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# Numerical investigation on window ejected facade flames

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ABSTRACT

A numerical simulation was performed to assess the ability of the used code to model a compartment fire with external flames. Thereafter, numerical investigations were performed in order to study the influence of geometrical parameters such as opening dimensions, opening position and presence of sidewalls at the opening on window ejected flames. The influence of the heat release rate was also discussed. These studies highlight the different phenomena in each configuration and their influence on the risk of vertical fire spread. Moreover, to study the influence of sidewalls at the opening, numerical results were compared to Lu's correlation (Lu et al., 2013, 2014) [1,2]).



## 1. Introduction

The façade is the interface between the inside and outside of a building. In this area, a lot of factors that facilitate dynamics of fire converge (unlimited amount of oxygen, verticality of the surface, wind,…). When the wall cladding is combustible these factors can be damaging but the vertical spread of fire can occur even when the façade is not combustible. Recently, there has been growing interest in Fire Safety of Façade. Many researchers have extensively studied this topic experimentally [1–3] and numerically [6–7]. Factors affecting a fire are primarily the fire source (type, load and distribution) and ventilation, such as size of openings and rate of burning. Generally, external flames appear when air supply inside the compartment is no longer sufficient. This is controlled by the openings dimensions and these flames can be considered in terms of flame shape (Height, width and depth) [1–3]. This paper presents a numerical investigation on ejected flame behavior from enclosure fires in different opening configurations (opening dimensions, opening positions and distance between sidewalls at the opening) and for different heat release rates. The influence of these parameters on fire spread along a façade was widely studied using small-scale tests. For example, Lu [1–2] carried out a series of experiments on reduce-scale models and proposed to correlate opening dimensions and sidewalls distance (D) by a global dimensionless parameter in order to explain the sidewall effects. Tang [3] used a similar configuration in order to study the influence of dimensions of an opening on the external flame properties. However, all these experiments were performed using a low heat release rate (lower than 250 kW) and with compartments not exceeding 80 cm square in shape. The aim of the present study is:

1. To assess the ability of the used code (FDS) to model a compartment fire with external flames.
2. To numerically assess the influence of the opening dimensions and its position on the excess heat release rate due to the burning excess fuel outside the compartment.
3. To numerically assess the influence of a "U" channel configuration on flame height along the facade above the opening.
4. To verify if the correlations obtained by [1–3] for small scale tests ($\sim$50 kW) are available for large scale compartment fires simulated with HRR=5.5 MW and 6.5 MW.

Finally, this study will identify and quantify the influence of geometrical parameters on external flames.

## 2. Numerical simulations

The use of computational fluid dynamic (CFD) and zone model has become an alternative means to predict the effects of a fire both inside and outside the fire room. Their predictions need to be validated with results taken during full-scale experiments. That's why, this first part of this study consists in a simulation of a compartment-tested fire [5] and then in the comparison of measured and predicted temperatures along the façade in order to

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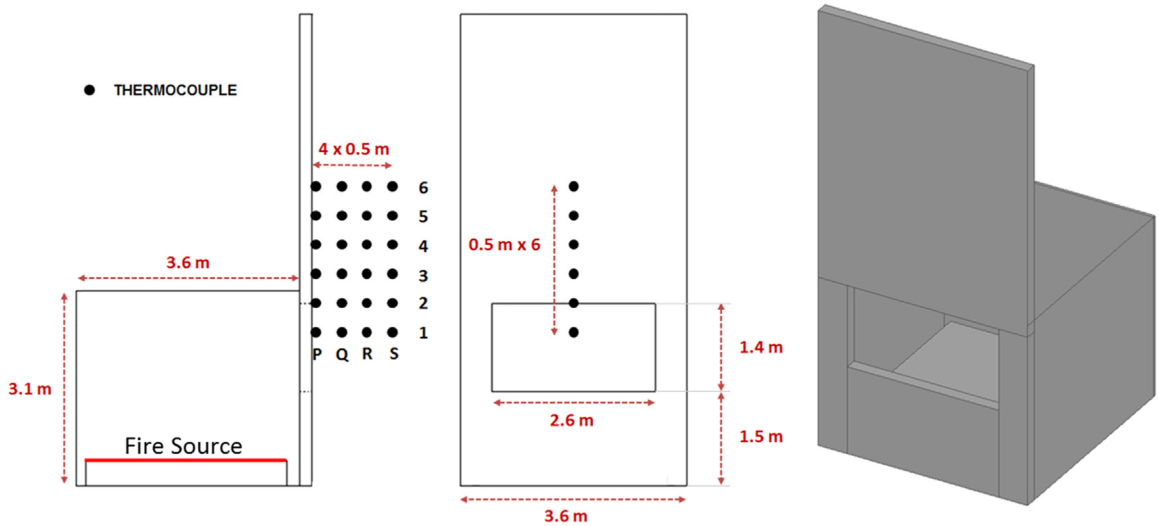


**Fig. 1.** Experimental and numerical setup for the simulation of a compartment fire.

**Table 1**
Material property for the façade wall.

| | Thermal conductivity (W/m K) | Density (kg/m$^3$) | Thermal specific capacity (J/kg K) | Thickness (m) |
|---|---|---|---|---|
| Façade – Ceiling | 0.20 | 450 | 1000 | 0.20 |
| Walls | 0.70 | 1600 | 840 | 0.12 |
| | 0.45 | 1050 | 840 | 0.20 |

assess the ability of the used code to model a compartment fire with external flames.

All the simulations were realized with the CFD (Computational Fluid Dynamics) tool FDS6.1 [4]. FDS default models were used to simulate each scenario. For any additional information about numerical models, the reader may refer to the User Guide [4]. The mesh cells used are cubic and measure 10 cm square. This value has been retained after a sensitive analysis using 5 cm, 10 cm and 20 cm mesh cells. Indeed, results with 20 cm were very away from experimental data and computation time with 5 cm was too long with no significant improvement in results. We assume that the flame area corresponds to an average gas temperature above 500 °C [5]. Below this value, there is no significant risk for exposed steel structures [8]. Flame height is calculated from the ground. Moreover, the excess heat release rate is calculated by the code.

### *2.1. Simulation of compartment fire with external flames (validation case)*

The fire compartment configuration is shown in Fig. 1. Opening dimensions are fixed and there is no sidewall at the opening. Façade wall height is 6.4 m. The wall properties (density, thermal conductivity and specific heat) in cold conditions are known and the same values are taken into account for the fire simulations. These values are presented in Table 1. A series of temperatures have been measured along the facade with thermocouples. The experimental data are from [5]. Positions of thermocouples are shown in Fig. 1. The fuel used was wood cribs. The mass loss of wood cribs was measured (Fig. 2a) during the experiment and used as input data in the simulation. The mass loss rate is prescribed on the upper face of the block shown on Fig. 1. The heat release rate has been calculated with a heat of combustion of 17.5 MJ/kg. This value is calculated by the code using the amount of energy released per unit mass of oxygen consumed and fuel

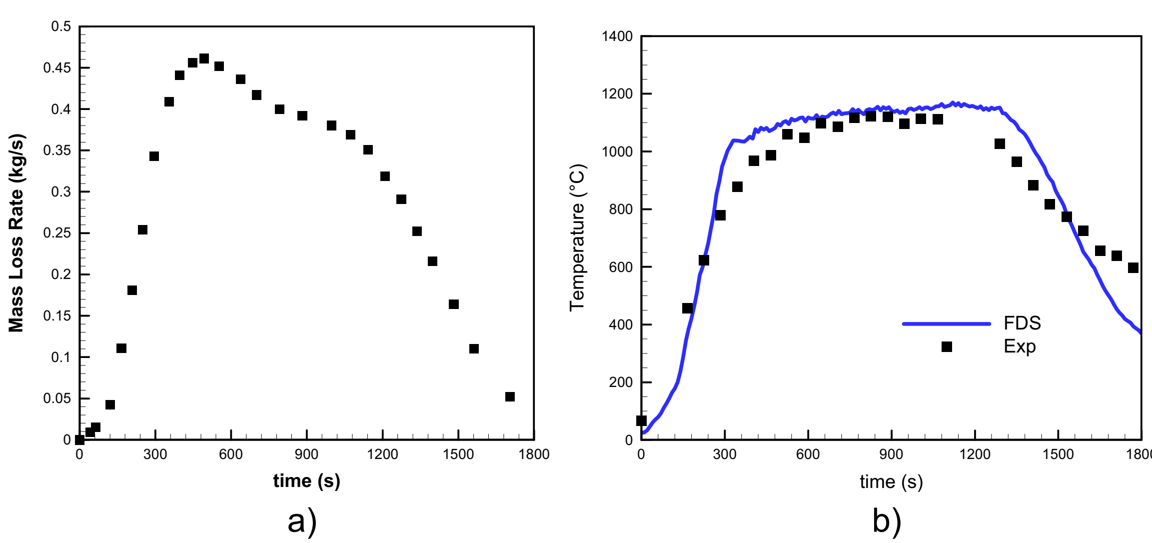


**Fig. 2.** a) Experimental mass loss rate used in the simulation. b) Evolution of temperatures inside the compartment.

formula. The chemical reaction for complete combustion of wood used for the simulation is:

$$C_{3.4}H_{6.2}O_{2.5}+3.62(O_2+3.76N_2) \rightarrow 3.32CO_2+3.10H_2O+0.01CO+0.07C_{soot}+N_2$$

In this simulation, calculation domain is 6.4 m high, 3.6 m large and 6.4 m deep and there is about 150,000 cells. Calculation time is about 50 h for 1800 s of physical time.

The evolution of the temperature inside the compartment (Fig. 2(b)) seems to be well reproduced, especially the increase in temperature and the steady state. Consequently, we can say that the amount of energy released inside the compartment is correctly estimated.

Fig. 3(a)–(c) show the evolution of measured and simulated temperatures for the position P, Q and R. Numerical predictions are in good agreement with experimental results for positions P (Fig. 3(a)) and R (Fig. 3(c)). We can therefore say that we have a good estimation of the flame depth. However, for each height, temperatures are overestimated at position Q (Fig. 3(b)). This position represents the continuous flame axis. The model seems to overestimate temperatures in this region. This induces an overestimation of the flame height. Nevertheless, in case of façade fire, a good estimation of near-wall thermal actions (position P) is necessary to study the contribution of a combustible or non-combustible façade on vertical fire propagation. This overestimation of the flame position should not affect the investigation presented in this paper because this phenomenon is observed in all simulations. Like statement, the aim of this study is to observe the behavior of external flame with different geometric constraints beside to have a true estimation of the flame height. In the lower part of position R, thermocouples are located outside of the flame zone. In this area, there is no convective flow unlike to the upper part. Temperatures are mainly due to flame radiation. Results obtained in position S are note presented because they are closed to those of the position R.

### 2.2. Influence of different parameters on external flames

When a fire occurs in a compartment, unburned combustible gases can be ejected through the opening due to a lack of oxygen inside the compartment. This phenomenon is controlled by the supply of air inside the compartment, that is, by the configuration of the opening. The aim of the following simulations is to assess the influence of different openings and geometrical configurations of the façade on the excess heat release rate (part of total HRR burning outside of the fire room) and on the flame heights. In order to obtain more accurate values of flame heights and flame temperatures and to observe more significantly the influence of each parameter, the HRR of the fire source is taken constant. In other words, only the fully developed phase of the fire is simulated because temperatures are at their highest during this phase. All data points plotted in the graphs have been obtained by averaging the numerical results over 500 s period.

#### 2.2.1. Influence of the opening dimensions

Based on the geometrical configuration of the previous study, a numerical investigation of the influence of opening dimensions was performed. Fig. 4 shows the configuration and tested parameters. For each simulation, the heat release rate of the fire source is fixed at 6.5 MW except when specified. The studied variables are the width of the opening (w), the height of the opening (h) as well

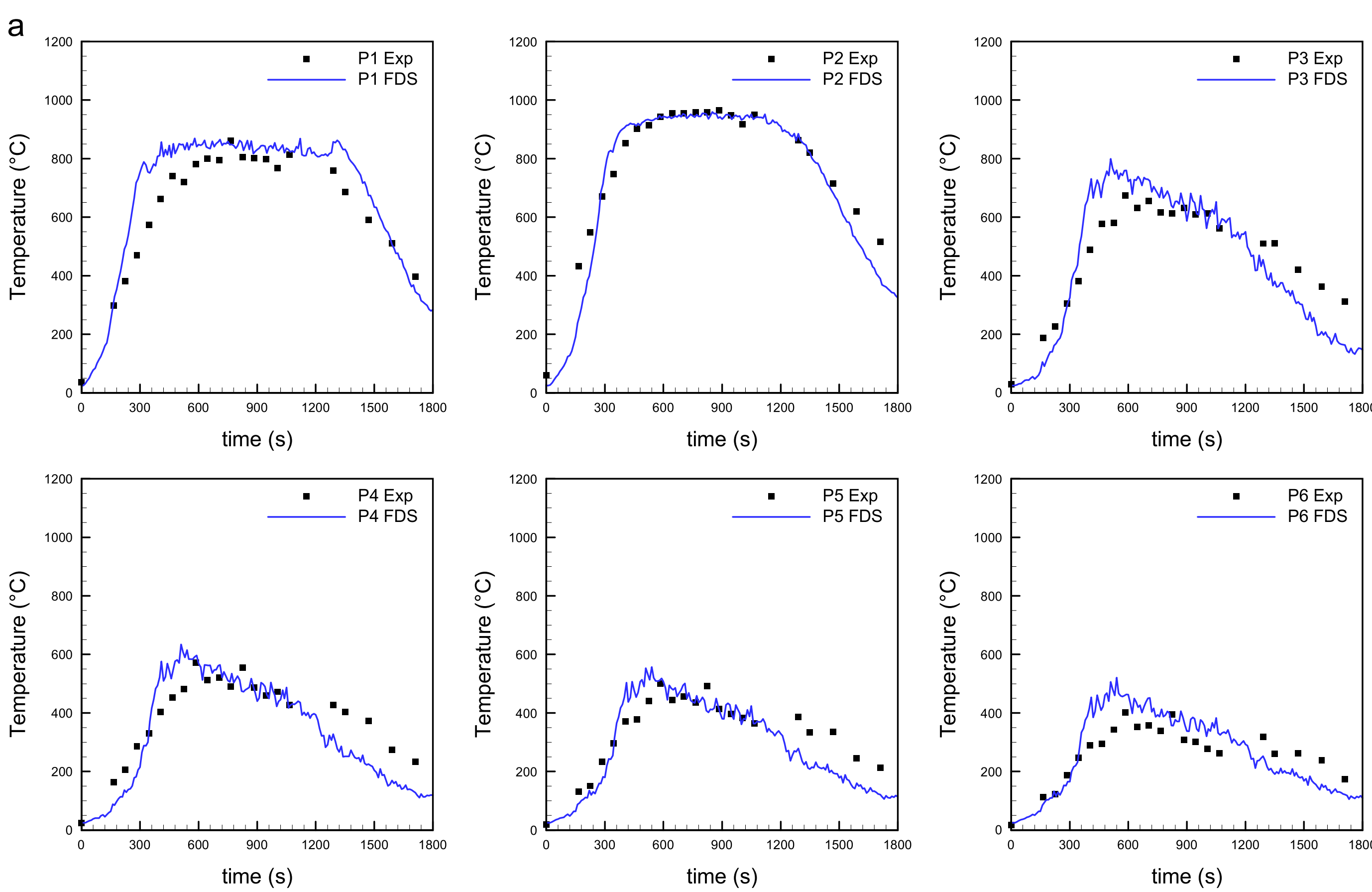


**Fig. 3.** (a) Temporal evolution of external temperatures at position P. (b) Temporal evolution of external temperatures at position Q. (c) Temporal evolution of external temperatures at position R.

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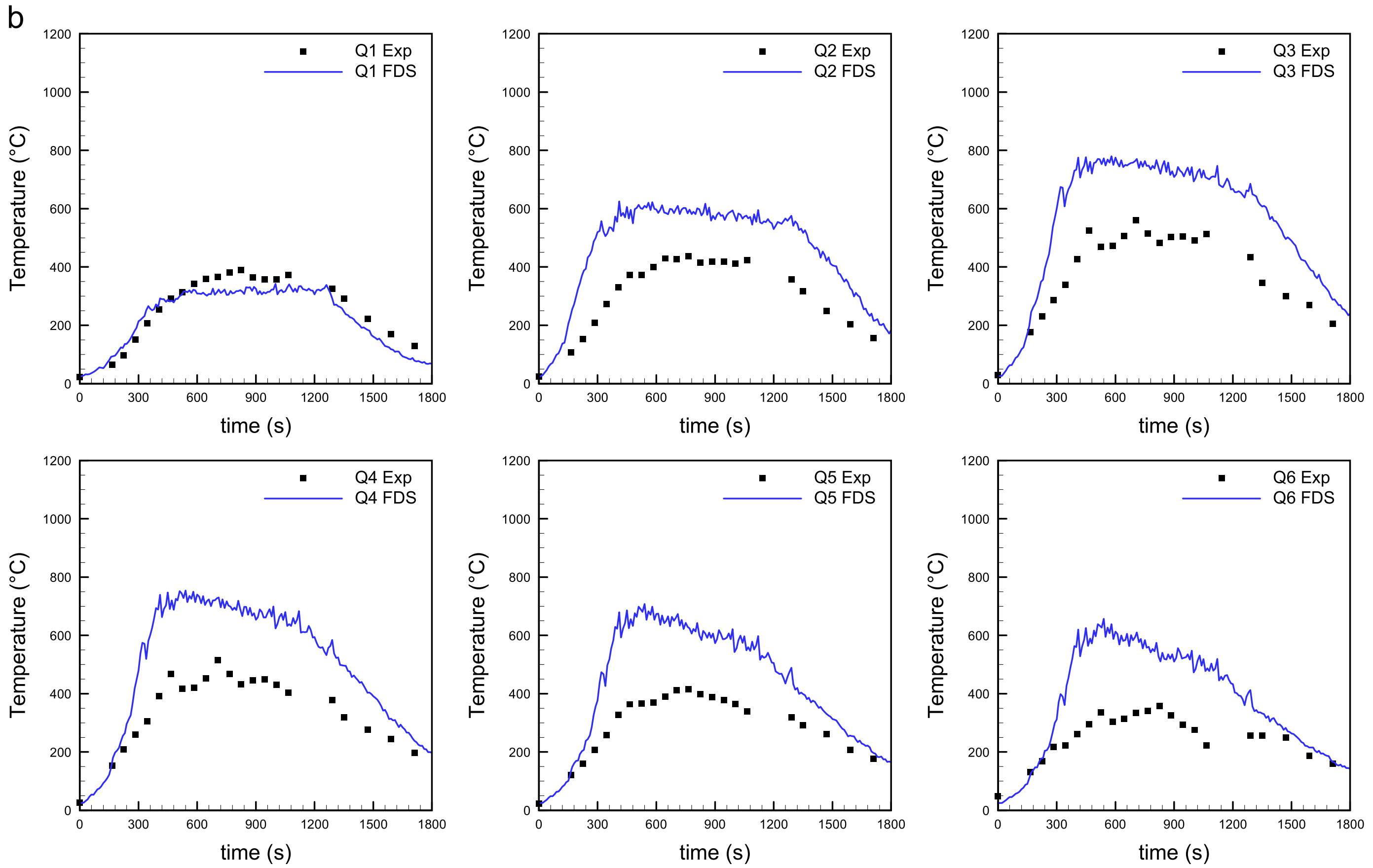


**Fig. 3.** (*continued*)

as its position from the lower floor (hs = spandrel height).

Numerical predictions of excess heat release rate are compared to theoretical values. Theoretical heat release inside the enclosure ($Q_{in}$) is given by [9]:

$$Q_{in} \approx 1500A\sqrt{h} \quad (1)$$

Where A is the opening area ($m^2$). External flames are created by excess fuel burning outside the fire room. This excess heat release rate ($Q_{ext}$) is given by:

$$Q_{ext} \approx HRR - Q_{in} \quad (2)$$

Figs. 5 and 6 respectively show the evolution of flame height as a function of the height and the width of the opening.

On these figures, it can be seen that excess heat release decreases with increasing of the area of the opening. A larger amount of fuel can burn within the compartment due to the increase of air entrainment through the opening. However, this lead to an increase of the heat released inside the compartment depending on the fire load available inside the fire enclosure. Damages within the compartment can be clearly more important. Moreover, for equivalent opening dimensions, opening position (hs) has an influence on the excess heat release rate (Qext) as shown in Fig. 7. Indeed, for the three cases, when there is no lintel above the opening, we can clearly see that there is an increase of about 50% of the amount of energy released outside the compartment. Consequently, presence of the lintel above the opening reduces the flame height. Excluding the case without lintel, the opening position does not seem to affect the air inflow through the opening. However, we can see that lintel influence slightly decreases as its length decreases (hs = 1.4 m and hs = 1.5 m). Thus, we can clearly identify two groups:

– Opening with a lintel, no influence is observing on Fig. 7 however lintel length.
– Opening without lintel, hot combustible gases can be directly ejected through the opening. Heat release rate is higher with this configuration and spread risk is increasing.

Globally, numerical predictions are in good agreement with theoretical values. Excess heat release rate seems to be well estimated. That's why temperatures inside the fire compartment is well predicted by the code in the validation case (Fig. 2).

### 2.2.2. *Influence of the heat release rate on external flames*

The influence of the total HRR on the external flames has been investigated. This parameter is one of the most important. Its value has an influence on the combustion inside the compartment and controls the excess heat release rate. The heat release rate varies from 4.5 to 8.5 MW. For each simulation, opening is 1.4 m high and 2.6 m wide. Flame height, excess of heat release rate and mass fluxes through the opening were observed and compared.

Fig. 8 shows the excess heat release ($Q_{ext}$) and the flame height as a function of the heat release rate. We can see that the evolution of the excess heat release rate as a function of the total heat release rate is almost linear. Moreover, numerical predictions are really closed to theoretical values from 1 Eq. (1). It is clear that the fuel load inside the compartment has a great influence on external flames. Indeed, flame height increases significantly with HRR increasing.

### 2.2.3. *Influence of sidewalls at the opening on the flame height*

In this section, the presence of sidewalls at the opening has been investigated. It is known that external flames are related to air entrainment. This configuration may be an important factor

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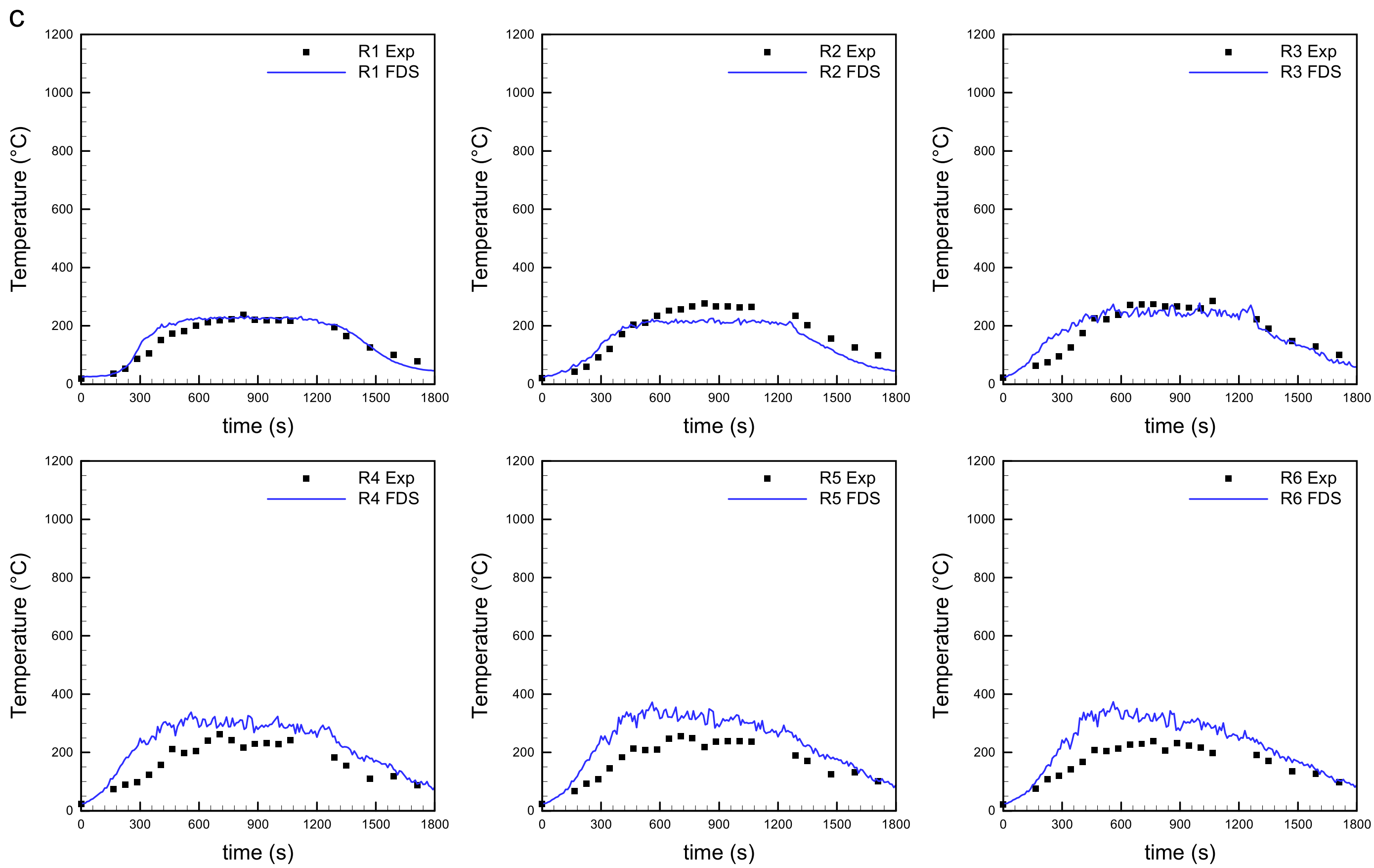


**Fig. 3.** (*continued*)

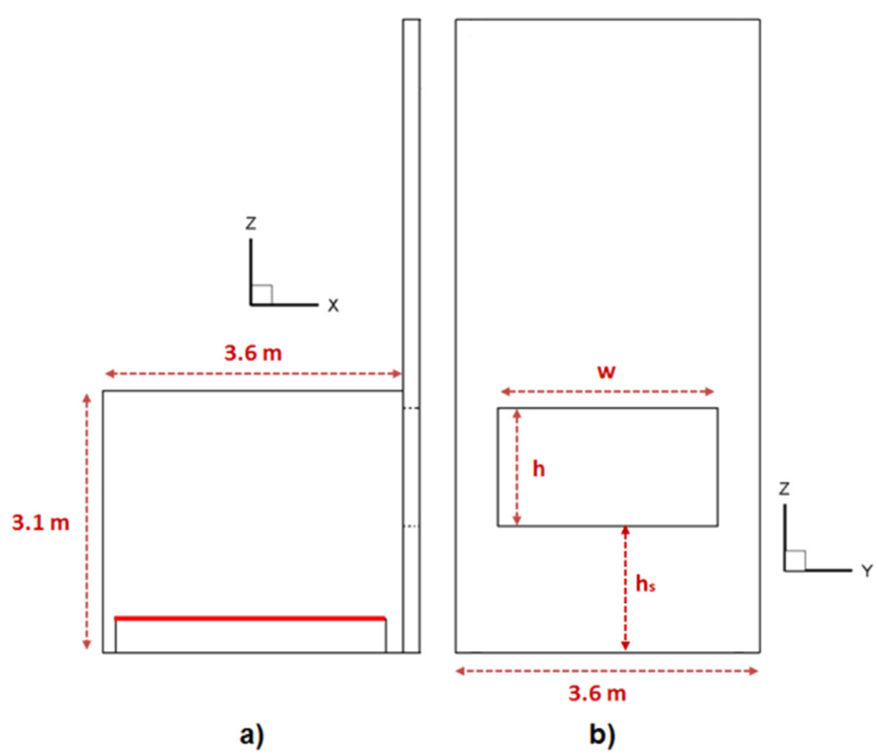


**Fig. 4.** Numerical setup: a) side view b) front view.

contributing to vertical fire spread due to a reduction of the air entrainment leading to a "chimney effect". Therefore, it is important to know the limit of the influence of these walls. The geometry is shown in Fig. 9. The fire room is identical to previous studies and the heat release rate is set at 6.5 MW. Three opening dimensions have been taken into account by increasing its height

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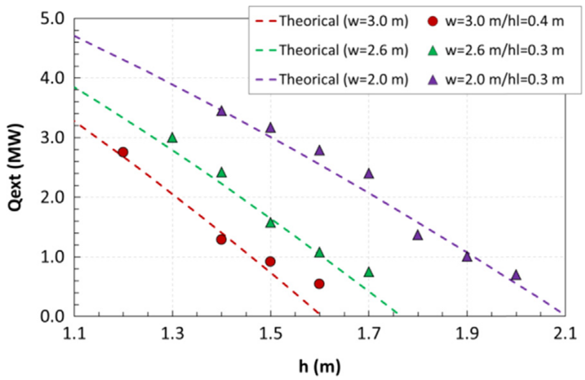


**Fig. 5.** Excess heat release as a function of opening height "h".

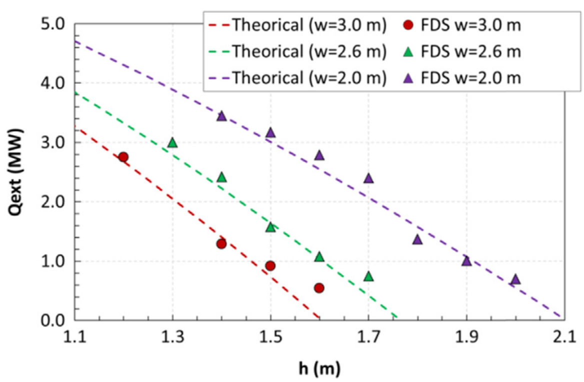


**Fig. 6.** Excess heat release as a function of the opening width "w".

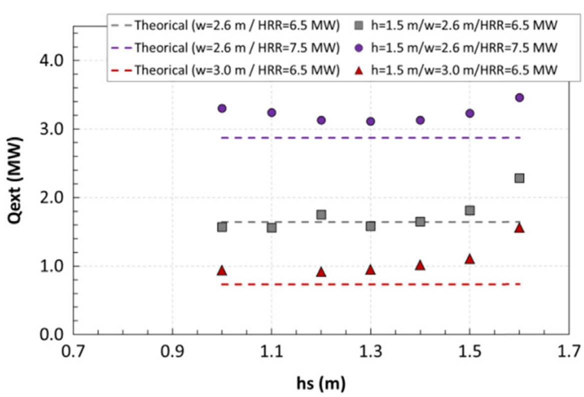


**Fig. 7.** Excess heat release as a function of the opening position "hs" (h = 1.5 m).

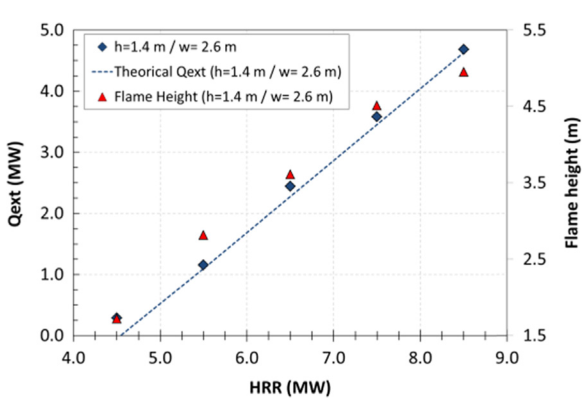


**Fig. 8.** Excess heat release rate and flame height as a function of the heat release rate.

first and then its width. Thus, for each simulation, the separation distance of the sidewalls (D) was increased from the edge of the opening (D = w) to an infinite distance corresponding to a case without sidewall. Moreover, a series of small-scale tests conducted by Lu [1–2] allowed to correlate opening dimensions and sidewalls distance (D) by a global dimensionless parameter (K) to explain the sidewall effects (Eq. (1)). Numerical results have been used to verify if this correlation is available for large-scale compartment fires up to 6.5 MW.

$$H_D = K \cdot H_0 \tag{3}$$

$H_0$ and $H_D$ are respectively the mean flame height without sidewall and with sidewalls at distance of D (m). The parameter K is dependent on w, h, D and L.

As shown in the Table 2, sidewalls have no influence on the compartment mean temperature, with a value of about 1100 °C regardless of the sidewalls distance D. So we can say that the presence of these walls does not affect the combustion inside the compartment. Moreover, the same behavior was observed with small scale tests [1,2].

Figs. 10–12 show the evolution of the flame height outside the compartment according to the separation distance (D) for three different opening dimensions. As expected, the maximum flame height is obtained when D = w for the three openings. The global behavior of the three cases is similar. Flame height decreases with increasing of D until walls had no more influence on the air entrainment.

We can explain this phenomenon by observing Fig. 13. When D = w, air entrainment occurs only on the front of the flame as shown on Fig. 13(a) (air entrainment is shown by arrows). The entrained air is less important and the combustion is therefore slower flame height increases significantly. Moreover, the flame is pushed against the façade (Fig. 13). This one is subject to more important thermal actions increasing spread risk as shown on Fig. 14(a). Air entrainment on flame sides increases with D increasing. This side air entrainment allows a faster combustion of pyrolysis gas ejected through the opening due to a more efficient mixture. This induces a decreasing of the flame height (Fig. 13) and contributes to decrease the flame temperature. Moreover, the flame comes off the facade and wall thermal actions over the façade are less important (Fig. 14).

On Figs. 10–12, numerical predictions are compared to the correlation. The three studied cases (Figs. 10, 11 and 12) were in good agreement with this correlation. As shown on Figs. 10 and 11, when w = 2.6 m, the influence of the sidewalls decreases rapidly. For these three cases, $K$ varies from 1.36 to 1.46, which corresponds to an increase in the flame height of approximately 40%. This can considerably increase the risk of fire spread to the upper floors. This influence seems to be still observable when sidewalls are at a relatively large distance from the edge of the opening. For example, when D = 6 m, numerical predictions and correlation indicate a flame height 40 cm higher compared to "no sidewall" (this value is indicated by a dot line). However, these simulations were realized with a "Heat Release Rate" equal to 6.5 MW and L = 2.6 m. Experimental studies show that flame height is closely dependent to these parameters [1,2]. Thus, additional simulations must be performed to study their influence.

## 3. Conclusions

First of all, a numerical simulation was performed to assess the ability of the used code to model a compartment fire with external flames. Overall predictions were in relatively good agreement in terms of magnitude and distribution. Indeed, near-façade thermal

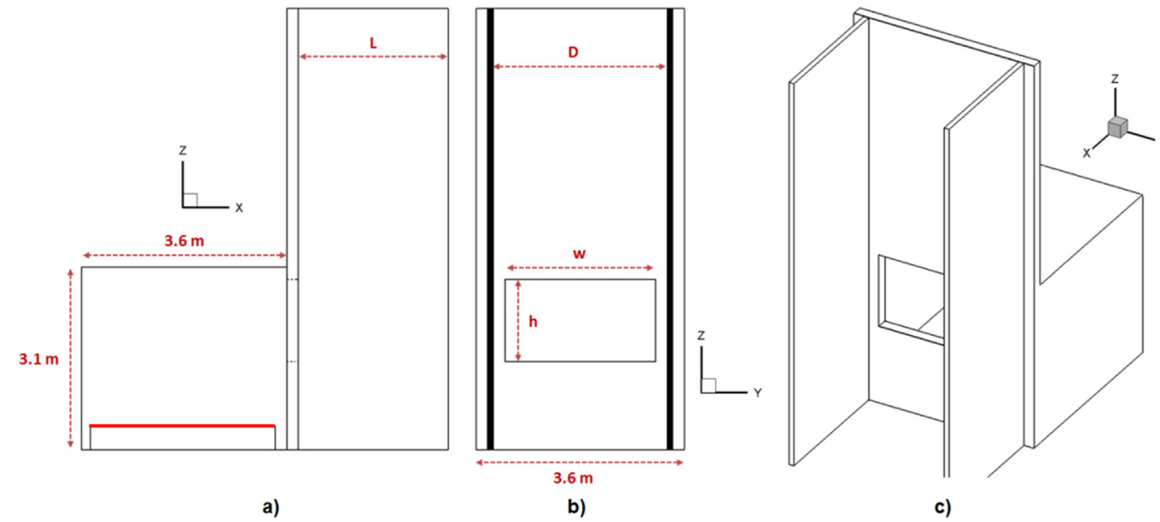


**Fig. 9.** Numerical setup: a) side view b) front view c) 3D view.

**Table 2**
Average temperature inside the compartment (w=2.6; h=1.4).

| Separation distance D (m) | 2.6 | 2.8 | 3.6 | 4.4 | 5.2 | No sidewall |
|---|---|---|---|---|---|---|
| Average temperature inside the compartment (°C) | 1094 | 1102 | 1110 | 1106 | 1097 | 1103 |

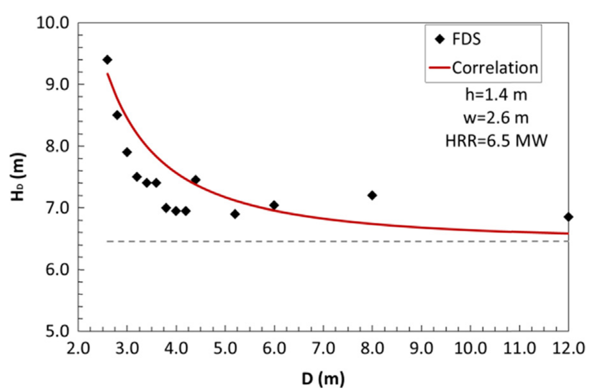


**Fig. 10.** Mean flame height vs. sidewall distances (D) h=1.4 m; w=2.6 m.

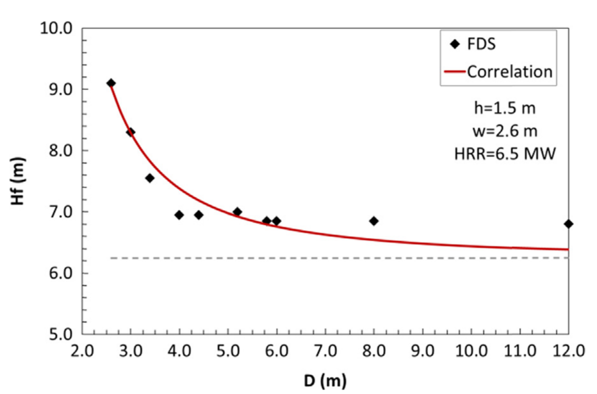


**Fig. 11.** Mean flame height vs. sidewall distances (D) h=1.5 m; w=2.6 m.

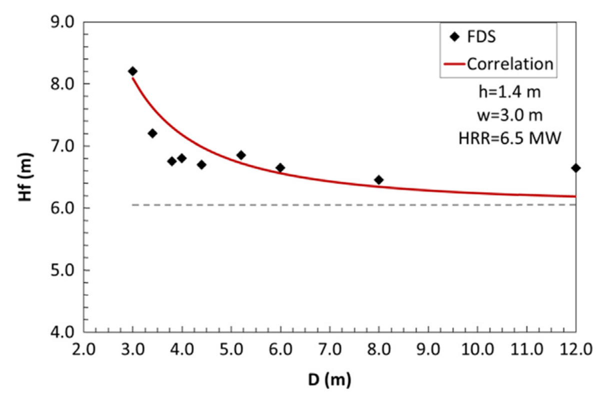


**Fig. 12.** Mean flame height vs. sidewall distances (D) h=1.4 m; w=3.0 m.

actions (position P) and flame thickness (position R) seem to be relatively well estimated by the model. However, some predictions were overestimated in the external combustion area induces an overestimation of the flame zone (position Q). We consider that the obtained results allow to properly study phenomena in the second part of this paper.

Secondly, numerical investigations were carried out highlighted the influence of geometrical parameters such as opening dimensions, opening position from the room floor, the heat release rate and the role of sidewalls at the opening on window ejected flames. From the obtain results, we can retain that flame height decreases with increasing opening dimensions due to a better combustion inside the compartment. Moreover, it is also observed that the height of the opening has a great influence than the opening width. Opening positions has an influence on the flame height. The presence of a lintel leads to decrease flame height because it blocks the unburned gas inside the fire compartment. As expected, flame height significantly increases with HRR increasing due to a larger amount of fuel ejected through the window. Furthermore, to study the influence of sidewalls at the opening, numerical results were compared to Lu's correlation. The three studied cases were in good agreement with the correlation. It was observed that flame height decrease rapidly with D increasing but the influence of sidewalls could be observed for large distance of D (6.0 m). Additional simulations with larger HRR and different opening dimensions must be performed in order to study more precisely this parameter. Thus, a critical distance corresponding to the distance at which the sidewalls have no influence could be determined for several cases.

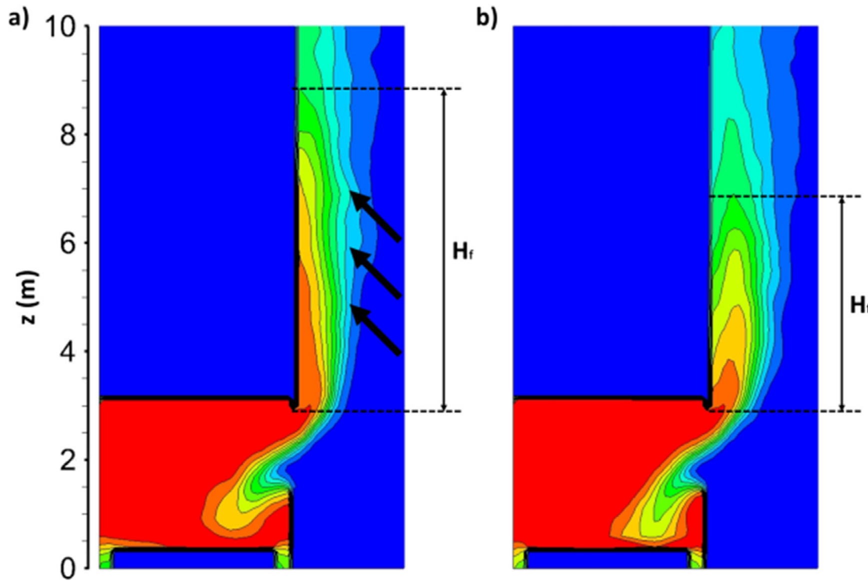


**Fig. 13.** Time-averaged temperature contours in the middle plane of the opening (h = 1.4 m; w = 2.6 m): a) D = 2.6 m; b) D = 5.2 m.

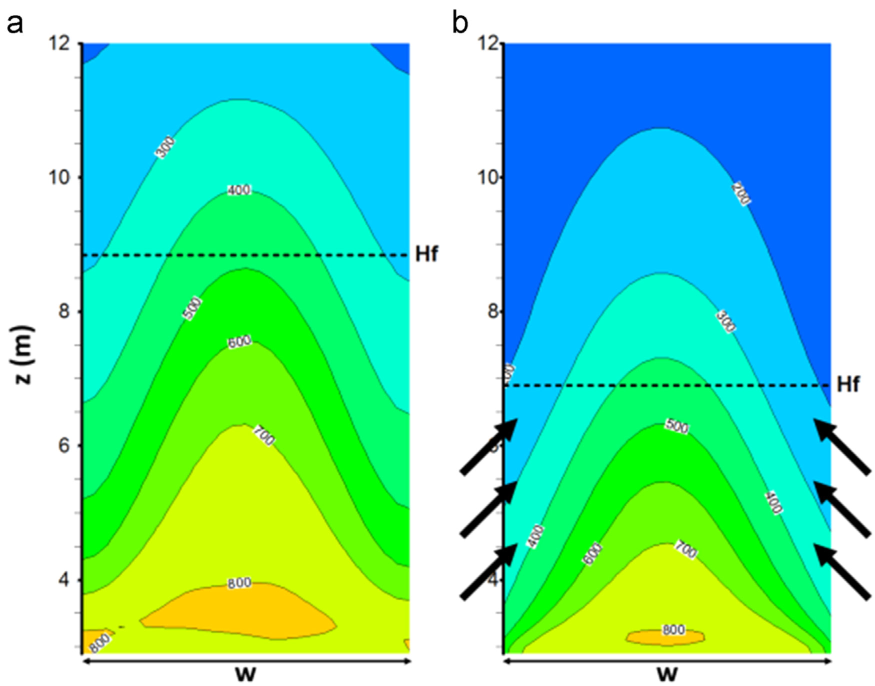


**Fig. 14.** Time-averaged wall temperature contours above the opening (h = 1.4 m; w = 2.6 m): a) D = 2.6 m; b) D = 5.2 m.

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