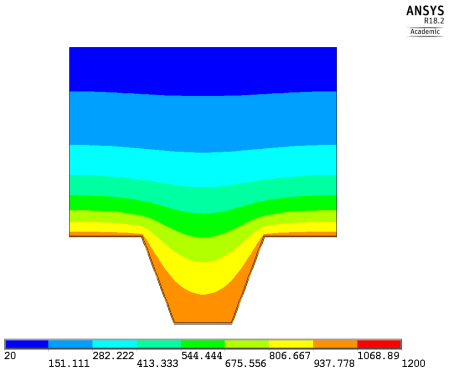
t = 72 min



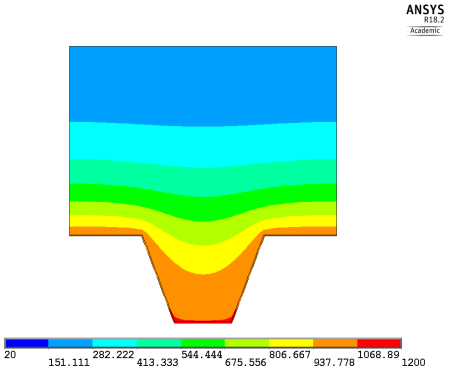
t = 108 min

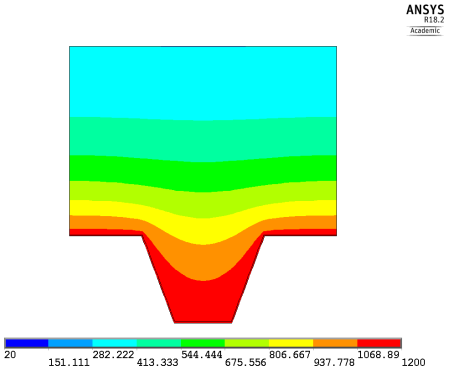


Tempo Crítico = 145 min



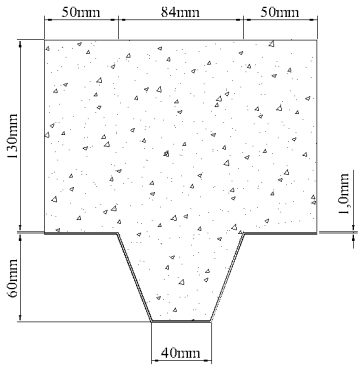
t = 14400s



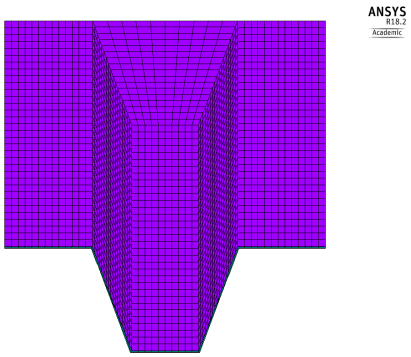


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.0mm

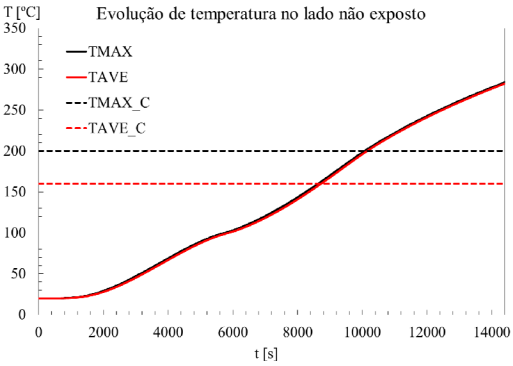
GEOMETRIA



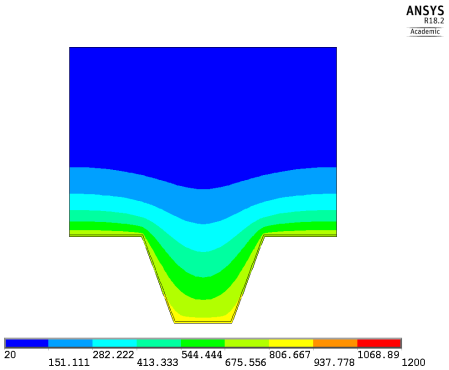
Malha



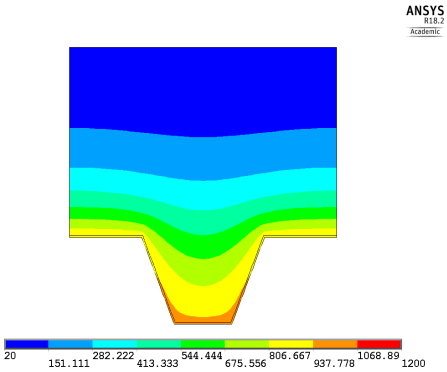
t = 36 min



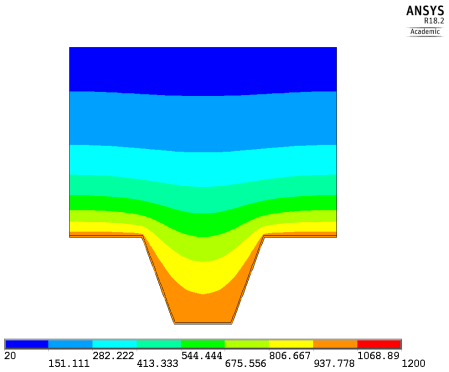
t = 72 min



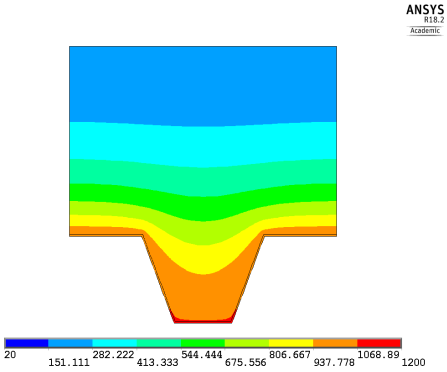
t = 108 min

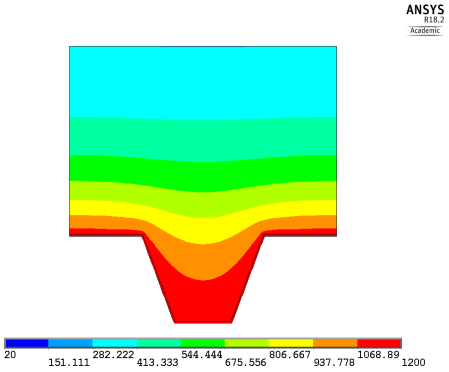


Tempo Crítico = 145 min



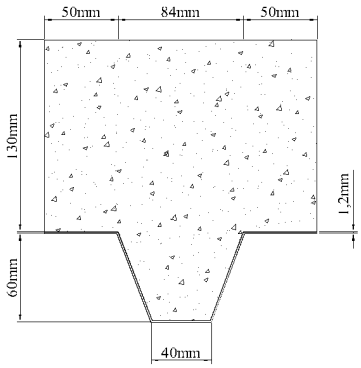
t = 14400s



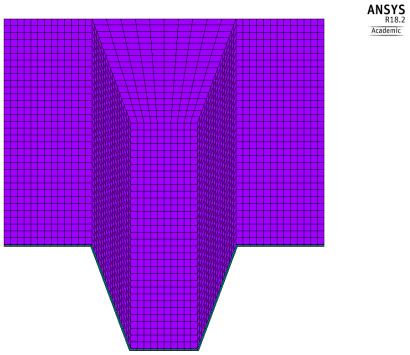


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.2mm

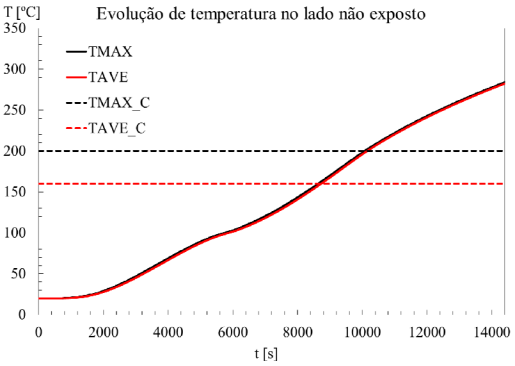
GEOMETRIA



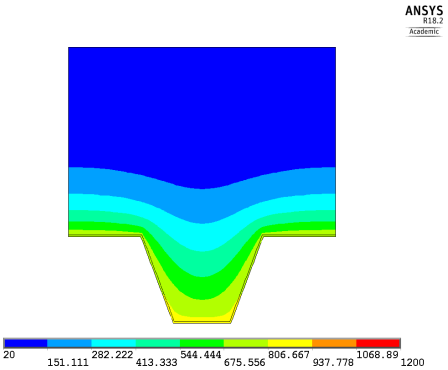
Malha



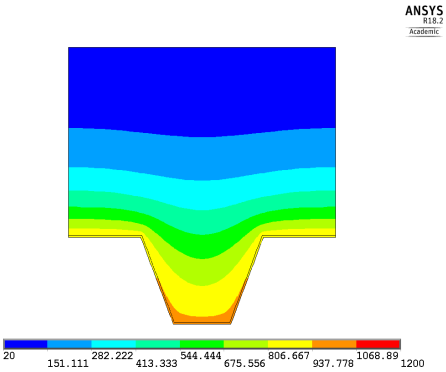
t = 36 min



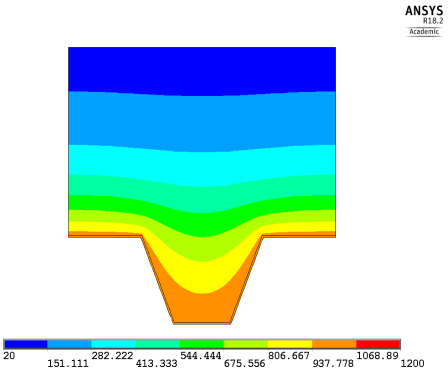
t = 72 min



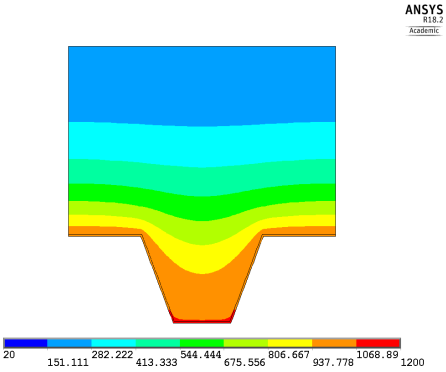
t = 108 min

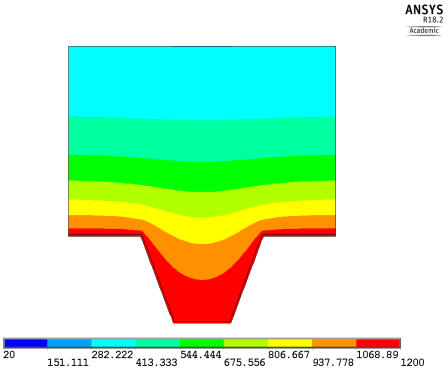


Tempo Crítico = 145 min



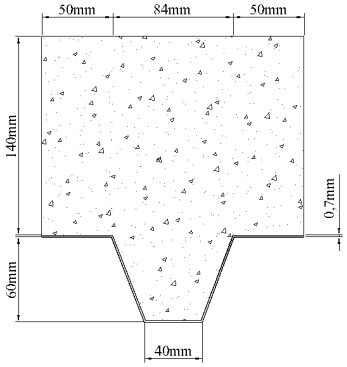
t = 14400s



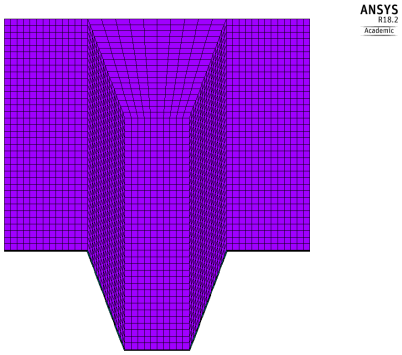


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.7mm

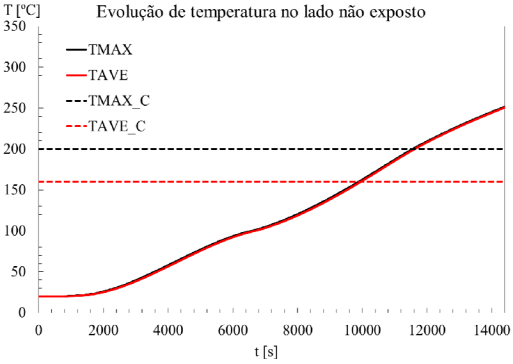
GEOMETRIA



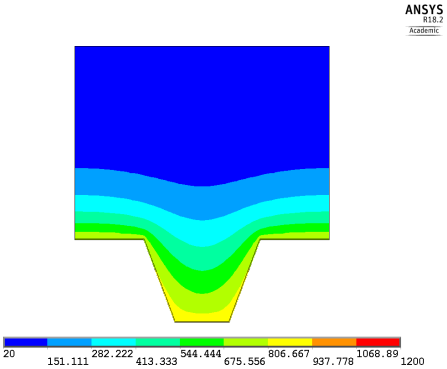
Malha



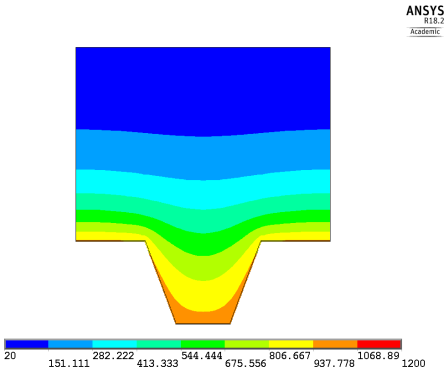
t = 41 min



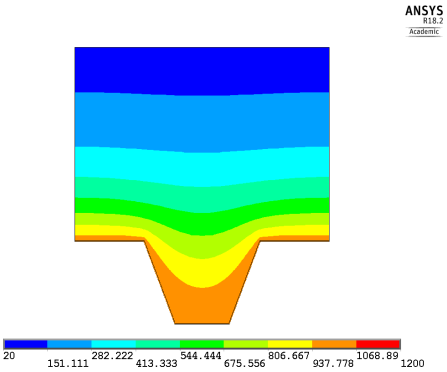
t = 82 min



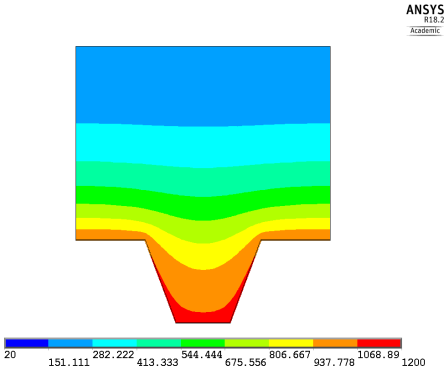
t = 123 min

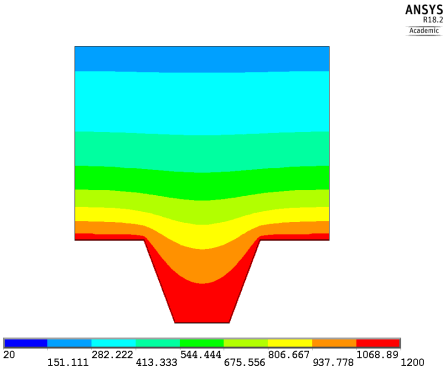


Tempo Crítico = 165 min



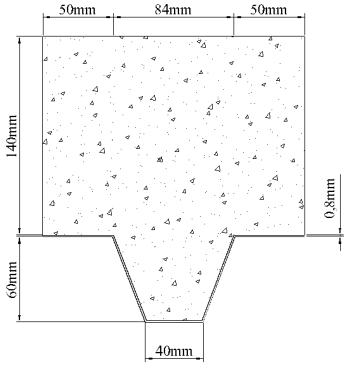
t = 14400s



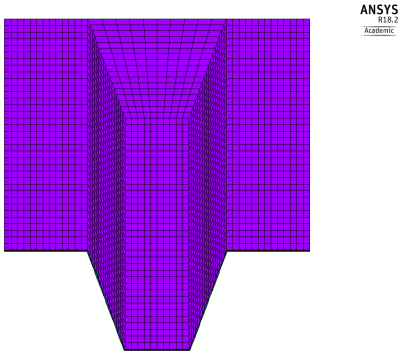


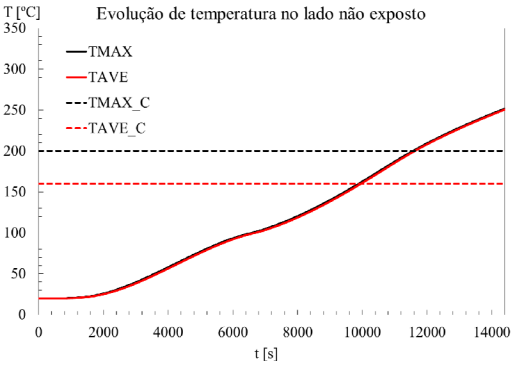
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.8mm

GEOMETRIA

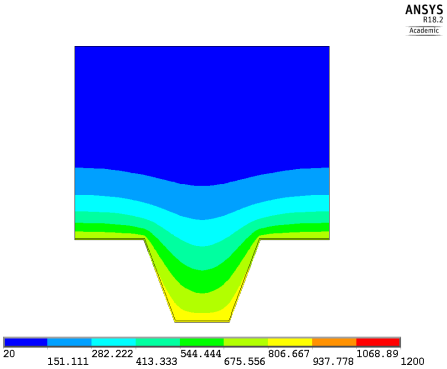


Malha



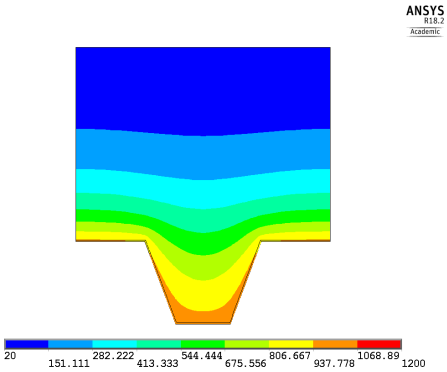


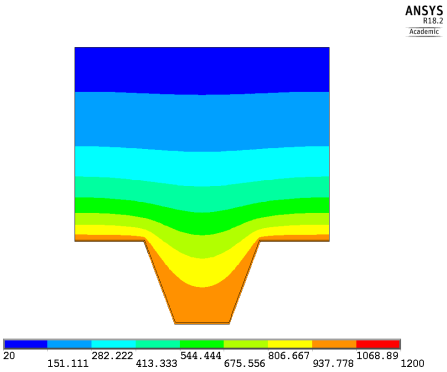
t = 41 min



t = 83 min

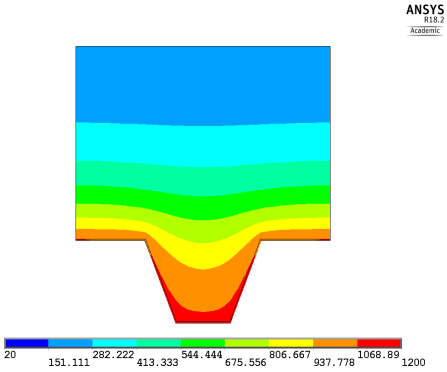
t = 124 min

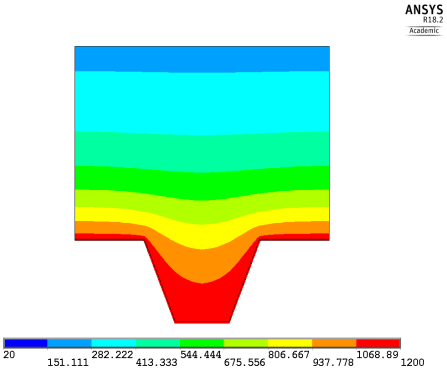




Tempo Crítico = 166 min

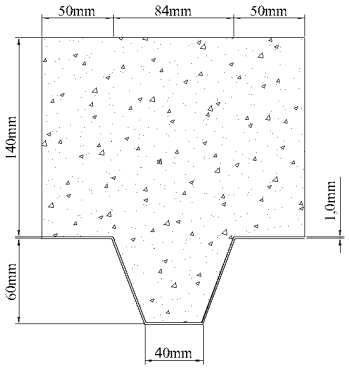
t = 14400s



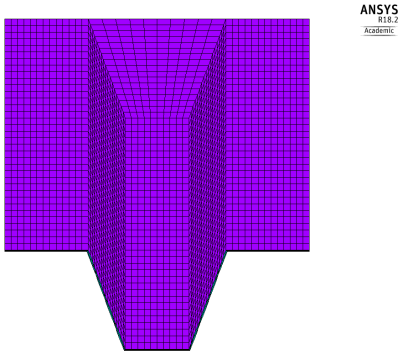


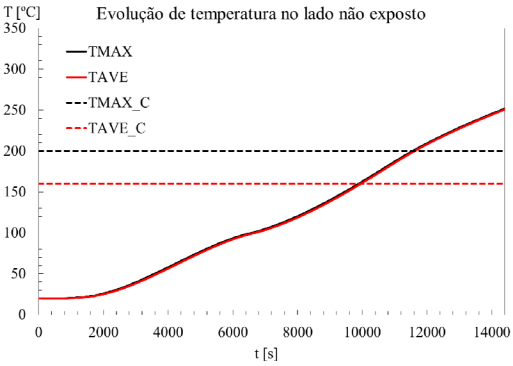
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.0mm

GEOMETRIA

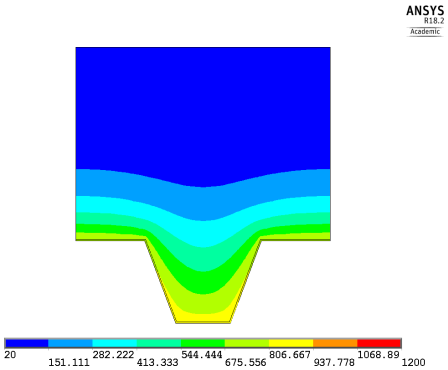


Malha

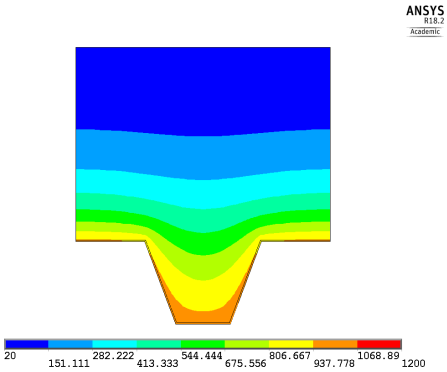




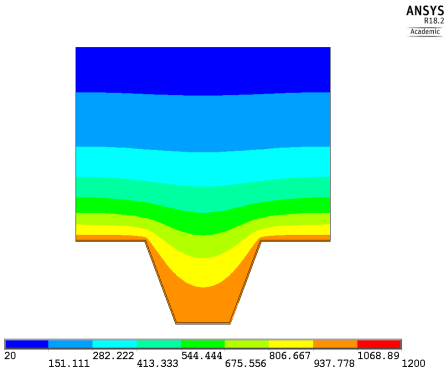
t = 41 min



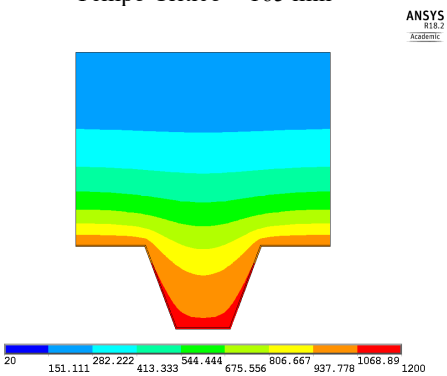
t = 82 min



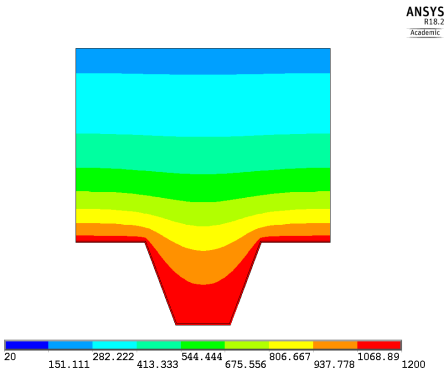
t = 123 min



Tempo Crítico = 165 min

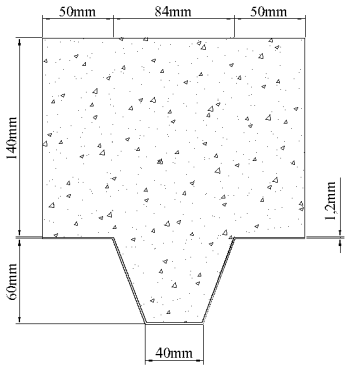


t = 14400s

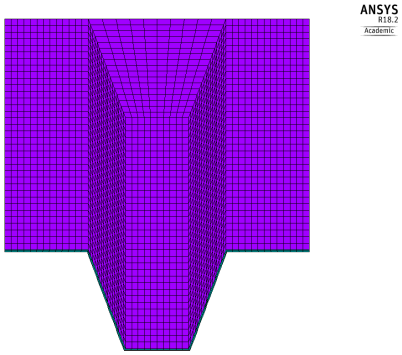


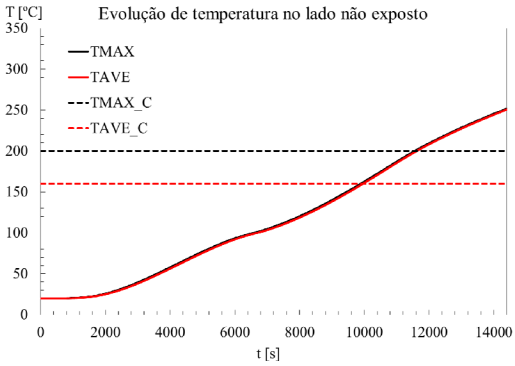
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.2mm

GEOMETRIA

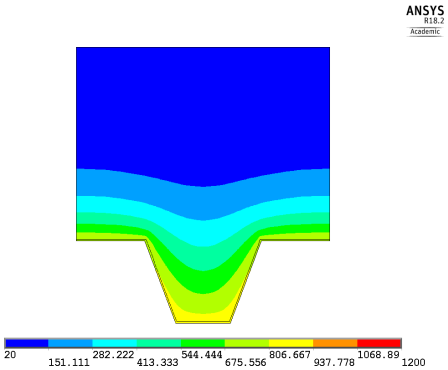


Malha

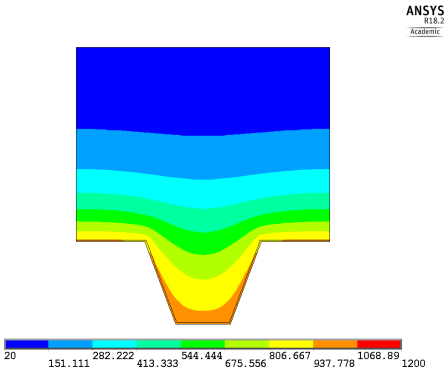




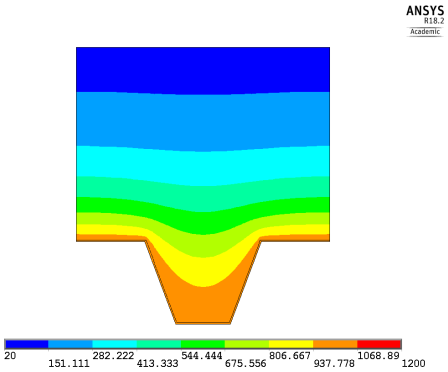
t = 41 min



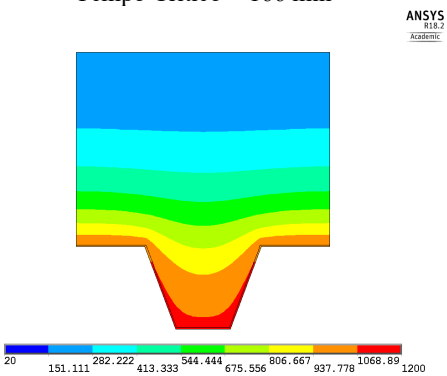
t = 83 min



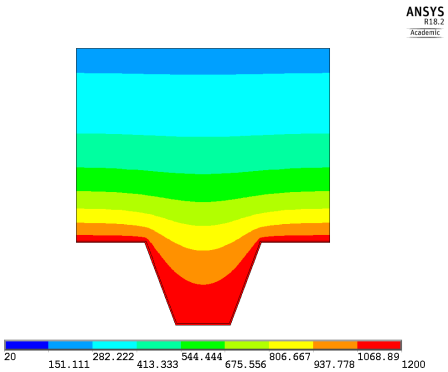
t = 124 min



Tempo Crítico = 166 min

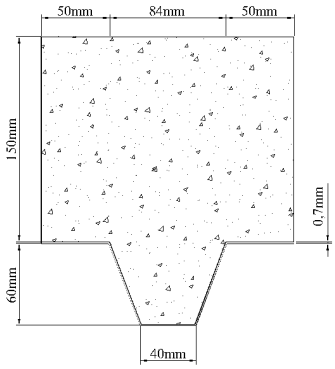


t = 14400s

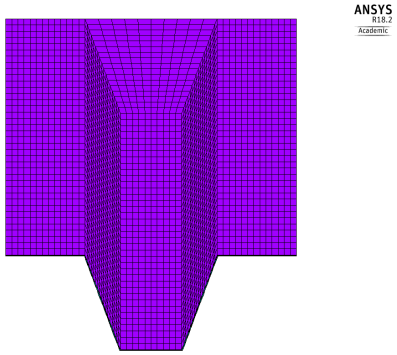


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.7mm

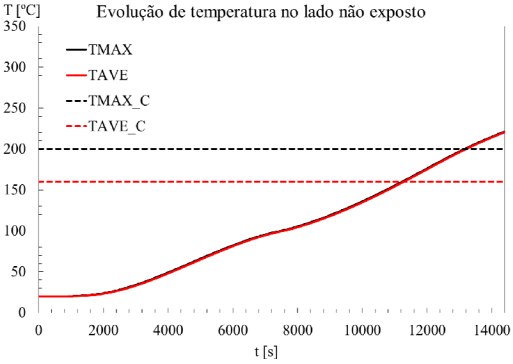
GEOMETRIA



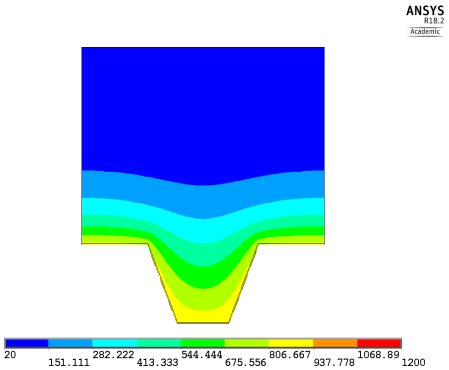
Malha



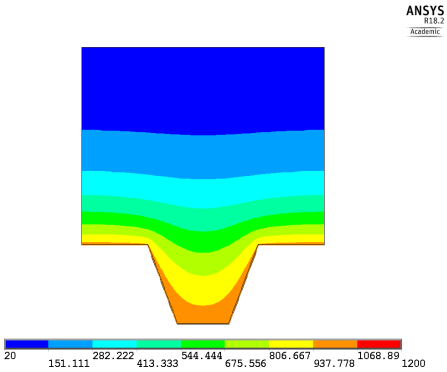
t = 47 min



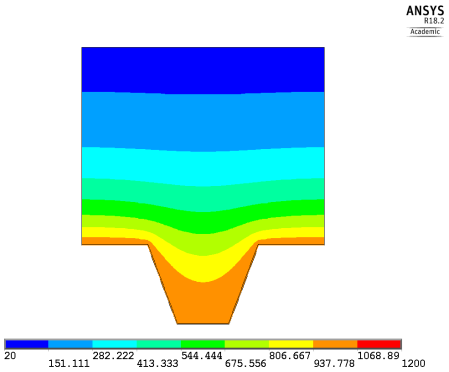
t = 94 min



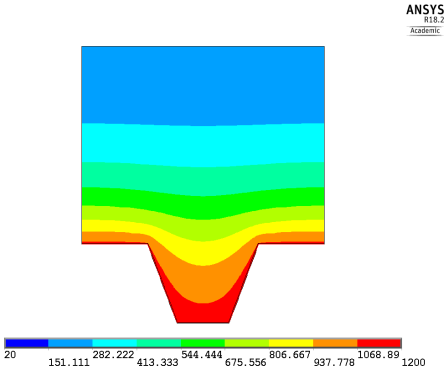
t = 141 min

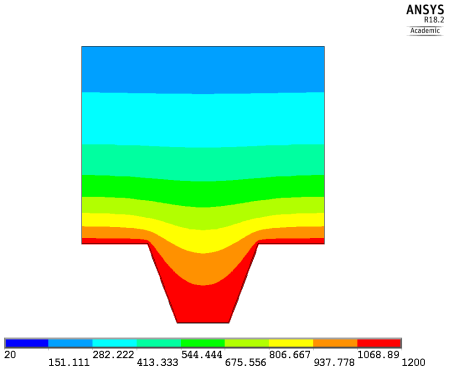


Tempo Crítico = 188 min



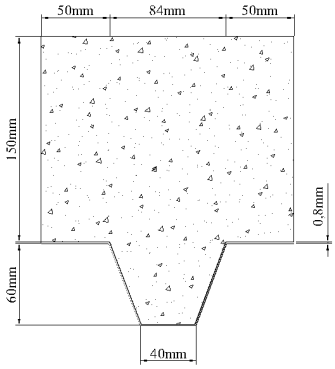
t = 14400s



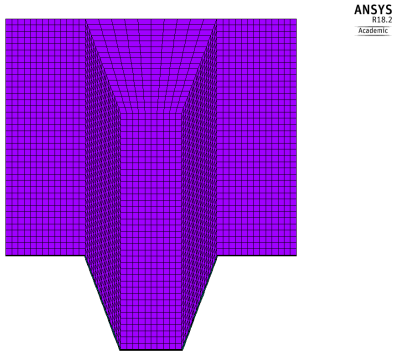


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.8mm

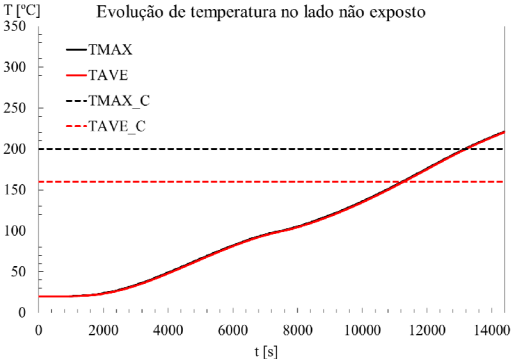
GEOMETRIA



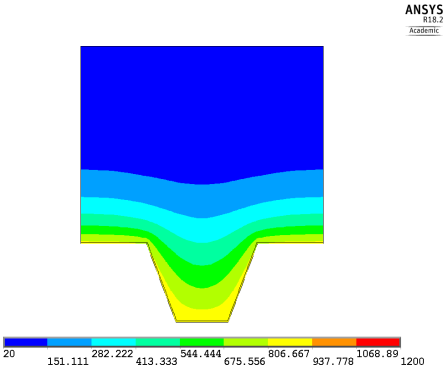
Malha



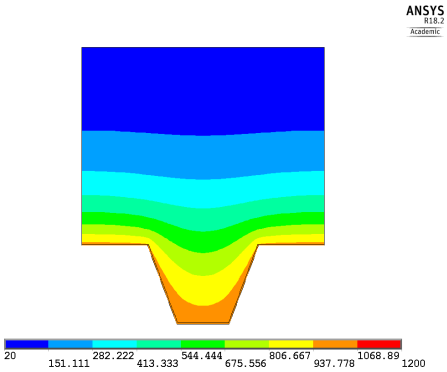
t = 46 min



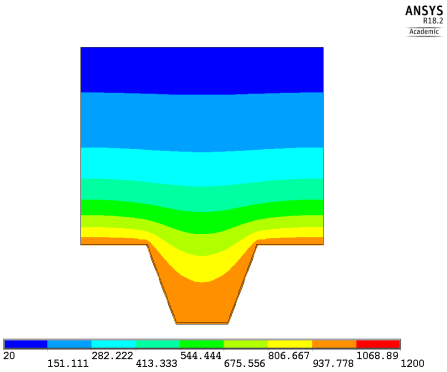
t = 93 min



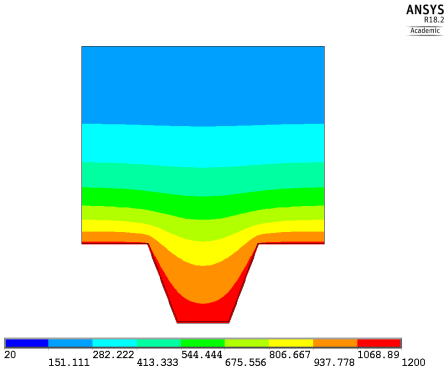
t = 140 min

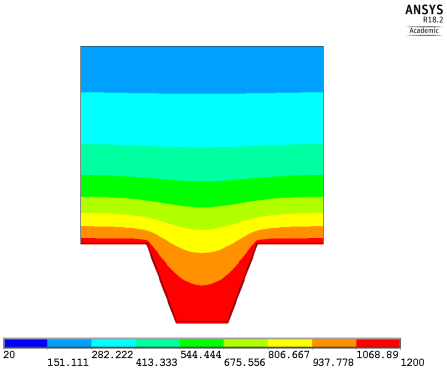


Tempo Crítico = 187 min



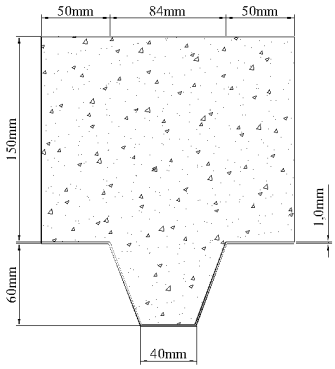
t = 14400s



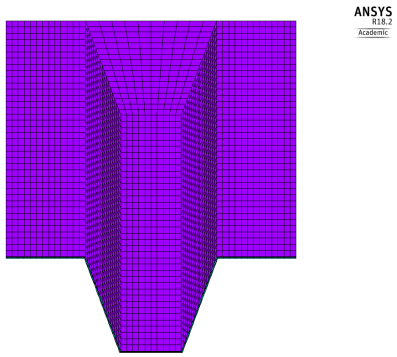


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.0mm

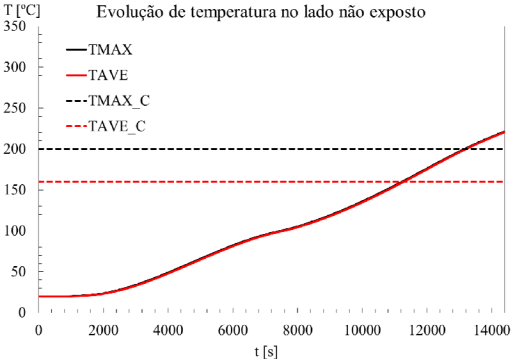
GEOMETRIA



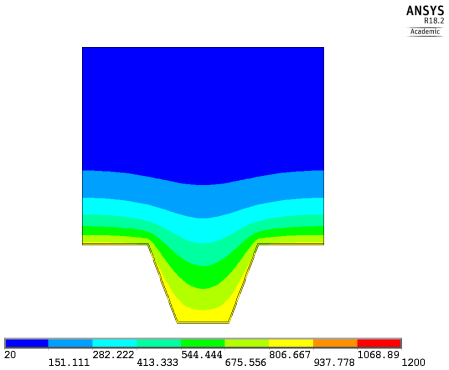
Malha



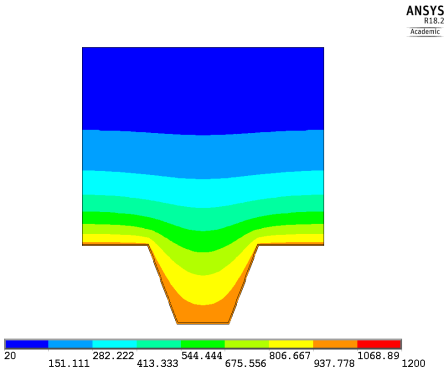
t = 47 min



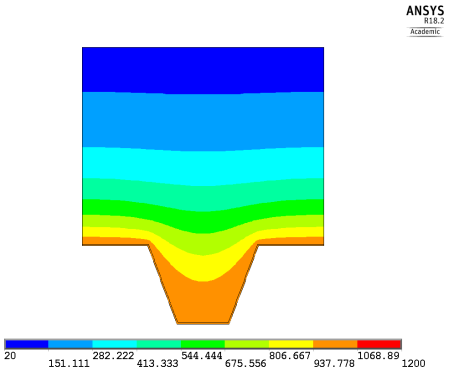
t = 94 min



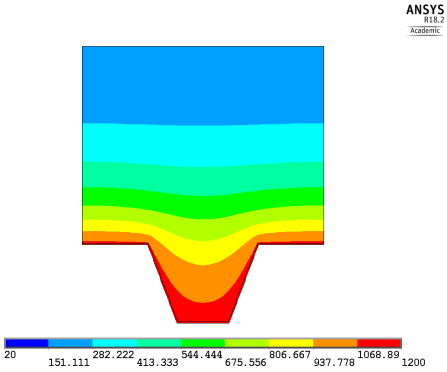
t = 141 min

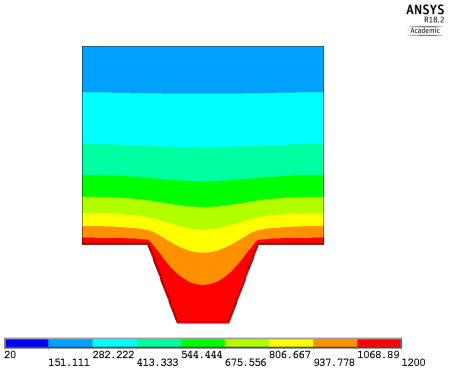


Tempo Crítico = 188 min



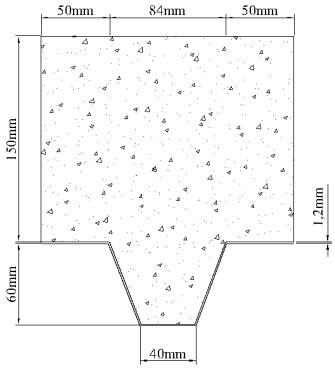
t = 14400s



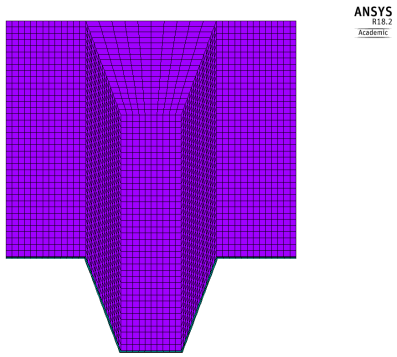


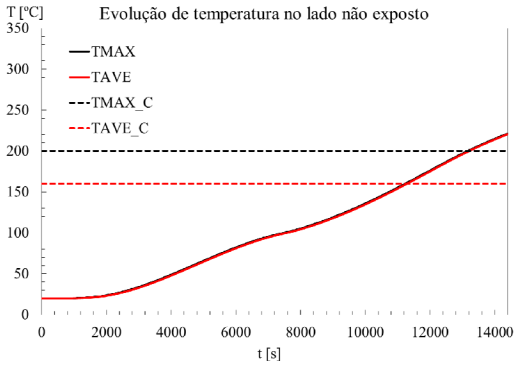
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.2mm

GEOMETRIA

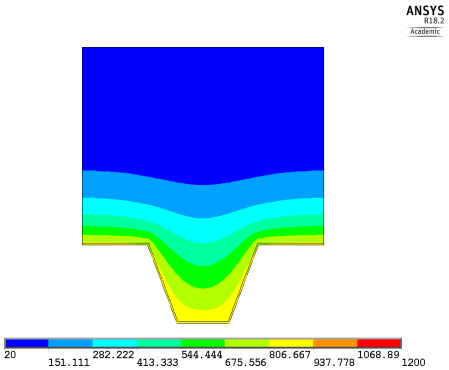


Malha



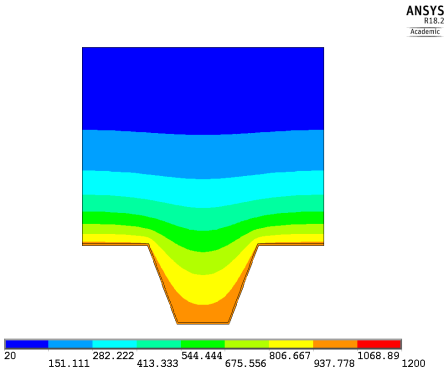


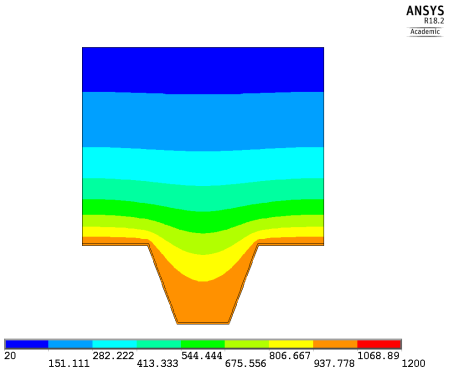
t = 47 min



t = 94 min

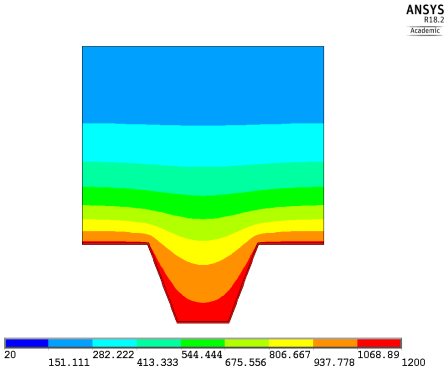
t = 141 min

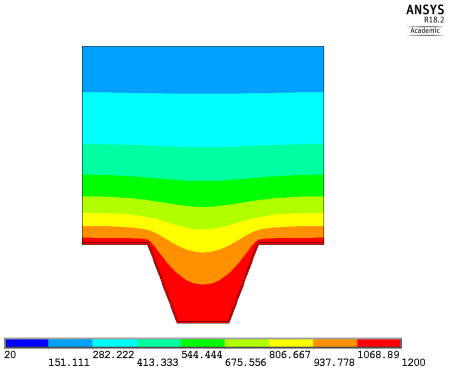




Tempo Crítico = 188 min

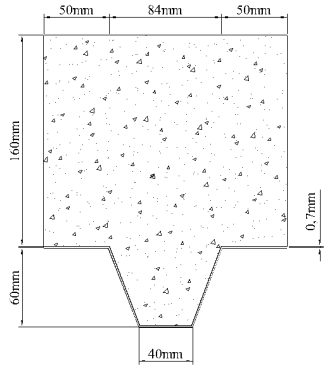
t = 14400s



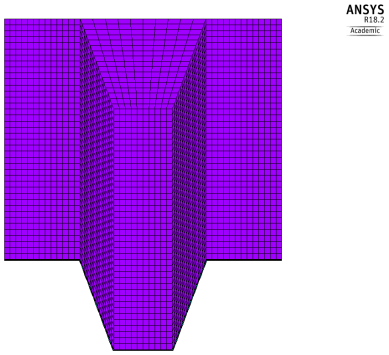


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.7mm

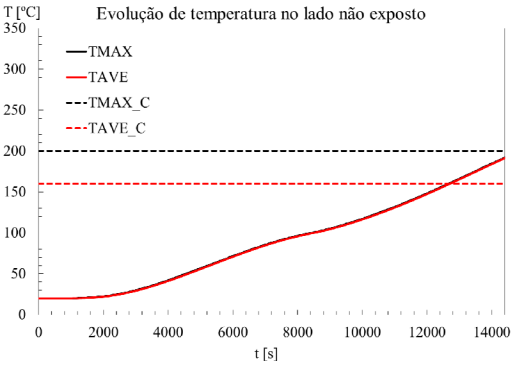
GEOMETRIA



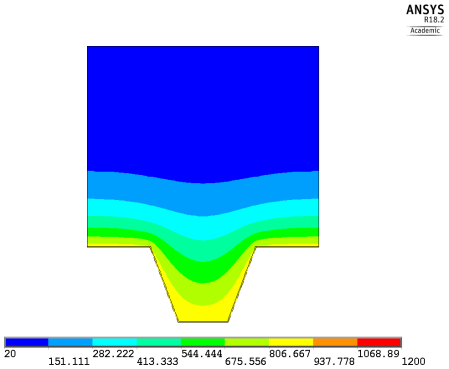
Malha



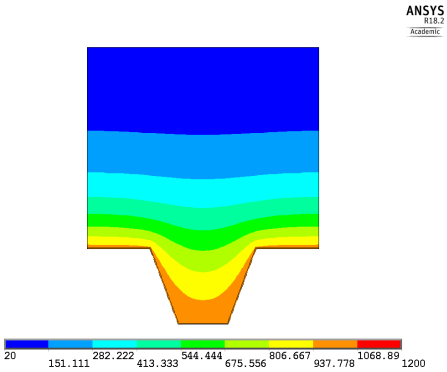
t = 52 min



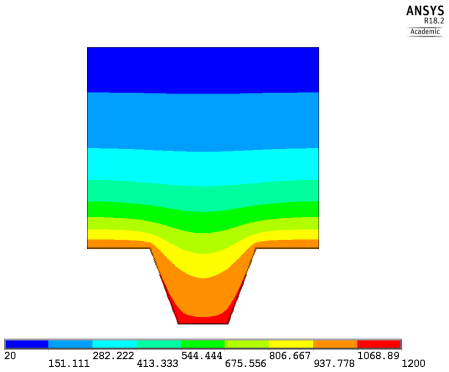
t = 105 min



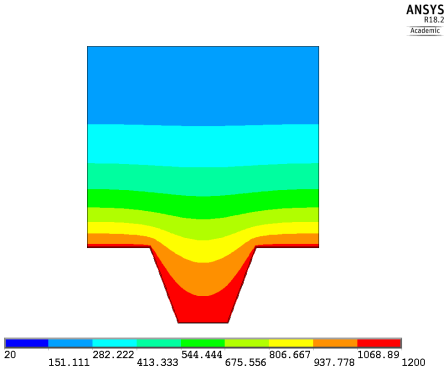
t = 158 min

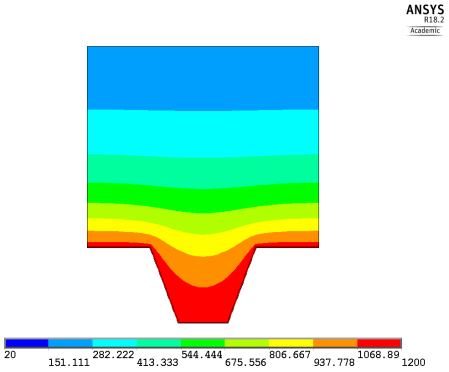


Tempo Crítico = 211 min



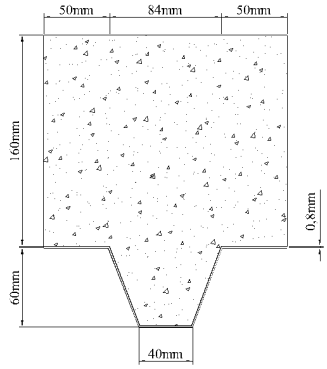
t = 14400s



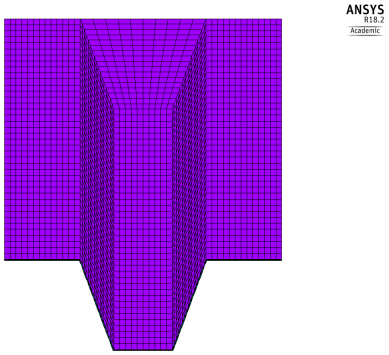


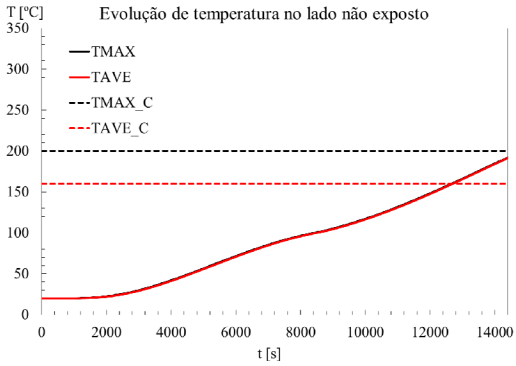
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.8mm

GEOMETRIA

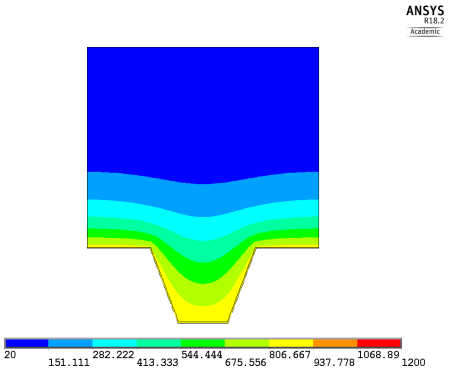


Malha



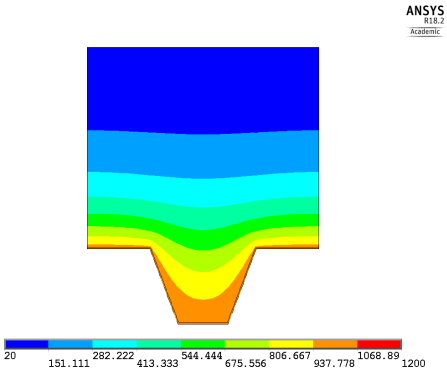


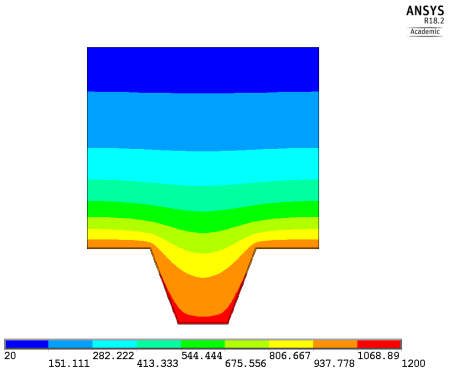
t = 53 min



t = 106 min

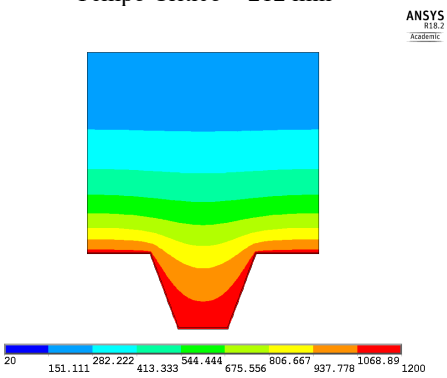
t = 159 min

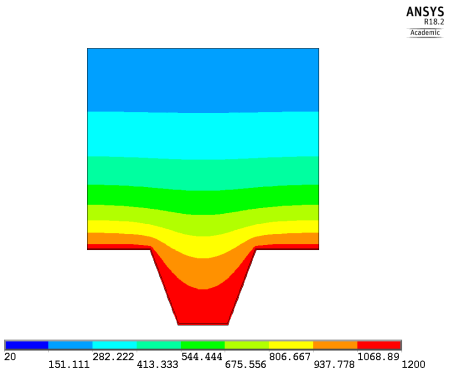




Tempo Crítico = 212 min

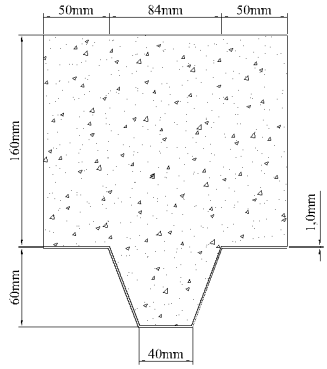
t = 14400s



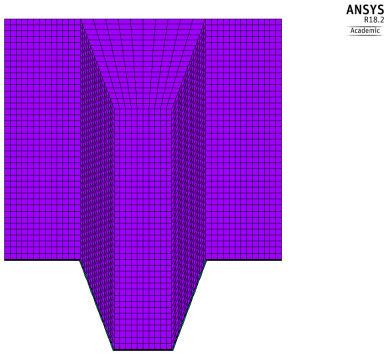


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.0mm

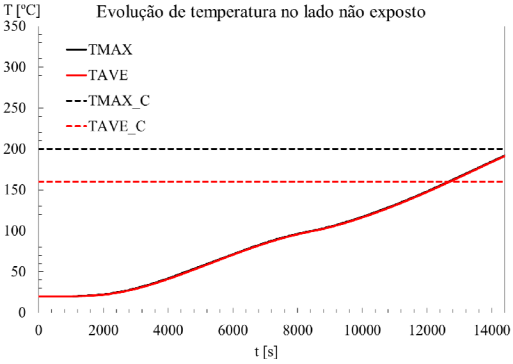
GEOMETRIA

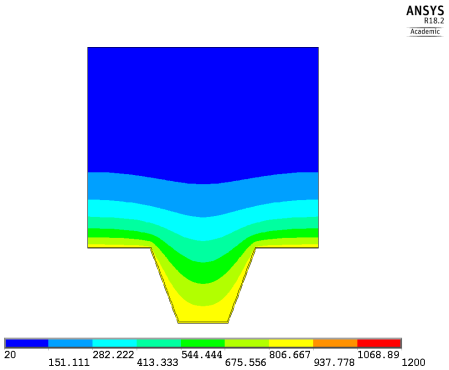


Malha



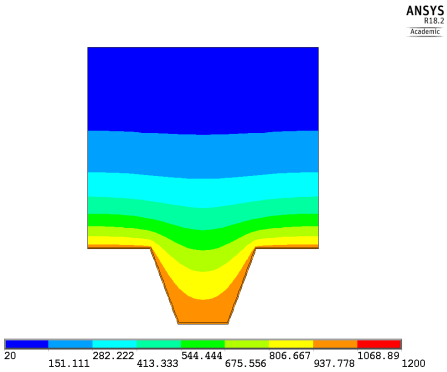
t = 52 min

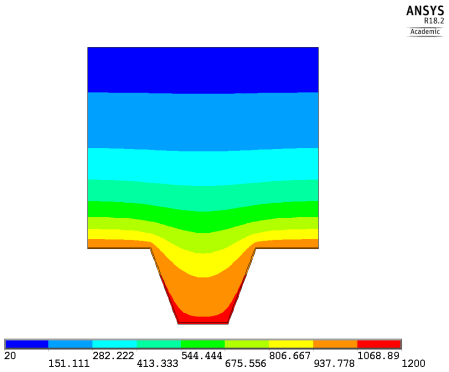




t = 105 min

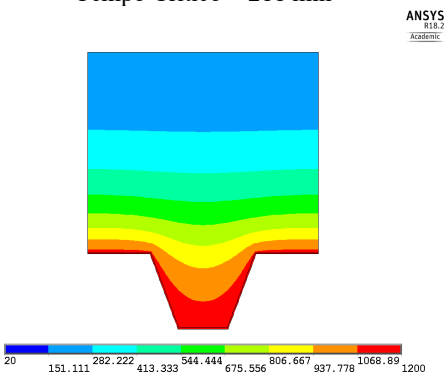
t = 158 min

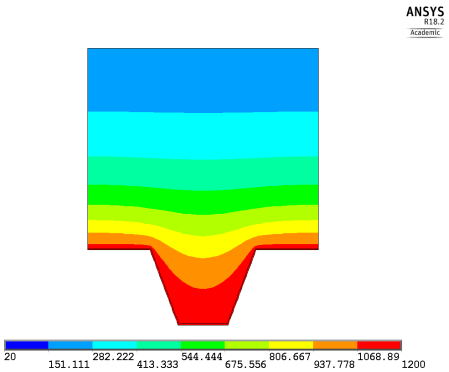




Tempo Crítico = 211 min

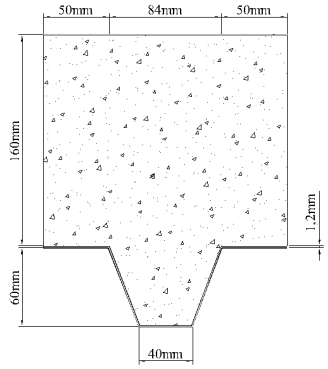
t = 14400s



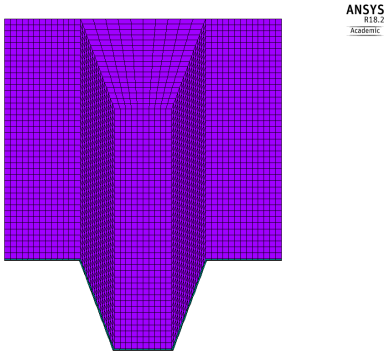


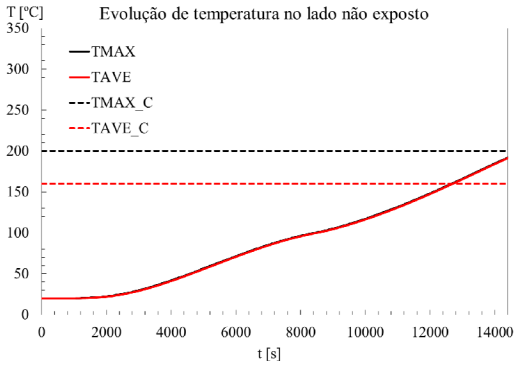
LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.2mm

GEOMETRIA

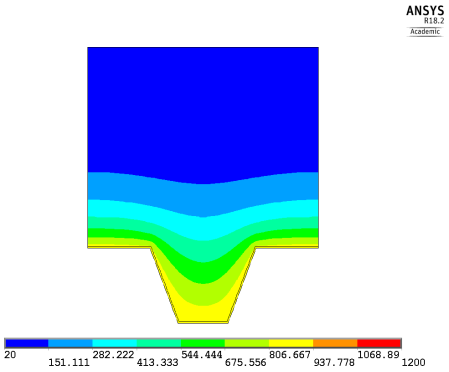


Malha



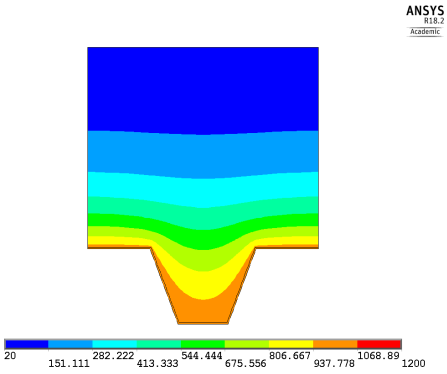


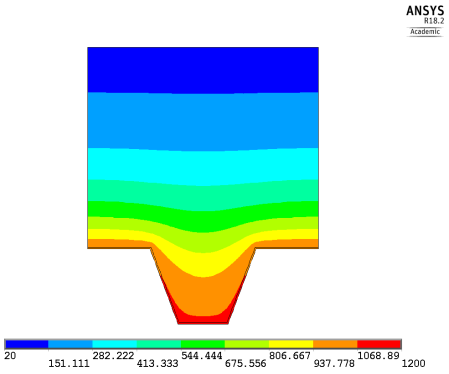
t = 52 min



t = 105 min

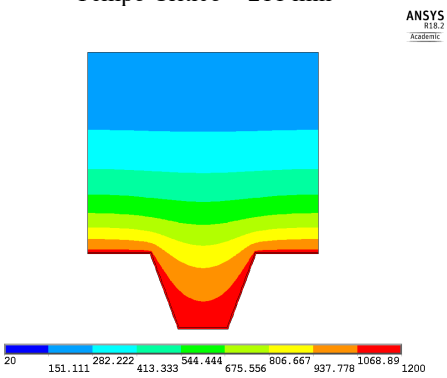
t = 158 min

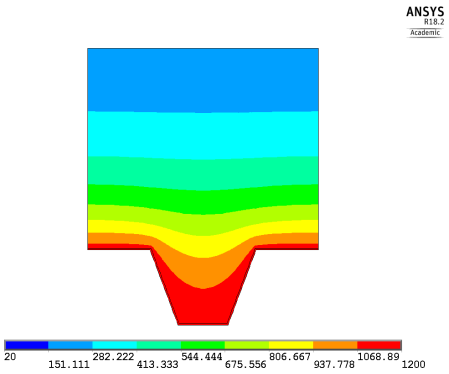




Tempo Crítico = 211 min

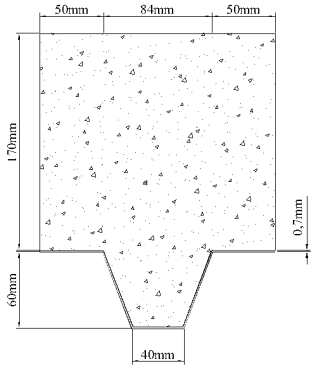
t = 14400s



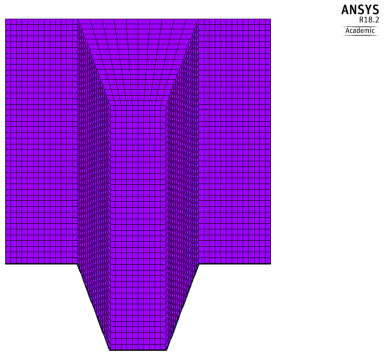


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.7mm

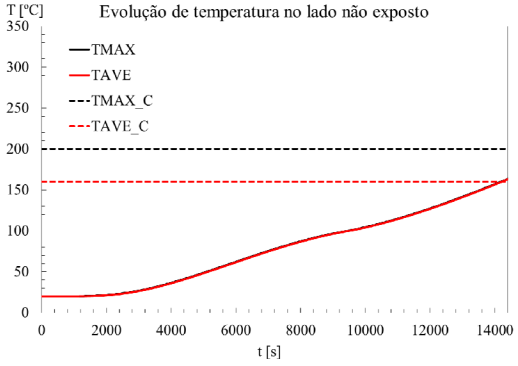
GEOMETRIA



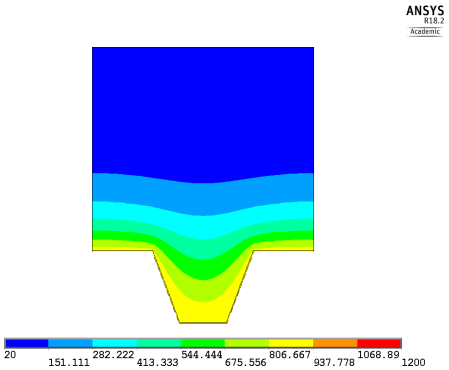
Malha



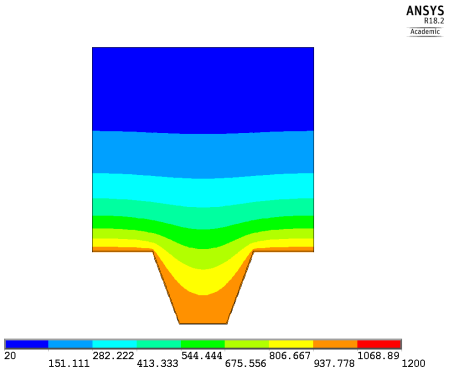
t = 59 min



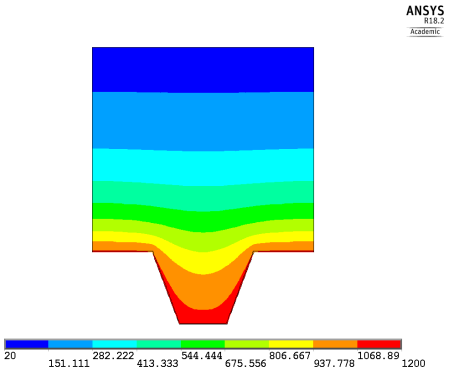
t = 118 min



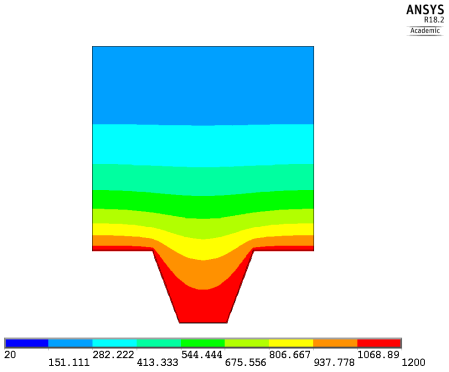
t = 177 min

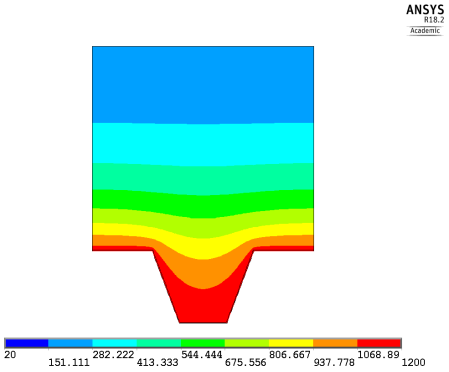


Tempo Crítico = 237 min



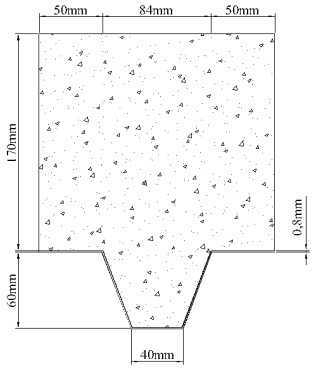
t = 14400s



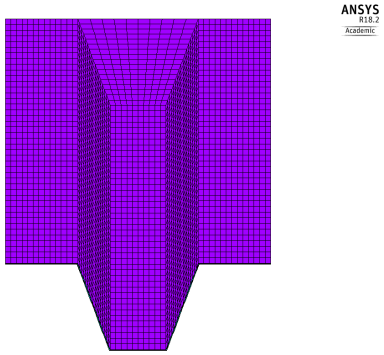


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.8mm

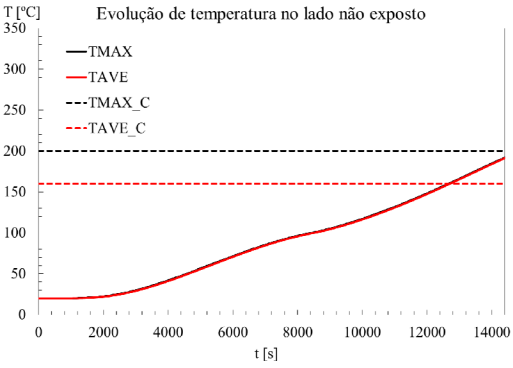
GEOMETRIA



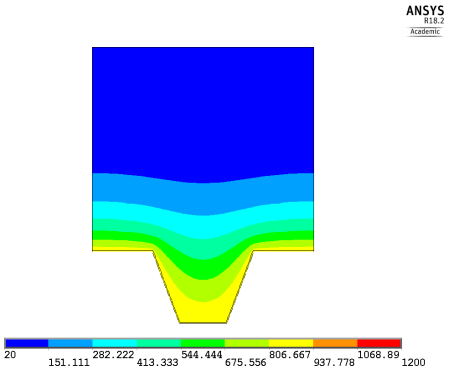
Malha



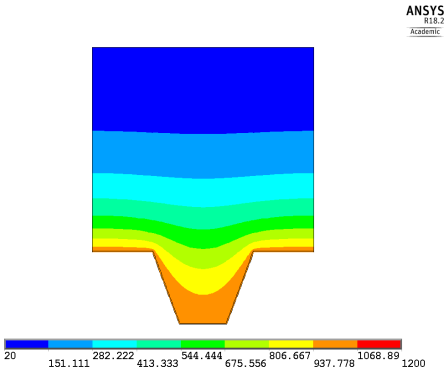
t = 59 min



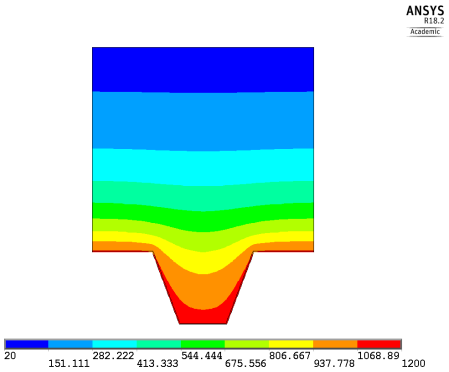
t = 118 min



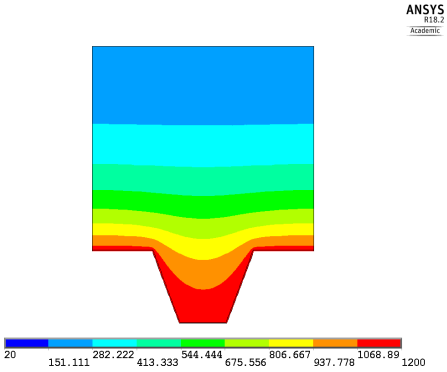
t = 177 min

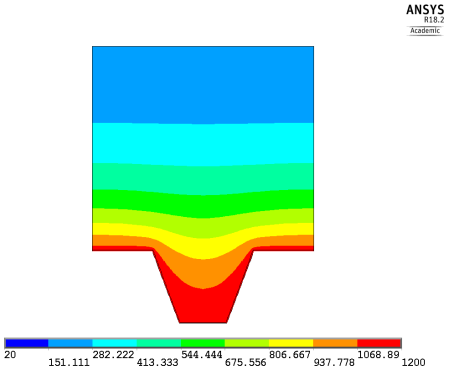


Tempo Crítico = 237 min



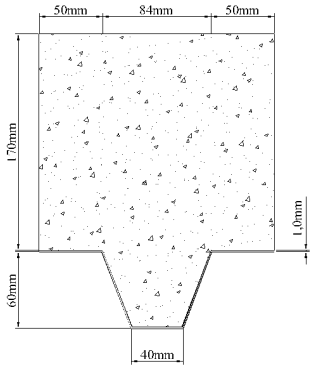
t = 14400s



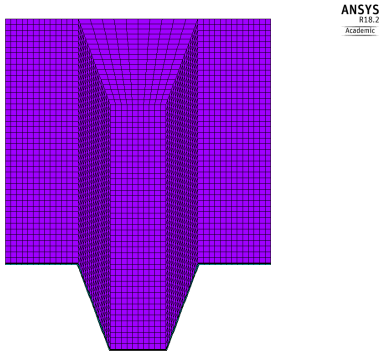


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.0mm

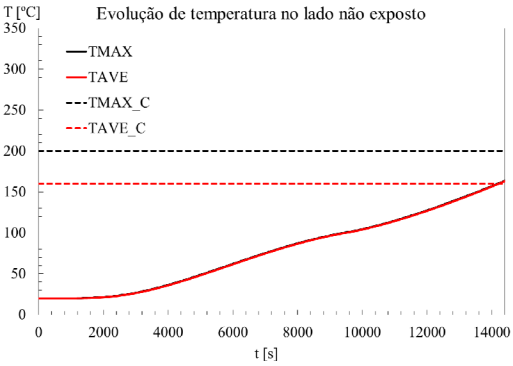
GEOMETRIA



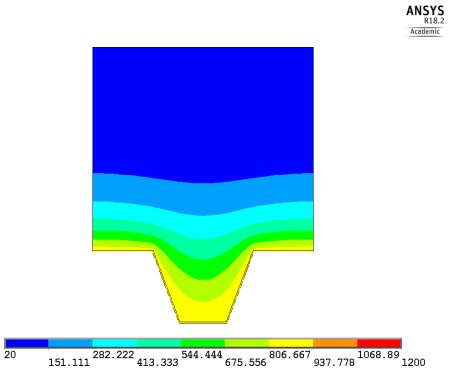
Malha



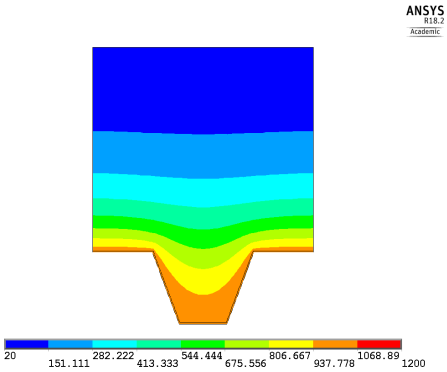
t = 59 min



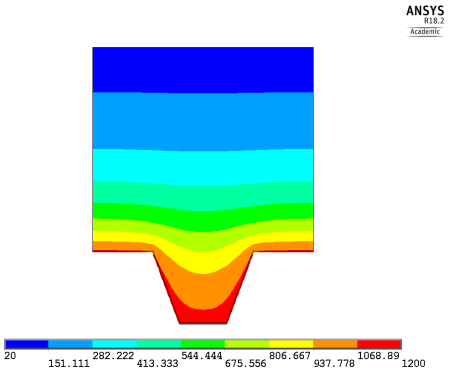
t = 118 min



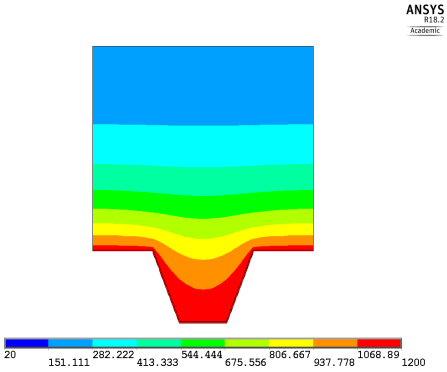
t = 177 min

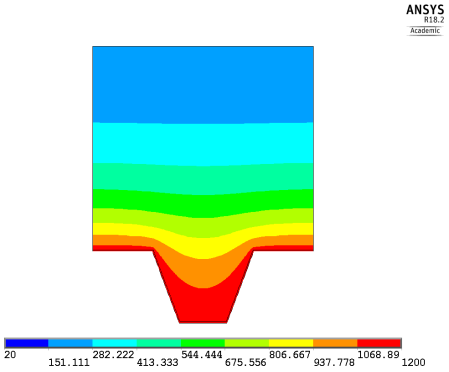


Tempo Crítico = 236 min



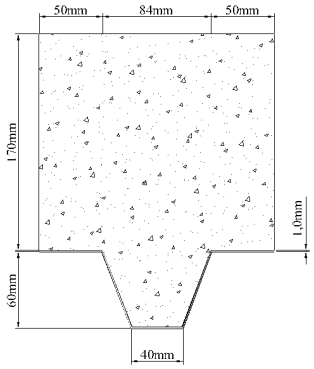
t = 14400s



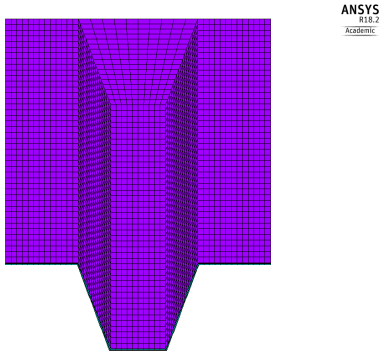


LAJE MISTA TRAPEZOIDAL (L1/L2=84/40mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.2mm

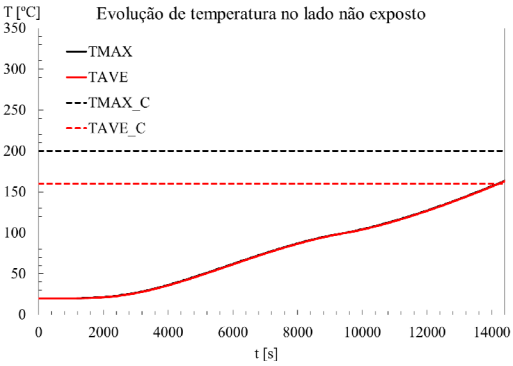
GEOMETRIA



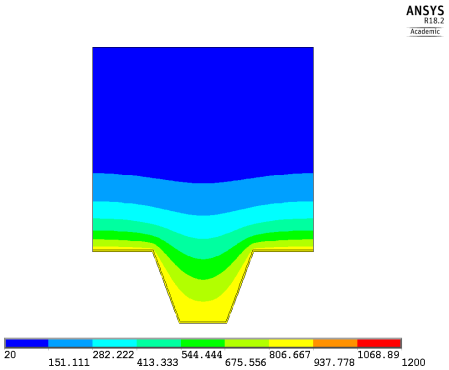
Malha



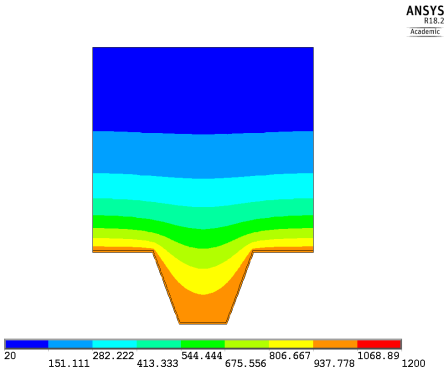
t = 59 min



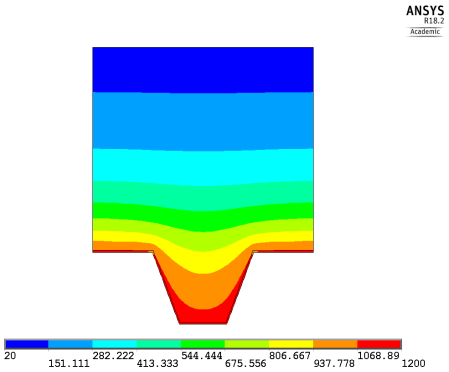
t = 118 min



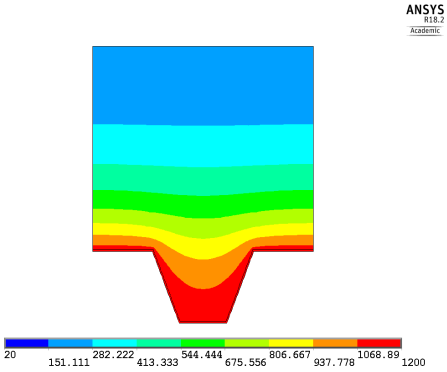
t = 177 min

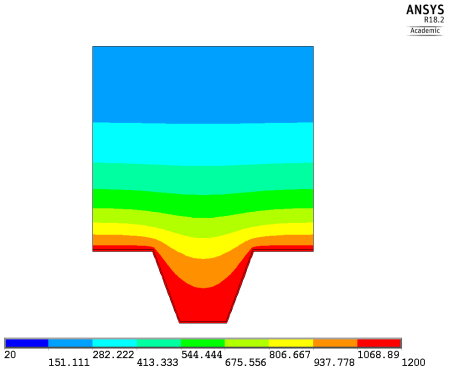


Tempo Crítico = 236 min



t = 14400s





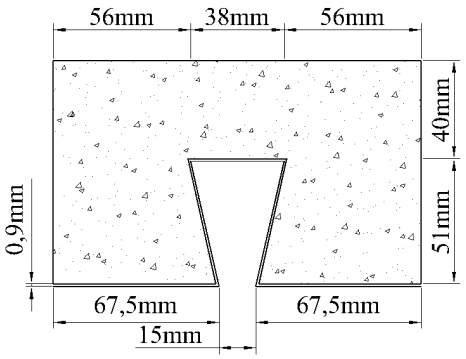
Anexo D

Análise térmica da seção transversal

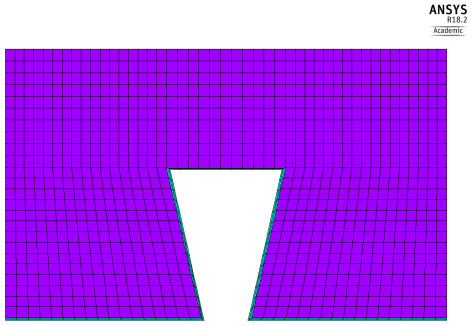
Método avançado de cálculo para lajes reentrantes: ANSYS.

LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.9mm

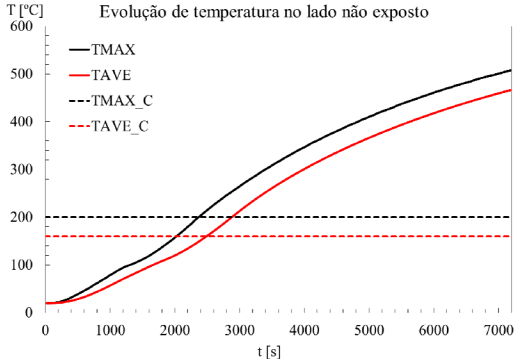
GEOMETRIA



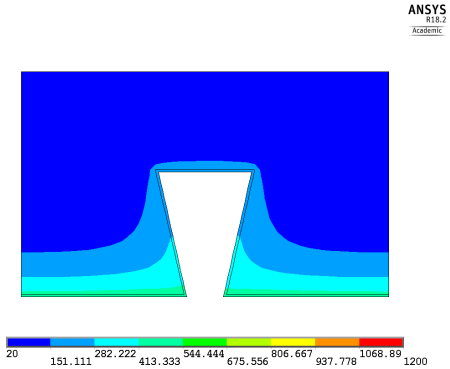
Malha



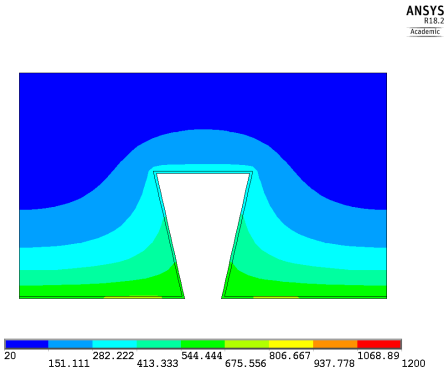
t = 9 min



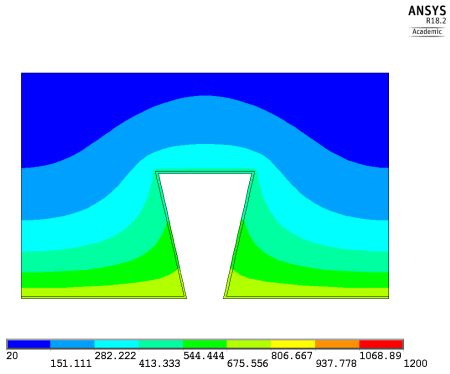
t = 19 min



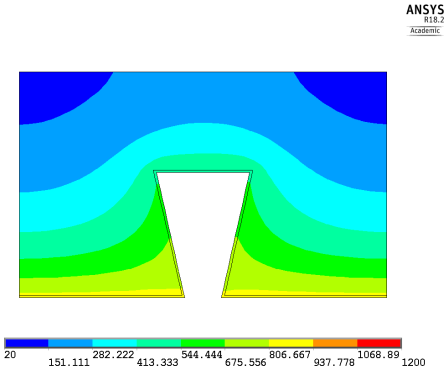
t = 29 min

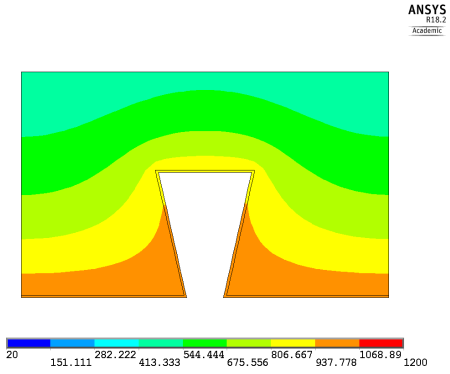


Tempo Crítico = 39 min



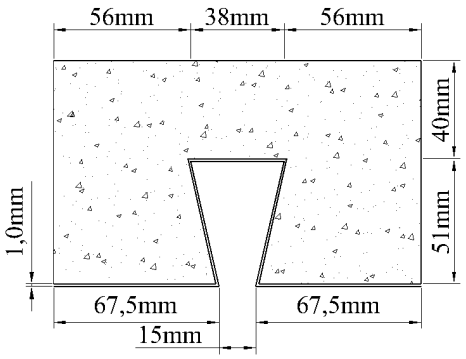
t = 7200s



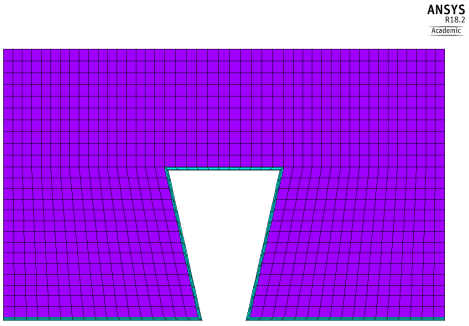


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.0mm

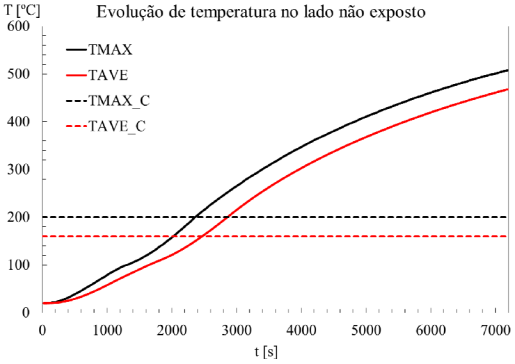
GEOMETRIA



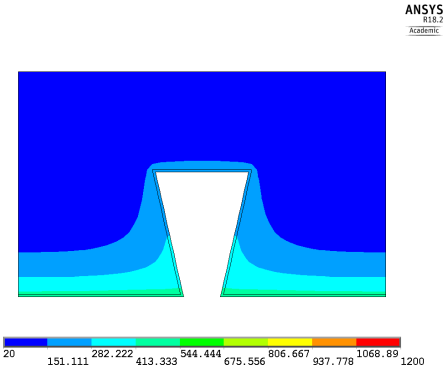
Malha



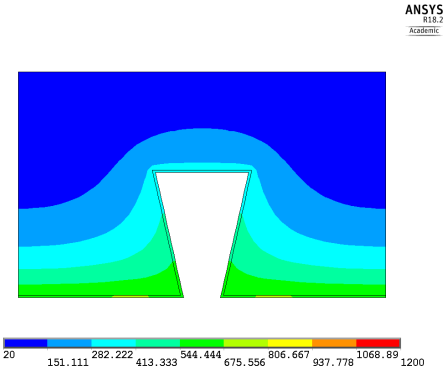
t = 9 min



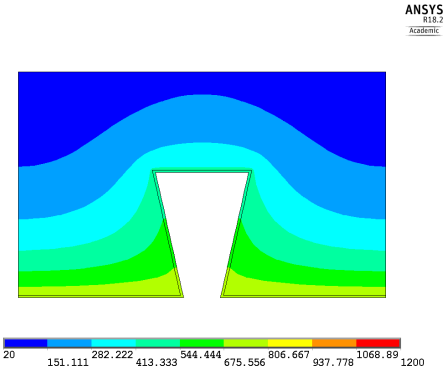
t = 19 min



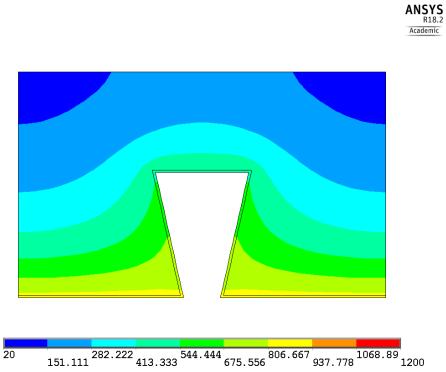
t = 29 min

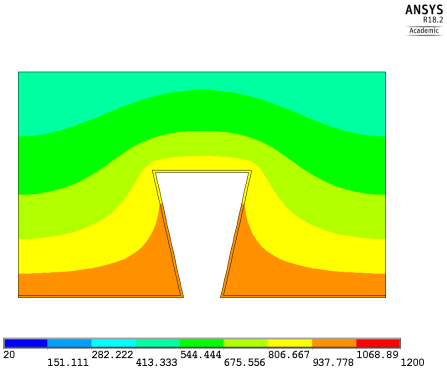


Tempo Crítico = 39 min



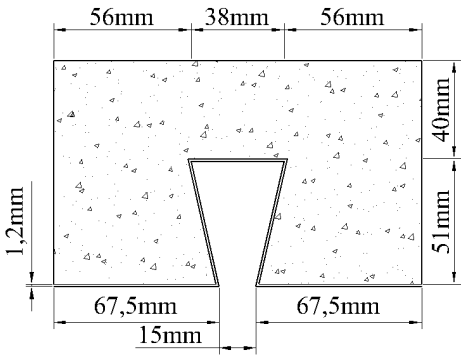
t = 7200s



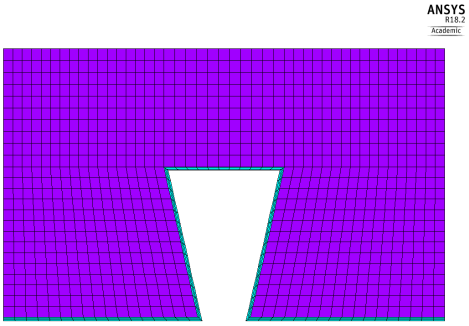


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.2mm

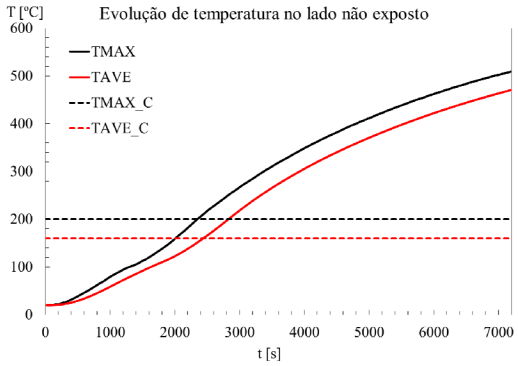
GEOMETRIA



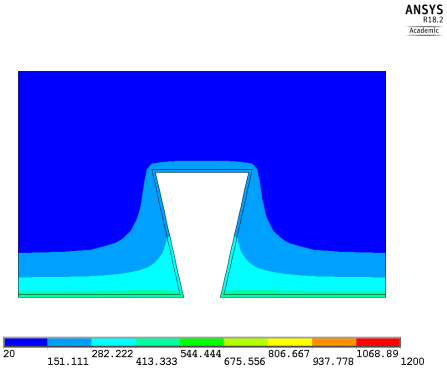
Malha



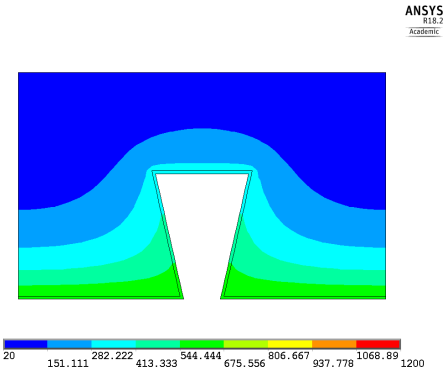
t = 9 min



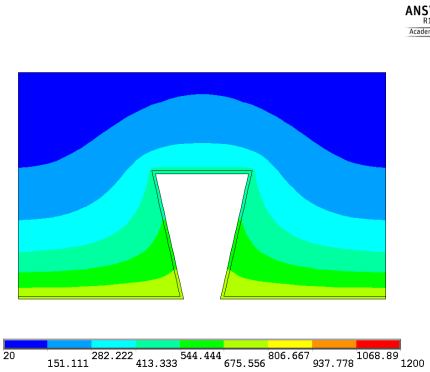
t = 19 min



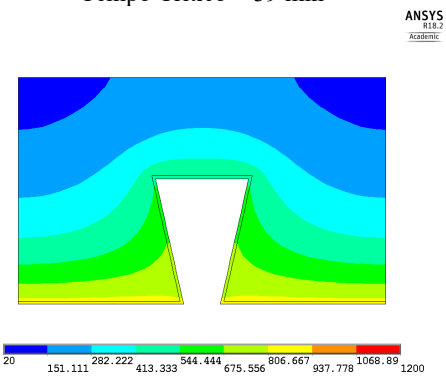
t = 29 min

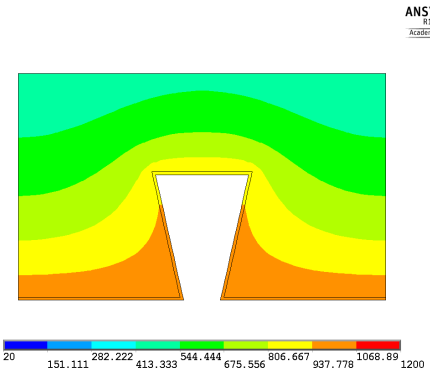


Tempo Crítico = 39 min



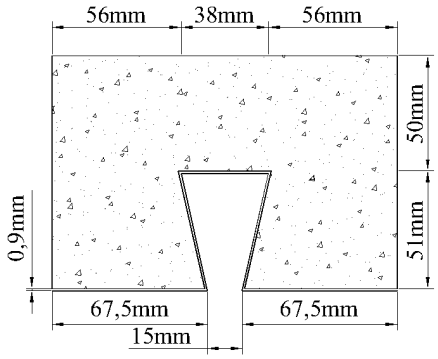
t = 7200s



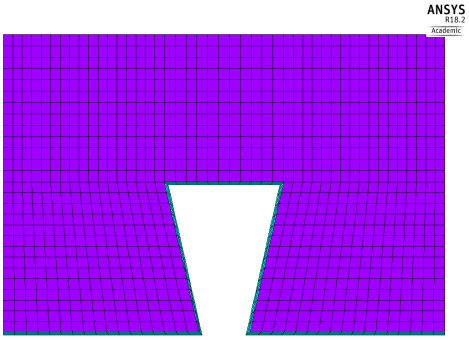


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.9mm

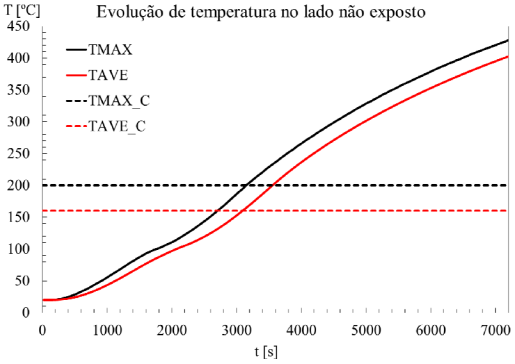
GEOMETRIA



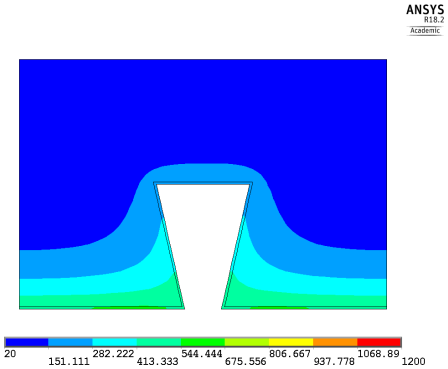
Malha



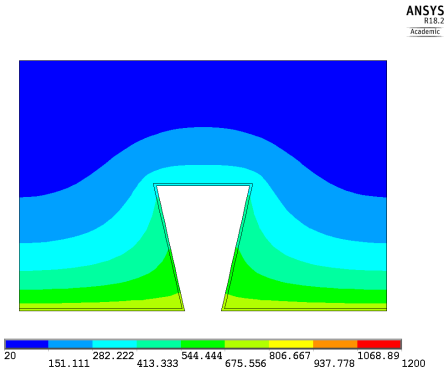
t = 12 min



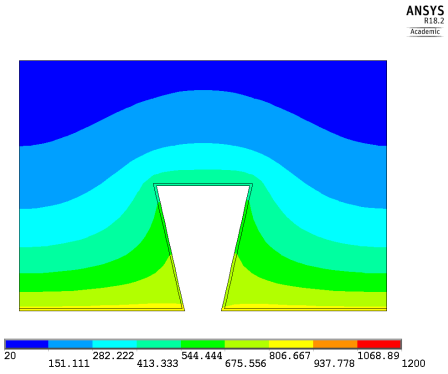
t = 25 min



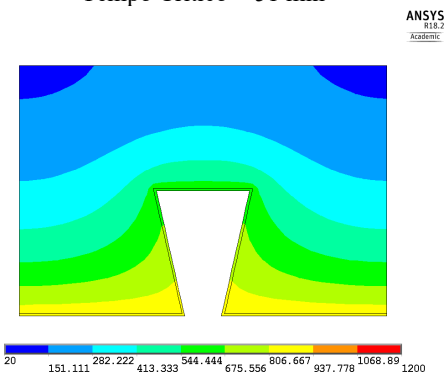
t = 38 min

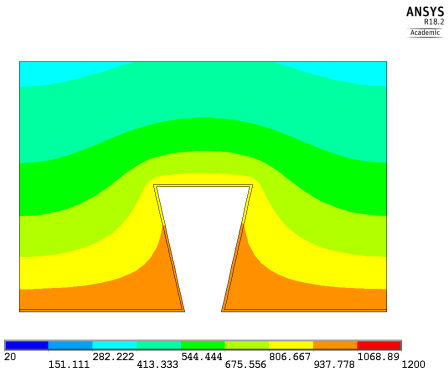


Tempo Crítico = 51 min



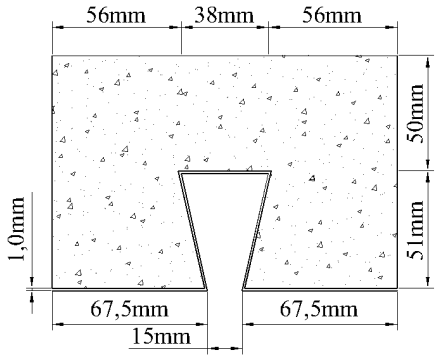
t = 7200s



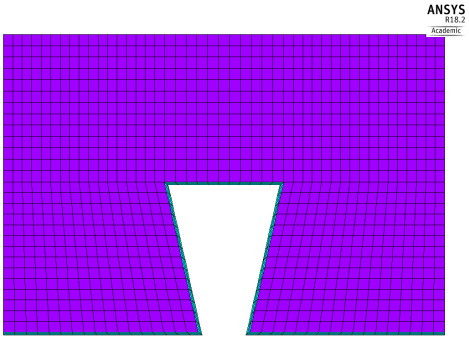


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.0mm

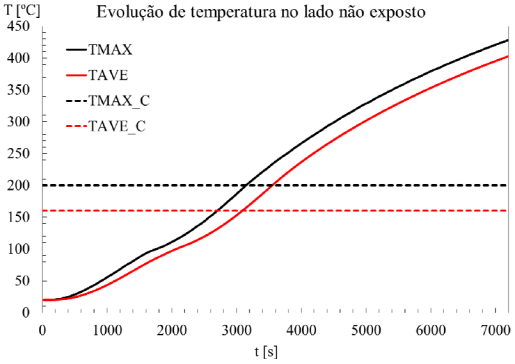
GEOMETRIA



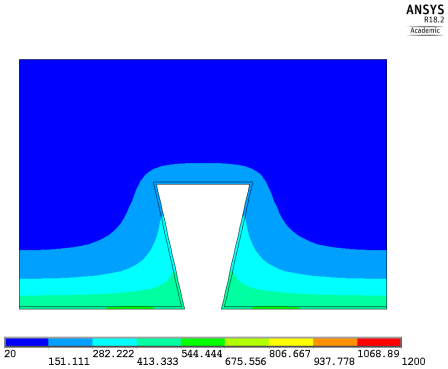
Malha



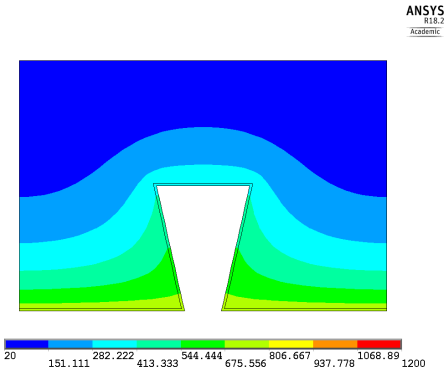
t = 12 min



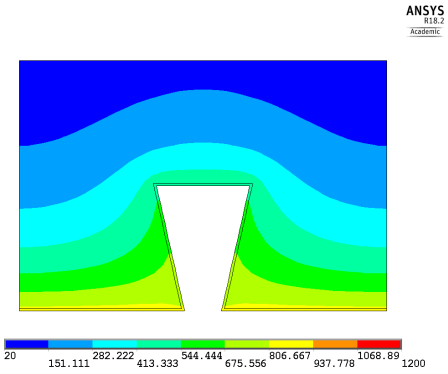
t = 25 min



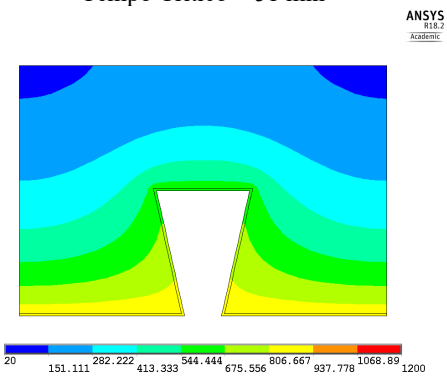
t = 38 min

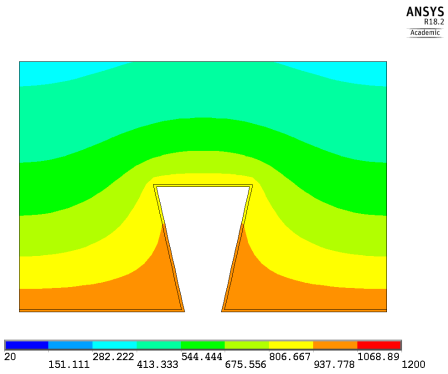


Tempo Crítico = 51 min



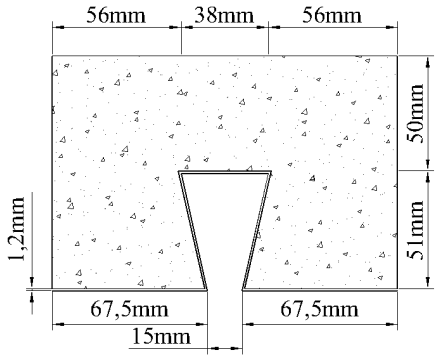
t = 7200s



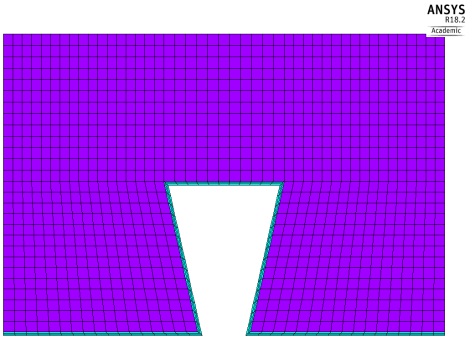


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.2mm

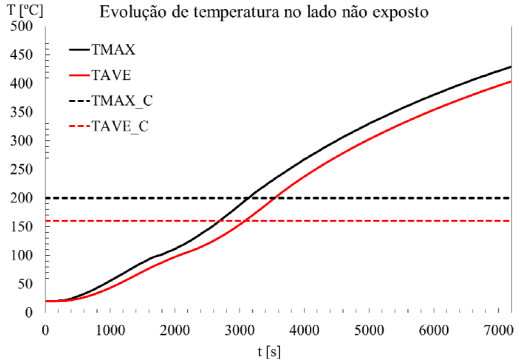
GEOMETRIA



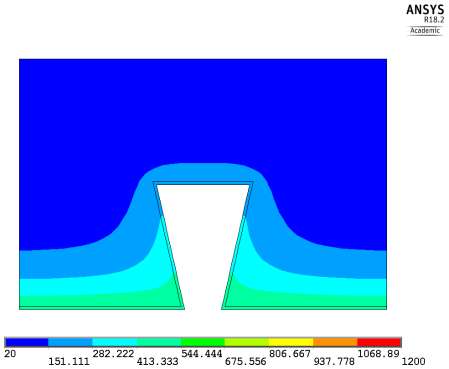
Malha



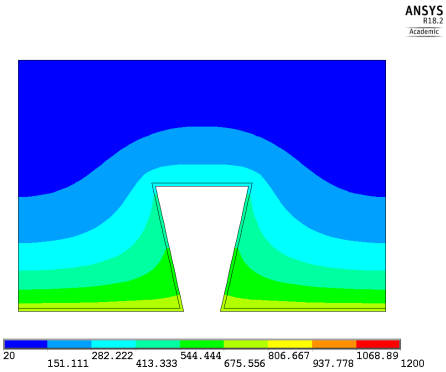
t = 12 min



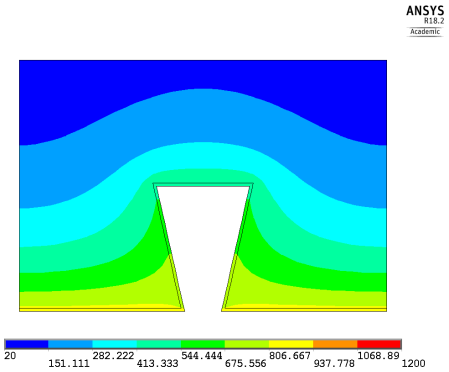
t = 25 min



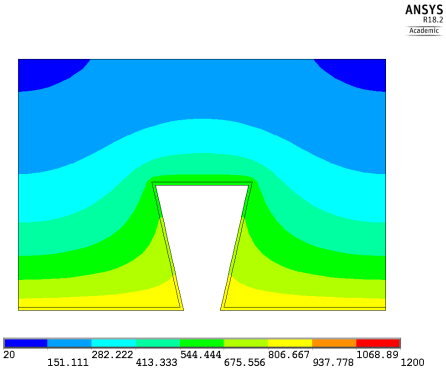
t = 38 min

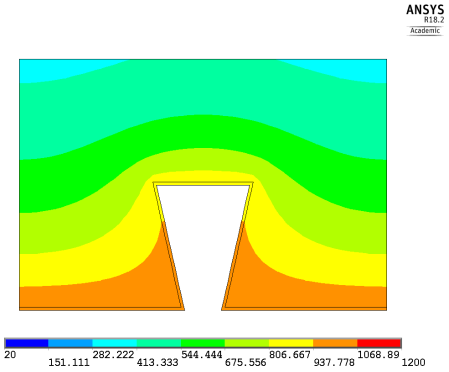


Tempo Crítico = 51 min



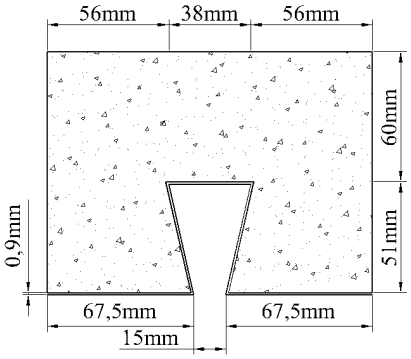
t = 7200s



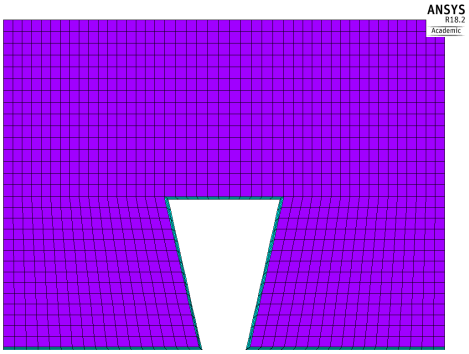


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.9mm

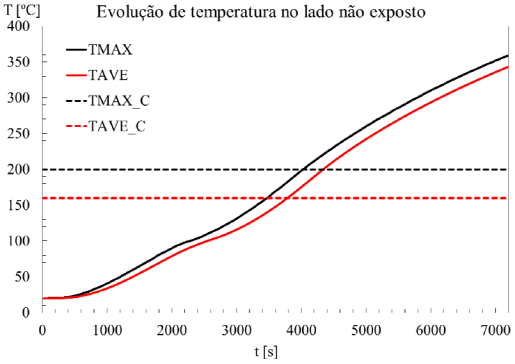
GEOMETRIA



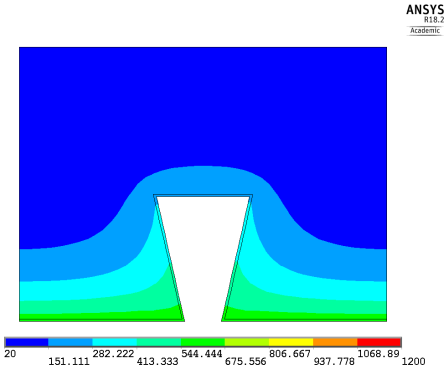
Malha



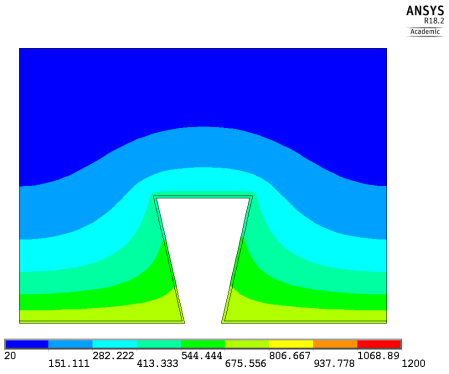
t = 15 min



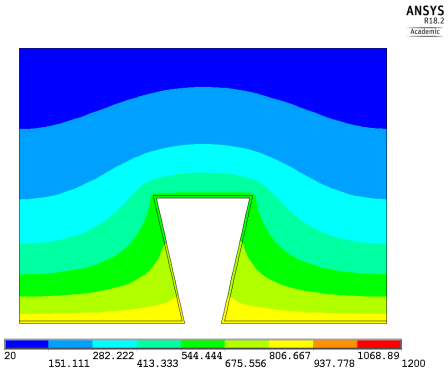
t = 31 min



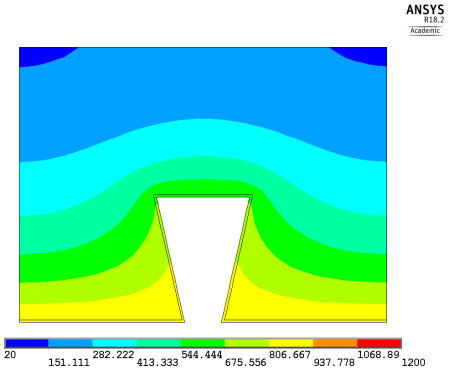
t = 47 min

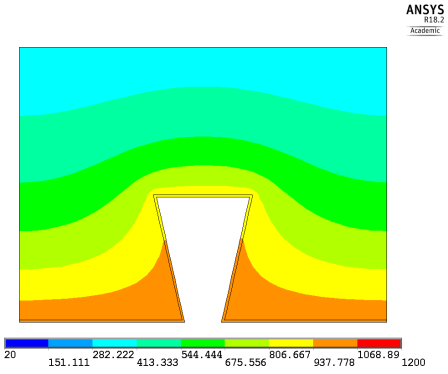


Tempo Crítico = 63 min



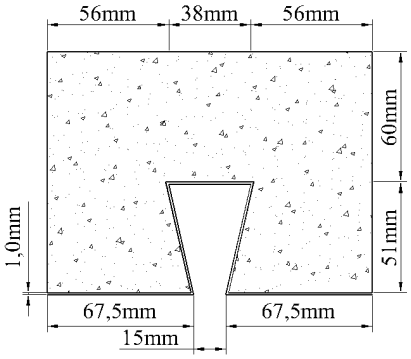
t = 7200s



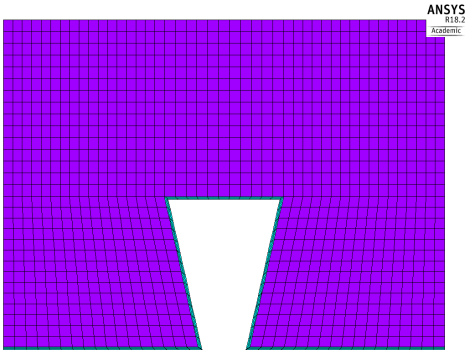


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.0mm

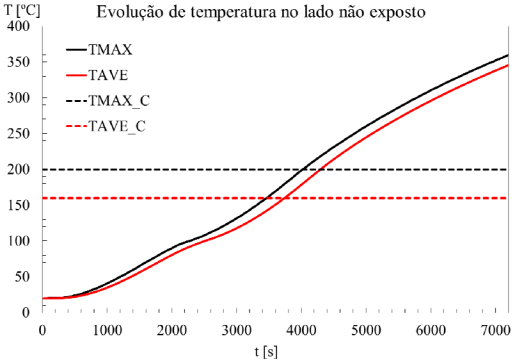
GEOMETRIA



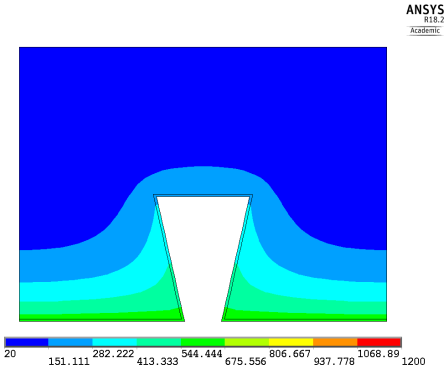
Malha



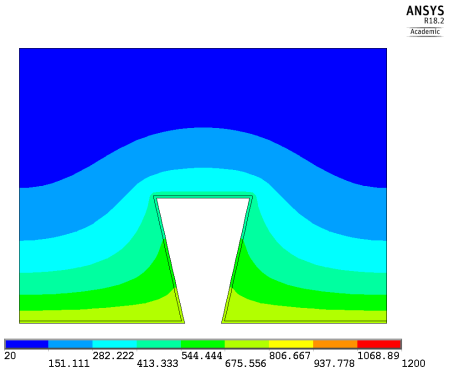
t = 15 min



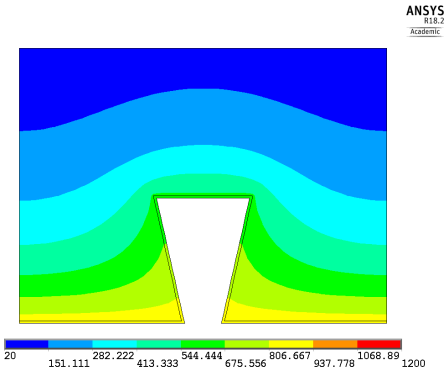
t = 31 min



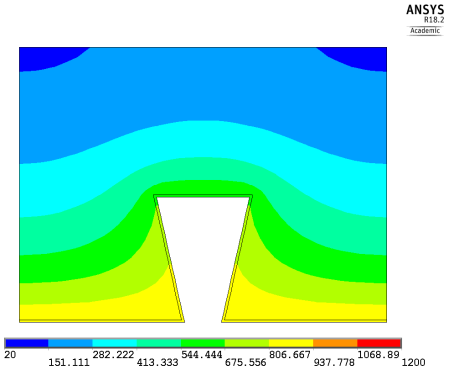
t = 46 min

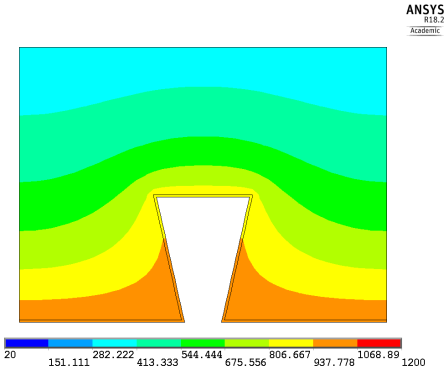


Tempo Crítico = 62 min



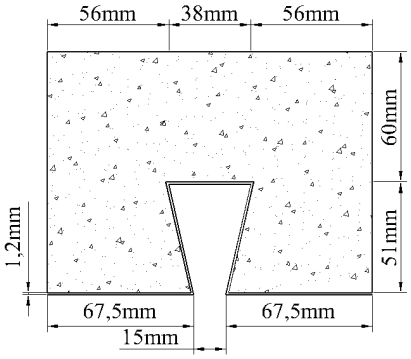
t = 7200s



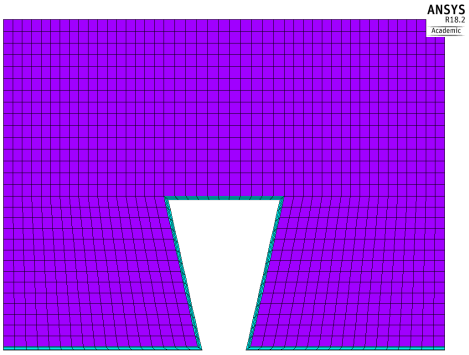


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.2mm

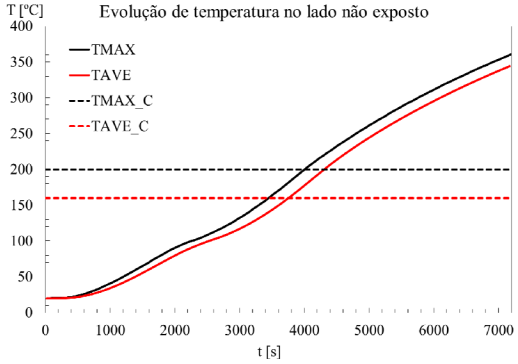
GEOMETRIA



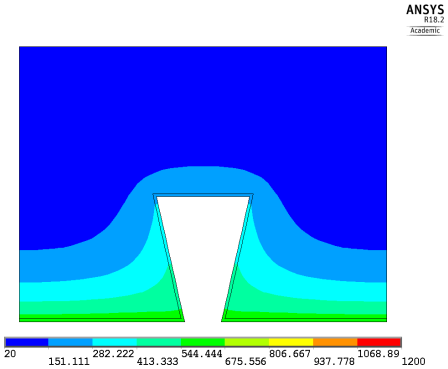
Malha



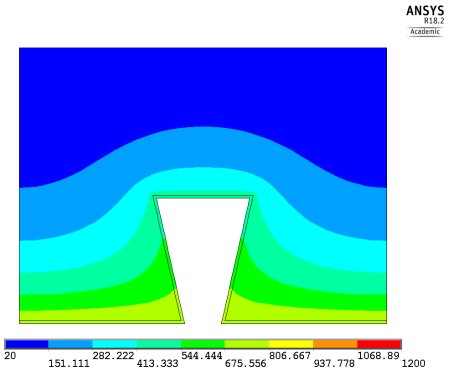
t = 15 min



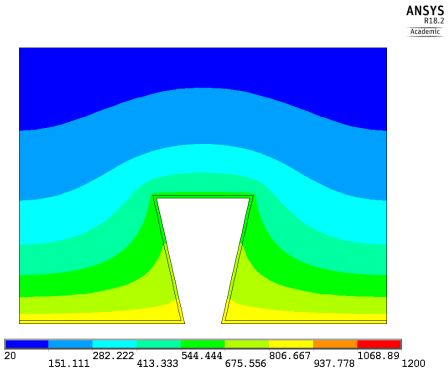
t = 31 min



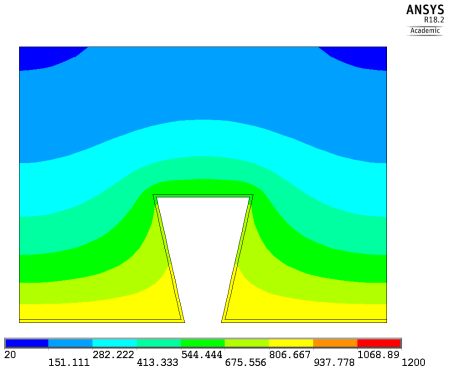
t = 46 min

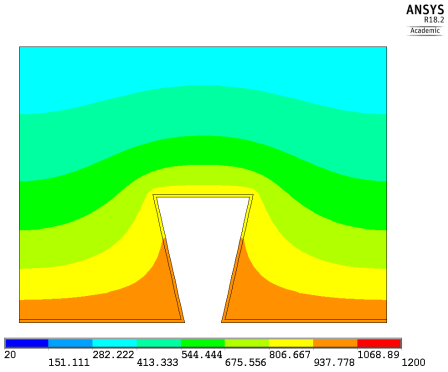


Tempo Crítico = 62 min



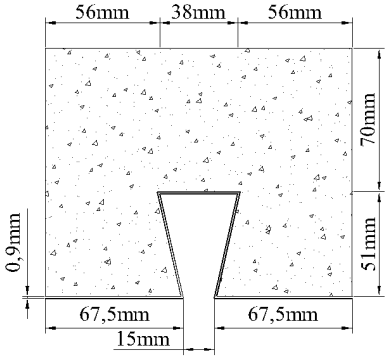
t = 7200s



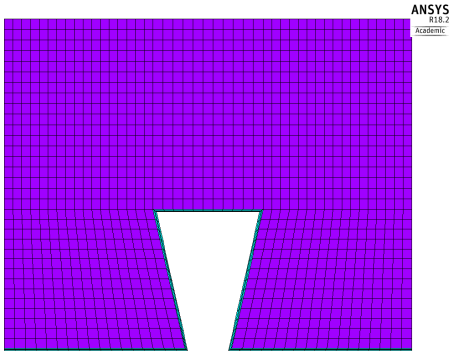


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.9mm

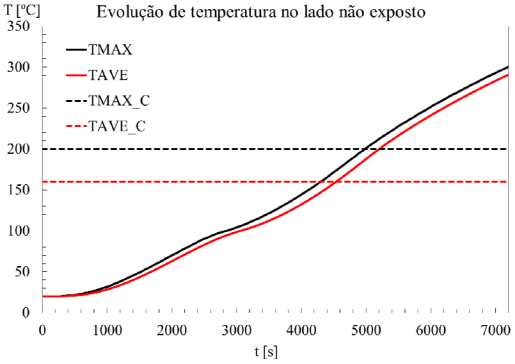
GEOMETRIA



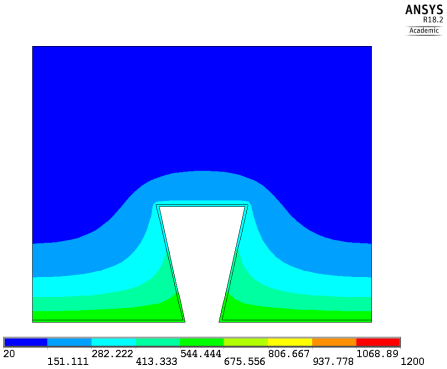
Malha



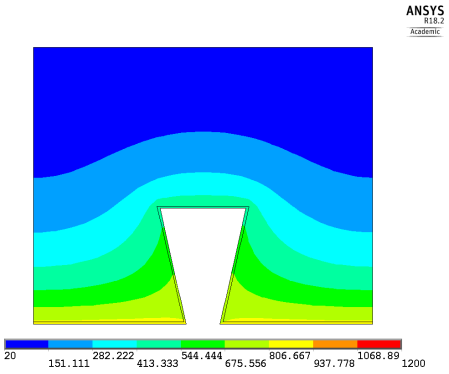
t = 18 min



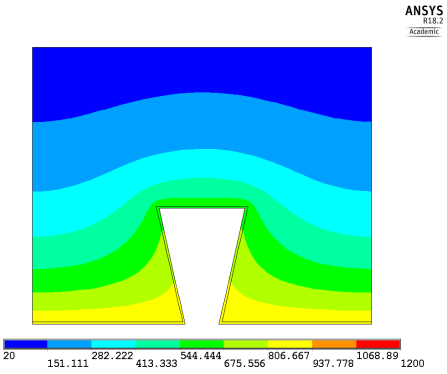
t = 37 min



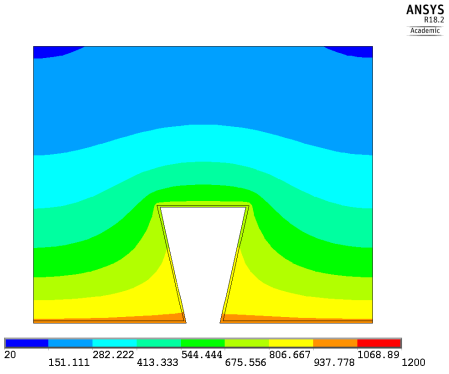
t = 56 min

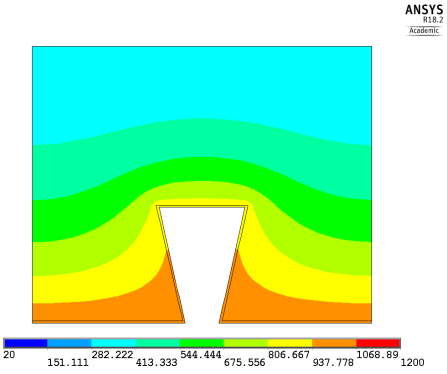


Tempo Crítico = 75 min



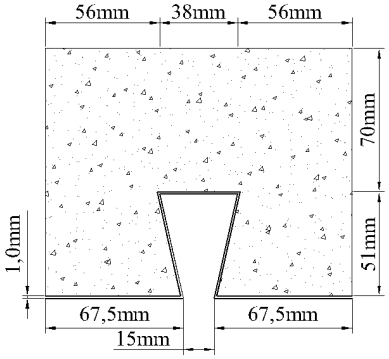
t = 7200s



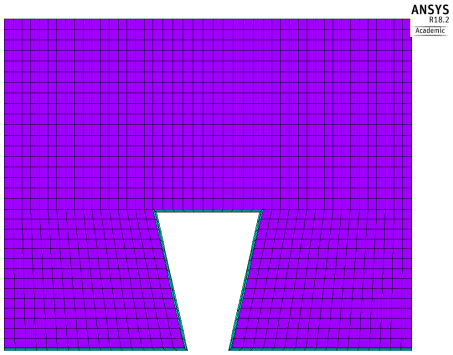


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.0mm

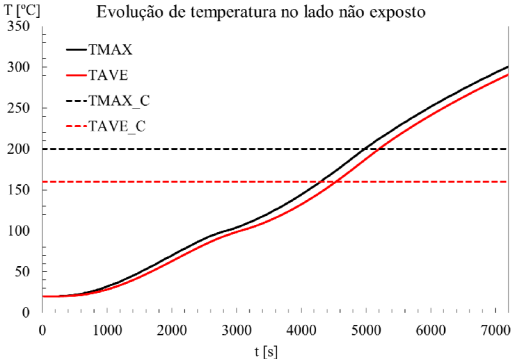
GEOMETRIA



Malha



t = 18 min



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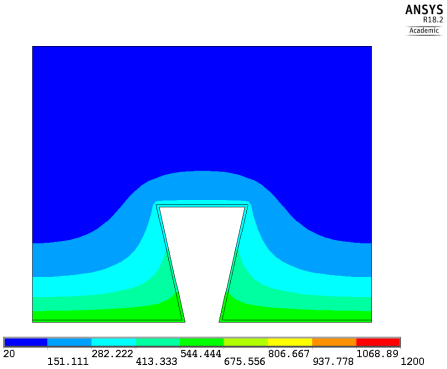

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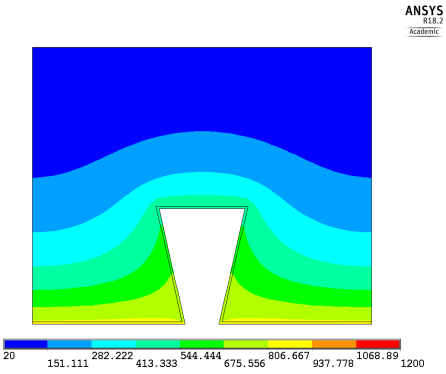
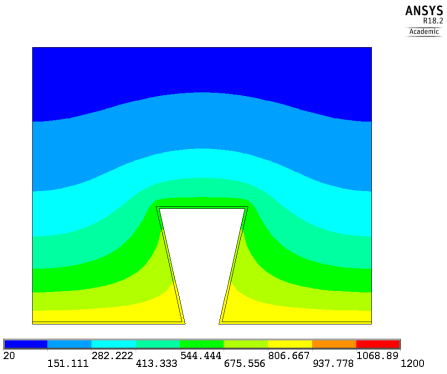
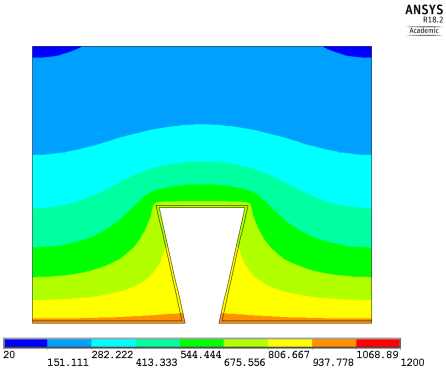
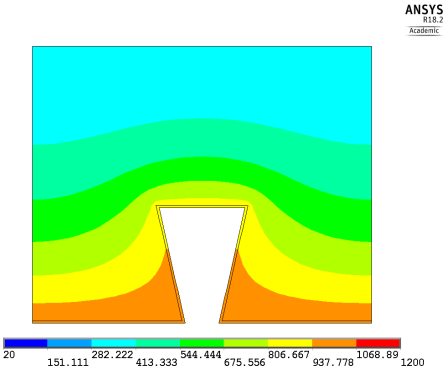


Tempo Crítico = 75 min



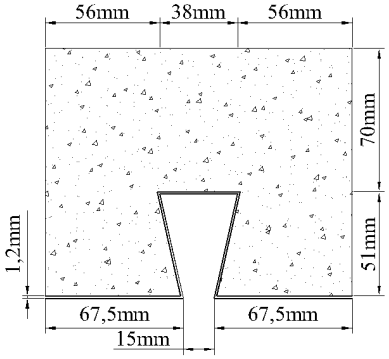
t = 7200s



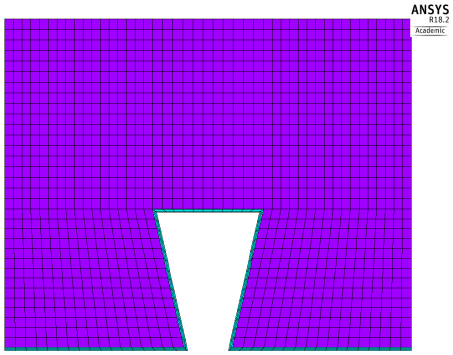


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.2mm

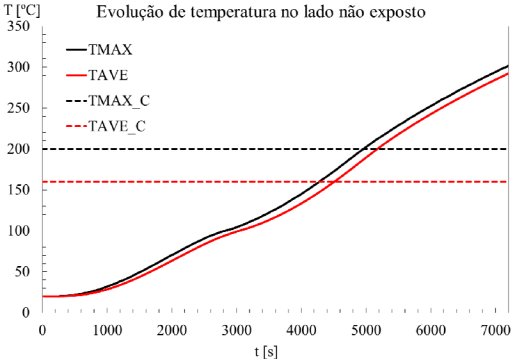
GEOMETRIA



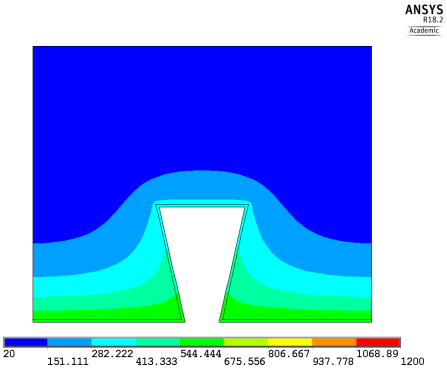
Malha



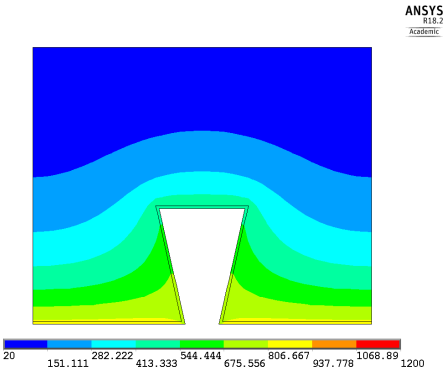
t = 18 min



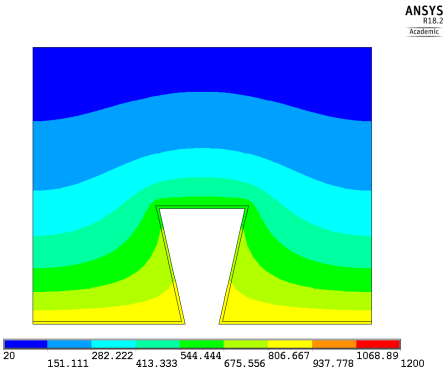
t = 37 min



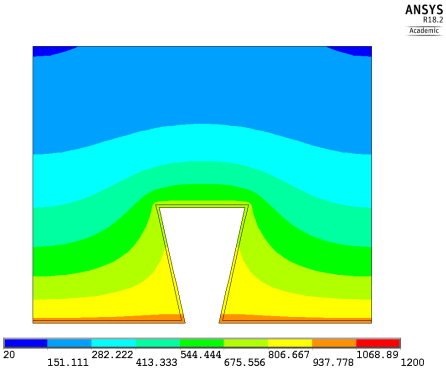
t = 56 min

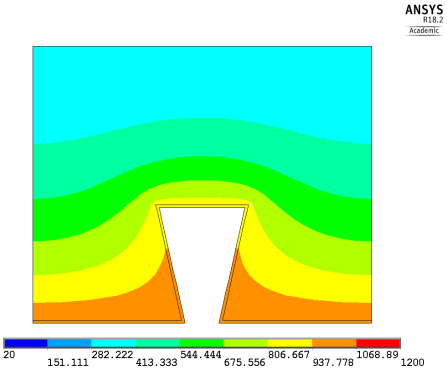


Tempo Crítico = 75 min



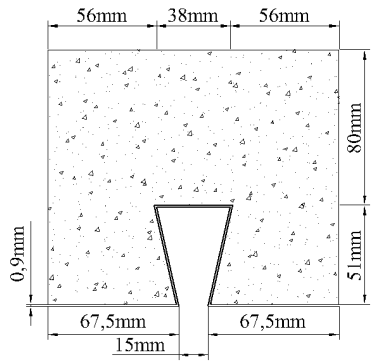
t = 7200s





LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.9mm

GEOMETRIA



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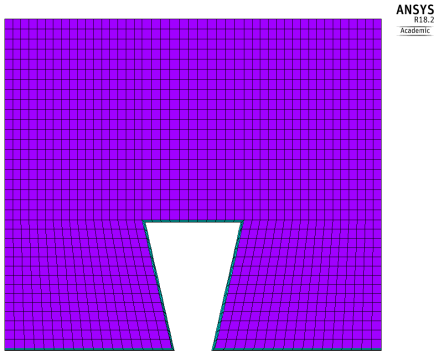
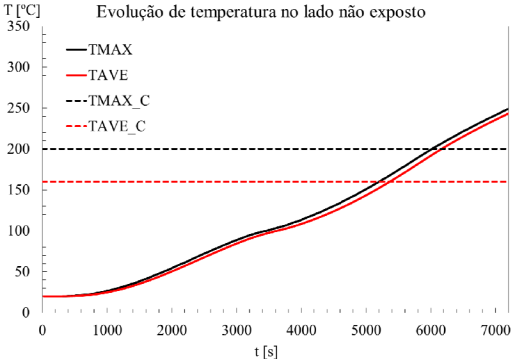
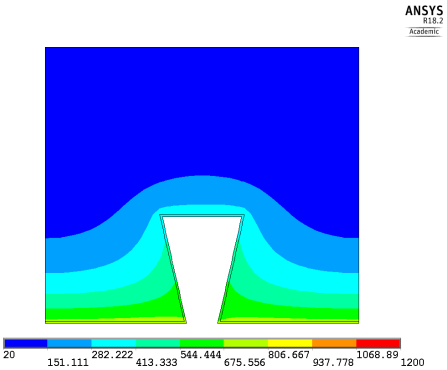


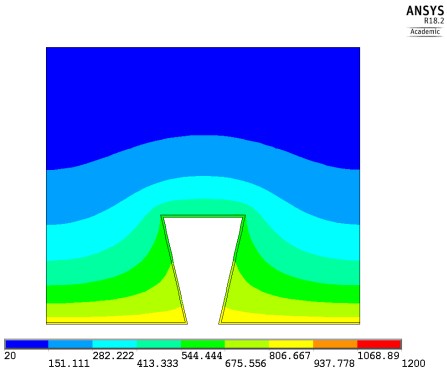
t = 22 min



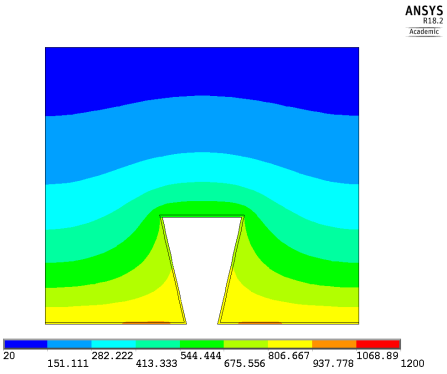
t = 44 min



t = 66 min



Tempo Crítico = 89 min



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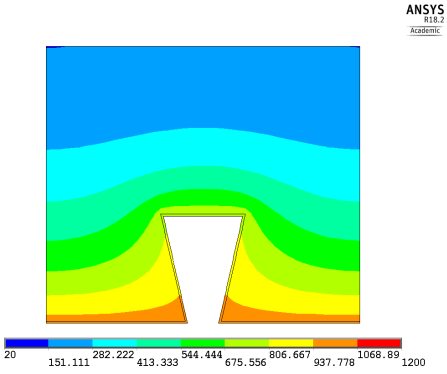
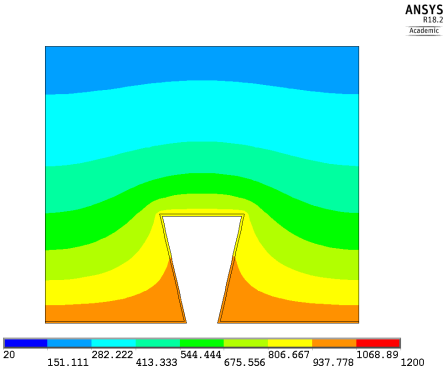
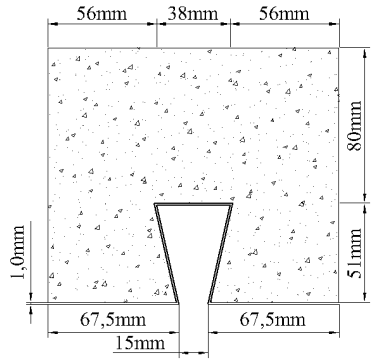


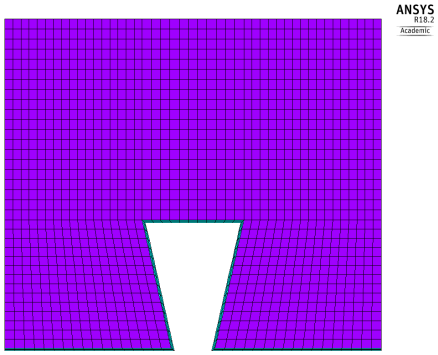


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.0mm

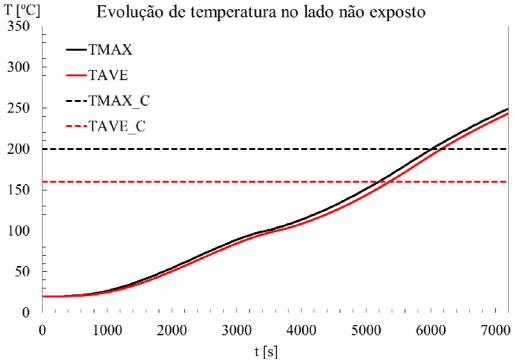
GEOMETRIA



Malha



t = 22 min



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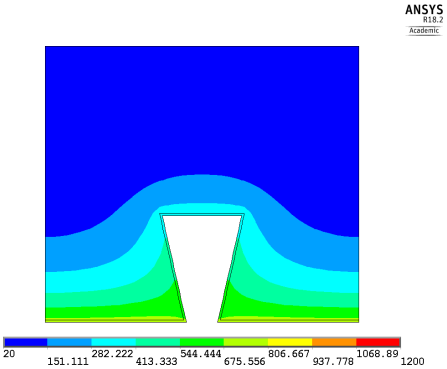
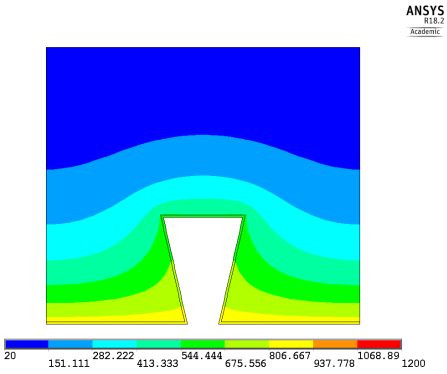
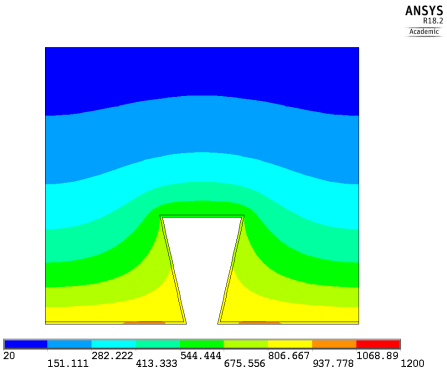


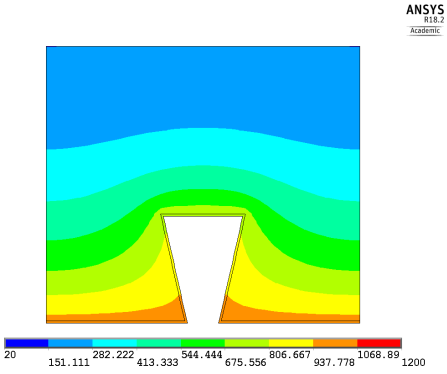
t = 66 min

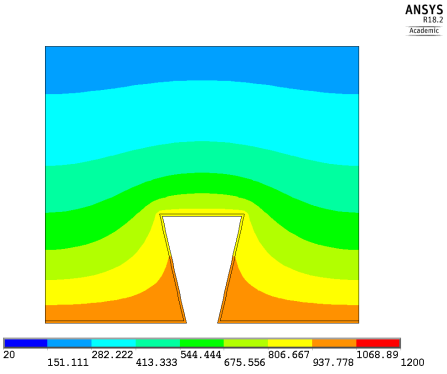


Tempo Crítico = 89 min



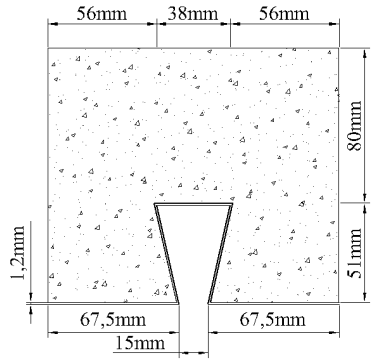
t = 7200s



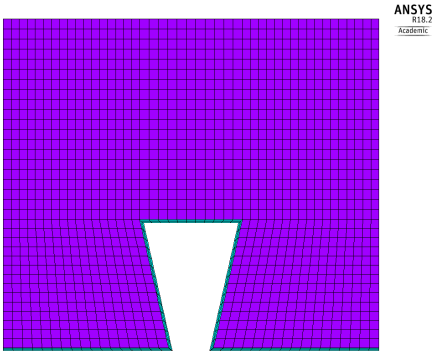


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.2mm

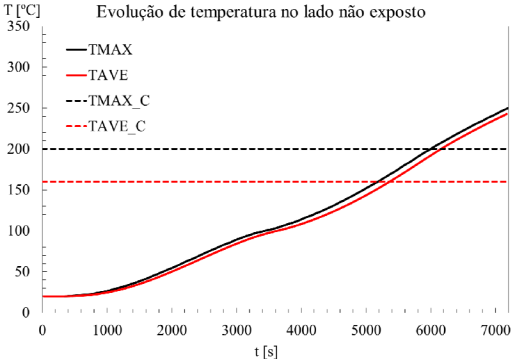
GEOMETRIA



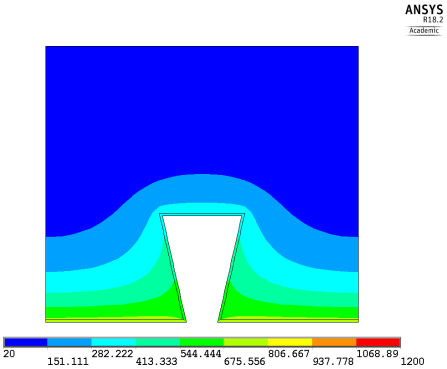
Malha



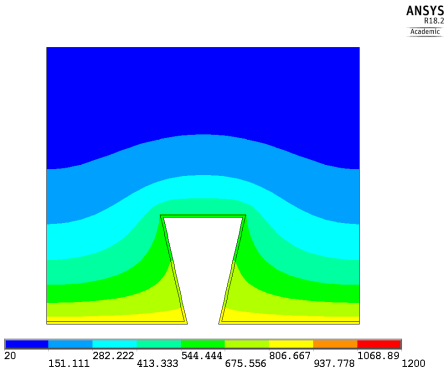
t = 22 min



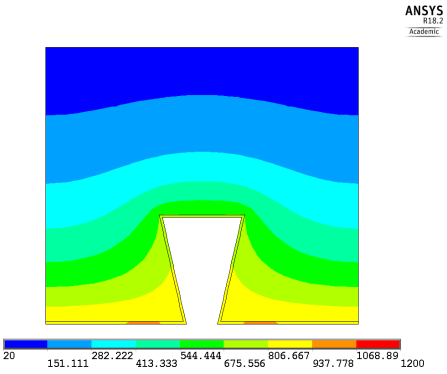
t = 44 min



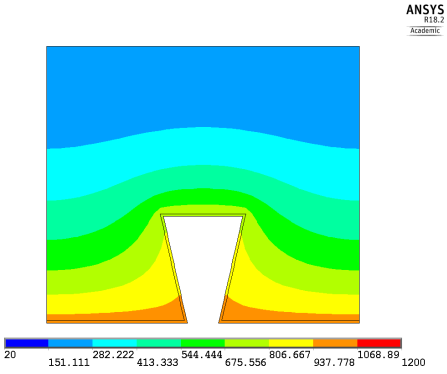
t = 66 min

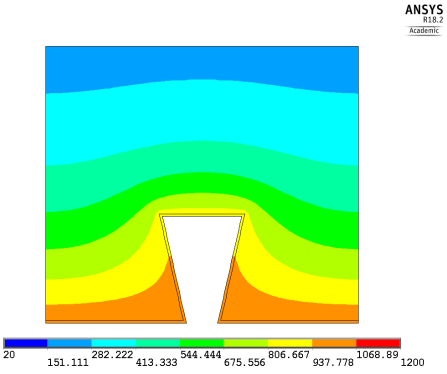


Tempo Crítico = 89 min



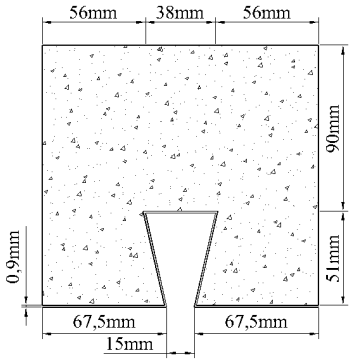
t = 7200s



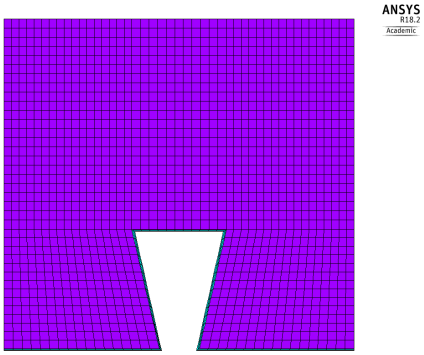


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.9mm

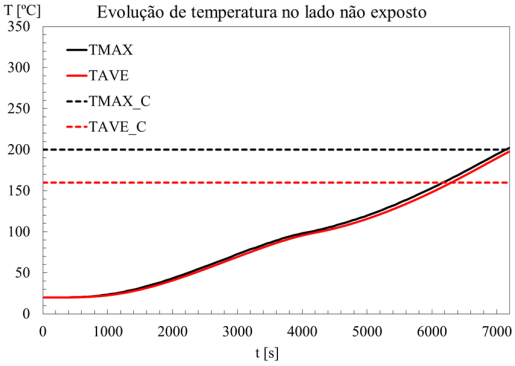
GEOMETRIA



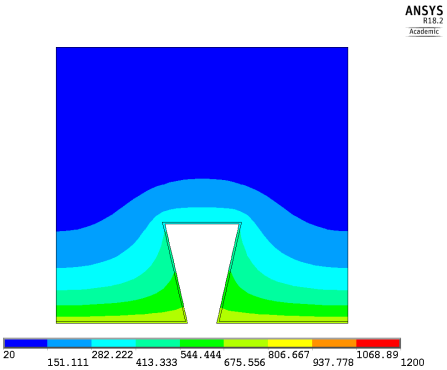
Malha



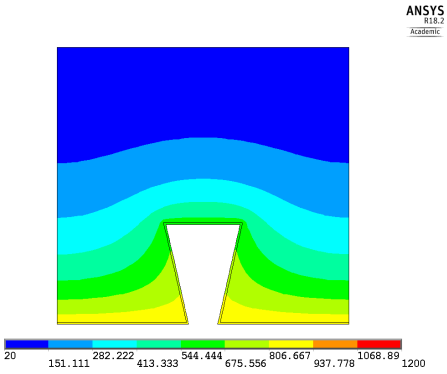
t = 26 min



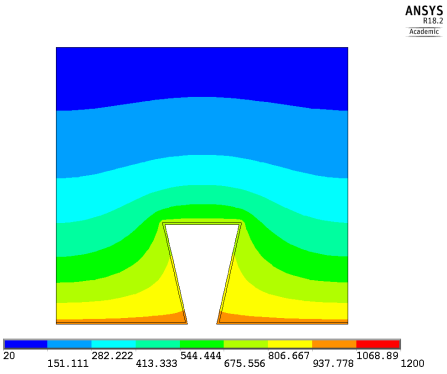
t = 52 min



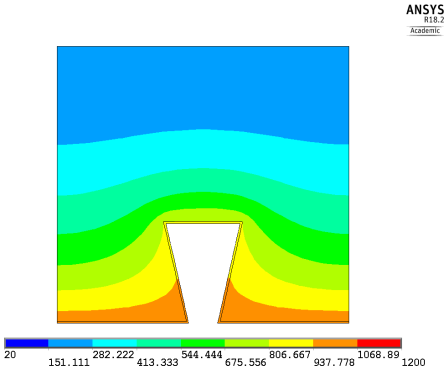
t = 78 min

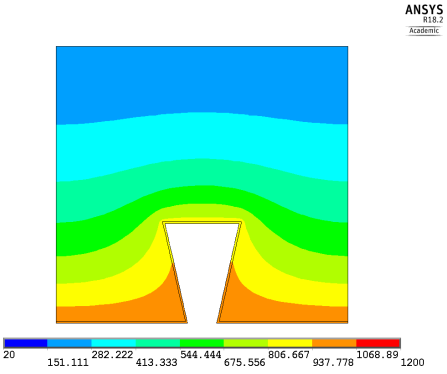


Tempo Crítico = 105 min



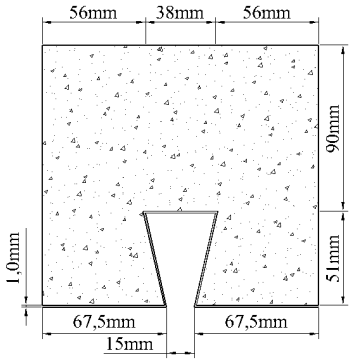
t = 7200s



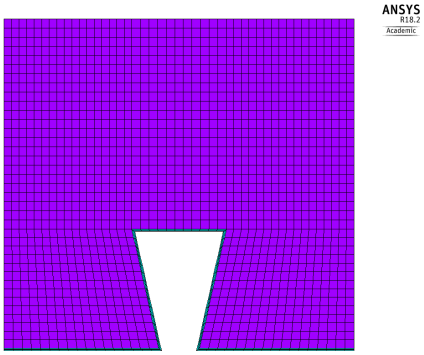


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.0mm

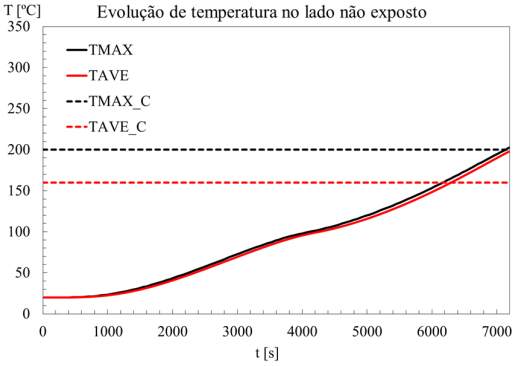
GEOMETRIA



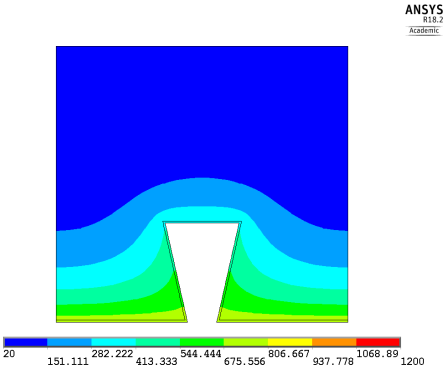
Malha



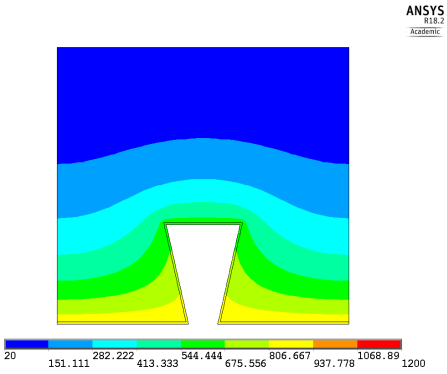
t = 26 min



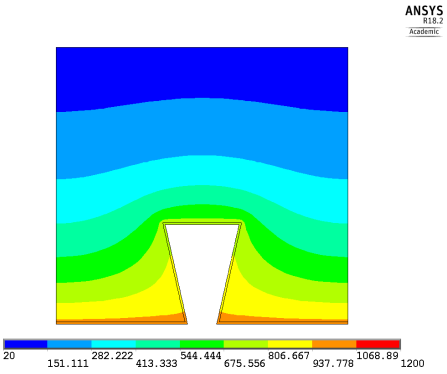
t = 52 min



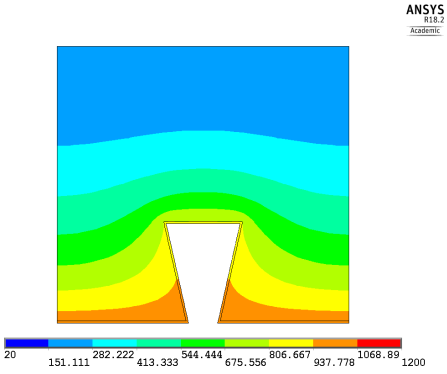
t = 78 min

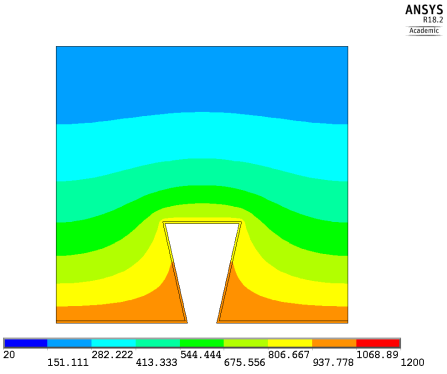


Tempo Crítico = 104 min



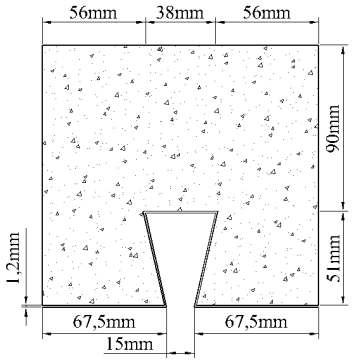
t = 7200s



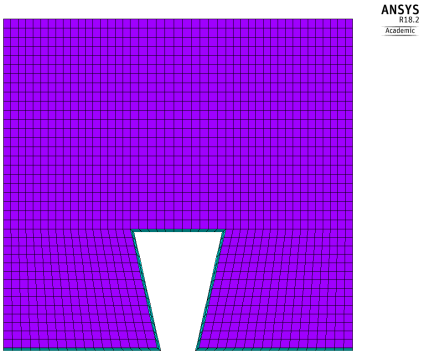


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.2mm

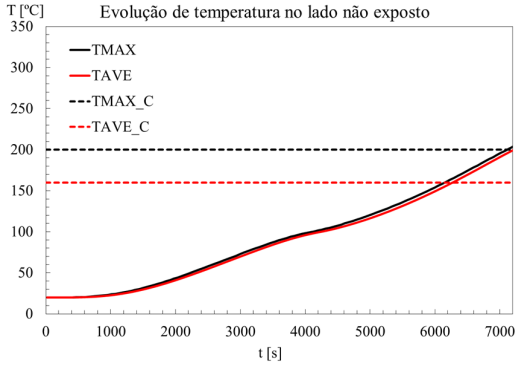
GEOMETRIA



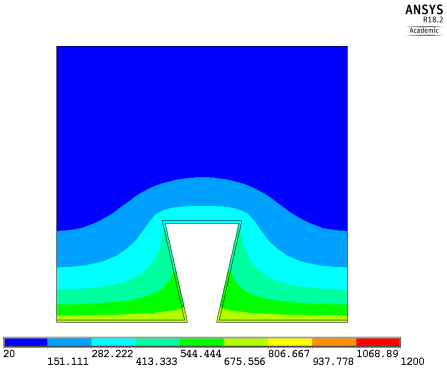
Malha



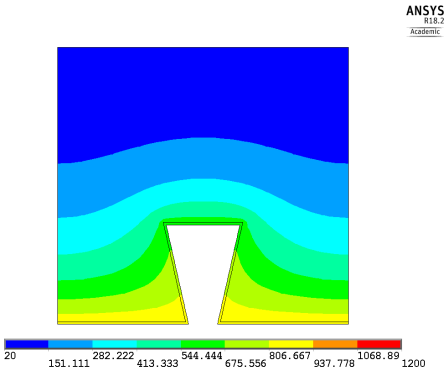
t = 26 min



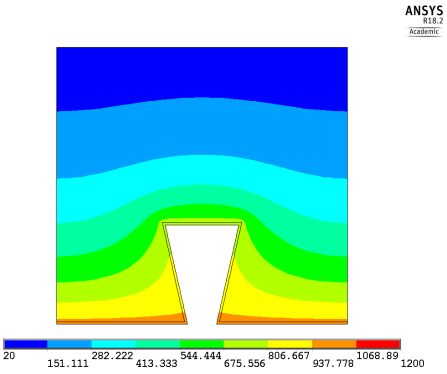
t = 52 min



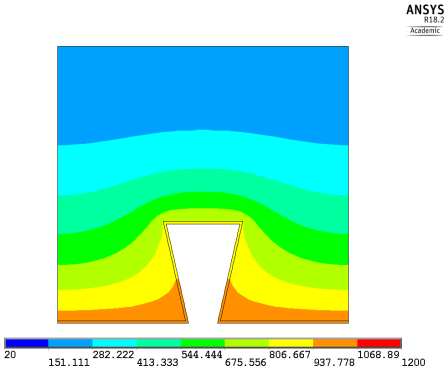
t = 78 min

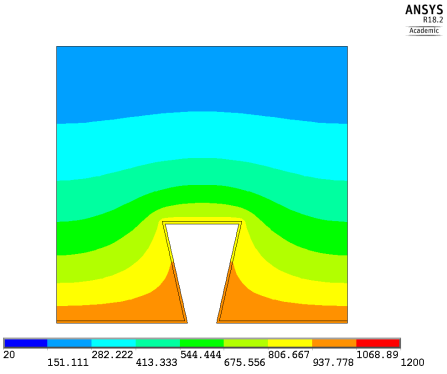


Tempo Crítico = 104 min



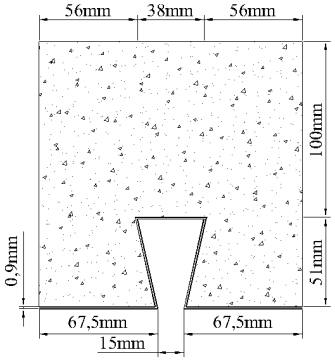
t = 7200s



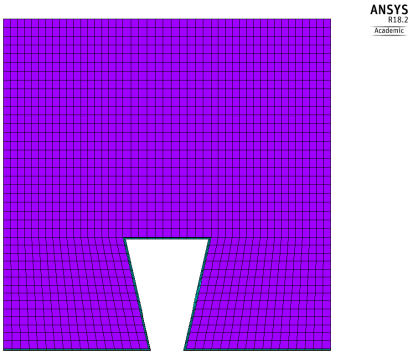


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.9mm

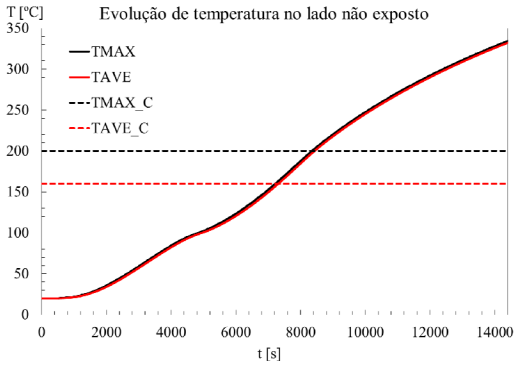
GEOMETRIA



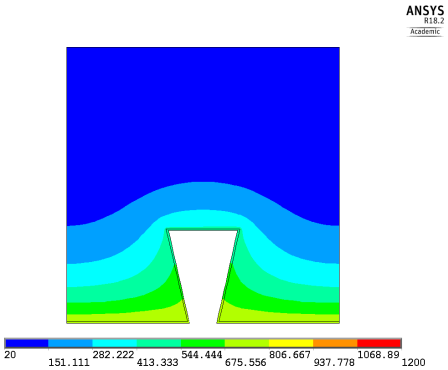
Malha



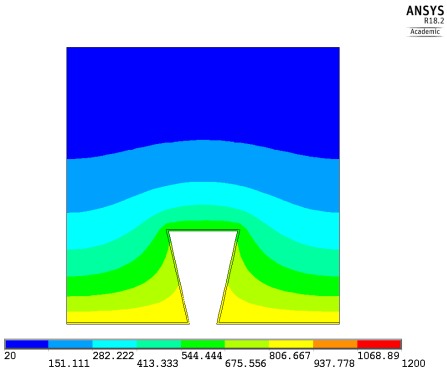
t = 30 min



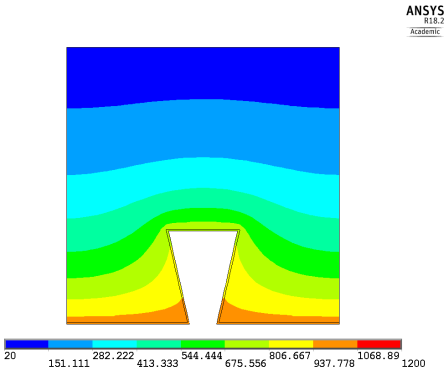
t = 60 min



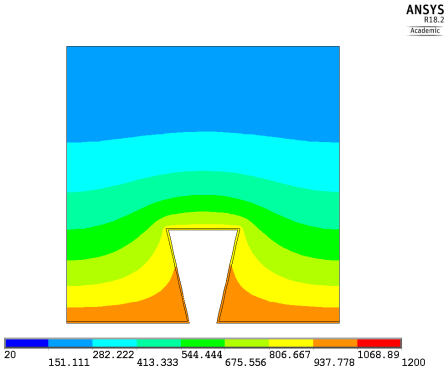
t = 90 min

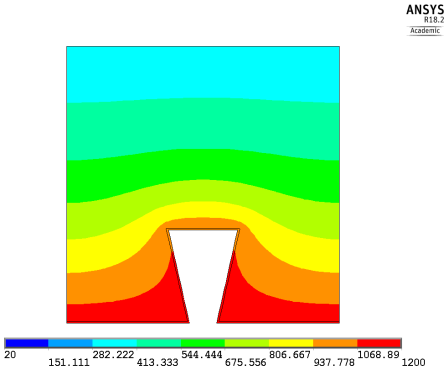


Tempo Crítico = 121 min



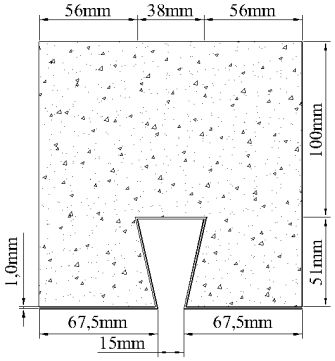
t = 14400s



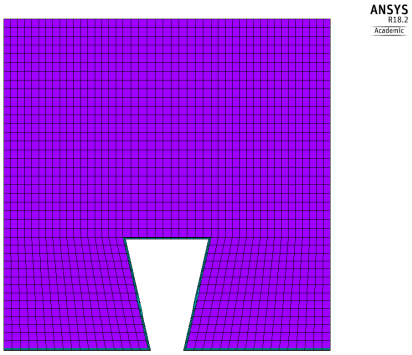


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.0mm

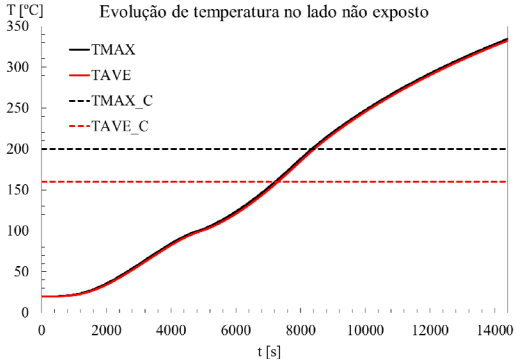
GEOMETRIA



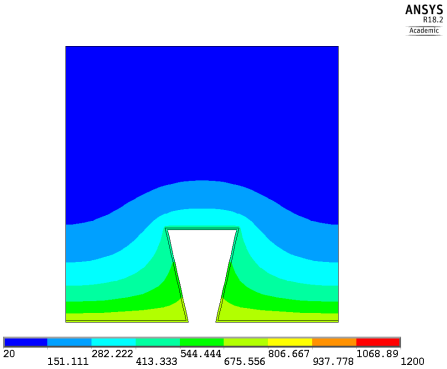
Malha



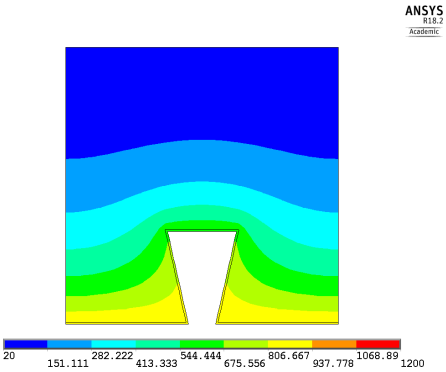
t = 30 min



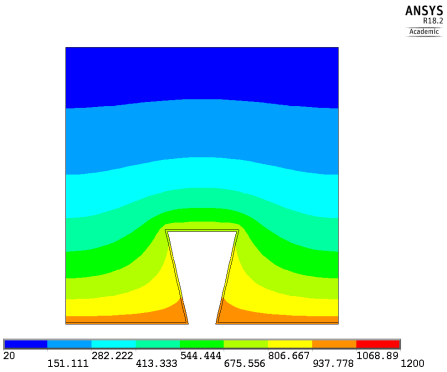
t = 60 min



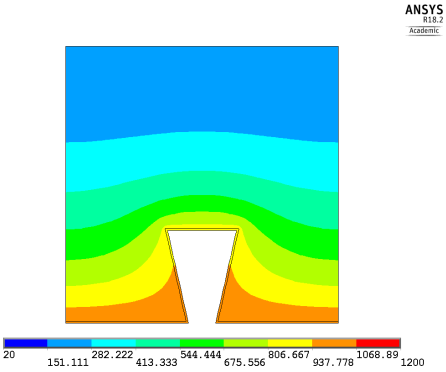
t = 90 min

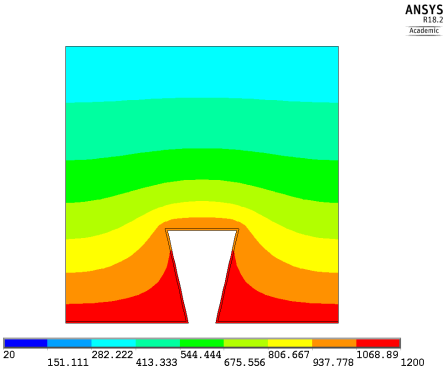


Tempo Crítico = 121 min



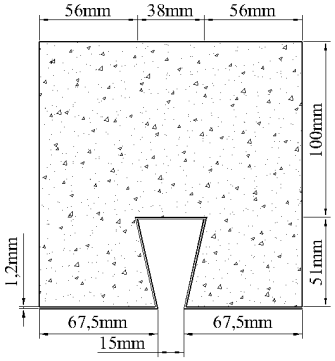
t = 14400s



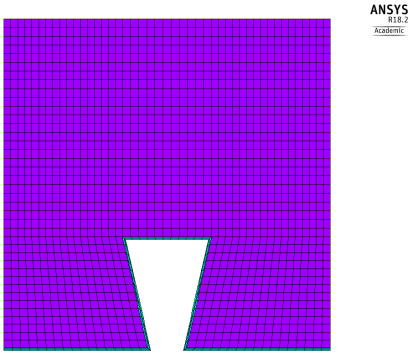


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.2mm

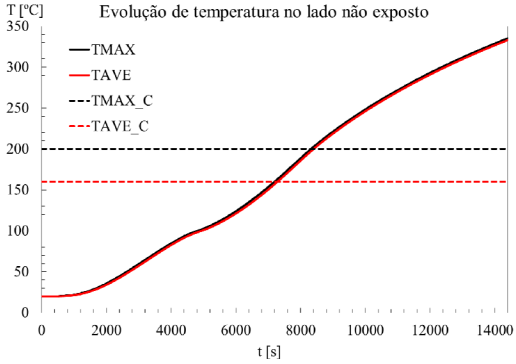
GEOMETRIA



Malha



t = 30 min



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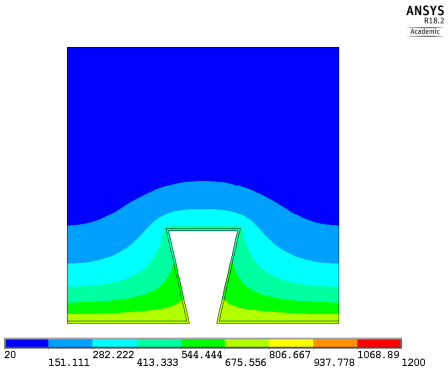
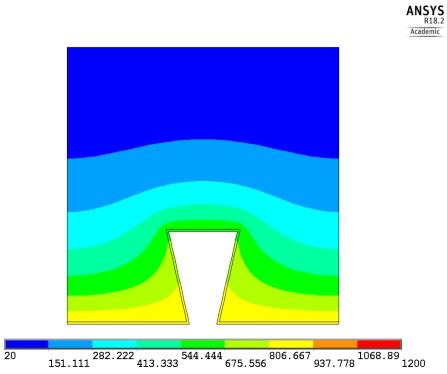
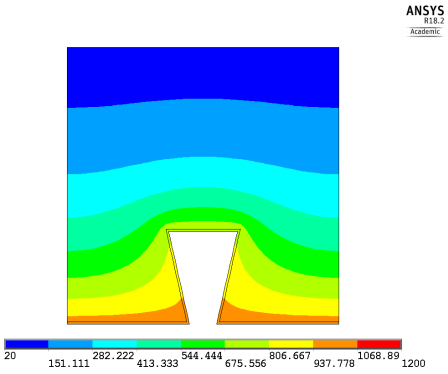


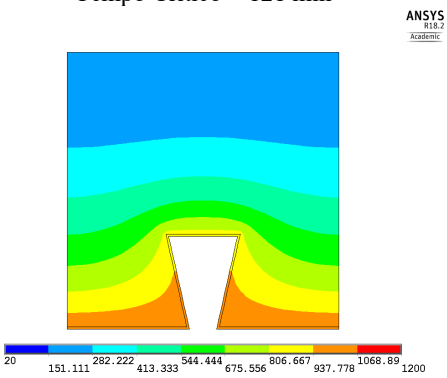
t = 90 min

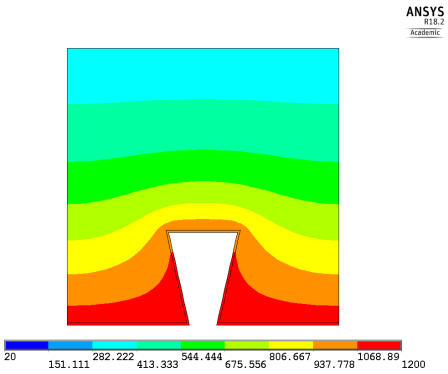


Tempo Crítico = 121 min



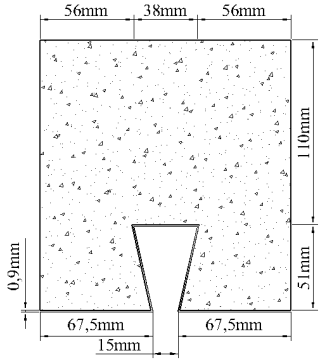
t = 14400s



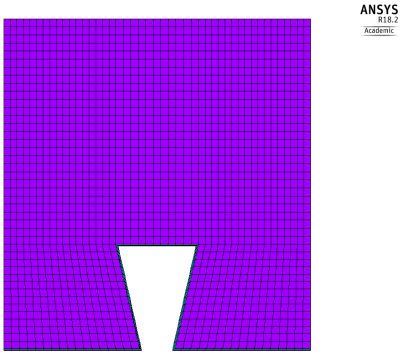


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.9mm

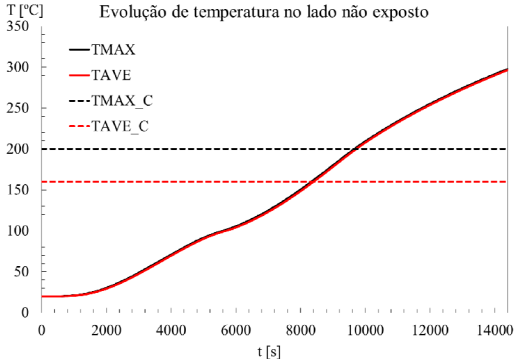
GEOMETRIA



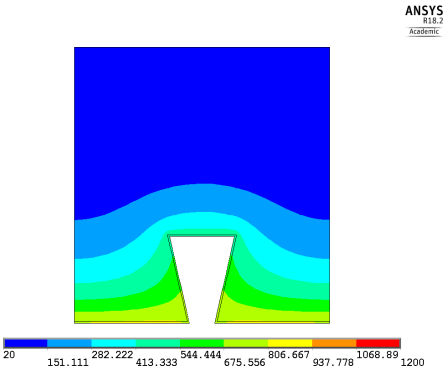
Malha



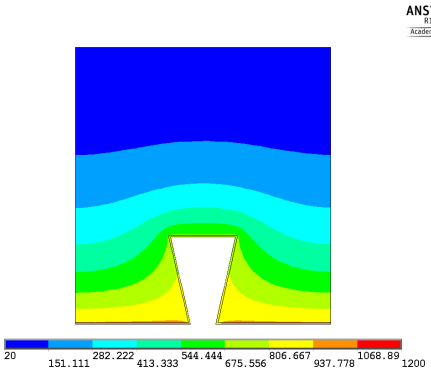
t = 35 min



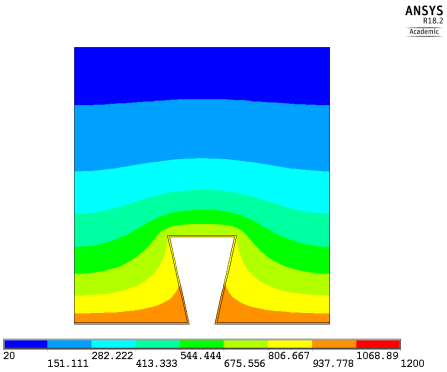
t = 70 min



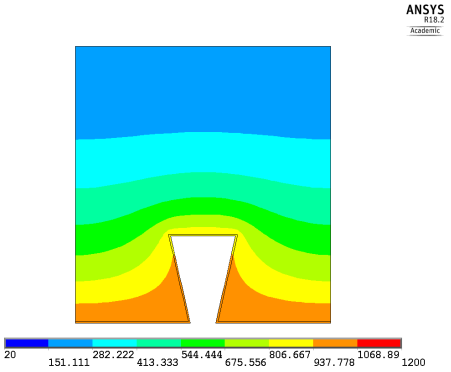
t = 105 min

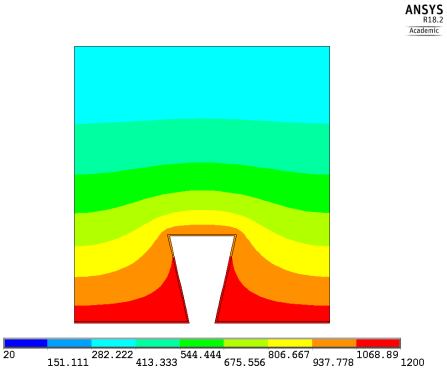


Tempo Crítico = 140 min



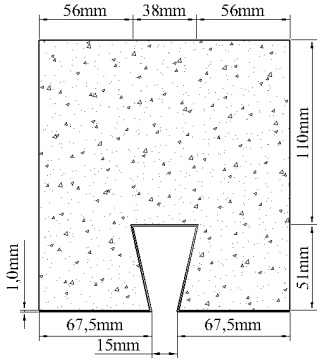
t = 14400s



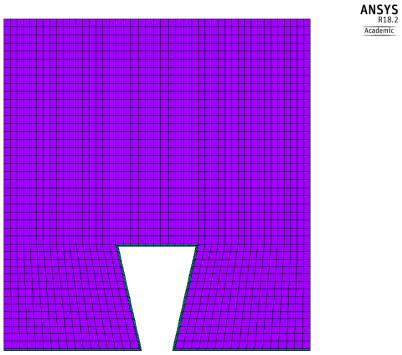


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.0mm

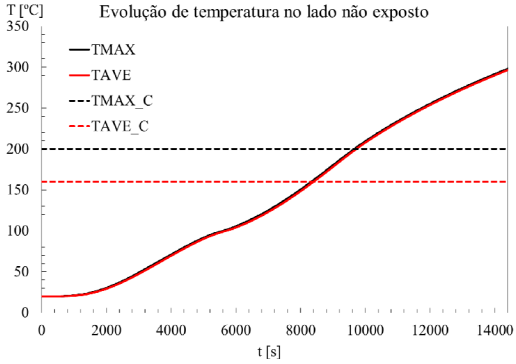
GEOMETRIA



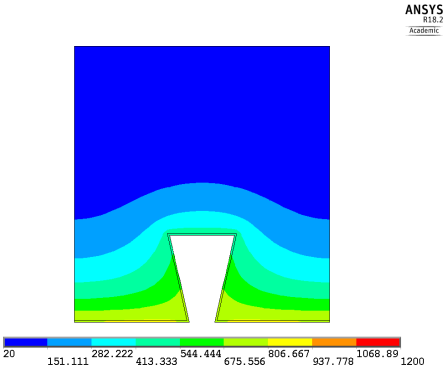
Malha



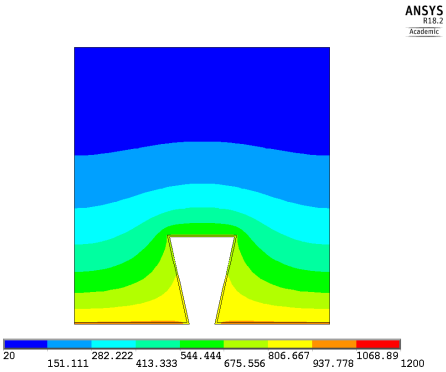
t = 34 min



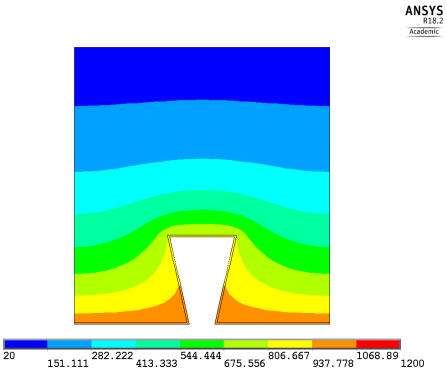
t = 69 min



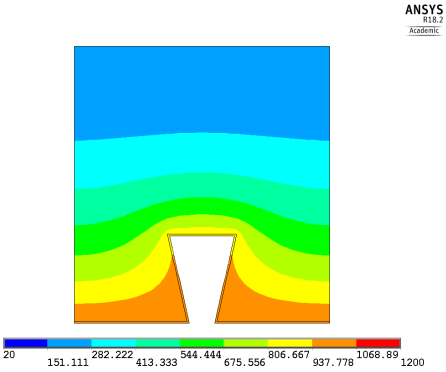
t = 104 min

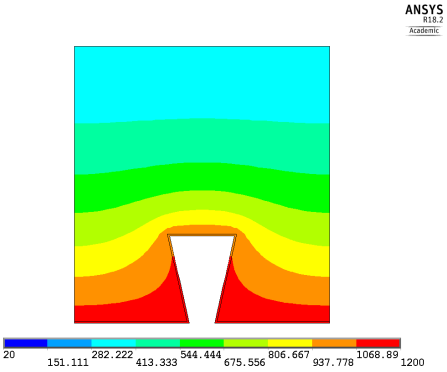


Tempo Crítico = 139 min



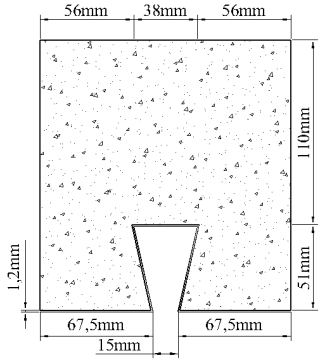
t = 14400s



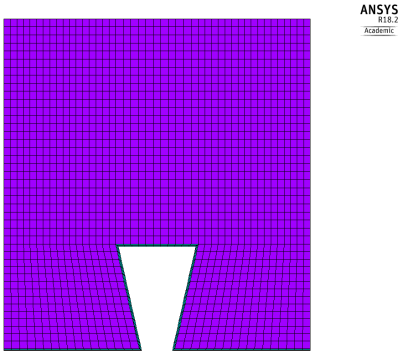


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.2mm

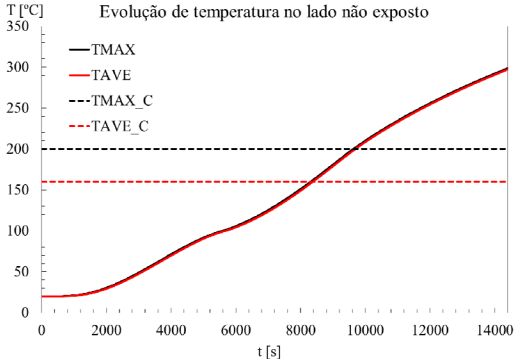
GEOMETRIA



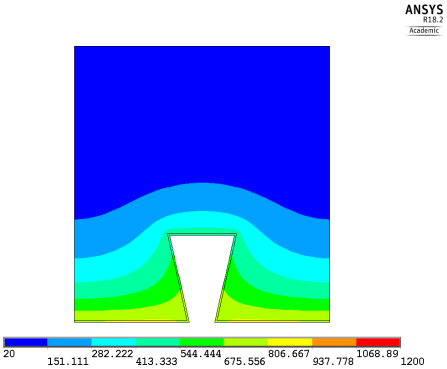
Malha



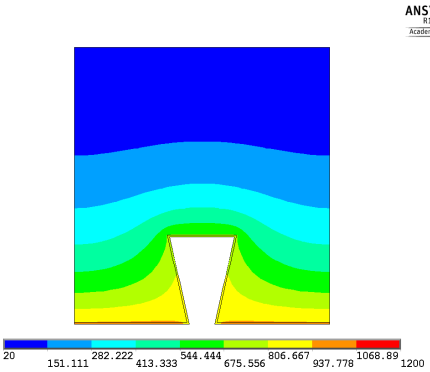
t = 34 min



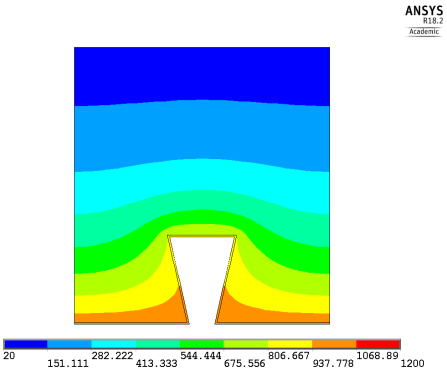
t = 69 min



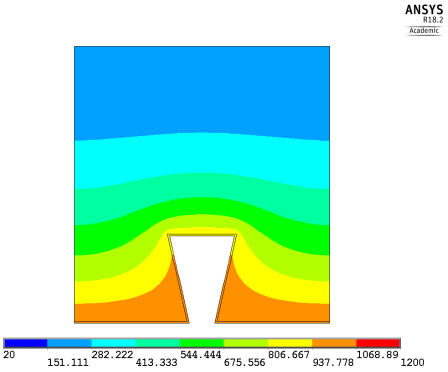
t = 104 min

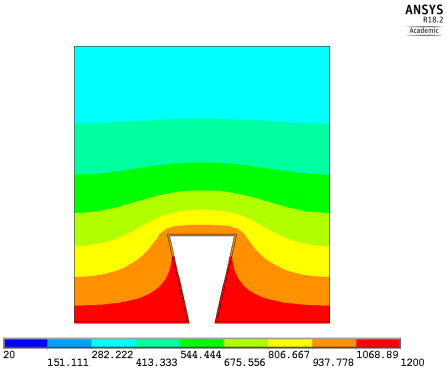


Tempo Crítico = 139 min



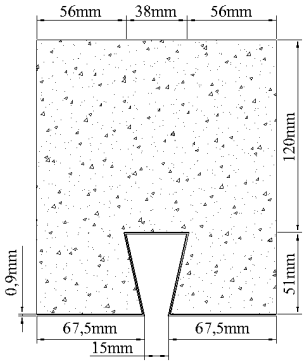
t = 14400s



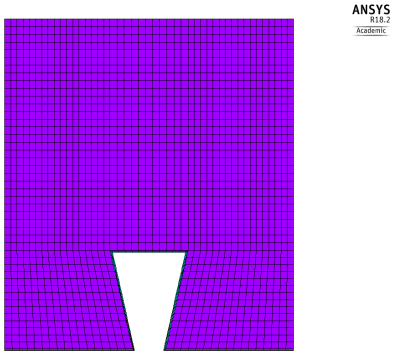


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.9mm

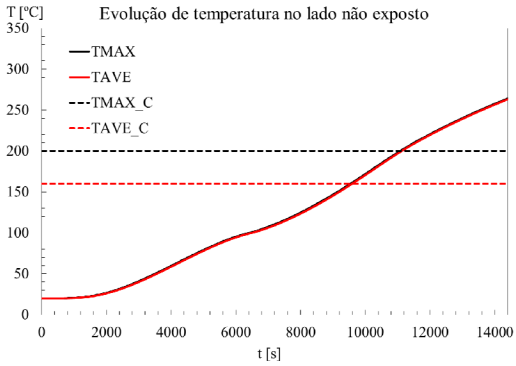
GEOMETRIA



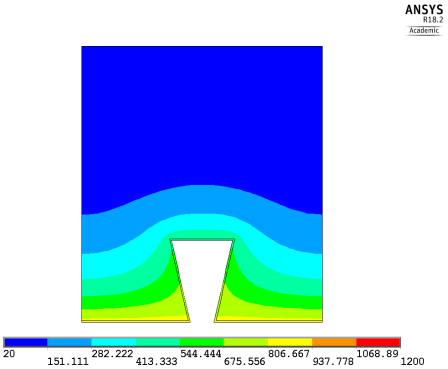
Malha



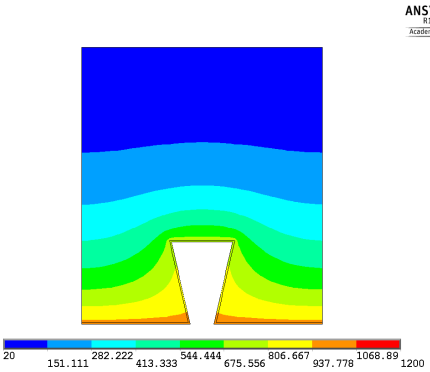
t = 39 min



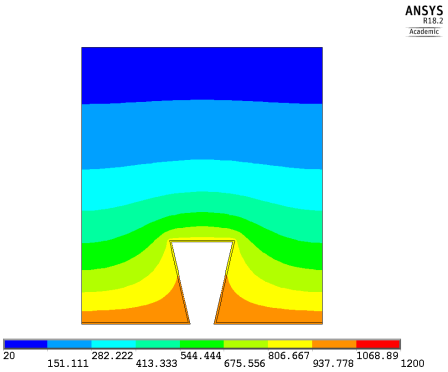
t = 79 min



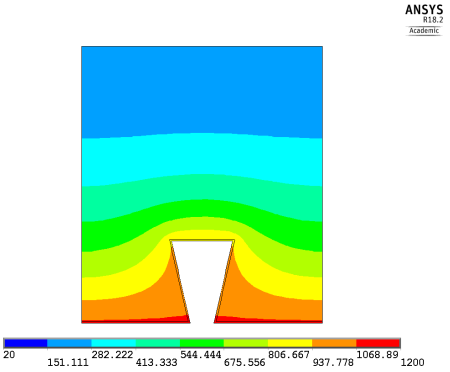
t = 119 min

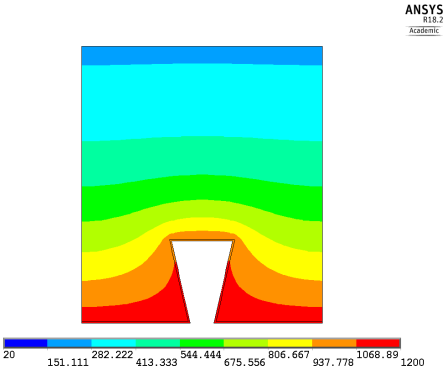


Tempo Crítico = 159 min



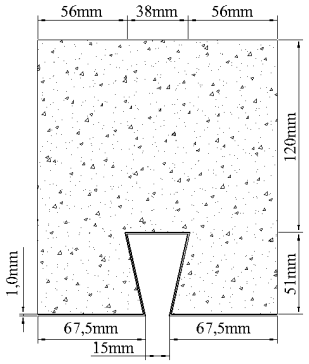
t = 14400s



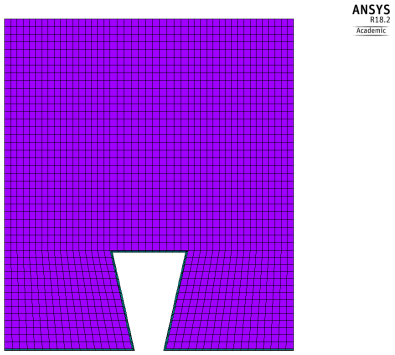


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.0mm

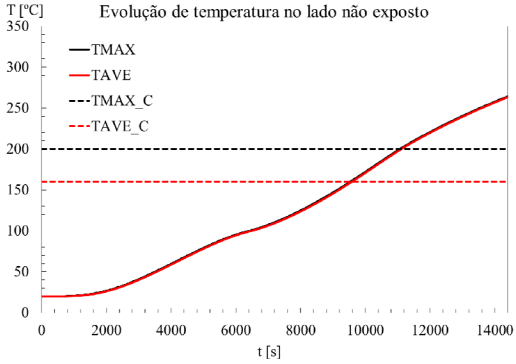
GEOMETRIA



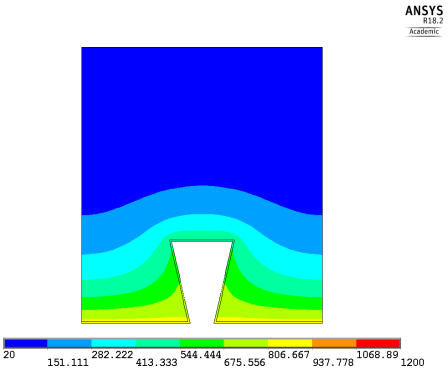
Malha



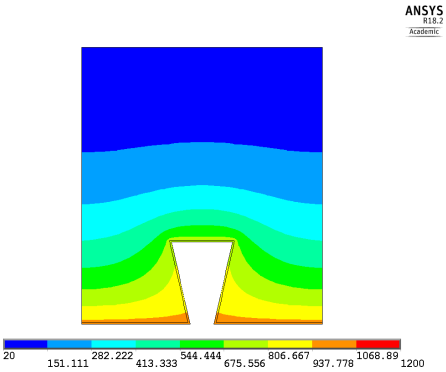
t = 39 min



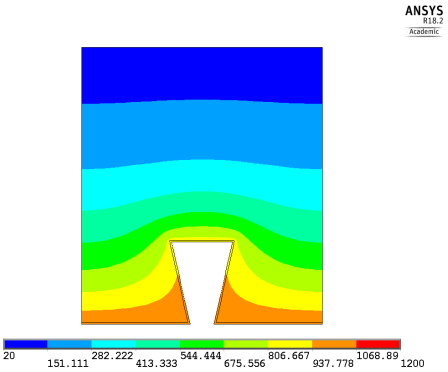
t = 79 min



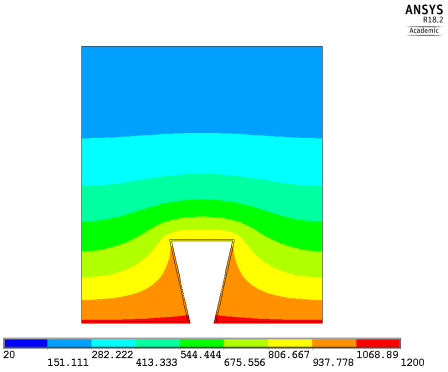
t = 119 min

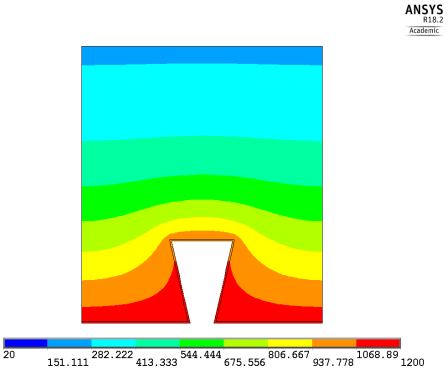


Tempo Crítico = 159 min



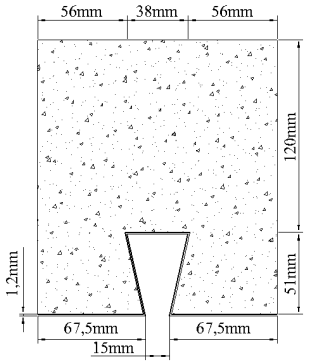
t = 14400s



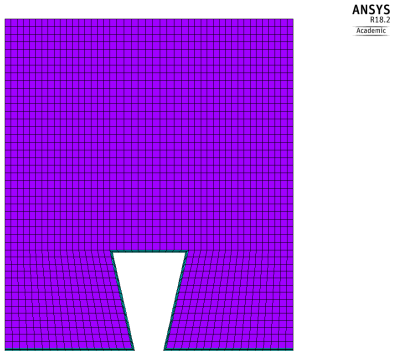


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.2mm

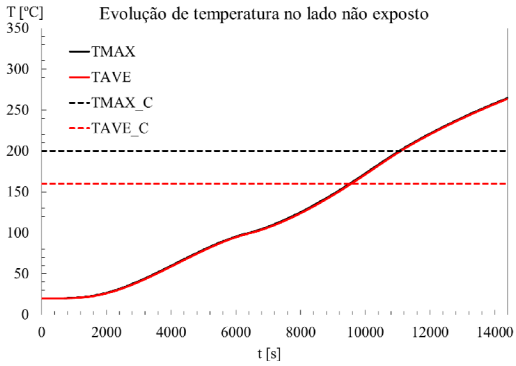
GEOMETRIA



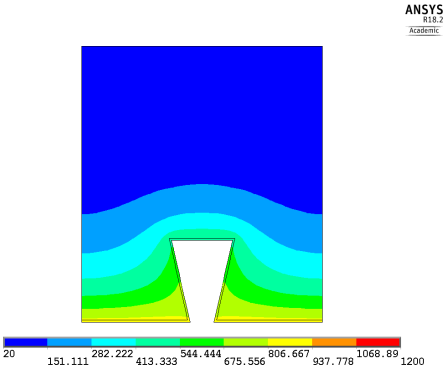
Malha



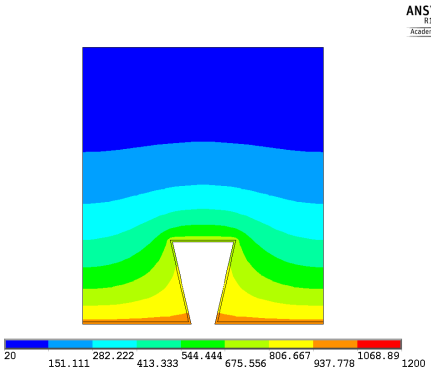
t = 39 min



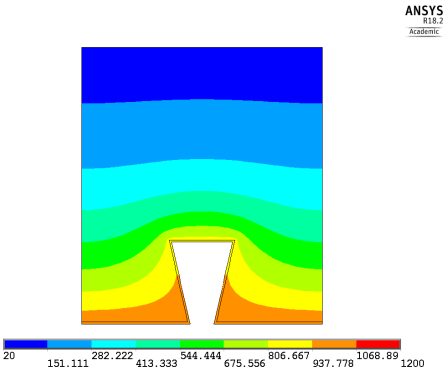
t = 79 min



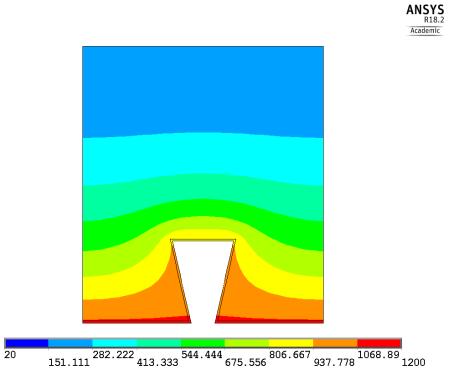
t = 119 min

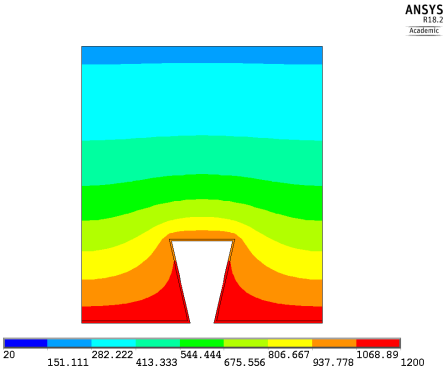


Tempo Crítico = 159 min



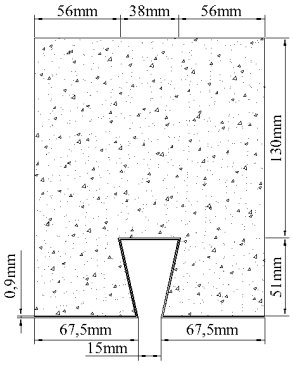
t = 14400s



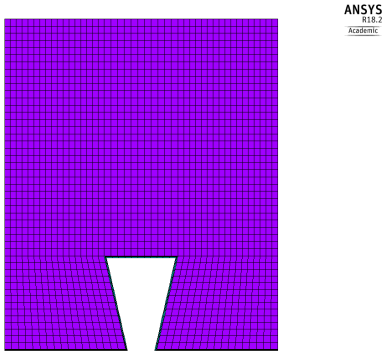


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.9mm

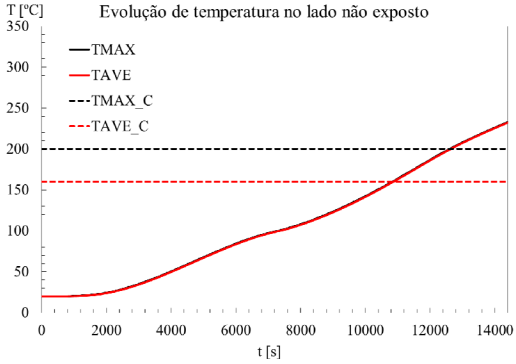
GEOMETRIA



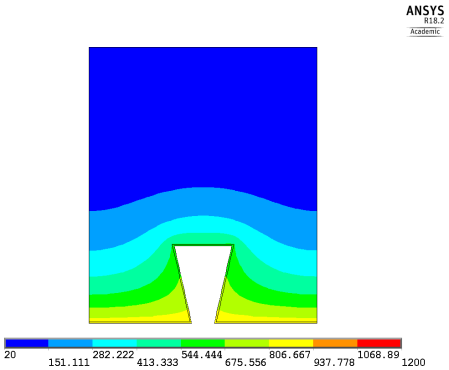
Malha



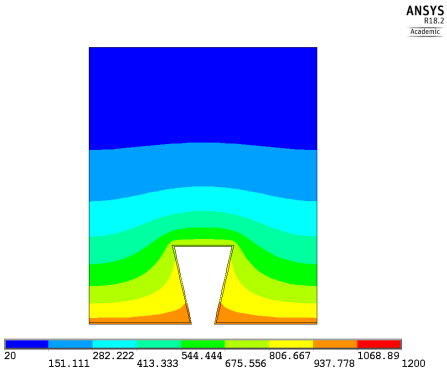
t = 45 min



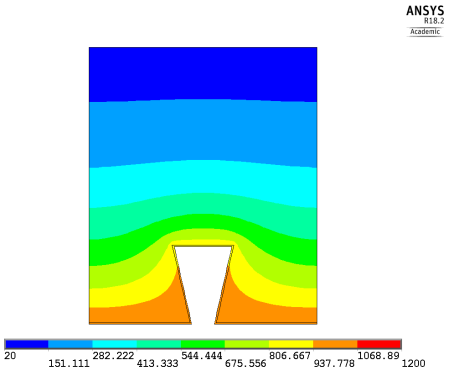
t = 90 min



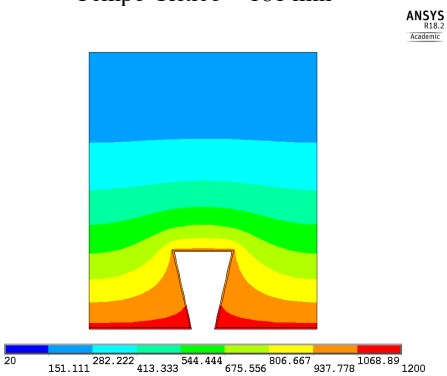
t = 135 min

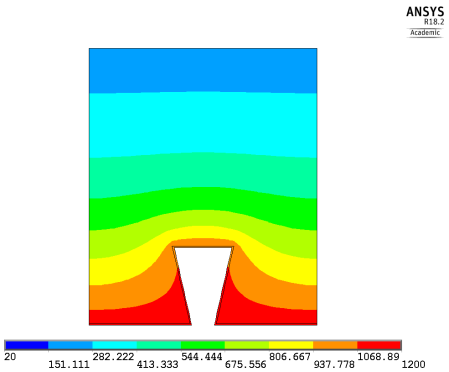


Tempo Crítico = 181 min



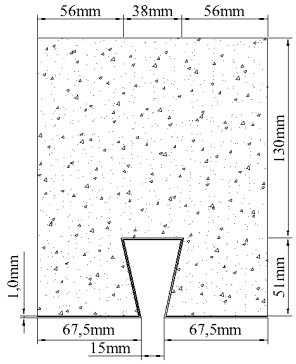
t = 14400s



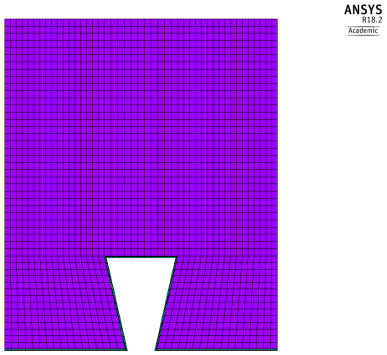


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.0mm

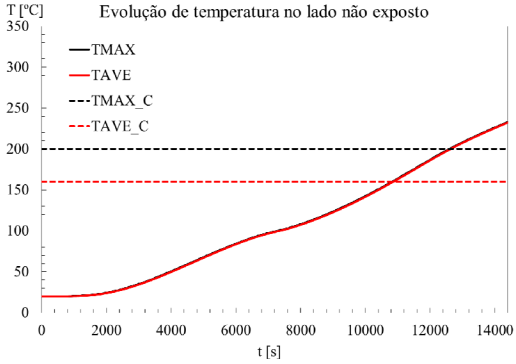
GEOMETRIA



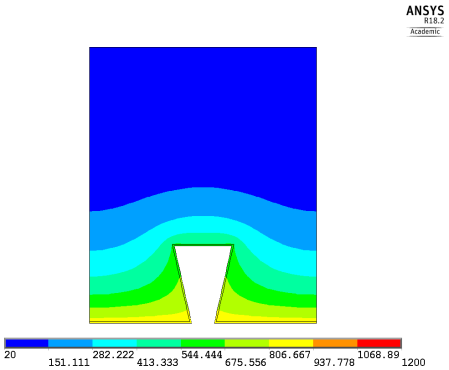
Malha



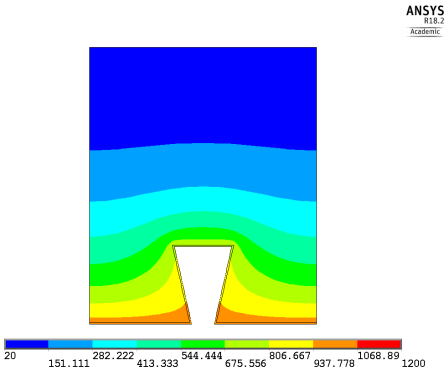
t = 45 min



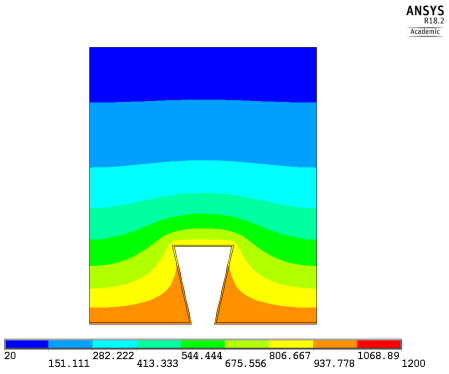
t = 90 min



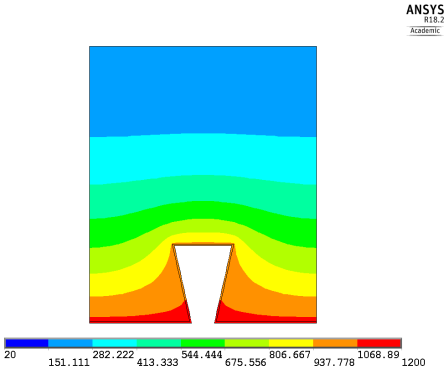
t = 135 min

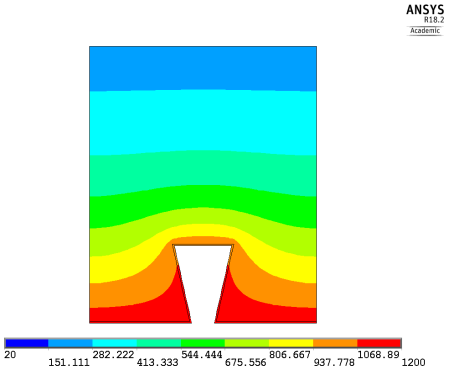


Tempo Crítico = 180 min



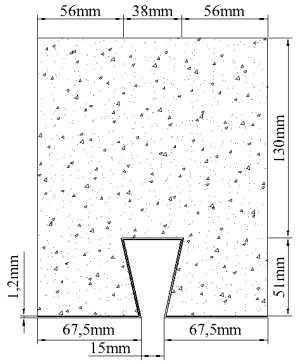
t = 14400s



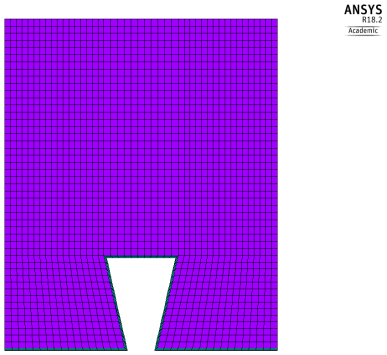


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.2mm

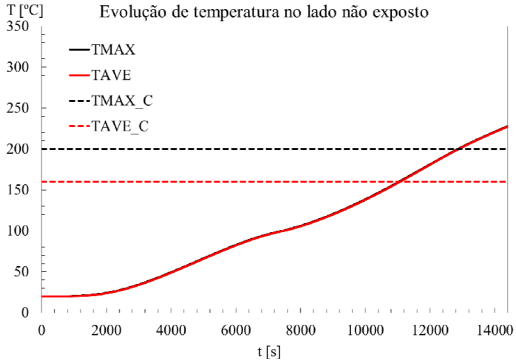
GEOMETRIA



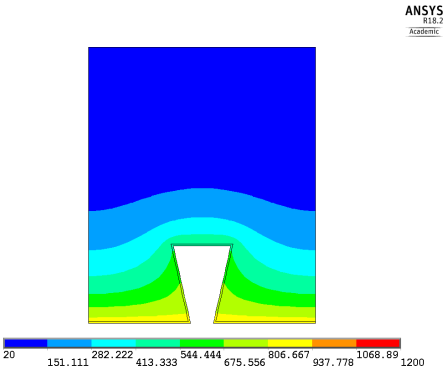
Malha



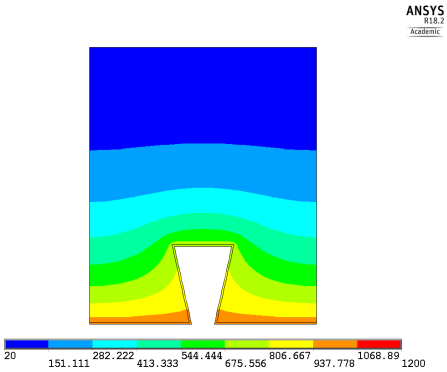
t = 46 min



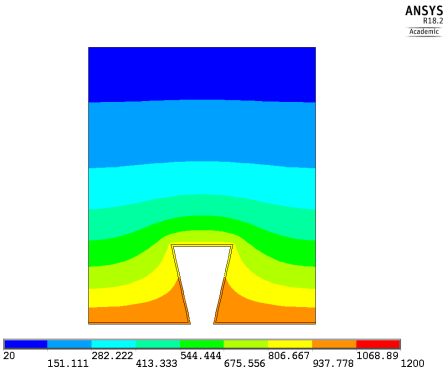
t = 92 min



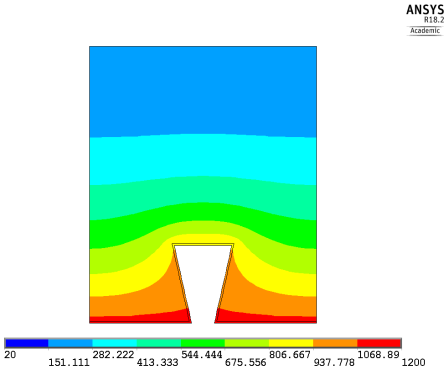
t = 138 min

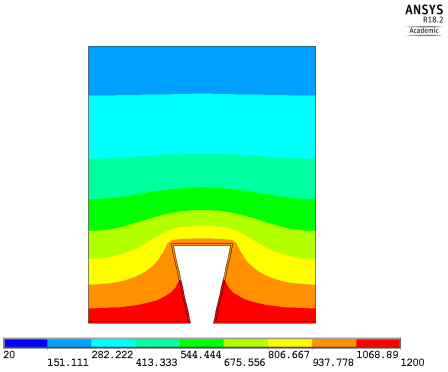


Tempo Crítico = 184 min



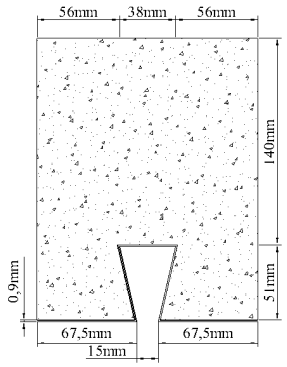
t = 14400s



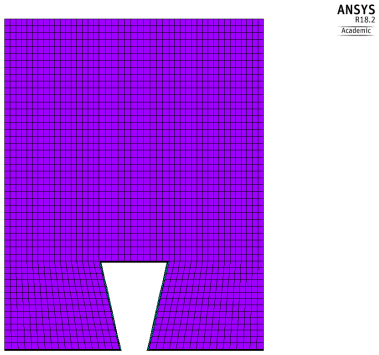


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.9mm

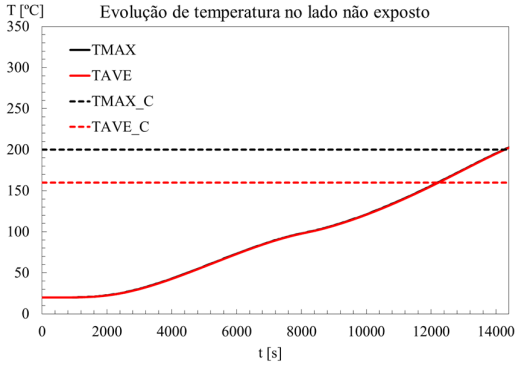
GEOMETRIA



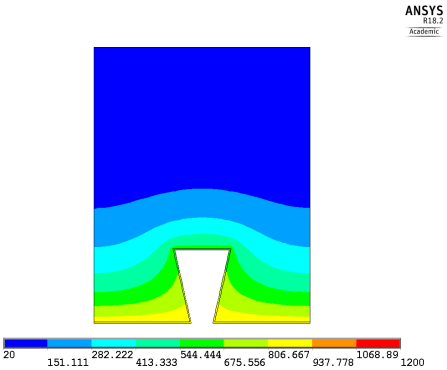
Malha



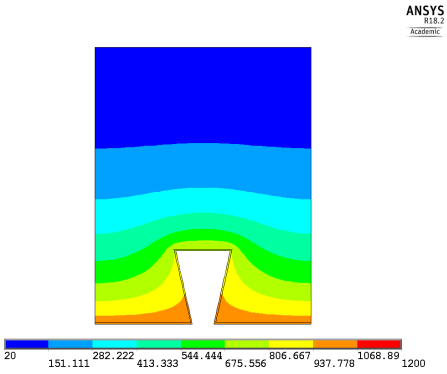
t = 50 min



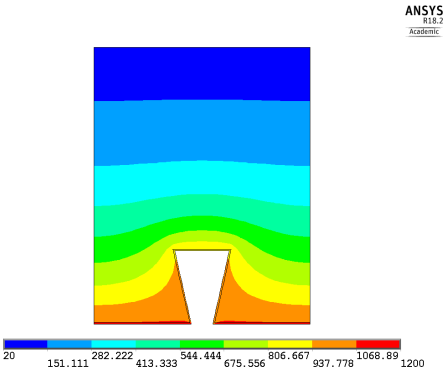
t = 101 min



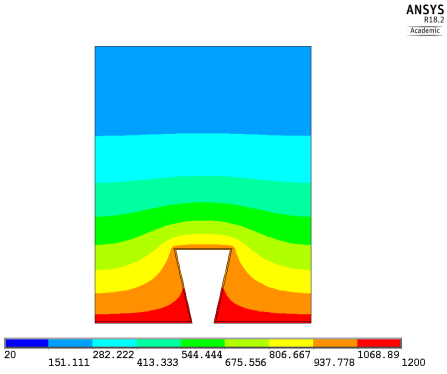
t = 152 min

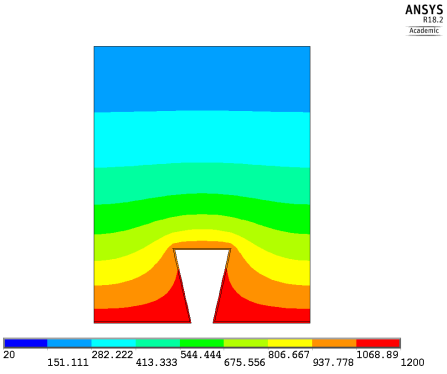


Tempo Crítico = 203 min



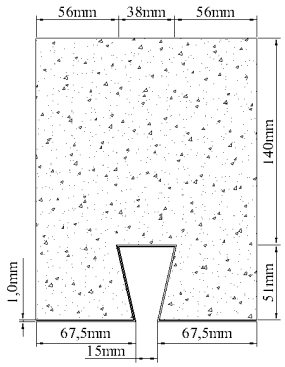
t = 14400s



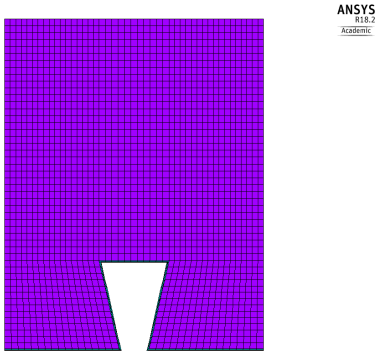


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.0mm

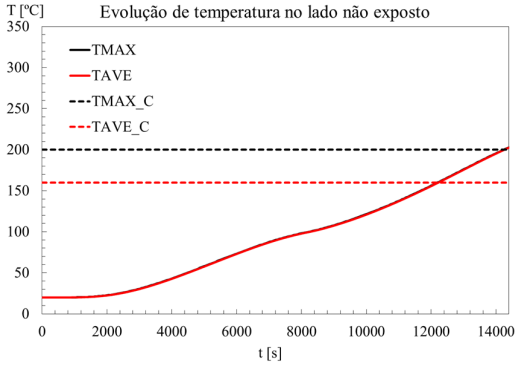
GEOMETRIA



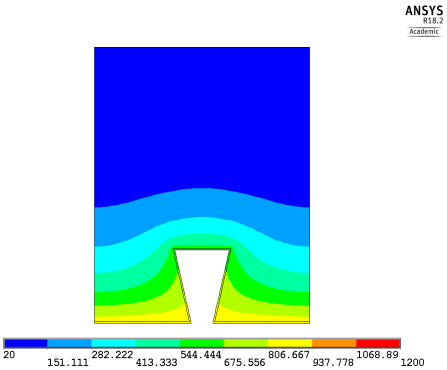
Malha



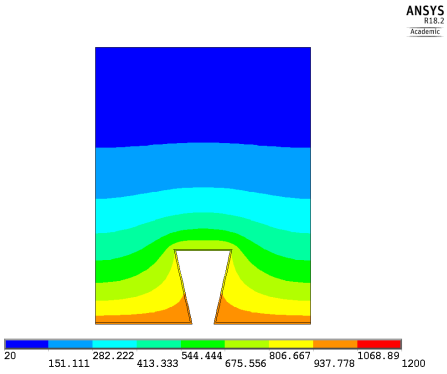
t = 51 min



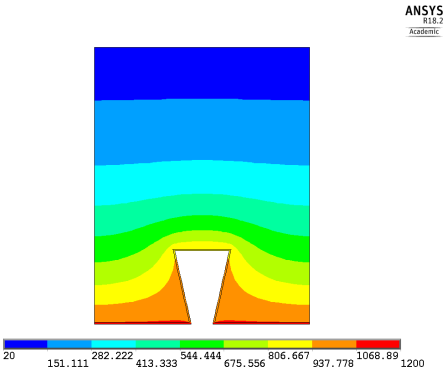
t = 102 min



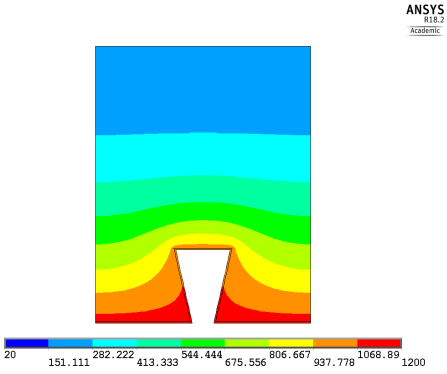
t = 153 min

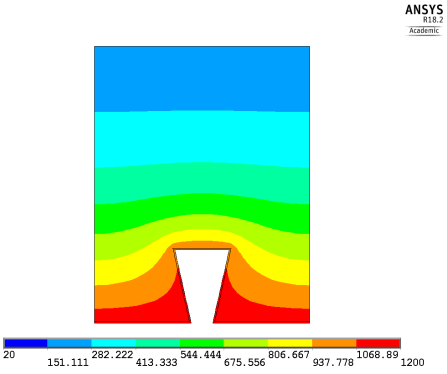


Tempo Crítico = 204 min



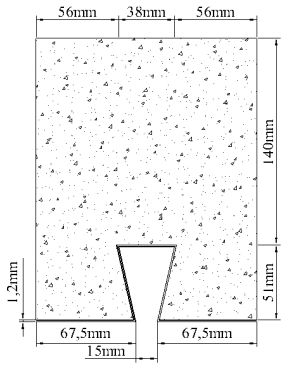
t = 14400s



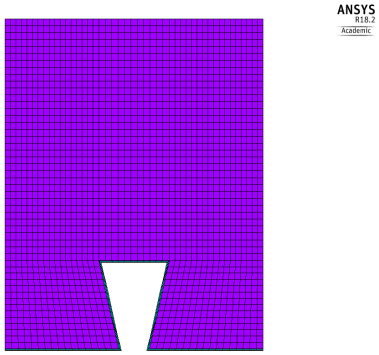


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.2mm

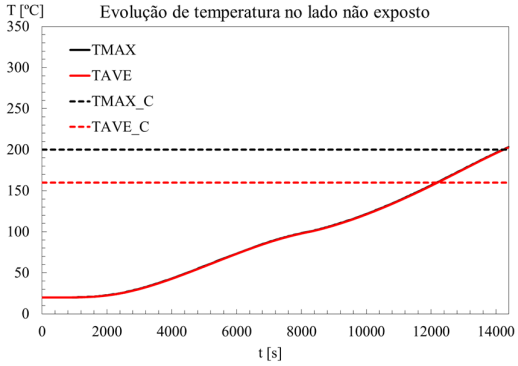
GEOMETRIA



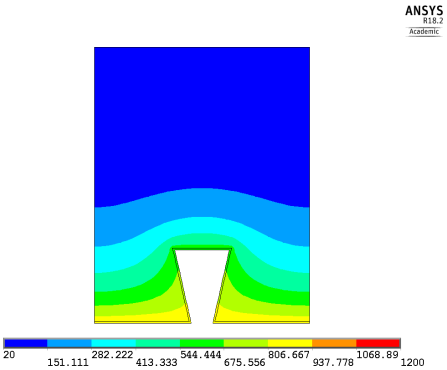
Malha



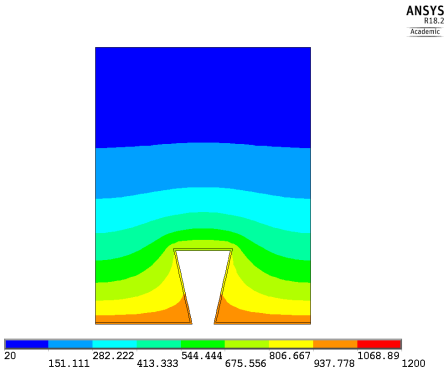
t = 50 min



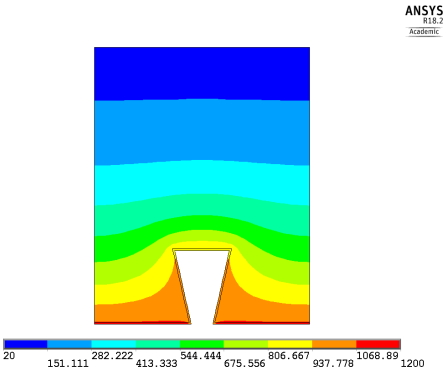
t = 101 min



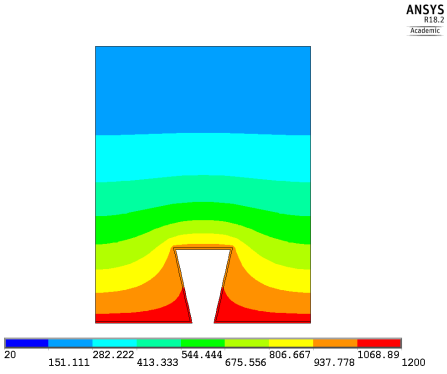
t = 152 min

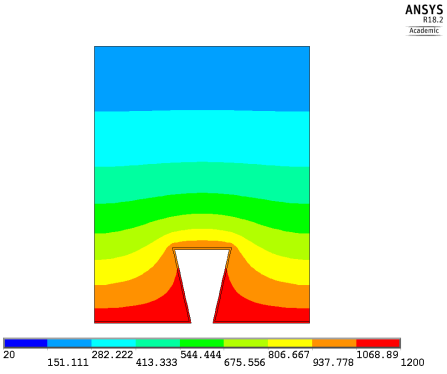


Tempo Crítico = 203 min



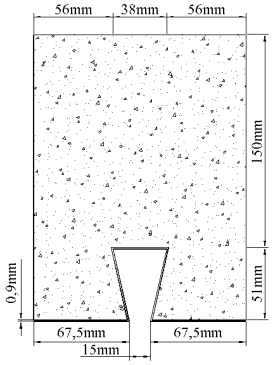
t = 14400s



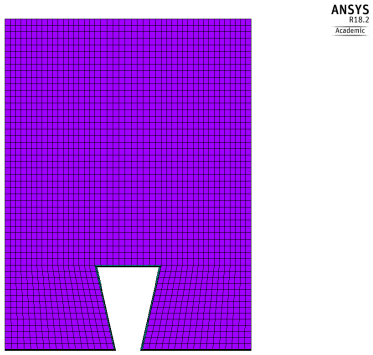


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.9mm

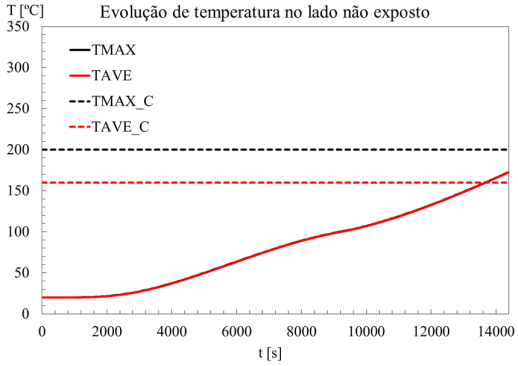
GEOMETRIA



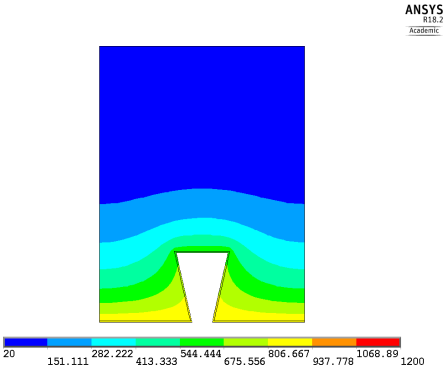
Malha



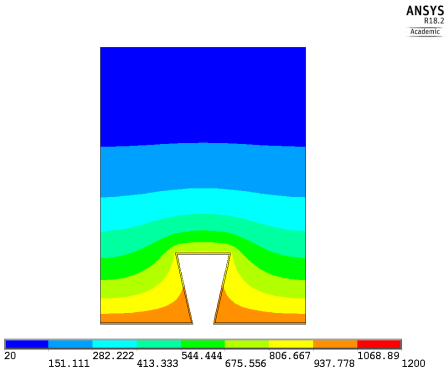
t = 57 min



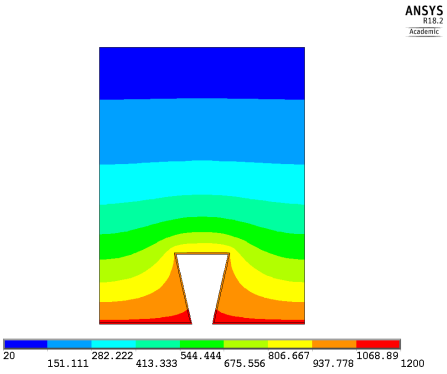
t = 114 min



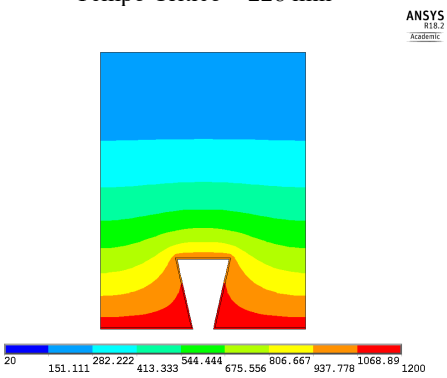
t = 171 min

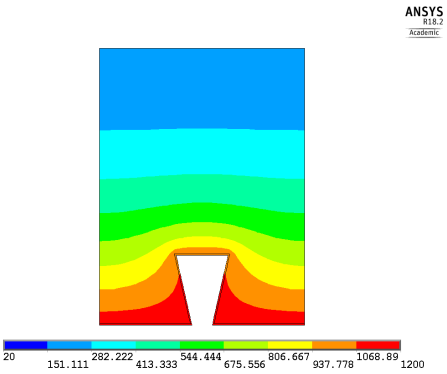


Tempo Crítico = 228 min



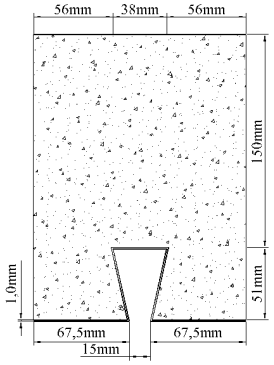
t = 14400s



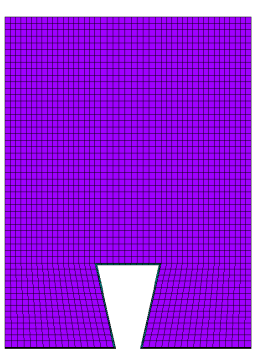


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.0mm

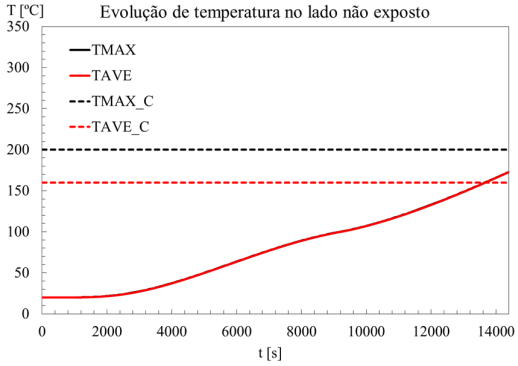
GEOMETRIA



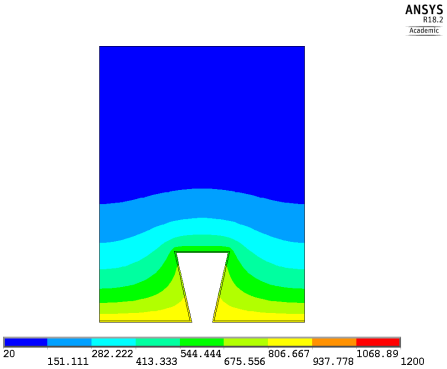
Malha



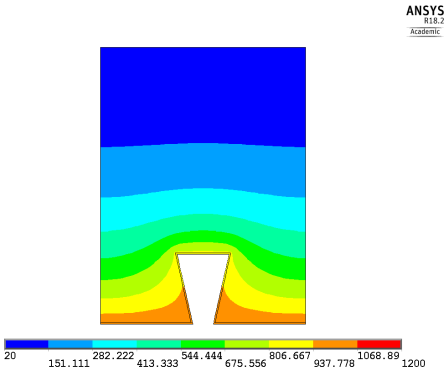
t = 56 min



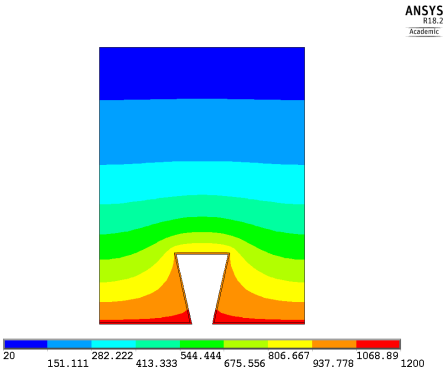
t = 113 min



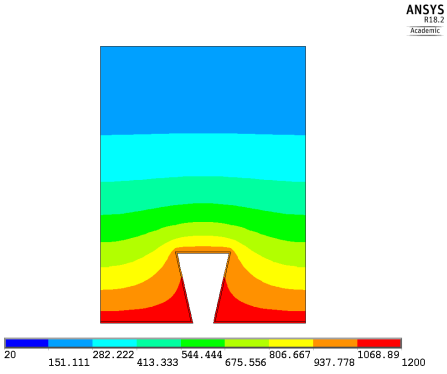
t = 170 min

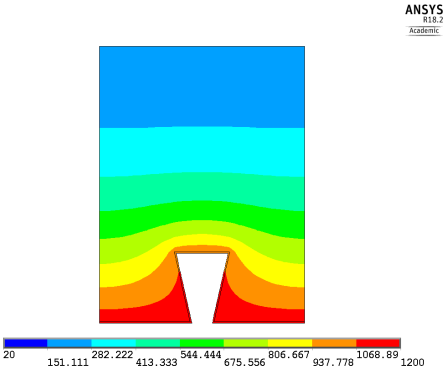


Tempo Crítico = 227 min



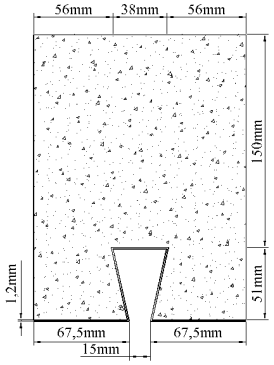
t = 14400s



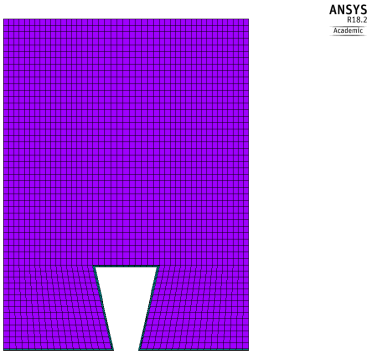


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.2mm

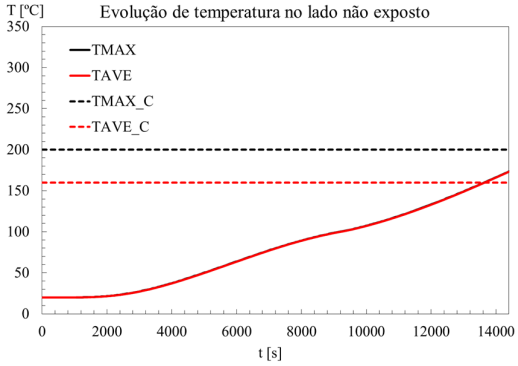
GEOMETRIA



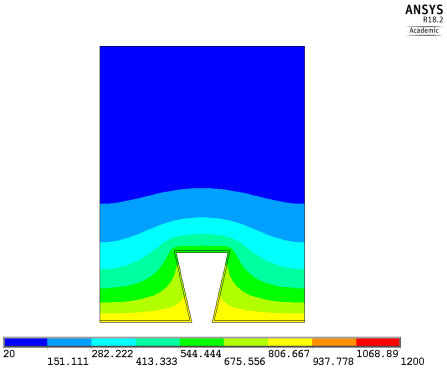
Malha



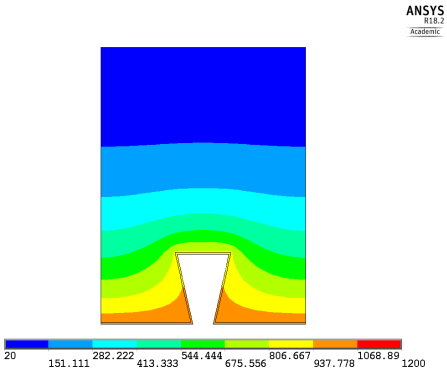
t = 56 min



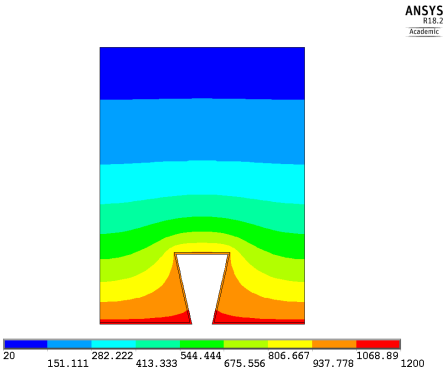
t = 113 min



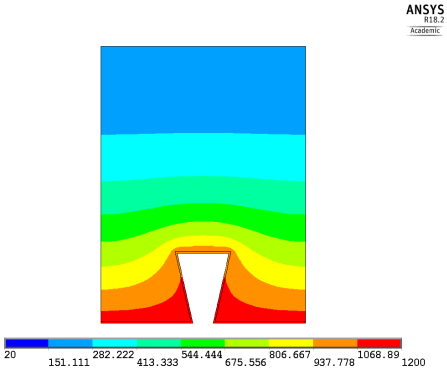
t = 170 min

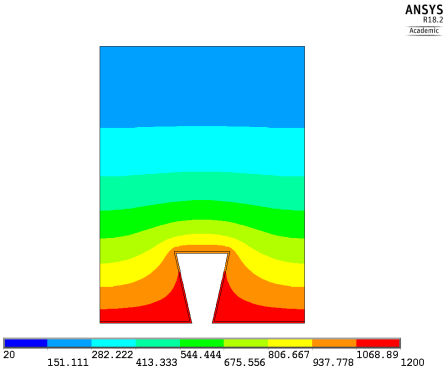


Tempo Crítico = 227 min



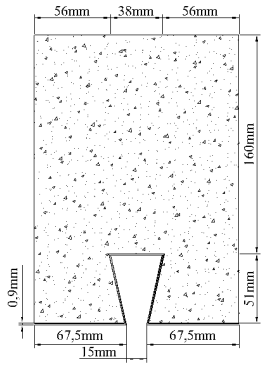
t = 14400s



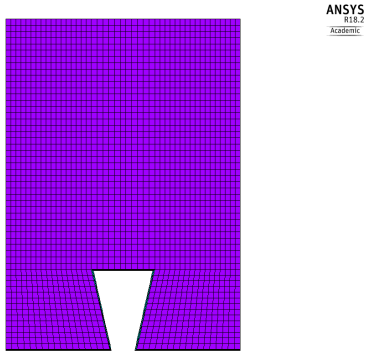


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.9mm

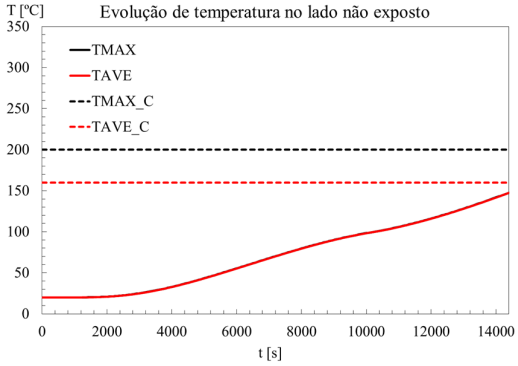
GEOMETRIA



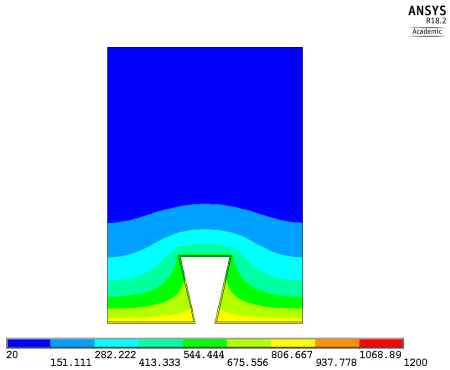
Malha



t = 48 min



t = 96 min



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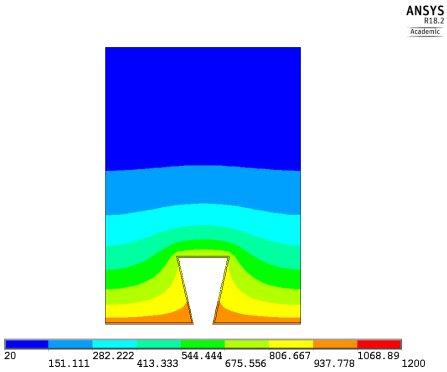
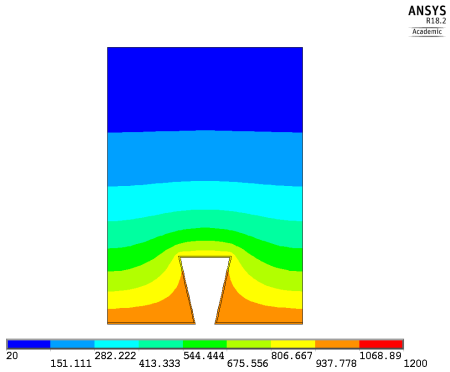


t = 192 min



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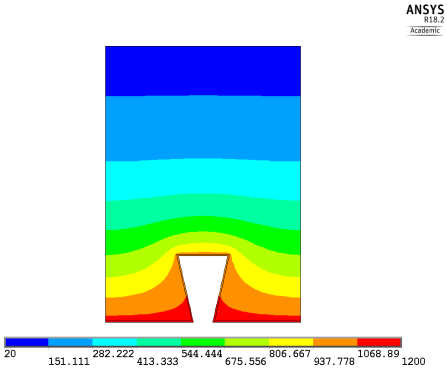
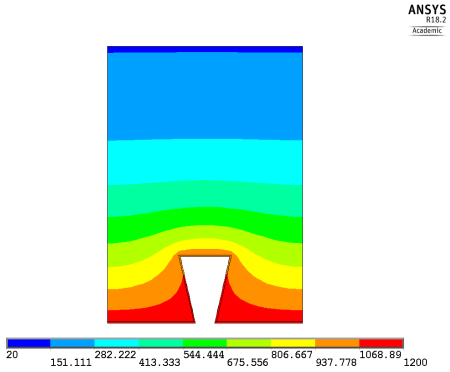
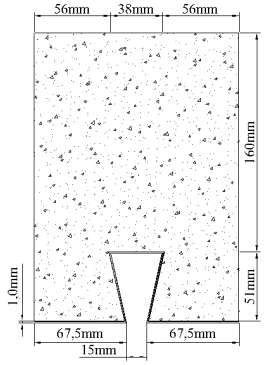


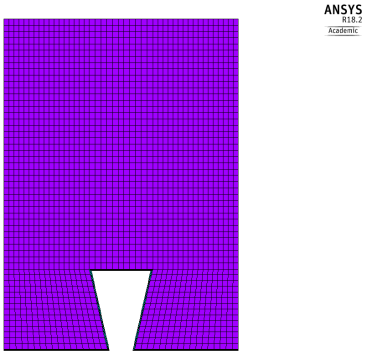


LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.0mm

GEOMETRIA



Malha



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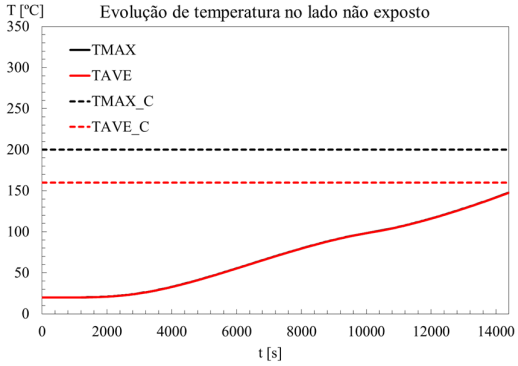

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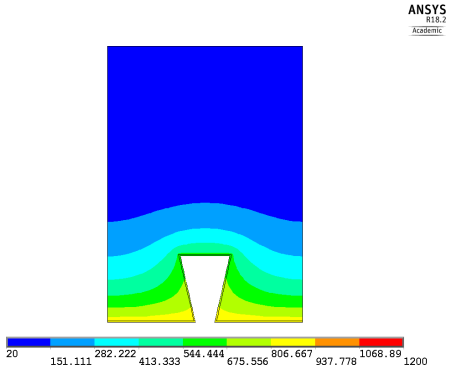

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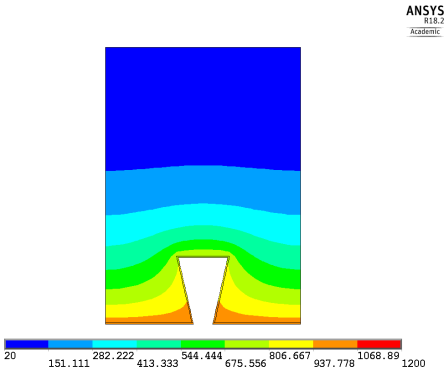

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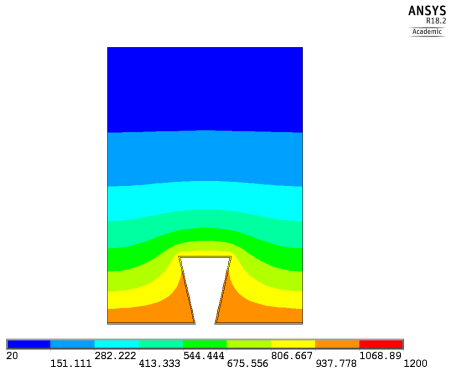

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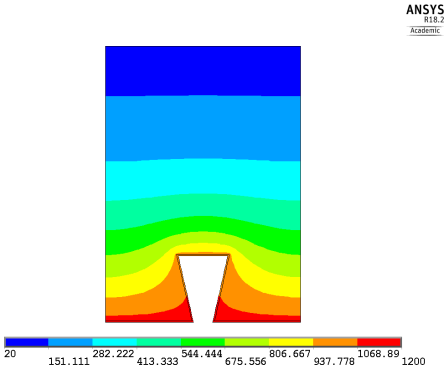
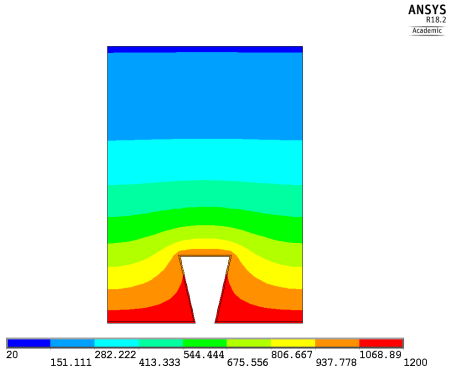
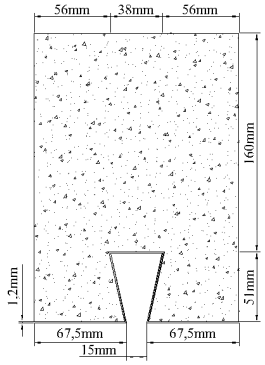




LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.2mm

GEOMETRIA



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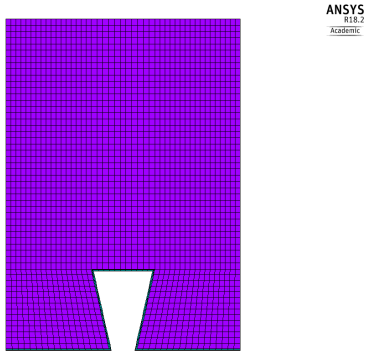

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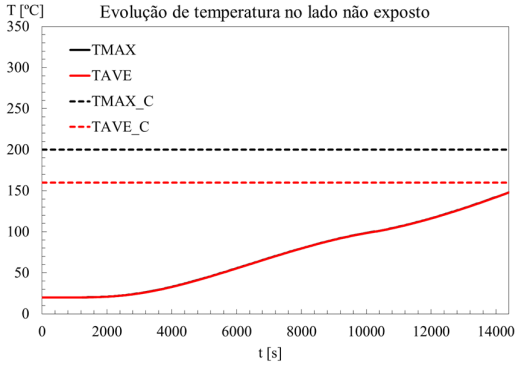

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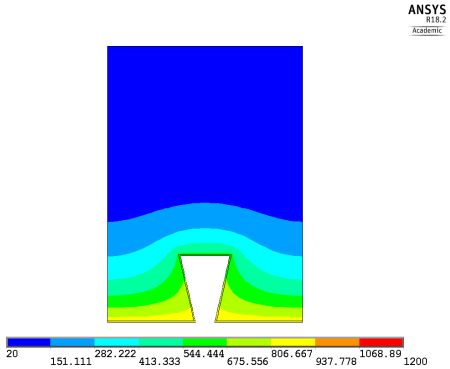

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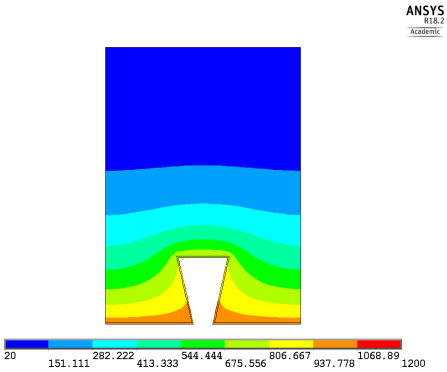
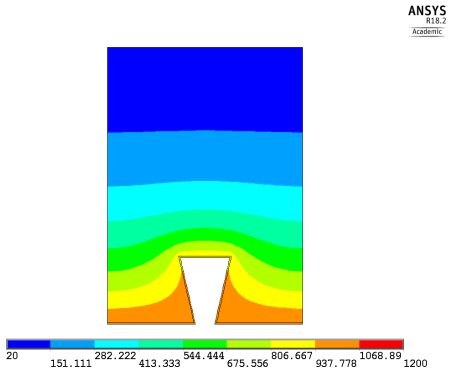
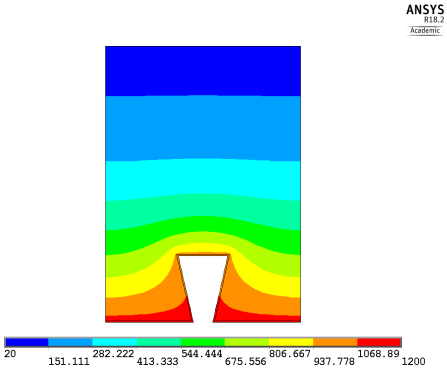
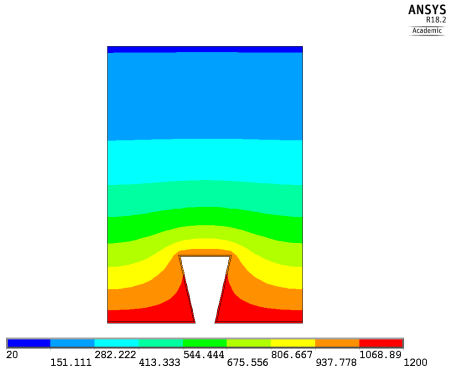


t = 192 min



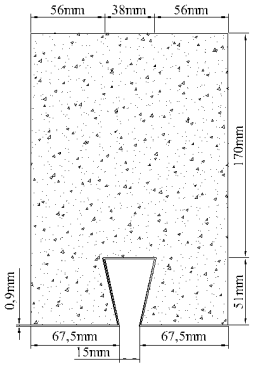
t = 14400s





LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.9mm

GEOMETRIA



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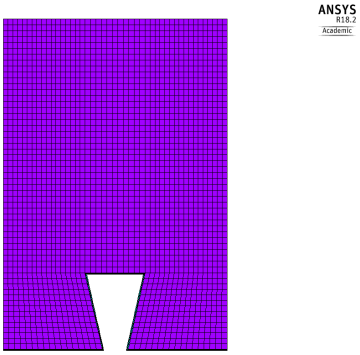

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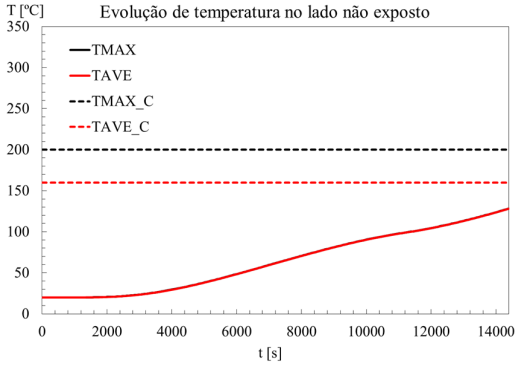

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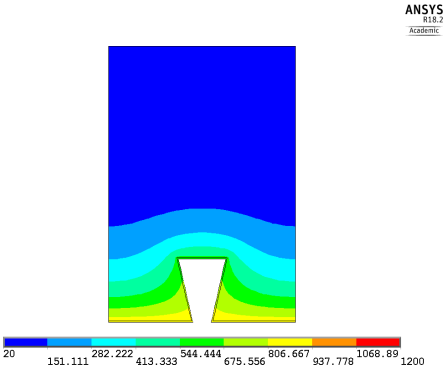

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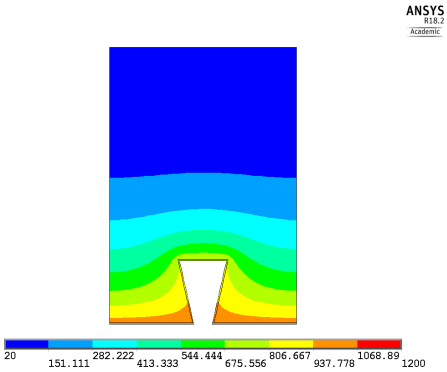

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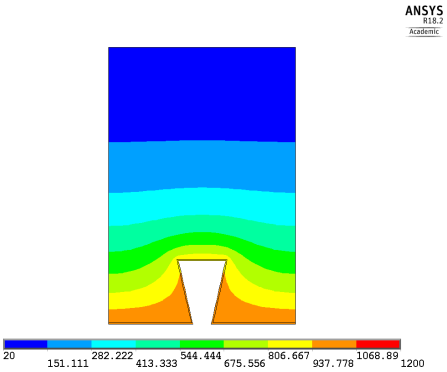

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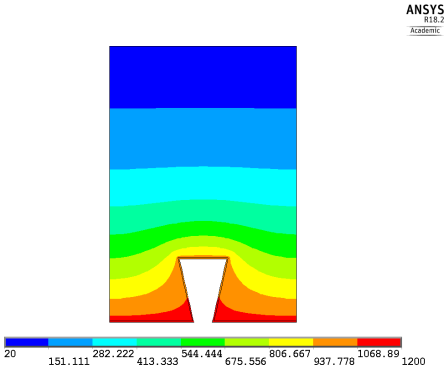
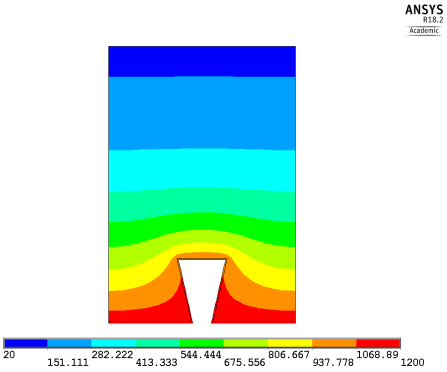
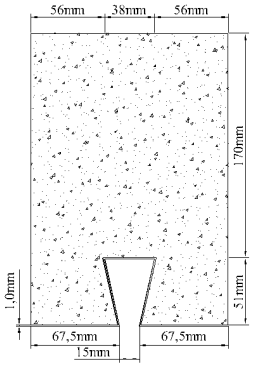




LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.0mm

GEOMETRIA



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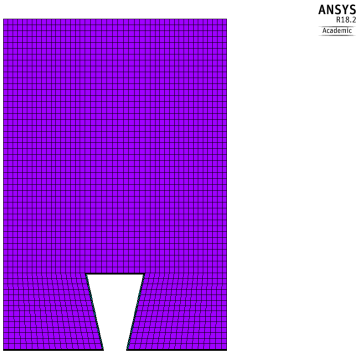

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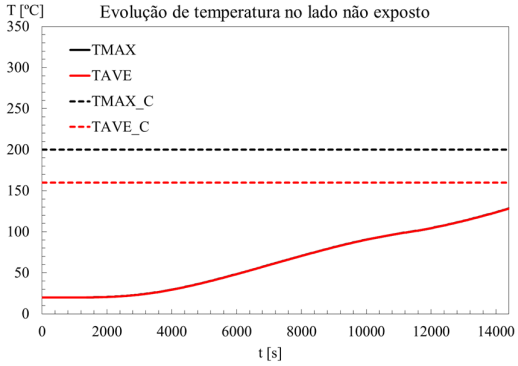

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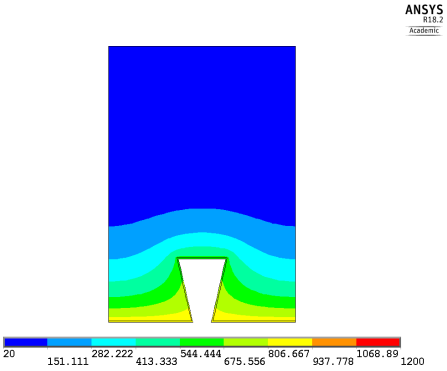

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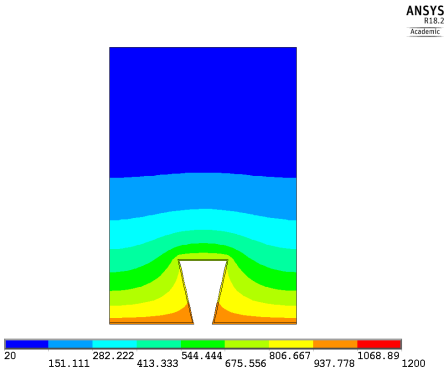

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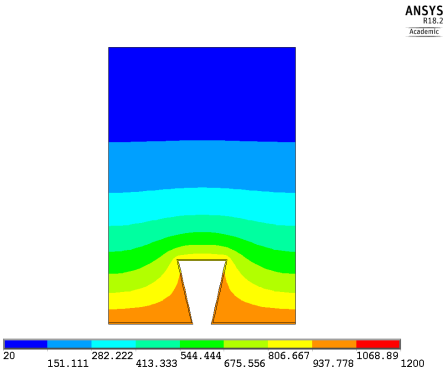

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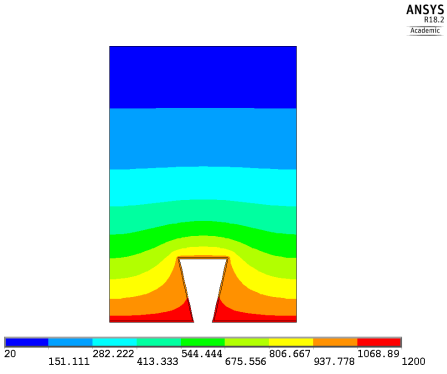
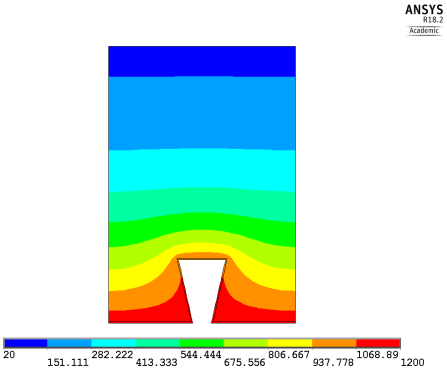
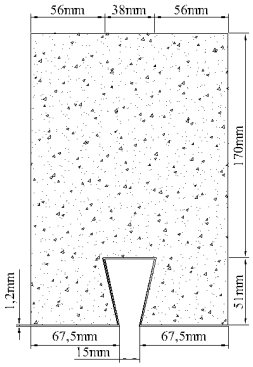




LAJE MISTA REENTRANTE (L1/L2=112/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.2mm

GEOMETRIA



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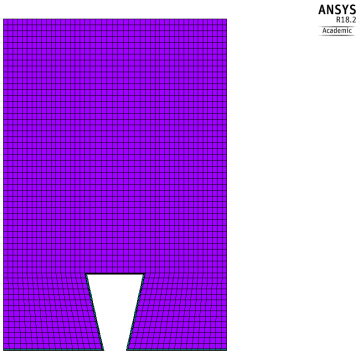

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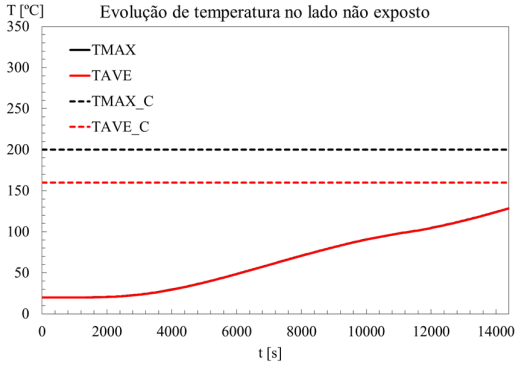

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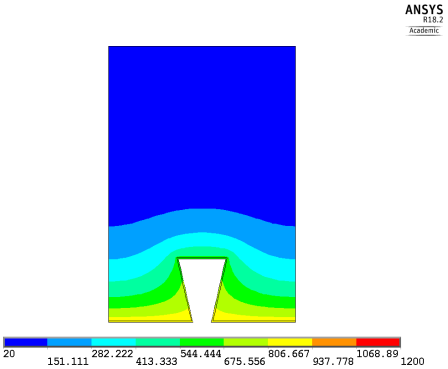

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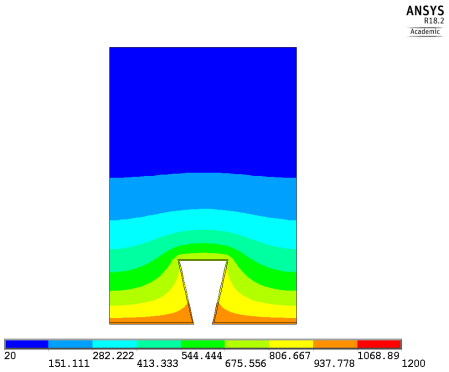
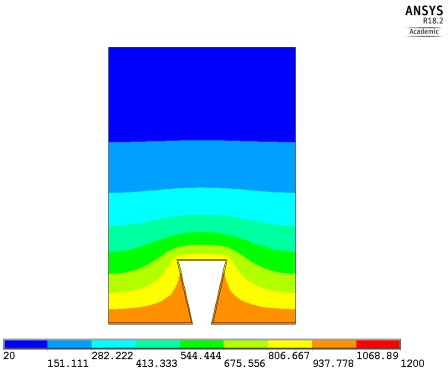
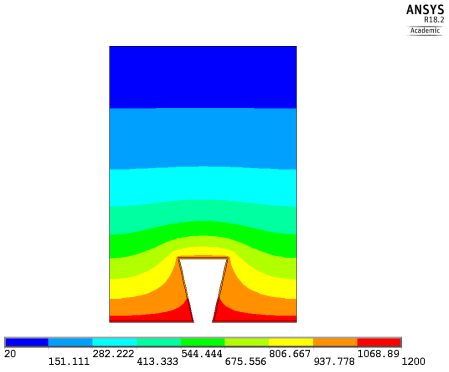
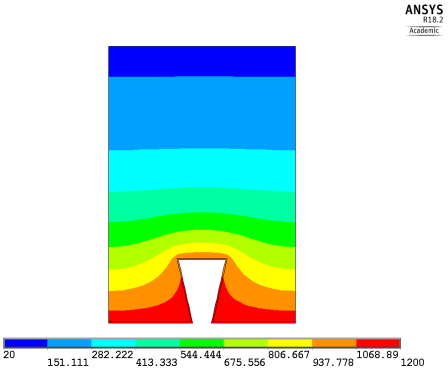


t = 192 min



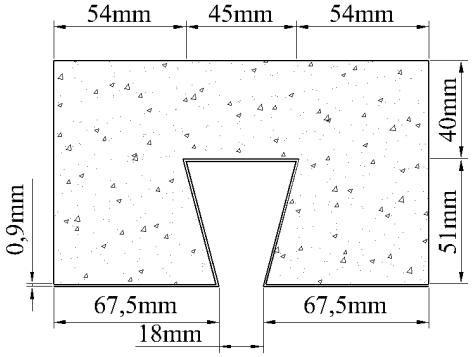
t = 14400s





LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 0.9mm

GEOMETRIA



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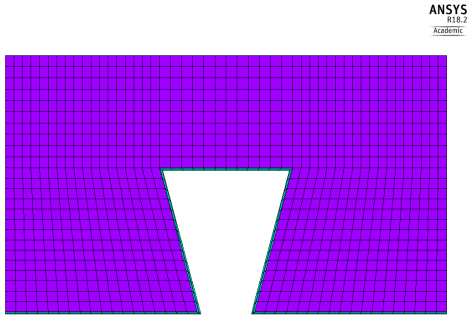

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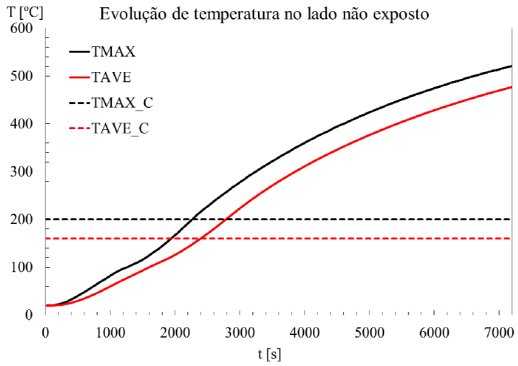
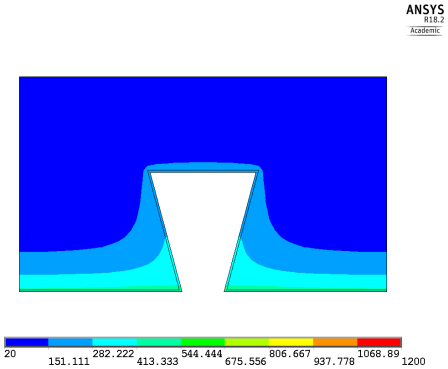
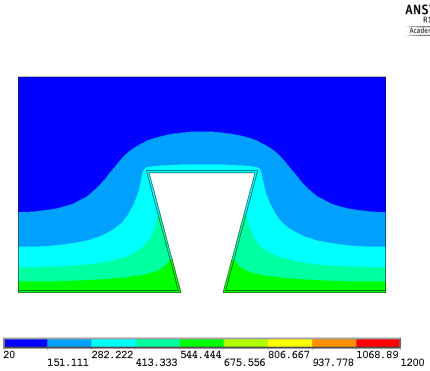


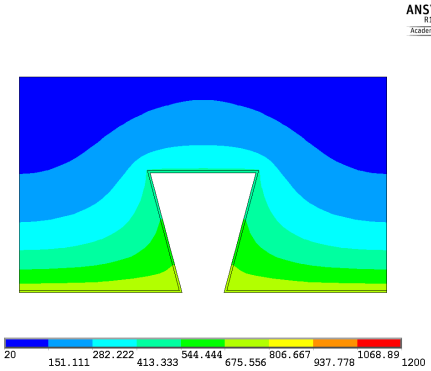
t = 18 min



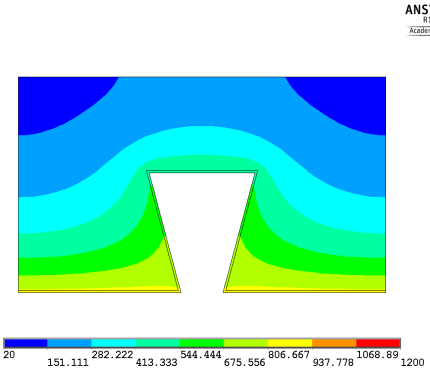
t = 27 min

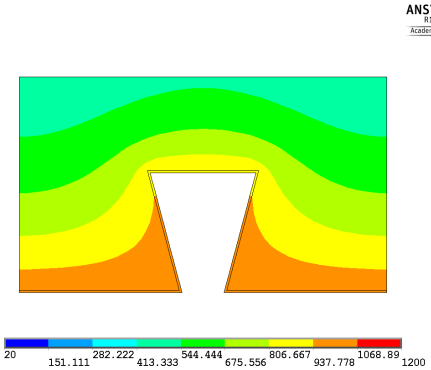


Tempo Crítico = 37 min



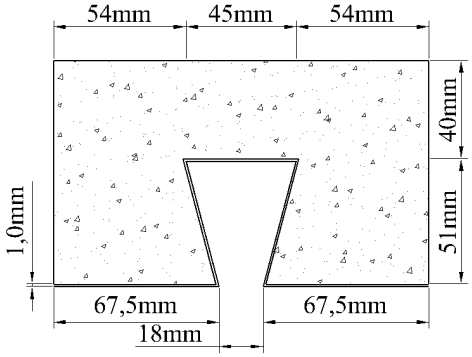
t = 7200s



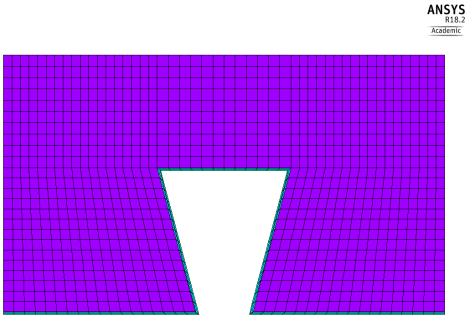


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.0mm

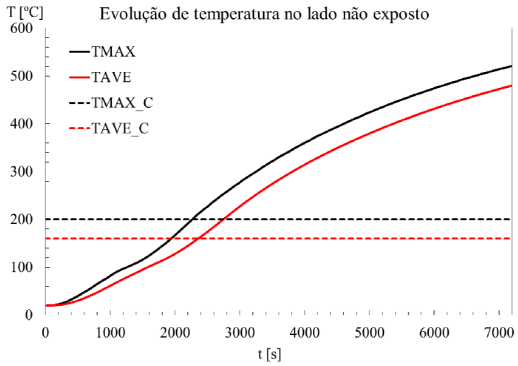
GEOMETRIA



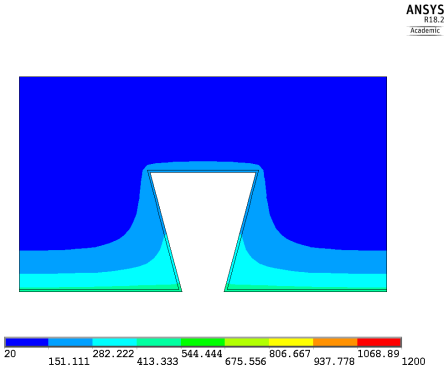
Malha



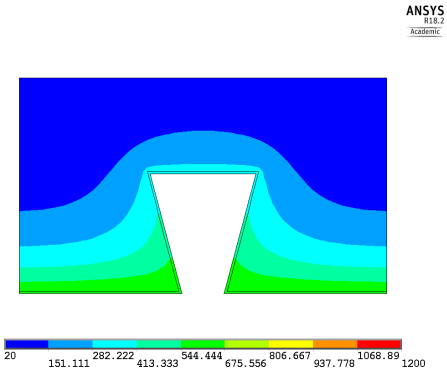
t = 9 min



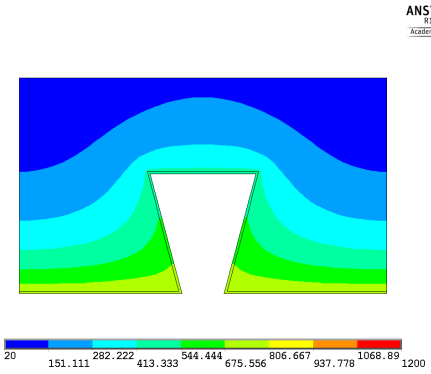
t = 19 min



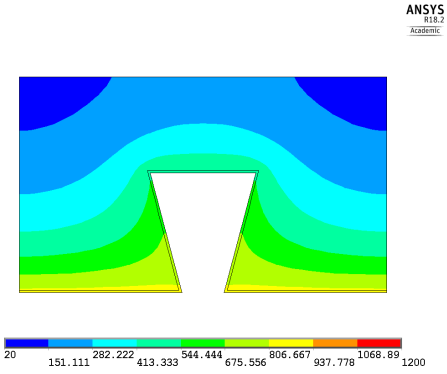
t = 28 min

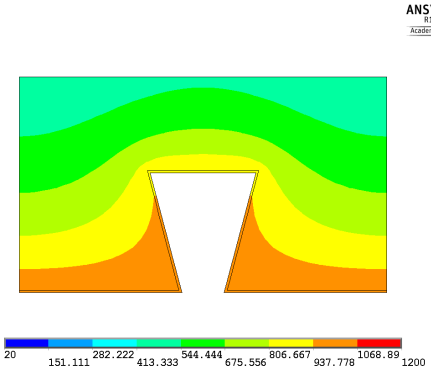


Tempo Crítico = 38 min



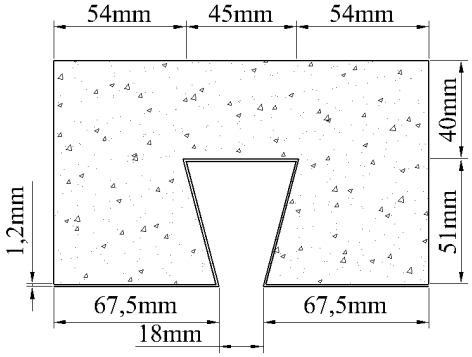
t = 7200s



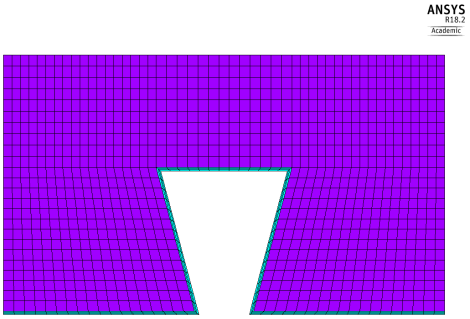


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 40mm E DECK DE AÇO DE 1.2mm

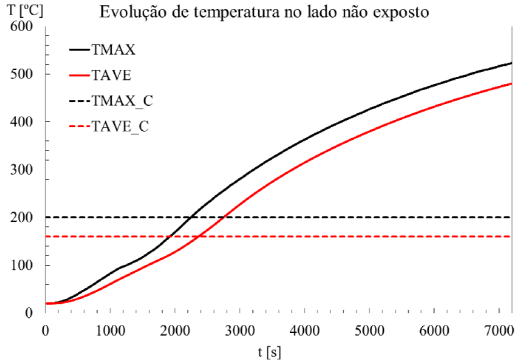
GEOMETRIA



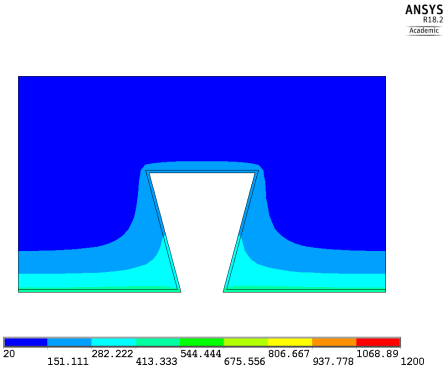
Malha



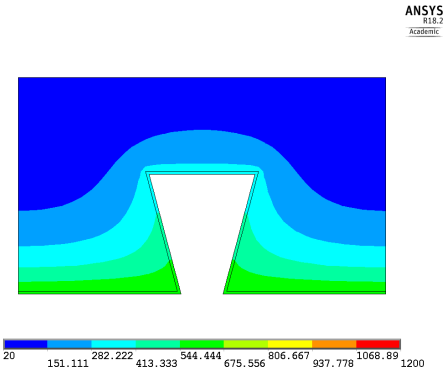
t = 9 min



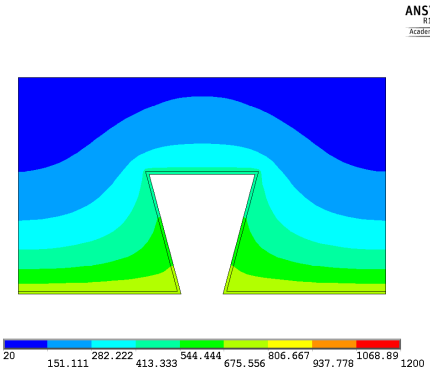
t = 19 min



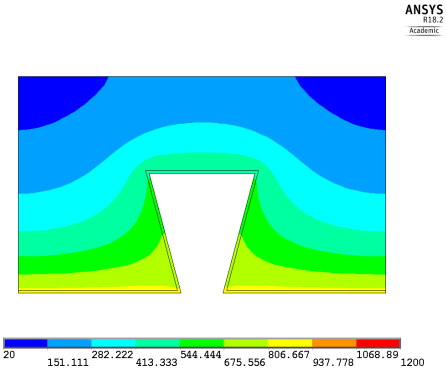
t = 28 min

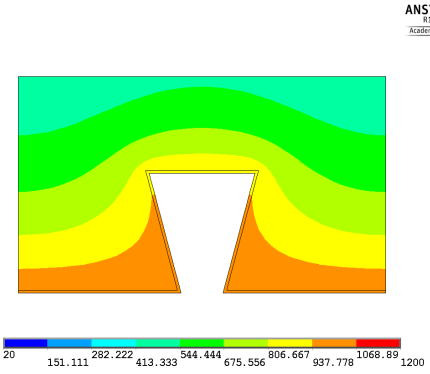


Tempo Crítico = 38 min



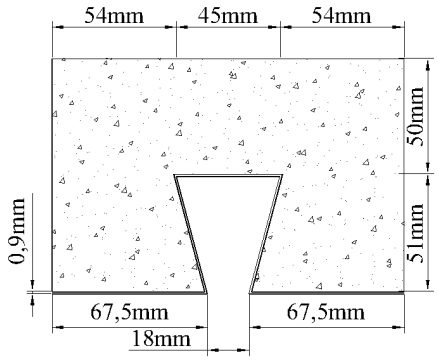
t = 7200s



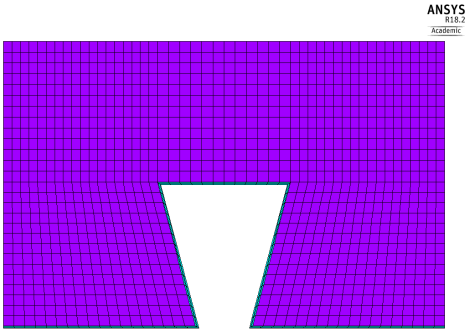


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 0.9mm

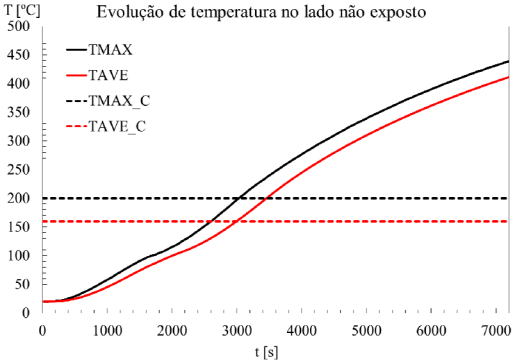
GEOMETRIA



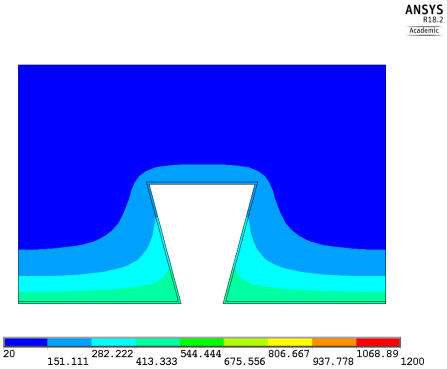
Malha



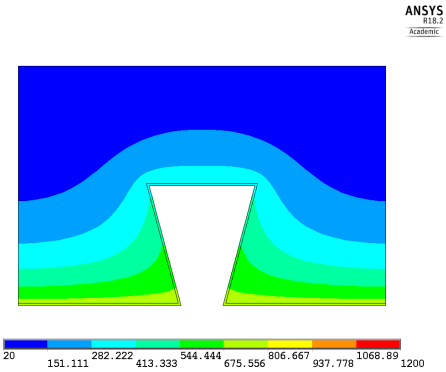
t = 12 min



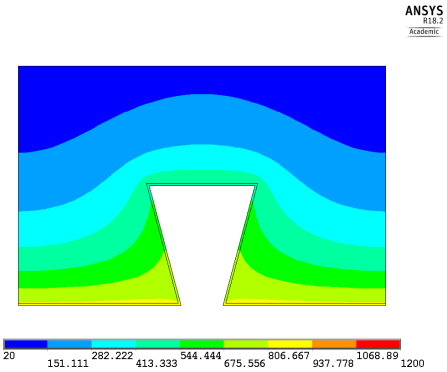
t = 24 min



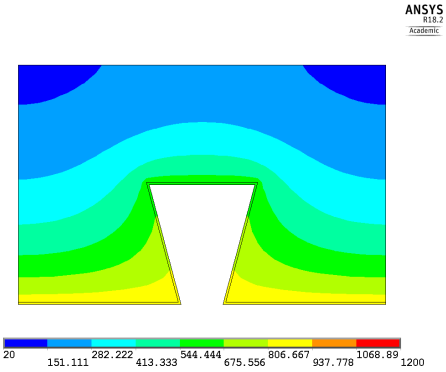
t = 36 min

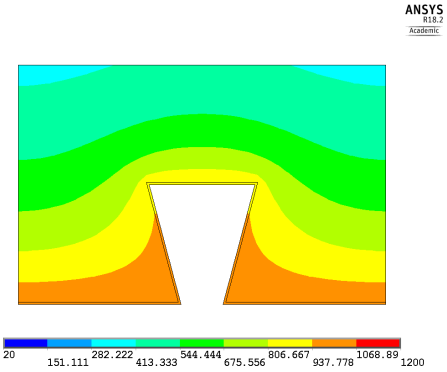


Tempo Crítico = 49 min



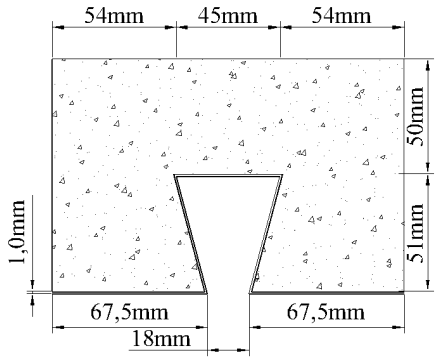
t = 7200s



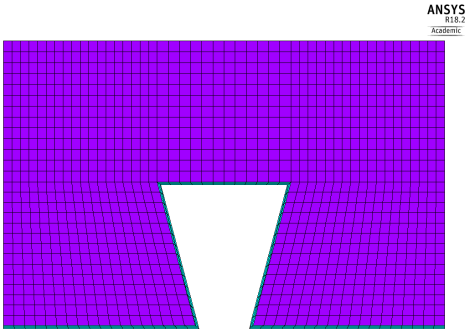


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.0mm

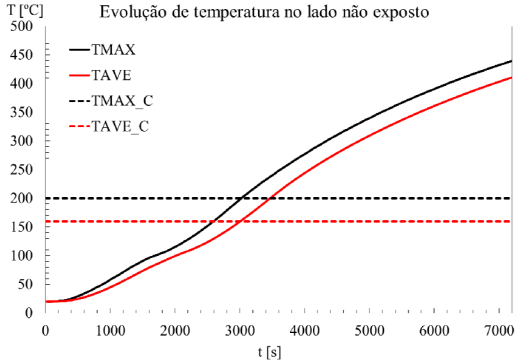
GEOMETRIA



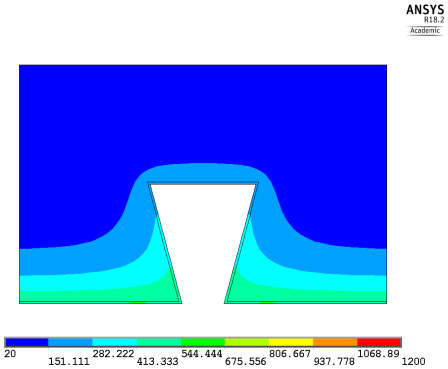
Malha



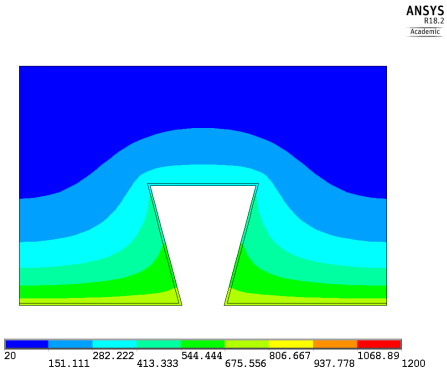
t = 12 min



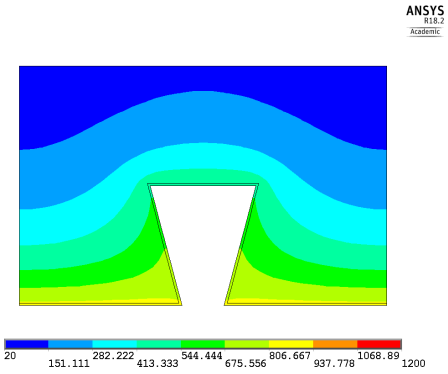
t = 25 min



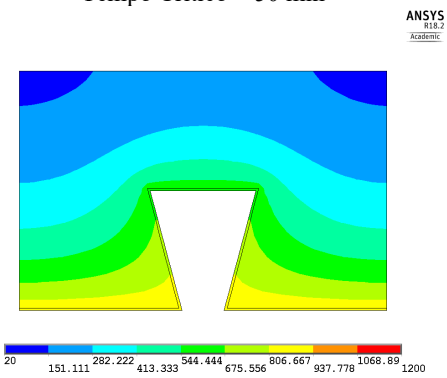
t = 37 min

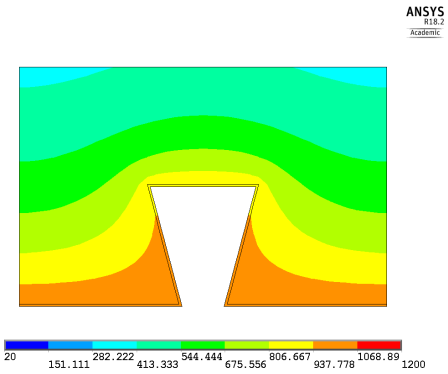


Tempo Crítico = 50 min



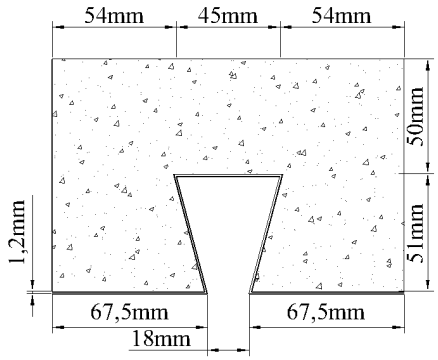
t = 7200s



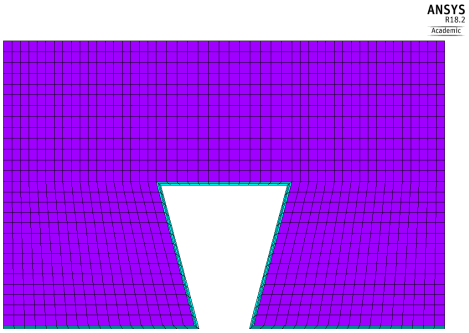


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 50mm E DECK DE AÇO DE 1.2mm

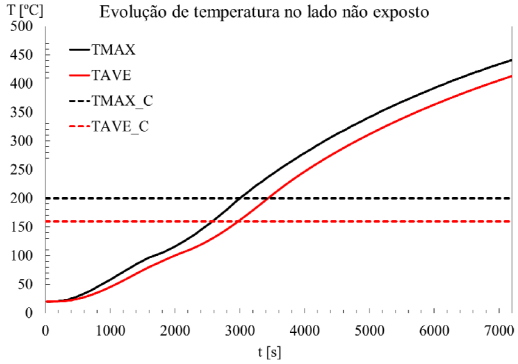
GEOMETRIA



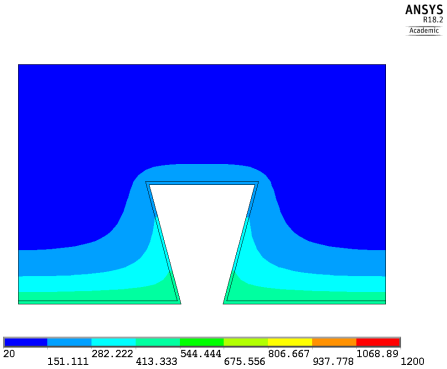
Malha



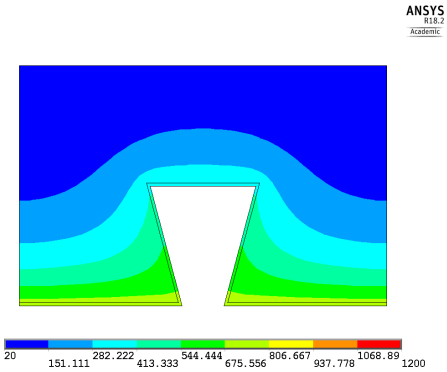
t = 12 min



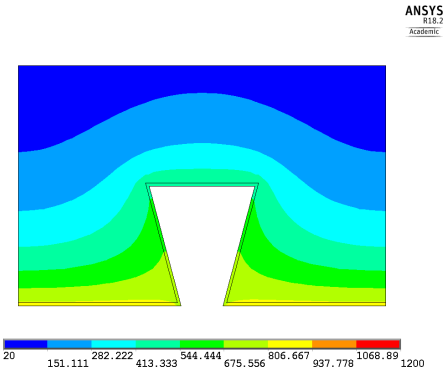
t = 24 min



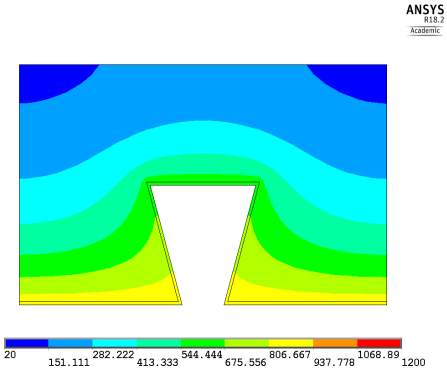
t = 36 min

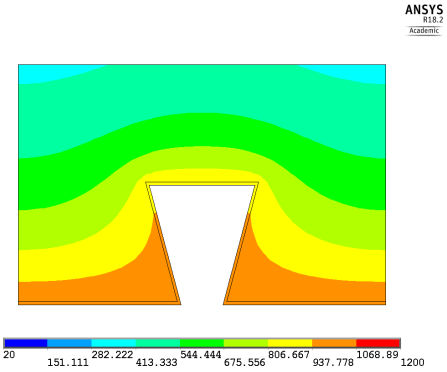


Tempo Crítico = 49 min



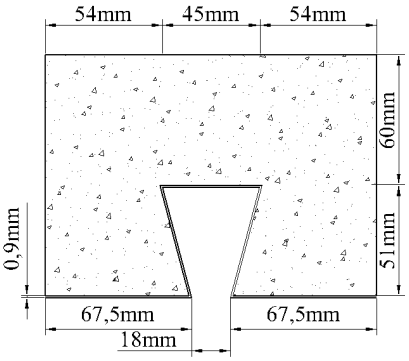
t = 7200s



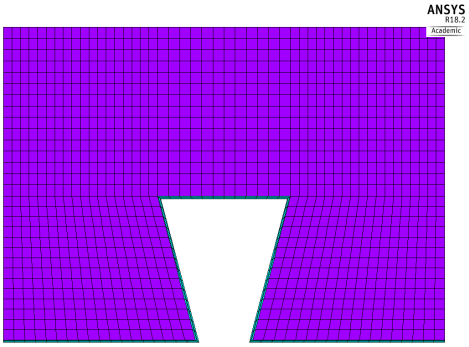


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 0.9mm

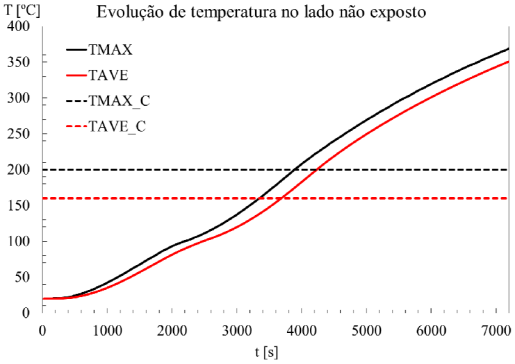
GEOMETRIA



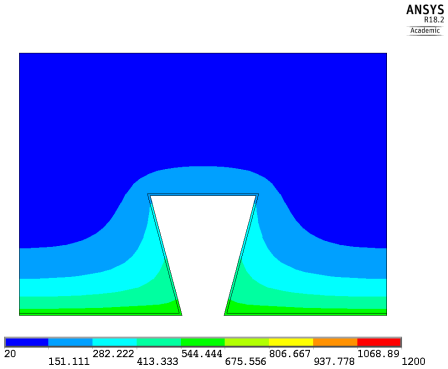
Malha



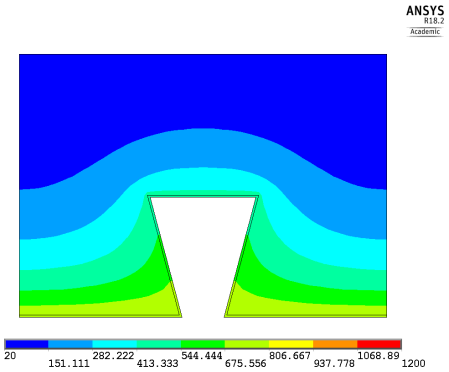
t = 15 min



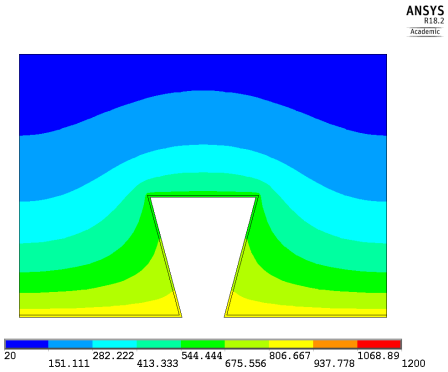
t = 30 min



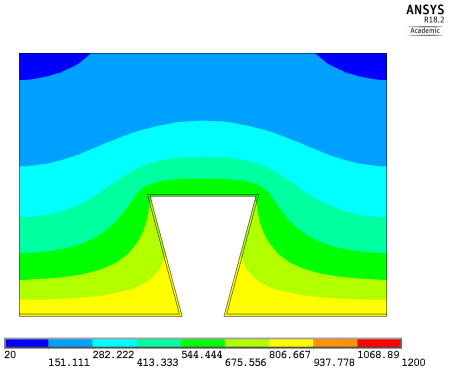
t = 45 min

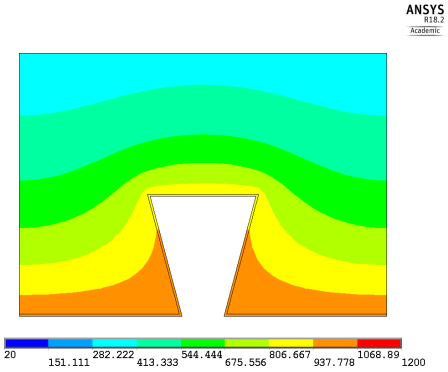


Tempo Crítico = 61 min



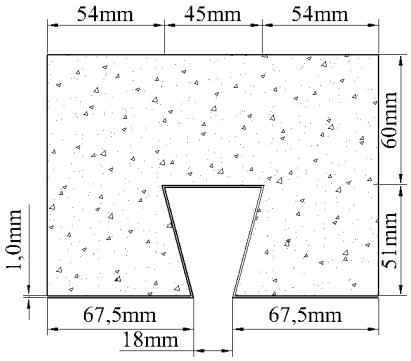
t = 7200s



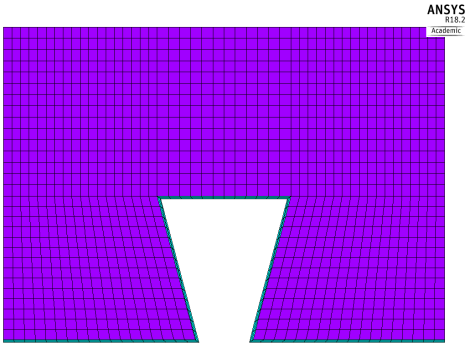


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.0mm

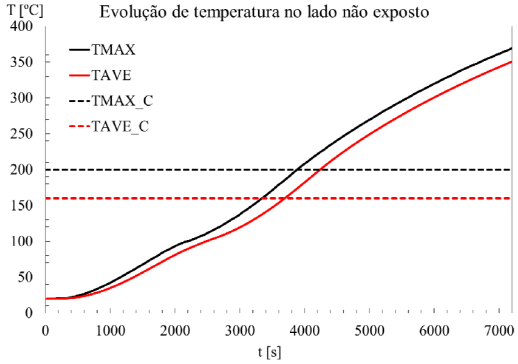
GEOMETRIA



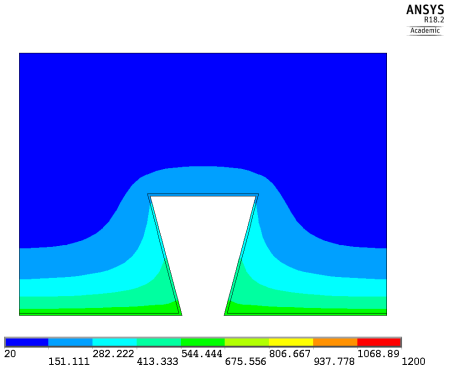
Malha



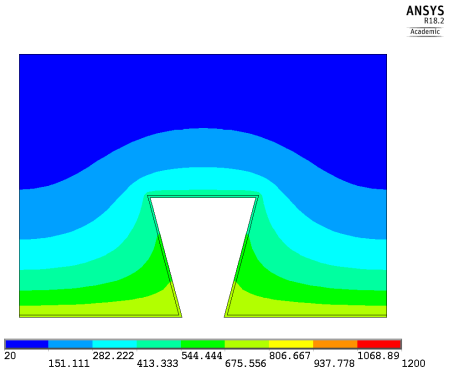
t = 15 min



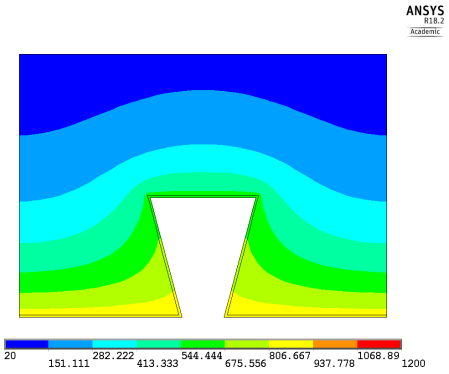
t = 30 min



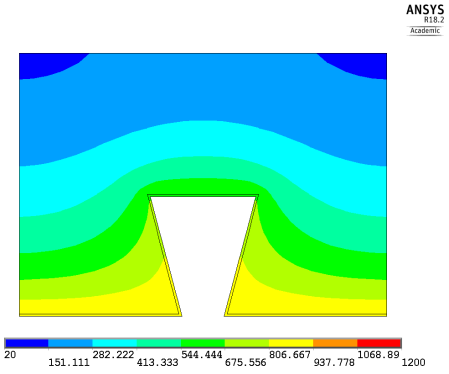
t = 45 min

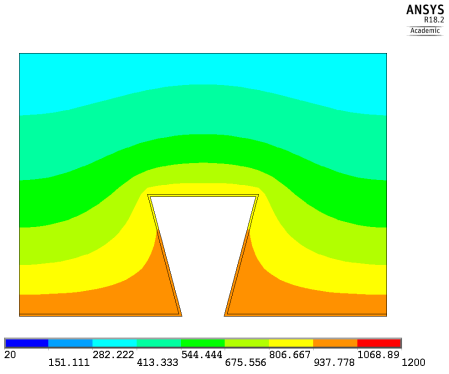


Tempo Crítico = 61 min



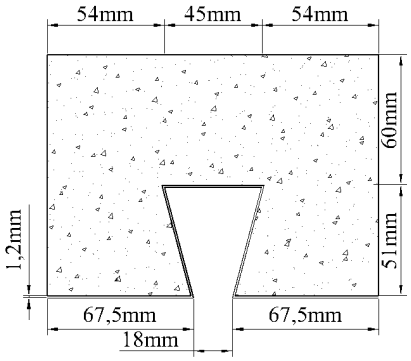
t = 7200s



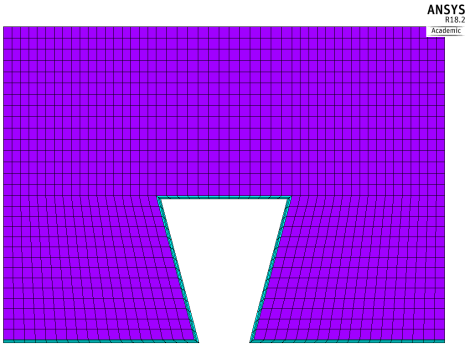


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 60mm E DECK DE AÇO DE 1.2mm

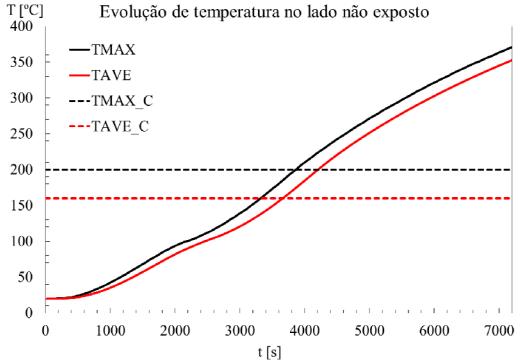
GEOMETRIA



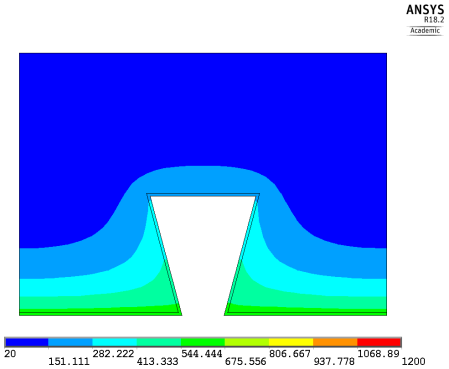
Malha



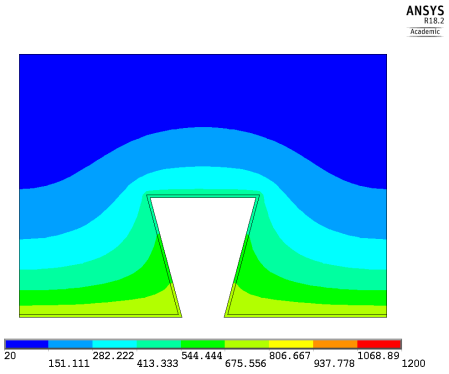
t = 15 min



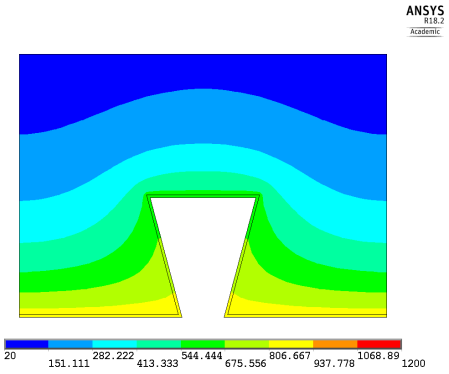
t = 30 min



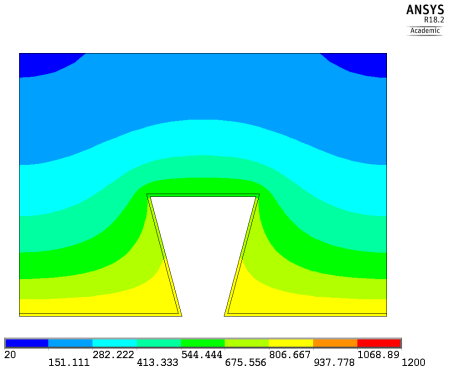
t = 45 min

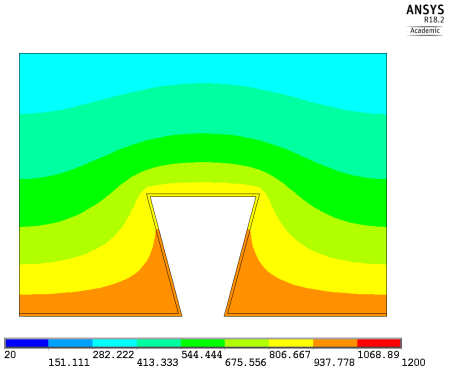


Tempo Crítico = 61 min



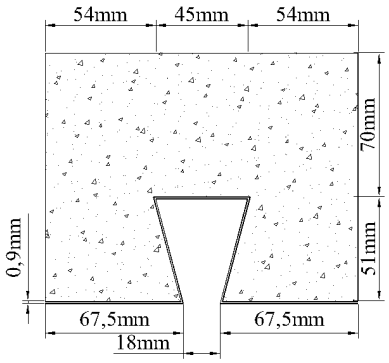
t = 7200s



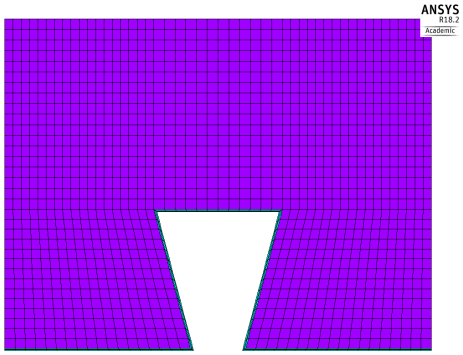


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 0.9mm

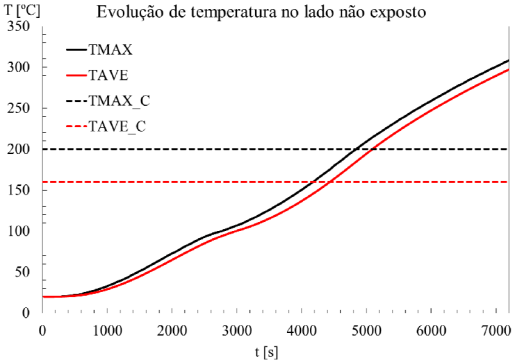
GEOMETRIA



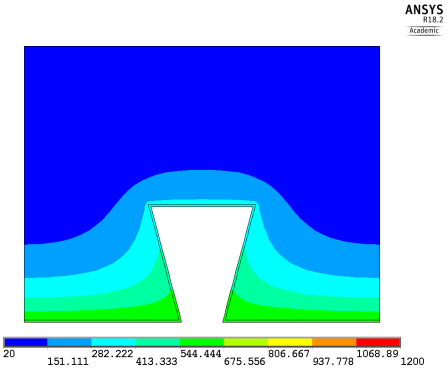
Malha



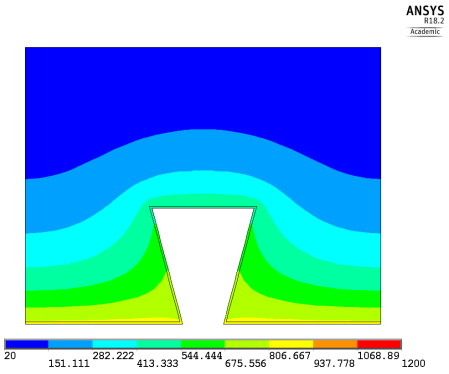
t = 18 min



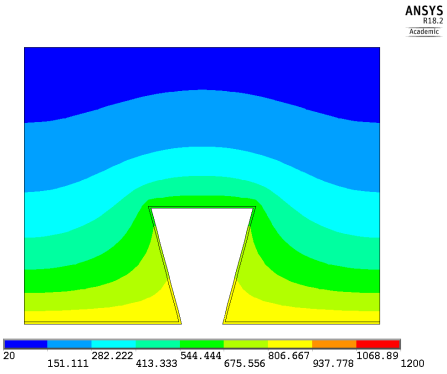
t = 37 min



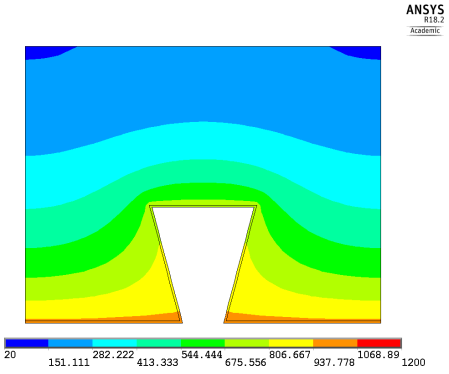
t = 55 min

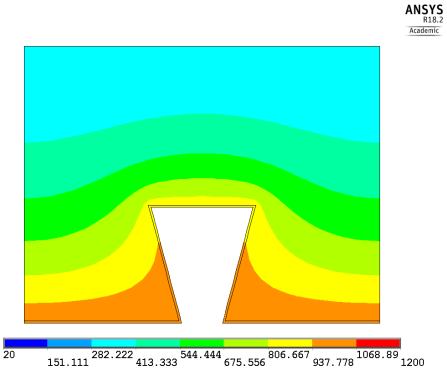


Tempo Crítico = 74 min



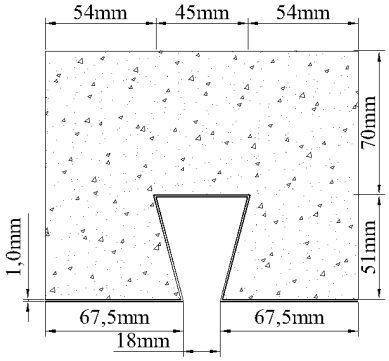
t = 7200s



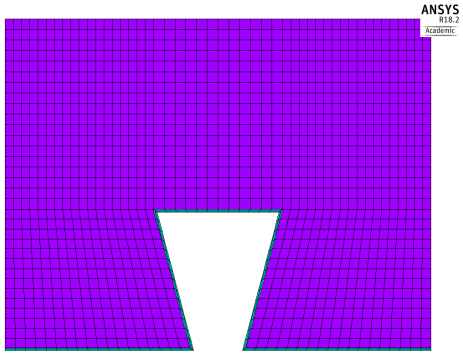


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.0mm

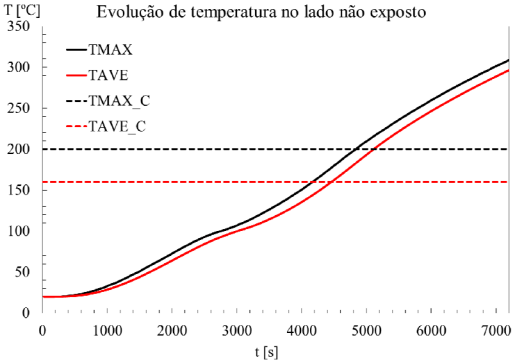
GEOMETRIA



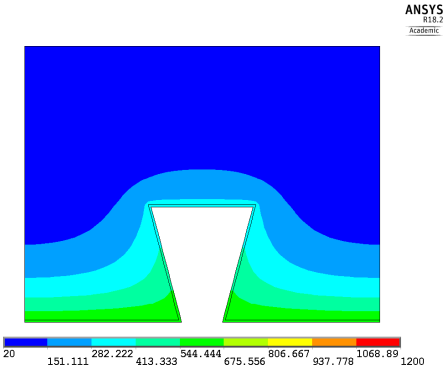
Malha



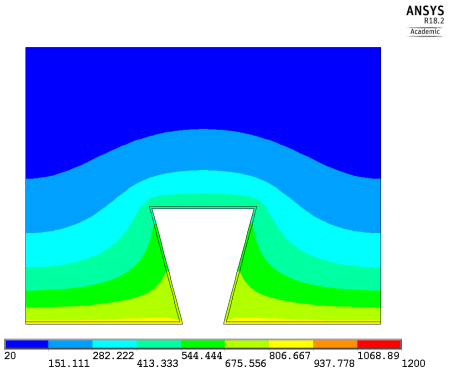
t = 18 min



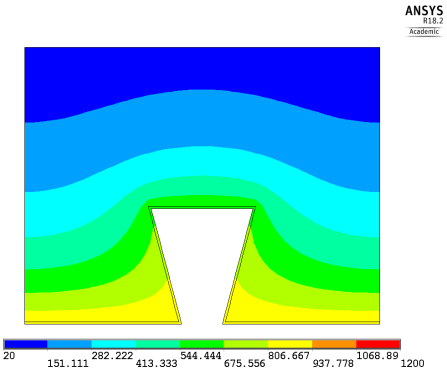
t = 37 min



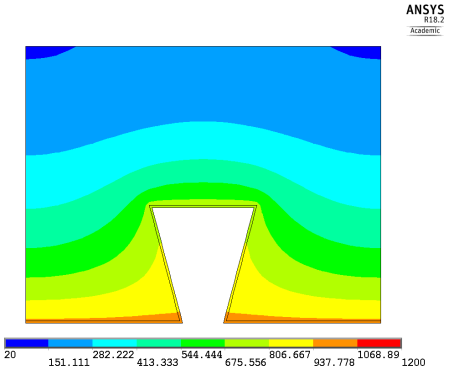
t = 55 min

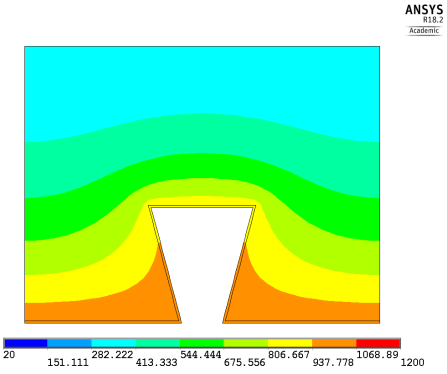


Tempo Crítico = 74 min



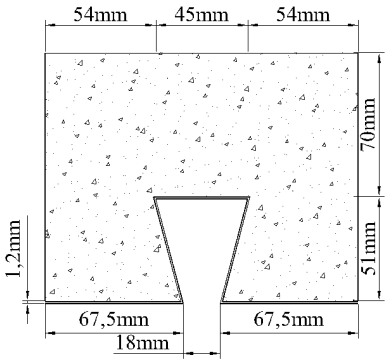
t = 7200s



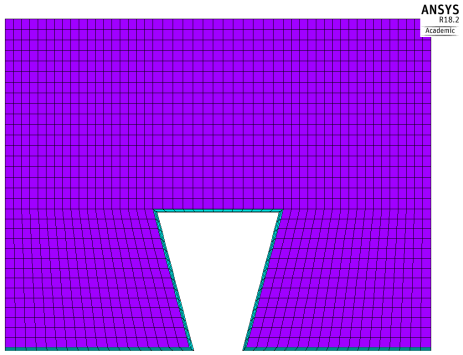


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 70mm E DECK DE AÇO DE 1.2mm

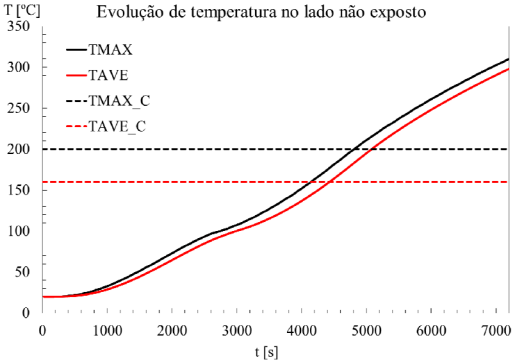
GEOMETRIA



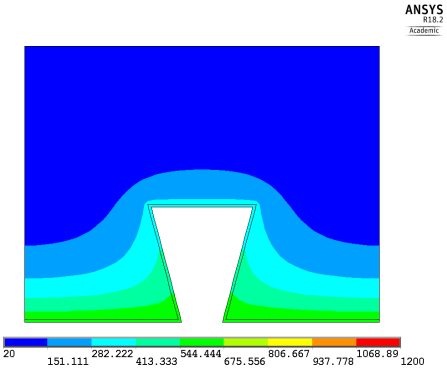
Malha



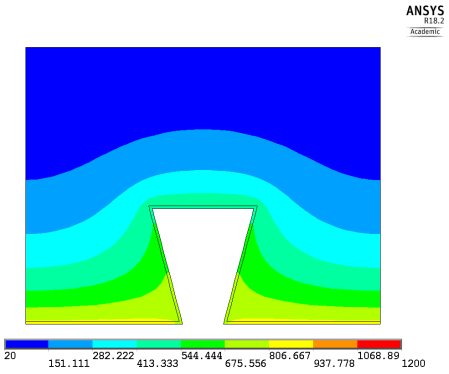
t = 18 min



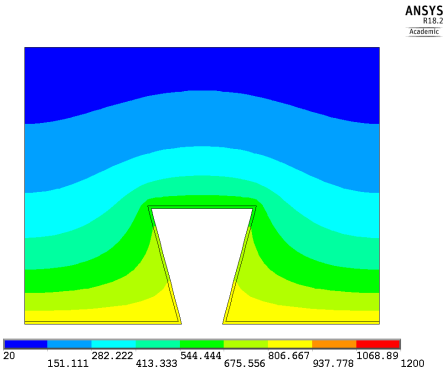
t = 36 min



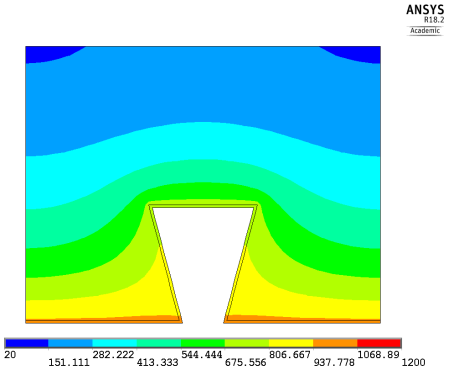
t = 54 min

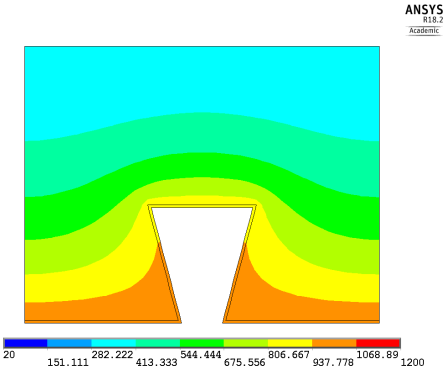


Tempo Crítico = 73 min



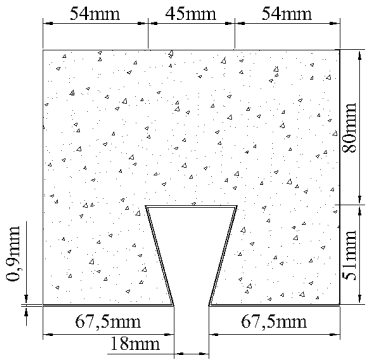
t = 7200s



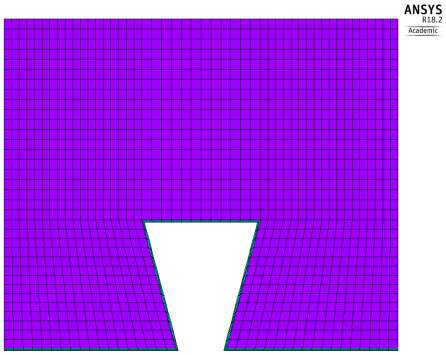


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 0.9mm

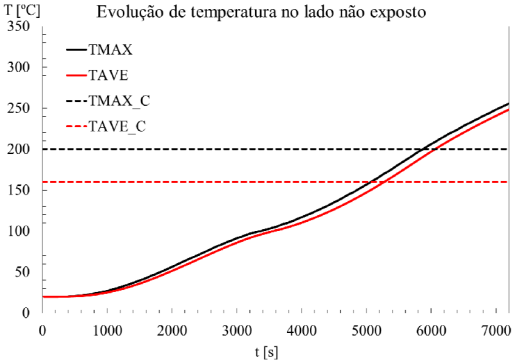
GEOMETRIA



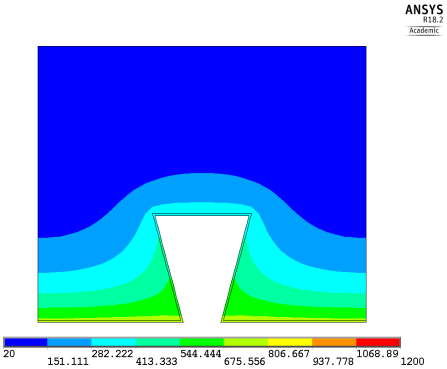
Malha



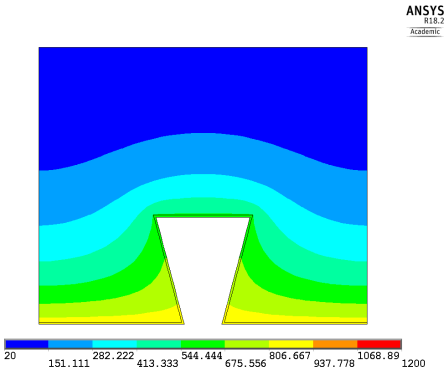
t = 22 min



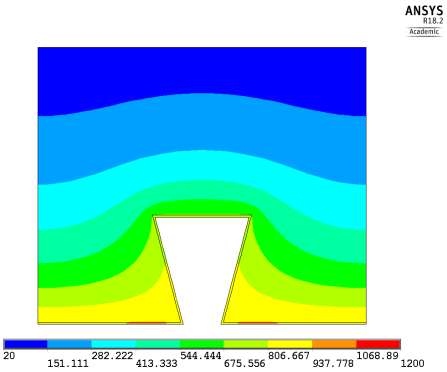
t = 44 min



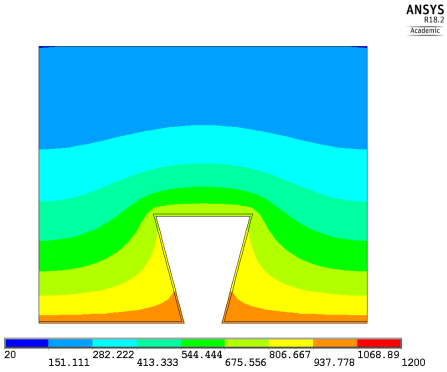
t = 66 min

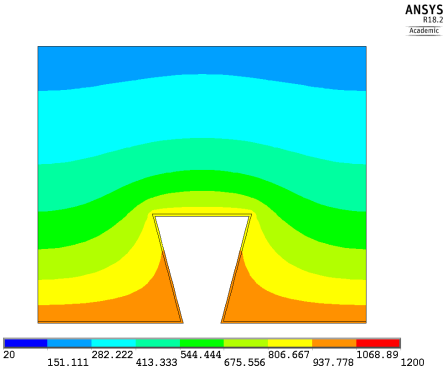


Tempo Crítico = 88 min



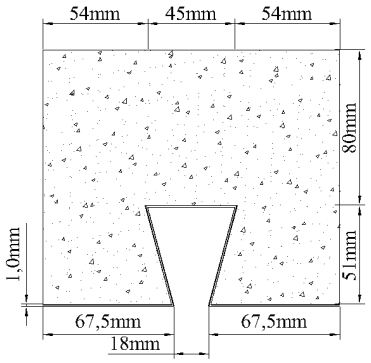
t = 7200s



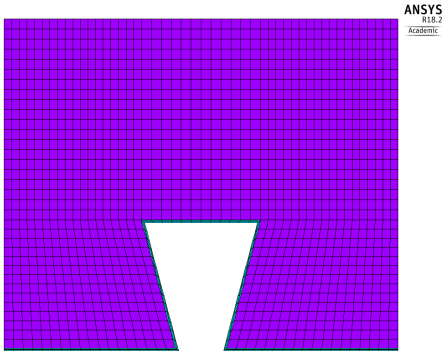


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.0mm

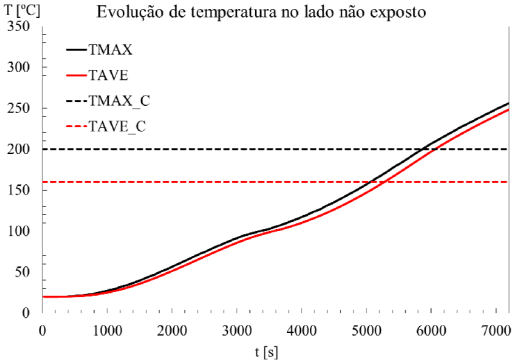
GEOMETRIA



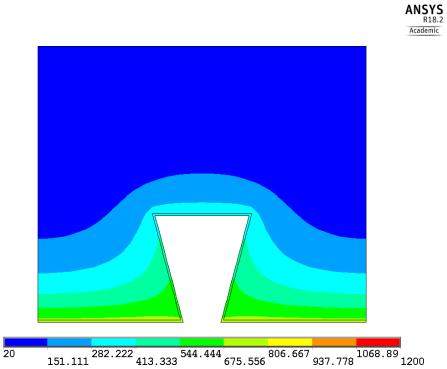
Malha



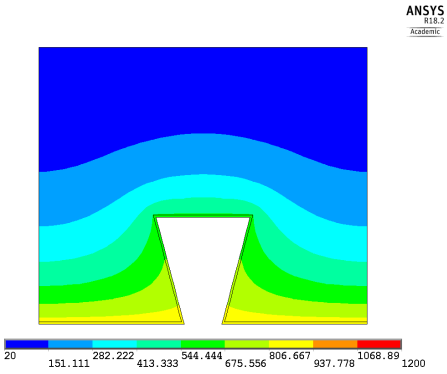
t = 21 min



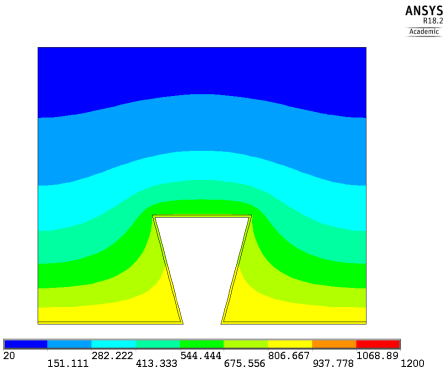
t = 43 min



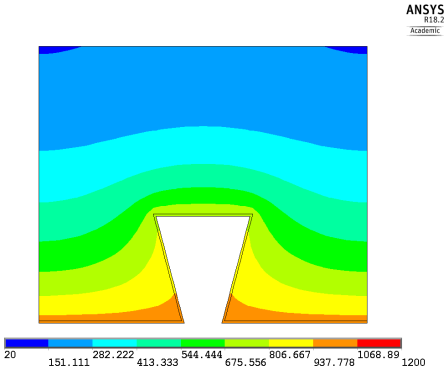
t = 65 min

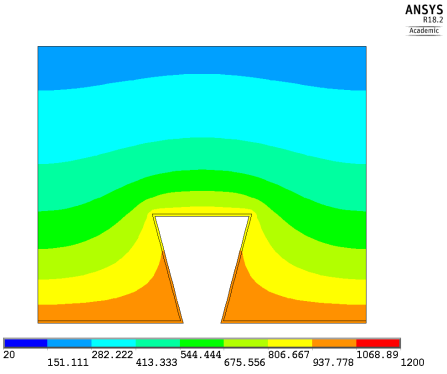


Tempo Crítico = 87 min



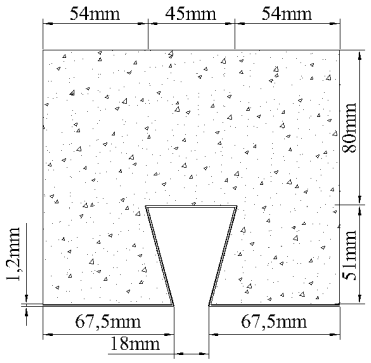
t = 7200s



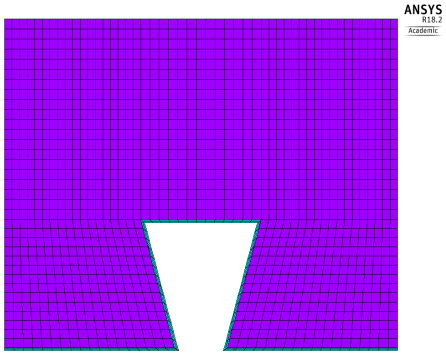


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 80mm E DECK DE AÇO DE 1.2mm

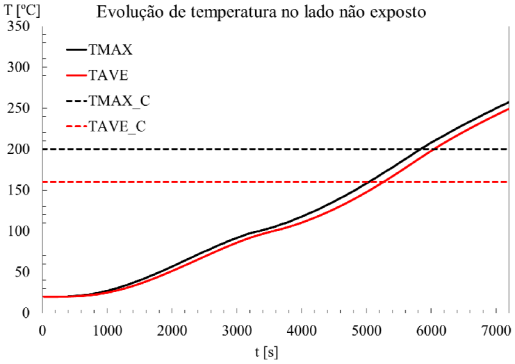
GEOMETRIA



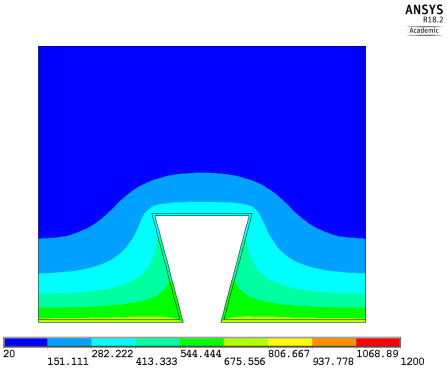
Malha



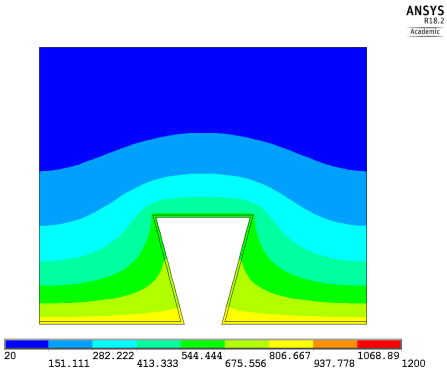
t = 21 min



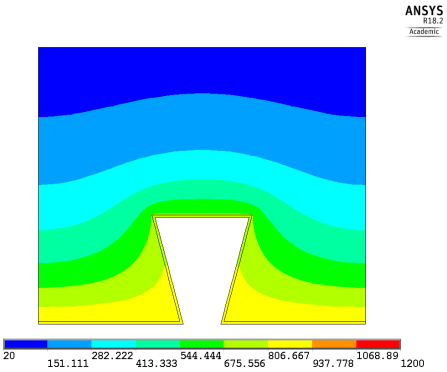
t = 43 min



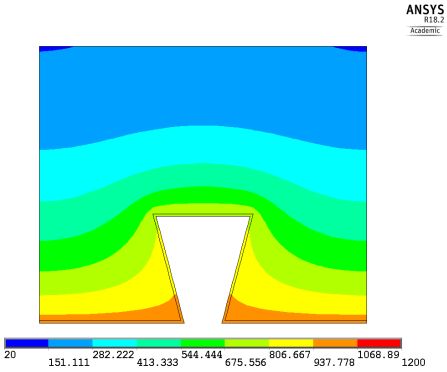
t = 65 min

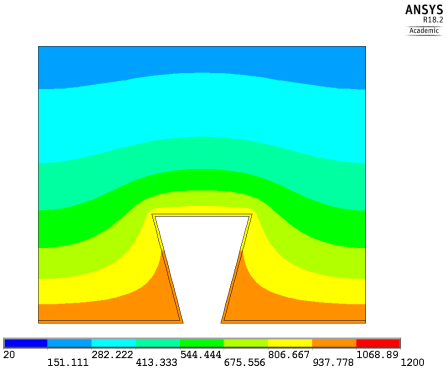


Tempo Crítico = 87 min



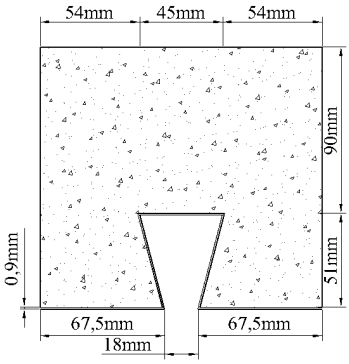
t = 7200s



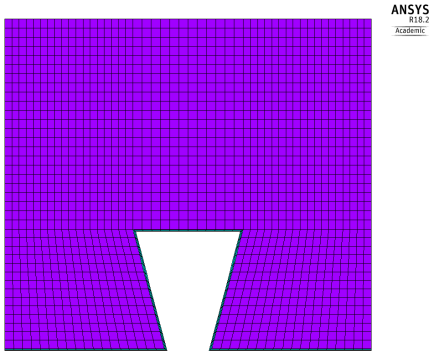


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 0.9mm

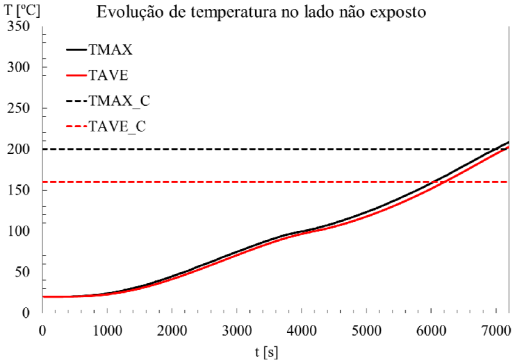
GEOMETRIA



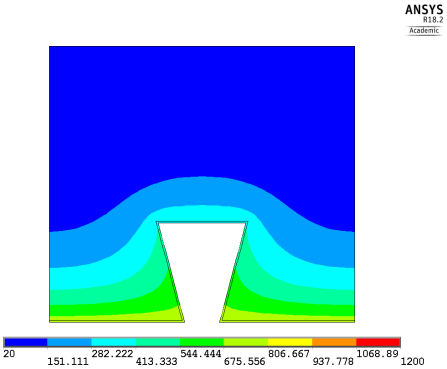
Malha



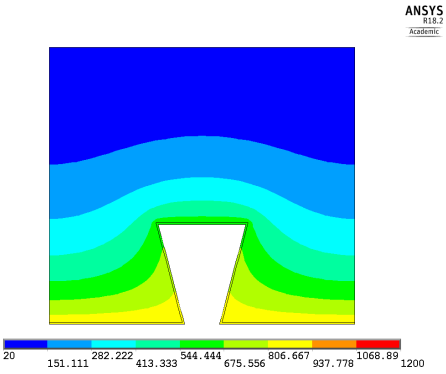
t = 25 min



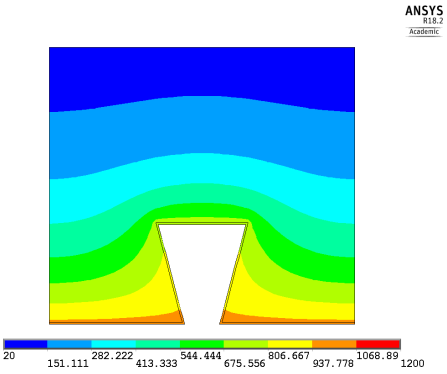
t = 51 min



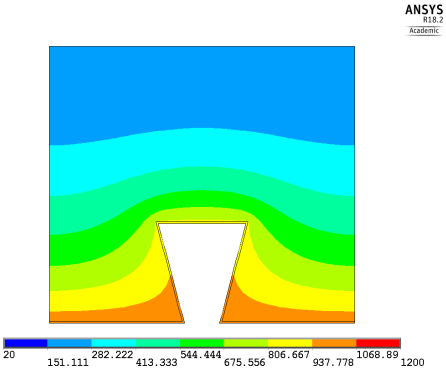
t = 77 min

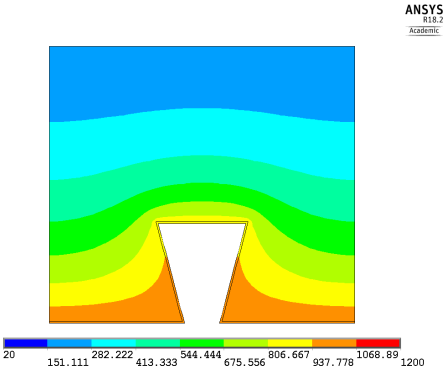


Tempo Crítico = 103 min



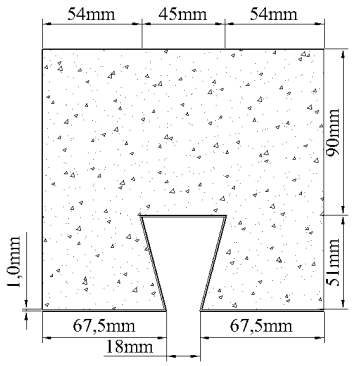
t = 7200s



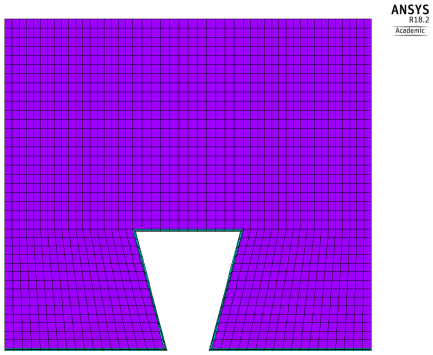


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.0mm

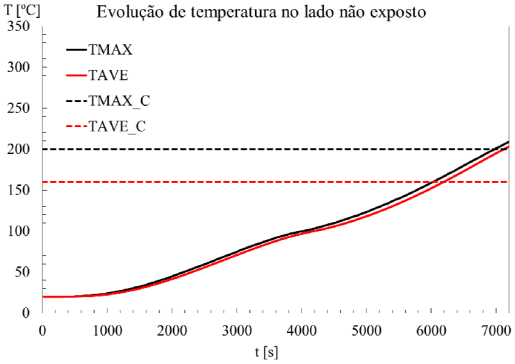
GEOMETRIA



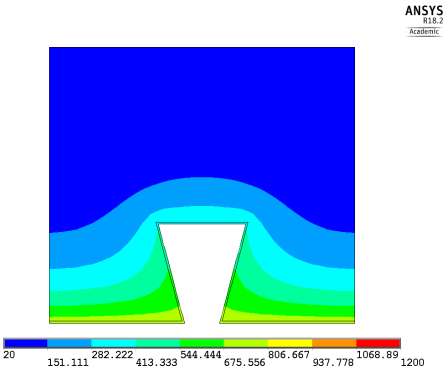
Malha



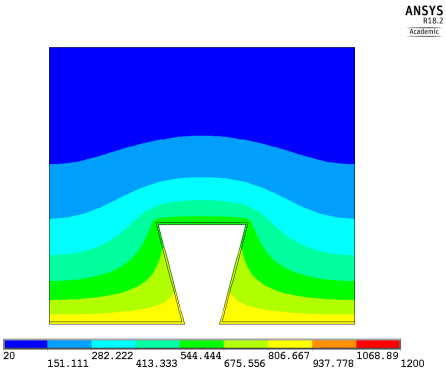
t = 25 min



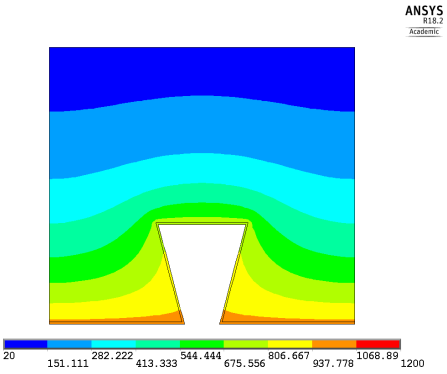
t = 51 min



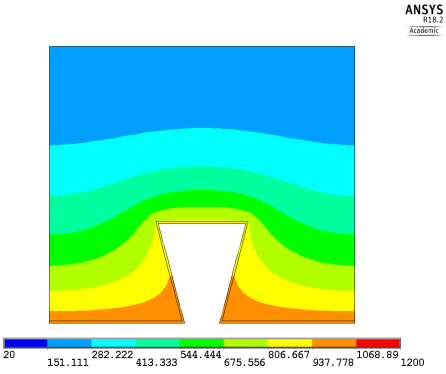
t = 76 min

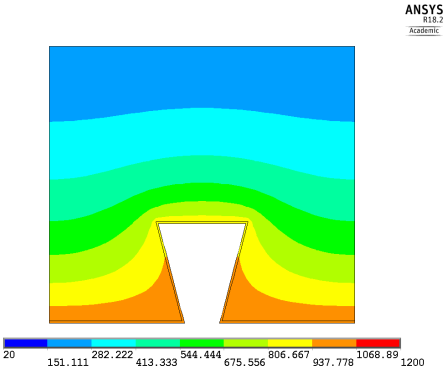


Tempo Crítico = 102 min



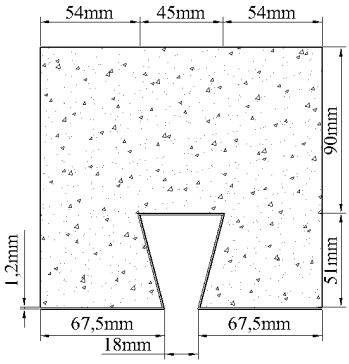
t = 7200s



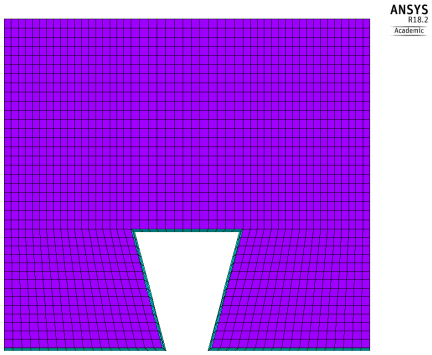


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 90mm E DECK DE AÇO DE 1.2mm

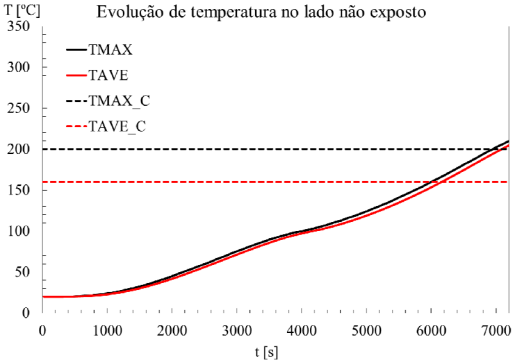
GEOMETRIA



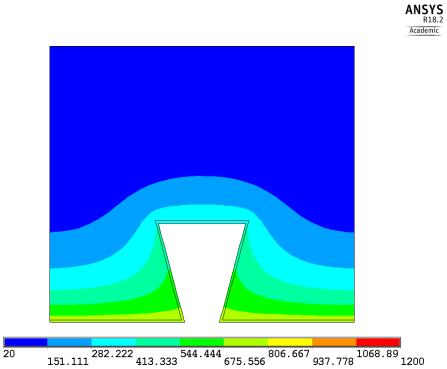
Malha



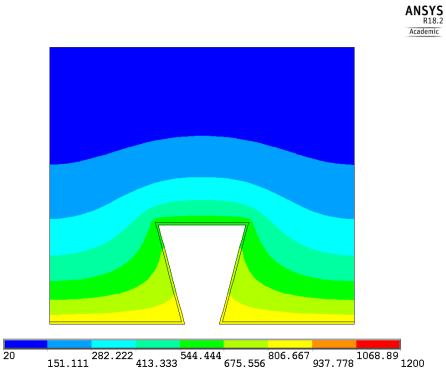
t = 25 min



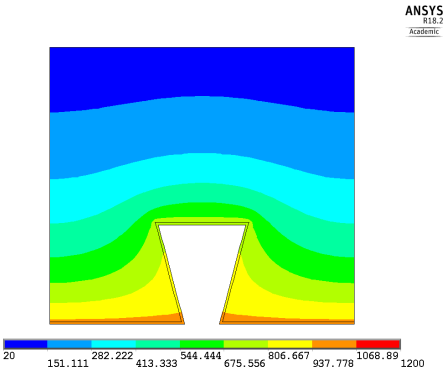
t = 51 min



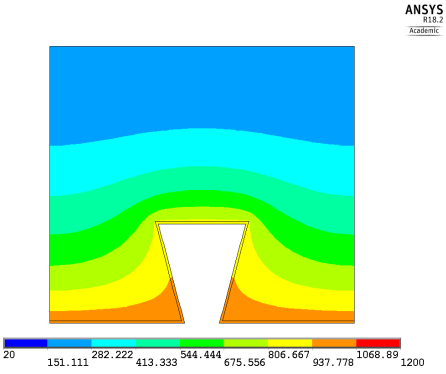
t = 76 min

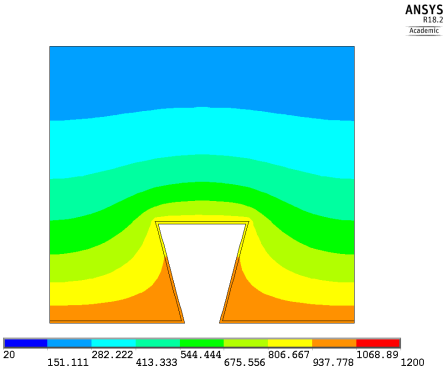


Tempo Crítico = 102 min



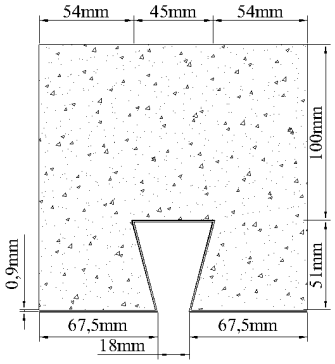
t = 7200s



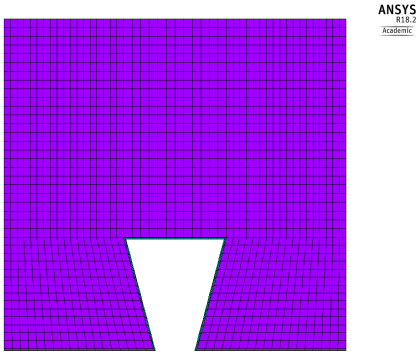


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 0.9mm

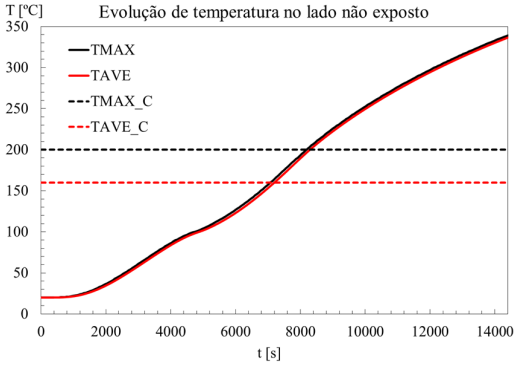
GEOMETRIA



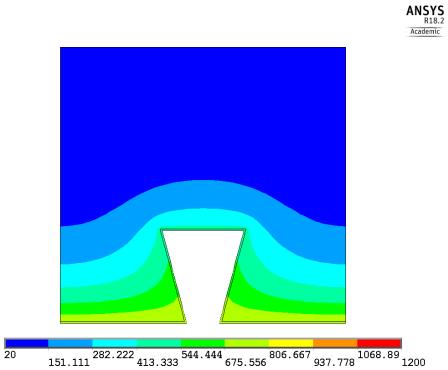
Malha



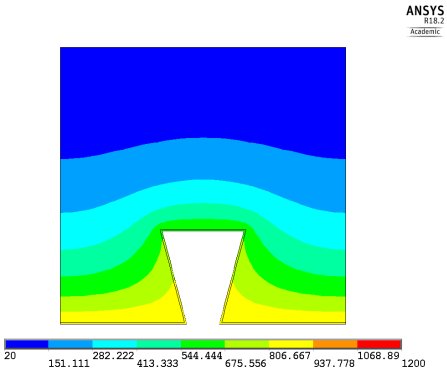
t = 30 min



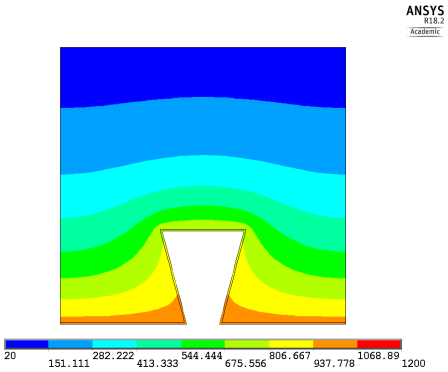
t = 60 min



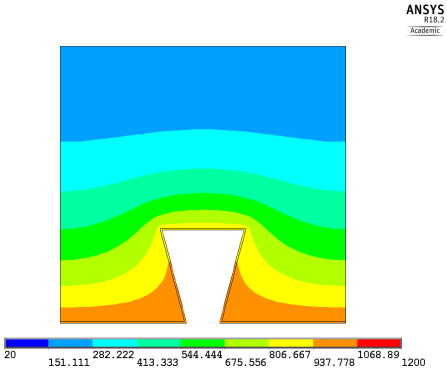
t = 90 min

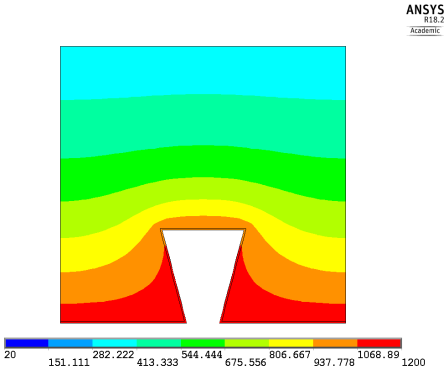


Tempo Crítico = 120 min



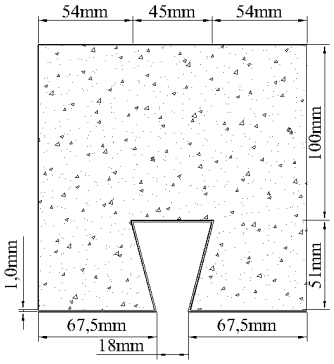
t = 7200s



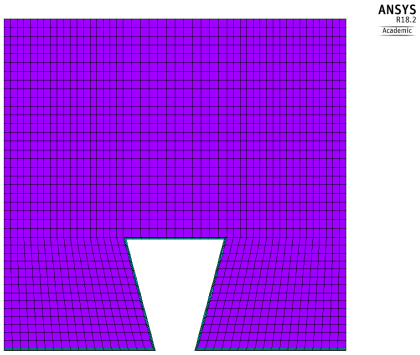


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.0mm

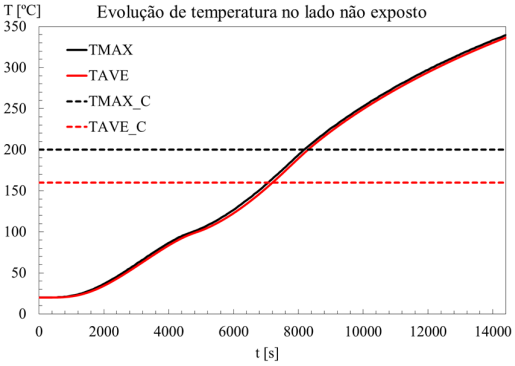
GEOMETRIA



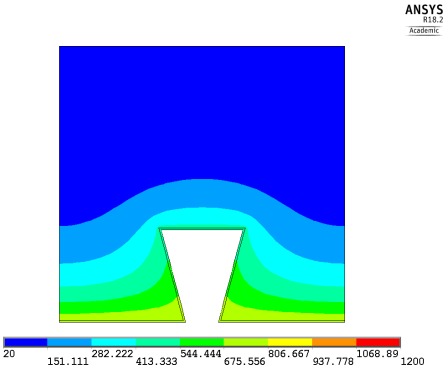
Malha



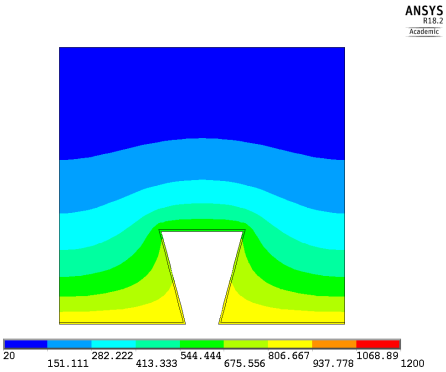
t = 29 min



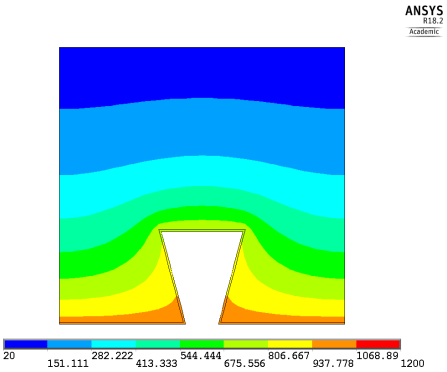
t = 59 min



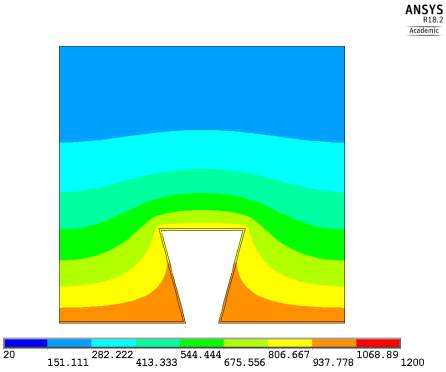
t = 89 min

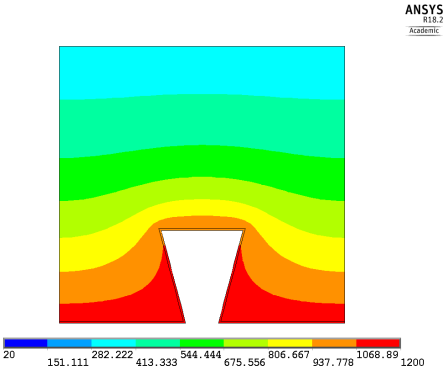


Tempo Crítico = 119 min



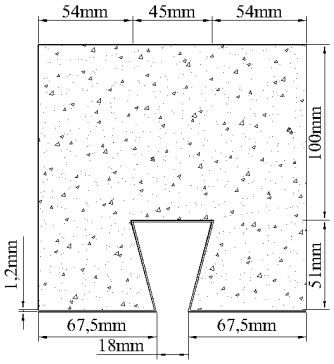
t = 7200s



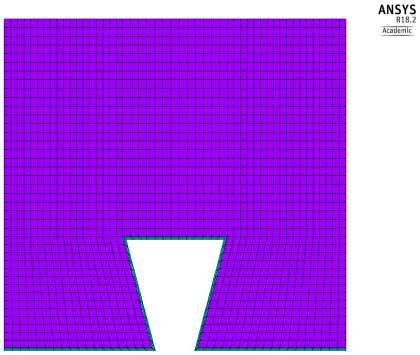


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 100mm E DECK DE AÇO DE 1.2mm

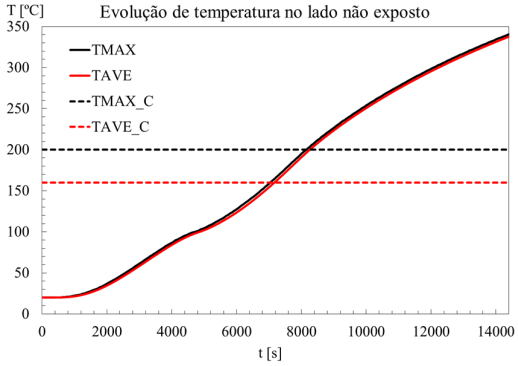
GEOMETRIA



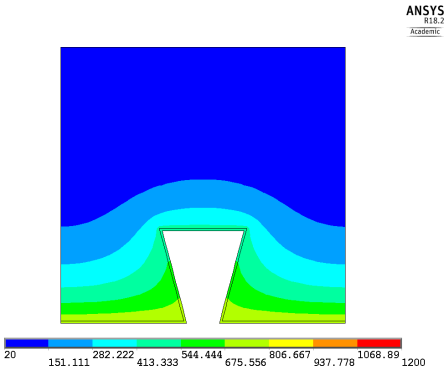
Malha



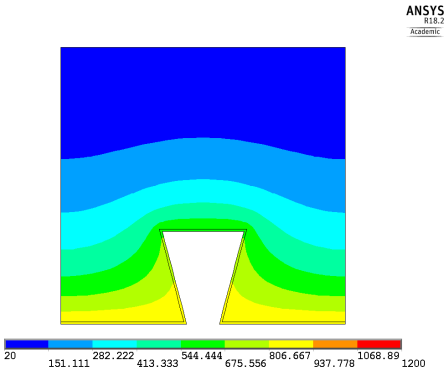
t = 29 min



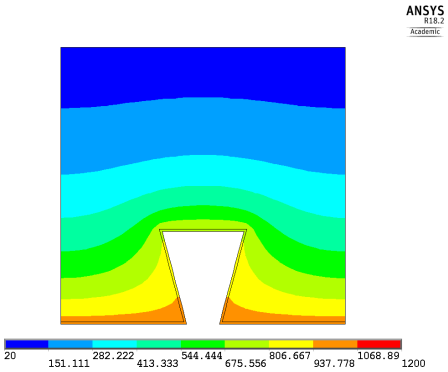
t = 59 min



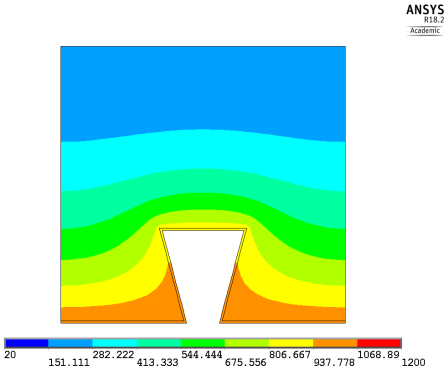
t = 89 min

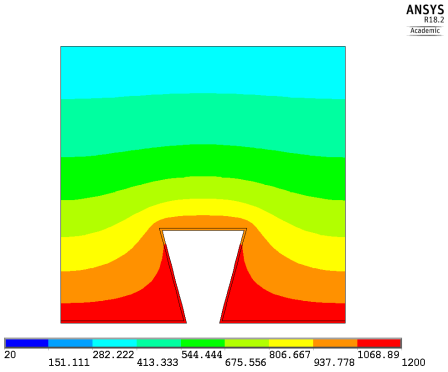


Tempo Crítico = 119 min



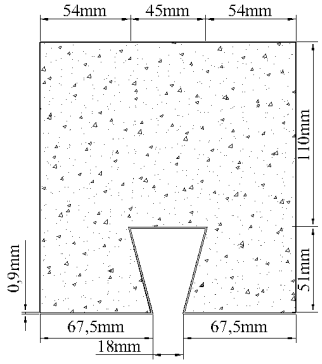
t = 7200s



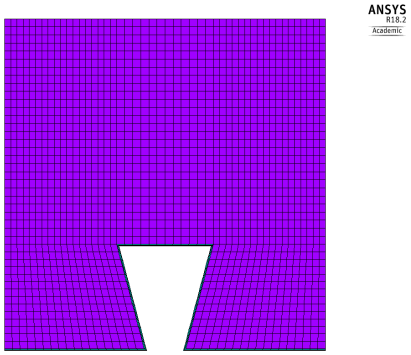


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 0.9mm

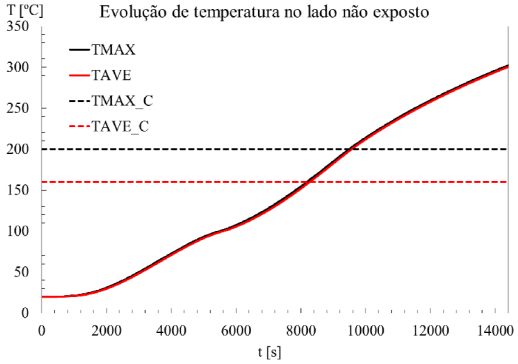
GEOMETRIA



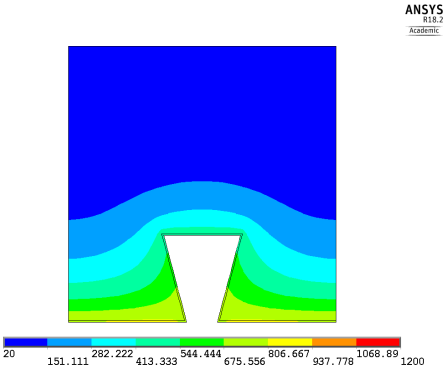
Malha



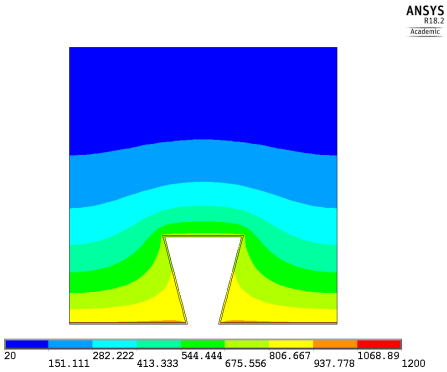
t = 34 min



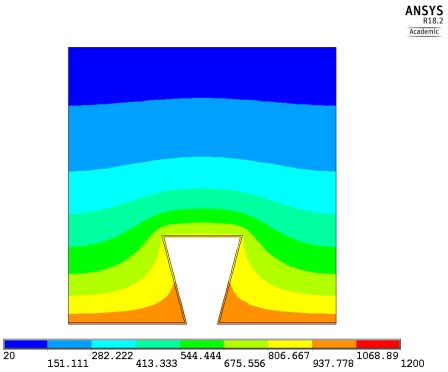
t = 69 min



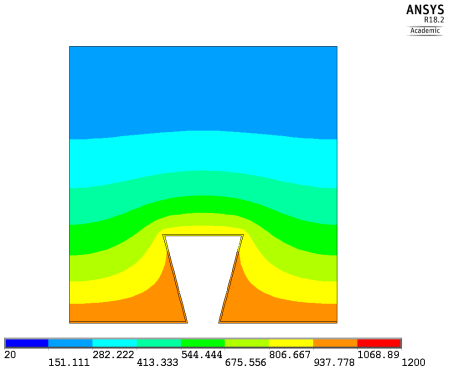
t = 103 min

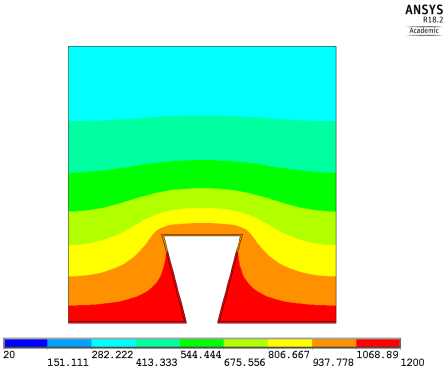


Tempo Crítico = 138 min



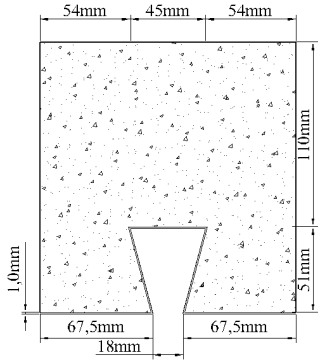
t = 7200s



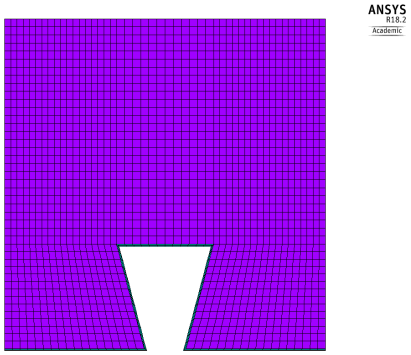


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.0mm

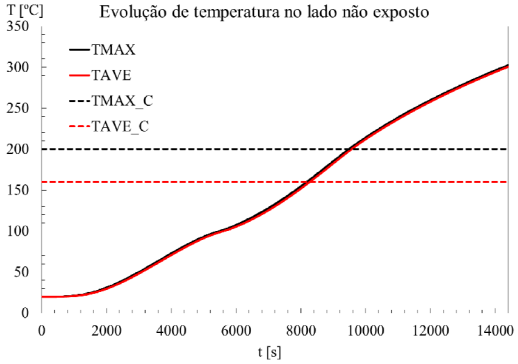
GEOMETRIA



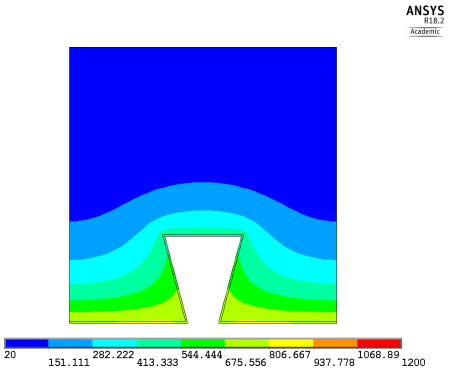
Malha



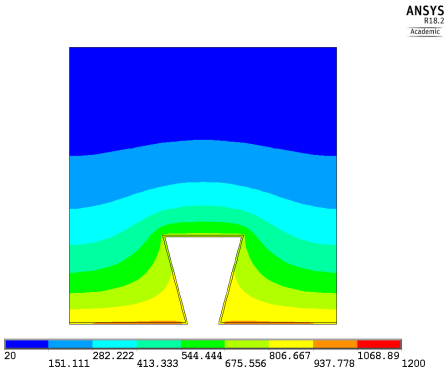
t = 34 min



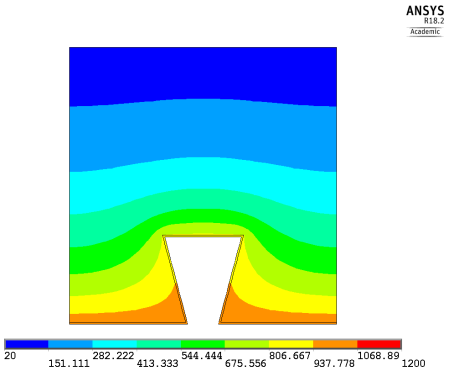
t = 68 min



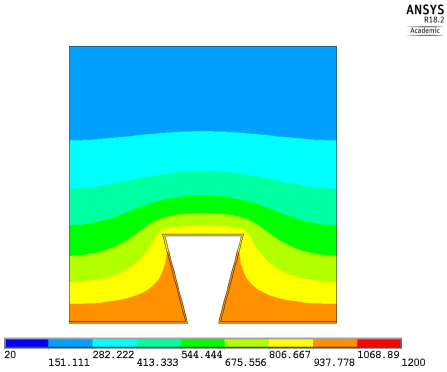
t = 102 min

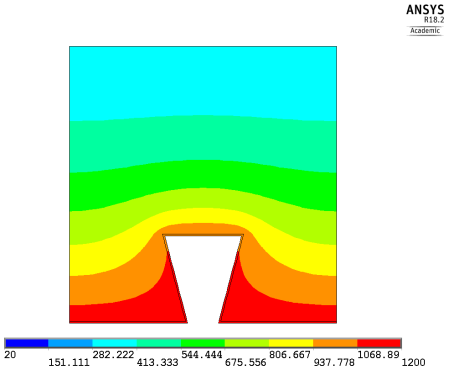


Tempo Crítico = 137 min



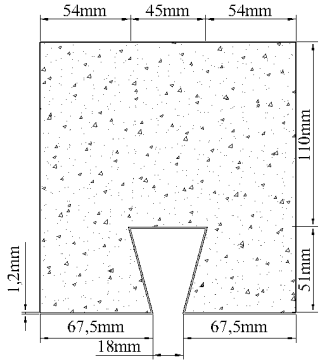
t = 7200s



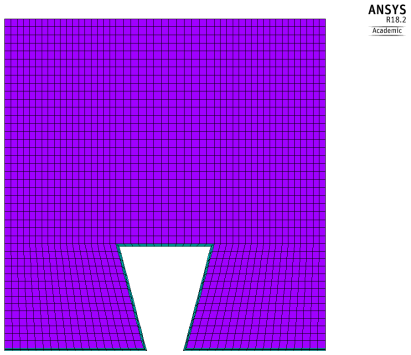


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 110mm E DECK DE AÇO DE 1.2mm

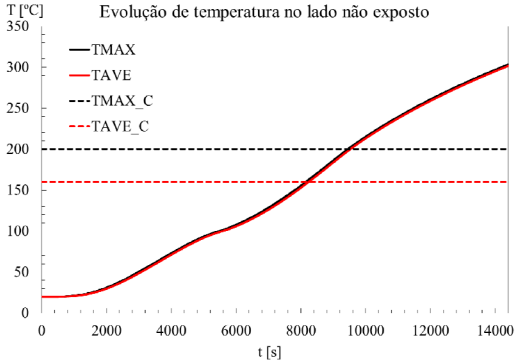
GEOMETRIA



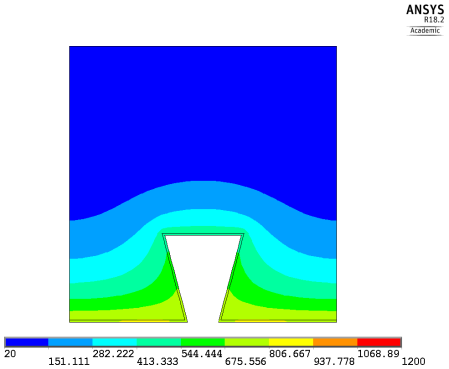
Malha



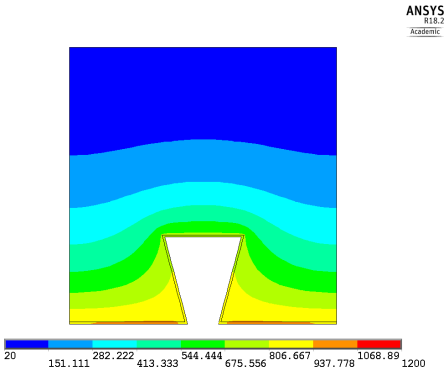
t = 34 min



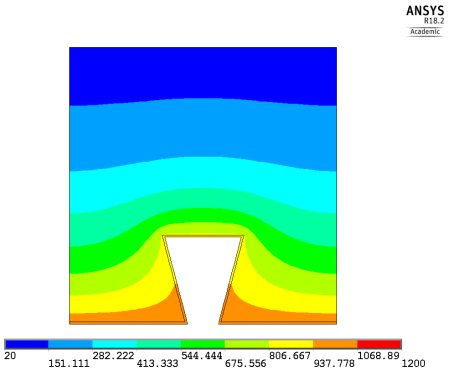
t = 68 min



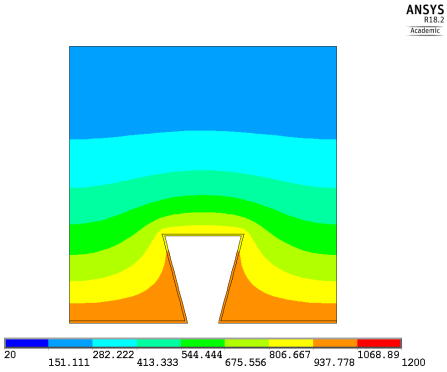
t = 102 min

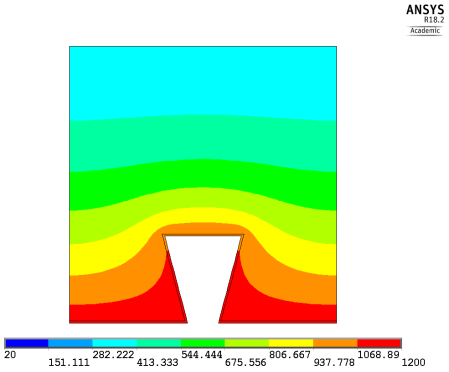


Tempo Crítico = 137 min



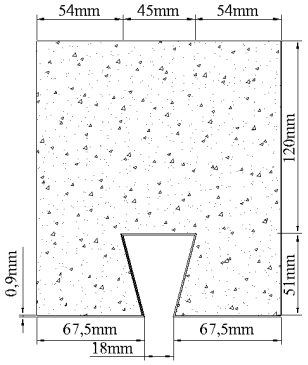
t = 7200s



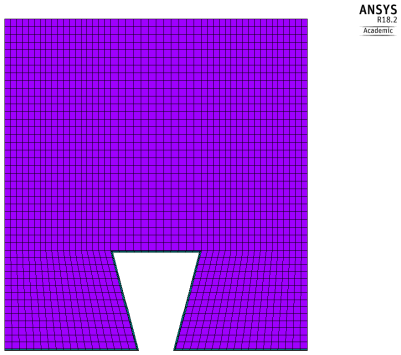


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 0.9mm

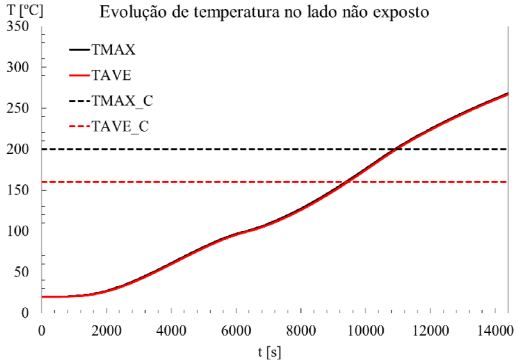
GEOMETRIA



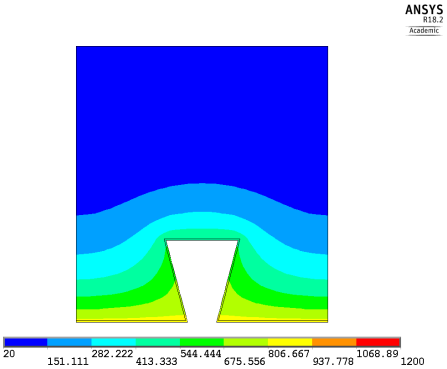
Malha



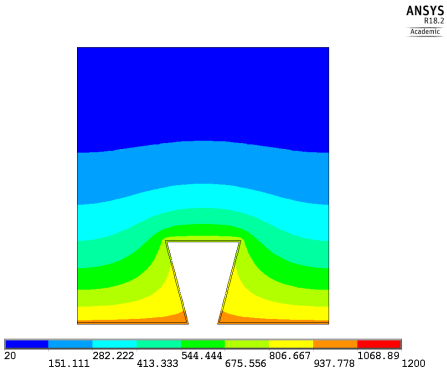
t = 39 min



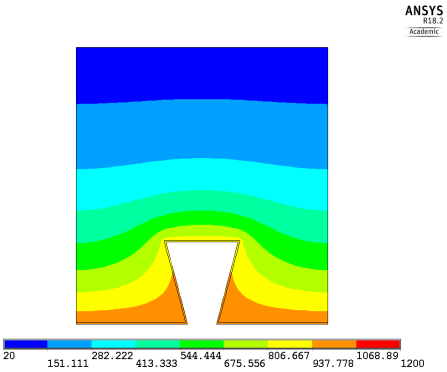
t = 78 min



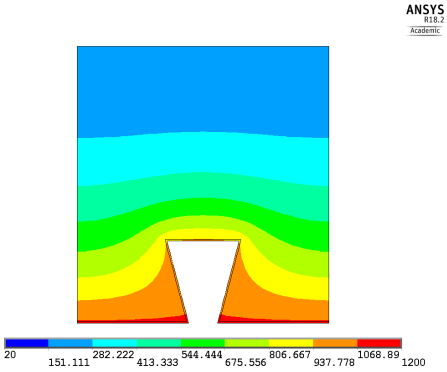
t = 117 min

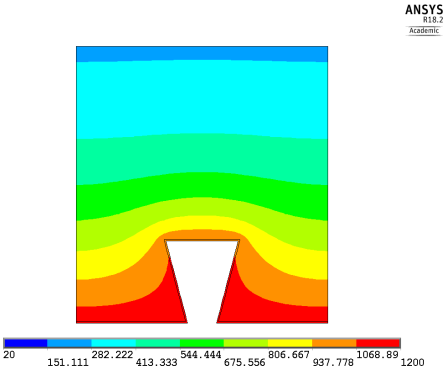


Tempo Crítico = 157 min



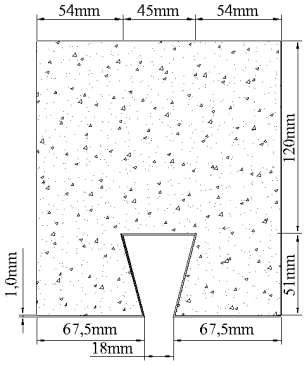
t = 7200s



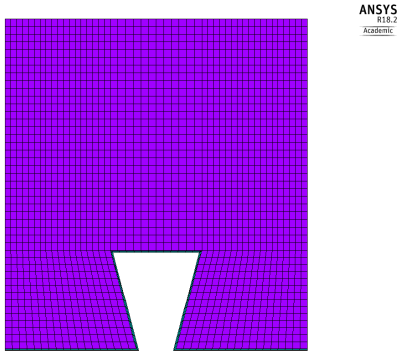


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.0mm

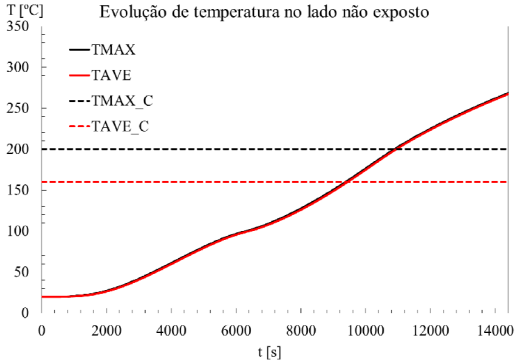
GEOMETRIA



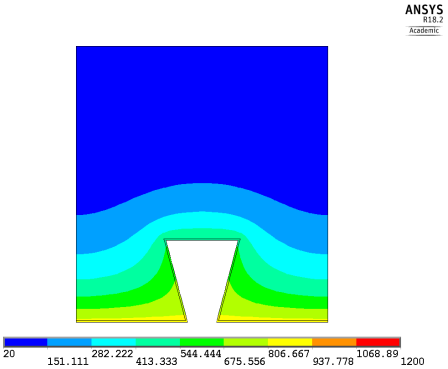
Malha



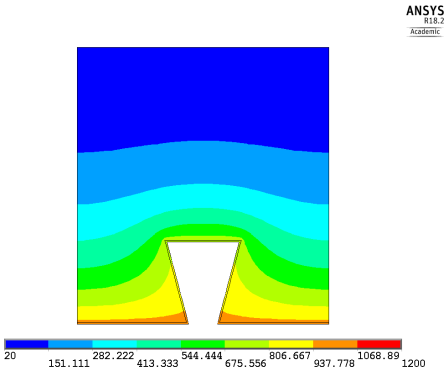
t = 39 min



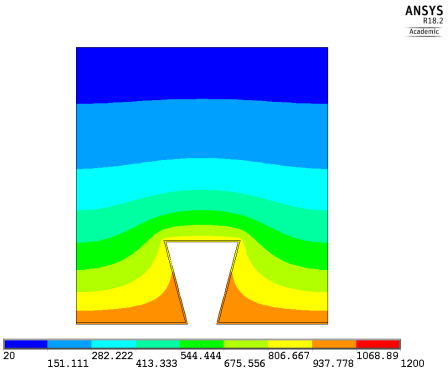
t = 78 min



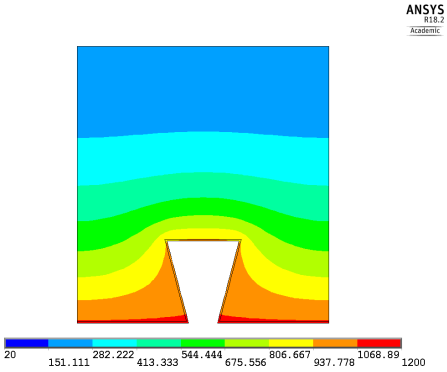
t = 117 min

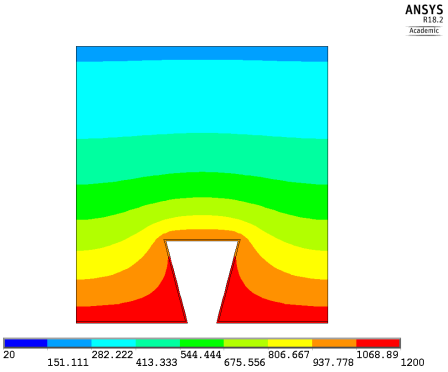


Tempo Crítico = 156 min



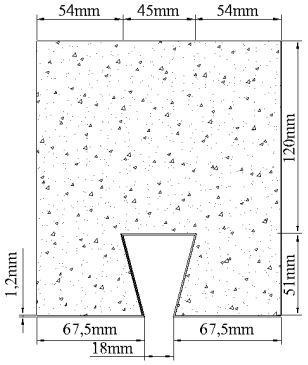
t = 7200s



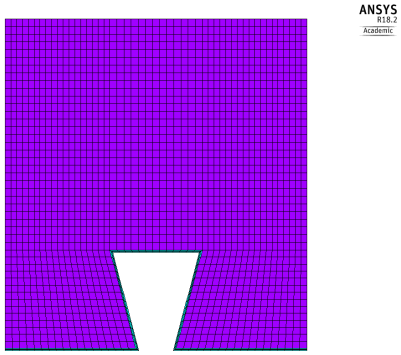


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 120mm E DECK DE AÇO DE 1.2mm

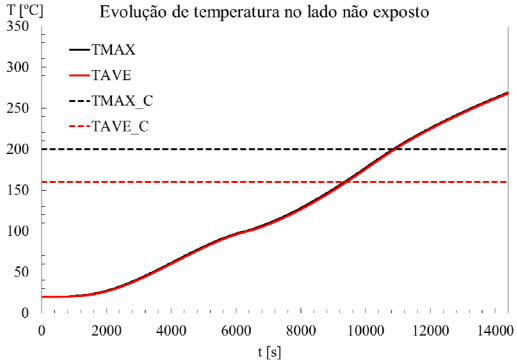
GEOMETRIA



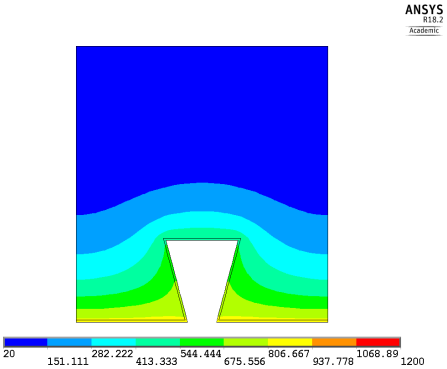
Malha



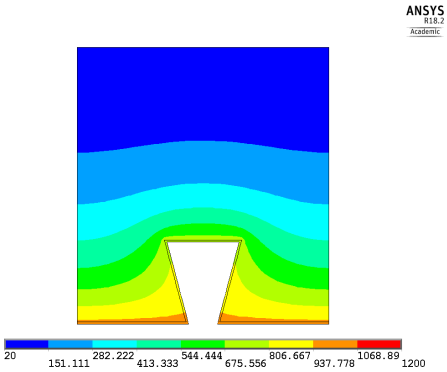
t = 39 min



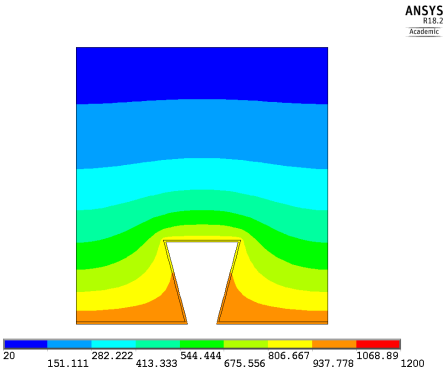
t = 78 min



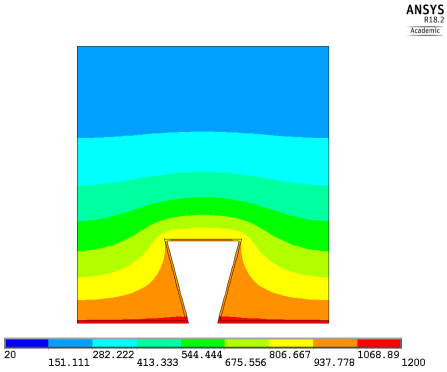
t = 117 min

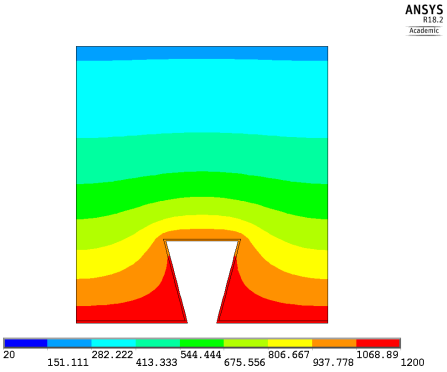


Tempo Crítico = 156 min



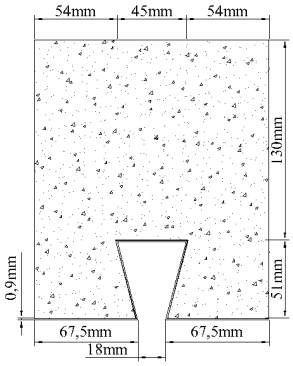
t = 7200s



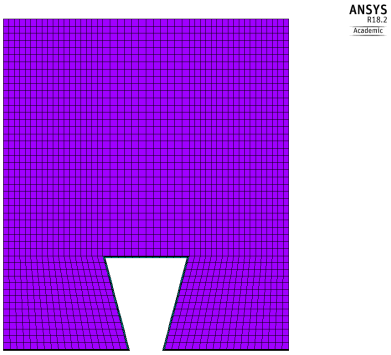


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 0.9mm

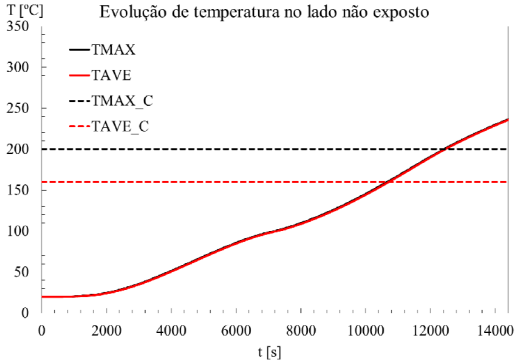
GEOMETRIA



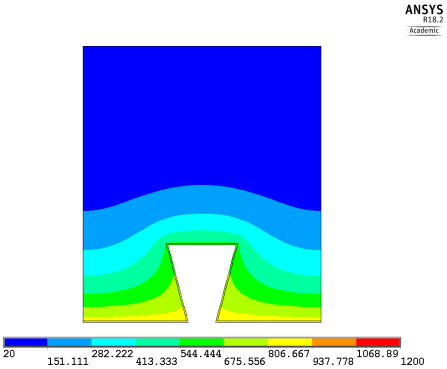
Malha



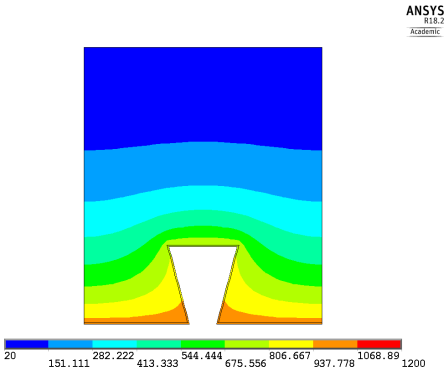
t = 44 min



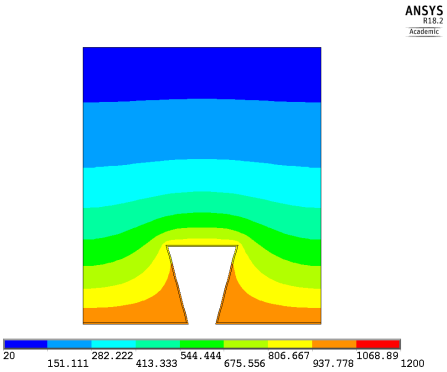
t = 89 min



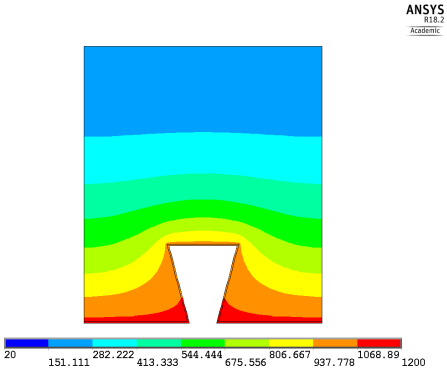
t = 133 min

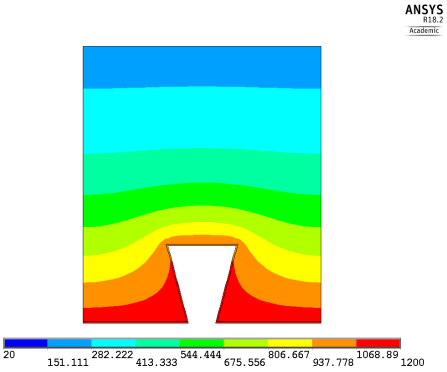


Tempo Crítico = 178 min



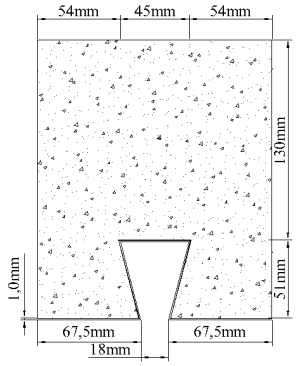
t = 7200s



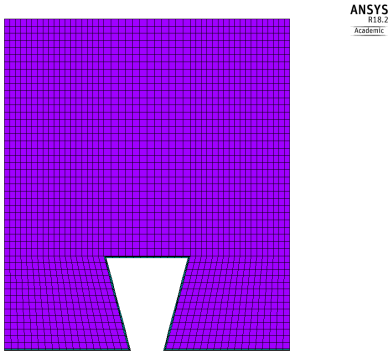


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.0mm

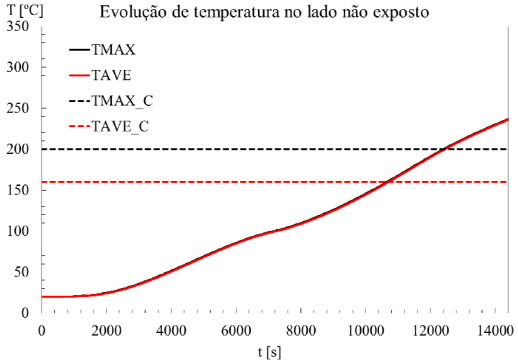
GEOMETRIA



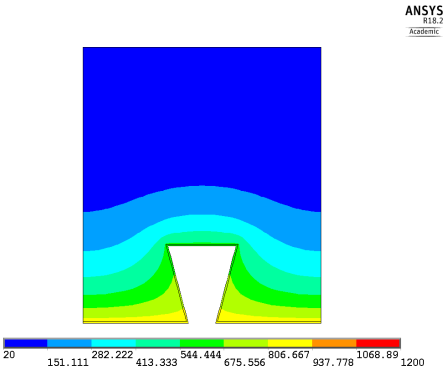
Malha



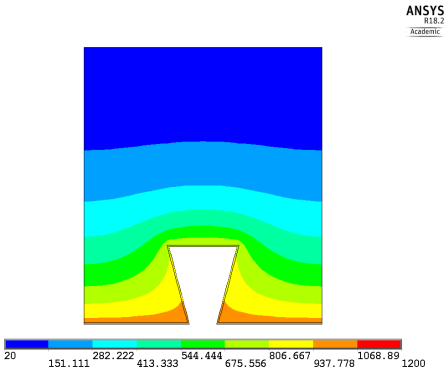
t = 44 min



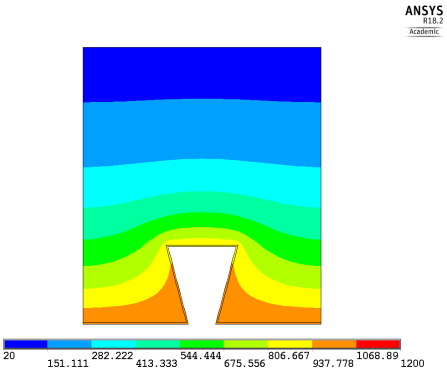
t = 88 min



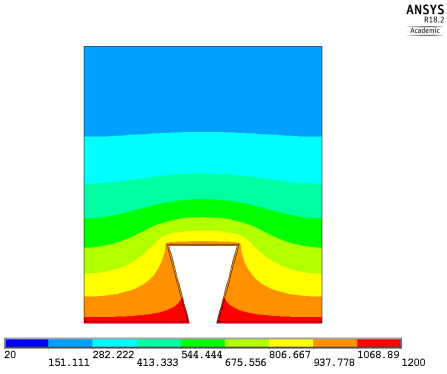
t = 132 min

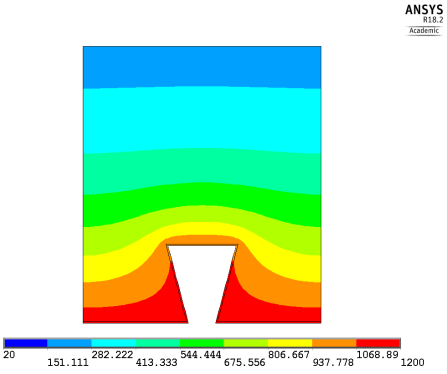


Tempo Crítico = 177 min



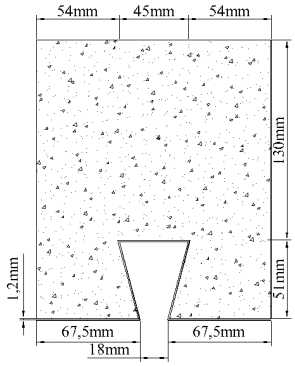
t = 7200s



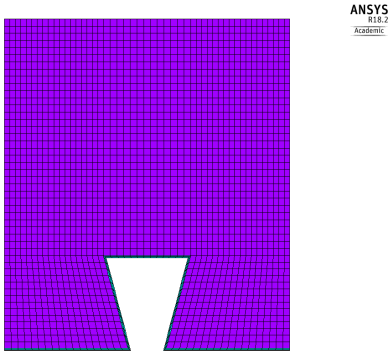


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 130mm E DECK DE AÇO DE 1.2mm

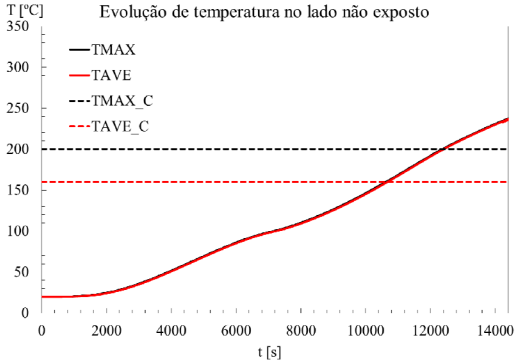
GEOMETRIA



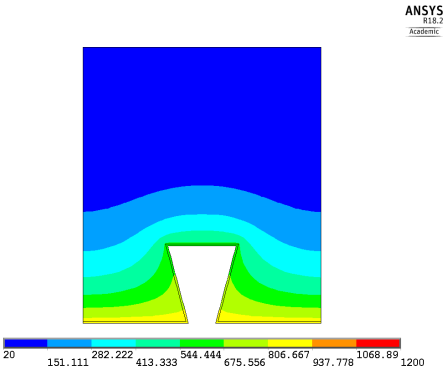
Malha



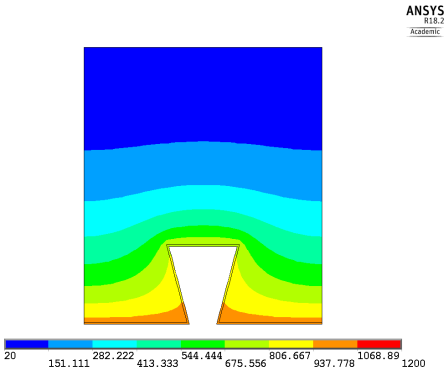
t = 44 min



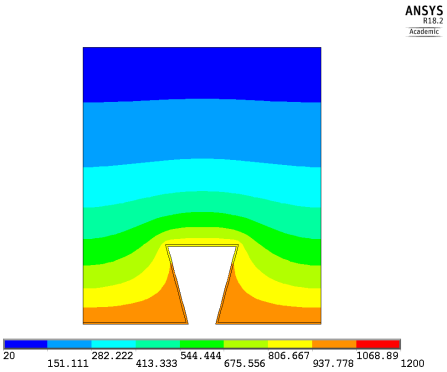
t = 88 min



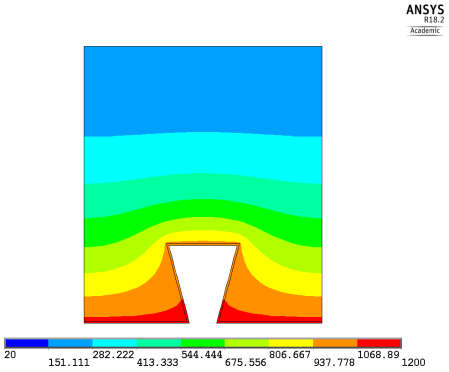
t = 132 min

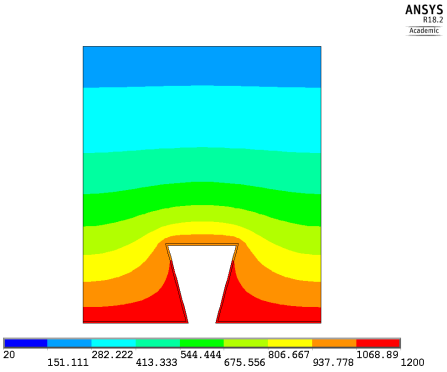


Tempo Crítico = 177 min



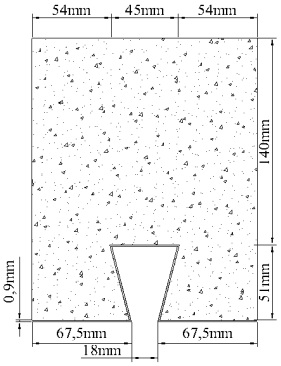
t = 7200s



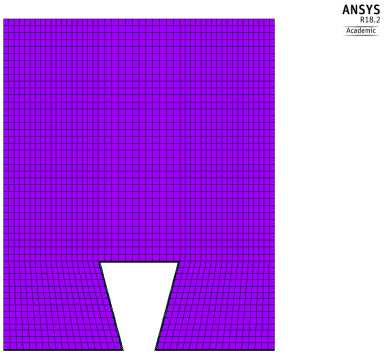


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 0.9mm

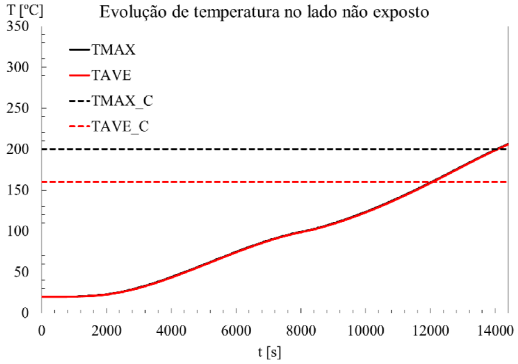
GEOMETRIA



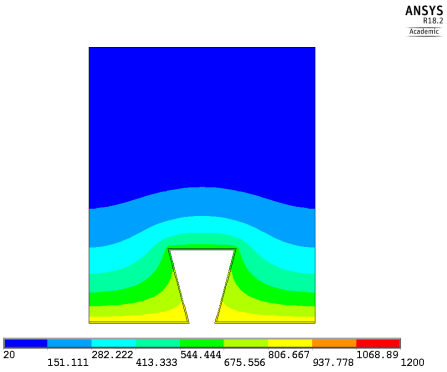
Malha



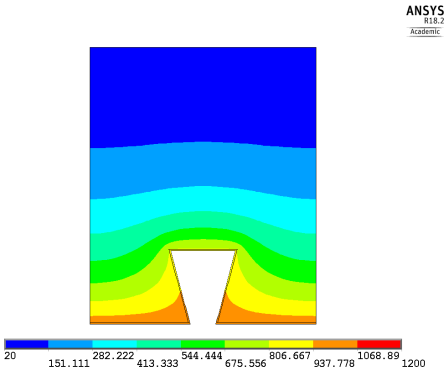
t = 50 min



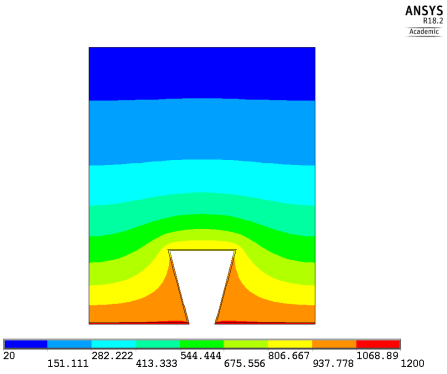
t = 100 min



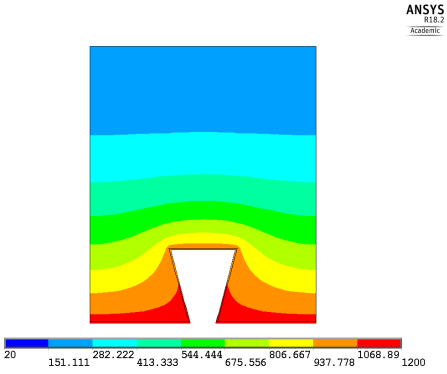
t = 150 min

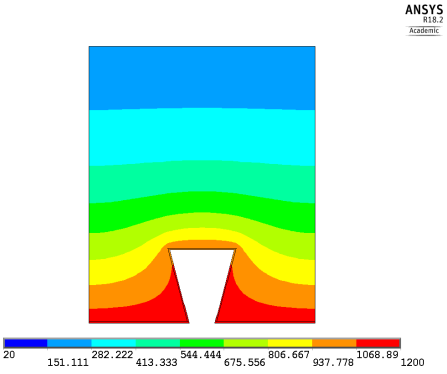


Tempo Crítico = 201 min



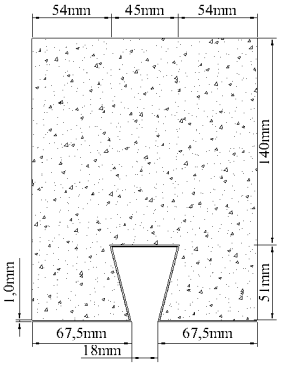
t = 7200s



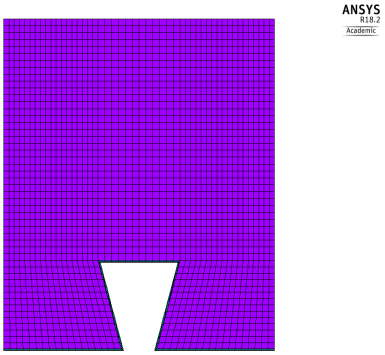


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.0mm

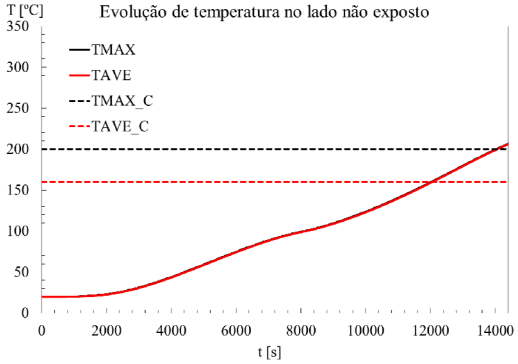
GEOMETRIA



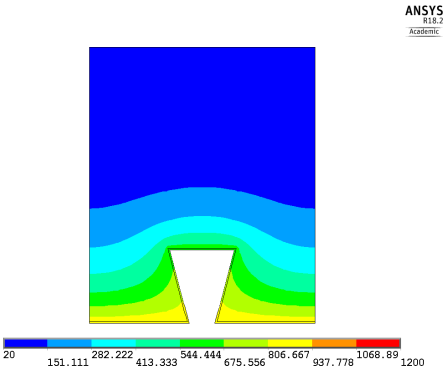
Malha



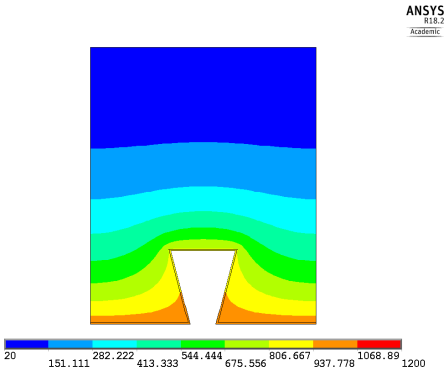
t = 50 min



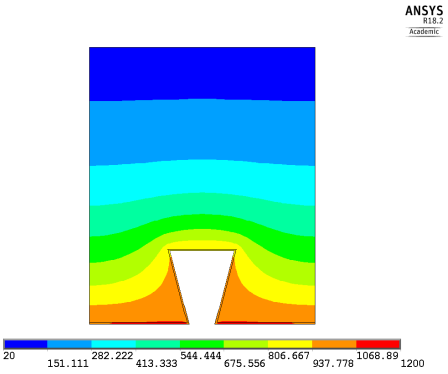
t = 100 min



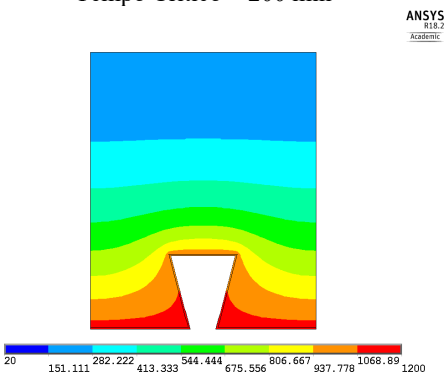
t = 150 min

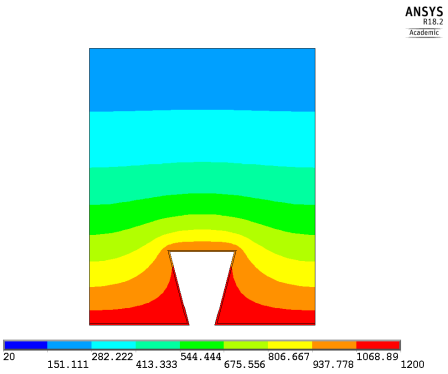


Tempo Crítico = 200 min



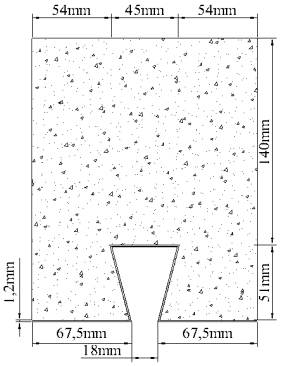
t = 7200s



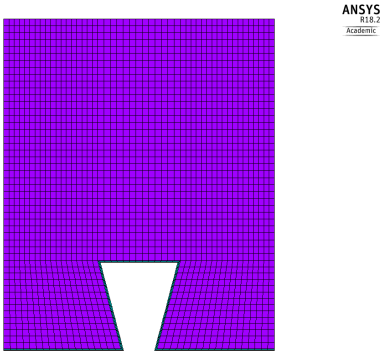


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 140mm E DECK DE AÇO DE 1.2mm

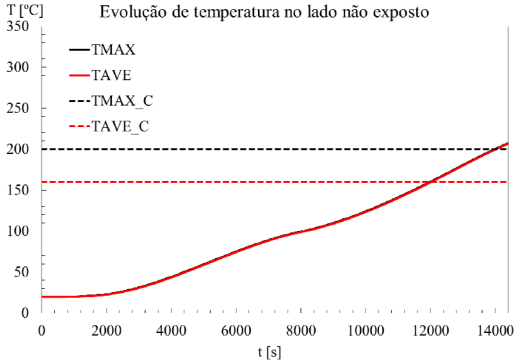
GEOMETRIA



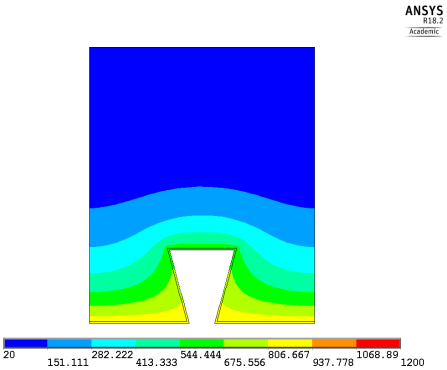
Malha



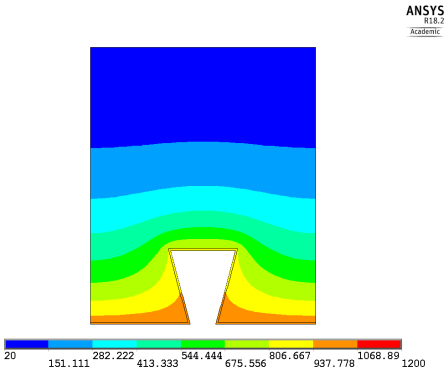
t = 50 min



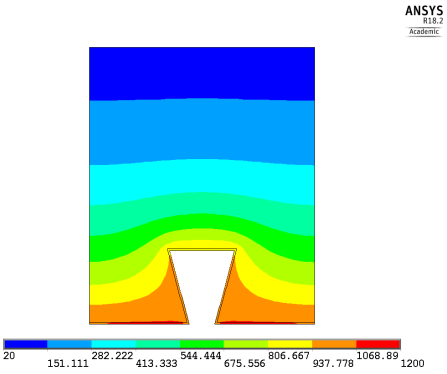
t = 100 min



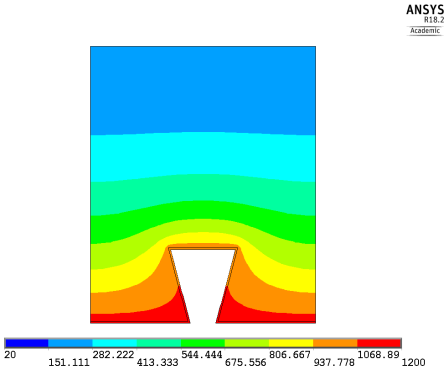
t = 150 min

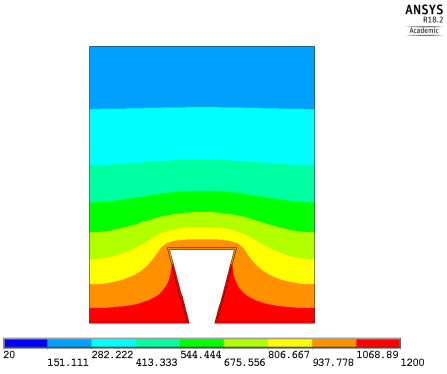


Tempo Crítico = 200 min



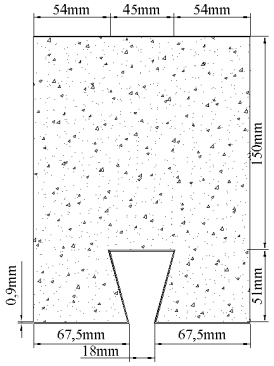
t = 7200s



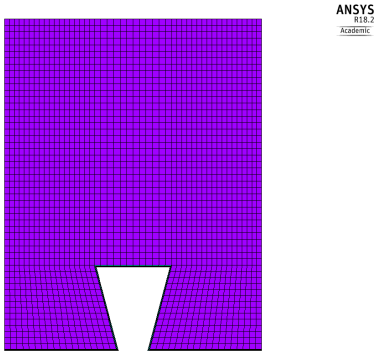


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 0.9mm

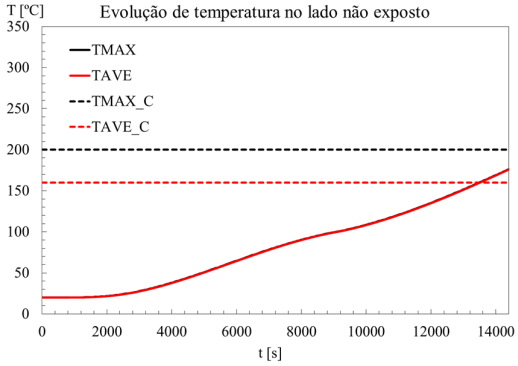
GEOMETRIA



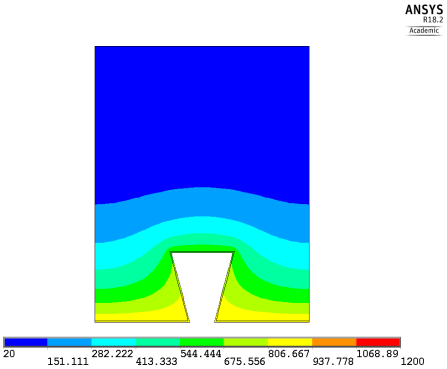
Malha



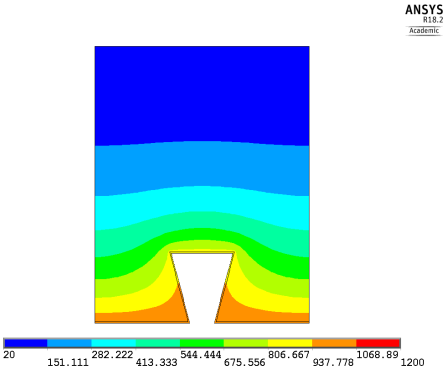
t = 56 min



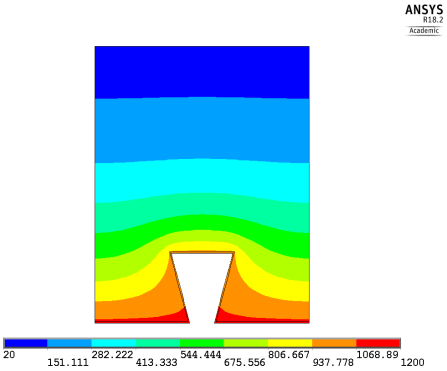
t = 112 min



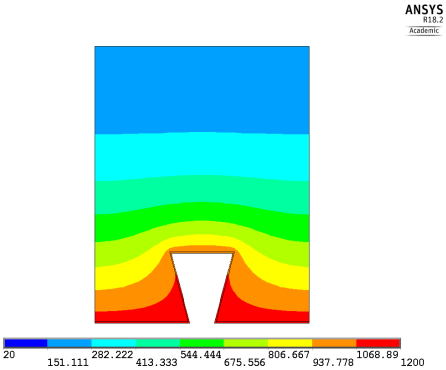
t = 168 min

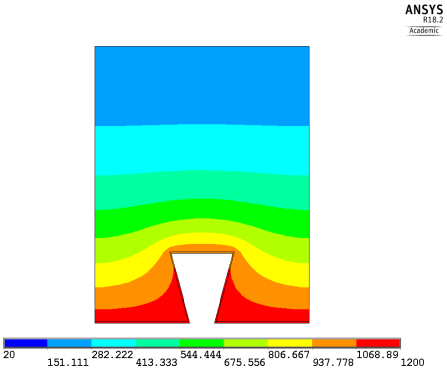


Tempo Crítico = 225 min



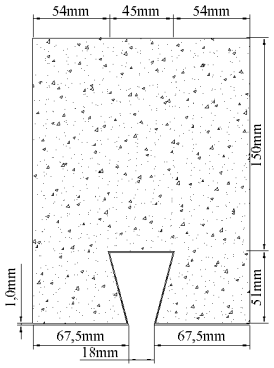
t = 7200s



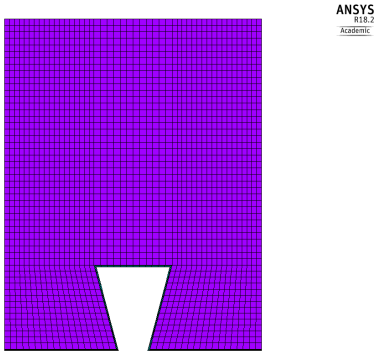


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.0mm

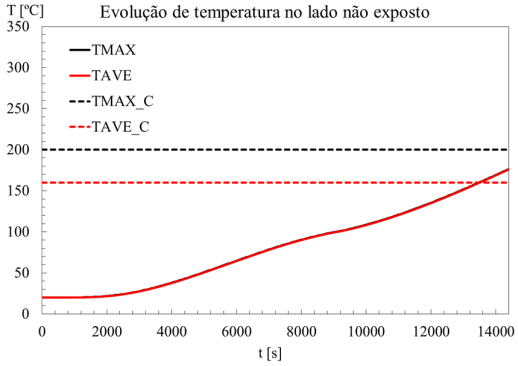
GEOMETRIA



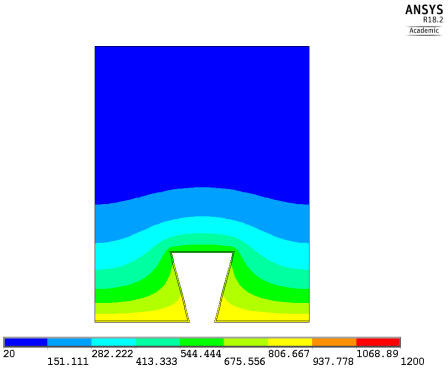
Malha



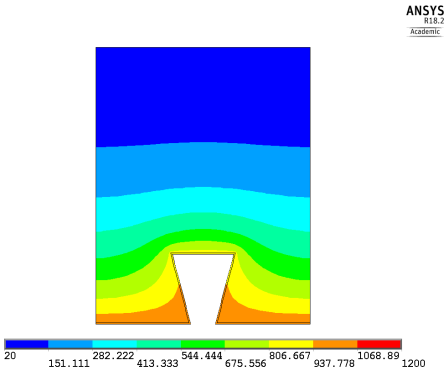
t = 56 min



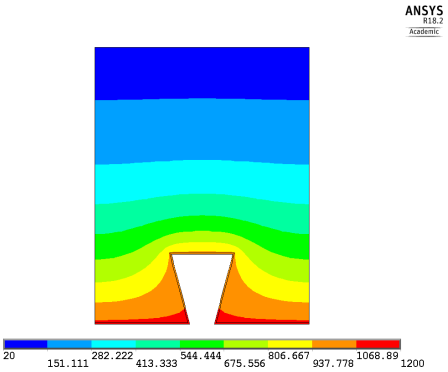
t = 112 min



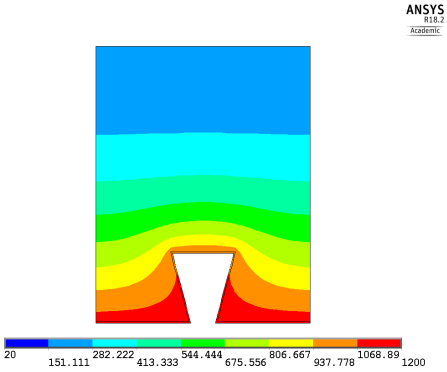
t = 168 min

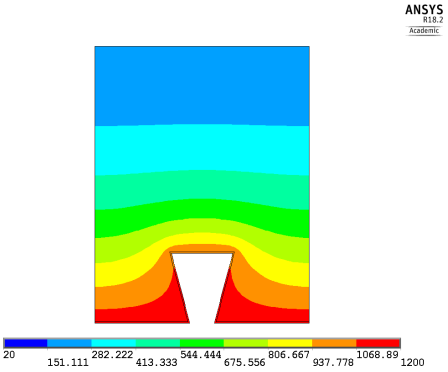


Tempo Crítico = 224 min



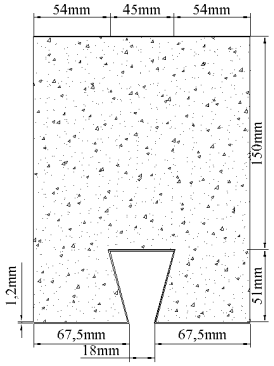
t = 7200s



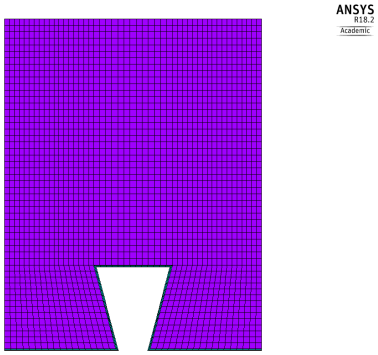


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 150mm E DECK DE AÇO DE 1.2mm

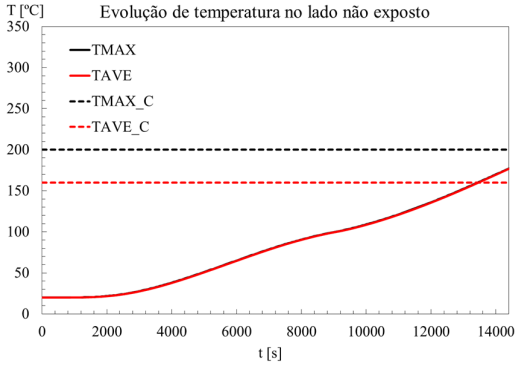
GEOMETRIA



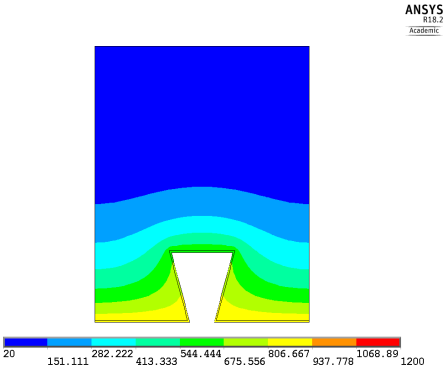
Malha



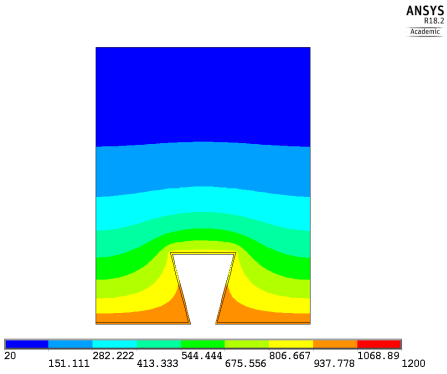
t = 56 min



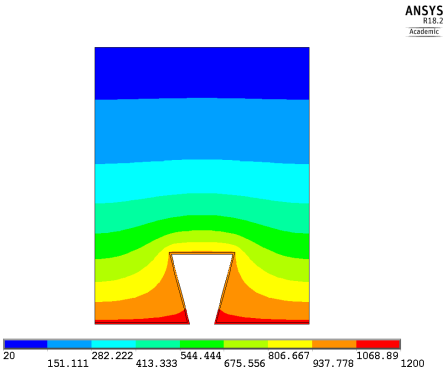
t = 112 min



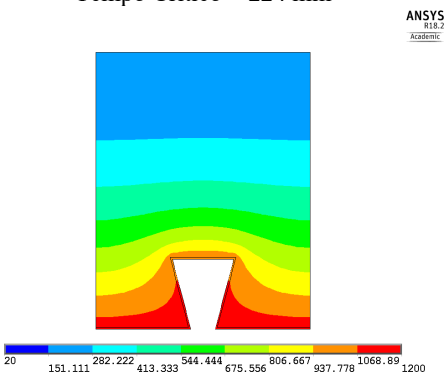
t = 168 min

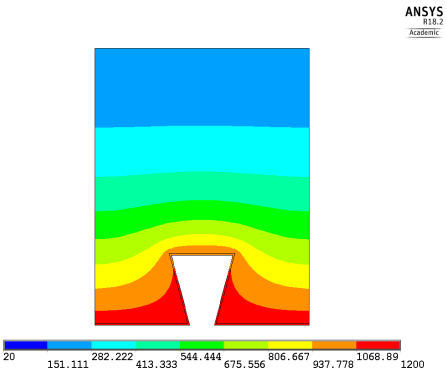


Tempo Crítico = 224 min



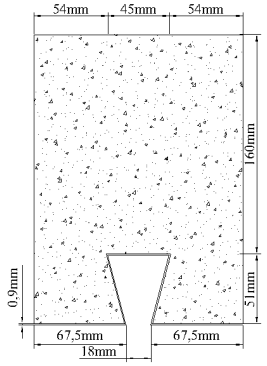
t = 7200s



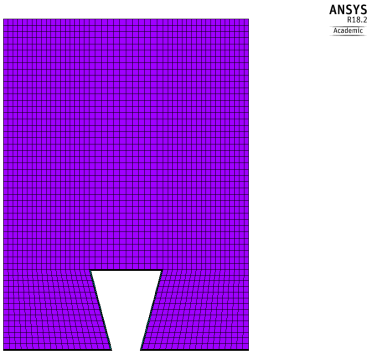


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 0.9mm

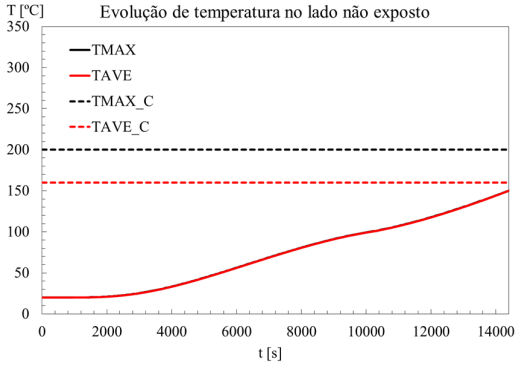
GEOMETRIA



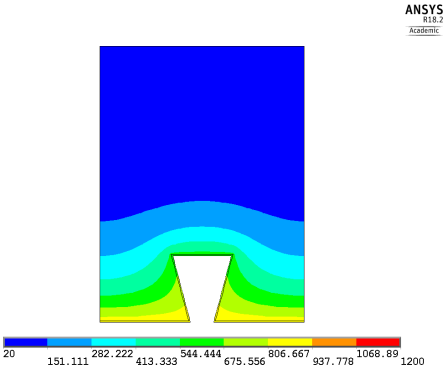
Malha



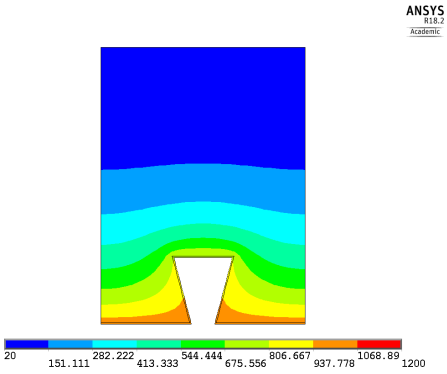
t = 48 min



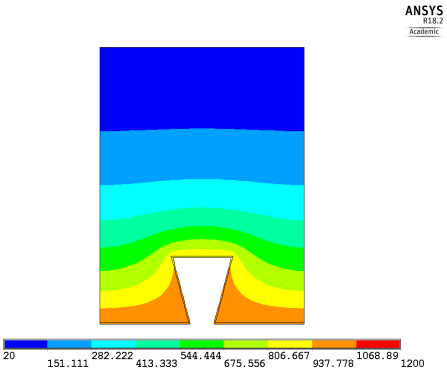
t = 96 min



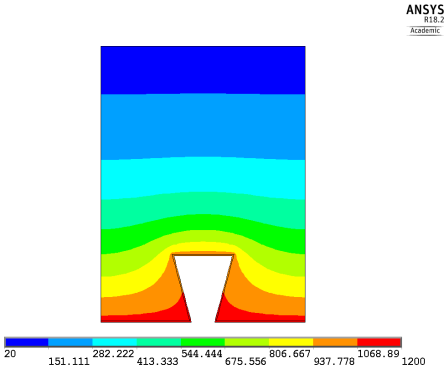
t = 144 min

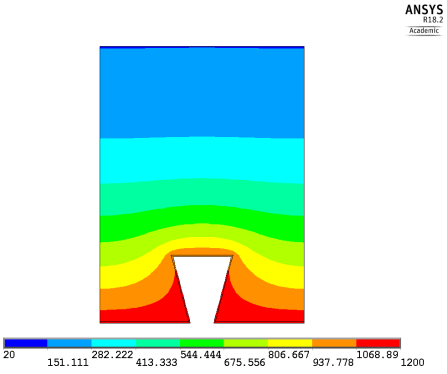


t = 192 min



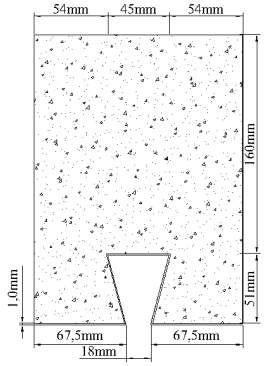
t = 14400 s



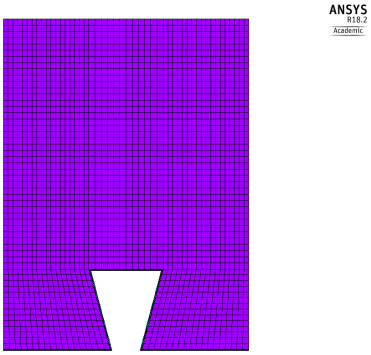


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.0mm

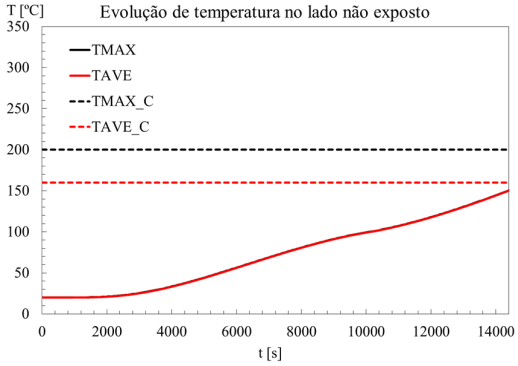
GEOMETRIA



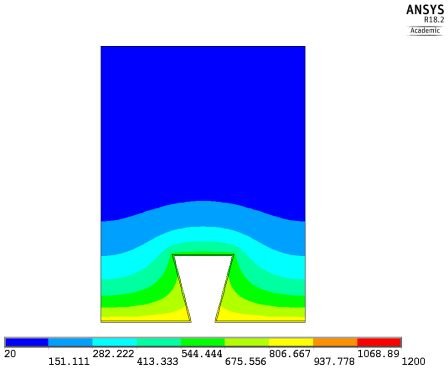
Malha



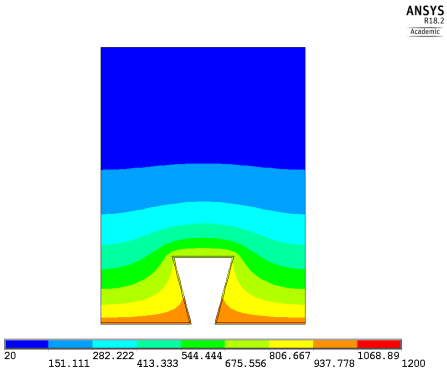
t = 48 min



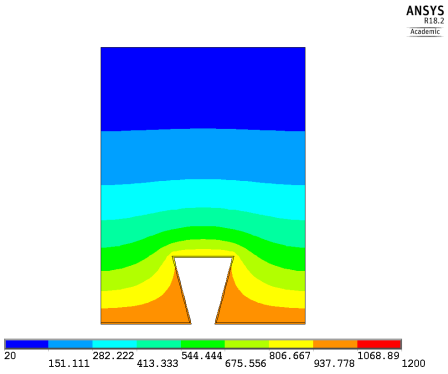
t = 96 min



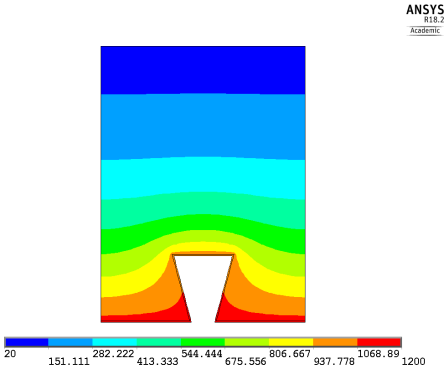
t = 144 min

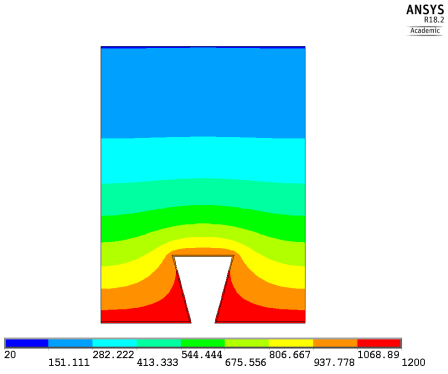


t = 192 min



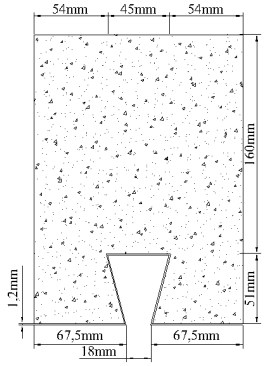
t = 14400 s



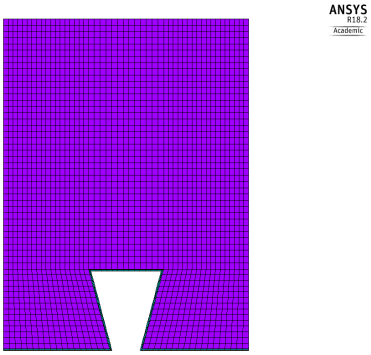


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 160mm E DECK DE AÇO DE 1.2mm

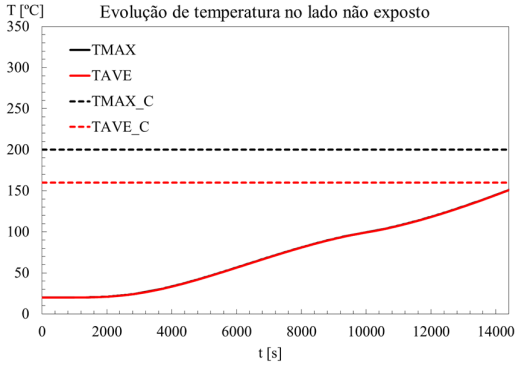
GEOMETRIA



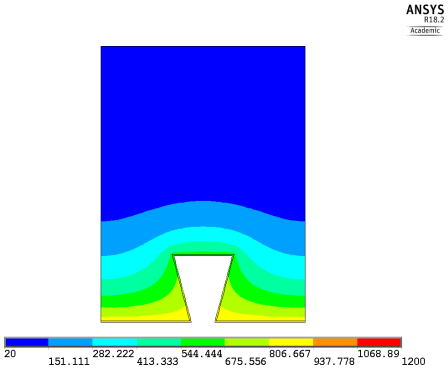
Malha



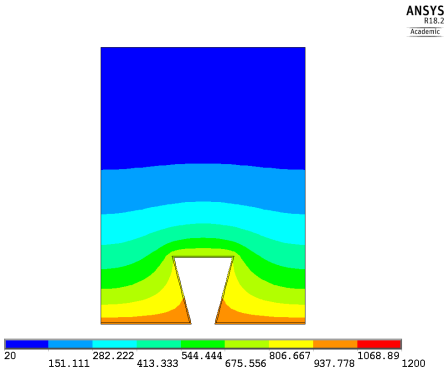
t = 48 min



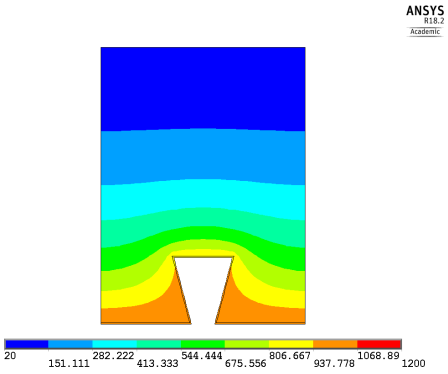
t = 96 min



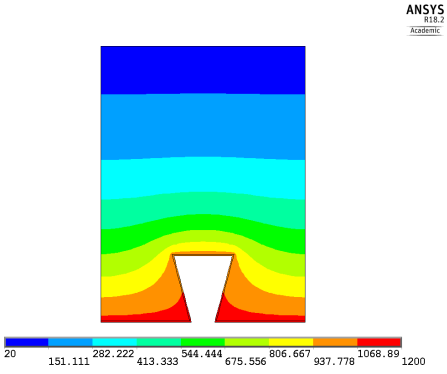
t = 144 min

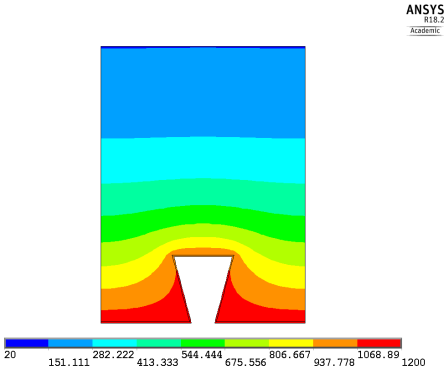


t = 192 min



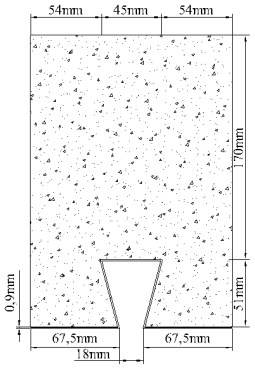
t = 14400 s



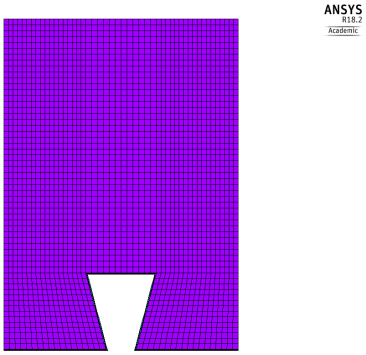


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 0.9mm

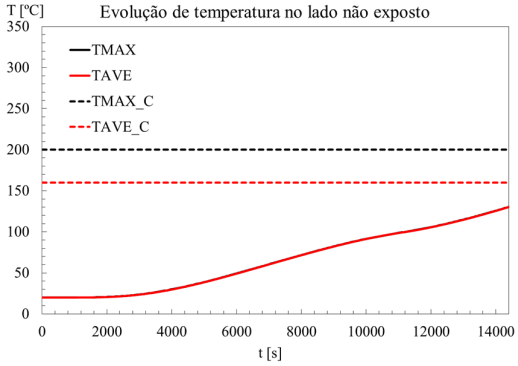
GEOMETRIA



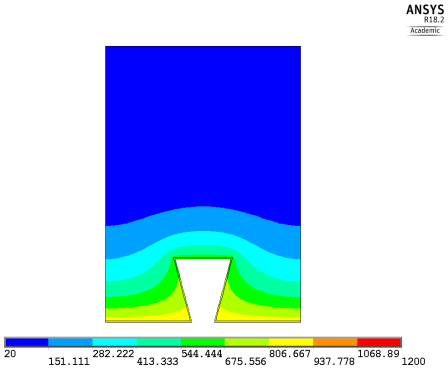
Malha



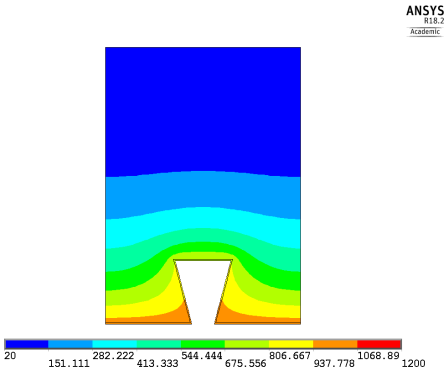
t = 48 min



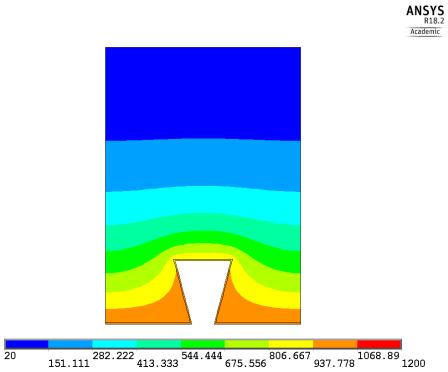
t = 96 min



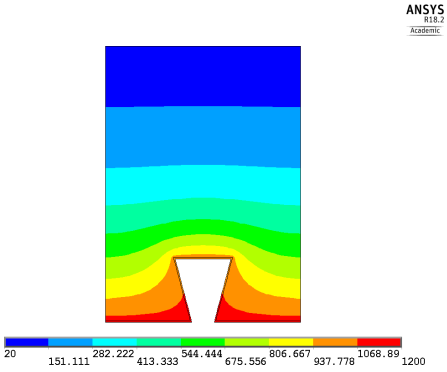
t = 144 min

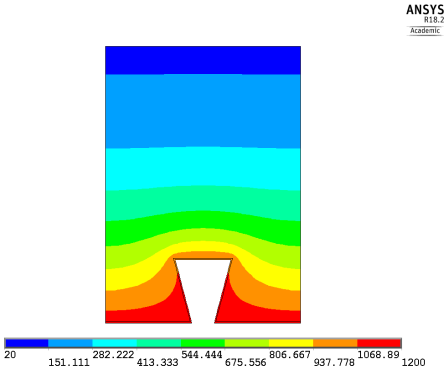


t = 192 min



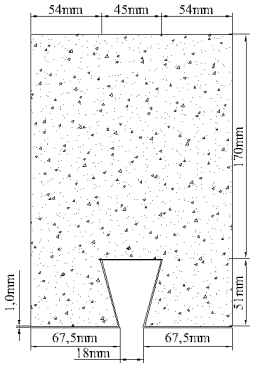
t = 14400 s



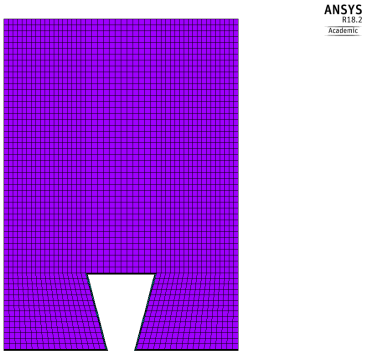


LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.0mm

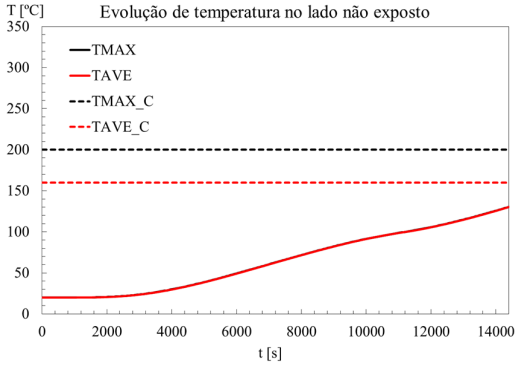
GEOMETRIA



Malha



t = 48 min



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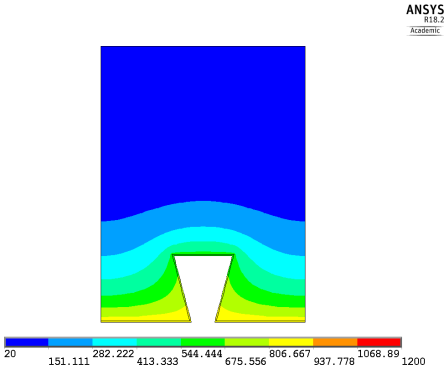

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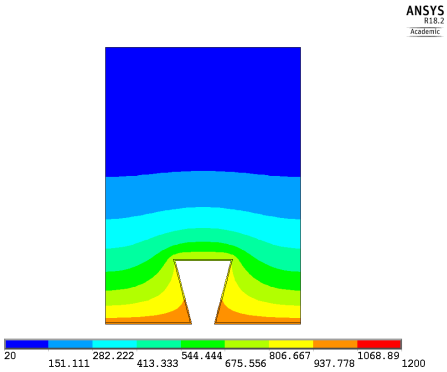
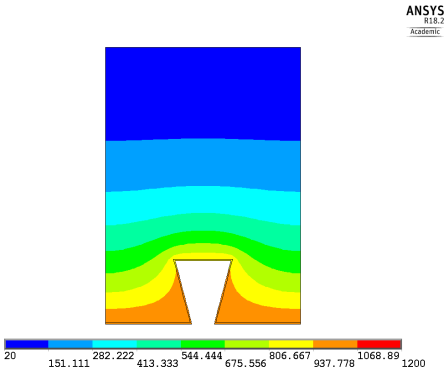


t = 192 min



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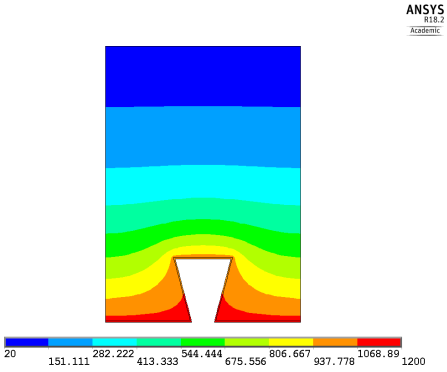
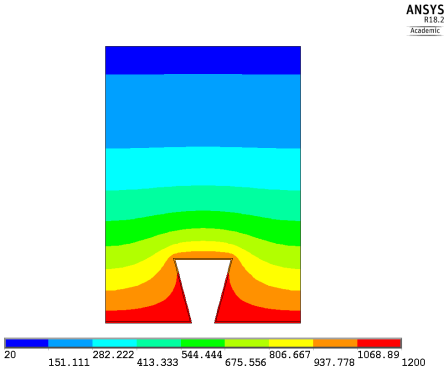
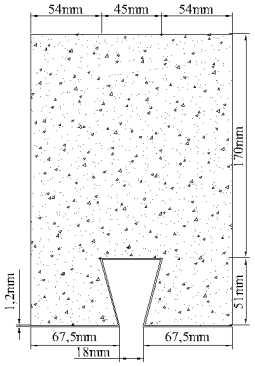




LAJE MISTA REENTRANTE (L1/L2=108/135mm/mm), CONCRETO DE 170mm E DECK DE AÇO DE 1.2mm

GEOMETRIA



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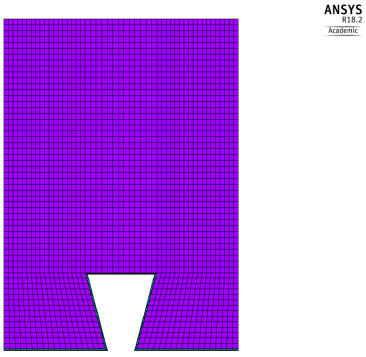

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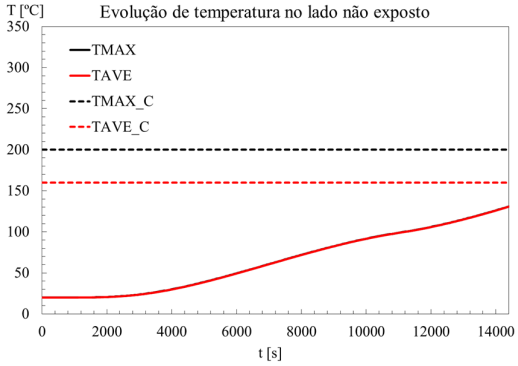

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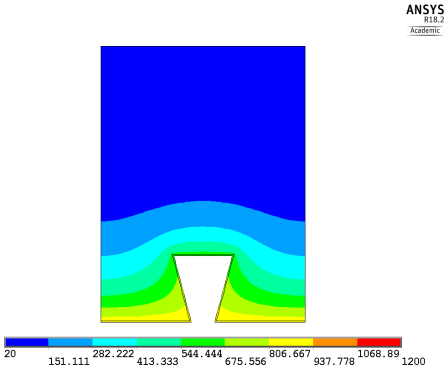

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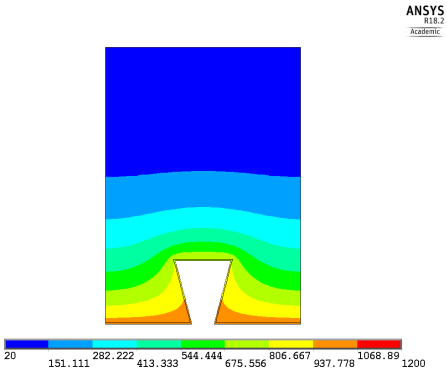

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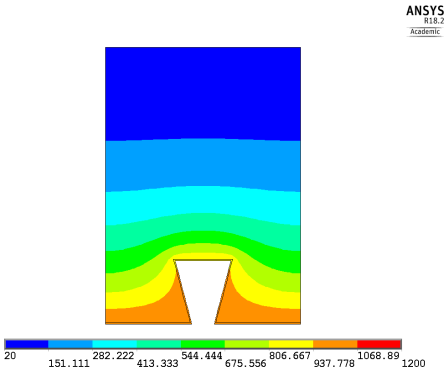

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