Towards a predictive model for incoming thermal fluxes during a fuel warehouse fire

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ABSTRACT

The prediction of released heat fluxes from fires is mandatory for any fire safety strategy. Indeed, the spreading time and directions of thermal fluxes are particularly critical in the situations of fuel warehouses, where temperature levels can induce primary and secondary inflammations in the neighbouring depots. Moreover, firefighters should operate in areas where the thermal environment is tolerable and in favour of efficient egress operations.

Several correlative models provided by some industrial organizations are applied to the study case of Naftal-Chiffa fuel warehouse (Blida, Algeria).

Various fire characteristics are predicted, in particular height and inclination of jet flames, in addition to the spatial distribution of heat fluxes on solid targets (human bodies and structures).

The analyses reveal that the safety distances corresponding to the threshold fluxes of 3 kw/m^2, 5 kw/m^2 and 8 kw/m^2 as provided by the IT-89 correlations, exhibit an important dispersion when relative humidity was different from 70% and the fuel tank was had no longer a square shape. In this direction, the present study was completed with a parametric analysis on the effects of climatic conditions (ambient temperature, relative humidity, wind speed) and storage tanks geometry on the distances relates to critical thermal fluxes.

Keywords: *Fire, Liquid fuel, Warehouse, Correlative model, Heat fluxes, Safety distances.*

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ATTESTATION

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Introduction

The prediction of released heat fluxes from fires is mandatory for any fire safety strategy.

Specifically, these fluxes are particularly critical in the case of the fuel tank fires where their levels can induce inflammation in the nearby deposits and even impair the personal safety response.

The main goal of this work is to look for the formulations that would help us to build a model of thermal effects during a fire in pool fire, while offering tools for predicting these fluxes. The case of the fuel deposit of the NAFTAL-Chiffa station, Blida is taken as our study case.

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Technology trends

- **Fire**

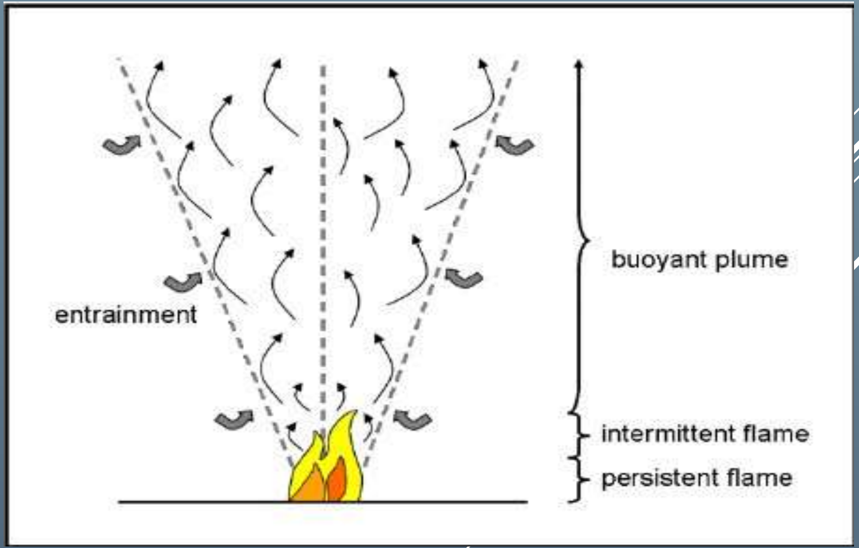
Simultaneous release of heat, light and flame produced by the lively combustion of certain bodies (wood, coal, etc.). So that there is a fire, it is necessary to find the three components of the fire triangle: fuel, oxidizer and energy.

- **Blaze**

A self-sustainning combustion that develops without control in time and space.

- **Flame**

A gas phase combustion zone commonly with light emission.



Pool fire

Pool fire or puddle fire, describes a blaze resulting from the combustion of a pool of a liquid fuel in an open atmosphere. This phenomenon mainly involves the pool surface are in contact with the air. The dimensions and the geometry of the pool can be quite variable.

The formation of a slick on the ground can be observed following the srpeading of a liquid substance or the fusion of solid bodies that liable to liquify under the effect of heat (ex : certain plastics, bitumens…etc).

Thermal effects in terms of incoming flux

1. Effects on humains:

- 3 kW/m², threshold of irreversible effects delimiting the « zone of significative dangers to human life »
- 5 kW/m², threshold of lethal effects delimiting the « zone of serious dangers to human life » mentioned in article L.515-16 of the
- environment code

- 8 kW/m², threshold of significative lethal effects delimiting the « zone of very serious dangers to human life » mentioned in article L.515-16 of the environment code.

2. Effects on structures

- 5 kW/m², threshold for significant window destruction.
- 8 kW/m², threshold of domino effects corresponding to threshold of serious damage to structures.
- 16 kW/m², threshold for prolonged exposure of structures corresponding to the threshold for very serious damage to structures excluding concrete structures.
- 20 kW/m², threshold of concrete resistance for several hours corresponding to the threshold of very serious damages on concrete structures.
- 200 kW/m², threshold of concrete ruin in a few tens minutes.

Fuels

Petrol

The auto gasoline is a light hydrocarbon oil used as a fuel in spark ignition engines.

Physical characteristics of gasoline:

- **Density at 15°C :** from 0.730 to 0.770
- **Reid vapor pressure :** 0.650 b
- **Distillation :** at 10% (70°C)
  at 50% (140°C)
  at 95% (195°C)

Chemical caracteristics of gasoline :

- **Copper strip corrosion :** 1b
- **Lead content :** 0.40 g/l
- **PCI m :** 42.7 (MJ/kg)
- **PCI v :** 32.2 (MJ/L)

Diesel

Diesel fuel must have, unlike gasoline, a strong tendancy to the self-ignition since the operating principle of the Diesel engine is based on the ignition of the fuel injected under high pressure in the previously compressed air.

Physical characterictics of Diesel fuel.

- **Density at 15°C :** from 0.810 to 0.860
- **Distillation :** at 65% (250°C)
  at 90% (350°c)
- **Kinematic viscosity at 20 °C :** 9
- **Flow point :** Winter -12°C / Summer -7°C

Chemical characteristics of Diesel fuel :

- **Cetane number :** 48
- **Flash point :** 55°C
- **PCI m :** 42.6 (MJ/kg)
- **PCI v :** 35.8 (MJ/L)

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Liquid fuel warehouses

Fuel deposits are storage warehouses of crude oil and liquid hydrocarbons. We can say that the activities of the repositories are :

- reception of products by (pipeline ; tank wagon ; ship / barge).
- Storage of received products.
- Loading petroleum products into tankers.

Identification of risks :

Fire

Boil over

Explosion

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Predictive models

Models for Heat release rate (Fizero)

Modèle Mudan et Croce :

$$\emptyset_0 = \emptyset_{max} \times e^{(-SD)} + \emptyset_{fumées} \times (1 - e^{(-SD)})$$

Modèle TNO

$$\emptyset_0 = \emptyset_{max} \times (1 - \varsigma) + \emptyset_{soot} \times \varsigma$$

avec :

$$\emptyset_{max} = m^{"}.FR \times \frac{\Delta hc}{1 + 4\frac{L}{Deq}}$$

Modèle TI-89 :

$$\emptyset = \emptyset_0 \times F(r) \times \Gamma(r)$$

le pouvoir émissif est considéré comme constant ; il a été pris égal à 29720 W/m².

Flame geometry modelling

Modèle de Heskestad :

$$H = \left(-1.02 + 15.6\, N^{\frac{1}{5}}\right) \times D$$

$$N = \frac{Cp_0\, T_0}{g\, \Delta Hc}\left(\frac{\eta_{comb} \times m'}{\rho_a}\right)\frac{r_s^3}{D^5}$$

$$r_s = 137.87\,\frac{x + y/4 + z/2}{12x + y + 16z}$$

Modèle de Thomas :

a. vent < 1 m/s :

$$L = 42 \times De \times \left(\frac{m''}{\rho_{air} \times \sqrt{g \times Deq}}\right)^{0.61}$$

b. vent > 1 m/s :

$$L = 55 \times Deq \times \left(\frac{m''}{\rho_{air} \times \sqrt{g \times Deq}}\right)^{0.67} \times (u^*)^{-0.21}$$

$$u^* = \frac{u_w}{\left(\frac{g \times m'' \times Deq}{\rho_{air}}\right)^{\frac{1}{3}}}$$

Winds effect

Inclinaison de la flamme :

la formule établie par l'American Gas Association (AGA) $u^* = \frac{u_w}{\left(\frac{g \times m'' \times D}{\rho_{air}}\right)^{\frac{1}{3}}}$ Si $u^* < 1$ alors $\cos\theta = 1$

sinon $\cos\theta = \frac{1}{\sqrt{u^*}}$

Welker et Sliepcevitch $\frac{\tan\theta}{\cos\theta} = 3{,}3 \left[\frac{D\,u_w}{v}\right]^{0.07} \left[\frac{u_w^2}{g\,D}\right]^{0.8} \left[\frac{\rho_g}{\rho_a}\right]^{-0.6}$

La formule de Thomas $\cos\theta = 0.7 \left[\frac{u_w}{\left(\frac{g \times m'' \times D}{\rho_a}\right)^{\frac{1}{3}}}\right]^{-0.49}$

Détermination de la hauteur de flamme :

Thomas propose la corrélation suivante :

$$H = 6.2 \times D \times [m''_{ad}]^{0.254} \times [u^*_{10}]^{-0.044}$$

et : $m''_{ad} = \frac{m''}{\rho_{a.}\sqrt{gD}}$

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Model for the radiattive attenuation

Cas d'un cylindre droit :

$$F_v = \frac{1}{\pi X} Arc\tan\left(\frac{L}{\sqrt{X^2-1}}\right) + \frac{L}{\pi}\left[\frac{(A-2X)}{X\sqrt{AB}} Arc\tan\sqrt{\frac{A(X-1)}{B(X+1)}} - \frac{1}{X} Arc\tan\sqrt{\frac{X-1}{X+1}}\right]$$

$$F_h = \frac{1}{\pi}\left[Arc\tan\sqrt{\frac{X-1}{X+1}} - \frac{(X^2-1+L^2)}{\sqrt{AB}} Arc\tan\sqrt{\frac{A(X-1)}{B(X+1)}}\right]$$

où : R = D/2 A = $(X+1)^2+L^2$

L = H/R B = $(X-1)^2+L^2$

X = x/R Fv : Facteur de forme pour une cible verticale

Fh : Facteur de forme pour une cible horizontale.

Formule IT-89 :

Dans l'IT-89, le facteur de vue se calcule donc selon la formule suivante :

$$F = 1.38 \times \frac{K^{1.7}}{r^2}$$

Cas d'un plan vertical :

$$F_v = \frac{1}{2\pi}\left[\frac{X}{\sqrt{1+X^2}} Arctg\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}} Arctg\left(\frac{X}{\sqrt{1+Y^2}}\right)\right]$$

Avec X=a/c Y=b/c

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Models for the atmospheric attenuation factor

1. La corrélation de Brzustowski et Sommer :

Elle donne le meilleur compromis entre précision et complexité.

$$\tau = 0.79 \times (100/d)^{1/16} \times (30.5/RH)^{1/16}$$

2. La corrélation de Lannoy : Elle est donnée par la relation suivante :

$$\tau = 0.33 + 0.67.\exp(-0.0002.w.d)$$

3. La corrélation de Bagster :

Elle est donnée par la relation suivante :

$$\tau = 2.02\,.\,(p_w.d)^{-0.09}$$

Avec:

$$p_w = RH.e^{\left(14.4114-\frac{5328}{Ta}\right)}.1.013 \times 10^5$$

4. Corrélation de Wayne :

Elle est donnée par la relation suivant

$$\tau = 1.006 - 0.017\,log \times (H2O) - 0.2368(\,log \times (H2O))^2 - 0.03188\,\log\times\,(CO2))^2$$

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Validation with respect to a small bin « 50m² »

Model	Pool surface area Afire (m²)	Dpool //Kpool (m)	Lflame (m)	Tilt/verticale (°)	Φzero (Kwatt/m²) Data GTDLI[5]	Φzero (Kwatt/m²)
IT-89 without wind	50	D=7.97	13.479400	0	30	29.72
		K=7.07	12.402340	0		29.72
IT-89 with wind	50	D=7.97	10.03404	54.109102		29.72
		K=7.07	9.188131	55.0524010		29.72
TNO without wind	50	D=7.97	13.479400	0	22.3	22.137420
		K=7.07	12.1402340	0		21.944640
TNO with wind	50	D=7.97	10.034040	54.109120	25.12	23.895670
		K=7.07	9.188131	55.524010		23.688710
Mudan and Croce without wind	50	D=7.97	13.479400	0	40	66.112860
		K=7.07	12.402340	0		71.371930
Mudan and Croce with wind	50	D=7.97	10.034040	54.109120		66.112860
		K=7.07	9.188131	55.524010		71.37930

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Relative gap

Model	Lflame (m) « GTDLI »[5]	ΔΨ L_{flame} (%)	Tilt (°) « GTDLI »[5]	ΔΨ Tilt (%)	ΔΨ Φ_{zero}(%)
IT-89 without wind	47	-71.3	00	0	For a rounded pool: Err= -0.93 For a square pool: Err=-0.93
		-73.6	00	0	
IT-89 with wind	38	-73.5	30	80	
		-75.8	60	-8	
TNO without wind	47	-71.3	00	0	Rounded pool: Err=-0.72
		-73.6	00	0	Square pool : Err=-1.59
TNO with wind	38	-73.5	30	80	Rounded pool = 5.5
		-75.8	60	-8	Square pool =-6.6
Mudan and Croce without wind	47	-71.3	00	0	For a rounded pool : Err=65.2 For a square pool : Err=78
		-73.6	00	0	
Mudan and Croce with wind	38	-73.5	30	80	
		-75.8	60	-8	

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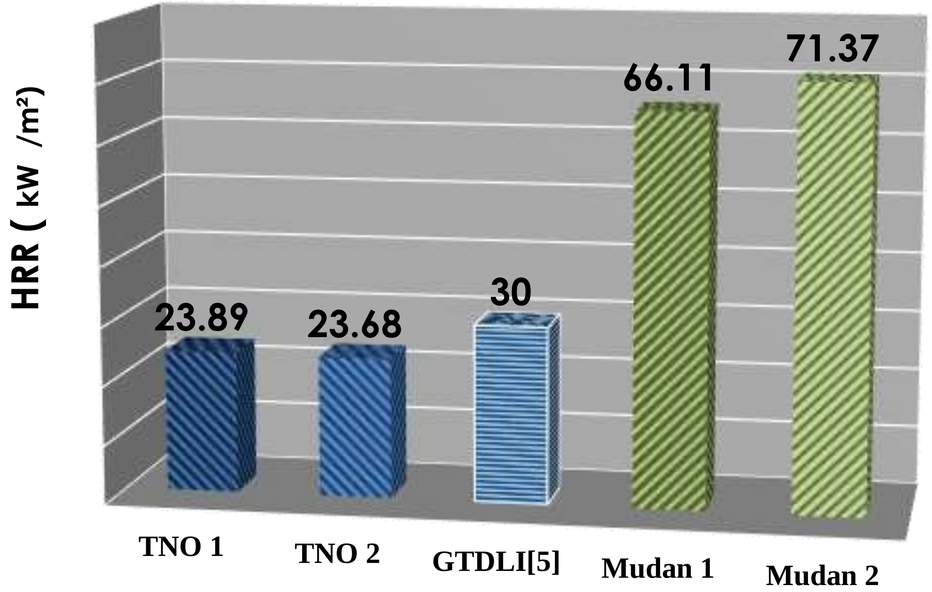
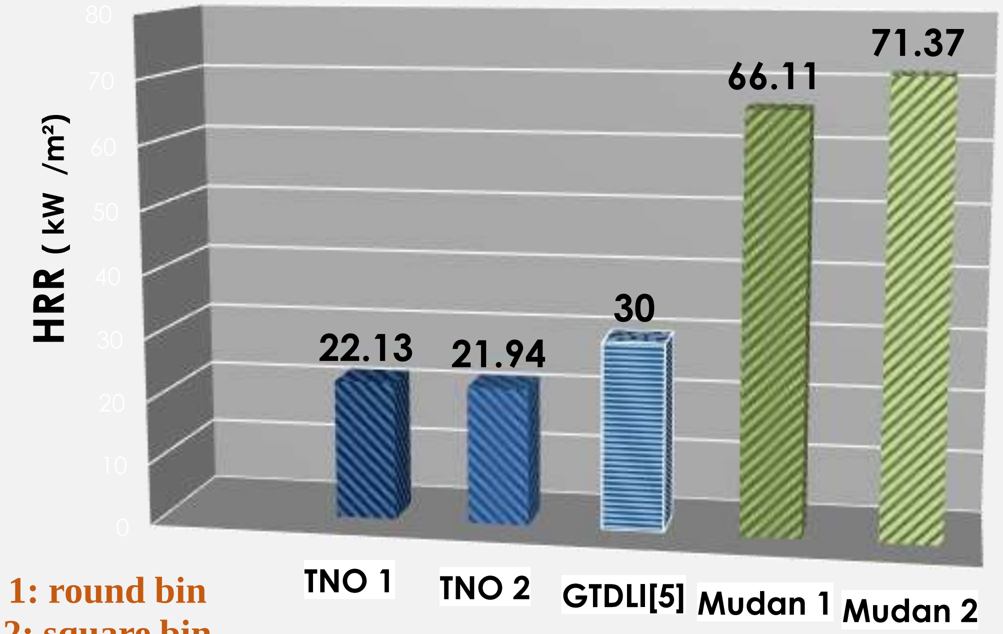
Calculation of HRR ''case with and without wind ''
Afire = 50 m² (TNO, Mudan & Croce model)

Calculations with wind A_{fire}= 50 m^2



1:bac rond
2: bac carré

Calculations without wind A_{fire}= 50 m^2



1: round bin
2: square bin

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Validation for a case of a large pool area (2400 m²)

Model	Bin surface Afire (m2)	Dpool //Kpool (m)	Lflame (m)	Tilt/verticale (°)	Φzero (kWatt/m²) Data GTDLI [5]	Φzero (kWatt/m2)
IT-89 without wind	2400	D=55.28	51.789520	0	30	29.72
		K=48.98	47.612410	0		29.72
IT-89 with wind	2400	D=55.28	41.657330	27.047900		29.72
		K=48.98	38.112520	28.764570		29.72
TNO without wind	2400	D=55.28	51.789520	0	24.8	26.038580
		K=48.98	47.612410	0		25.749270
TNO with wind	2400	D=55.28	41.657330	27.047900	27.6	27.87200
		K=48.98	38.112520	28.764570		27.588460
Mudan and Groce withou wind	2400	D=55.28	51.789520	0	20	20.157850
		K=48.98	47.612410	0		20.336180
Mudan and Groce with wind	2400	D=55.28	41.657330	27.047900		20.157850
		K=48.98	38.112520	28.764570		20.336180

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Relative deviations

Model	Lflame(m) « GTDLI » [5]	ΔΨ L_{flame} (%)	Tilt(°) « GTDLI » [5]	ΔΨ Tilt (%)	ΔΨ Φ_{zero} (%)
IT-89 without wind	47	10	00	0	For a round bin: Err= -0.93 For a square bin : Err=-0.93
		1.3	00	0	
IT-89 with wind	38	9.6	30	-9.8	
		0.2	60	-52	
TNO without wind	47	10	00	0	Round bin:4.7
		1.3	00	0	Square bin : 3.6
TNO with wind	38	9.6	30	-9.8	Round bin :0.97
		0.2	60	-52	Square bin : 0.21
Mudan and Groce with wind	47	10	00	0	For a round bin : Err= 0.78 For a square bin : Err=1.68
		1.3	00	0	
Mudan and Groce with wind	38	9.6	30	-9.8	
		0.2	60	-52	

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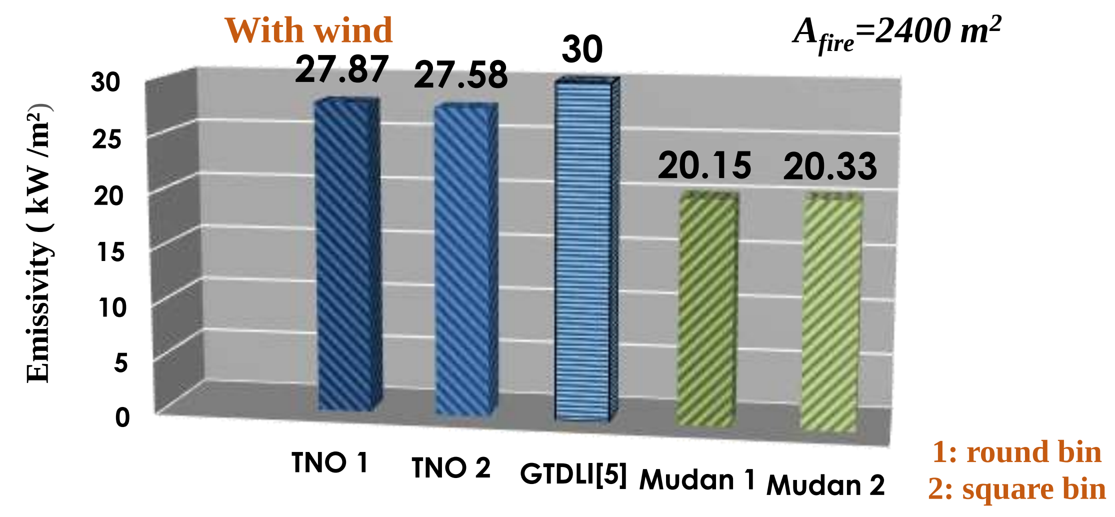
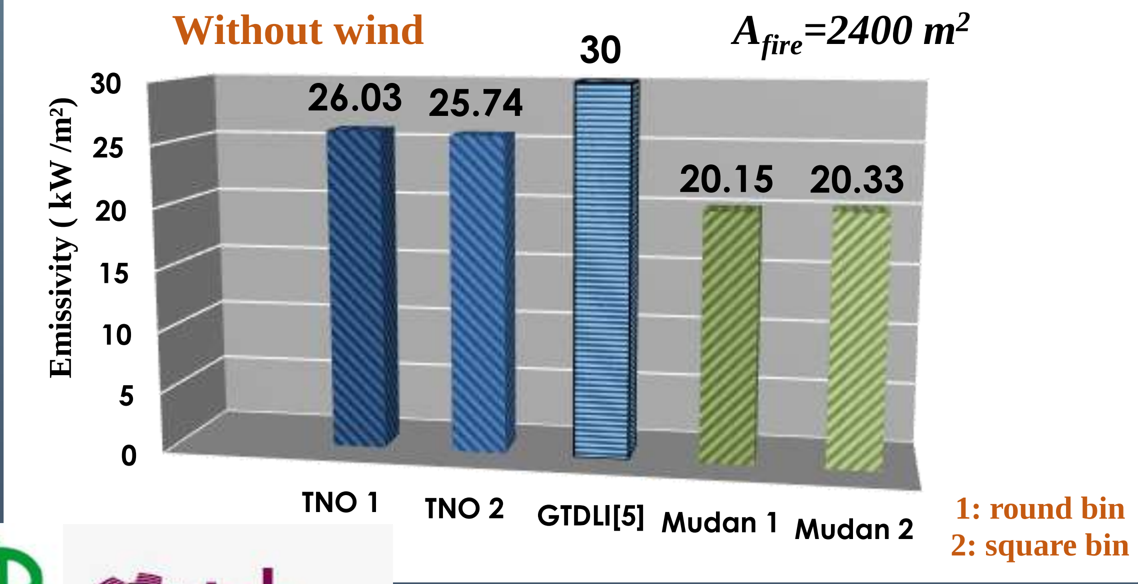
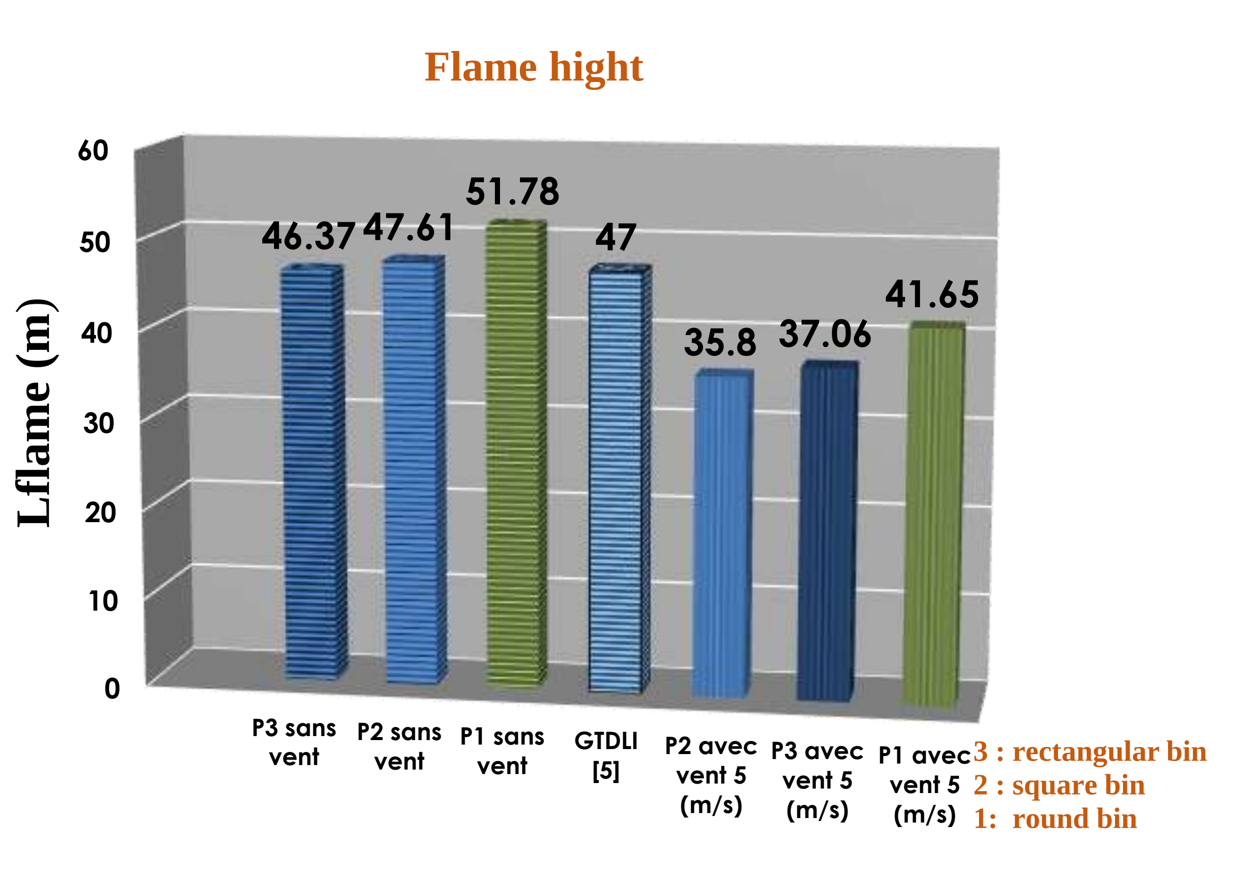
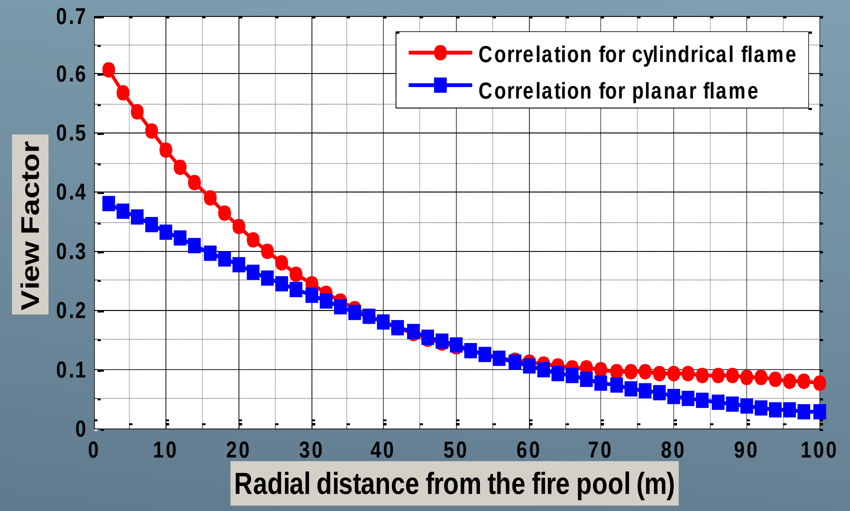
Calculation of the HRRand the flame hight ‘’windy case ‘’ Afire = 2400 m² (TNO, Mudan & Croce models)

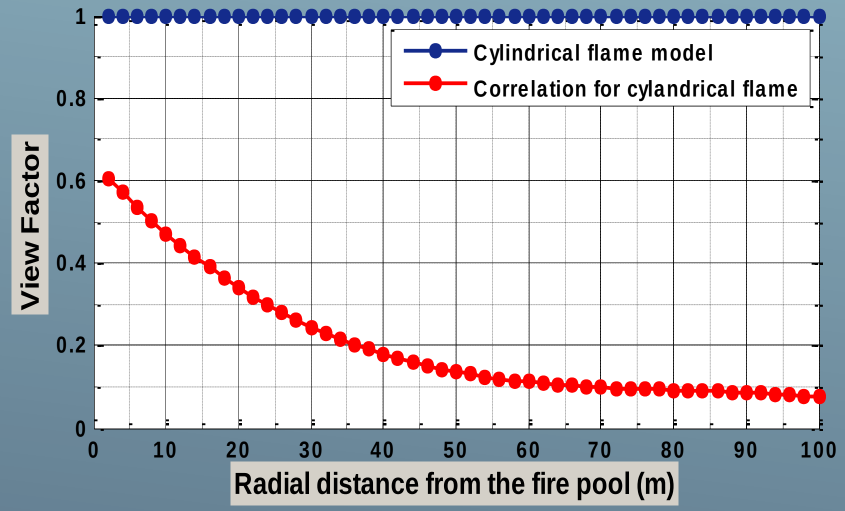


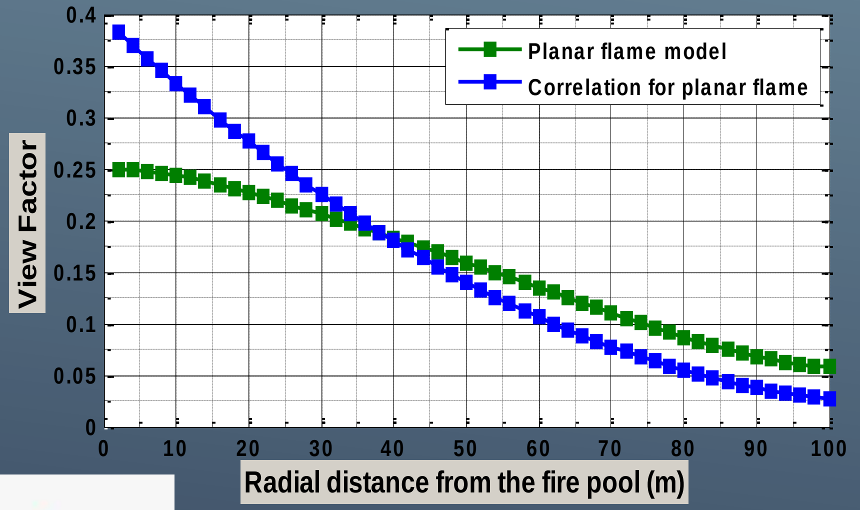


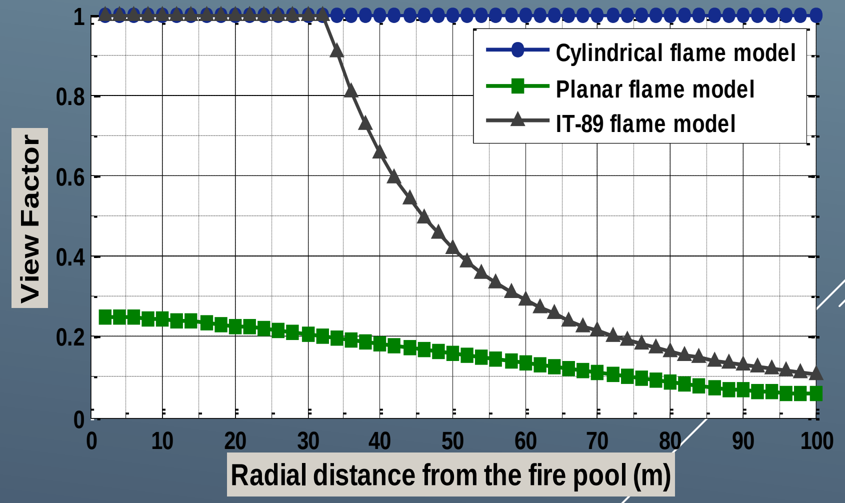


View factor evolution .vs. distance between the target and the flame front









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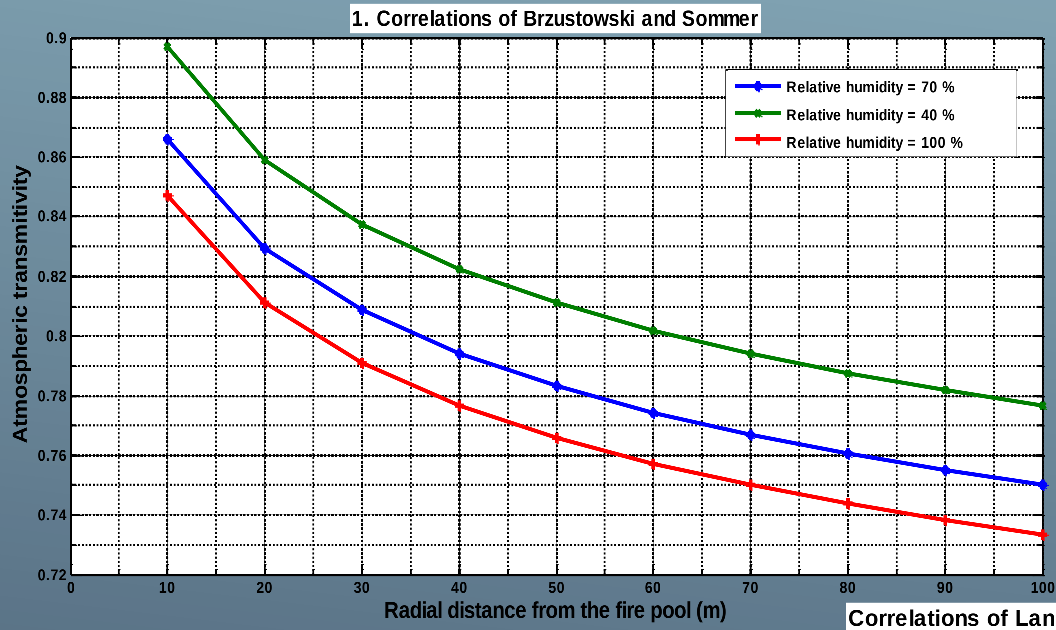
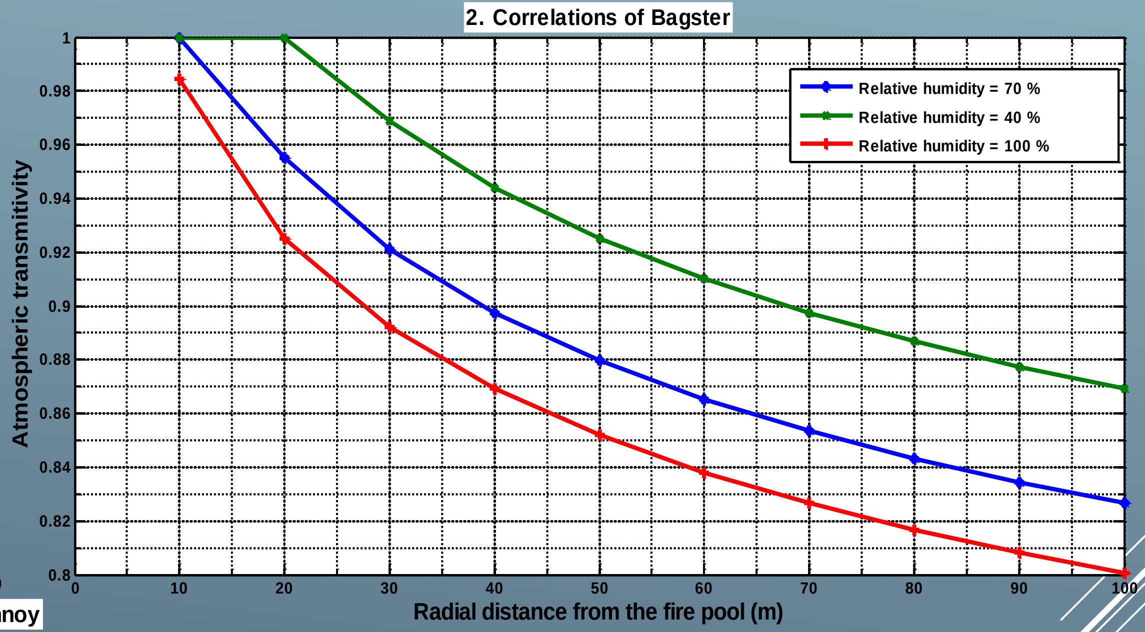
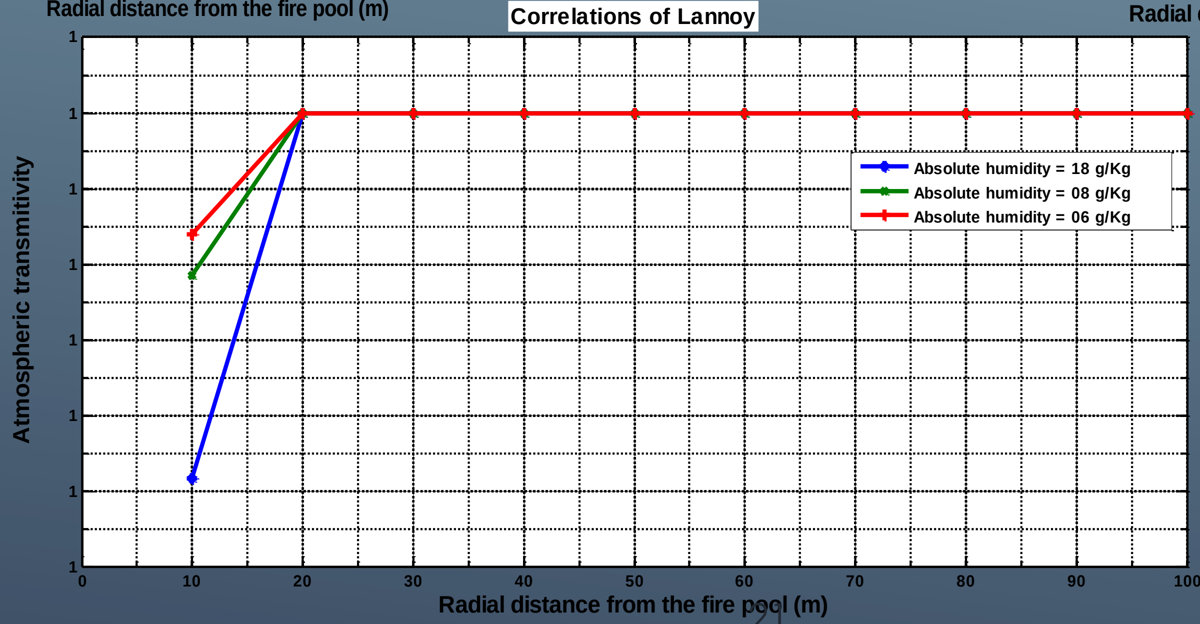
Models effect on the attenuation factor







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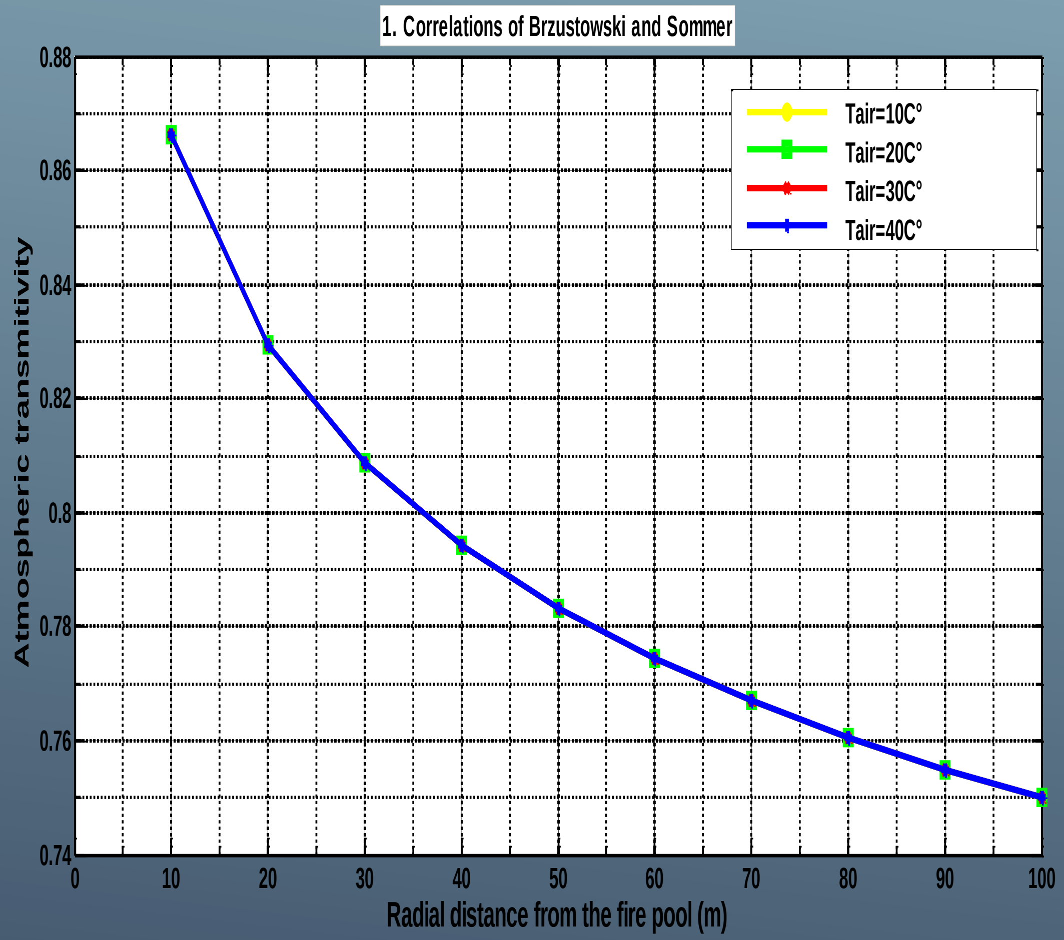
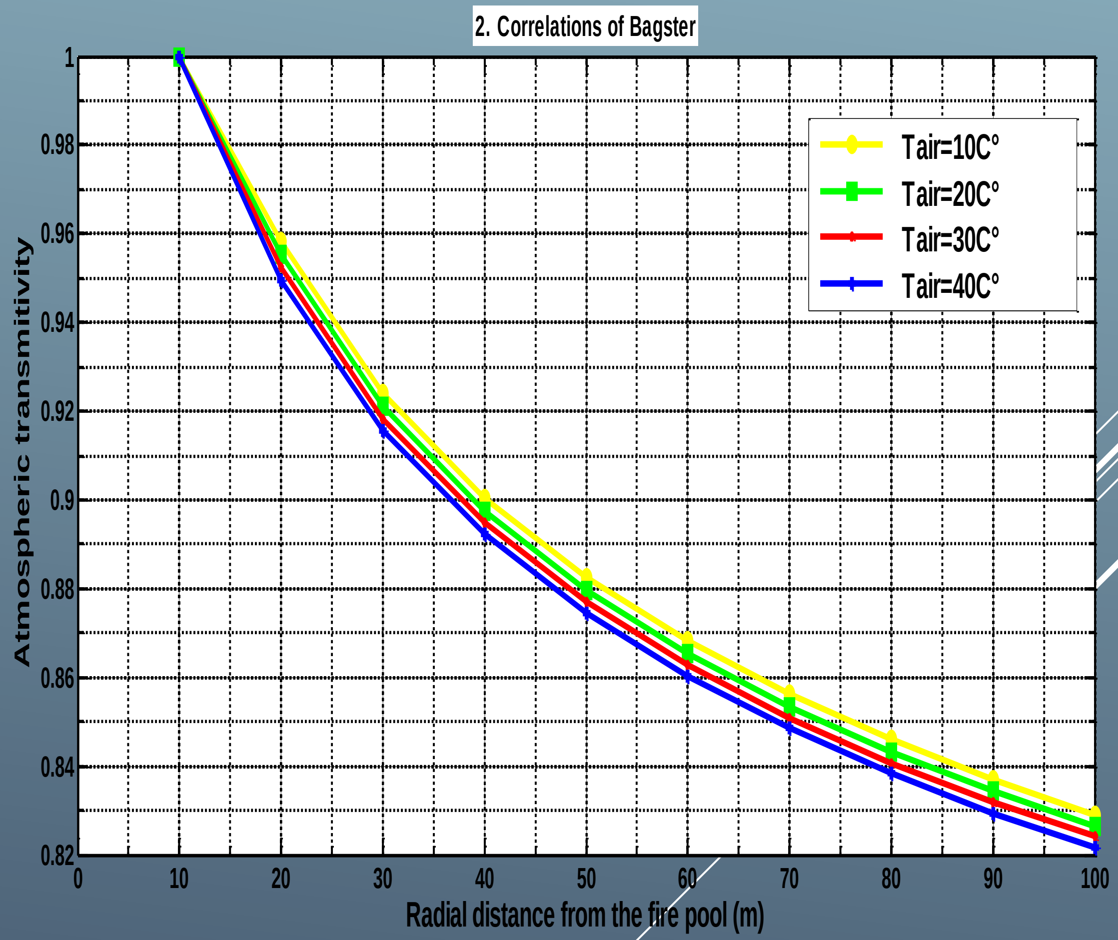
Effect of external temperature





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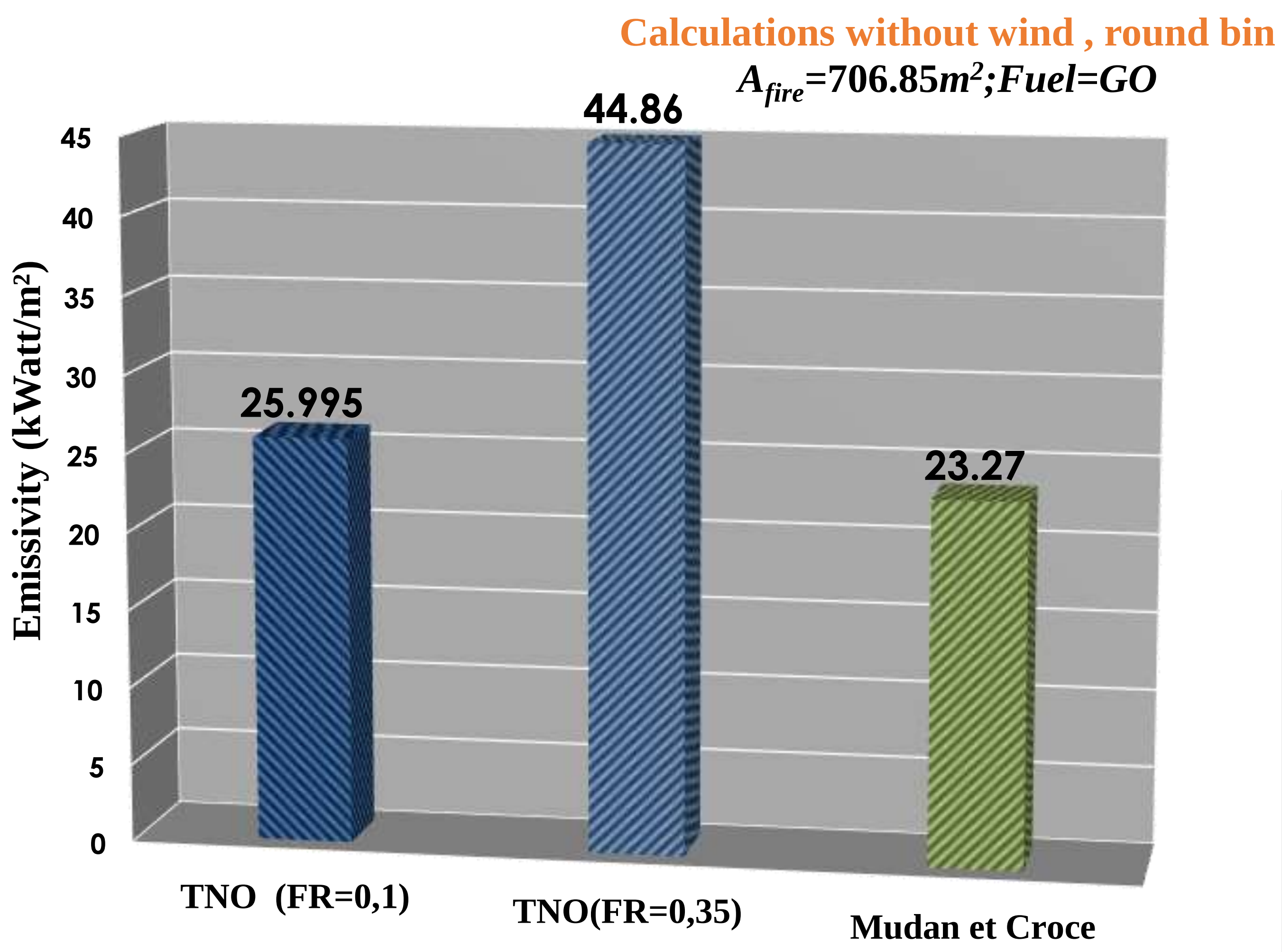
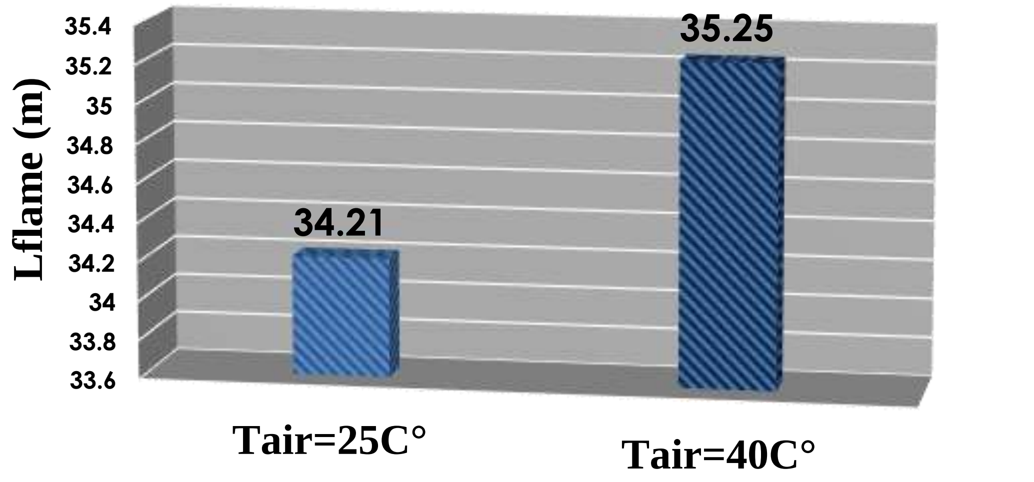
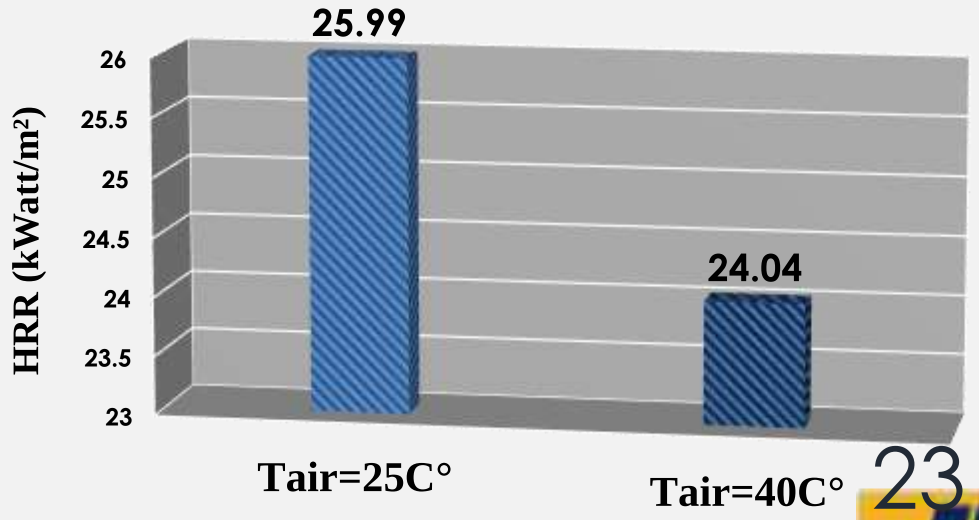
Calculation for the case of a Diesel tank (Scenario 1)







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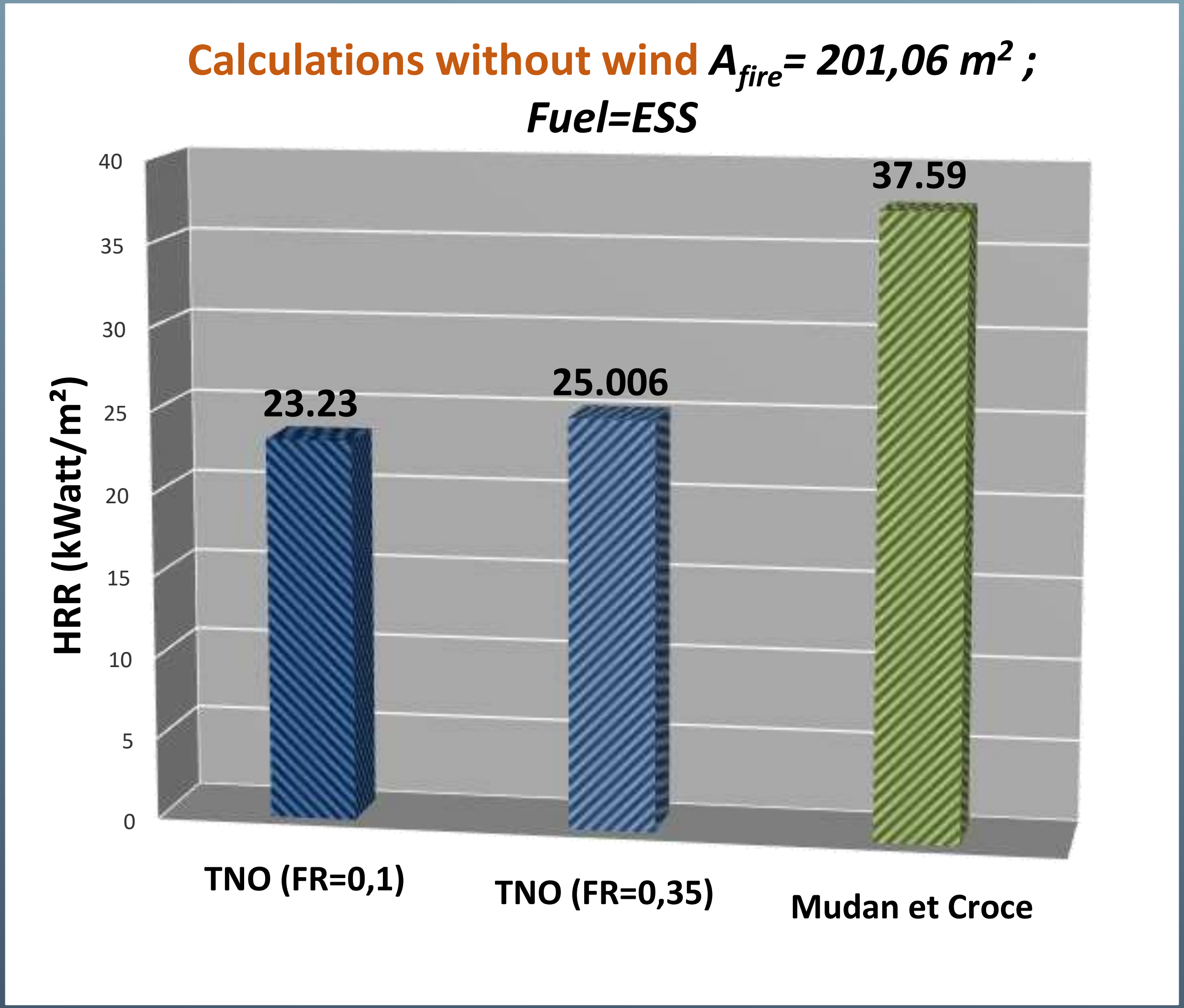
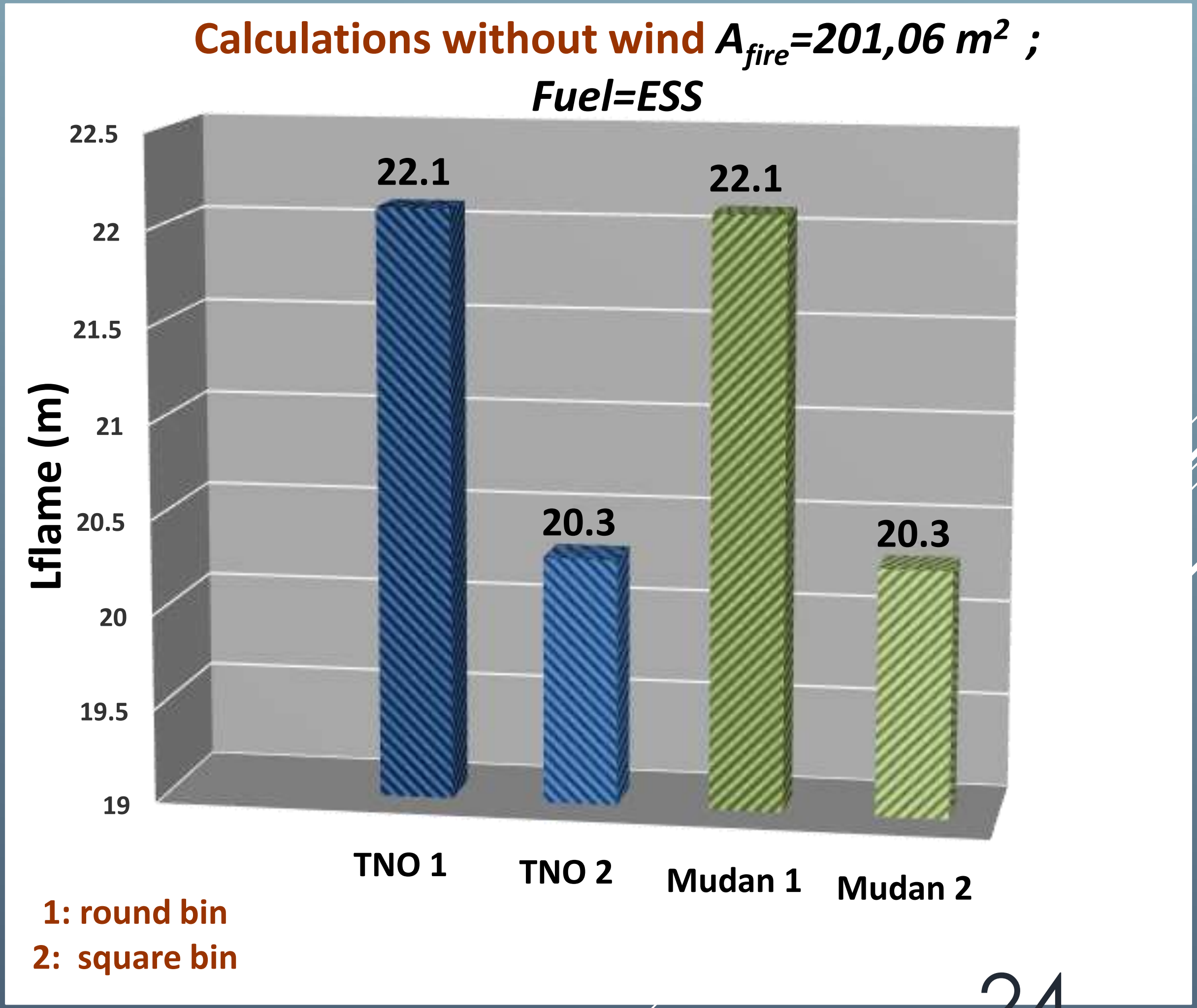
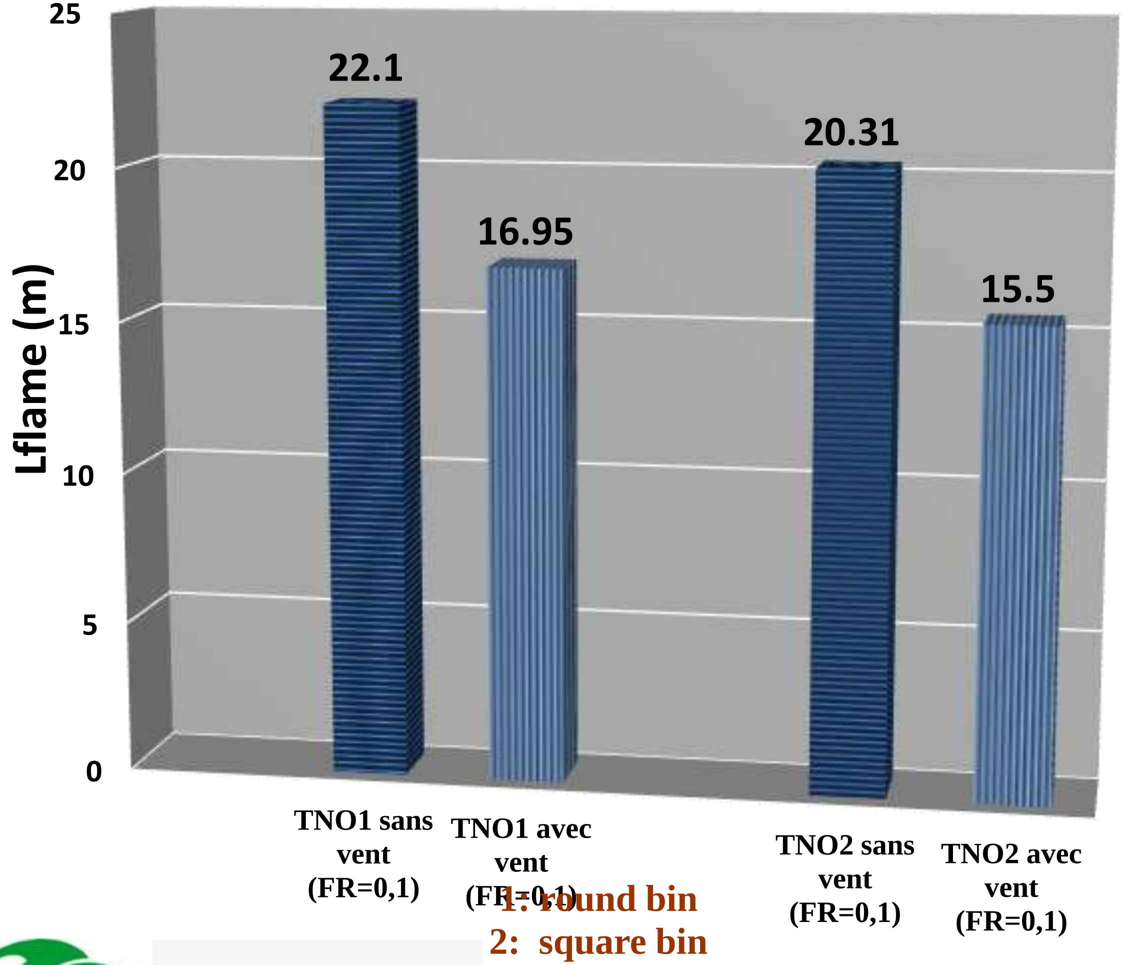
Calculations for the case of a Super Gasoline tank (Scenario 2)

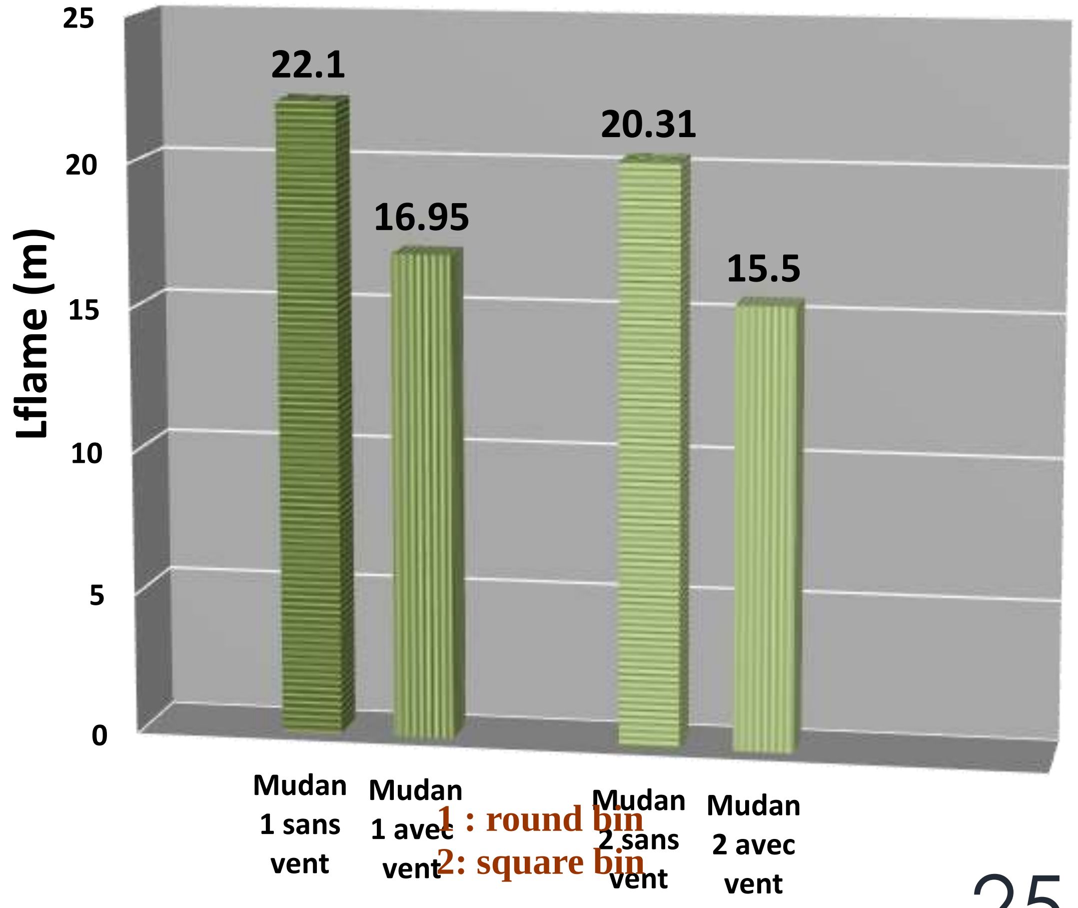




Calculations with wind A_{fire}=201,06 m²; Fuel=ESS



Calculations with wind A_{fire}=201,06 m²



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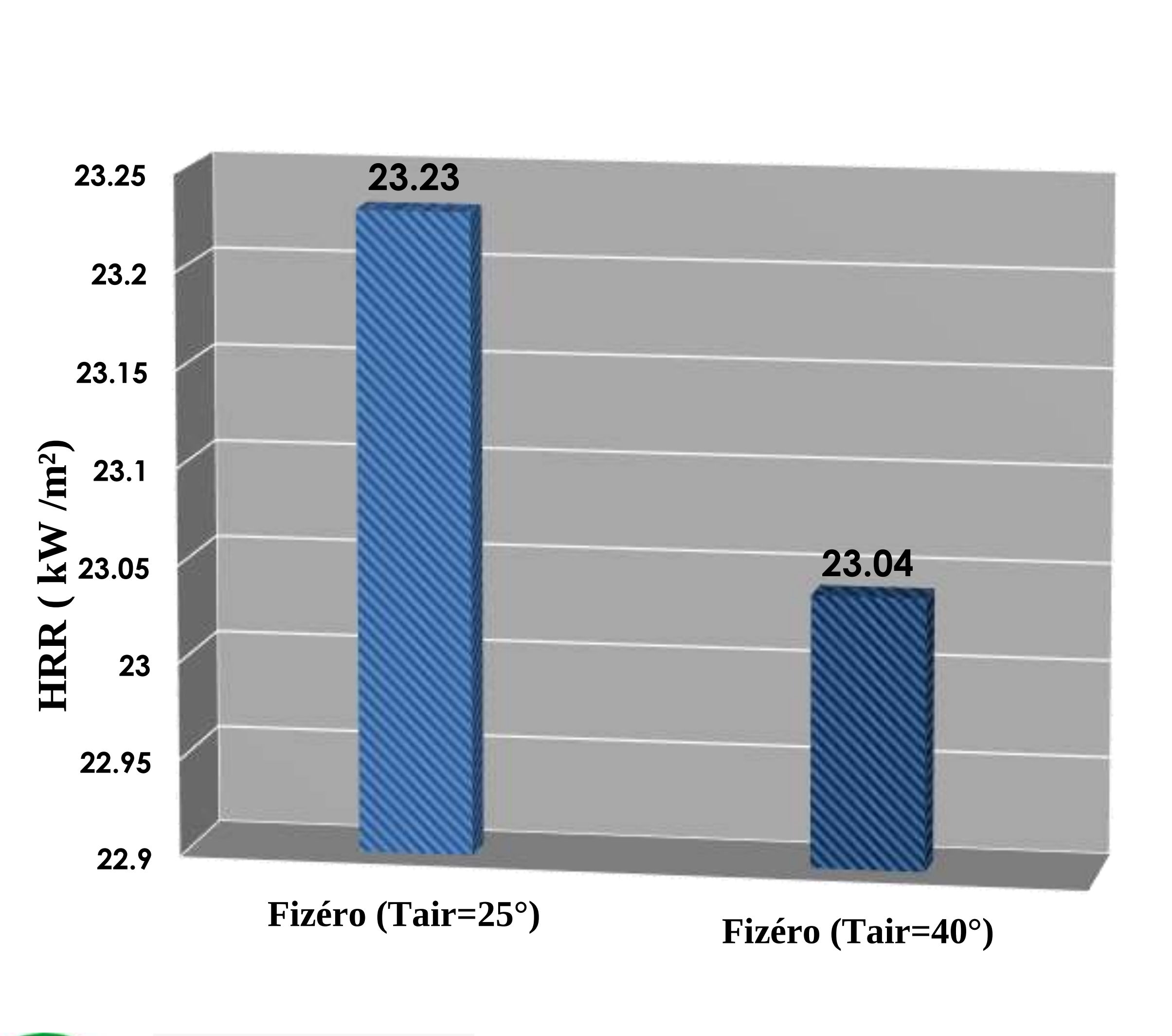
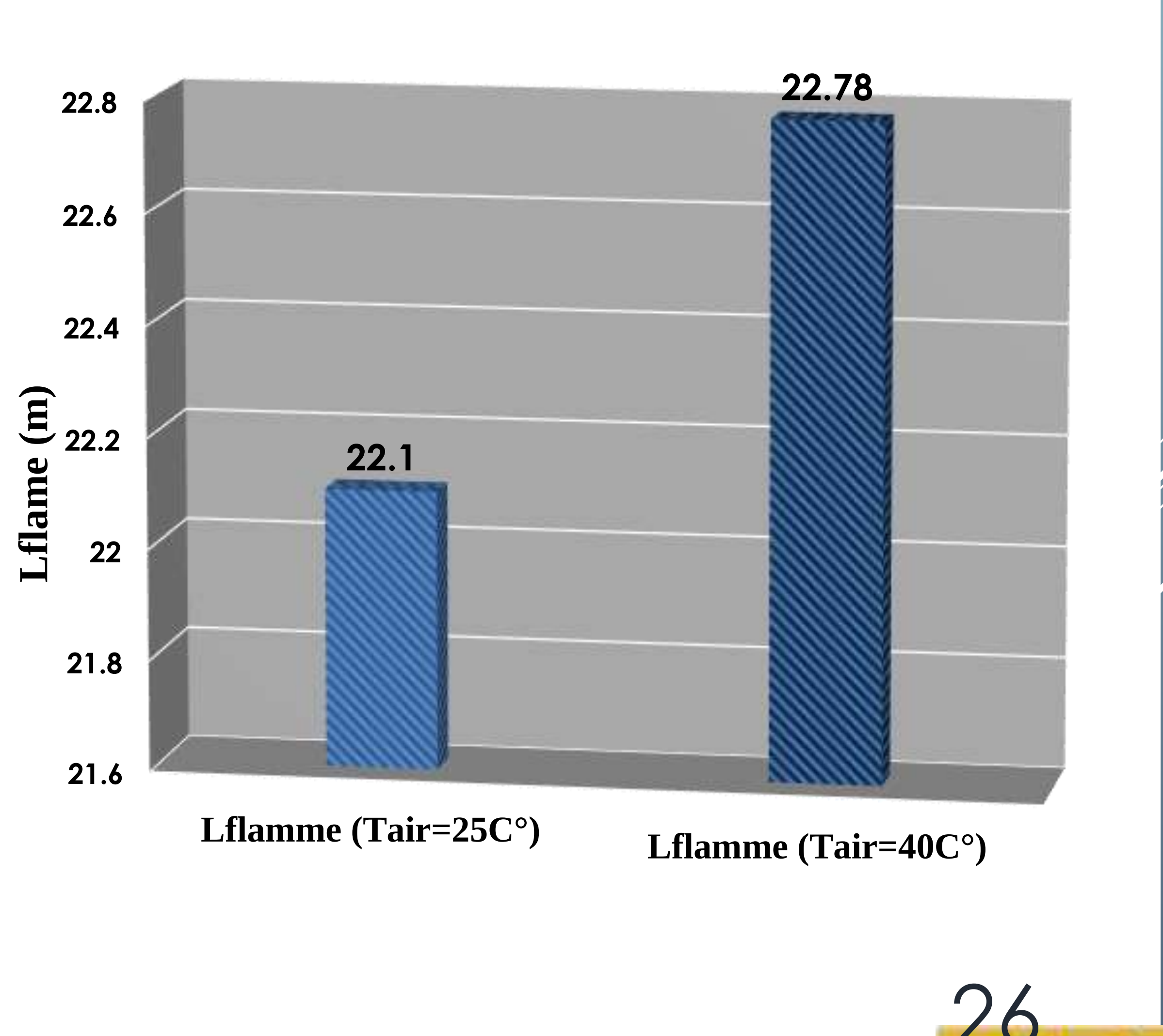
Effect of air temperature on pool HRR





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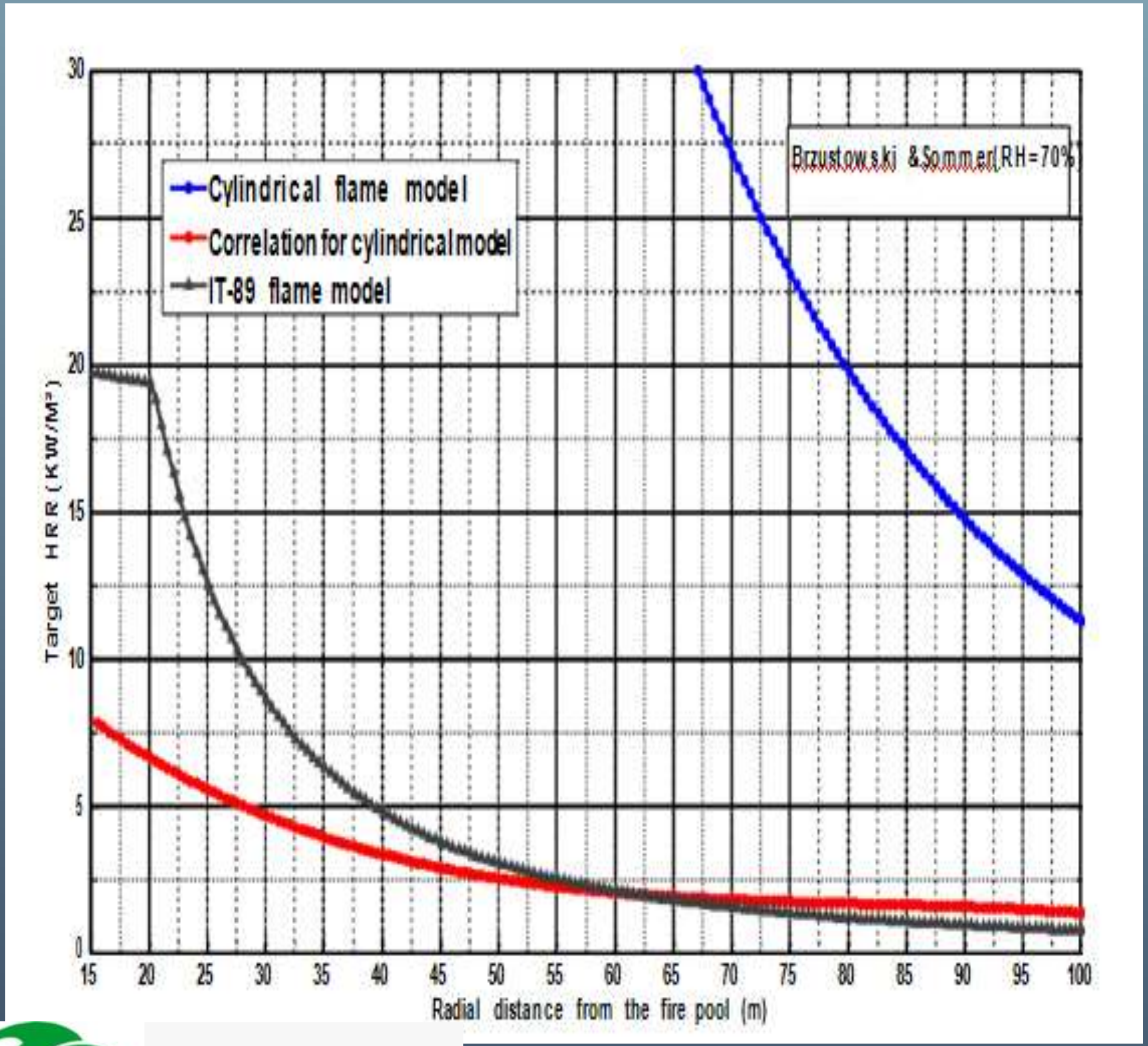
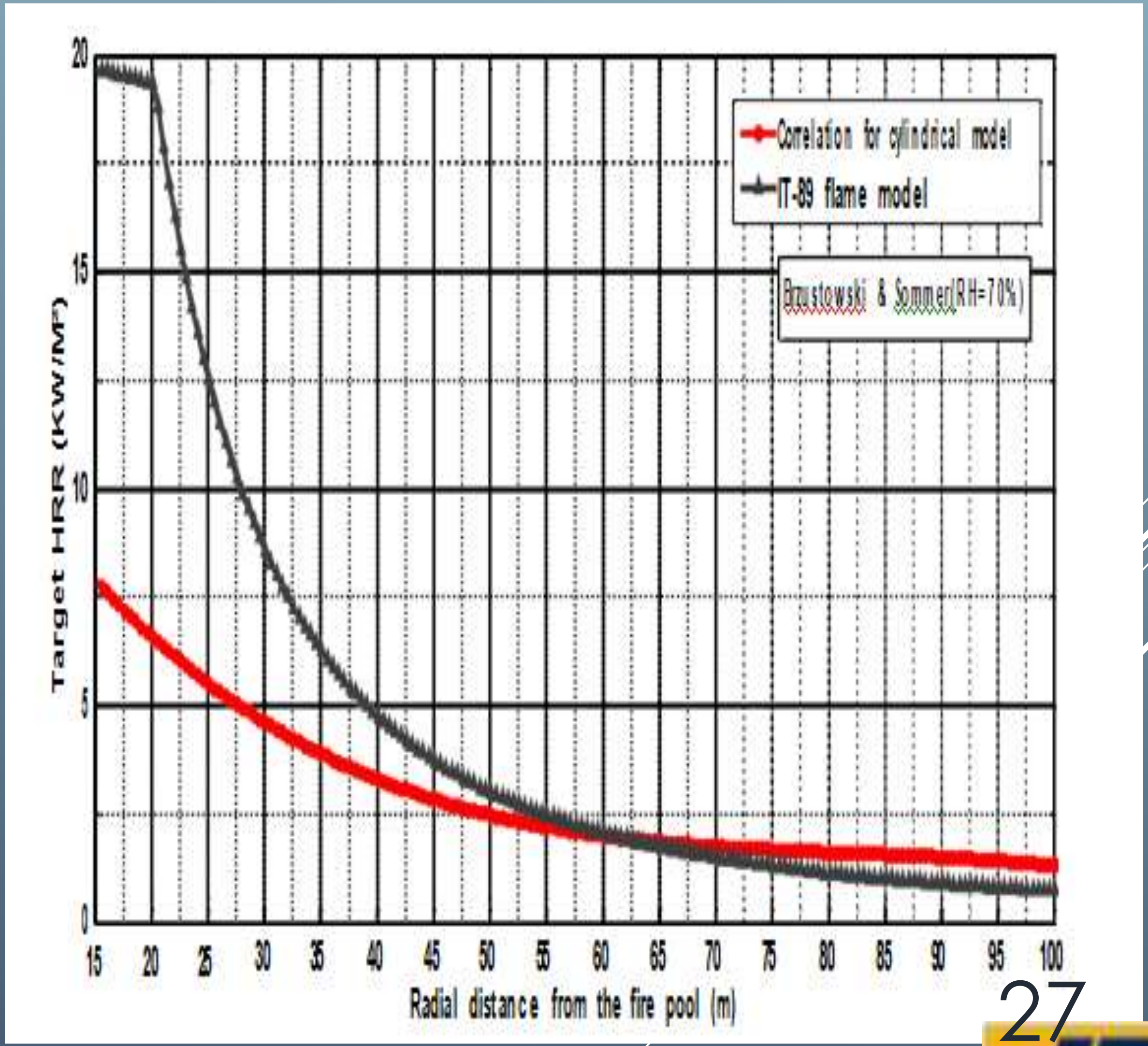
Target HRR .vs. distance (scenario 1)





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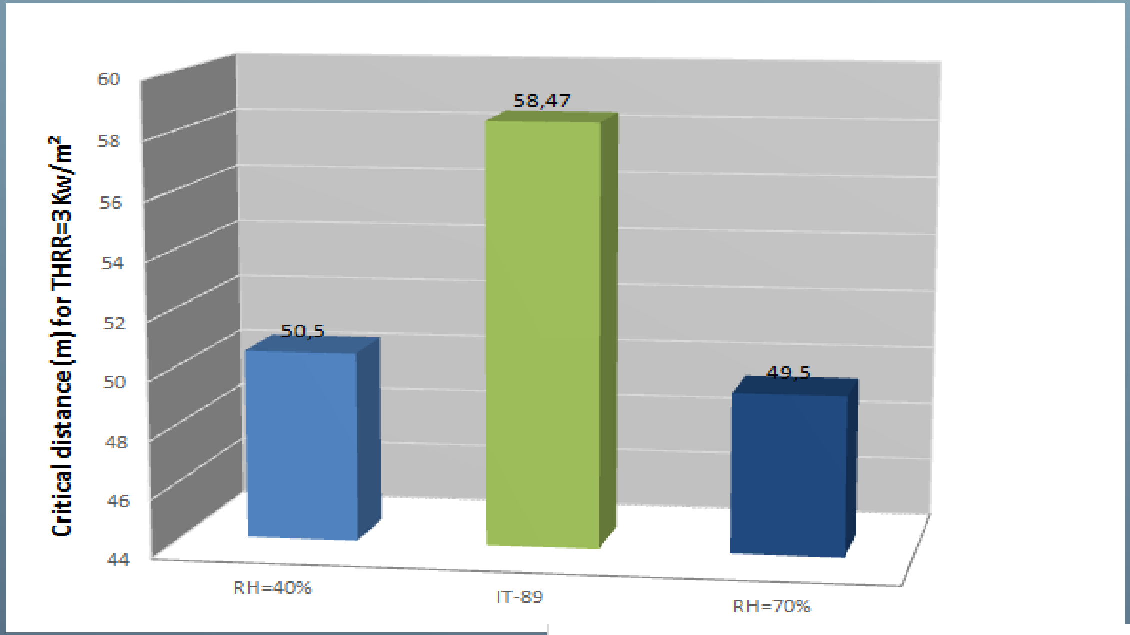
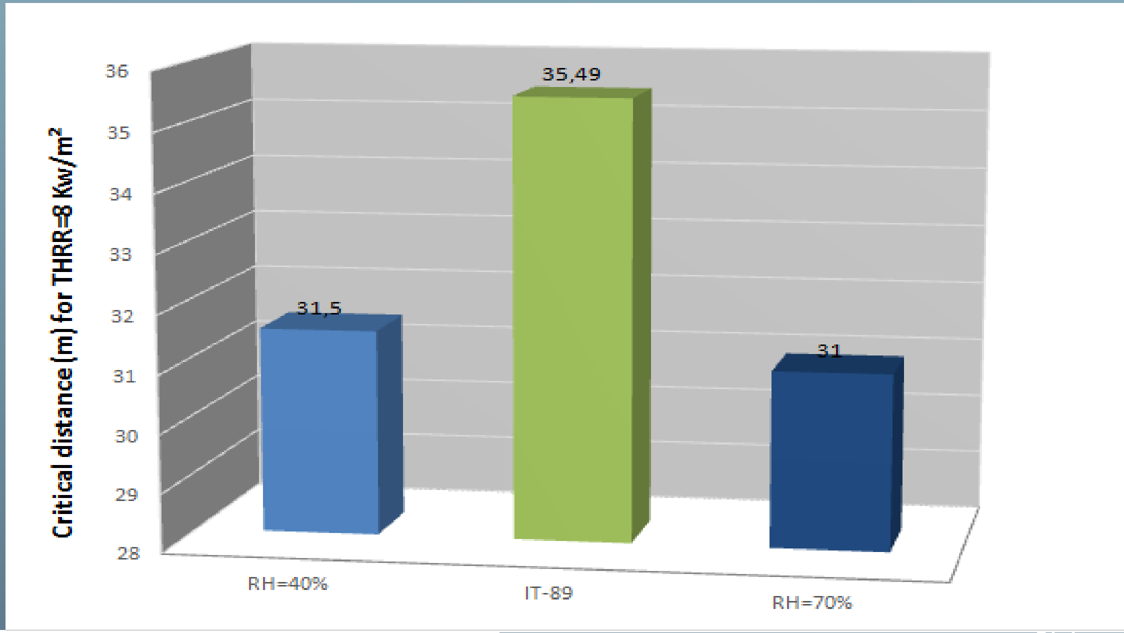
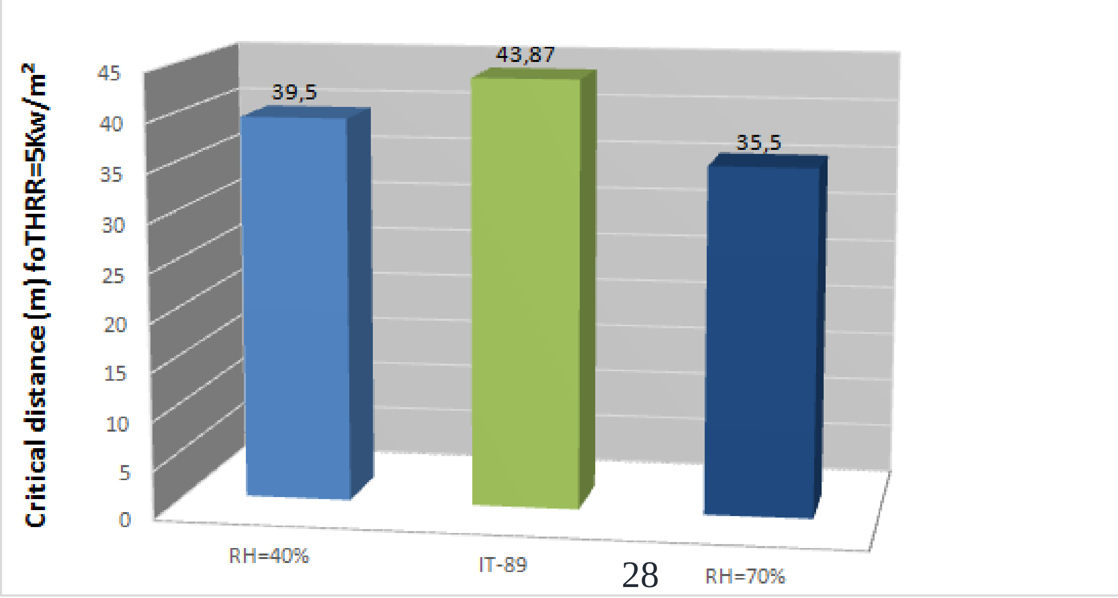
Relative humidity effects on critical distances values







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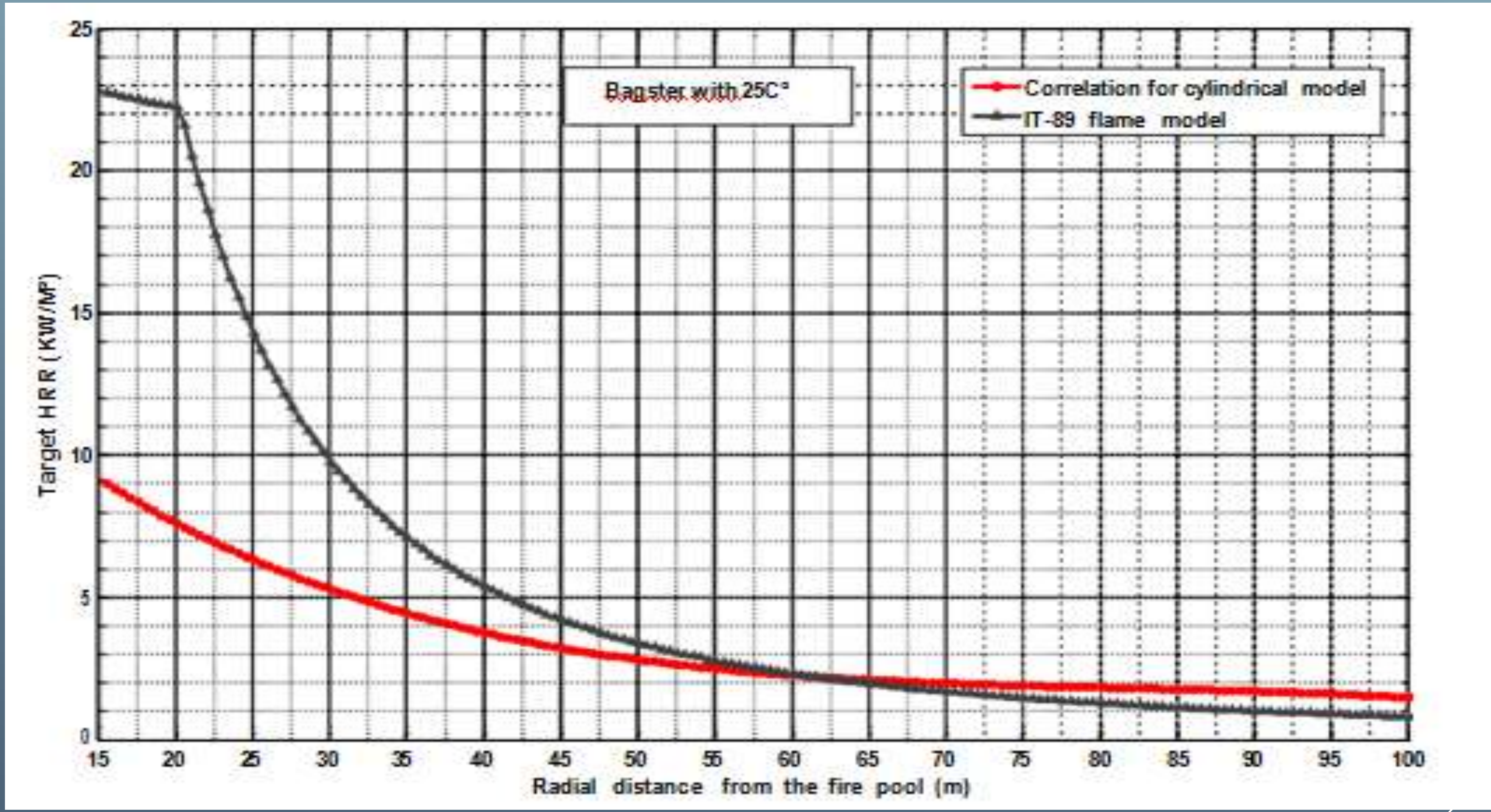
Effects of T_{air} on effect distances



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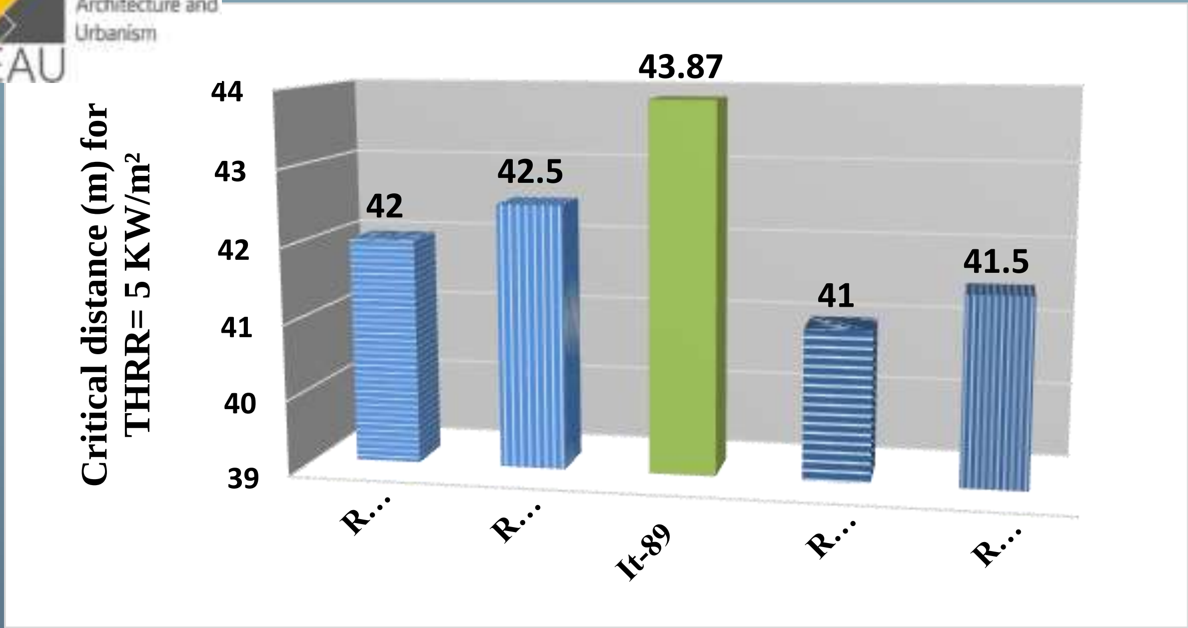
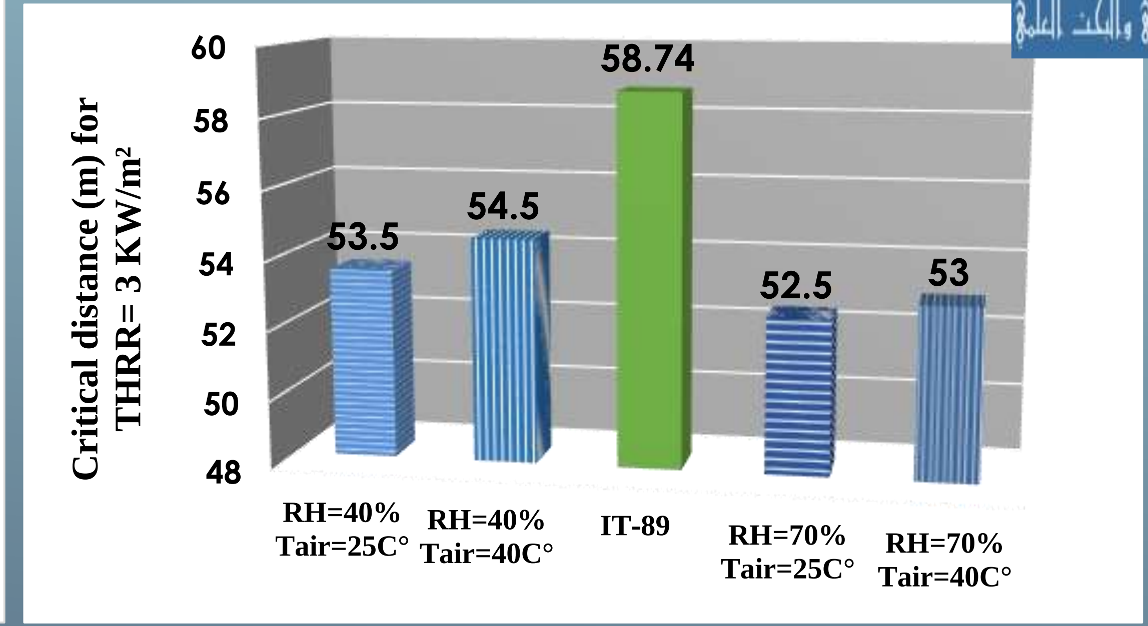
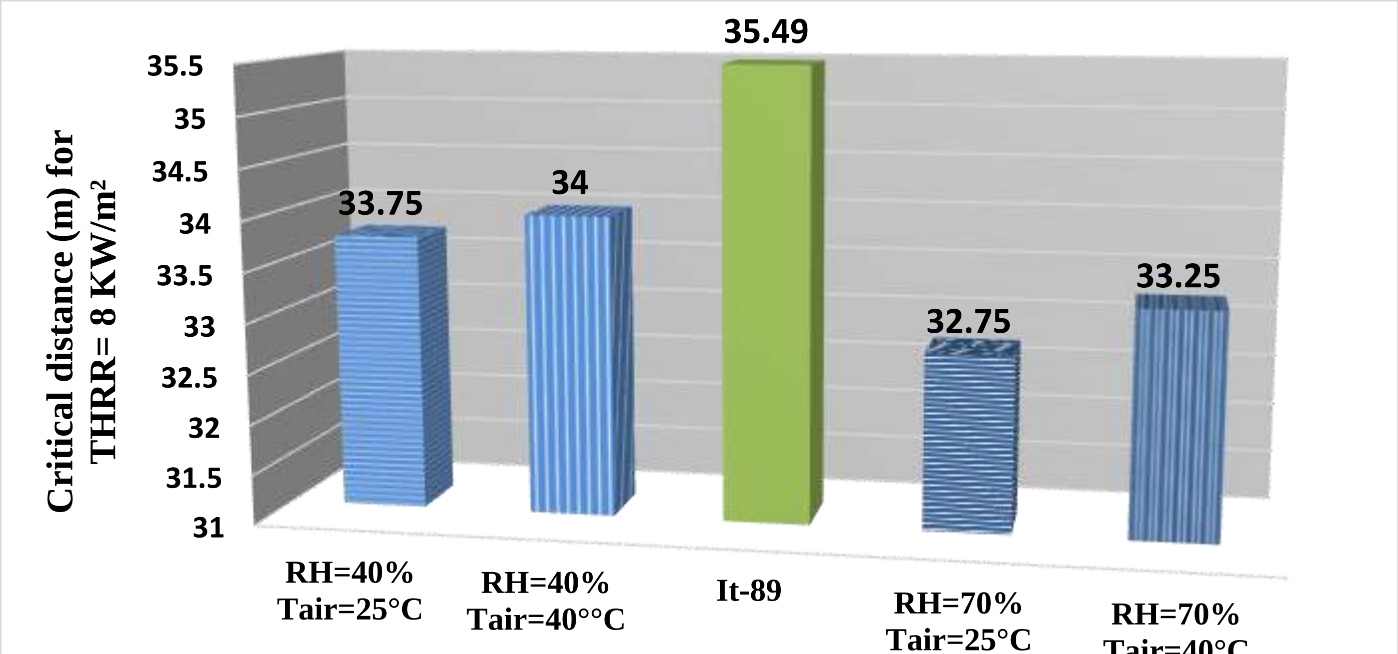




The following histograms show the effect of temprature and relative humidity on the effect distances



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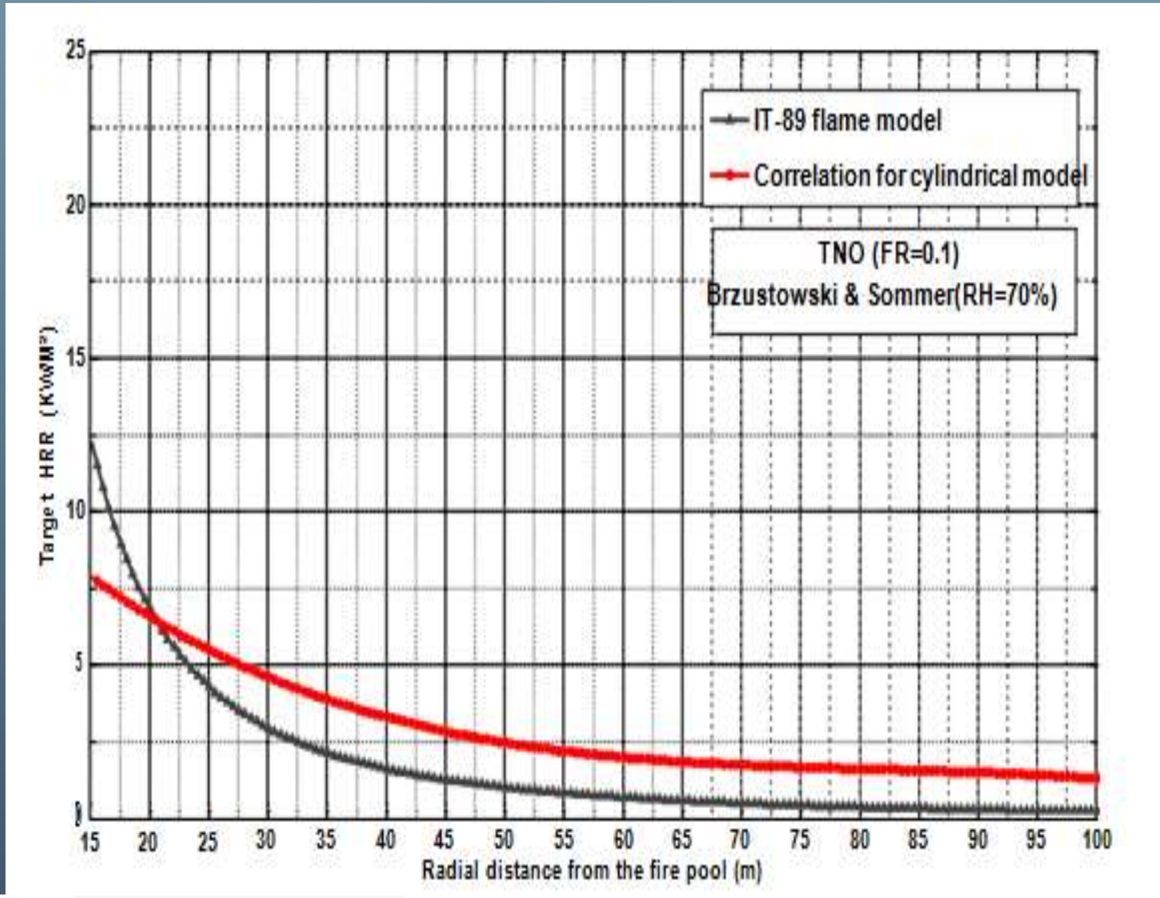
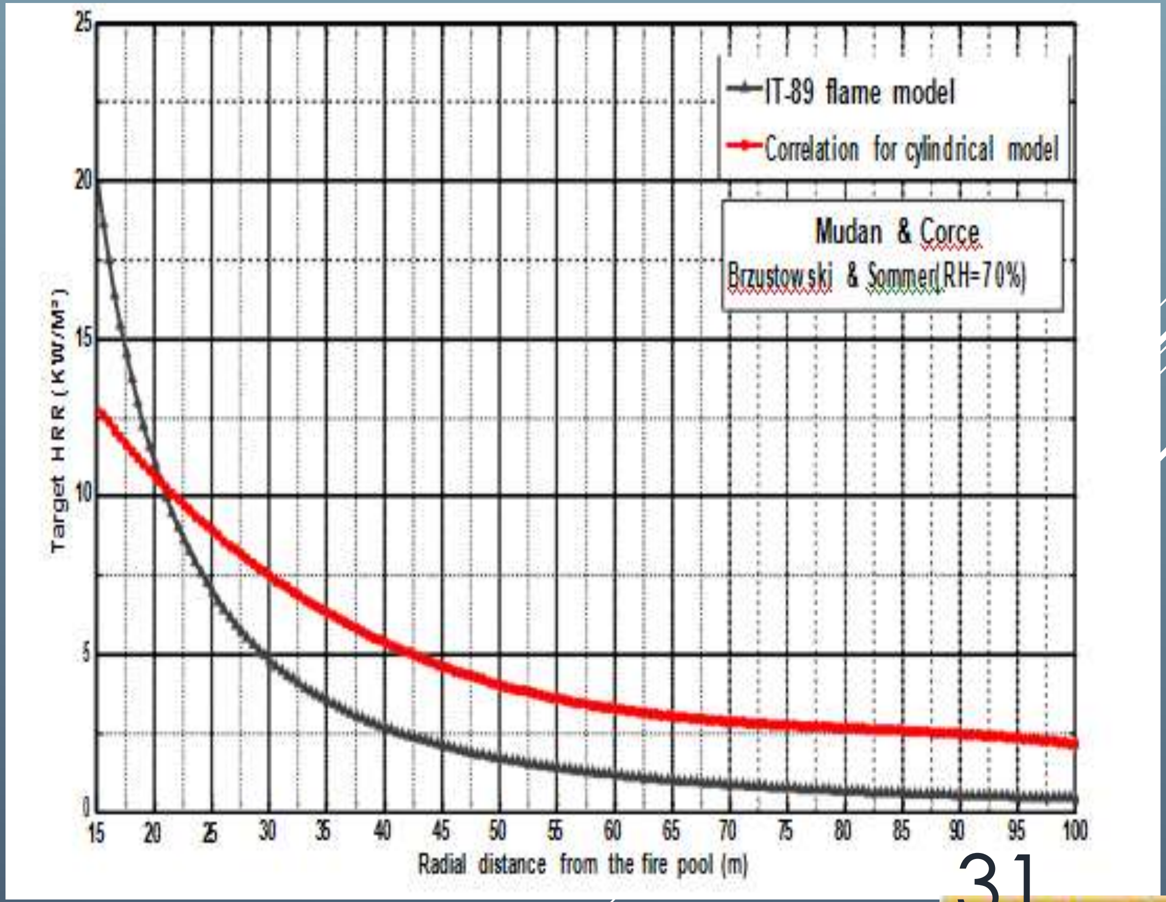
Distribution of HRR. vs. distance (Scénario 2)

Heat flux (TNO) and (Mudan & Corce) as a function of the distance between the target and the flame front





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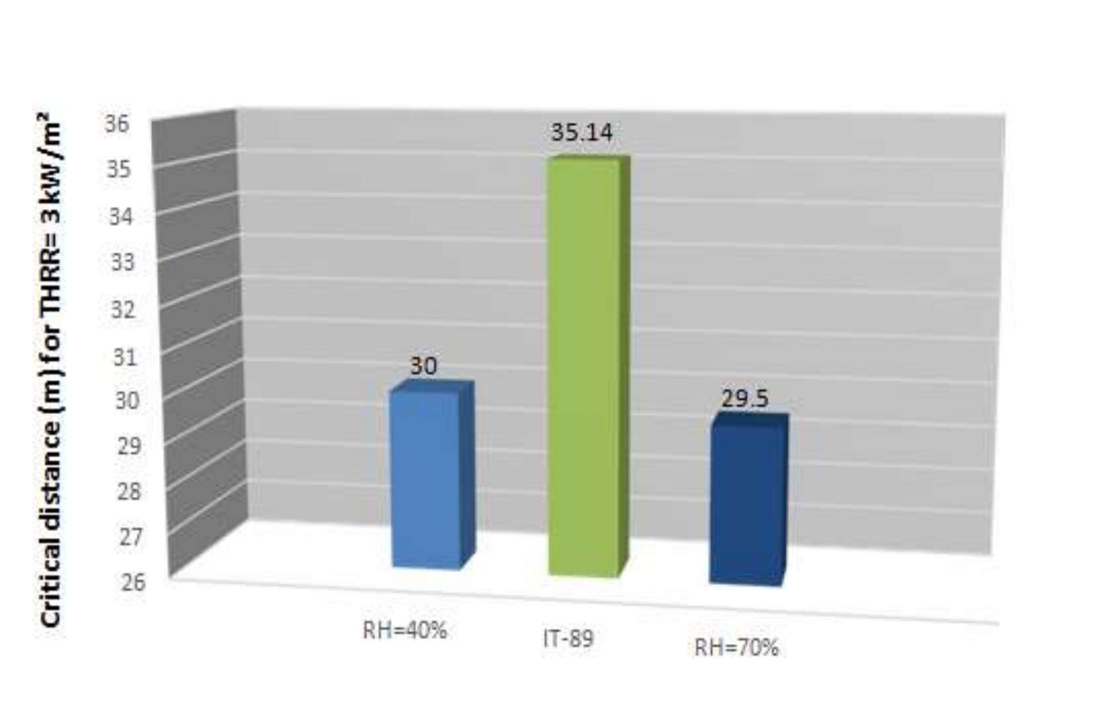
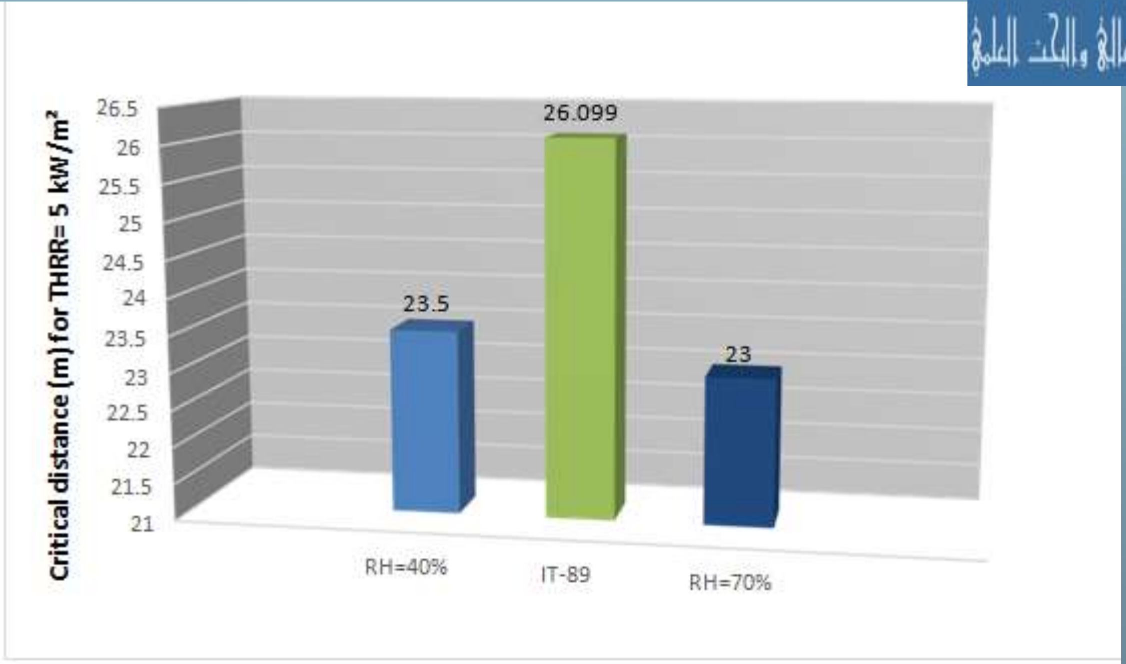
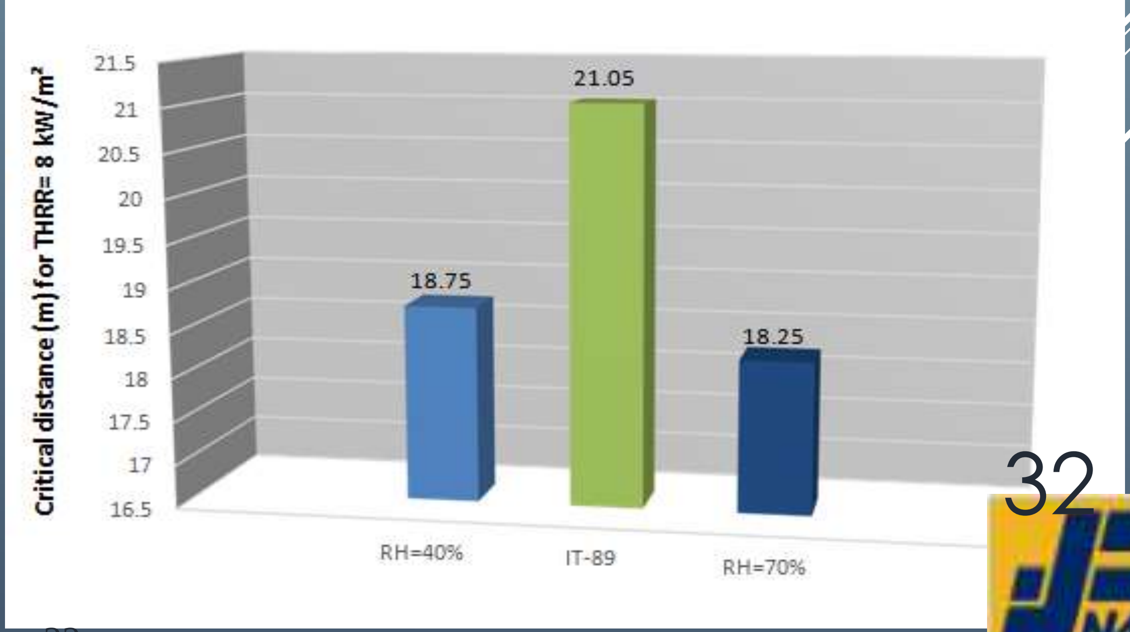
Relative humidity (RH) on distances







Effect of the air temperature on the critical distance for a heat release rate of 3kW/m,5kW/ m et 8kW/m

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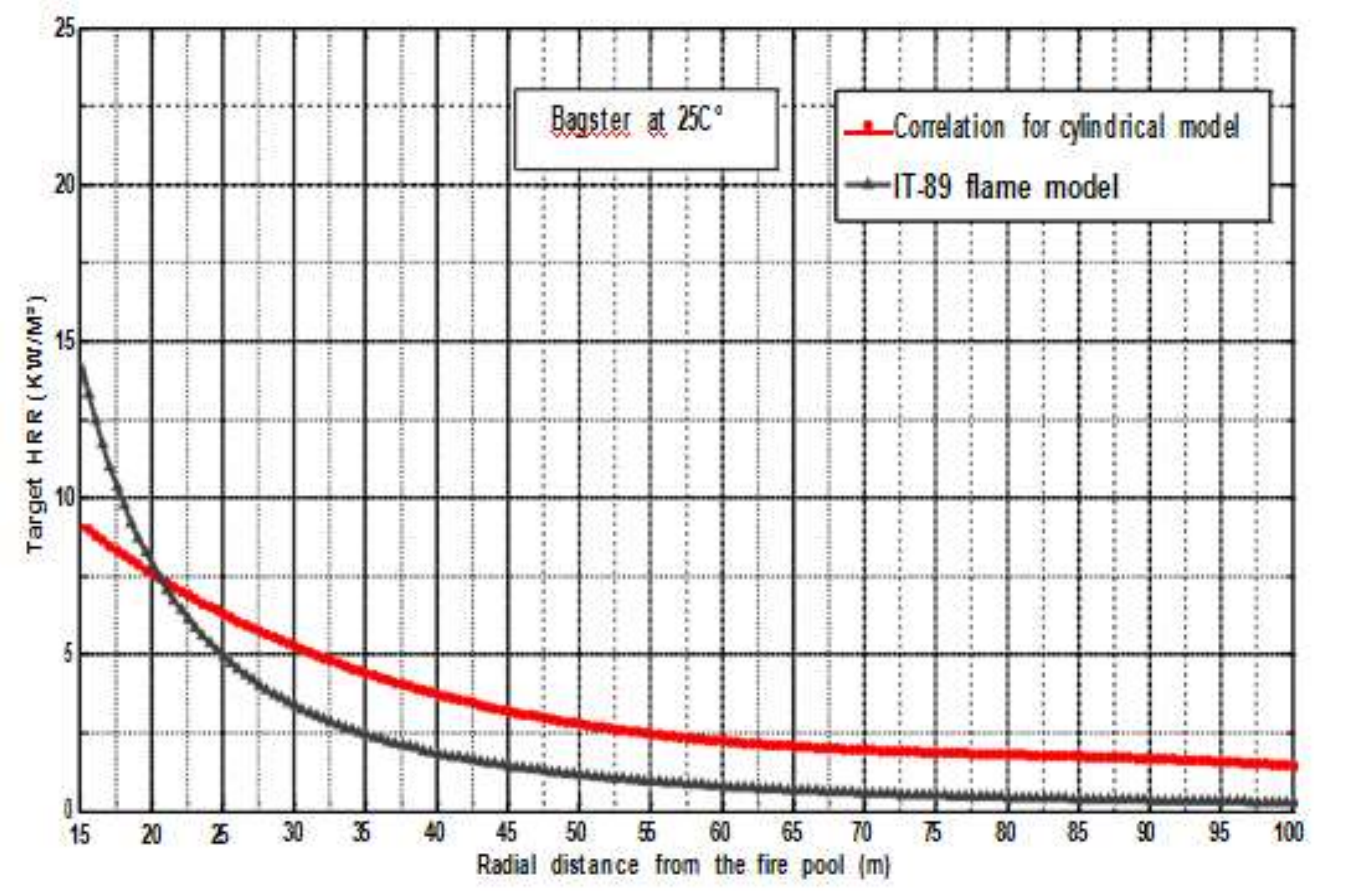
Effects of T_{air} on distance



Distribution of the heat release rate as a function of the distance between the target and the flame front

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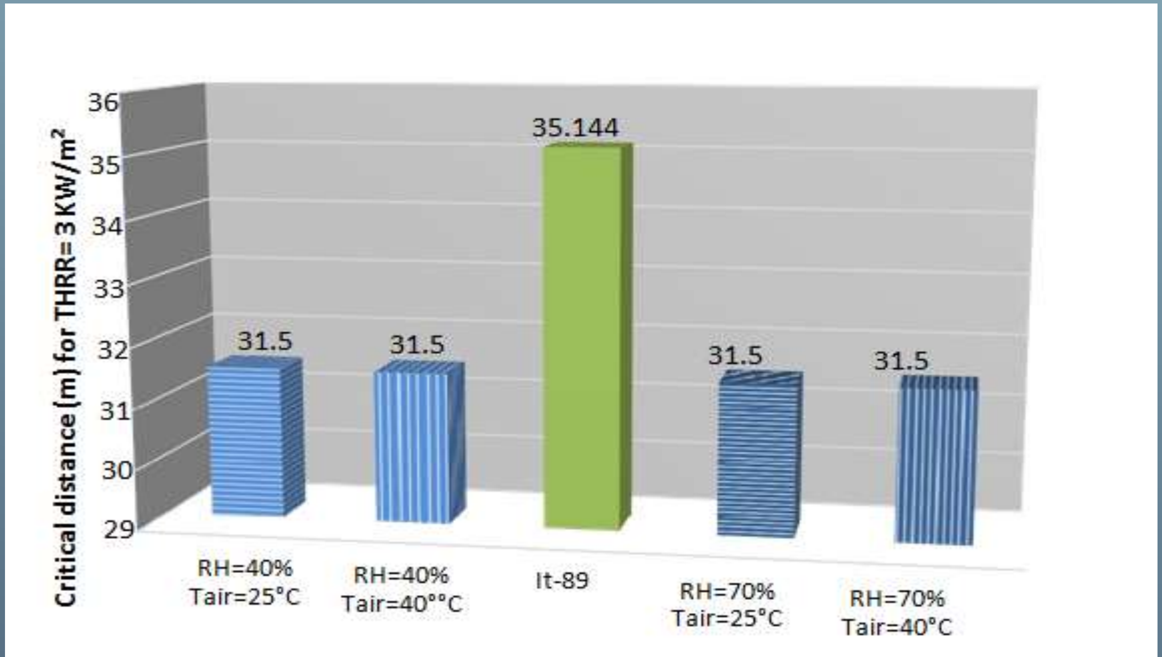
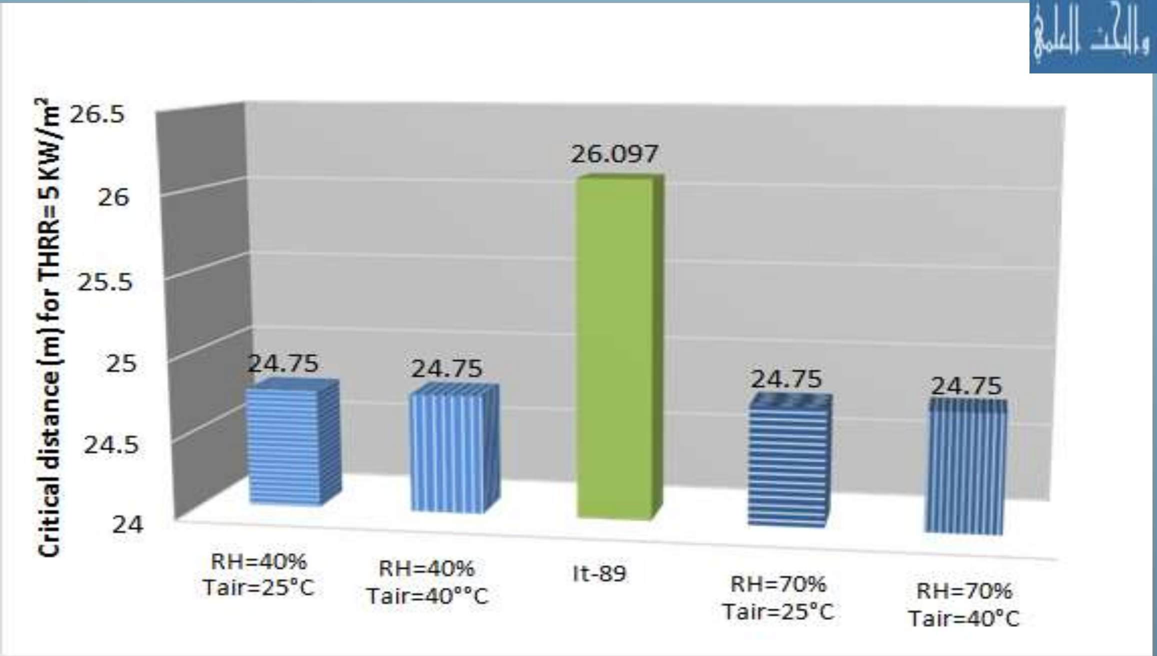
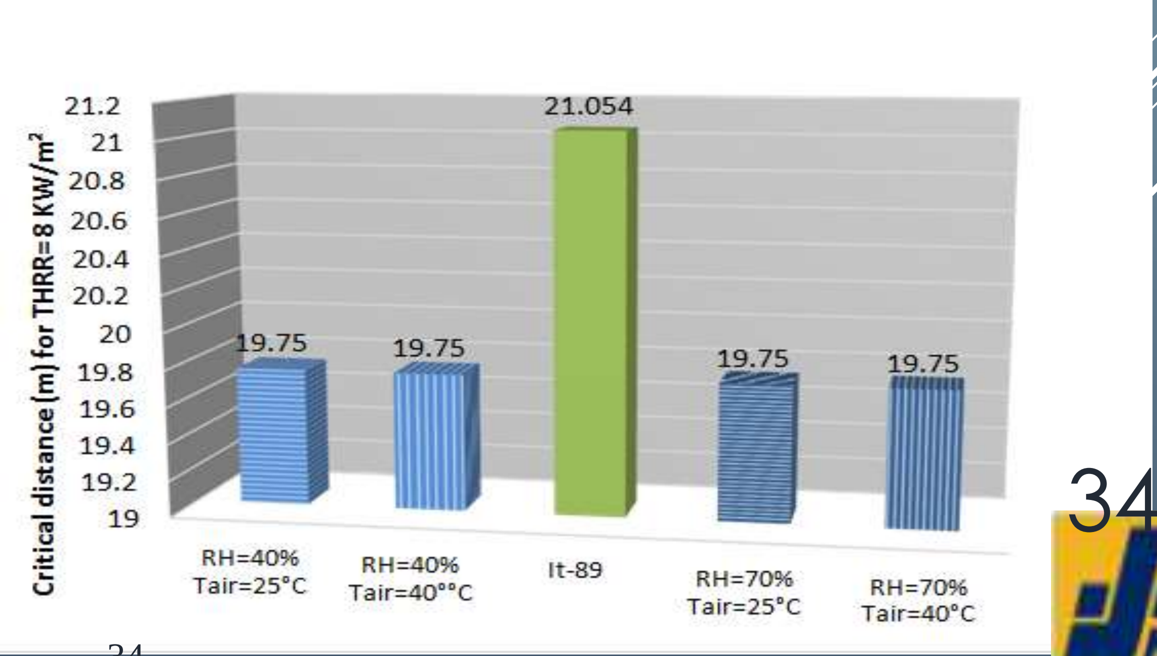
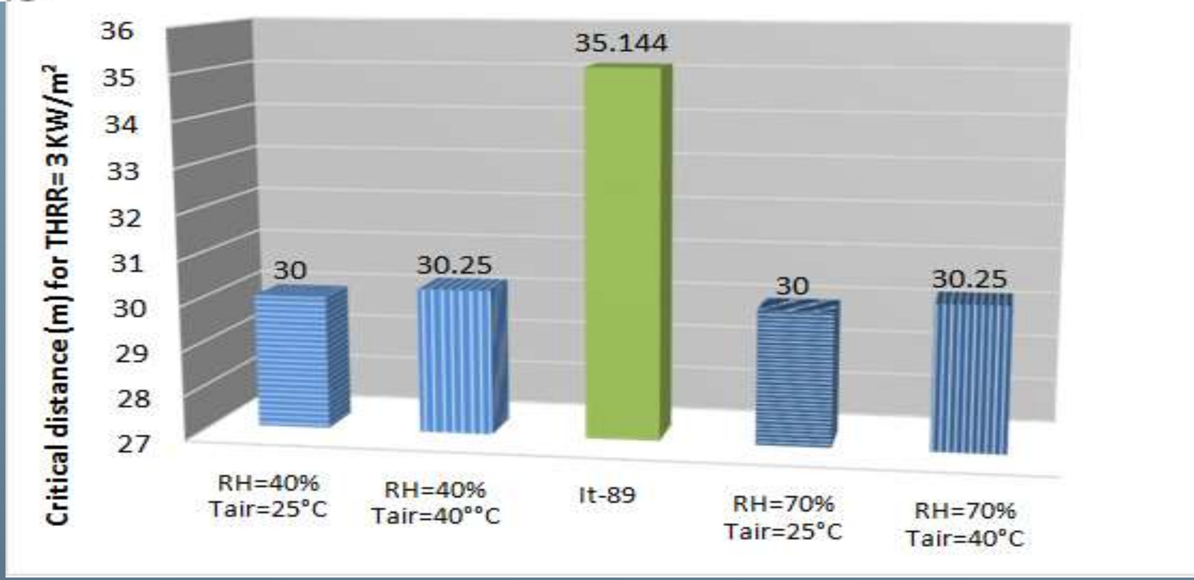


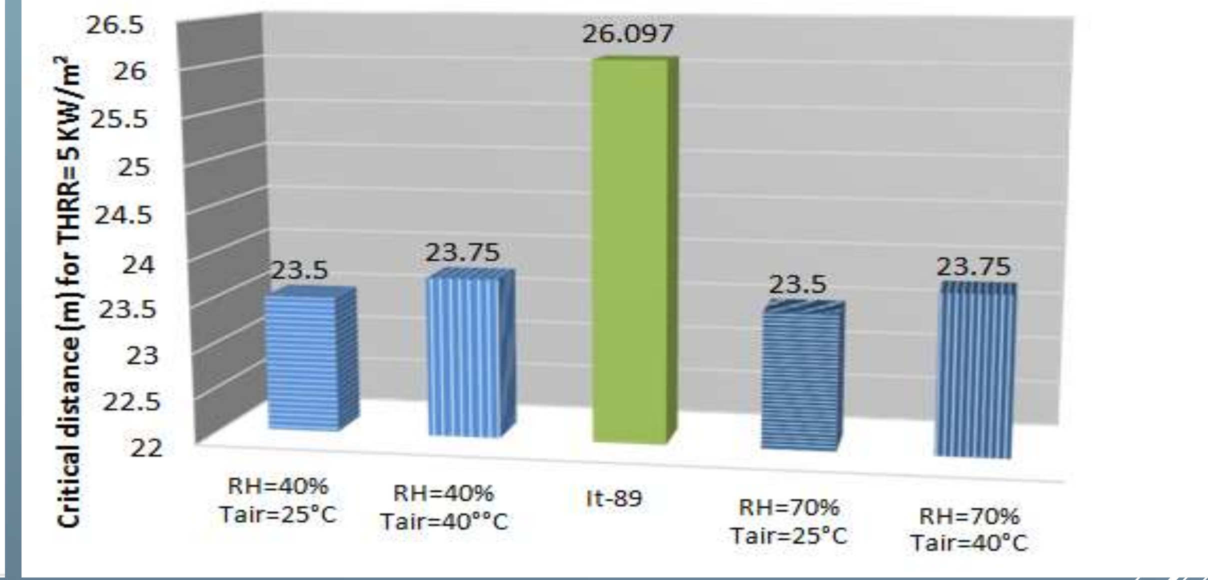


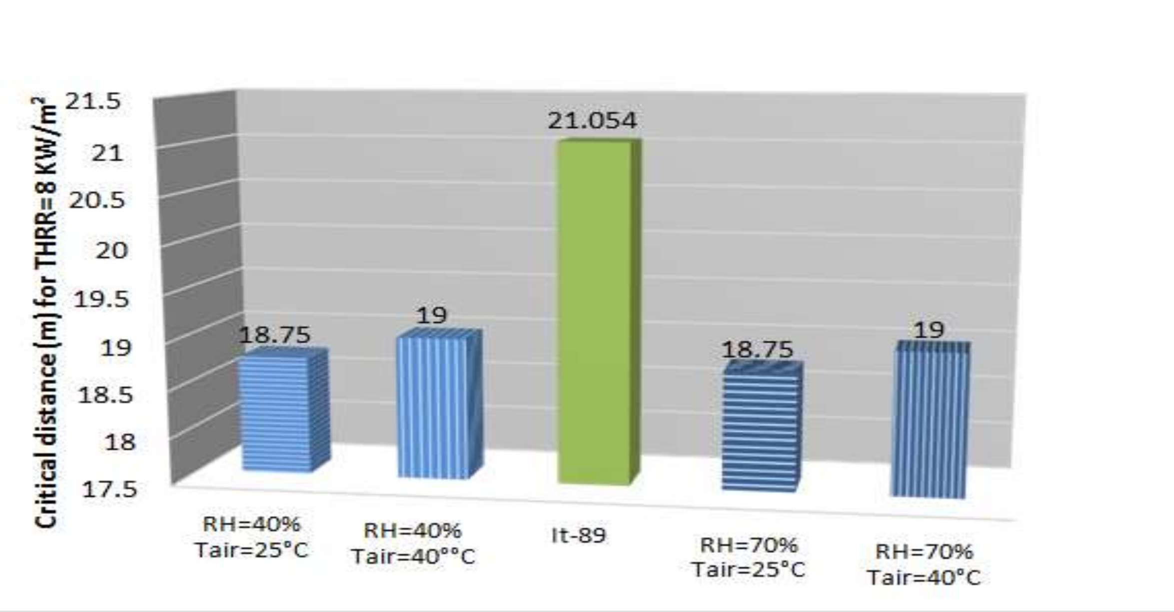


Effect of the air temperature on the critical distance for a heat flux of (round bin)

3kW/ m, 5kW/m et 8kW/m







Effect of the air temperature on the critical distance for a heat release rate of (square bin)

3kW/ m, 5kW/m et 8kW/m

35

The type of view factor (plane or cylindrical) will be chosen according to the different types of fire (the geometry of the pool on fire).

For Fizéro's, Mudan's and Croce's calculations is the most suitable model but for large surface fire tanks; on the other hand for small surfaces the model of TNO is the most adapted in which the effects with wind and without wind are both important.

CONCLUSIONS

For the atmospheric transmissivity factor, we see that it is advisable to specify the absolute humidity of the site in the Lannoy model which does not seem suitable for small distances, on the other hand the Bagster and Brzustowski and Sommer models appear to be Being the most suitable models for the evaluation of GammaAir in the humidity value has little influence on the atmospheric transmissivity factor.

It was also noted that the effect distances in the values of the regulatory thresholds for heat fluxes are 3kW / m², 5 kW / m² and 8kW / m calculated by us are smaller compared to the distances of IT-89 in both case RH = 40% and RH = 70%.

THANK YOU FOR YOUR ATTENTION