CILASCI

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5º CONGRESSO IBERO-LATINO-AMERICANO EM SEGURANÇA CONTRA INCÊNDIOS

5th IBERIAN-LATIN-AMERICAN CONGRESS ON FIRE SAFETY

15-17 /07/ 2019 - Porto, Portugal

Atas dos Artigos
Proceedings (full papers)

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U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

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PREFACE

The Iberian-Latin American Congress on Fire Safety (CILASCI) is held once every two years, with the aim of disseminating scientific and technical knowledge in the field of fire safety, integrating different players involved in this area of knowledge. The first edition of the Iberian-Latin American Congress on Fire Safety (CILASCI 1), was held in Natal (Brazil) between 10-12 March 2011. The second congress (CILASCI 2) was held in Coimbra (Portugal), between May 29 and June 1, 2013. The 3rd and 4th editions took place on the South American continent. The third congress (CILASCI 3) was held in Porto Alegre (Brazil) from November 3 to 6, 2015, while the fourth congress (CILASCI 4) was held in Recife (Brazil) from 9 to 11 October 2017. The CILASCI 5 will take place in the city of Porto (Portugal) from 15 to 17 July 2019, and presents 5 invited lectures and 78 manuscripts (full papers) from researchers around the world (Algeria, Australia, Belgium, Brazil, China, Czech Republic, France, Hong Kong, Italy, Mozambique, Portugal, Spain, United Kingdom and United States).

the 5th Iberian-Latin-American congress on fire safety reflects the new developments achieved on active and passive fire protection, on evacuation and human behaviour under fire, on computational modelling of structures and materials under fire, on explosion and risk management, on architectural issues for fire safety in buildings, on fire dynamics, on the experimental analysis of materials and structures under fire, on fires in special buildings and spaces, on fire-fighting operations and equipments, and on the behaviour of structures and materials under fire.

The Fire Safety is reaching new developments as a result of new research, development and innovation around the world, based on the excellence level of the research, the support of new skilled professionals and due to the existence of advanced training programmes in fire science technology. This development will increase the safety level of people, buildings, and products, but also is going to produce an impact in the economy of each country, with a positive impact on society.

The organizing committee believe that this congress will address to our delegates a wide forum of discussion about the recent developments in Fire Safety, promoting the exchange of ideas and international cooperation.

The organizing Committee would like to thanks to all authors and delegates.

On the behalf of the Organizing Committe
Paulo A. G. Piloto

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NUMERICAL VALIDATION OF THE FIRE PERFORMANCE OF FIRE FIGHTER CLOTHING AND EXPERIMENTAL TESTS



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Keywords: Radiant heat; Fire fighter; Protective clothing; Heat transfer.

1. INTRODUCTION

The Fire Protection Clothe (FPC) of firefighters have been investigated over the last years in several terms to improve the safety of their users. FPC are designed to save the firefighters from excessive heat and fire conditions, allowing for a period of time, usually required for a rescue mission, fighting fire, or withdrawing from direct flame contact. The FPC fabrics are design in order to settle a certain degree of comfort to firefighters when exposed to accidental conditions. The heat source, intensity of fire, time of exposure, and other variables affect the protection performance of the FPC. The FPC is a multilayer assembly composed of various types of woven and nonwoven fabrics. Conventional fibres such as cotton, wool, and viscose and high-performance fibres such as aramid, polybenzimidazole, and polybenzoxazole (PBO) are used in FPC [1].

The FPC of firefighters has traditionally been a multilayer fabric containing an outer shell, moisture barrier, thermal liner and sometimes an inner layer. The outer shell fabric should protect the firefighters from fire in flash-fire conditions or when entering into a fire compartment. It needs to have sufficient tensile strength with acceptable abrasion and cut resistance. The fibre used for the outer layer is usually selected from a high-performance flame-retardant fibre. The purpose of the moisture barrier is to include breathability in FPC. This barrier protects the inner side from liquid water while it allows the moisture vapor to pass through it. Firefighters will be protected from

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hot water while the sweat can be vaporized and dissipated to the external side. The thermal liner may contain a nonwoven attached to a face cloth or can be independent. The thermal liner is the most critical part in the fabric’s multilayer, because it has the biggest impact on thermal protection.

Different Investigations have been conducted to test the fabrics and also to evaluate the fire effect into the human skin. In 1971, Alice Stoll et al. [2] presented an experimental investigation to determine the temperature along the fabrics and skin, using a manikin submitted to radiant heat flux. The experimental temperatures were compared with the analytical formulae developed by the authors and good agreement was presented. The lower limit for threshold value for skin injury was identified to be about 44" C. This temperature refers to the inner layer of skin, about 80 μm below the external skin surface, and injury continues even during cooling. Skin damage occurs a hundred times faster at 50 ºC and skin tissue is destroyed at 72ºC. In 2000, Sun et al. [3] studied the radiant protective performance, air permeability, vapor evaporation, and the thermal resistance of clothing depend on the chemical and physical structures of fabrics. Results indicate that the higher the thickness or the heavier the weight, the better the radiant protection is. In the same year 2000, Mell et al. [4] presented a one-dimensional heat transfer model for firefighters’ protective clothing, assuming that fabrics were dry and that the fabric temperatures were below the point of thermal degradation (melting or charring). The model incorporates a finite difference scheme to solve the energy equation on both solid and gas domains, approximating the first order derivatives instead of the second order, and using a second-order Runge-Kutta scheme for time stepping. The model was validated with experimental results, being the major difference between them equal to 5 ºC inside the garment and 24 ºC in the outer shell surface temperature. This manuscript received the 2001 Harry C. Bigglestone Award for Excellence from The Fire Protection Research Foundation. In 2005, Kutlu et al. [5], also conclude that the most important factors which influences the thermal protective performance ratings is the thickness and the fibre type of the fabrics. They also investigated the FPC durability, submitting the fabrics to 10 cycles of machine washing at 40 ºC. They verified a decrease on tear strengths of the fabrics, but a increase on the thermal protective performance due to the fluffing effect together with the increased amount of entrapped air between layers. Lawson et al in 2010 [6], decided to improve their model from 2000, introducing the wet conditions for fabrics and introducing a material database for thermal properties, used to manufacture firefighters’ protective clothing (Protective Clothing Performance Simulator). The model included the governing equations used for solving the transient heat and mass (moisture) transfer through firefighters’ protective clothing when subjected to a radiant heat flux. The maximum difference between the experimental results and the numerical results were within 10% accuracy. Results showed that moisture in the fabrics tends to vaporize during heating, being part of it diffused and then condensed on different parts of the fabric, depending on local temperature. In 2012 Ghazy et al. [7], developed a finite volume model for the transient heat transfer in firefighters’ protective clothing, using a more sophisticated and appropriate analysis for the air gaps entrapped in the clothing system. The numerical results indicated that the influence of the air gaps in the clothing systems increases from the exterior to the interior zone of the fabrics. Since then, different authors in 2015 made their contribution to research based on the moisture effect and durability of the firefighting protective clothing with regard to washing cycles [8]. Others in 2016 [9] developed a 3D model based on Computational Fluid Dynamics to simulate the flame manikin inside a combustion chamber to determine the temperature field in each layer of the assembled fabrics. The results were validated with experimental results point by point. In 2018, S. Dahamni et al [10] presented a numerical simulation to predict the incoming thermal flux on a firefighter a protective clothing, trying to evaluate the effect of ventilation conditions in the confined compartment. Despite the importance of mechanical ventilation devices, ventilation flow rates may lead to tremendous heat fluxes revealing the appearance of flashover or backdraft conditions.

The thermal performance, the mechanical resistance and durability are important characteristics that should be evaluated under extreme accidental conditions. This investigation deals with the analysis of the thermal performance of different multilayer fabrics. Two different fabrics were experimentally tested at the Tsinghua University, China, using small radiant heat flux, while four different fabrics were experimental tested at the Polytechnic Institute of Bragança, using small and average radiant heat flux. Both experimental results are presented, based on the testing method to the evaluation of the materials assemblies when exposed to a source of radiant heat NP EN 6942 [11], using a similar conical radiant heater calorimeter, based on the standard EN ISO 13927 [12]. The specimens were setup on the top a copper plate, directly exposed to a specific level of radiant heat flux. The times for temperature rise of 12 ºC and 24 ºC in the calorimeter are recorded and expressed as radiant heat transfer indexes. The percentage of heat transmission factor is also determined.

This investigation is also focused on the numerical modelling of experimental tests to evaluate the thermal performance of the fire fighter clothing. First a 2D numerical validation is presented to asset the thermal model and materials properties. This numerical model solves a nonlinear transient thermal analysis under low thermal radiation [11]. The numerical validation is based on the bench scale cone calorimeter experience test [12] or equivalent, exposing the fabrics to a low and medium thermal radiation of 1, 2, 3, 5, 7, 10 and 20 [kW/m^2], following the procedures of NP EN ISO 6942 [11]. The numerical results agree reasonably well with experimental results, which allow the authors to present a parametric analysis.

2. RADIATION TESTS

The radiation test required a calorimeter and a system device to measure the temperatures in each layer and in the unexposed surface of the copper plate, using an acquisition frequency of 10 Hz. Figure 1 represents the setup used for experiments at the Polytechnic Institute of Bragança (IPB). This setup was similar to the one used at the Tsinghua University (TU). Thermocouples type K were used to measure the temperatures on the top of each fabrics. Additionally, infra-red thermal images were collected from the outer shell. The copper plate has 1.6 mm and is bent in the longer direction into an arc deformed shape mode. This plate is located in a mounting block square piece of asbestos-free non-combustible heat insulation board.

The incident heat flux should be selected from three different levels: Low, Medium and High level. This investigation used low heat radiation level (<10 kW/m2) and medium radiation level (20 kW/m2). The heat flux was calibrated with a heat flux sensor, taking into consideration the position of the specimens (60 mm below the bottom of the cone calorimeter).

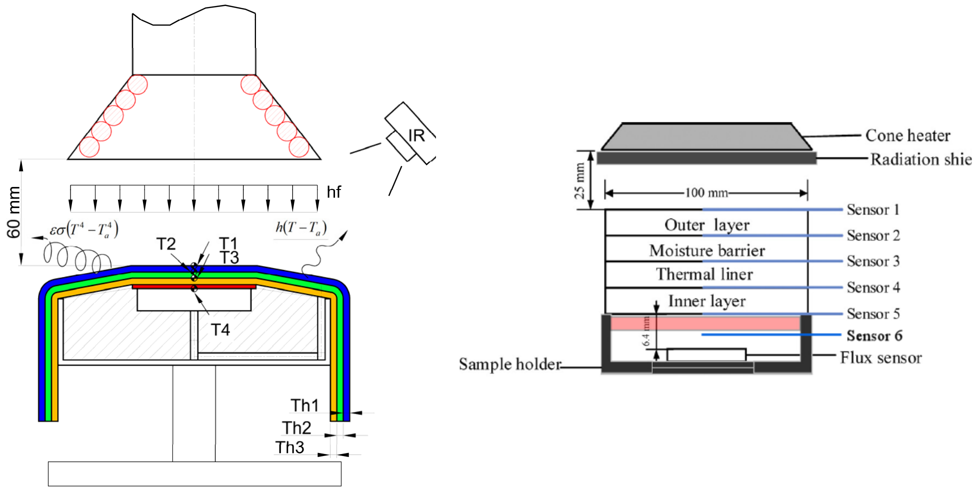
The specimens were prepared with a length of 200mm and width of 100 mm and fastened in both sides, using special weights to ensure the fabrics in position. The movable protective screen is withdrawn and the test starts. The time t_{12} to achieve a temperature rise of 12 ºC and the time t_{24} to achieve a temperature rise of 24 ºC were determined. The difference is also required to determine the transmitted heat flux density from the surface below the last layer of the assembly. The transmitted heat flux density, Q_c, is calculated according to Eq.1.

$$Q_c = \frac{M \cdot C_p}{A \cdot (t_{24} - t_{12}) / 12} \tag{1}$$

M represents the mass of the copper plate [kg], the C_p represents the specific heat of the copper [kJ/kg K], A is the area of the copper plate [m2] and the $(t_{24}-t_{12})/12$ represents the mean rate of the temperature rise [ºC/s].

The heat transmission factor $TF_{(Q0)}$ for the incident heat flux density level Q_0 is given by Eq. 2.

$$TF(Q_0) = \frac{Q_c}{Q_0} \tag{2}$$



a) Setup from Poly. Institute of Bragança. b) Adapted from Tsinghua University [13].
Figure 1: Cone radiation test for the analysis of fire fighter clothing.

3. EXPERIMENTAL TESTS

The thermal performance of the assembled fabrics is presented in the following two sections. The first section presents the experimental results obtained at TU, China, while the second section presents the experimental results obtained at IPB, Portugal.

3.1. Tests developed at the Tsinghua University (China)

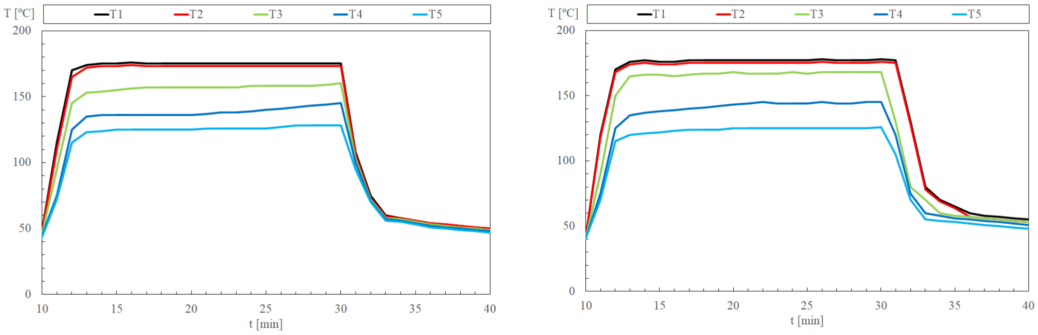
The objective of this study was to investigate the effects of low-level thermal radiation on the thermal protective performance of protective clothing during dry and wet tests. Only the results of the dry tests are presented herein for two different assembly fabrics, identified as assembly 01 and 02, se Table 1.

Table 1: Fabrics used for multi-layer firefighter protective clothing [13].

		Assembly 01			Assembly 02		
LAYER ID	**LAYER TYPE**	**THICK. [mm]**	**TRADE NAME**	**DENSITY [g/m^2]**	**THICK. [mm]**	**TRADE NAME**	**DENSITY [g/m^2]**
1	Outer shell	0.44	Nomex	200	0.44	Nomex	200
2	Moisture Barrier	0.62	Neo-Guard (PTFE)	105	0.12	Breath-Tex Plus (Goretex)	119
3	Thermal liner	2.60	Aralite	150	2.60	Aralite	150
4	Inner layer	0.31	Plain weave	120	0.31	Plain weave	120

The specimens were preconditioned in a temperature and humidity chamber (20 ± 2◦C and 65 ± 3% RH) for 24 h, and then sealed in a plastic bag for another 24 h before the experiment. Thermocouples of Type K with the diameter of 0.4 mm were sewn on the centre of each layer, to measure the temperature distribution through the clothing.

Each test specimen was placed under the cone heater and submitted to an incident heat flux density level Q_0 of 1, 2, 3, 5, 7 and 10 kW/m^2. The time history temperature curve is only presented for 5 kW/m^2, see Figure 2. The main difference between assembly 01 and 02, when submitted to this incident heat flux is related with the temperature T3 (temperature bellow layer 2).



a) Assembly 01 under 5 kW/m^2. b) Assembly 02 under 5 kW/m^2.

Figure 2: Cone radiation test for the analysis of fire fighter clothing at 5Kw/m^2.

According to the experimental results, the heat flux transmitted from the assembly to the unexposed side is 0.75 KW/m^2 and 0.675 kW/m^2, respectively for assembly 01 and 02. The heat transmission factor $TF_{(Q0)}$, for this heat flux is 15% and 13.5%, respectively. Fu et al. [13] presented an approximation to the heat transmission factor, based on the fitting analysis between the incident heat flux and the transmitted heat flux, see Eq. 3 and 4 for assembly 01 and 02, respectively.

$$Q_c = 0.151 \cdot Q_0 - 0.016 \tag{3}$$

$$Q_c = 0.142 \cdot Q_0 - 0.018 \tag{4}$$

3.2. Tests developed at the Polytechnic Institute of Bragança (Portugal)

The objective of this study was to investigate the effects of low and medium thermal radiation on the thermal performance of protective clothing during dry tests, using a 3-layer assembly. The results of the dry tests are presented for four different assemblies, see Table 2, and two incident heat flux density levels Q_0=5 kW/m^2 and Q_0=20 kW/m^2, identified from specimen 01 to specimen 08, se Table 3.

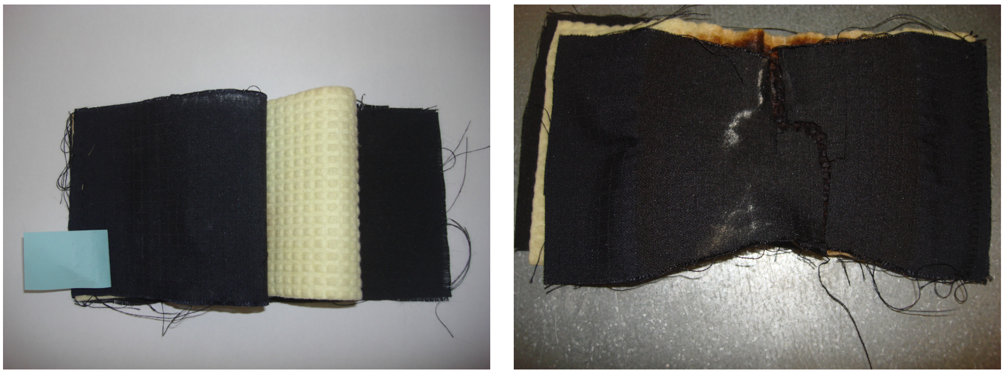
Table 2: Fabrics used for multi-layer firefighter protective clothing.

		Assembly 01			Assembly 02			Assembly 03			Assembly 04		
LAYER ID	LAYER TYPE	THICK. [mm]	CODE NAME	DENSITY [g/m^2]	THICK. [mm]	CODE NAME	DENSITY [g/m^2]	THICK. [mm]	CODE NAME	DENSITY [g/m^2]	THICK. [mm]	CODE NAME	DENSITY [g/m^2]
1	Outer shell	0.46	TB1	240	0.47	TB2	250	0.45	TB3	210	0.38	TB4	230
2	Thermal Barrier	0.6	BT1	140	0.6	BT1	140	0.6	BT1	140	0.6	BT1	140
3	Inner layer	0.1	F1	130	0.1	F1	130	0.1	F1	130	0.1	F1	130

Table 3: Test specimens and main results.

Specimen Id	Assembly Id	Heat flux Density [kW/m^2]	t_{12} [s]	t_{24} [s]	t_{24}- t_{12} [s]	Q_c [kW/m^2]	$TF_{(Q0)}$ [%]
01	01	5	39.3	81.9	42.0	1.57	31.6
02	02	5	63.4	101.1	37.7	1.75	35.2
03	03	5	64.2	101.8	37,6	1.76	35.3
04	04	5	41.3	77.0	35.7	1.86	37.1
05	01	20	15.9	28.4	12.5	5.31	26.6
06	02	20	16.0	25.4	9.4	7.08	35.4
07	03	20	29.3	38.5	9.2	7.23	36.1
08	04	20	13.6	21.1	7.5	8.91	44.6

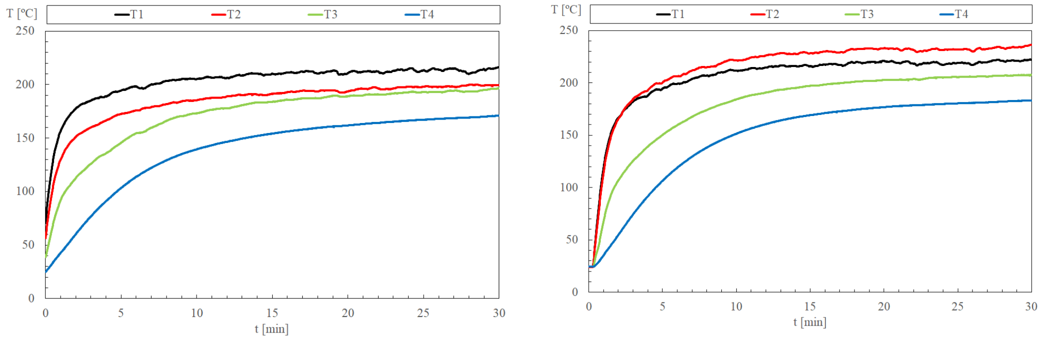
The assembly 01 presents the smaller transmitted heat flux density, and consequently the smaller heat transmission factor, for both incident heat flux densities. Figure 3 represents the final state of each specimen after test. The fibres of the specimen 01 are not affected when submitted to low heat radiation level, but are strongly affected at medium heat radiation level.



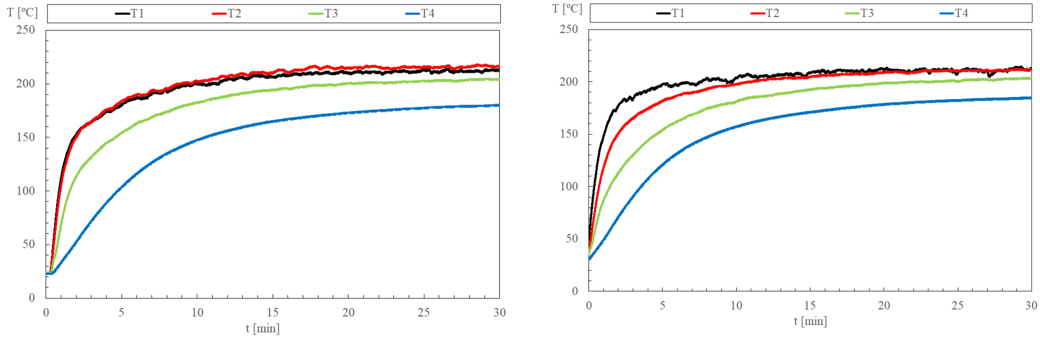
a) Specimen 01 (assembly 01). b) Specimen 05 (assembly 01).

Figure 3: Final state of the assembly, after being submitted to 5 and 20 kW/m^2.

The time history temperature curve is represented for every specimen in Figure 4 for an incident radiant heat flux of 5 kW/m^2.



a) Assembly 01 under 5 kW/m^2. b) Assembly 02 under 5 kW/m^2.

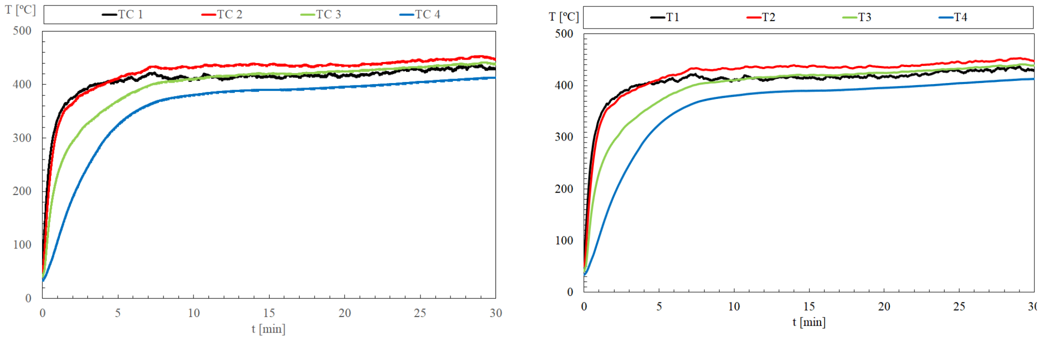


c) Assembly 03 under 5 kW/m^2. d) Assembly 04 under 5 kW/m^2.

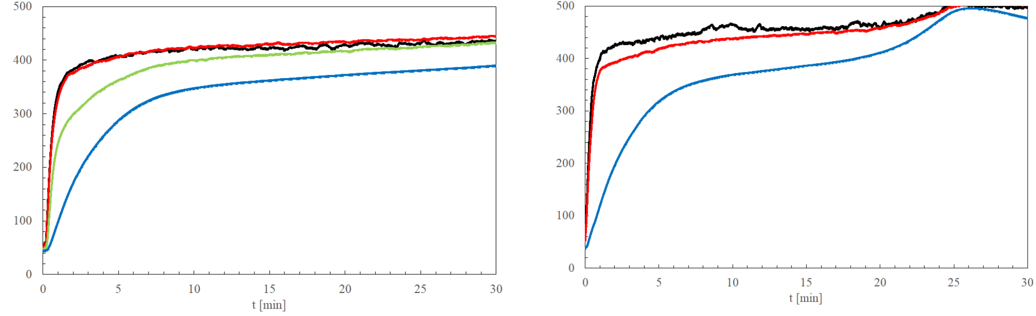
Figure 4: Cone radiation test for the analysis of fire fighter clothing at 5 kW/m^2.

The maximum temperature is almost the same in this set of results, but for long time exposure (30 minutes), the difference between T1 and T4 is higher for the assembly 01.

The time history temperature curve is also presented for specimens submitted to an incident heat flux density of 20 kW/m^2, see Figure 5. The specimen 05 had the smallest heat transmission factor. For long time exposure, Specimen 7 presents the highest temperature difference between T1 and T4.



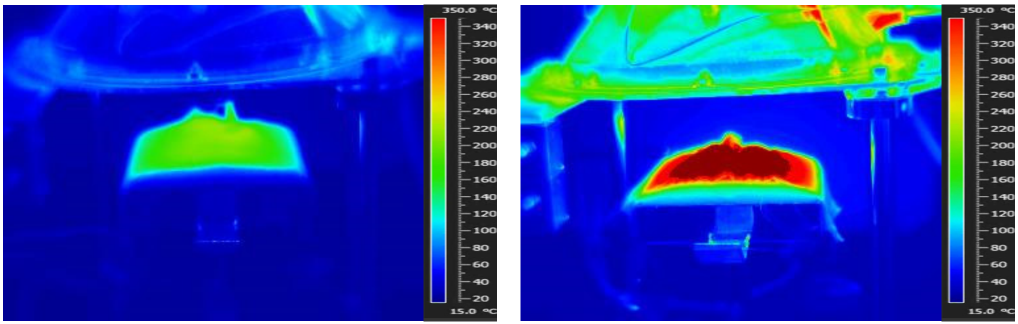
a) Assembly 01 under 20 kW/m^2. b) Assembly 02 under 20 kW/m^2.



c) Assembly 03 under 20 kW/m^2. d) Assembly 04 under 20 kW/m^2.

Figure 5: Cone radiation test for the analysis of fire fighter clothing at 20 kW/m^2.

Figure 6 presents the infrared thermal images for the assembly 01, when submitted to 5 and 20 kW/m^2, during the initial stage of the tests (5 minutes after the start). The temperature scale was fixed between 15 ºC and 350 ºC.

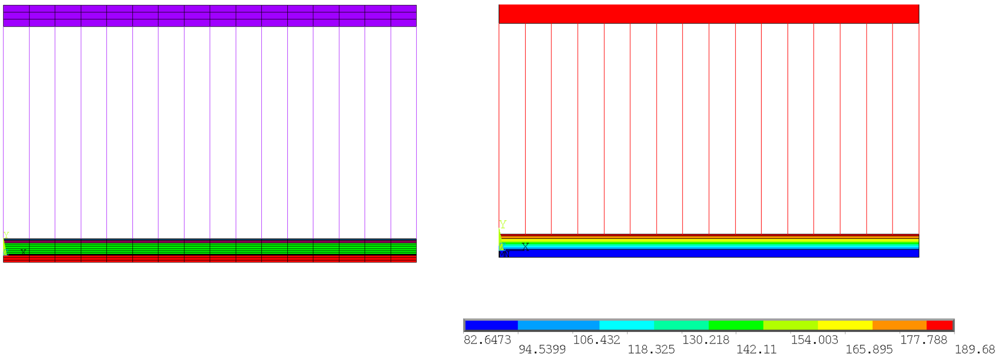


c) Assembly 01 under 5 kW/m^2. d) Assembly 01 under 20 kW/m^2.

Figure 6: Infrared thermal results for the assembly 01, after 5 minutes heat exposure.

4. SIMULATION MODEL AND PARAMETRIC ANALYSIS

The 2D finite element model was defined, based on the discretization of the thickness of each specimen. Authors decided to validate the numerical model using the experimental results developed at the Tsinghua University (China). The model assumes 100 mm width and all defined thicknesses for the fabrics of each assembly. This model uses PLANE55, which is a four-node element, with linear interpolating functions, using full integration scheme. Due to the limitation of this element, an additional model was considered above the fabrics model to receive the incident heat flux. The contact between both models is made with an additional finite element, COMBIN39, using linear interpolating functions and exact integration, see Figure 7. The model also includes the thickness of the material used bellow the assembly (copper with 1.6 mm). The contact between all the layers and the copper plate is considered perfect.



a) Finite element mesh.

b) Assembly 01 (4 layers) submitted to 5 kW/m^2, after 5 minutes exposure.

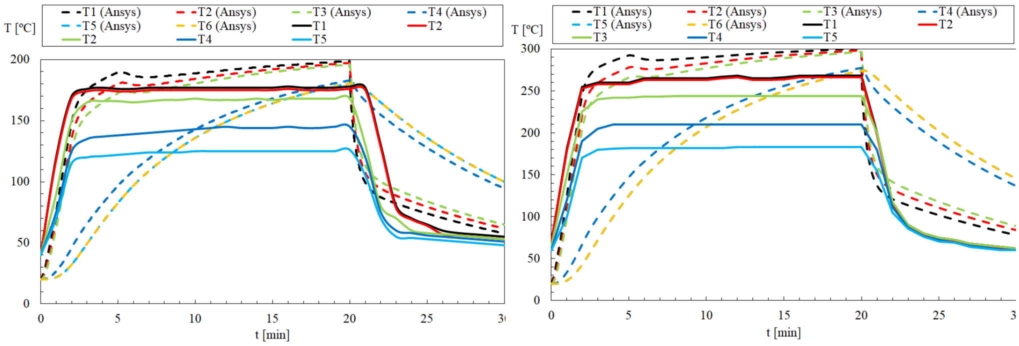
Figure 7: Finite element mesh and temperature field after 5 minutes of heat exposure.

On the top surface of the outer shell, the heat loss by convection and radiation was considered. The convection coefficient changes with the effect of the temperature [14]. The bulk temperature is considered equal to 20 ºC. An adiabatic thermal condition is applied on the bottom surface of the copper plate.

The model considers the non-linear behaviour of the material, based on the temperature dependent thermal properties [15] obtained by experimental tests for low temperature values. The thermal properties for copper were defined according Hust et al. [16]. The solution is non-linear and the time step may change from 60 to 1 seconds, depending on the convergence of the solution process. The experimental tests present a heating stage during 20 seconds and a cooling stage for 10 seconds.

The time history post processor of the numerical simulation, for the temperature of each layer, is compared in Figure 8, only for two incident heat fluxes (5 and 10 kW/m^2) and for the assembly 01. The other simulations gave similar results when compared with the experimental results.

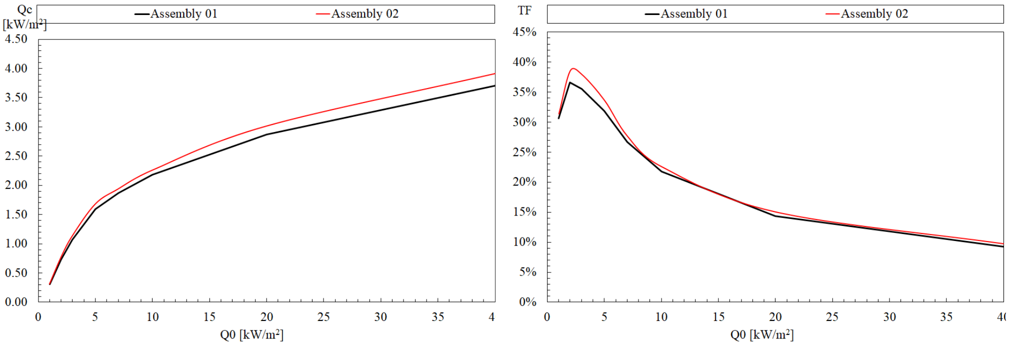
The predicted maximum temperature agrees very well with the experimental measurements for all tested incident heat fluxes, for T1, T2 and T3. The other simulation results, T4, T5 and T6 are not in agreement with the measured values. This difference can be explained by the boundary conditions used bellow the copper plate.



Assembly 01 (4 layers) submitted to 5 kW/m^2 Assembly 01 (4 layers) submitted to 10 kW/m^2

Figure 8: Comparison of results.

All the required parameters, normally used for testing, were considered in simulation. A parametric analysis was developed by simulation, based on the models used for the experimental tests developed at the Tsinghua University (China). A new set of simulations was developed for the following incident heat fluxes Qo= 1,2,3,5,7,10,20 and 40 kW/m^2.



a) Transmitted heat flux vs incident. b) Heat transmission factor.

Figure 9: Parametric analysis.

5. CONCLUSIONS

This investigation presents two different experimental tests based on the NP EN 6942, to evaluate the thermal behaviour of materials and material assemblies when exposed to a source of radiant heat. Small and medium radiant heat fluxes were considered.

Different fabrics were tested. The main results prescribed by the standards are presented and compared. The assembly 02 at the TU China is a four-layer fabrics and presents the smallest transmission factor, while the assembly 01 at IPB Portugal is a three-layer fabrics and presents the smallest transmission factor of its series.

The numerical model is able to predict most of the temperature layers. The parametric analysis revealed that there in a non-linear relation between the incident heat flux and the transmitted heat flux. The heat transmission factor decreases with the increase of the incident flux.

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