EFFECT OF RATIO BETWEEN INCOMING COOL AIR AND OUTGOING HOT GASES ON BEHAVIOR OF COMPARTMENT FIRE

by

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Many factors have an influence on the development of compartment fire notably on its heat release rate as well as on its capability to propagate and become a flashover situation. The main element which rapidly conveys fire from a compartment to another is hot smoke flowing out through openings of the compartment source of fire. The present work aims to experiment the impact of the variation of heat release rate of the source on the behavior of fire. So, five fire tests with different heat release rates were thus carried out in a reduced scale room. Temperature of burned gases inside the room, were measured during tests by sensors connected to a data acquisition system. Results revealed that temperature of burned gases as well as its content in CO, evolves differently according to two ranges of the incoming air/outgoing gases ratio. The first range of which the ratio is lower than 2, corresponds to the case where both parameters decrease rapidly. The second range of which the ratio is higher than 2, corresponds to the case where both parameters decrease moderately. The transition from the first to the second range, points out the passing from the ventilation-controlled fire to the fuel-controlled fire. A relation expressing the variation of the mass-flow rate of outgoing burned gases according to the heat release rate of the fire source has been given.

Key words: *compartment fire, heat release rate, incoming cool air, outgoing hot gases*

Introduction

Compartment fire is a complex and unpredictable phenomenon whose behavior depends on several factors such as heat release rate (HRR) of the fire source, dimensions of compartment and ventilation induced by fire through openings. Hot gases are at the origin of the propagation of fire from the room source to neighbor rooms, facilitating thus the propagation of fire in all over the building. The majority of deaths and injuries caused during fire are due to the exposition to smokes, which are characterized by its opacity and its composition in polluting particles (CO and soot). Indeed, opacity impedes safe evacuation of occupants while polluting particles once inhaled, can immediately lead to death. Production of hot gases during fire mainly

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depends not only on the HRR of the source but also on the ventilation level of the compartment. If an unexpected fire is not suppressed [1], the produced hot gases could provoke a generalization of fire in the entire room whether its temperature exceeds 600 °C because of the emitted radiation, which can ignite potential combustibles far from the source [2-5]. Compartment fires have as principal characteristic the relative lack of air in the combustion process. That lack in air induces a non-complete reaction which induces the release of toxic gases and soot particles. In fact, due to the moisture of elements involved in fire and the incoming air-flow through opening(s), the combustion reaction will relatively produce soot particles and toxic gases of which the most dangerous is carbon monoxide [6-9].

Buoyancy-driven flows are phenomena which govern motion of gases inside the room during fire. Studying these flows in a full-scale test is dangerous and expensive, reason why similarities methods are often used through dimensionless analysis [10]. Especially, the concept of geometric similarity is the one used in buildings fires for corresponding results of the reduced scale fire tests with the full scale. Indeed, in the field of compartments fires studies, many researches are done in the reduced scale and the found results are converted into full scale results using methods such as Froude modelling. Some parameters like HRR, temperature, and velocity of gases can be extrapolated into full scale fire situation. Many works were done by some authors using that scaling technics [11-16]. The HRR, $\dot{Q}$, of the fire depends on the burning rate, $\dot{m}_\mathrm{f}$, of combustible, it is calculated using the relation given by eq. (1) where terms χ and ΔH_c represent the combustion efficiency and calorific value of combustible, respectively [17]:

$$\dot{Q} = \dot{m}_\mathrm{f}\,\chi\Delta H_\mathrm{c} \tag{1}$$

In compartment fires which are driven by buoyancy flows, the mass-flow rate of ambient cool air entrained in the compartment through the lower portion of the door has been assumed as given in eq. (2) [18, 19], and the mass-flow rate of burned gases or smokes flowing out from the compartment through the upper portion of the door, has been assumed by Rocket [20] as:

$$\dot{m}_\mathrm{in} = 0.50 W_0 H_0^{3/2} \tag{2}$$

$$\dot{m}_\mathrm{out} = \frac{2}{3} C_d \rho_0 W_0 H_0^{3/2} \sqrt{2\mathrm{g}\left(1-\frac{Z_\mathrm{N}}{H_0}\right)\frac{T_0}{T_\mathrm{g}}\left(1-\frac{T_0}{T_\mathrm{g}}\right)}\left(1-\frac{Z_\mathrm{N}}{H_0}\right) \tag{3}$$

where C_d is worth 0.7 represents the flow coefficient, Z_N – the height of discontinuity between hot gases and cool air layers, W_0 and H_0 – the width and height of the opening, respectively.

The objective of the present paper is to study the effect of the ratio between incoming cool air and outgoing hot gases on the fire behavior, notably on the temperature of smokes accumulated at ceiling as well as its content in CO. So, using a reduced scale compartment with an open door, five tests were carried out using fire sources with different HRR. The first part of this paper presents the materials and methods and the second part is devoted to the interpretation and discussion of results.

Material and methods

Experimental set-up

The reduced room in which experimental tests were carried out is of dimensions L × W × H: 0.50 m × 0.50 m × 0.50 m, fig. 1. It includes an open door of dimensions $W_0 \times H_0$:

0.40 m × 0.20 m. Walls, ceiling, and floor of that experimental room were constructed with wood panels of thickness 15 mm, and of which thermal properties such as density, conductivity and specific heat are worth 840 kg/m^3, 0.20 W/m^{2}K, and 1880 J/kgK, respectively. Set at the centre of floor, fig. 2, five pans with different inner diameters (130 mm, 97 mm, 75 mm, 65 mm, and 53 mm), filled with an amount of diesel fuel, were each one used as fire source. The whole was set on an electronic balance so that to measure the mass loss rate of fuel during experiment. Determination of CO content of burned gases was performed using the gas analyzer Testo-320 (range: 0…4 000 ppm, resolution of 1 ppm) of which the probe has been placed in the upper side of compartment. The data acquisition system Agilent-34970 was used to record automatically data according to a given time step. Temperature of burned gases was measured owing to an array of eight N-type thermocouples (range: –100 °C…1 300 °C, resolution of 1°) installed along the height of the experimental room, tab. 1, and connected to the Agilent-34970. The experiment protocol consisted on igniting the preheated diesel fuel and performing measurements over time until the steady-state is reached (when temperatures given by sensors do not vary any more). Each fire test has been repeated three times and only the average data were interpreted.

Figure 1. Experimental room in which experiments were carried out

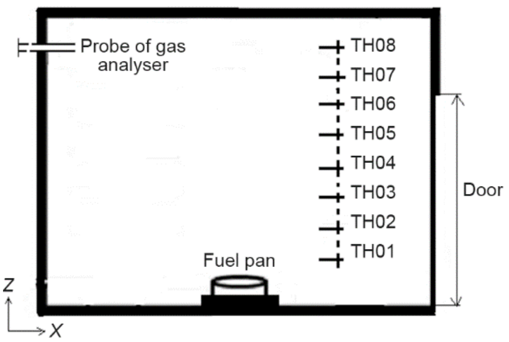

Figure 2. Locations of temperature sensors and fire source inside the domain

Table 1. The *x*, *y*, and *z* positions of the temperature sensors inside the experimental room

Designation	TH01	TH02	TH03	TH04	TH05	TH06	TH07	TH08
x [m]	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
y [m]	0.45	0.06	0.06	0.06	0.06	0.06	0.06	0.06
z [m]	0.45	0.12	0.17	0.22	0.27	0.32	0.37	0.41

Results and discussion

Accuracy of experiments

Repeating the experiments intended to bring out the repeatability of measurements. As illustration, fig. 3 presents the three repeated and average temperature profiles of Experiment 1 (TH05) and Experiment 2 (TH06). It can be noticed on that figure that the standard deviations of both experiments are less than 5 °C.

Heat release rates of experiments

Each pan has been used as fire source, that gave five experiments which were carried out in the same experimental conditions. Figures 4-8 present the profiles of temperature inside the domain at different altitudes of the room. On these figures, two phases can be distinguished. The first phase corresponds to the growth phase during which there is a progressive rise in temperature at different points of the domain. After that first stage, follows the steady-state during which the fire source is fully developed. During that full-development phase, the fire source is piloted by a constant burning rate of combustible. Measurement of the mass loss during that steady-state enabled determining the average burning rate of fuel. Table 2 presents the average values of burning rate obtained for each experiment. By taking the combustion efficiency and the calorific value of diesel fuel equal to 0.80 MJ/kg and 44.4 MJ/kg [21], respectively, the HRR of different experiments were then calculated, tab. 2).

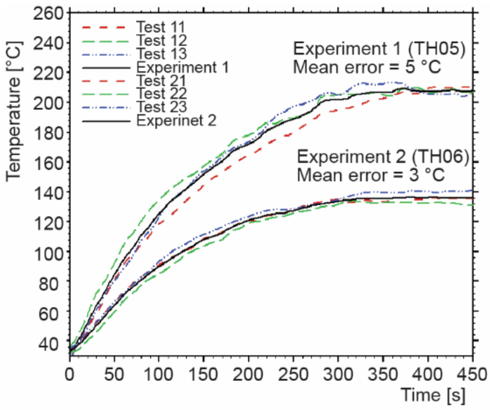

Figure 3. Illustration of the repeatability of experiments

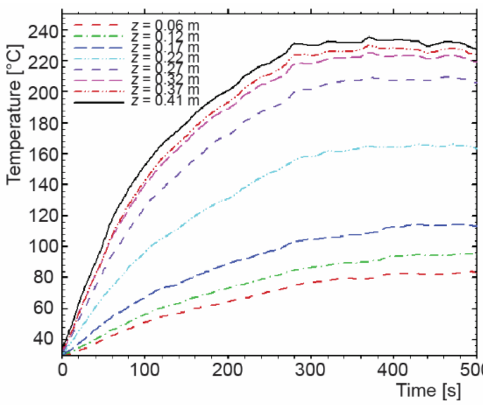

Figure 4. Profiles of temperature inside the experimental domain at different heights while using the fuel pan of diameter 0.130 m

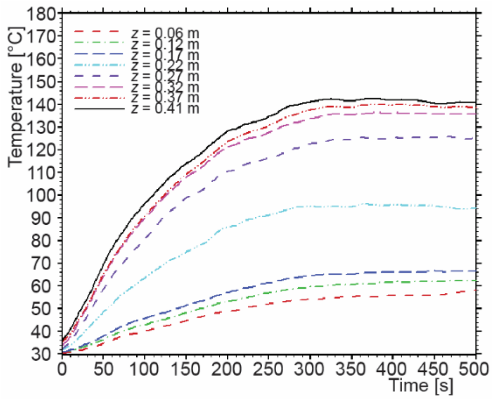

Figure 5. Profiles of temperature inside the experimental domain at different heights while using the fuel pan of diameter 0.097 m

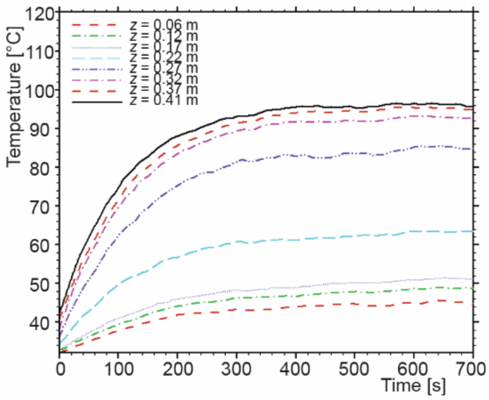

Figure 6. Profiles of temperature inside the experimental domain at different heights while using the fuel pan of diameter 0.075 m

Figure 9 presents the vertical profile of temperature plotted during the steady-state of each fire experiment, precisely at time t = 400 seconds. In spite of the change of the HRR, the shape of the curve does not change. Two zones can thus be identified: the zone of burned gases located at the upper portion of the room and the zone of cool air located at the lower portion of the room. The discontinuity height Z_N between both zones remains constant and is almost worth 0.25 m. As stated in [20], that value always represents the half of the compartment height whatever the HRR in the compartment.

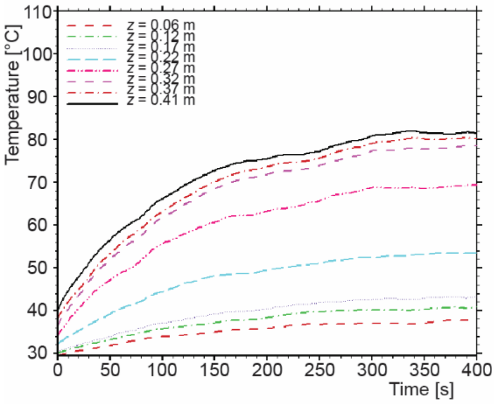

Figure 7. Profiles of temperature inside the experimental domain at different heights while using the fuel pan of diameter 0.065 m

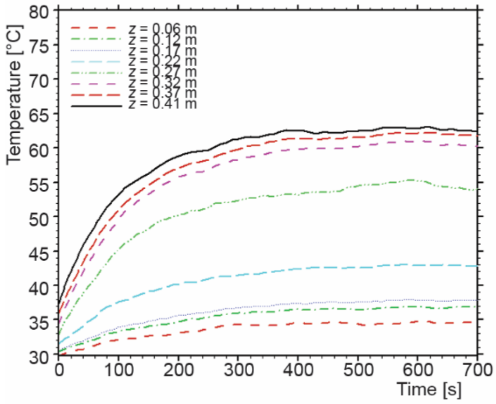

Figure 8. Profiles of temperature inside the experimental domain at different heights while using the fuel pan of diameter 0.053 m

Table 2. Values of average burning rates and HRR of experiments

Experiment	D [m]	$\dot{m}_f$ [10^{-3} kgs^{-1}]	$\dot{Q}$ [kW]
1	0.130	0.110	4.00
2	0.097	0.048	1.80
3	0.075	0.017	0.62
4	0.065	0.014	0.50
5	0.053	0.0075	0.27

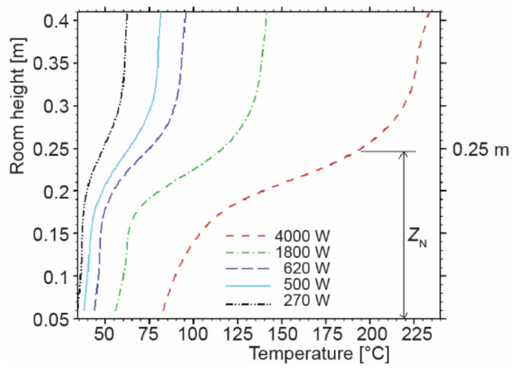

Figure 9. Vertical profiles of temperature during the steady-state at time t = 400 seconds

Table 3 reports the maximal temperature reached by hot gases as well as its content in CO all of them measured during the fully-developed fire stage. The mass-flow rates of incoming cool air and outgoing burned gases were calculated and also reported. It is observed that temperature of gases at ceiling increases with the HRR and since the rate of outgoing gases depends on that temperature, it will also vary while the rate of incoming air will remains constant because of the fact that it only depends on the size of opening. So, the more HRR increases, the more temperature of smokes at ceiling is high. That rise in temperature induces the out flowing of gases with high velocity.

The ratio between the incoming air and the outgoing burned gases was also deduced. Figure 10 presents the variation of burned gases temperature inside the room, and its CO content according to this ratio. It is observed that temperature of these burned gases and its content in CO evolve differently according to two ranges of the incoming air/outgoing gases ratio. The first range corresponds to the case of which the ratio is lower than 1.95, where both parameters decrease rapidly. The second range corresponds to the case of which the ratio is higher than 1.95, where both parameters decrease weakly. That simultaneous transition of these parameters (temperature and CO content of burned gases) around value 2 of the ratio is due to the passing of fire from the ventilation-controlled fire to the fuel-controlled fire. Indeed, when the room size is larger than the source size, walls do not have any significant influence on fire, the combustion process is thus piloted by the burning rate of combustible. But when the size of the fire source is non-negligible compared to the room size, fire is piloted by ventilation. The lack of sufficient air in the room during the ventilation-controlled fire, involves not only an accumulation of burned gases inside the compartment but also the production of more soot particles and toxic gases; reason why the temperature and the CO content of burned gases raise while the ratio between incoming air/outgoing gases decreases.

Table 3. Maximal values of parameters determined during steady-state of experiments

$\dot{Q}$ [kW]	T_g [K]	$\dot{m}_{out}$ [kgs^{-1}]	$\dot{m}_{in}$ [kgs^{-1}]	$\dot{m}_{in}/\dot{m}_{out}$	CO [ppm]
0.270	336.0	0.00931	0.02530	2.72	40.0
0.500	353.0	0.01080	0.02530	2.34	70.0
0.620	368.0	0.01170	0.02530	2.16	110.0
1.800	413.0	0.01340	0.02530	1.89	240.0
4.000	508.0	0.01480	0.02530	1.71	480.0

By plotting the mass-flow rate of burned gases according to the HRR, fig. 11, it is remarked that it varies in a logarithmic way with the HRR. By applying a mathematical interpolation on these experimental data, the best theoretical model (R^2 = 0.984) expressing the mass-flow rate of outgoing burned gases according to energy rate, is given by:

$$\dot{m}_{out} = a\ln(\dot{Q}) + b \tag{4}$$

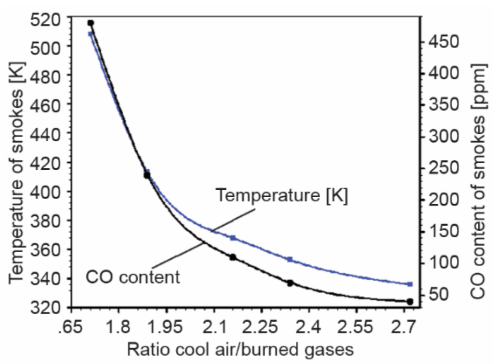

Figure 10. Variation of CO content and temperature of smokes accumulated at the ceiling

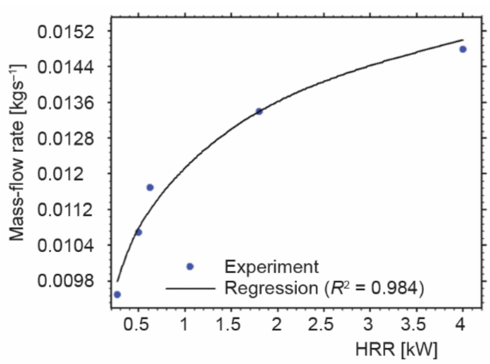

Figure 11. Variation of the mass-flow rate of outgoing gases according to HRR

Coefficients a and b can be determined analytically or empirically. They will depend mainly on the compartment characteristics such as the nature of walls, dimensions of compartment, and entering air-flow. Especially for the present work, these coefficients are worth 0.002 and 0.0122, respectively.

Conclusion

This worked aimed to study the effect of the ratio between incoming cool air and outgoing burned gases on the HRR of the source during compartment fire. It outcomes in this study that the transition from under-ventilated fire to moderately ventilated fire is done around value 2 of the ratio. Future works will be focused on the extrapolation of these results into the full-scale fire situation and performing comparison.

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Nomenclature

C_d – flow coefficient, [–]
D – fuel pan of diameter, [m]
H – height of room, [m]
H_0 – height of opening, [m]
ΔH_c – calorific value of fuel, [MJkg^{-1}]
L – length of room, [m]
$\dot{m}_f$ – burning rate of fuel, [kgs^{-1}]
$\dot{m}_{in}$ – mass-flow rate of cool air, [kgs^{-1}]
$\dot{m}_{out}$ – mass-flow rate of hot gases, [kgs^{-1}]
$\dot{Q}$ – heat release rate, [W]
T_0 – ambient temperature, [°C]
T_g – burned gases temperature, [°C]
W – width of room, [m]
W_0 – width of opening, [m]
Z_N – neutral height, [m]

Greek symbols

χ – combustion efficiency, [–]
ρ_0 – density of cool air, [kgm^{-3}]

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