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THE INFLUENCE OF VENTILATION ON THE TEMPERATURE VARIATION RESULTING FROM BURNING A WOOD CRIB INSIDE A CONFINED SPACE

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The objective of this paper is to analyze how natural ventilation is influencing the temperature variation in an enclosed space. Experimental tests are carried out in a test room with a door and two windows. Several seven tests of burning a wood crib were conducted in different ventilation scenarios. It was found that there are certain areas where ventilation does not influence the maximum temperature developed in the burning process. It has also been observed that ventilation influences the stratification of the vertical air temperature profile.

Keywords: confined space, experiments, ventilation, temperature, wood crib.

1. Introduction

The way a fire spreads inside an enclosed space is influenced either by the amount of fuel material available in the room or by the amount of oxygen required to support the combustion process. For this reason, the influence of ventilation on the development of a fire is a particularly important element, which needs to be carefully analyzed.

Since the magnitude and intensity of a fire are greatly influenced by the temperature inside the fire compartment, the most important prediction that a fire model can make is to estimate the temperature of the smoke and hot gases layer [1]. The temperature prediction of the smoke and hot gases layer inside a room characterized by natural ventilation, the temperature value being higher than a room with forced ventilation [2], can be achieved using the McCaffrey, Quintiere and Harkleroad correlation (MQH) [3]. A correlation capable of estimating the temperature value of the smoke and hot gases layer in the case of fires characterized

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either by a low level of ventilation or a high level of ventilation has also been developed. Thus, it was obtained that the method used led to results similar to the experimental ones, only in the case of poorly ventilated fires, as opposed to highly ventilated fires, where similar results were obtained from the use of the MQH correlation [4]. The smoke and hot gases layer temperature is an important parameter, along with its height, in terms of the hot gases mass flow prediction, necessary to analyze the exposure of persons, caught by a fire, to the heat and smoke released during its development [5]. In order to predict the smoke and hot gases layer mass flow, temperature and height, both inside a fire compartment and in an adjacent room, a method based on two empirical models similar to the MQH correlation was used. This method is based on the principle of energy and mass conservation [6]. The Law correlation has been developed, this being a formula that shows the dependence of the air mass flow on the ventilation factor $(\text{door area} / \text{door height})^{1/2}$, of the ratio between the width and height of the door and of the smoke layer temperature, in the case of rooms characterized only by door-type configuration [7]. Window-type configurations give ventilation a high level of complexity compared to doors, due to the effect produced by the window sill height. Thus, a general mass flow equation has been developed, which can be applied to ventilation both through doors and windows. Providing an accuracy of up to 15 % compared to experimental data, the equation is based on a theoretical model represented by an ideal ignition source and two stationary zones, not realizing the mixture between the smoke layer and air [8]. The air volume accumulated at an opening, the ambient air currents and the effects of the thermal response influence the fuel material mass loss [9].

This article is an experimental approach of how natural ventilation through openings with different room configurations influences the temperature inside the fire compartment.

2. Experimental study

The experiment consists of burning a wood crib in a test room using seven ventilation scenarios.

2.1. The experimental stand

The test room, equipped with a door and two windows, has the walls built of aerated concrete, knows as BCA in Romanian, and the resistance pillars, the floor and the ceiling being made of concrete. The dimensions of the room are shown in Fig. 1.

The experimental stand consists of the following elements:

- (1) A plate tray with a thickness of 2 mm and dimensions 1.20 x 1.20 x 0.20 m, used to collect wood materials that break out of the wood crib during its burning the plate tray is protected by a plasterboard against premature thermal degradation;
- (2) A support bracket for the wood crib and the liquid fuel tray used to ignite the wood crib;
- (3) An ethanol tray;
- (4) A cubic wood crib with a side size of 0.60 m.

The experimental stand inside the test room is shown in Fig. 2.

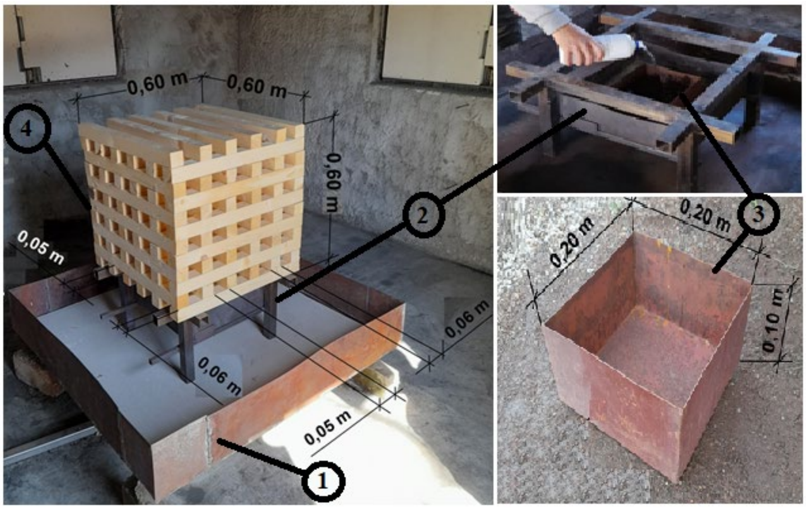

Fig. 1. Test room

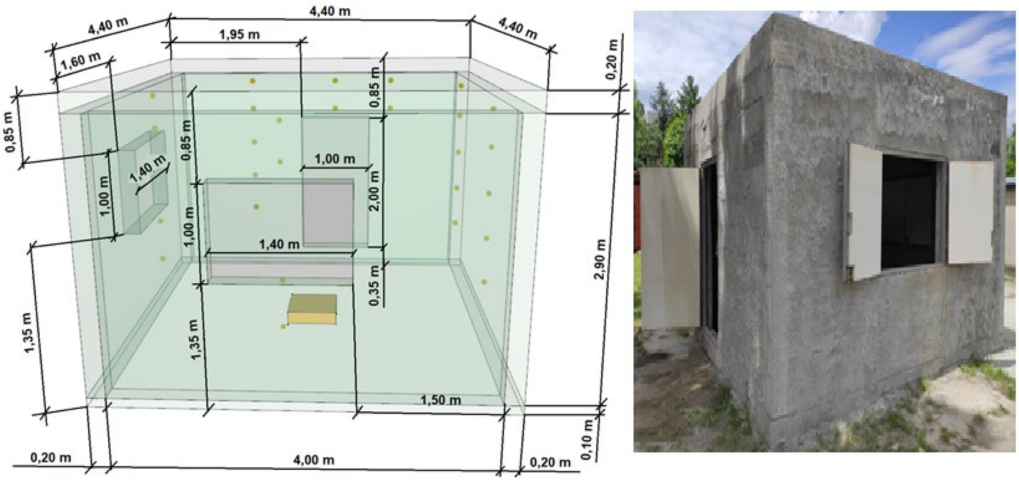

Fig. 2. Experimental stand

The wooden crib consists of 72 pine wood baguettes, with dimensions of 0.60 x 0.60 x 0.05 m, arranged in 12 orthogonal layers. Each layer consists of 6 wooden baguettes, located at a distance of 0.50 m from each other.

2.2. Measuring equipment

The measuring equipment used is as follows:

- Electronic weighing platform for measuring the wood crib mass loss, having a maximum capacity of 300 kg and a division of 50 g;
- For temperature measurements inside the test room 27 K type thermocouples were used, with a length of 40 cm, and outside the room 1 thermocouple with a length of 180 cm, with a measuring range of 0 - 1200°C.

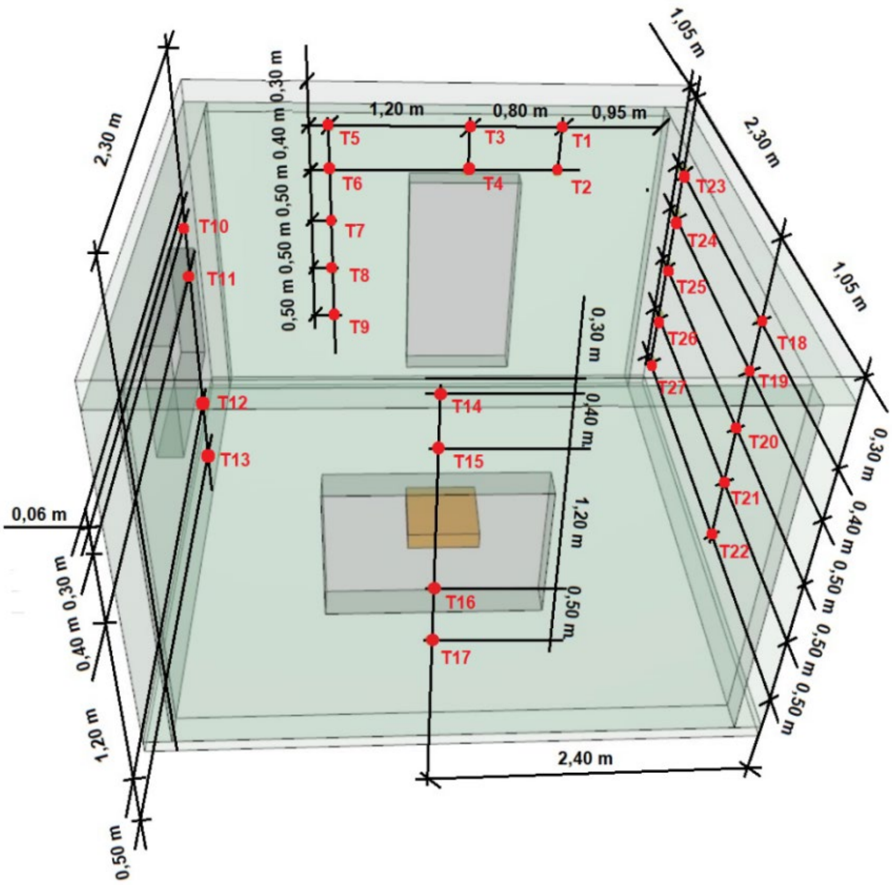

Fig. 3. Arrangement of 27 thermocouples inside the test room

The 27 thermocouples used inside the test room, from T1 to T27, were placed according to Fig. 3. The height to the floor at which the layers of thermocouples are placed is: 2.80 m - layer 1; 2.40 m - layer 2; 1.90 m - layer 3 1.40 m - layer 4; 1.20 m - layer 5; 0.90 m - layer 6; 0.70 m - layer 7.

2.3. Ventilation scenarios

In the experimental study, 7 ventilation scenarios were used, namely: ***Scenario 1*** – open door; ***Scenario 2*** – door and window located on the right side open; ***Scenario 3*** – door and window located on the wall diametrically opposite the door, open; ***Scenario 4*** - door, window located on the right side and window located on the wall diametrically opposite the door, open; ***Scenario 5*** - window located on the right side, open; ***Scenario 6*** - window located on the wall diametrically opposite the door, open; ***Scenario** 7* - window located on the right side and window located on the wall diametrically opposite the door, open. The 7 ventilation scenarios were characterized by a wood crib free burning, located in the middle of the test room, for 1800 s.

3. Results and discussions

3.1. Maximum temperature values

Of the 27 thermocouples used, the T3, T4, T11 and T15 thermocouples recorded the highest maximum temperature values, being in the top 5 places. Also, the maximum value was recorded by thermocouple T3, as shown in Fig. 4 except in ***Scenario** 7*, where the maximum temperature was recorded by T15, thermocouple T3 having the second maximum value.

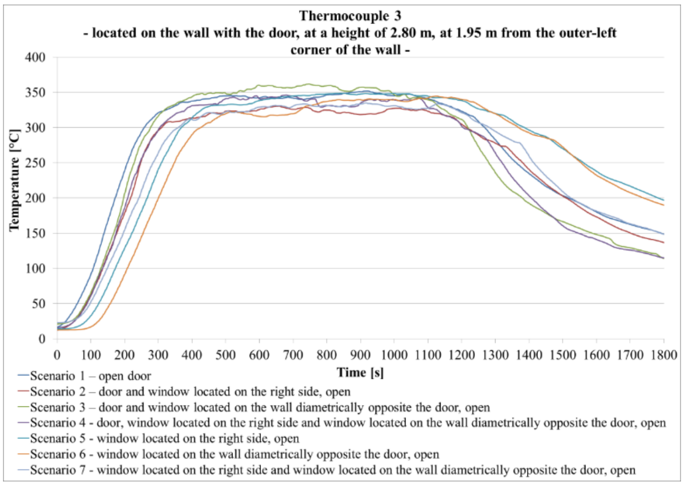

Fig. 4. The temperature change recorded by T3 thermocouple over time

The maximum mean value of the temperature values recorded by each thermocouple layer was obtained from layer 2, followed by those obtained for layers 1, 3 and 4, for all 7 ventilation scenarios. In the last 3 places, in size, the maximum values of the average temperature of layers 5, 6 and 7 thermocouples were recorded, according to Table 1.

Table 1

The maximum temperature mean values recorded by each thermocouple layer.

Scenario (opening area -m^2)	**The maximum temperature mean values [°C]**						
	Layer 2	Layer 1	Layer 3	Layer 4	Layer 6	Layer 5	Layer 7
3 (3.40)	326.66	319.40	205.00	85.13	63.20	62.75	56.60
1 (2.00)	324.17	312.24	270.63	139.80	75.00	63.77	58.15
5 (1.40)	320.33	313.77	263.33	171.13	73.97	69.00	65.95
7 (2.80)	318.36	307.17	207.63	92.37	67.75	67.30	66.17
6 (1.40)	317.51	309.64	260.73	158.37	67.80	66.90	65.30
4 (4.80)	309.96	297.80	139.43	68.57	55.40	53.30	52.65
2 (3.40)	302.54	288.61	205.53	75.27	53.10	51.73	48.70

Fig. 5 shows the time variation of the mean temperature values recorded by layer 2 thermocouples for each ventilation scenario.

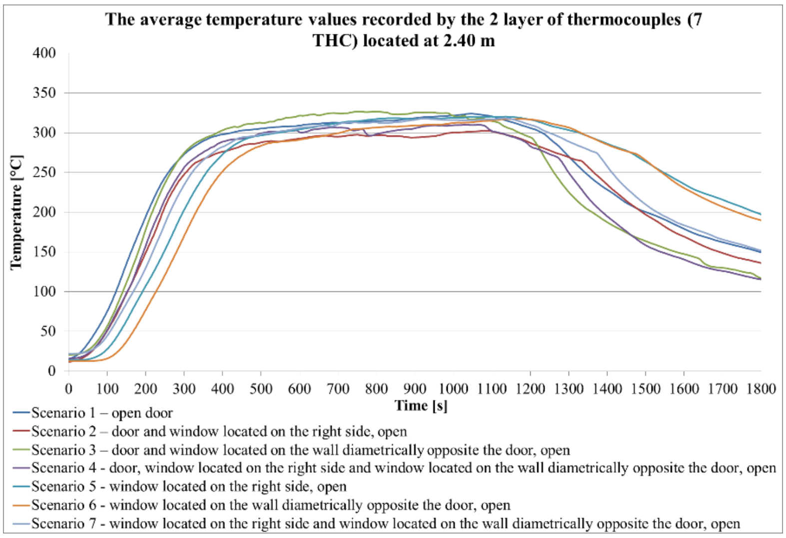

Fig. 5. Average temperature values recorded by layer 2 of thermocouples

For layer 1, the highest maximum temperature value was recorded for ***Scenario 3*** (361.90 °C) and the lowest was recorded for ***Scenario 2*** (330.50 °C) both by thermocouple T3. For layer 2, the highest maximum temperature value was recorded for ***Scenario 3*** (351.50 °C) and the lowest was recorded for ***Scenario 2*** (320.50 °C), both T4 thermocouple. For layer 3, the highest maximum temperature value was recorded for ***Scenario 1*** (284.80 °C) and the lowest was recorded for ***Scenario 4*** (156.20 °C), both by thermocouple T7. For layer 4, the highest maximum temperature value was recorded for ***Scenario 5*** (172.60 °C) and the lowest was recorded for ***Scenario 4*** (76.10 °C), both by thermocouple T26. For layer 5, the highest maximum temperature value was recorded for ***Scenario 6*** (89.90 °C) and the lowest was recorded for ***Scenario 4*** (57.60 °C), both by thermocouple T12. For layer 6, the highest maximum temperature value was recorded for ***Scenario 5*** (78.00 °C) and the lowest was recorded for ***Scenario 2*** (55.40 °C), both by T27 thermocouple. For layer 7, the highest maximum temperature value was recorded for ***Scenario 7*** (75.60 °C) and the lowest was recorded for ***Scenario 2*** (55.50 °C), both by thermocouple T13.

The shortest time measured since the wood crib was lit, during which the highest temperature value recorded at each thermocouple layer is reached, was obtained under ***Scenario 2***, equal to **659 s**. The highest value of time was obtained in ***Scenario 6***, being between **1122 and 1130 s**.

3.2. Average temperature values

In the 7 ventilation scenarios, out of the 27 thermocouples used, the T3, T4, T11 and T15 thermocouples recorded the highest average temperature values, being in the top 6 places in size. Also, the maximum mean temperature value was recorded by the T3 thermocouple, except in ***Scenario 7***, where the maximum mean temperature value was recorded by the T15 thermocouple, the T3 thermocouple having the second value in size.

Table 2

The average of the mean temperature values recorded by each thermocouple layer

Scenario (opening area -m^2)	**The average of the mean temperature values [°C]**						
	Layer 2	Layer 1	Layer 3	Layer 4	Layer 6	Layer 5	Layer 7
5 (1.40)	251.46	246.43	195.66	78.00	48.15	46.87	45.87
1 (2.00)	248.67	240.28	201.66	80.63	53.72	45.38	42.36
7 (2.80)	243.10	235.87	153.40	65.37	51.29	50.82	50.13
6 (1.40)	241.43	235.89	188.11	71.51	46.16	44.43	43.88
3 (3.40)	237.27	231.81	148.34	63.41	48.14	48.02	43.18
2 (3.40)	231.95	222.15	152.85	51.34	39.64	37.24	36.08
4 (4.80)	227.72	220.29	110.35	51.73	41.32	41.31	38.44

The maximum mean value of the average temperature values recorded by each thermocouple layer was obtained from layer 2, followed by those obtained for layers 1, 3 and 4 for all 7 ventilation scenarios. In the last 3 places, in size, the maximum values of the average temperature of layers 5, 6 and 7 thermocouples were recorded, according to Table 2.

For layer 1, the highest average temperature value was recorded for ***Scenario 5*** (272.49 °C) and the lowest was recorded for ***Scenario 4*** (250.11 °C) both by thermocouple T3. For layer 2, the highest average temperature value was recorded for ***Scenario 5*** (263.75 °C) and the lowest was recorded for ***Scenario 4***

(244.14 °C), both by T4 thermocouple. For layer 3, the highest average temperature value was recorded for ***Scenario 1*** (212.53 °C) and the lowest was recorded for ***Scenario 4*** (120.64 °C), both by thermocouple T7. For layer 4, the highest average temperature value was recorded for ***Scenario 1*** (86.54 °C) and the lowest was recorded for ***Scenario 2*** (56.09 °C), both by thermocouple T26. For layer 5, the highest average temperature value was recorded for ***Scenario 1*** (60.55 °C) and the lowest was recorded for ***Scenario 2*** (41.96 °C), both by thermocouple T12. For layer 6, the highest average temperature value was recorded for ***Scenario 7*** (50.88 °C) and the lowest was recorded for ***Scenario 2*** (39.74 °C), both by T27 thermocouple. For layer 7, the highest average temperature value was recorded for ***Scenario 5*** (48.68 °C) and the lowest was recorded for ***Scenario 2*** (39.72 °C), both by thermocouple T13.

4. Correlation used for temperature prediction

The upper layer temperature estimation of gas resulting from the combustion produced inside a fire compartment can be performed using the MQH method. The calculation for ***Scenario 1 - open door*** is carried out, the input data being related to: fire compartment, ambient conditions, thermal properties of the fire compartment wall, the heat release rate (HRR) - maximum HRR value obtained in the test, 640 kW, was used.

For the purposes of the graph shown in Fig. 6, data derived from the use of Fire Dynamics Tools (FDTs) developed by the ***US Nuclear regulatory Commission*** were processed and compared [10].

The MQH method [3] is characterized by the following equation:

$$\Delta T_g = 6{,}85 \left\{ \frac{\dot{Q}^2}{\left[\left(A_V h_V{}^{1/2}\right)(A_T h_k)\right]} \right\}^{1/3} \tag{1}$$

where: T_g is the temperature of the gas upper layer resulting from combustion [K];

T_a, ambient temperature [K];

$\Delta T_g = T_g - T_a$, increase temperature of the gas upper layer resulting from the combustion above the ambient temperature [K];

$\dot{Q}$ – HRR by the fire resulting from the wood crib burning [kW];

A_V – the surface of the ventilation opening [m^2];

h_V – the height of the ventilation opening [m];

h_k – convective heat transfer coefficient [$\mathrm{kW/(m^2K)}$];

A_T – the total sum of the compartment surfaces, excluding the area of the ventilation opening [m^2] and:

$$A_V = w_V \cdot h_V = 2{,}00\ m^2 \tag{2}$$

where w_V represents the width of the ventilation opening [m].

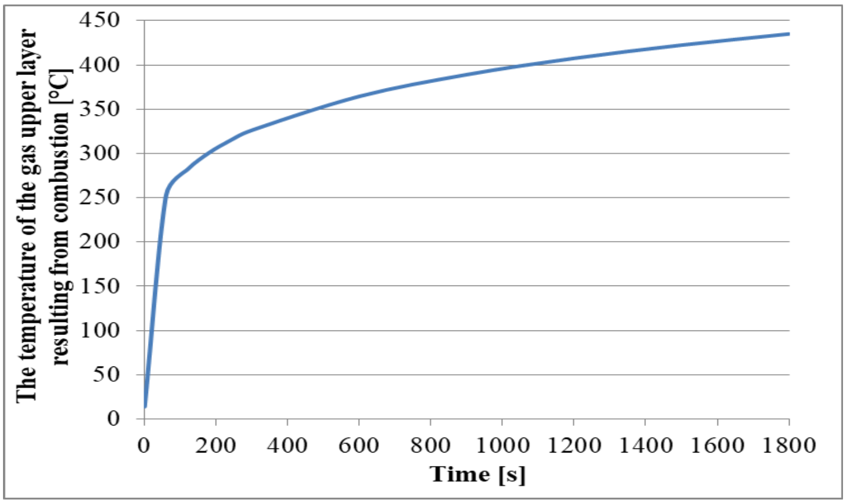

Fig. 6. The upper layer temperature estimation of gas using the MQH method.

Following the use of the MQH correlation, the estimated average temperature value is 319.04 °C, and the maximum value is 435 °C, at the height between 2.25 – 2.90 m from the floor.

Table 3

Theoretical and experimental results of the smoke and gases upper layer temperature

	The temperature of the upper layer of gas resulting from combustion [°C]		**Height to the floor [m]**
	Mean value	Maximum value	
The MQH method	**319.04**	**435.00**	2.25 – 2.90
Experimental results in *Scenario 1*	201.66	270.63	1.90
	248.67	324.17	2.40
	240.28	312.24	2.80
Average of experimental results - *Scenario 1*	**230.20**	**302.34**	1.90 – 2.80

Table 3 presents the comparative analysis of the theoretical results, obtained from the use of the MQH correlation, and experimental, in ***Scenario 1 – open door***.

5. Conclusions

The influence of ventilation status on a confined space in fire is a well-known subject in the literature and still interesting and helpful in management of fire detection in modern buildings.

In this study, an analysis of the experimental results obtained from burning a wood crib in a confined space was carried out to determine the influence of ventilation on the temperature increase inside the test room.

In the 7 ventilation scenarios, the highest temperature values have always been recorded in certain areas of the test room. Thus, regardless of the number and type of ventilation openings, in the areas above the door (T3, T4), above the window located on the right side of the door (T11) and above the window diametrically opposite the door (T15), the highest temperature values were recorded in the first 5 in size (the values recorded by the 4 thermocouples were in the first 5 positions, compared to the values recorded by the other 23 thermocouples). Also, the maximum temperature was recorded by T3 thermocouple, except in ***Scenario 7***, where the maximum temperature was recorded by T15, with T3 thermocouple having the second value in size. The highest temperature values were usually recorded above the ventilation openings most likely due to the non-sealing of the ventilation openings (when they were closed), respectively the opening of the doors and/or windows. This led to fresh air entering the bottom of the openings and increasing the speed of smoke and hot gases released at the top of the ventilation openings.

The ventilation did not influence the mean and maximum temperature values recorded by thermocouples located on each of the 7 layers, which usually increased with the increase in the height to the floor at which the respective thermocouple layer is located, with 2 exceptions.

First exception is that the mean and maximum values of the average temperature values recorded by thermocouples forming the layers located at the top surface of the wood crib (layer 5 - 1.20 m) respectively, below this level (layer 6 - 0.90 m and layer 7 - 0.70 m), do not fall in direct proportion to the height. This is because the wood crib is located 0.60 m above the floor, and the speed of cold air flowing into the room from the outside increases below the wood crib, also driving the warm air located above the floor, which affects the stratification of the air. However, the values recorded by thermocouples of layers 5, 6 and 7 are close.

Second exception is that the average and maximum temperature values recorded by thermocouples forming layer 1 (located 2.80 m from the floor) are about 7 – 14°C lower than values recorded by thermocouples forming layer 2 (located 2.40 m from the floor). This can be explained by the fact that the wood crib is not located directly on the floor, but 0.60 m from it. Taking into account that about 16 % of the total energy released by burning a wood crib leads to heating the gases inside a fire compartment [11], the thermal radiation emitted by the flames reaches a higher height relative to the floor (compared to the situation where the wood crib would have been placed directly on the floor). This leads to a higher heat transfer to the smoke and hot gas layer located at a height of 2.40 m.

The area of ventilation opening influences the average value of the temperature values recorded by thermocouples in each layer. Thus, with the exception of ***Scenario 6***, with the increase of the surface of the ventilation openings, the average value of the temperature values recorded by thermocouples in the composition of the upper layers arranged at 2.80 m and 2.40 m from the floor decreases. This is because, with the decrease in the area of the ventilation openings, there is a reduction in the amount of oxygen available in the room, which leads to incomplete combustion and the release of more unburned gases.

The resulting unburned gases, characterized by high temperature values, rise to the top of the test room, where the highest temperature values are recorded.

The shortest time measured since the wood crib was lit, during which the highest temperature value recorded at each thermocouple layer is reached, was obtained under ***Scenario 2***, equal to **659 seconds** (the value of the ventilation opening is the second in size, which leads, on the one hand, to an influx of oxygen into the room sufficient to support the combustion process, and on the other hand, to a sufficient amount of oxygen to sustain the combustion process. to prevent the loss of a very large amount of heat compared to the scenario where the ventilation opening area is the largest, with the maximum temperature being reached in the shortest time).

The longest time was obtained under ***Scenario 6***, being between **1122 and 1130 seconds** (the value of the ventilation opening is minimal, which leads to a lower inflow of oxygen in the room and an incomplete combustion process, the maximum temperature is reached after a long time).

Thus, it is found that by using the MQH correlation for the prediction of the upper smoke and hot gases layer temperature values, the values are overestimated compared to the temperature values obtained from the combustion test.

Based on the results obtained from the experimental tests performed, in terms of fire safety engineering, the following main conclusions can be drawn, with practical applicability:

- given that the surface value of the ventilation openings is inversely proportional to the temperature value of the upper layer of smoke and hot gases, when designing a residential building it is recommended to create windows with larger areas;
- taking into account that the highest temperature values were recorded at the upper level of the ventilation openings and at the ceiling level, for extinguishing a fire (located in the generalized combustion phase) which manifests itself in a room it is recommended to discharge the water jet from outside the room, on its ceiling by the ventilation opening; after a significant reduction in the temperature inside the room it can be entered to discharge the water jet directly to the outbreak;
- following this study, management measures may be applied to monitor the evolution of a fire that appeared, for example, in a room within an office building.

Thus, considering that in all scenarios the T3 thermocouple, located above the door at 0.1 m from the ceiling, recorded the highest temperature, a temperature sensor can be placed in this position. Its role will be to monitor the evolution of temperature in any space of an office building, in which there is a risk of fire. Each sensor is coupled to a SCADA system (Supervisory Control And Data Acquisition), being set to warn both acoustically and visually of the possibility of a fire occurring and developing. Thus, if the temperature recorded in the monitored rooms increases, for example, more than 60 °C, the temperature limit at which the sensors can be set, the fire alarm is triggered. The value of 60°C of the alarm trigger temperature represents 17.32% of the maximum temperature recorded by T3 within Scenario 4, when the surface of the ventilation opening is the largest.

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