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Thermal and species characterization of naturally under-ventilated room fires

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Abstract. Fires in vitiated atmospheres, characterized by a reduction in available oxygen for combustion and an increase in surrounding oxygen, remain a relevant issue in fire science and engineering. This study presents a comprehensive experimental campaign to analyse combustion in vitiated atmospheres of a heptane pool fire located within a naturally ventilated enclosure compartment. The experimental tests were conducted using a reduced-scale room configuration, containing devices to measure gas concentration and temperature. The experimental setup involved a series of tests with various opening configurations to systematically investigate the effects of the natural ventilation on combustion behaviour. The results demonstrate the influence of different opening configurations on combustion, with one specific setup leading to extinction due to oxygen depletion.

1. Introduction

Enclosure fire, which is the common building fire scenario, causes enormous casualties because of the trapped toxic smoke and enhanced heating inside a confined space. Despite the simplicity of the configuration and fire scenario, it is still challenging to predict the compartment-fire development as there are complex processes related to heat transfer and combustion processes [1]. Due to these difficulties, combustion in vitiated atmospheres has been primarily analysed in small and bench-scale tests where boundary conditions, such as oxygen concentration in the gas flow, can be adjusted to define the desired condition for the analysis [1] [2]. These controlled studies have allowed the development of parameters that analytically correlate oxygen availability with combustion typology. One of the most employed parameters is the Global Equivalence Ratio (GER), which correlates the fuel mass loss with the oxygen inflow and the stoichiometric combustion relation to define whether a combustion is underventilated or fuel-controlled. However, these studies are often based on bench-scale tests, such as the Fire Propagation Apparatus (FPA), and other environment conditions affecting the combustion regime cannot be studied.

A milestone in compartment fires theory was proposed by Kawagoe [4] for the relationship of the ventilation, gas phase temperatures and burning rates based on the Bernoulli equation and test observations at different scales of a flow coefficient. Several studies have developed laboratory-scale experimental campaigns to evaluate compartment boundary conditions during combustion. A reduced-scale compartment of 1.8 m^3 with a ventilation system was employed in

[3] to analyse the effect of radiative heat fluxes on the burning rate of elevated dodecane pool fire in a well-ventilated compartment. The results showed that the mass loss rate (MLR) remains quasi-constant when the flame does not impinge on the ceiling, whereas ceiling impingement causes a drastic increase in the MLR. Additionally, in [4], the same experimental set up was used to analyse the effect of ceiling on burning rate of heptane and ethanol pool fires. The results confirmed the increase in MLR with the elevation for all fuel types. In [5] an analysis on the effect of a ceiling opening into the autoextinction of heptane pool fire was presented. This study employed a 0.75 m^3 compartment and the section of the pool and the opening was modified finding an exponential correlation between extinction and ceiling opening section. A related investigation [6] presents a study of self-extinction time of n-heptane pool fire in closed compartments. Experiment considered a 0.75 m^3 compartment and pool fire diameters varying between 0.1 m to 0.3 m. They found that the fire self-extinction occurred when local oxygen mole fraction in the vicinity of the flame decreased to a level of 10.7-15.3%.

The present study aims to analyse combustion in naturally ventilated vitiated atmospheres. A laboratory-scale experimental campaign was performed to analyse the influence of the opening size on combustion and its correlation with the GER. The influence on dependent variables, such as temperature and gas concentration, has been also examined.

2. Experimental set-up

2.1 Experimental set-up definition

The specific goal of this study makes it necessary the design and development of an ad-hoc setup to define a controlled scenario to analyse the combustion behaviour in naturally ventilated enclosures. Based on the reviewed literature, a medium-scale compartment has been defined as shown in Figure 1. This configuration, with the shape of a cube of 0.5 m side, has a total volume of 0.125 m3. It has an opening of a fixed width of 0.15 m and adjustable height. The walls of the systems are made of gypsum plasterboards.

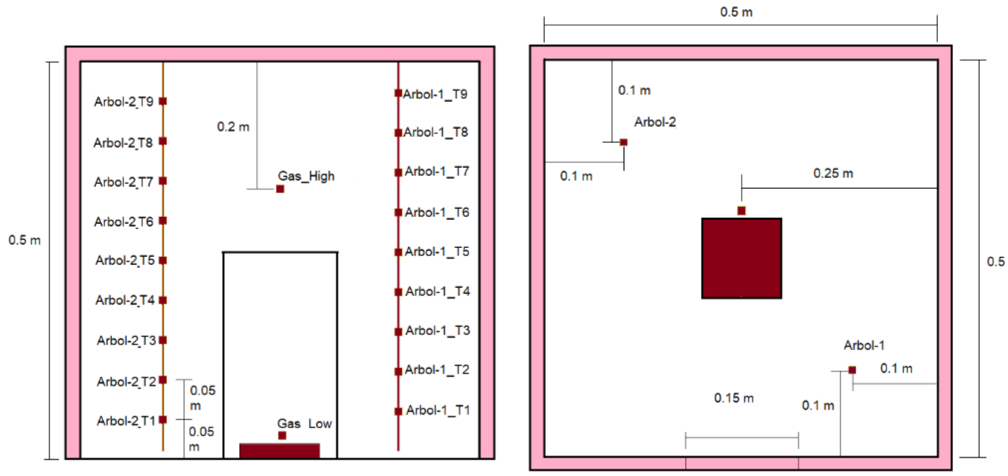

Figure 1. Scheme of the experimental ad-hoc medium scale compartment.

In order to understand combustion behaviour, different devises has been instaled in the set-up. As Figure 1 shows it has been installed two thermocouples trees, with 9 thermocouples in each sepparated 5 cm between them. Additionally, two devises to measure gas concentration (O2, CO2 and CO) has been instaled at the height of the fire source and at 0.3 m over the floor.

2.2 Cases configuration

In order to understand and analyse the combustion behaviour under vitiated atmospheres in a natural ventilated compartment, the influence of the variation in the opening height was examined. The open height (H_0) has taken the values of 0.05 m (ME_Hep-1 cases), 0.15 m (ME_Hep-2 cases) and 0.25 m (ME_Hep-3 cases). This parameter is related with ventilation, and impacts the oxygen availability for combustion.

The pool fire selected in the present experimental campaign contains heptane as fuel and have an square section of 0.1 m per side. Heptane is widely used in nuclear facilities studies and this context. According to the literature, the theoretical MLR of heptane is 0.101 kg/sm² giving an estimated heat release rate of 5.26 kW for a pool fire of 0.01 m² [7]. The following table shows an estimation of the theoretical GER for the different cases to be analysed in the experimental campaign.

$$\phi = \frac{\dot{Q}}{13.4 \cdot 0.5 \cdot 0.23 A_0 \sqrt{H_0}} = \frac{\dot{Q}}{1.541 A_0 \sqrt{H_0}}$$

Table 1. Description of the cases and theoretical GER.

Case	$\dot{Q}$ (kW)	A_0 (m^2)	H_0 (m)	GER [ϕ]	Combustión
ME_Hep-1	5.26	0.0075	0.05	2.035	Under-ventilated
ME_Hep-2	5.26	0.0150	0.10	0.719	Well-ventilated
ME_Hep-3	5.26	0.0375	0.25	0.182	Well-ventilated

3. Results and discussions

3.1 Observations

Firstly, the observations performed during the experiments are presented. Table 2 shows the extinction times for the 9 experimental tests, and the corresponding mass consumption. This reflects that the experimental test ME_Hep-1 that consider the lower aperture undergo an extinction due to a lack of oxygen, with a fuel residue between 52 % and 82 % of the initial mass. The other two scenarios allow the total consumption of the fuel mass. This is in accordance with the theoretical GER analyses that indicate that the case ME_Hep-1 was under-ventilated, while the other two were well-ventilated.

Table 2. Observations during experimental campaign.

Case	Extinction time (s)	Initial mass (g)	Final mass (g)	Extinction cause
ME_Hep-1	130-120-80	61	32-44-50	Oxygen lacks
ME_Hep-2	320-320-310	61	0	Fuel consumption
ME_Hep-3	290-280-260	61	0	Fuel consumption

The following are several captures of the fire spread in different tests of the ME_Hept-1, ME_Hept-2 and ME_Hept-3 cases. The first row represents the ME_Hept-1b fire development every 30 s. The second row shows the fire development in the ME_Hept-2b case. And the third row represents the fire development in the ME_Hept-3a. The ME_Hept-1 case (Figure 2) shows the influence of the lack of oxygen, as evidenced by the low-intensity flame, as gases are releasing without the necessary oxygen to combust. Figure 3 shows the fire development in ME_Hept-2b every 60 s. Although the flame intensity is higher compared to ME_Hept-1, the snapshots at 180 seconds and 240 seconds show that the flame extends to the surroundings of the pan, searching for oxygen to burn the unburned gases. This effect can be more evident in the ME_Hept-3 case illustrated in the Figure 4. It can also be observed that no combustion of the flame occurs in the upper part of the compartment, due to the lack of oxygen available for the combustion. This confirms that theoretical GER calculation defines the global situation of the scenario, but in these cases flames has to move searching for the available oxygen.

Figure 2. Captures of ME_Hept-1b at 30 s, 60 s, 90 s and 120 s.

Figure 3. Captures of ME_Hept-2b at 60 s, 120 s, 180 s and 240 s.

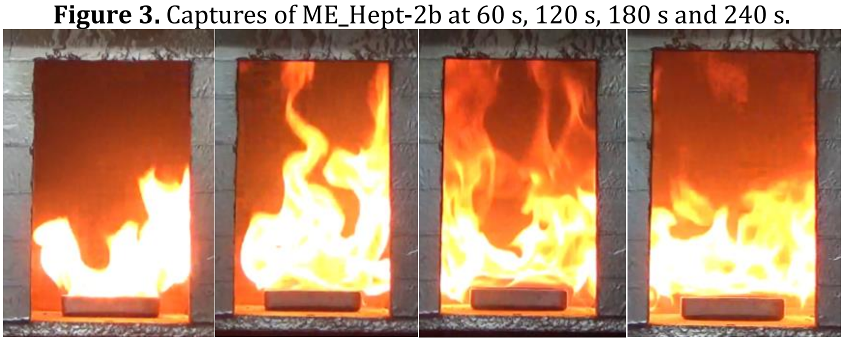

Figure 4. Captures of ME_Hept-3a at 60 s, 120 s, 180 s and 240 s.

3.2 Effect on gas concentration

In this subsection the concentrations of O_2 and CO_2 at various heights within the experimental compartment during the combustion tests are analysed. The results showed that the oxygen concentration significantly decreases in the ME_Hep-1 cases, leading to fire extinction at an O_2 concentration of around 8 % (Figure 5). In the ME_Hep-2 and ME_Hep-3 cases, the oxygen concentration remained at levels sufficient to allow complete combustion of the fuel. At around 180 s, a decrease in the O_2 concentration in the surroundings of the pool fire in ME_Hept-3 test is observed, decreasing below 10 %. Nevertheless, combustion remains as flames move to the surroundings to find available O_2 for combustion. As shown in Figure 6, the CO_2 concentrations increase as combustion progresses following the inverse tendency of the O_2 concentration.

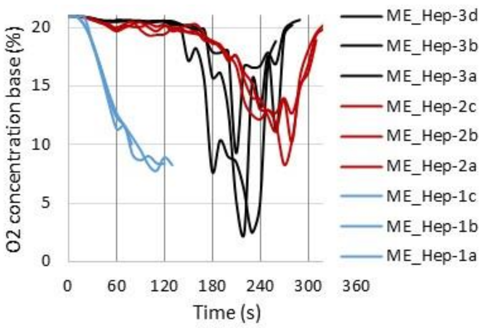

Figure 5. O_2 concentration at the pool fire.

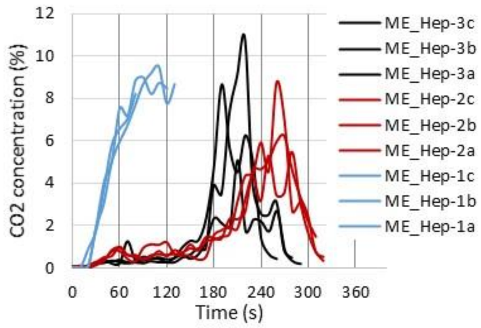

Figure 6. CO_2 concentration at the pool fire.

Now, Figure 7 and Figure 8 represent the comparison of the O_2 and CO_2 concentration results at a height of 0.3 m over the floor. Here lower values of O_2 concentrations are observed, reaching minimums values of approximately 3 and 5 %. This is validated with the results presented in the previous section where it can be seen no combustion in the upper part of the compartment. Similar to the behavior of gas concentrations in the vicinity of the fire source, the evolution of CO_2 exhibits an inverse trend compared to that of O_2.

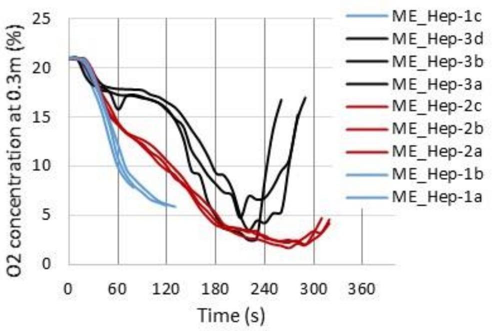

Figure 7. O_2 concentration at 0.3 m height.

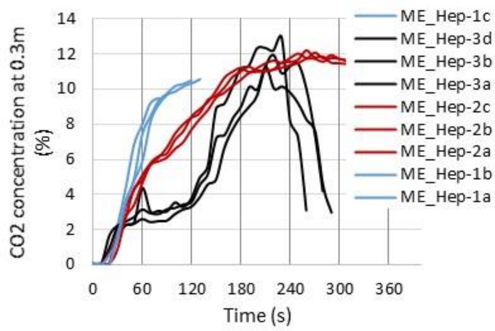

Figure 8. CO_2 concentration at 0.3 m height.

3.3 Effect on hot gas layer

The temperatures were measured using two thermocouple trees (A1 and A2) in the compartment. The values were employed to calculate hot gas layer height (z) (Figure 9) and hot gas layer temperature (*HGLT*) (Figure 10). The results represent the average of the three repeatability tests. Figure 9 shows a higher hot gas layer height in the two thermocouple trees in the ME_Hept-1 cases. In all experimental tests, the hot gas layer height rapidly decreases below the 0.3 m, which was employed to measure the O_2 and CO_2 concentrations in the previous section. According to the hot gas layer temperature (Figure 10), the highest temperatures were recorded in the ME_Hep-3 cases, followed by ME_Hep-2 and ME_Hep-1 cases. This is due to the greater presence of O_2 where large openings are used, allowing for more complete and efficient combustion. In the earliest stages of combustion, the ME_Hept-1 and ME_Hept-2 cases obtain higher temperature values.

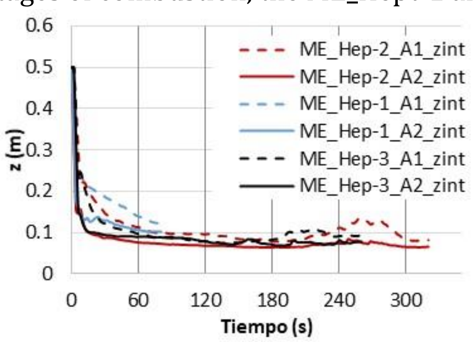

Figure 9. HGL height comparison.

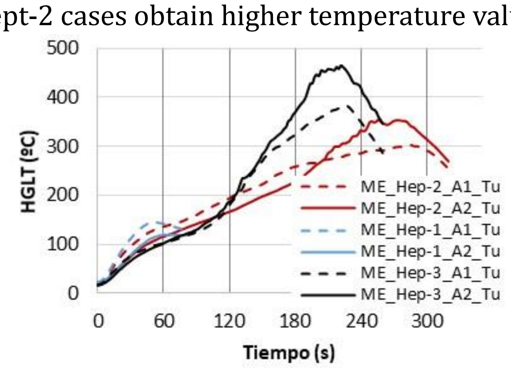

Figure 10. HGL temperature comparison.

4. Conclusions

The results obtained in this study demonstrate the significant influence of natural ventilation and the height of the opening on combustion behaviour in vitiated atmospheres. Some findings of the study consist on the capture and representation of the influence of the opening in naturally ventilated compartment combustion. The theoretical GER for the ME_Hep-1 cases (2.035), that defines an under-ventilated combustion, was able to predict the extinction due to a lack of oxygen in this case. The theroetical well-ventilated cases, defined by GER lower than 1, also predict the total consumption of the heptane. Nevertheless, experimental results show how the flame moves towards oxygen-rich areas inside the compartment, highlighting the dynamic nature of combustion in response to varying oxygen availability. Extinction was found when oxygen concentration decreased to 8% in the vicinity of the pool. This value was lower than reported in previous studies [8], which found that heptane fire self-extinction in a completely closed compartment occurred when local oxygen mole fraction in the vicinity of the flame decreased to to levels between 10.7 and 15.3%. Hot gas layer temperature analysis reveals a higher initial temperature increase in compartmegrants with smaller openings. However, as combustion evolves, compartments with larger openings exhibit a grater final temperature increase. This indicates that while smaller openings may initially trap more heat, larger openings eventually allow for more complete combustion and higher overall temperatures.

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