

EXPERIMENTAL RESEARCH ON THE FORMATION OF HOT SMOKE AND GASES IN A BURNING ENCLOSURE AND ON THEIR FLOW THROUGH THE VENTILATION OPENINGS

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Prezenta lucrare constă în propunerea unei instalații experimentale pentru a vizualiza și analiza mișcarea fumului și gazelor fierbinți, precum și formarea stratului de fum într-un spațiu incendiat, funcție de gradul de ventilare al încăperii, corelat cu încărcarea termică a focarului și inerția termică a incintei. Într-un spațiu incendiat și suficient ventilat se formează două zone: zona superioară cu fum și zona inferioară fără fum (mai puțin contaminată cu fum). Experimentele realizate în această cercetare au avut ca obiectiv principal demonstrarea teoriei de bază că grosimea celor două straturi este funcție de suprafața golurilor de ventilare și mărimea focarului.

This paper proposes an experimental set-up to view and analyze the movement of smoke and hot gases and the formation of the smoke layer in a burning enclosure, the latter depending on the degree of ventilation of the room, thermal loading of the furnace and the thermal inertia of the enclosure. Inside a sufficiently ventilated burning enclosure, two areas develop: the upper – containing smoke and hot gases - and the lower one, containing relatively fresh air. Experiments conducted in this research were primarily aimed at demonstrating the basic theory that the thickness of the above layers depends on the ventilation holes and the size of the firebox.

Key words: fire, smoke, gas temperature, fire plume, smoke filling, ventilation

1. Introduction

Specialists in fire safety have agreed that in case of a building fire, the largest number of victims is generated by the intoxication with smoke and hot

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gases, [1; 2]. Therefore, improvement of knowledge on these fire effluents (e.g. hot smoke and gases) may lead to saving lives.

In a normal real fire occurred in an enclosed space that has ventilation openings, smoke and hot gases from the fire are positioned at the upper part of the room volume, resulting two distinct layers: the upper layer of smoke and hot gases and the lower one with breathable air. The two layers are in the same volume, so their heights are inversely proportional and researches showed that their height depend on the total area of ventilation openings, the size of the outbreak and the thermal inertia of the burning area, [3].

Knowing, however, that combustion can not occur without mass exchange and oxygen intake, [4], lead to the idea that the heights of the two layers depend on the amount of smoke discharged from the volume that houses the fire; the volume of discharged smoke depends directly on the size of ventilation openings. Calculations for sizing a ventilation system which is to be used in a fire are based on the principles of energy mass and momentum conservation. Thus, based on the knowledge of the mass flow of smoke and hot gases passing through the openings, estimated by using empirical relationships based on thermal performance of the enclosure, one can determine the area of ventilation openings in order to achieve a suitable height for the bottom layer of clean air, [5].

The practical part of the article contains experiments conducted by the authors, in an experimental enclosure. By using a burning firebox and different areas of ventilation openings for each experiment and also by registration of the pressure and temperature with electronic instruments, one obtained, in different situations, the approximate level of the separation plan situated between the two layers in the burning enclosure.

The final purpose of the paper is the provision of appropriate and simplified calculation tools - based on the relations and experiments assessed in the present paper – to the designers of ventilation installations or to fire safety specialists, for proper sizing of the ventilation and smoke extraction systems used in case of fires in enclosures.

2. Simplified mathematical model to verify experimental data

Openings such as doors and windows are the main ways that allow fire and combustion products to spread outside the room of origin. The openings also allow air to reach the combustion zone and thereby influence the size of the fire.

Physical models given in Figs. 1 and 2 represent the phenomenon of natural smoke evacuation model, the two areas approach, [6]. Fig. 1 is the case when the ventilation opening, through which gas exchange is made, is only on the side, and in Fig. 2 opening for smoke and heat is the ceiling, and the opening for fresh air intake is located on the side, beneath the smoke layer.

The following notations were adopted: height of the opening H_o [m] (fig. 1), height of neutral pressure plane H_N [m], height of smoke layer base positioning H_D [m], density of hot gases in the upper layer ρ_g [kg/m^3], lower layer air density ρ_a [kg/m^3], the absolute temperature of gas in the upper layer T_g [K] and lower one T_a [K], the area of the ceiling opening used to evacuate smoke and hot gases A_c [m^2] and the area of the air intake admission opening in the lower layer A_l [m^2] (fig. 2), the mass flow of the exhausted gases \dot{m}_g [kg/s] and the mass flow of air entering the burned area \dot{m}_a [kg/s].

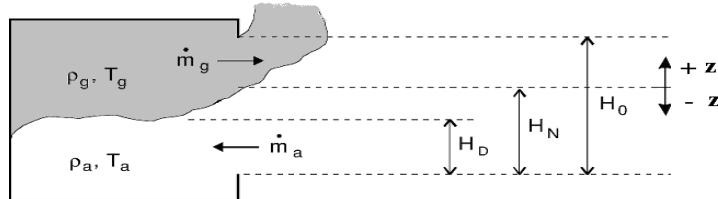


Fig. 1. Layers development in a burning enclosure, the lateral opening case

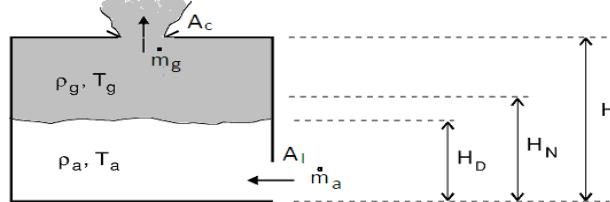


Fig. 2. Layers development in a burning enclosure, case with lateral intake opening and also ceiling exhaust one

Conservation of mass in a burning room, means that in equilibrium, through all the ventilation holes, the mass flows entering and leaving the room are equal $\dot{m}_g = \dot{m}_a$.

The parameters of the air in the lower layer presented in the following, , are considered to be similar to the ones outside the enclosure: $\rho_a = 1.2 \text{ kg}/\text{m}^3$ and $T_a = 293.15 \text{ K}$ [6; 7].

Exhaust gas mass flow through the opening (door) for the case shown in Figure 1, considered in relation to height (z) due to pressure difference, can be represented by the relation

$$\dot{m}_g = \frac{2}{3} C_d W \rho_g \sqrt{\frac{2(\rho_a - \rho_g)g}{\rho_g}} (H_o - H_N)^{3/2} \quad (1)$$

where: C_d is the flow performance coefficient (considered to be 0.6 for the door or for the window, g is the gravitational acceleration [m/s^2], and W is the width of opening [m]).

Mass flow of air drawn into the fire room in case of Figure 1 is represented by the relationship

$$\dot{m}_a = \frac{2}{3} C_d W \rho_a \cdot \sqrt{\frac{2 \cdot (\rho_a - \rho_g) g}{\rho_a}} (H_N - H_D)^{1/2} \left(H_N + \frac{1}{2} H_D \right) \quad (2)$$

For the case of Figure 2 the difference of pressure at the level of the ventilation openings is constant, so their mass flows can be calculated with the relations:

$$\dot{m}_g = C_d A_c \rho_g \cdot \sqrt{\frac{2 \cdot (H - H_N) \cdot (\rho_a - \rho_g) \cdot g}{\rho_g}} \quad (3)$$

and

$$\dot{m}_a = C_d A_l \rho_a \cdot \sqrt{\frac{2 \cdot (H_N - H_D) \cdot (\rho_a - \rho_g) \cdot g}{\rho_a}} \quad (4)$$

The mass loss or the typical rate of combustion for most fireboxes is between 0.01 and 0.05 kg/s·m² and can have a value between 1 and 10 % of the mass flow passing through an opening, so most times it is ignored.

Expressions used for calculating mass flow of gases out of the burning room and air entering contain three unknown items: ρ_g , H_N and H_D .

The hot gas density is evaluated by subtracting the absolute temperature T_g of carbon layer with a semi empirical relationship, [7], the mass flow into the smoke plume \dot{m}_p rising at H_D height is considered to be equal to the mass flow of exhaust gases \dot{m}_g through the opening, [6]. By evaluating the system of equations obtained from $\dot{m}_g = \dot{m}_a = \dot{m}_p$ equality, H_N and H_D heights are derived.

In engineering calculations it is more convenient to express the temperature for the values of gas density, [7], by applying the principles of ideal gases that are comparable with the hot gases, so $\rho = \frac{353}{T}$ or $\rho_g \cdot T_g = \rho_a \cdot T_a$.

The temperature in the smoke layer can be inferred by McCaffrey's expression, quoted in [6], evaluated by experiments and statistical correlations, based on simplified energy and mass balance. Thus, the temperature rise of smoke layer, $\Delta T = T_g - T_a$ can be deduced from the relation

$$\Delta T = 6.85 \left(\frac{\dot{Q}^2}{A_o \sqrt{H_o} h_k A_T} \right)^{1/3}, \quad (5)$$

where, \dot{Q} is the heat flow from the firebox [kW], A_o is the surface of the opening [m²], H_o is the height of the opening [m], A_T is the total area of the room minus

area of the room opening [m^2], and h_k is the actually heat transfer coefficient [$\text{kW}/\text{m}^2\text{K}$].

For the evaluation of h_k , McCaffrey et al., [6], have examined various areas of materials used in experiments, defining h_k as follows:

$$\text{a) for } t < t_p \quad h_k = \sqrt{\frac{k\rho c}{t}}; \quad \text{b) for } t \geq t_p \quad h_k = \frac{k}{\delta}$$

where: k , ρ , c and δ are the conductivity [W/mK], the density [kg/m^3], the specific heat [J/kgK] and the thickness of the solid surface materials [m] which delimits the burning area; t_p calculated as $t_p = \frac{\delta^2}{4\alpha}$ is the thermal penetration time [s].

The time when the conduction may be considered almost stationary is defined as the thermal penetration time t_p . This time can be calculated with the above relationship and indicates the period during which 15% of the increase in temperature from the firebox reaches the outside face of the solid. Here α is the thermal diffusion, also given by $\alpha = k/\rho c$ [m^2/s], found in various standards.

The thermal properties of the material, the thickness of the walls of the used experimental chamber, δ and the thermal penetration time are presented in Table 1.

Table 1

Thermal properties, wall thickness and wall thermal penetration time

k (W/mK)	c (J/kgK)	ρ (kg/m^3)	δ (m)	t_p (s)
0.48	840	1440	0.0125	95.274

For the 600 s time evaluated in the researches, b) the case above applies ($h_k = k/\delta$).

The heat flow released by a firebox in a burning area basically controls the most part of the consequences of fire by increasing the flame, the smoke plume, hot gas temperature and gas flow that feeds the smoke layer.

The maximum energy flow \dot{Q} [MW] is deduced in most cases from empirical data, [6; 8], by the appropriate ratio between the mass loss per unit area \dot{m}'' [$\text{kg}/\text{m}^2\text{s}$], horizontal surface combustion A_f [m], the total heat of combustion ΔH_c [MJ/kg] and the combustion efficiency χ , all found in the equation below

$$\dot{Q} = A_f \dot{m}'' \chi \Delta H_c \quad . \quad (6)$$

For the chosen fuel (flexible polyurethane) were extracted from the literature, [6], the following values:

$$\dot{m}'' = 0.025 \text{ kg}/\text{m}^2\text{s}, \Delta H_c = 25.2 \text{ MJ/kg} \text{ and } \chi = 0.7.$$

Many applications in the field of fire safety are based on estimating the properties of hot gas layer, i.e. its growth rate. This assessment is directly

dependent on the amount of mass and energy carried by the smoke plume into the upper layer (layer of hot gases).

Empirical relationship presented by Thomas, [7], for calculating the mass flow of the plume that rises to a H_D height of smoke layer is the most appropriate for the fire scenarios used in experiments as the flame height is smaller than the horizontal surface of the fire (fire perimeter or diameter). Thus the mass flow of gas in the smoke plume that enters the hot smoke layer can be calculated with the equation

$$\dot{m}_p = 0.188 \cdot P \cdot H_D^{3/2}, \quad (8)$$

where P is the fire perimeter.

The experimental room has the following dimensions: length $L = 2.0$ m, width $l = 1.2$ m and height $H = 1.8$ m. From these dimensions one calculates the area of the walls without openings $A_T = 2 \cdot (L \cdot l + L \cdot H + l \cdot H) - (A_o)$. For the physical model in Figure 1, the area of the opening is $A_o = H_o \cdot W$, open for the physical model in Figure 2 with an opening in the ceiling, the total area of the openings is $A_o = A_c + A_l$, in which case $H_o = H$.

The combustible has the following dimensions: length a , width b and height h resulting its horizontal burning area $A_f = a \times b$ and the perimeter $P = 2 \cdot (a + b)$.

The geometrical parameters for H_o , W , A_l , A_c , A_f and P used in calculations to evaluate the experimental data, are extracted from Table 2.

Based on the presented mathematical model, one calculates the position of the smoke layer, H_D , for each test, by introducing in calculations the parameters from the experimental tests for the thermal properties (k , ρ , c , δ) and the geometrical ones (H_o , A_o , A_T , A_c , A_l , W) of the experimental room, also the data for the combustible item: geometrical (A_f , P) and burning properties (\dot{m}'' , ΔH_c , χ), as well as data for the ambient (ρ_a , T_a). The comparation of the results from calculations with the experimental measurements proved the reliability of the simplified mathematical model in experimental applications.

3. The experimental set up

The experimental set-up shown in Figs. 3 and 4, is composed of the following elements:

- Fire resistant gypsum board room with dimensions 2.0 x 1.2 x 1.8 m, with ventilation holes cut on one side and / or ceiling, with variable surfaces;
- Temperature readout system consisting of five thermocouples placed inside the structure, as shown in Fig. 3. Thermocouples are K type (Cromel-Alumel, without protection pocket);

- Fine micro manometer for measuring pressure differences;
- Window glass of 5 mm thickness positioned on a side wall;
- Solid Fuel of parallelepiped shape with varying sizes, located in the center of the test chamber;
- Recording device for temperature and pressure measurements;
- System for data recording and processing;

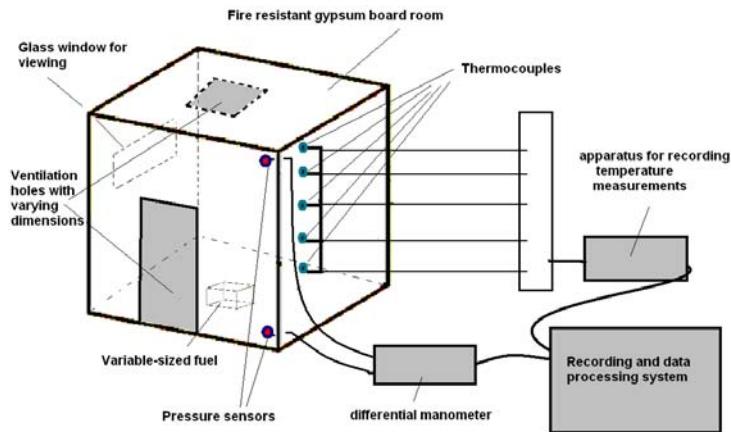


Fig. 3. Layout of the experimental stand



Fig. 4. Measuring and data recording system

1 - thermocouples, 2 - apparatus measuring the pressure difference between the two areas, 3 - experimental chamber, 4 – firebox inside the experimental stand, 5 - recorder measurement; 6 - system for data recording and processing

The fuel chosen for most tests was polyurethane or polystyrene in various quantities. The materials used in these experiments are not randomly chosen, but by their known thermal properties (for walls, floor and ceiling of the room) and burning properties (for fuel), in order to obtain a controlled combustion of fuel

and increases of temperatures not above 500 °C (temperature that leads to not needed characteristic flashover phenomenon). One also, using some preliminary calculations and then by experimenting with small quantities of fuel, one tried to establish the conditions not to exceed temperatures of 300 °C in order to avoid damage to the measuring instruments - thermocouples situated into the fire chamber.

In the enclosure, five thermocouples were mounted at equal 30 cm height to each other and 30 cm distance from the wall containing the opening, as shown in the picture below (Fig. 4), first thermocouple being installed at 10 cm below the ceiling of the room, and the last - thermocouple 5 - being positioned at 50 cm height from the floor. The pressure difference was recorded with a device having flexible tubes mounted heads up against the ceiling and down near the floor near the open side. The burning of fuel, the formation of smoke plume and the movement of hot gases were able to see through a 5 mm thick glass positioned in a side wall of the experimental chamber and also through the openings.

4. Experimental results

Using the above presented experimental stand, twenty tests were performed, of which six are detailed below six. Test data 1, 2, 7, 8, 9 and 10 chosen for this work can be viewed in Table 2.

Table 2.

List of representative tests made on the experimental stand

No item.	No. Test	Dimensions of the combustible ($a \times b \times h$) [cm]	Dimension of the openings		Type of combustible
			In ceiling [cm] (A_c)	Door [cm] ($H_o \times W$ sau A_l)	
1	Test 1	70 x 30 x 15	45 x 40	60 x 50	Polyurethane
2	Test 2	55 x 28 x 17	20 x 30	30 x 50	-//-
3	Test 7	55 x 25 x 15	0	30 x 50	-//-
4	Test 8	65 x 35 x 14	0	65 x 60	-//-
5	Test 9	50 x 28 x 20	0	65 x 60	Polystyrene
6	Test 10	40 x 30 x 25	45 x 40	50 x 60	-//-

One can note for each test, different size and fuel type and size of ventilation openings, the latter obtained by filling the space that is intended to be deducted from the maximum opening, as shown in Fig. 4.

Basically, the tests were carried out aiming at the following steps:

1. choose the size of the fuel and the dimensions of the openings;
2. ignite the fuel situated in the center of the structure, on the floor;
3. record in time the values of temperature and the pressure differences;
4. process all data for each test assessing the position of the plan between the two layers;

5. perform a comparative analysis of the data of all tests and draw the conclusions;

Graphs obtained from the tests can be seen in Figures 5 to 10, each associated with a test. Each figure contains, two graphs: one for temperature values recorded over time and the other for the difference in pressure

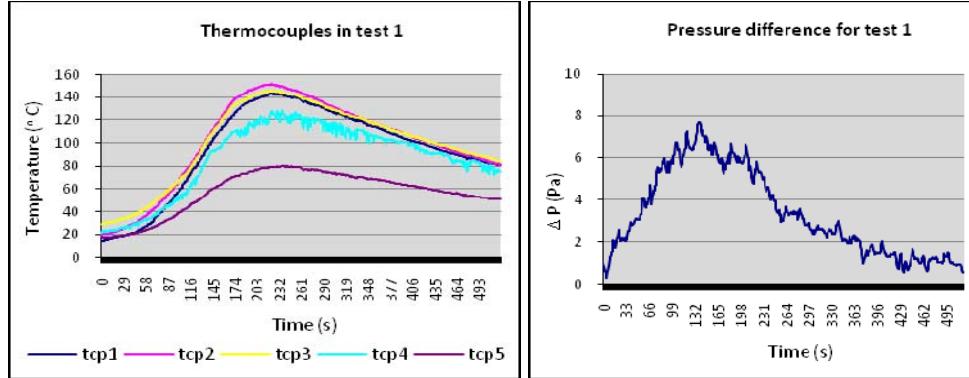


Fig. 5. Graphic records of thermocouples and pressure difference for test 1

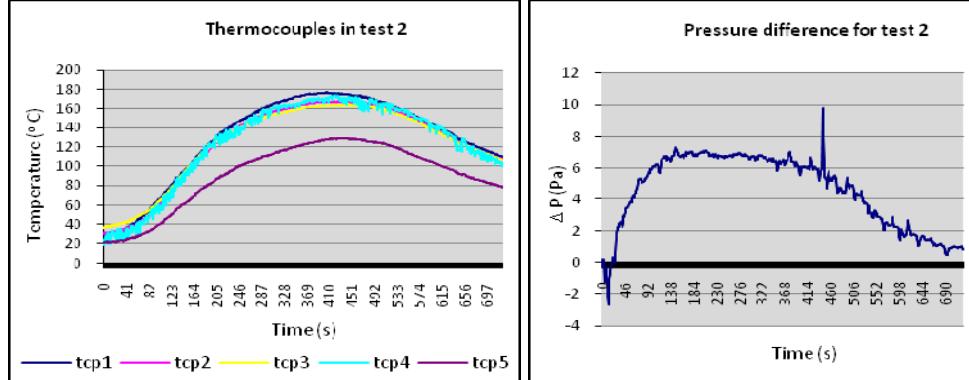


Fig. 6. Graphic records of thermocouples and pressure difference for 2

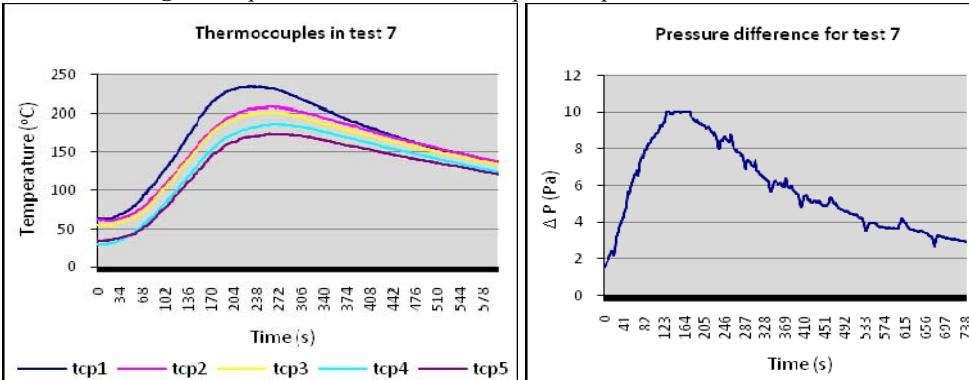


Fig. 7. Graphic records of thermocouples and pressure difference for test 7

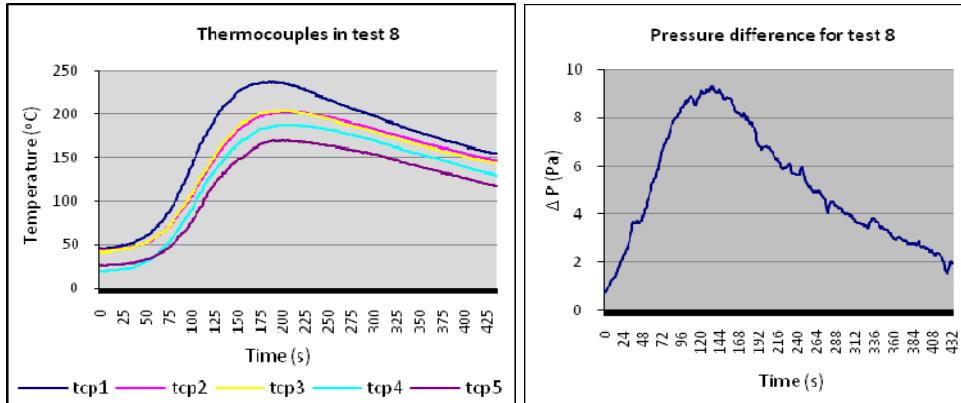


Fig. 8. Graphic records of thermocouples and pressure difference for test 8

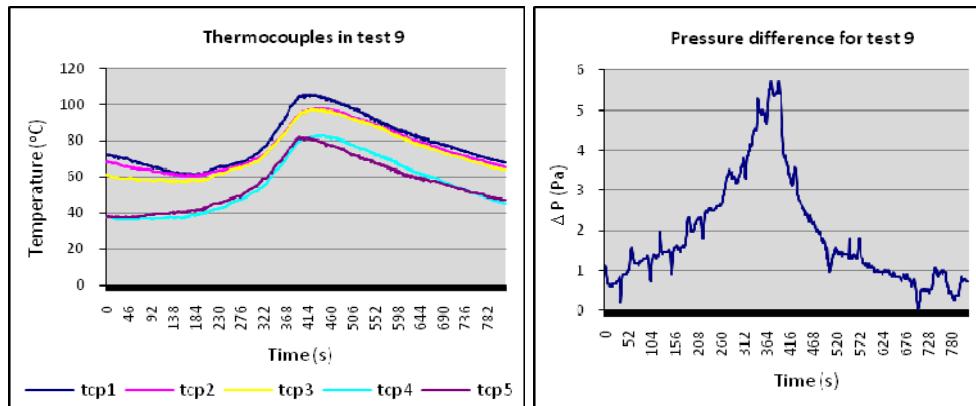


Fig. 9. Graphic records of thermocouples and pressure difference for test 9

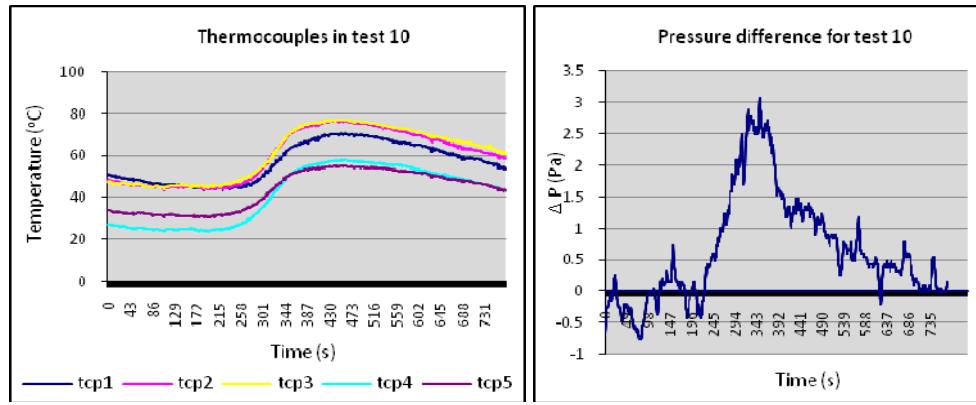


Fig. 10. Graphic records of thermocouples and pressure difference for test 10

5. Comments on results

By analyzing the graphs, one can give the following relevant conclusions concerning the experimental model:

- For the tests 1 and 2 (Figs. 5 and 6), cases when the temperatures did not exceed 180 °C, thermocouple 5 gives temperatures with 40 °C greater than the other thermocouples. This can be explained by the fact that inside this type of enclosure, for a firebox that can generate up to 200 °C, with an appropriate degree of ventilation, the smoke layer (its basic line) is situated above the fifth thermocouple. In other words, the smoke layer is positioned between 50 and 80 cm from the floor of the room on fire. For tests 7 and 8 (Fig. 7 and 8) close values of temperature for all five thermocouples can be explained by their position in the hot smoke layer, because of a lower degree of ventilation in relation to temperature (heat flux) released by the firebox. This conclusion can be better strengthened following the results of tests 9 and 10 (Fig. 9 and 10) for which a temperature rise of up to 100 °C, even for a different degree of ventilation for these two cases, the layer of smoke is positioned between thermocouples 4 and 3, i.e. at a height between 80 and 110 cm;

- Increases pressure on the room, namely the pressure differences recorded in the experiments between the top and bottom of the room on fire, had shown that they are dependent on the flow of heat from the firebox (the heat of the firebox) and the surfaces of ventilation opening. For all tests was intended that the firebox have enough air (oxygen) for combustion.

6. Conclusions

The main conclusion drawn from these experiments is that the position on height of the smoke layer and height of neutral pressure plane can be correlated with the degree of ventilation, by calculating the ratio between the area of ventilation openings used to exhaust smoke and heat from the fire and the area of fresh air intake openings, but only after one knows what mass flow must be evacuated in order to maintain this height of the smoke layer position. This can be done after assessing the temperature of the gases inside the smoke layer and the mass flow of gases from the fire plume that enters the smoke layer. The height of the positioning of the smoke layer is considered as safety height (space) for people situated inside burning spaces and it is an important design criterion for various locations where these ventilation and smoke exhaust systems are mandatory.

Based on undertaken experimental studies, more detailed conclusions have resulted. Particularly, noteworthy are the one that follows.

The hypothesis that the layer of smoke and hot gases from the combustion of fuel is positioned at the top of the burning room was practically demonstrated

by the records of temperature thermocouples positioned vertically in the experimental tests.

The values of the five thermocouples give information concerning the approximate height where the smoke hot layer begins (powerful increase in temperature value), on the vertical scale. These experimental results substantiate the theory of formation of two layers (fresh air layer and the layer containing smoke and hot gases) for a fuel controlled fire (with proper ventilation) inside a relatively closed space (with ventilation holes), [9; 10].

It was shown that the height or thickness of layers formed in the burning chamber can be adjusted by the area of ventilation openings (exhausted mass flow of gas) and by the temperature of the layer (the thermal loading of the firebox).

By evaluating a probable fire for which the fuel parameters (heat release rate, area, perimeter or diameter) and thermal characteristics and geometry of the burning space are known, one can calculate the area of the openings needed for smoke evacuation and also for the intake of breathable air, all in order to gain safely evacuation for persons trapped in the burning areas.

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