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Influence of source elevation on a pool fire in a forced-ventilated enclosure.

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ABSTRACT

In nuclear facilities, fires can spread until reaching the upper part of a closed and mechanically-ventilated compartment. In this area of the room, the fire sources are under-oxygenated, but lie in an environment with significant radiative heat flux. Previous studies dealt with elevated fires, and results showed that fire pan elevation affects two phenomena: the combustion process and the flows inside the room. The present study aims to understand the effects of elevation on fire dynamics in a special ventilation configuration: air inlet in the lower part of the compartment, and vitiated air exhaust in the upper part. A series of tests was carried out in a reduced-scale apparatus, with a 0.09 m diameter pan filled with dodecane liquid fuel and placed at various heights. Two aspects were analyzed: the mass loss rate (MLR) and the gas temperature inside the room. First of all, the experimental results confirm the coupled and antagonistic effects of decreasing oxygen concentration and increasing temperature on the mass loss rate that were already highlighted in the literature. In addition, these results also show the role played by the flame height on the change in the combustion regime. Finally, vertical temperature stratification is much more pronounced when the fire is elevated until a certain height. Beyond this limit, stratification starts to disappear.

KEYWORDS: Burning rate, compartments, elevated fires, pool fires.

INTRODUCTION

In nuclear power plants, facilities often consist of closed, but mechanically-ventilated compartments. If a fire occurs, it can spread to the upper part of the room (e.g. cable tray fires). The fire is then evolving in an environment with a low oxygen concentration since smoke pollutes this area, and a high temperature, due to the radiation heat fluxes from smoke and the nearby ceiling. However, the increase in radiative heat flux contributes to the rise in fire power, while the decrease in oxygen concentration has the opposite effect. These two physical phenomena therefore have both combined and antagonistic effects. In this context, they compete with each other, and according to their respective contributions, combustion is driven by either under-oxygenation or external heat flux. Understanding elevated fire dynamics is thus of great interest in the field of nuclear safety.

In numerous research articles, elevated fires are only one series of tests among others, designed to study fairly broad topics, such as fires in mechanically-ventilated compartments for Backovsky *et al.* [1] and Cetegen [2], or are only a means of achieving specific combustion regimes such as ghosting flames in Yang *et al.* [3] and Sugawa *et al.* [4]. More recently, studies have started to consider elevated fires as an issue in its own right.

When dealing with this issue, studies addressing this subject consider various ventilation configurations, depending on the applications intended for the work. Thus, the articles of Tiwari *et al.* [5], Polukhina [6], Mounaud [7], Coutin *et al.* [8],[9] and Zhang *et al.* [10] dealt with elevated fires in a naturally-ventilated compartment, the works of Wang *et al.* [11] and Zhang *et al.* [12],[13] a closed compartment and Pretrel a closed and mechanically-ventilated compartment [14]. The conditions of each study differ substantially. Some use a gas fire source (propane) [7],[8],[9], others liquids with various hydrocarbons, ranging from heptane [6],[10],[11],[12],[13] to diesel [5] and

dodecane [14]. Some tests were carried out at a large scale, and others at a reduced one, with compartments of various sizes organized in different ways, especially for openings in naturally-ventilated compartments. There can be door openings of different dimensions located in the side walls of the compartment [5],[6],[7], as well as ceiling vents [10].

These various configurations lead to different results, especially for the mass loss rate (MLR). Figure 1 combines the results of the various articles on this subject, and presents a dimensionless mass loss rate, noted MLR^* , which corresponds to the ratio between the mean MLR and the mean MLR at ground level, as a function of z^* , the non-dimensional elevation (ratio between the pan elevation and the compartment height). Mean MLR was calculated for tests with a quasi-steady phase and computed over this period, which may vary from one test to another. Results show two opposite trends: an increase in MLR^* with pan elevation for closed compartments, and a decrease in MLR^* with elevation for naturally- and mechanically-ventilated rooms. These two trends illustrate the combined effects of under-oxygenation, which reduces elevated fire power, and the increase in radiative heat flux, which, on the contrary, enhances pyrolysis. These results therefore show that, under specific surrounding conditions, either radiative heat flux or oxygen concentration is predominant and drives the combustion process. However, the specific surrounding conditions for each regime are currently fairly misunderstood, and the relationship between burning rate, radiative heat fluxes and oxygen concentration is not yet exactly determined. It is interesting to note that closed compartments seem to generate an environment in which radiative heat flux prevails. Similarly, mechanically- and naturally-ventilated boxes create environmental conditions for which oxygen concentration drives combustion. Thus, the geometry of the device, as well as the ventilation configuration (type, positions, directions, flow rates and speeds) influence the emergence of these regime and are therefore crucial when studying elevated fires.

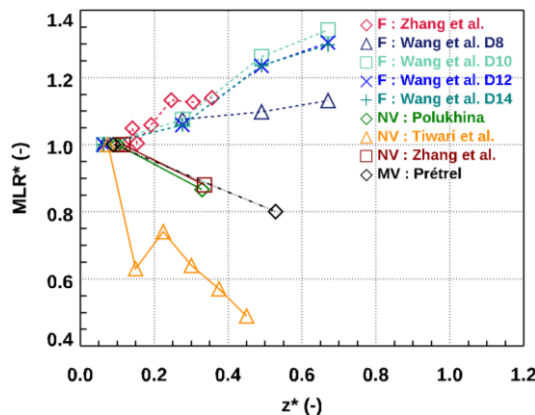


Fig. 1. MLR^* as a function of the dimensionless elevation z^* .

In an attempt to explain these trends, the authors study combustion efficiency and combustion regimes. The results show that the pan elevation affects combustion quality: the higher the fire, the worse the combustion rate. Indeed, in a polluted atmosphere, the fire can access less oxygen and the combustion reaction is consequently less efficient. Moreover, elevated fire tests can sometimes be divided into two groups: those for which the flame does not impinge on the ceiling and the MLR has a quasi-steady phase, and those for which the flame impinges on the ceiling and the MLR is largely unsteady. We can infer that flame height is involved in combustion regime changes. The fire elevation therefore affects combustion, but results illustrate that it likewise has an effect on flows within the compartment, i.e. everything related to the room filling process by smoke, thermal stratification or concentration fields. The results indeed show that the interface between smoke and fresh air does not go down to the floor as it would for a ground test, but stops at the pan level. The lower part of the compartment will then continue to be filled through wall jets. After some time, the smoke accumulates

on the ground and rises up until it fills the whole compartment. Finally, the results illustrate a more pronounced smoke stratification for elevated fires than for ground-level fires. We can infer a hot upper layer and a cold lower one. Moreover, the higher the fire, the more significant the break between these two layers.

Despite a growing interest in recent years, the understanding of elevated fires is still relatively limited. The present study aims to understand the effects of elevation on fire dynamics in a specific configuration with natural air inlet in the lower part of the room and mechanical vitiated air exhaust in the upper part. This configuration has not been investigated in the literature yet. The analysis is based on a series of reduced-scale tests, performed in the NYX facility of the Institut de Radioprotection et de Sûreté Nucléaire (IRSN). Two aspects are investigated: the burning rate and gas temperature in the compartment.

TOOLS AND METHODOLOGY

Experimental setup

The experimental device NYX has already been used for previous studies [15], [16], [17]. This fire test apparatus is a 1:4 reproduction of one room of IRSN's large scale DIVA facility, and therefore has the following dimensions: $L = 1.5$ m (length), $W = 1.25$ m (width) and $H = 1$ m (height) for a total volume of $1,875$ m³. Its walls are made of a double layer: the first one is a 2 mm thick steel plate ($\rho = 7817$ kg/m³, $k = 51.9$ W/K/m, $C_p = 446$ J/kg/K, with ρ the density, k the conductivity and C_p the specific heat) and the second one is a 25 mm thick calcium silicate layer ($\rho = 2700$ kg/m³, $k = 0.22$ W/K/m, $C_p = 920$ J/kg/K). In order to see inside the compartment with cameras placed outside, one of the double-layer walls is replaced by a glass plate. Since the chosen ventilation configuration for this work comprises a natural fresh air inlet and a mechanical exhaust, openings are milled in the lower part, on the longest sides of the compartment. These openings are 0.75 m long, 0.10 m high and are centered. Smoke is extracted through two vents located in the upper part of the compartment. A picture and a brief description of NYX are given in Fig. 2.

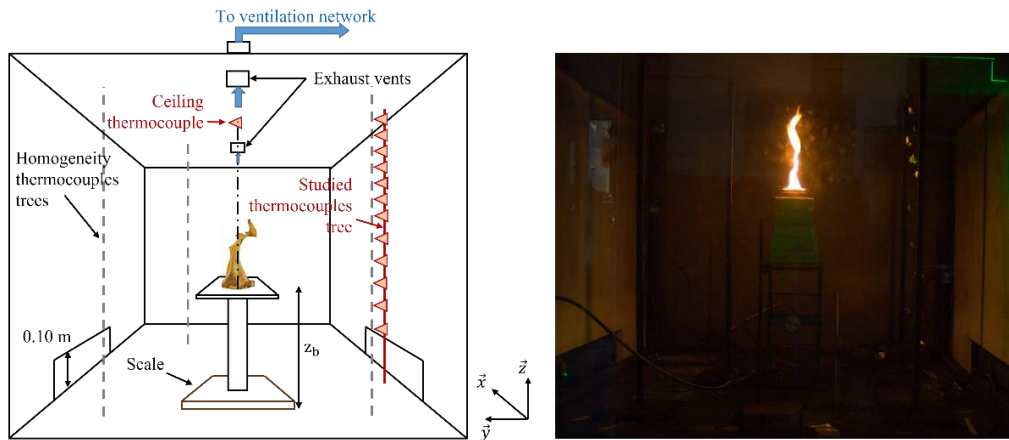


Fig. 2. A lateral view of the NYX apparatus is shown on the left. The triangles represent the thermocouples. The righthand image shows an example of a test for $z_b/H = 0.62$.

The weighing system used to measure fuel mass loss all along the test is a SARTORIUS scale with a precision of 0.01 g. The burning rate is then computed using the time derivative of the mass loss. K-type thermocouples with a diameter of 0.5 mm are used to measure gas temperature in order to study thermal stratification. These thermocouples evaluate the temperature up to 1300 °C with a precision of 3 °C. They are distributed over 4 vertical trees located outside the plume region. Three lateral trees

are placed in the compartment corners with 4 thermocouples. They are used to assess compartment gas temperature homogeneity. The fourth tree ($x = -0.15$ m , $y = -0.35$ m with the pan center as the origin) is composed of 12 thermocouples distributed every 0.1 m between 0.165 m and 0.665 m, and then every 0.05 m from 0.665 m to 0.965 m to improve discretization near the ceiling and catch the steep gradient. This mast will provide the data used for the analysis. Finally, a thermocouple is placed over the center of the pan, near the ceiling, at 0.95 m from the floor. Bidirectional probes placed in the exhaust ventilation ducts measure flow rates between 0 m³/h and 130 m³/h with an error not exceeding 4% of the reading data. All measurements are recorded by a National Instrument (NI) system at a frequency of 1 Hz.

Fire source

In order to simplify the study, the chosen fire source is a hydrocarbon pool fire, and more precisely dodecane ($\Delta H = 42$ MJ/kg and $T_b = 210$ °C with ΔH the combustion enthalpy and T_b the boiling temperature). A volume of 0.134 L of fuel is poured into a borosilicate pan with an inner diameter of 0.09 m and a height of 0.028 m. This volume, poured for all tests, corresponds to an average fuel mass of 101.72 g \pm 1.5 g.

Since the tests are carried out in a compartment, a reference in the open atmosphere is needed. Correlations are commonly used such as Babrauskas' [18], or Heskestad's [19]. However, they are only partially or not validated at all for such a small pan size. For this reason, the 0.09 m diameter pan was characterized in an open atmosphere in terms of flame height and MLR using a weighing system and a camera. With the mass loss, a mean burning rate of 0.06 g/s \pm 6% was determined. In order to evaluate the flame height in a free atmosphere, image processing was based on a method from Audouin *et al.*[20]. All the pictures are digitized: a threshold at which the flame is considered to be present in a pixel was chosen, which allowed each pixel to be assigned a value of 0 (flame is absent) or 1 (flame is present). The pictures were then computed with an arithmetic mean: the mean image obtained corresponds to the flame probability. Two heights are calculated for this image: a first one corresponding to a flame probability of 95% and the other a probability of 5%. The flame height is finally defined as the mean of these two values, with a correcting coefficient of 0.8. This method leads to a value of 0.167 m \pm 2%.

Methodology

Eleven tests were carried out with the 0.09 m diameter pan. The initial extraction flow rate was set to 50 m³/h. This high value was chosen in a first approach in order to get rid of the smoke interface effect on the fire. The pan is then placed in the center of the compartment at a height z_b . The different configuration settings are described in Table 1. The fuel is manually poured into the pan, and the fire is manually ignited with a propane burner. Finally, the glass wall is closed a few seconds after ignition. The mass loss, gas temperature, but also the flow rate which may slightly change after ignition, are measured throughout the test.

z_b/H	0.06	0.15	0.20	0.31	0.39	0.51	0.62	0.72	0.77	0.81	0.87
Initial fuel mass (g)	100.2	102.2	101.2	101.5	101.8	101.8	101.4	102.1	102.3	100.9	101.6

Table 1. Test settings

RESULTS

Elevation effects on the mass loss rate

The first variable of interest is the MLR. Variation in burning rate over time is given for various elevations in Fig. 3: for illustration purposes not all elevations are plotted on this graph. The curves are divided into two groups. Figure 3 shows tests with a slightly decreasing MLR with pan elevation

(group I), and Fig. 3 b tests with an increasing burning rate with elevation (group II). Moreover, the open atmosphere MLR for a 0.09 m diameter pan is added to each graph to facilitate comparison.

The group I graph shows three significant points. First, all the curves share the same behavior. During the ignition period, the increase in MLR is similar for all tests whether confined or not. Around 150 s, elevated fires carried out in NYX start to dissociate from the one performed in an open atmosphere and at ground level. Their burning rates decrease until reaching a quasi-steady phase. This phase is never completely steady because of the apparatus thermal inertia and the fixed fuel volume used. The MLR then increases slightly because of the borosilicate pan. At the end of the fire, only a small volume of fuel indeed remains: this small quantity is strongly heated by the pan and the flame. This is a common phenomenon for pool fires with variable fuel height during the combustion process. The last phase is the fire extinction by lack of fuel for all the tests performed. Secondly, fire duration increases with pan elevation: from around 2090 s for the ground-level fire to 3160 s for $z_b/H = 0.62$. Since the fuel mass is constant for the whole campaign, fire duration quantifies the heat release rate of a fire, i.e. if the fire duration increases, it implies that the burning rate falls. Thirdly, the ground fire MLR is similar to the fire in a free atmosphere, whereas elevated fire burning rates are lower than for the ground-level test.

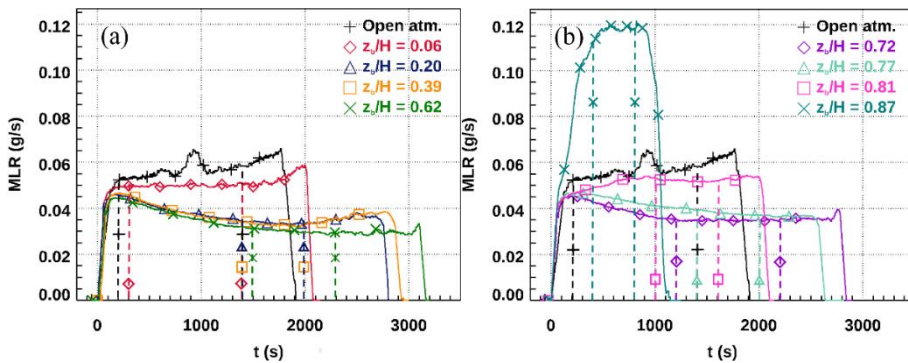


Fig. 3. MLR as a function of time for various elevations. (a): decreasing burning rate with elevation tests (group I); (b) increasing MLR with pan elevation tests (group II).

Group II fire tests show contrasting results. The ignition and dissociation period are similar for all tests as previously described. From $z_b/H = 0.72$, the steady value of the MLR is slightly greater than the value observed for group I. Beyond $z_b/H = 0.72$, MLR keeps climbing until reaching almost twice the open atmosphere burning rate for the highest fire ($z_b/H = 0.87$). Consequently, fire duration only reduces with pan elevation from 2840 s for $z_b/H = 0.72$ to 1150 s for the highest test.

These two graphs clearly illustrate that elevation affects the MLR and fire duration. Furthermore, this effect is much more significant for group II fire tests. In order to focus on the effects of elevation on the fire, Fig. 4 shows the ratio between the mean MLR for tests carried out in NYX and mean MLR for the open atmosphere fire as a function of non-dimensional pan elevation. The mean mass loss rates are computed over the quasi-steady period defined by dashed lines for each test as shown in Fig. 3.

In Fig. 4, regions A and B combine tests from group I, and region C shows tests from group II. The ground-level test MLR is, as explained before, almost the same as in a free atmosphere. Then, between the floor and the first elevation ($z_b/H = 0.15$), the burning rate shows a drastic decrease of around 40%. Actually, the inlet openings are located between these two elevations, i.e. the fire test performed below z_a (a value representing the opening upper limit) is in front of the air inlet. This position can explain the similar MLRs for open-atmosphere and ground-level tests.

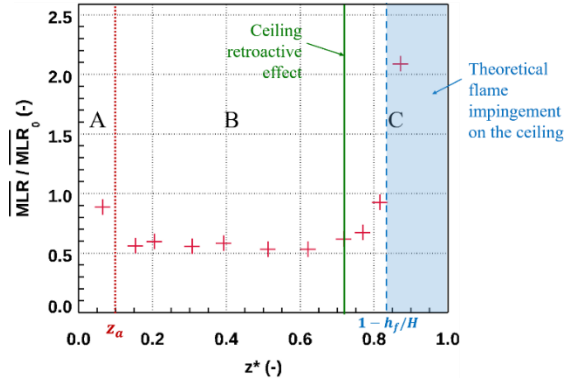


Fig. 4. Ratio between mean MLR and mean open atmosphere MLR as a function of non-dimensional pan elevation.

In region B, mean MLR ratio decreases slightly. Elevation does not have a significant influence. However, from a height $z_b/H = 0.72$, a distinct behavior appears: in region C, the effect of elevation is much more visible with a rapidly-increasing mean MLR ratio.

This graph highlights two phenomena. First of all, the results underline a change in combustion regimes between regions B and C, symbolized by a continuous green line. From the height of $z_b/H = 0.72$, the flame begins to impinge on the ceiling. The Fig. 5 displays flame pictures for region B and C tests. For $z_b/H = 0.62$, the flame does not impinge on the ceiling, whereas for $z_b/H = 0.72$, some parts of the flame start touching it. For $z_b/H = 0.81$, the flame starts spreading over the ceiling and finally, for $z_b/H = 0.87$, the flame impinges continuously on and spreads over the ceiling. When the flame reaches the ceiling, it is heated up as shown by the graph in Fig. 6. It displays the value of the nearby ceiling thermocouple as a function of non-dimensional pan elevation. At $z_b/H = 0.72$, the temperature near the ceiling is greater than $300\text{ }^\circ\text{C}$. Beyond this elevation, this temperature is even above $600\text{ }^\circ\text{C}$, i.e. for these tests, the thermocouple close to the ceiling is inside the flame [21]. Since the ceiling is heated up, it produces additional heat fluxes which come back to the fuel surface. The flame, which spreads along the ceiling, also generates more radiative heat fluxes compared to a classical vertical flame (e. g. $z_b/H = 0.62$). Radiative heat fluxes back to the fuel surface are therefore not only composed by vertical flame fluxes, but also retroactive fluxes from the ceiling and the spreading flame. This phenomenon enhances fuel pyrolysis, which is directly linked to heat fluxes received by the fuel surface. Since beyond $z_b/H = 0.72$, the higher the fire, the flatter the flame, this change of shape explains the significant increase in the MLR at the greater elevation.

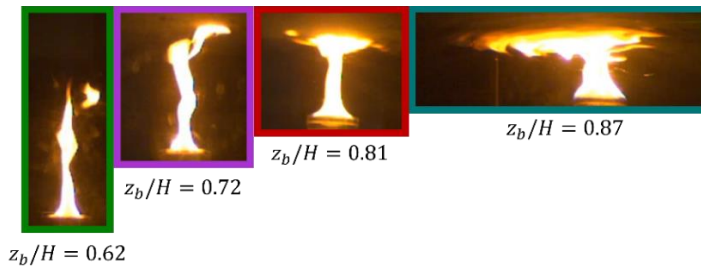


Fig. 5. Qualitative analysis of flame behavior for different pan elevations.

In Fig. 4, the dashed blue line represents the region where the 0.09 m diameter pan flame should theoretically impinge on the ceiling. This limit position is based on the open atmosphere flame height. The results show that the ceiling feedback begins earlier than this limit (near $z_b/H = 0.72$): the ceiling

effect is thus non-negligible even if the flame does not touch the ceiling continuously. Nevertheless, flame height seems to play a role in the change in combustion regime.

The second phenomenon highlighted by Fig. 4 is the competition between the decrease in oxygen concentration and the increase in radiative heat fluxes for the mass loss rate. In region B, the mean MLR ratio falls lightly. At these elevations, external heat fluxes have only a weak impact on the MLR, in which case, oxygen concentration drives the combustion process. On the contrary, in region C, radiative heat fluxes prevail and lead the combustion. This explains why the mass loss rate increases sharply beyond $z_b/H = 0.72$. In the literature, these two tendencies were not obtained in the same configuration except for Polukhina, who only achieved results for two different heights.

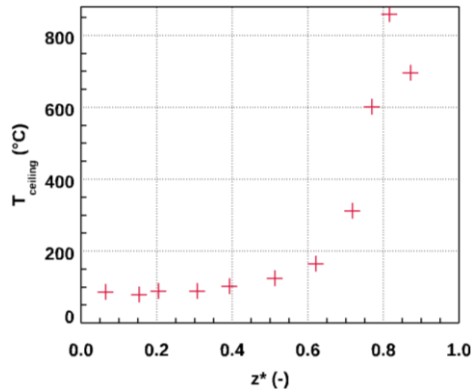


Fig. 6. Temperature at a height of 0.95 m, centered on the fuel pan as a function of non-dimensional elevation.

Elevation effects on gas temperature

Figure 7 displays variation in temperature over time for tests at various heights. A typical temperature profile generally follows the same trends as the MLR. Thus, they all show a first stage with a rapid temperature increase, then for the group I test ($z_b/H = 0.31$), temperatures decrease until a quasi-steady period. For group II pool fires, gas temperatures keep increasing slowly for $z_b/H = 0.72$, and quickly for $z_b/H = 0.87$. Despite these differences, all the curves presents a quasi-steady phase. Mean values can be defined over this period.

In a stratified compartment, temperature profiles are combined into two distinct groups: one group of thermocouples in the warm and dense smoke, where high temperatures are measured, and one group of thermocouples outside the smoke, where lower temperatures are measured. For $z_b/H = 0.06$, no group of thermocouples is visible: thermal stratification is very weak. For $z_b/H = 0.31$, two groups are discernible: the first with the two highest thermocouples, and the second with the other 4 thermocouples. However, the break between these two groups is not clear since the cold layer has temperatures ranging from 20 °C to 40 °C. For $z_b/H = 0.72$, all thermocouples except the one at a height of 0.965 m measure rather cold temperatures. The temperature differences between these two groups are quite significant. The same stratification type is visible for $z_b/H = 0.87$, but the colder thermocouple group shows larger temperature amplitudes: the stratification begins to disappear. This variation in temperature over time can also be used to compare compartment thermal trends for tests with seemingly similar MLRs. For example, the ratios between mean MLR and mean open atmosphere MLR for $z_b/H = 0.31$ and $z_b/H = 0.72$ are almost similar, but their temperature profiles show different thermal structures. For $z_b/H = 0.31$, temperatures decrease just after the ignition phase until stabilization, while for $z_b/H = 0.72$ they only increase. Thermal stratification is also much more pronounced for $z_b/H = 0.72$: the top layer is warmer and the bottom one colder with very clustered thermocouples, which means that the break between them is largely pronounced.

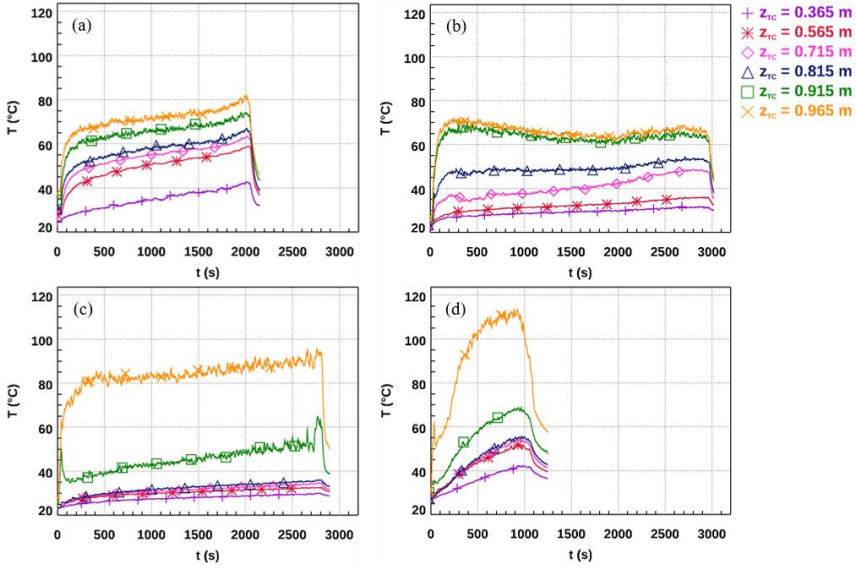


Fig. 7. Variation in temperature over time. (a): $z_b/H = 0.06$; (b): $z_b/H = 0.31$; (c): $z_b/H = 0.72$; (d): $z_b/H = 0.87$.

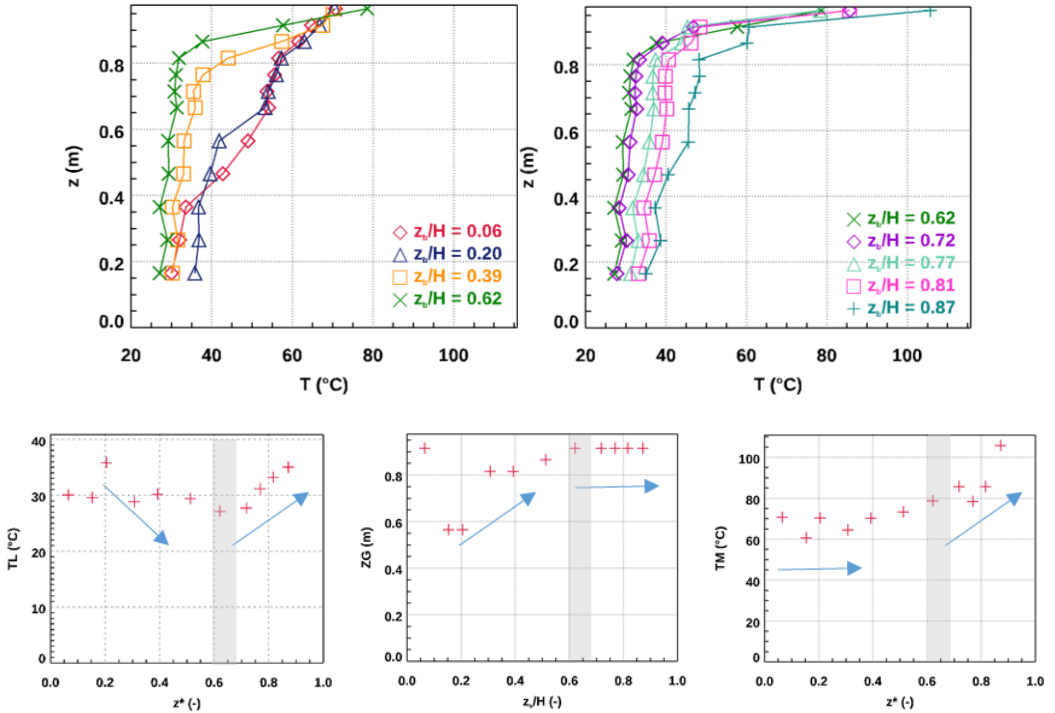


Fig. 8. On the top, the mean vertical temperature profiles for various elevations. On the bottom, from left to right, the lowest temperature, the maximum gradient position and the maximum temperature extracted from the temperature profiles.

Figure 8 shows the average vertical temperature profiles (computed on the quasi-steady phase) for tests at different elevations. Since all the thermocouple trees show homogeneous results, data come from the one with the most thermocouples. In order to interpret the variation in thermal stratification,

three quantities are considered : the lowest temperature (TL), the location of the highest gradient ZG (that can be considered as a possible interface between two layers) and the maximum temperature (TM). The lower and upper layers can be considered to be below and beyond the vertical position of the maximum gradient respectively. The variation in the three quantities versus the pool elevation (provided in Fig. 8) shows two typical regimes, one for low elevations and one for high elevations. For the first regime for low fire elevations, the lowest temperature decreases with elevation due to the fact that the heating of the lower layer by flame radiation decreases as the fire is elevated. The maximum temperature does not increase significantly and follows the same trend as the MLR that remains constant for low elevations. The location of the interface climbs due to the increase in fire elevation. The second regime, for high elevations, shows different vertical temperature profiles. The lowest and the maximum temperatures increase because the MLR increases and the flame impinges on the ceiling. In addition, the interface position does not change substantially because it has already reached a high position close to the ceiling. The critical position that distinguishes the two regimes is located around 0.6-0.7 (in grey in Fig. 8).

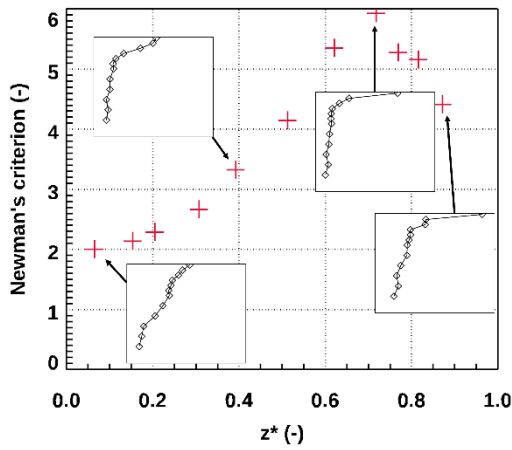


Fig. 9. Newman's criterion and temperature profile shapes for various elevations.

In order to quantify the thermal stratification in a tunnel, Newman [22] proposed a criterion, defined as follows:

$$NC = \frac{\Delta T_{cf}}{\Delta T_{av}} = \frac{T_{ceiling} - T_{floor}}{T_{mean} - T_{floor}} \quad (1)$$

where NC is the Newman's criterion, $T_{ceiling}$ the gas temperature near the ceiling, T_{floor} the gas temperature near the floor, and T_{mean} the mean temperature in the region of interest. Even though the configuration studied is not a tunnel, this criterion can be a relevant indicator for variation in stratification with fire elevation. This criterion is plotted in Fig. 9 as a function of the non-dimensional height. It supports the findings explained earlier: the value of the criterion increases with elevation until a maximum at the height $z_b/H = 0.72$, and then decreases. That is to say stratification is indeed clearer when the fire is elevated, but until a limit beyond which it starts to vanish. This limit seems to be related to flame impingement.

CONCLUSION

This work aims to study the effects of elevation on fire dynamics by focusing on the mass loss rate and gas temperature. The chosen ventilation configuration consists of natural air inlet in the lower part and vitiated air exhaust in the upper one. The analysis is based on a series of small-scale dodecane

pool fire tests in an apparatus with a weighing system, to determine the mass loss rate, and thermocouples for measuring gas temperature. The results show that elevation affects the MLR in two ways. In a first range of heights, the influence of elevation is quite small, the mass loss rate decreases rather slowly: the reduction of available oxygen explains this decrease. In a second range, when the flame begins to impinge on the ceiling, the effects of elevation are more pronounced, and the MLR increases sharply until being well above its open atmosphere value. Since the pool fire is close to the ceiling and smoke, it lies in an environment with great radiative heat fluxes, which control the combustion and hence the increase in mass loss rate. The results also confirm the link between flame height and changes in the combustion regime for elevated fires. Finally, the study of the gas temperature in the compartment shows that stratification actually increases with pan elevation, but up to a maximum value, and then decreases. These findings, obtained in an original ventilation configuration, support and complete previous studies on elevated fires.

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