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# FIRE DYNAMICS IN OPEN COMPARTMENTS

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## ABSTRACT

With the aim to increase fire safety in open compartments, such as open car parks, some correlative models were used to test the ability to recover both dynamics and thermal characteristics of a ceiling-jet flow. The heat flow, coming from a burning vehicle, occurs when the fire plume impinges the ceiling and develops in the radial direction of the fire axis. Both temperature and velocity predictions are decisive for sprinklers positioning, fire alarms positions, detectors (heat, smoke) position and activation times and back-layering predictions. This investigation deals with a parametric analysis using different fire events (class of the vehicle) and two fire scenarios. Some correlative formulations were used: Alpert, Cooper, Heskestad & Delichatsios and Motevalli & Marks. An advance calculation method (CFAST) based on a two-zone model formulation was used to compare the results, as well as the CFD software ANSYS Fluent, based on the finite volume method. A total of 16 simulation results were obtained taking into consideration 2 different heights for the compartment (H=3m and H=5m), 4 different car classes (fire events), 6 radial positions (R) and two software (CFAST and ANSYS Fluent). The correlative model from Motevalli & Marks overestimates the dynamic characteristics in small compartments. The two zone model overestimates the maximum temperature in the biggest compartment and the CFD results for temperature and velocity are always higher than the other calculation methods.

***Keywords:*** open car parks, ceiling jet; correlative models, two zone models (CFAST), field models (ANSYS Fluent)

## INTRODUCTION

Fire events in car parks have been a major problem for buildings, vehicles and humans. The main causes of fire propagation are the combustible materials of the vehicles. The estimate time for fire propagation has been experimentally determined to be 12 minutes (D. Joyeux *et al*., 2002) or 15 minutes between vehicles, according to the recommendation of European Convention for Constructional Steelwork (ECCS, 1993).

A statistical analysis showed that the car class is important and 90% of the vehicles involved in fires are classified as class 1, 2 or 3 (Schleich *et al*., 1999). Another research project based on statistical analysis (D. Joyeux *et al*., 2002) say that approximately 98% of the fires were restricted to less than 4 cars, 4 cars were burning in only 2 cases, while 1 fire involved 5 cars and 2 fires involved 7 cars. A research revealed that approximately in 97% of the fires only 1 burning car was involved (Li Yuguang *et al*., 2007). The Building Research Establishment (BRE, 2010) developed a study of 3096 fire events developed during 12 years, where 51% started with the ignition of a car, but in most cases, no fire spread to other cars was identified.

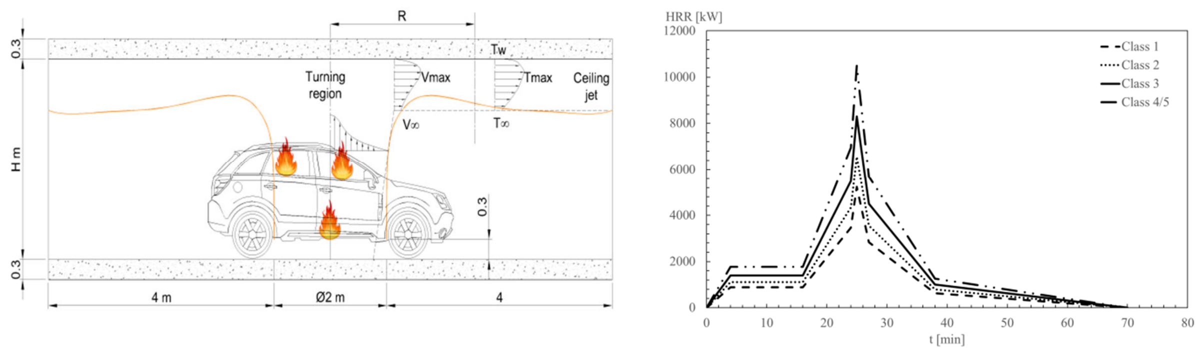
However, contradicting the statistics, 1400 cars were destroyed due to a big fire event at the Liverpool Echo Arena on the 1st of January of 2018. The fire is reported to have reached temperatures of 1000 ºC and the building presents a huge damage level on slabs and other structural elements.

The detection of a fire in a compartment while the fire is small enough to be easily controlled is one of the most important fire safety engineering issues. The velocity and temperature of the gases due to the fire in the compartment are the two main dynamic characteristics that must be considered in fire events. These predictions are decisive for the position of sprinkler, fire alarms and detectors (heat and smoke).

The aim of this paper is to test the ability of four correlative models (Alpert, Cooper, Heskestad & Delichatsios, Motevalli and Marks) on the dynamic and thermal characteristics of the ceiling jet flow, comparing the results to the software CFAST (two zones model) and ANSYS Fluent (field model). Four vehicle classes in different fire scenarios in open car parking were considered for analysis.

## SOLUTION AND METHODS

According to car fire experiments, most of the flames extend from the wind screens of the vehicles, describing a cylindrical plume zone with 2m on diameter, see Figure 1(a). The Heat Release Rate (HRR) also was obtained by car fires experiments. Figure 1(b) shows a comparison of the HRR curves for different classes. As the figure shows, the HRR of class cars 4 and 5 have the same values in time. The HRR of all the fire events increases from zero to a maximum value in time equal to 25 minutes and decreases to zero at the end of the event.




(a) (b)

Fig, 1 - (a) Model and parameter values under analysis. (b) HRR for different class of cars.

Correlative models are used to estimate temperatures and velocities of the hot gases in a ceiling jet flow. This can help safety engineering to obtain an estimate prediction of sprinkler and fire detectors activation, as well to estimate damage to the structure and ceiling. There are a few correlations models for ceiling jets available for different applications. This investigation is focused on the correlative models of Alpert, Cooper, Heskestad & Delichatsios and Motevalli & Marks.

Alpert (Alpert, 1972) developed correlations for the maximum gas velocity and temperature in jet flows induced by large-scale fires. The correlations are based on the ceiling height above the surface of the fuel, also consider the real HRR of the fire and are valid for the plume zone and for the ceiling jet zone, see Eqs. 1-4.

$$V_{max} = 0,197\frac{\dot{Q}^{1/3}\,H^{1/2}}{R^{5/6}}, \qquad if\ R/H > 0,15 \qquad \text{Eq. 1}$$

$$V_{max} = 0,96\left(\frac{\dot{Q}}{H}\right)^{1/3}, \qquad if\ R/H \leq 0,15 \qquad \text{Eq. 2}$$

$$T_{max} = T_{\infty} + 5,38\frac{\left(\dot{Q}/_{R}\right)^{2/3}}{H}, \qquad if\ R/H > 0,18 \qquad \text{Eq. 3}$$

$$T_{max} = T_{\infty} + 16,9\frac{\dot{Q}^{2/3}}{H^{5/3}}, \qquad if\ R/H \leq 0,18 \qquad \text{Eq. 4}$$

Where $T_{\infty}$ is the ambient temperature, $\dot{Q}$ is the heat release rate of the fire, $H$ is the height of the ceiling and $R$ is the radial centre line distance of the flame. The velocity in the ceiling jet region ($R/H > 0,15$) and temperature in the same location ($R/H > 0,18$) depend on the radial centerline distance of the flame. The velocity in the plume zone ($R/H \leq 0,15$) and temperature in the same location ($R/H \leq 0,18$) depend also on the geometry of the compartment (height).

In 2011, Alpert (Alpert, 2011) reviewed the previous equations, based on the knowledge of the flame's virtual origin. The new correlations were formulated using the ceiling height above the virtual origin and the convective heat release rate $\dot{Q}_c$, as well as the Heskestad and Delichatsios equations, see Eqs. 5-8. For $r/H \leq 0,15$ and $r/H \leq 0,18$, the equations were not modified.

$$V_{max} = 0,215\frac{\left(\dot{Q}_c/_{H}\right)^{1/3}}{\left(^{r}/_{H}\right)^{1,003}}, \qquad if\ r/H > 0,15 \qquad \text{Eq. 5}$$

$$T_{max} = T_{\infty} + 5,289\frac{\dot{Q}_c^{\ 1/3}\big/_{H^{5/3}}}{\left(^{r}/_{H}\right)^{0,611}}, \qquad if\ r/H > 0,18 \qquad \text{Eq. 6}$$

$$V_{max} = 0,2526\frac{\dot{Q}_c^{\ 1/3}}{(H-z_0)^{1/3}}\left(\frac{r}{H-z_0}\right)^{-1,0739}, \qquad if\ \frac{r}{H-z_0} > 0,246 \qquad \text{Eq. 7}$$

$$T_{max} = T_{\infty} + 6,721\frac{\dot{Q}_c^{\ 2/3}}{(H-z_0)^{5/3}}\left(\frac{r}{H-z_0}\right)^{-0,6545}, \qquad if\ \frac{r}{H-z_0} > 0,134 \qquad \text{Eq. 8}$$

Where $\dot{Q}_c$ represents the convective part of the HRR ($\dot{Q}_c$ =0,8$\dot{Q}$) and $z_0$ is the virtual origin, given by (Heskestad, 1995), Eq. 9.

$$z_0 = 0,083\dot{Q}^{2/5} - 1,02D \qquad \text{Eq. 9}$$

Where $D$ represents the diameter of the fuel source. The value $z_0$ can be negative (below of the fuel source), indicating that the area of the fuel source is large compared to the energy being released by the area. For fire sources where the fuel releases high energy in a small area, $z_0$can be positive (Karlsson; Quintiere, 2000).

Cooper developed correlations to estimate the properties of the flame and the characteristics results of the jet flow. Cooper's equations are valid when a part of the flame is flowing to the upper layer and reaching the ceiling (Cooper, 1982; Beyler, 1986), see Eqs. 10-12.

$$T_{max} = T_\infty + 28{,}1\dot{Q}^{2/3}H^{-5/3}\exp\left(-1{,}77\frac{R}{H}\right), \qquad if\ 0 \le R/H \le 0{,}75 \qquad \text{Eq. 10}$$

$$T_{max} = T_\infty + 5{,}77\dot{Q}^{2/3}H^{-5/3}\left(\frac{R}{H}\right)^{-0{,}88}, \qquad if\ 0{,}75 \le R/H \qquad \text{Eq. 11}$$

$$V_{max} = 0{,}26\left(\frac{R}{H}\right)^{-1{,}1} H^{-1/3}\dot{Q}^{1/3}, \qquad if\ 0{,}2 \le R/H \le 4 \qquad \text{Eq. 12}$$

Heskestad & Delichatsios developed correlations for maximum temperature and velocity based on subsequent tests of Alpert's analysis. Generally, the results of this correlation predict a higher gas temperature and velocity than the results using the equation proposed by Alpert (Evans, 2016). The expressions relate fire size, fire growth rate, height above fire, radial distance of fire, gas temperature and gas velocity. The proposed correlations are described below (Heskestad; Hamada, 1993; Evans, 2016; Mehaffey, 2003).

$$T_{max} = T_\infty + 2{,}75\left(0{,}188 + 0{,}313\frac{R}{H}\right)^{-4/3}\dot{Q}^{2/3}H^{-5/3}, if\ 0 < R/H \le 8 \qquad \text{Eq. 13}$$

$$V_{max} = 0{,}197\left(\frac{R}{H}\right)^{-0{,}63}\left(0{,}188 + 0{,}313\frac{R}{H}\right)^{-2/3} Q^{1/3}H^{-1/3}, if\ 0{,}4 < R/H \le 8 \qquad \text{Eq. 14}$$

Heskestad examined the experimental data and found that the centre line temperature and centre line speed obey the following equations (Karlsson; Quintiere, 2000).

$$T_{max} = T_\infty + 25\left(\frac{\dot{Q}_c^{\ 2/5}}{H - z_0}\right)^{5/3} \qquad \text{Eq. 15}$$

$$V_{max} = \left(\frac{\dot{Q}_C}{H - z_0}\right)^{1/3} \qquad \text{Eq. 16}$$

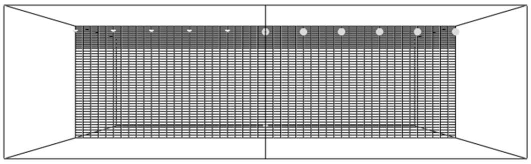
Motevalli and Marks performed detailed measurements using cross-correlation velocimetry for unconfined ceiling fire in transient and stationary conditions. The correlations of Motevalli and Marks are described below (Motevalli and Marks, 1991; Mehaffey, 2003).

$$V_{max} = 0{,}0415\left(\frac{R}{H}\right)^{-2}\dot{Q}^{1/3}H^{-1/3} + 0{,}427\left(\frac{R}{H}\right)^{-1}\dot{Q}^{1/3}H^{-1/3} + 0{,}281\dot{Q}^{1/3}H^{-1/3}, \qquad if\ 0{,}26 \le R/H \le 2 \qquad \text{Eq. 17}$$

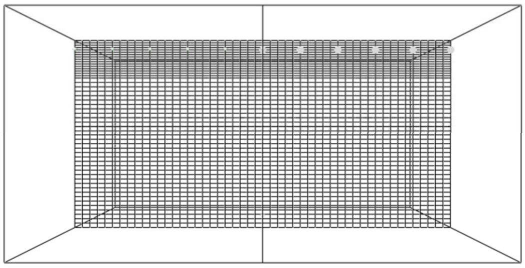
$$T_{max} = T_\infty + 0{,}23\left(\frac{R}{H}\right)^{-2}\dot{Q}^{2/3}H^{-5/3} + 5{,}2\left(\frac{R}{H}\right)^{-1}\dot{Q}^{2/3}H^{-5/3} + 2{,}7\,\dot{Q}^{2/3}H^{-5/3}, \quad if\ 0{,}26 \le R/H \le 2{,}0 \qquad \text{Eq. 18}$$

CFAST is a two-zone fire model that predicts the thermal environment caused by a fire within a compartmented structure. The main system inputs are: dimensions of the compartment, dimensions and positions of the horizontal and vertical flow openings (doors, windows and vents), ventilation specifications, fire properties and specifications of the sprinklers and detectors. The outputs of the program are: the conditions in the compartment, heat transfer to walls and targets, fire intensity, flame height, flow rates through openings and detector and sprinkler activation times (Peacock et al, 2017). A convergence test was performed for both compartments and the grid was defined as 50 for both compartments, according to Figure 2.

ANSYS Fluent software is a computational fluid dynamics (CFD) software which includes well-validated physical modelling and is capable of deliver fast and accurate results. The model boundary conditions for the four classes were obtained in the software CFAST for both compartments at a point located on the floor of the vehicle. The velocity and temperature are specified instead of the heat release rate, see Figures 3 and 4. This simplification is preferred in comparison to the adiabatic non-premixed combustion model (Robert Viall; Karl Wiegand, 2008).

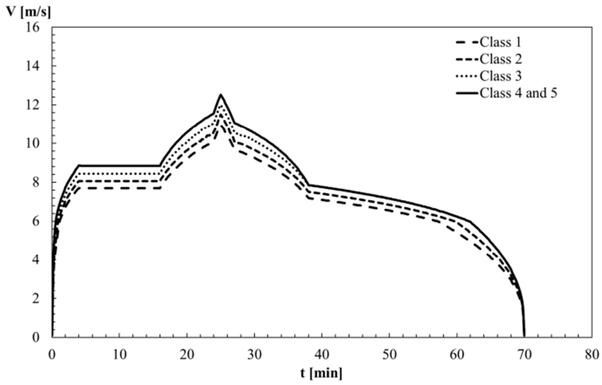


(a)

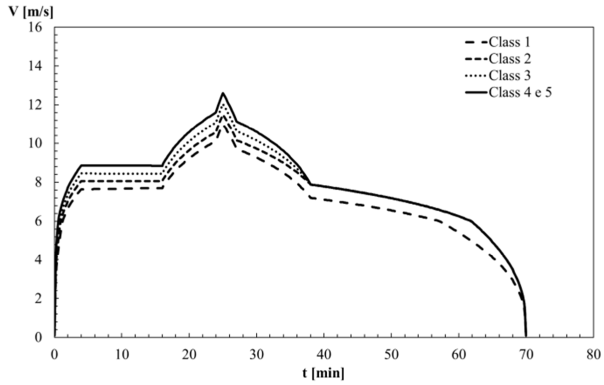


(b)

Fig, 2 - (a) Grid for the compartment 1 (H=3 m). (b) Grid for the compartment 2 (H=5 m).

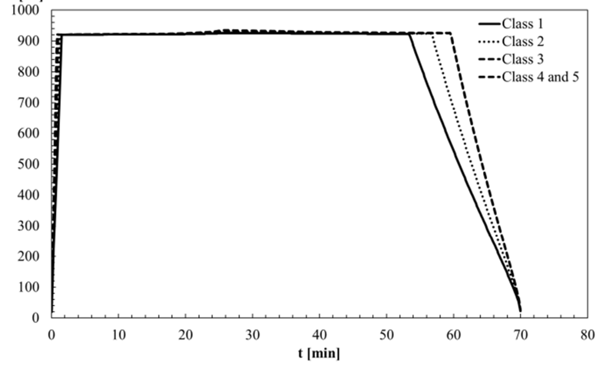



a)

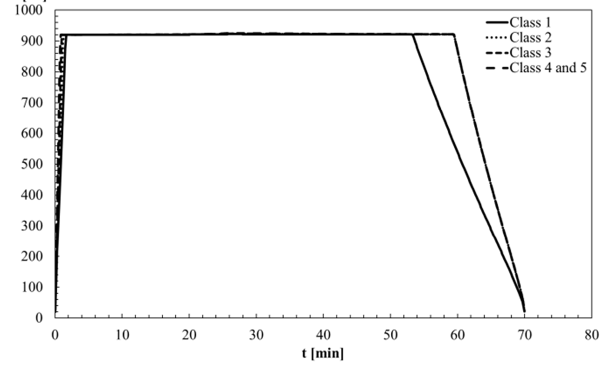



b)

Fig. 3 - (a) Velocity used for the compartment 1. (b) Velocity used for the compartment 2.



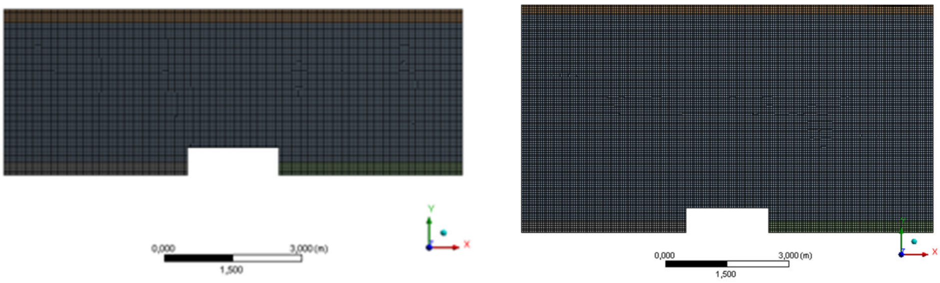

a)




b)

Fig. 4 - (a) Temperature used for the compartment 1; (b) Temperature used for the compartment 2.

A convergence test was performed to define the mesh in software ANSYS Fluent for both compartments. For the face and the edges, a 0.05 m mesh with rigid behaviour was adopted, according to Figure 5.



a) b)

Fig. 5 - (a) Mesh for the compartment 1 (H=3 m); (b) Mesh for the compartment 2 (H=5 m).

The geometry used for the compartments was: 10 m wide, 10 m long and 3 m high for the first compartment and 10 m wide, 10 m long and 5 m high for the second one. The compartment has openings on the left and right side and a concrete slab on the bottom and top, with a thickness of 0.3 m. The ambient temperature was assumed to be 20 ºC. The maximum velocity and temperature were calculated for six radial positions. A total of 16 simulation results were obtained taking into consideration 2 different heights for the compartment (H=3 m and H=5 m), 4 different car classes (fire events), 6 radial positions (R).

All the materials properties were considered temperature dependent during the CFD simulation, including the solid part and the fluid part. Figure 6 represents the main thermal properties involved in simulation.

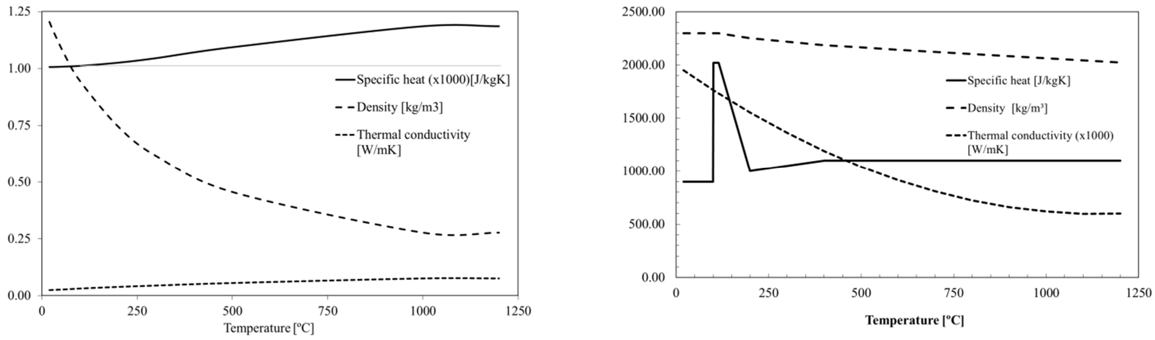



Fig. 6 - Thermal properties for air and concrete.

## RESULTS

The results of the maximum speed and maximum temperature near the ceiling depend on the classes of the vehicles. From the results of velocity and temperature, calculated by the correlative models, the maximum speed and the maximum temperature during fire are determined for the time equal to 25 minutes. The maximum speed and temperature values increase with the class of the cars. In all cases, the maximum temperature and velocity decrease with the R/H ratio, as expected.

The figures below show that the maximum velocity and maximum temperature depend on the ratio R/H for a specific time of simulation equal to 25 minutes. The ratio for the first compartment are R/H= 0, 0.37, 0.74, 1.11, 1.48 and 1.85 and for the second compartment are R/H= 0, 0.21, 0.42, 0.64, 0.85 and 1.06, which corresponds to all the radial positions evaluated (R=1,2,3,4 and 5 m).

Figure 7 and Figure 8 represent the maximum velocity and maximum temperature for the compartment 1 (H=3 m). Figure 9 and Figure 10 represent the same results for compartment 2 (H=5 m).

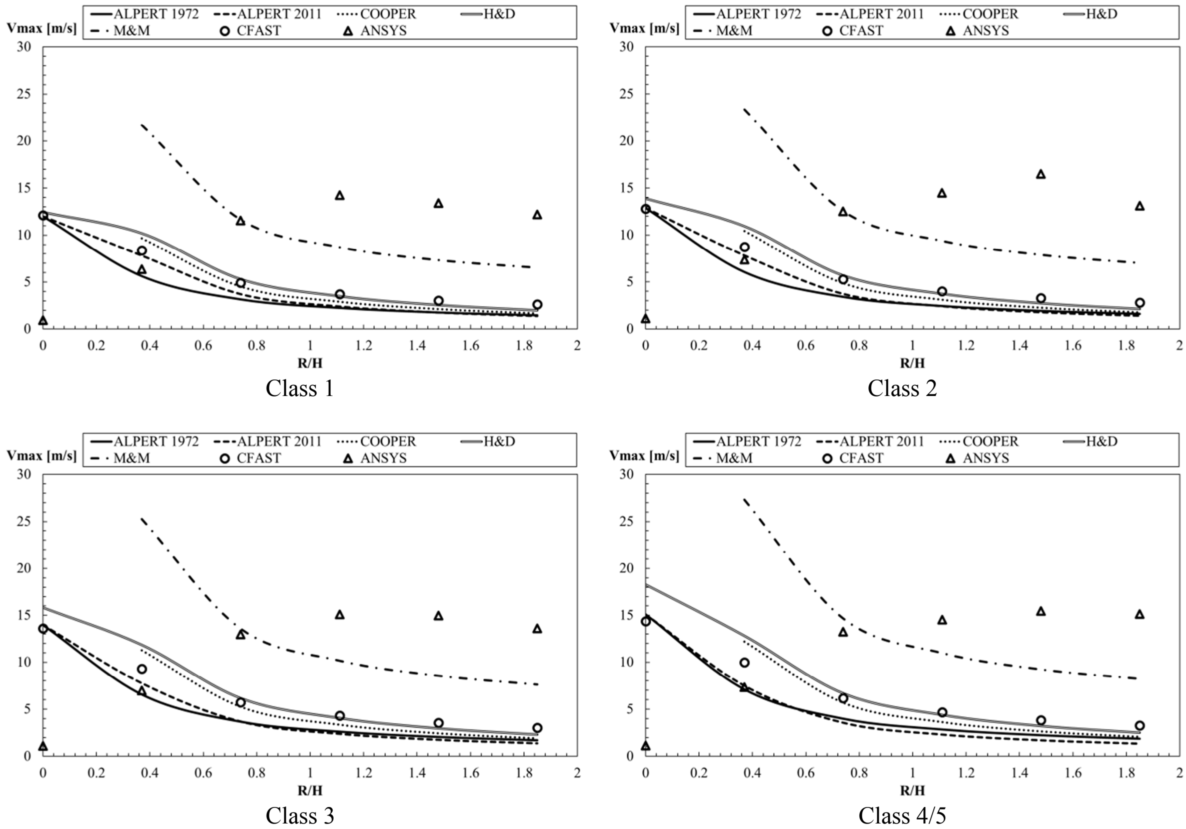



Fig. 7 - Maximum velocity for the compartment 1.

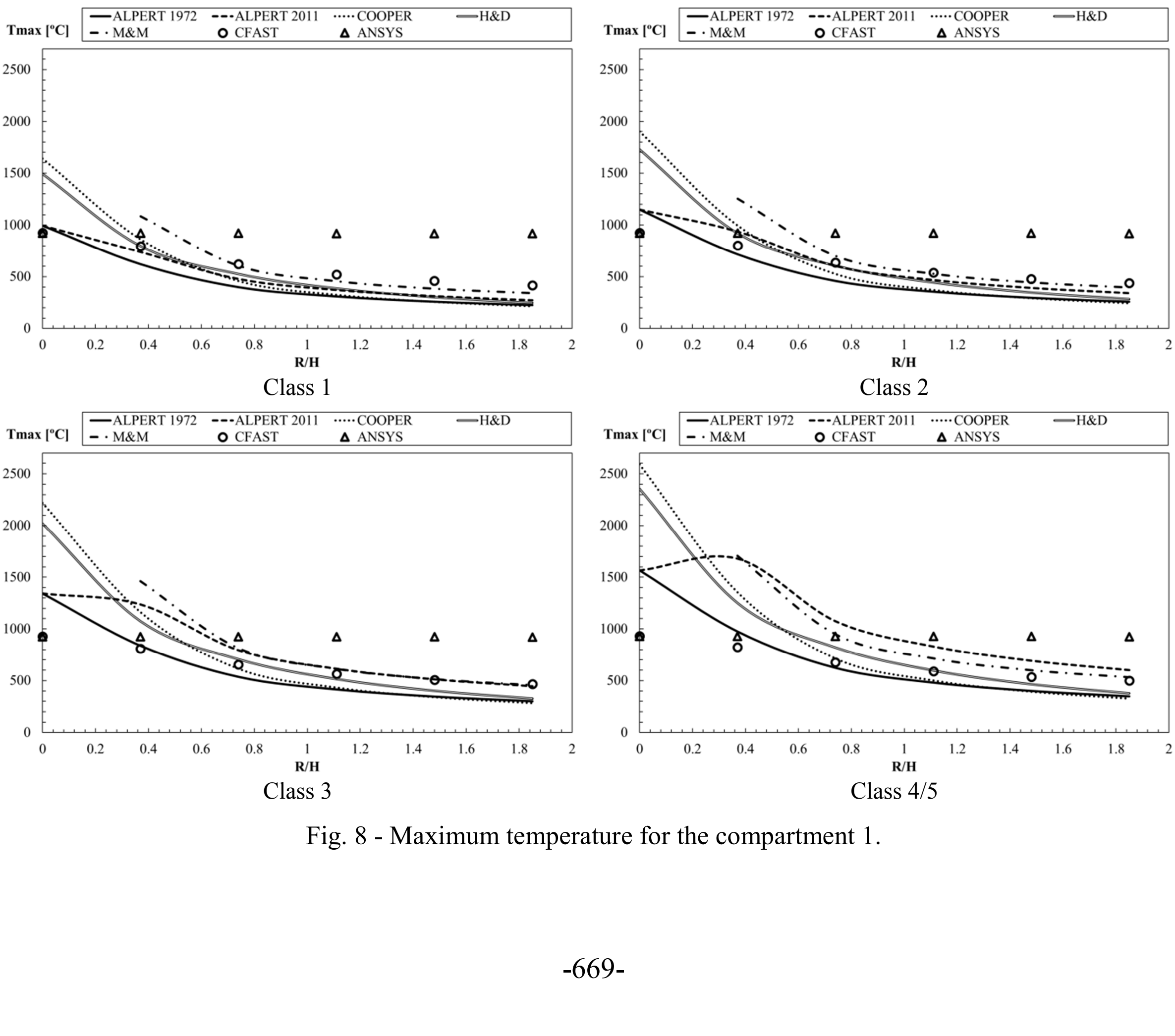



Fig. 8 - Maximum temperature for the compartment 1.

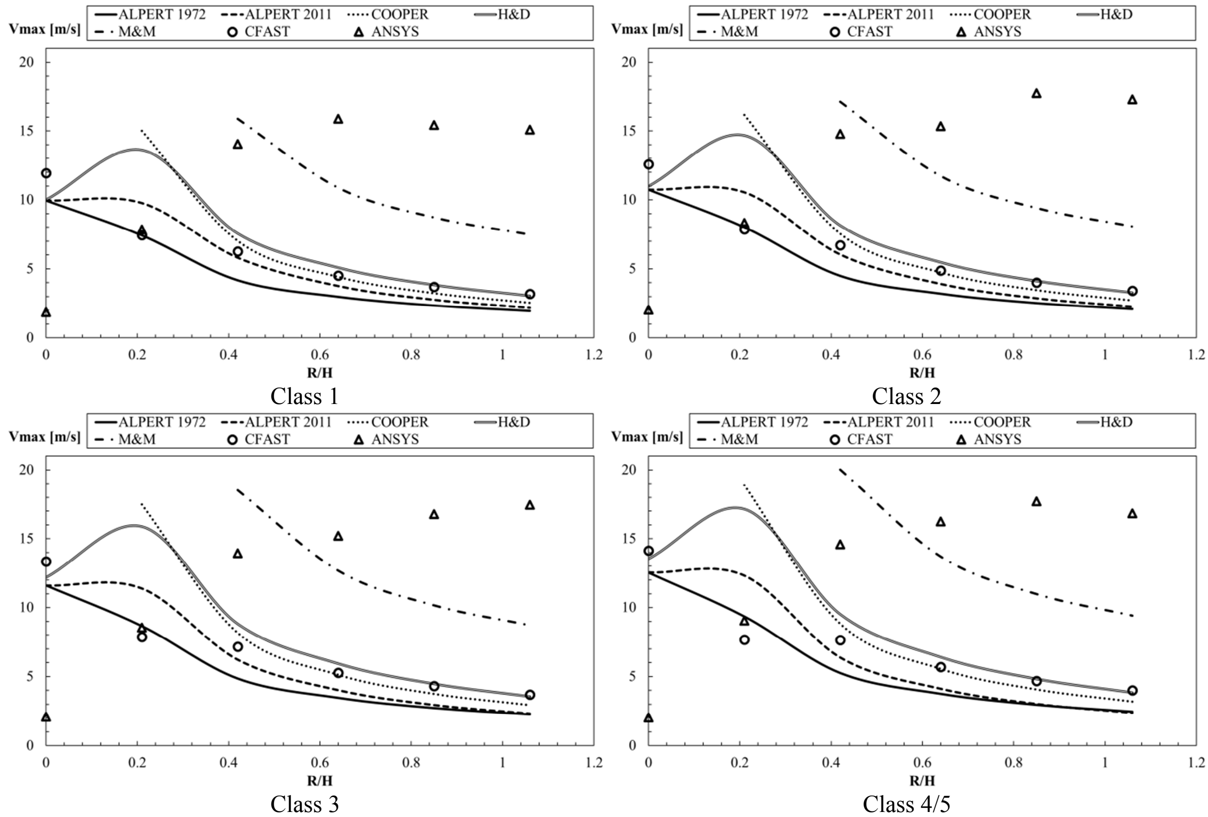



Fig. 9 - Maximum velocity for the compartment 2.

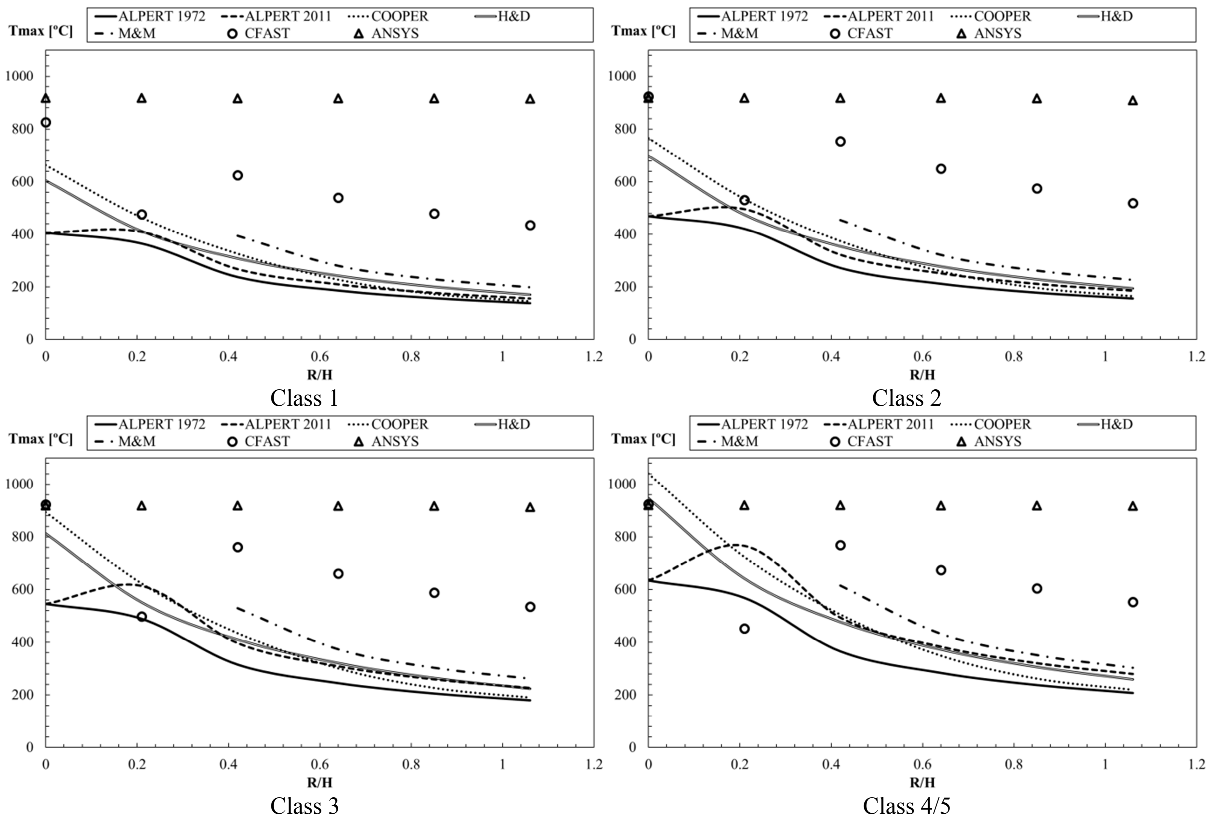



Fig. 10 - Maximum temperature for the compartment 2.

## CONCLUSIONS

This work presented a study on the thermal and dynamic characteristics of a fire induced ceiling jet in open car parks. The results were calculated with correlative models (Alpert, Cooper, Heskestad and Delichatsios, Motevalli and Marks) and two distinct programs (CFAST e ANSYS Fluent). Four classes of cars were considered for analysis in two distinct open car parks (H=3 m and H=5 m). The model proposed by Motevalli and Marks presents higher maximum temperatures for all calculated R/H scenarios. When the R/H ratio increases, the results for the maximum temperatures obtained from all correlative models (Heskestad and Delichatsios, Cooper and Alpert) get closer. The model of Alpert of 2011 and Cooper's results for the velocity are usually in between the results of Alpert 1972 and Heskestad and Delichatsios. As the ratio R/H increases, the results of Cooper and Heskestad and Delichatsios approaches to the Alpert's 1972 results. The model proposed by Motevalli and Marks proposes higher maximum velocity for all calculated R/H. The velocity values obtained by the software CFAST are consistent with the results of the correlative models. For a compartment of H=3 m, the results of CFAST for temperatures are also close to the results of the correlative models. For a compartment of H=5 m, the results of the CFAST are generally higher than the results of the correlative models. The maximum temperature decreases for R=1, due to the transition position from fire plume to well established ceiling jet. The results of ANSYS Fluent differ from the correlative models and the software CFAST. Due to a low-pressure area formed near the ceiling, the velocity when R=0 is close to zero. Then, the velocity increases with the radial positions. The temperatures remain almost constant in time for all the radial positions and they are usually higher than those obtained in correlative models and CFAST.

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