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Influence of heat release rate on the temperature of the hot gas layer in closed spaces

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Abstract. The study used for the elaboration of this article presents the influence of the heat release rate (HRR) on the hot gas layer and temperature development in a specified fire compartment with natural ventilation. The influence of the ventilation factor and the thermal properties of the internal linings (chipboard, gypsum board and expanded polystyrene) are considered as well. Two fire scenarios are taken into account, namely, the compartment has a door opening, respectively a window opening, the heat flow released by fire taking, on the row, the values of 250 kW, respectively 500 kW. Also, it uses the empirical method of McCaffrey, Quintiere and Harkleroad (MQH) to estimate the temperature of the hot gas layer inside the fire compartment.

Keywords: heat release rate, natural ventilation, hot gas.

1. Introduction

The prediction of the temperature of combustion gases is of particular importance because, on the basis of it, an assessment of the hazardous conditions arising from the consequences of the fire can be carried out both on people's lives and on structural components of the building.

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In order to determine the temperature of the hot gas layer, a series of correlations have been developed as a result of numerous studies and researches.
A simplified temperature estimate can be achieved, in the case of rooms with natural ventilation, using the MQH correlation [1]. McCaffrey, Quintiere and Harkleroad developed a statistical, adimensional correlation for estimating the temperature of the hot gas layer in confined spaces with natural ventilation, for which the source of the fire was placed in the center of the compartment.
Also, a correlation has been developed capable of predicting the temperature of hot gases both in the case of poorly ventilated fires and in the case of heavily ventilated fires. This correlation was established and validated by comparison with a set of experiments and by comparison with the MQH correlation. Thus, in the case of poorly ventilated rooms, it was found that the new correlation led to results closer to the experimental values, compared to the strongly ventilated rooms, where were obtained results similar to the MQH correlation [2].
Using the Law correlation [3], the method of estimating the maximum temperature in the natural ventilation fire compartments, based on a series of tests performed on a natural scale, a formula for the mass flow of hot gases was developed, which shows its dependence by the ventilation factor ($(\text{door area}/\text{door height})^{\frac{1}{2}}$), the aspect ratio of the door ($\text{door width}/\text{door height}$) and smoke layer temperature. This formula does not apply to window configurations [4]. Window ventilation is more complex than through doors due to the effect given by the height of the window sill. A general formula for the mass flow of hot gases was developed by using a theoretical model represented by an ideal fire source, at the floor level, and two stationary areas, characterized by the fact that the mixture between the smoke layer and the air does not take place. Thus, by combining the configurations for ventilation through doors and windows in a single equation, a formula with an accuracy of up to 15% was obtained compared to the available experimental data [5].
Predicting the mass flow rate of hot gases is of particular importance in assessing the exposure of people to heat and smoke from fire. In this sense, an equation has been developed whose practical application is the fact that, based on it, the mass flow rate of hot gases can be estimated, in case the height of the hot gas layer is known. Thus, it was found that the mass flow rate is dependent on the height and temperature of the hot gas layer when evacuating from a fire compartment [6].
The temperature of the upper layer of hot gases influences the rate of fuel mass loss. Thus, a new correlation has been developed that makes the prediction of the mass loss of the fuel and which is dependent on the effects of the thermal response, the ambient wind and the amount of air accumulated at a door opening. This correlation reflects the fact that increasing the wind speed would result in the flames coming out the door and restricting the air entering the door, which would reduce the mass loss of fuel [7].
Depending on the type of ventilation used and the existence of openings in the fire compartment, there are several empirical methods for estimating the temperature of the hot gas layer. Thus, if the fire compartment is naturally ventilated, the method of

McCaffrey, Quintiere and Harkleroad (MQH) is used, if it is forced ventilated, the methods of Foote, Pagni and Alvares (FPA) [8], respectively Deal and Beyler (DB) [9] are used, and in the case where the fire compartment is closed, Beyler's method is used [10].
This study describes how to calculate the temperature of the hot gas layer in a compartment with natural ventilation using the method of McCaffrey, Quintiere and Harkleroad (MQH). The interior finishes of the compartment considered in this parametric study are: chipboard, gypsum board and decorative polystyrene panel.

2. Estimating the temperature of the hot gas layer in a natural ventilation compartment using the MQH method

Eight datasets comprising more than 100 experiments were used to achieve MQH correlation.
The temperature recorded inside the fire compartment is influenced by both the air supplying the fire and the place where the air enters the compartment. As a rule, in the case of the experiments in which the way of manifesting the fires in the closed spaces is evaluated, a room with a single opening of rectangular dimension provided at the wall level is used. Such scenarios are often encountered in real life, where natural ventilation is usually achieved through a single opening having a door or window type configuration.
The hot gas layer that is formed in a compartment descends at the opening level until a quasi-static balance between the mass flow into the hot gas layer, respectively outwards, is reached.
McCaffrey, Quintiere and Harkleroad developed a statistical, adimensional correlation for estimating the temperature of the hot gas layer in confined spaces with natural ventilation. Shall be obtained

$$\Delta T_g = 6.85\left(\frac{\dot{Q}^2}{A_v\sqrt{\mathrm{h_v}}A_T h_k}\right)^{\frac{1}{3}} \tag{1}$$

where
$\Delta T_g = T_g - T_a$ - increased gas temperature in the upper layer than ambient temperature (K),
$\dot{Q}$ – heat release rate (kW);
A_v – ventilation opening area ($\mathrm{m^2}$);
h_v – opening height (m);
h_k – effective heat transfer coefficient ($\mathrm{kW/m^2K}$);
A_T – total area of the compartment covering the edges of the surface,
excluding the surface of the ventilation openings ($\mathrm{m^2}$).
Calculation of the ventilation opening area is given by the formula

$$A_v = (w_v)(h_v) \tag{2}$$

where
w_v - width of the opening(m);

h_v - height of the opening(m).
The total area of the interior surfaces of the fire compartment is obtained using the expression

$$A_T = 2w_c l_c + 2h_c w_c + 2h_c l_c - A_v \quad (3)$$

where
w_c - width of the compartment (m);
l_c - length of the compartment (m);
h_c - height of the compartment (m).

Effective heat transfer coefficient, h_k, is the constant of proportionality between the heat release rate and the temperature difference. It is calculated according to the penetration time, t_p, the time required for the temperature to be transferred into the material. If the combustion period does not exceed the heat penetration time, the surface material will retain much of the transferred energy. Thus, h_k has the following expression

$$h_k = \begin{cases} \sqrt{\frac{k\rho c}{t}}, & t \le t_p \\ \frac{k}{\rho}, & t > t_p. \end{cases} \quad (4)$$

where,
$k\rho c$ - thermal inertia of interior construction $(\mathrm{kW/m^2K})^2$sec, (thermal property of the material responsible for increasing the temperature);
k - thermal conductivity of the material (kW/mK);
ρ - material density (kg/m^3);
c - thermal capacity (J/kgK);
t - time after ignition (sec).
Thermal penetration time is approximated

$$t_p = \frac{\rho c_p}{k}\left(\frac{\delta}{2}\right)^2 \quad (5)$$

where,
c_p - specific heat of the material (J/kgK);
δ - material thickness (m).

3. Fire Scenarios

It is considered a compartment having the following internal dimensions: width 3,1 m, length 5,4 m and height 2,1 m (as can be seen in figure 1); it is naturally ventilated and there are analized two scenarios: for the first scenario, the opening is a door having a width of 0,9 m and height of 2 m, located at floor level; for the second, the opening is a window having a width of 1,4 m, height of 1 m, located at a distance of 0,8 m above the floor.
The finishing material of the interior surfaces is, chipboard, gypsum board and decorative polystyrene panel, with the thickness of 1,2 cm, 1,25 cm, respective 2

cm, the method of calculation using the values of thermal properties of materials [11].
The heat release rate (HRR) takes, on the row, the value 250 kW și 500 kW. Ambient temperature (T_a) is considered 25 ℃, specific air heat (c_a) is 1,00 kJ/kgK and ambient air density (ρ_a) is 1,18 kg/m^3.

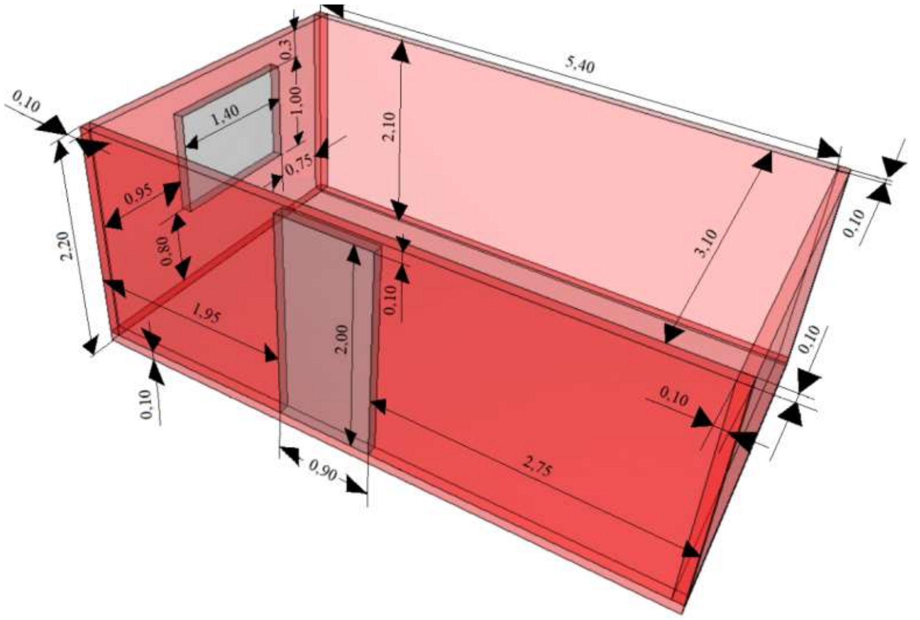

Fig. 1 Fire Compartment Dimensions.

4. Assumptions and limitations used

The fire is considered to be located in the center of the room, the value of HRR being constant. Ventilation openings are not placed in the ceiling. Rooms have standardized, dimensions parallelepiped, the method being less used in large rooms. The heat flux entering and leaving the walls of the room is considered to be one-dimensional, ignoring the corners and edges of the compartment.
It is considered that the heat loss takes place following the mass flow that exits through the openings of the room, the method is not applying if a significant time elapses before the hot gases exit through its openings.
The method is used for rooms where the temperature of the hot gas layer near the ceiling reaches 600 °C. Also, the compartment is naturally ventilated, achieving a quasi-static balance between the mass flow that enters and the mass flow that comes out of the hot gas layer.
Also, the contribution of the finishing materials to the development of the fire is not considered, but only the influence of the thermal properties of the materials and, in particular, the thermal transfer coefficient.

5. Results. Analysis of results

In order to obtain the comparative graphs presented in Figures 2-5, was processed and compared the data resulted from the use of Fire Dynamics Tools (FDTs) developed by the US Nuclear Regulatory Commission [11].
Analyzing figures 2 and 3, it is found that the temperature of hot gases reaches the maximum value in the 2nd minute, approx. 520 °C (polystyrene), in the 4th minute, approx 280 °C (chipboard), in the 5th minute, approx. 275 °C (gypsum board) for HRR-250 kW, and for HRR-500 kW, in the 2nd minute , approx. 820 °C (polystyrene), in the 4th minute, approx 430 °C (chipboard), in the 5th minute, approx. 420 °C (gypsum board).

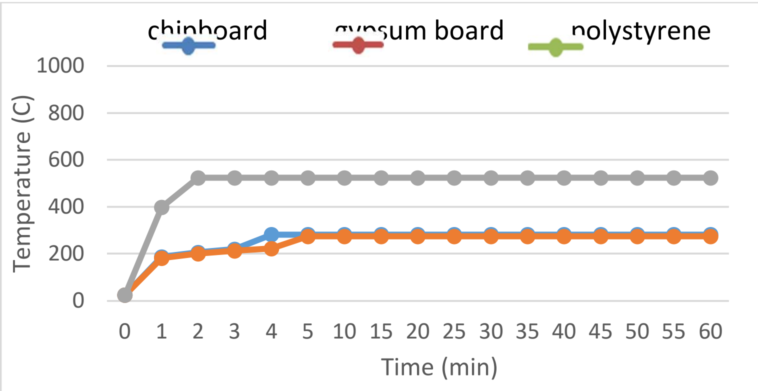

Fig. 2. The evolution of hot gas temperatures in the case of natural ventilation through the window - HRR 250 kW.

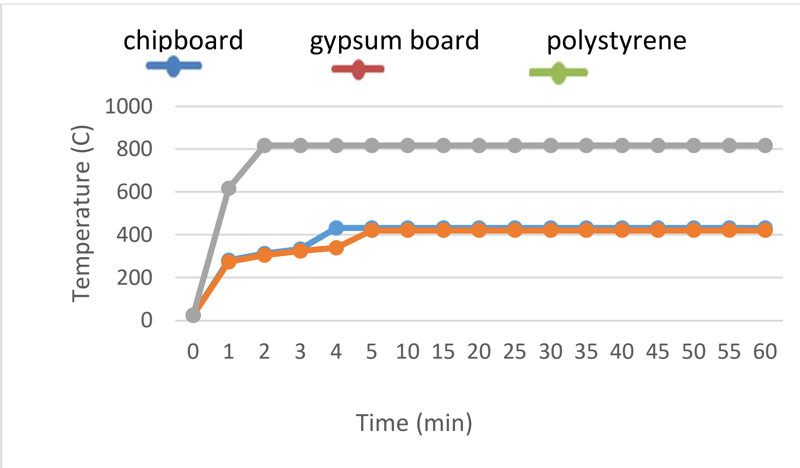

Fig. 3. The evolution of hot gas temperatures in the case of natural ventilation through the window – HRR 500 kW.

Analyzing figures 4 and 5 it is found that the temperature of hot gases reaches the maximum value in the 2nd minute, approx. 430 °C (polystyrene), in the minute 4, approx 235 °C (chipboard), in the 5th minute, approx 230 °C (gypsum board) for HRR-250 kW, and for HRR-500 kW, in the 2nd minute, approx. 675 °C (polystyrene), in the 4th minute, approx. 360 °C (chipboard), in the 5th minute, approx. 350 °C (gypsum board).

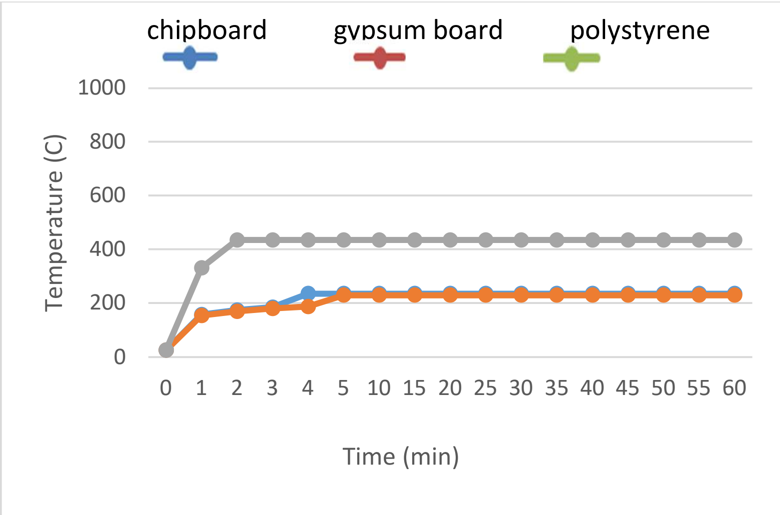

Fig. 4. The evolution of hot gas temperatures in the case of natural ventilation through the door - HRR 250 kW.

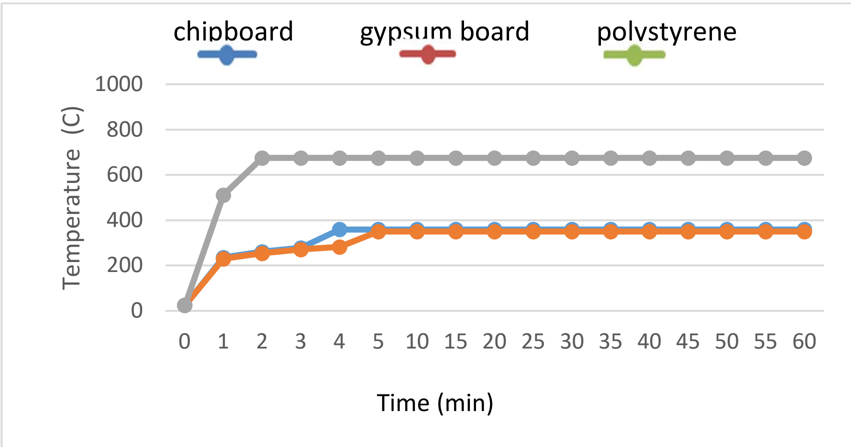

Fig. 5 The evolution of hot gas temperatures in the case of natural ventilation through the door - HRR 500 kW.

6. Conclusions

The heat release rate (HRR) increases with the temperature of the combustion gases. The temperature of the combustion gases depends on the thermal insulation coefficient of the building materials of the fire compartment. In the case of walls with polystyrene finish, the maximum temperature of the combustion gases shall be reached during the shortest time, as compared with the internal finishing compartments of chipboard or gypsum board for which close values are obtained (the thermal properties of the chipboard and gypsum board have close values). HRR values corroborated with enclosure openings configurations have a reverse proportional relationship. Thus, the larger the surface of the opening, the lower the temperature of the combustion gas is. At an HRR value for the compartment fitted with the door (250 kW/500 kW) equal to the HRR value for the compartment fitted with the window (250 kW/500 kW), the temperature of the combustion gases is higher in the case of compartments fitted with the window, compared with the door.

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