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# Burning Rate and Carbon Monoxide Production for an elevated pool fire in a weakly ventilated compartment

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**Abstract.** This work concerns the study of fires in ventilated compartments, and in particular scenarios involving fire located in the upper part of a room near ceilings and in under-ventilated conditions. These complex scenarios are poorly understood and require better knowledge for fire risk assessment. A reduced-scale experimental study with dodecane pool fires was carried out to investigate the coupled influence of fire elevation and compartment ventilation flowrate. The fire characteristics of interest are burning rate and CO production. The results show that fire elevation and ventilation flow rate have opposite influence on burning rate. The net balance is a positive effect of elevation, increasing the burning rate even in an oxygen-poor environment. On the contrary, elevation and ventilation flowrate have a same positive influence on CO production and contribute to its increase. This work shows the complexity of a fire in the upper part of a poorly ventilated room and provides new knowledge to improve its prediction for safety assessments.

## 1. Introduction

Compartment fires are scenarios widely encountered in industry, and in the nuclear facilities in particular. A poorly understood configuration, requiring additional research, is that of an elevated fire near the ceiling and in a weakly ventilated enclosure. In this case, the fire is in a vitiated, oxygen-poor environment that is also hot due to the heat fluxes emitted by the ceiling. These two antagonist features on the burning rate makes challenging its prediction. Previous studies as Zhang et al. [1], [2] Tiwari et al. [3] or Vaux et al. [4], worked on both phenomena simultaneously, air vitiation and proximity of the ceiling and showed evidence of the two antagonistic effects. The poorly ventilated environment tends to decrease the fire heat release rate because of the lack of oxygen and elevation of the fire tends to increase fire heat release because of a rise of external heat fluxes. However, both phenomena were always coupled making the interpretation of the results more difficult as well as the determination of their respective contributions. In order to separate the two effects, Georges et al. [5] only studied the effect of fire elevation in a well-ventilated compartment. Experimental results obtained at reduced scale highlight two combustion regimes for the mass loss rate (MLR) depending on the fire elevation. When the flame does not impinge on the ceiling, the MLR remains nearly constant whatever elevation. When the flame impinges on the ceiling, the MLR sharply increases because of external heat fluxes coming from the ceiling. The present study aims to investigate experimentally at reduce-scale the additional effect of the vitiation in reducing the ventilation flow rate in the compartment. The analysis focuses on two variables important for fire safety assessment, the MLR and the carbon monoxide production. This work highlights the complexity of this specific scenario for safety issues and enables to quantify the coupled effect of ceiling distance and under-

ventilation. The paper presents first the experimental device and then the results focusing on the MLR and the CO production.

## 2. Experimental set-up and fire test campaign

The experimental set-up is the NYX reduced-scale compartment from IRSN of 0.975 m high (H), 1.25 m wide (W) and 1.5 m long (L) (Fig. 1). Its walls are made of two layers: inside, an insulating calcium silicate plate ( $\rho = 760 \text{ kg.m}^{-3}$ ,  $k = 0.22 \text{ W.K}^{-1}.\text{m}^{-1}$ ,  $C_p = 970 \text{ J.kg}^{-1}.\text{K}^{-1}$ ) of 0.025 m thick, on which a steel sheet ( $\rho = 7817 \text{ kg.m}^{-3}$ ,  $k = 51.9 \text{ W.K}^{-1}.\text{m}^{-1}$ ,  $C_p = 446 \text{ J.kg}^{-1}.\text{K}^{-1}$ ) of 0.003 m thick is tacked. Fresh air comes from the bottom of the room via two rectangular openings of 0.10 m high and 0.75 m wide in the longest walls. One of the walls is replaced by a glass plate to have a visual access to the inside of the compartment. Vitiated air is extracted at the upper part of the room thanks to two vents. These are connected to a controlled fan, enabling the volumetric extraction flow control. The fire sources are dodecane pool fires (heat of combustion of  $42 \text{ MJ.kg}^{-1}$ , stoichiometric ratio  $r=3.65$  and boiling temperature of 483 K). The fuel is poured into circular borosilicate pans with given diameter.

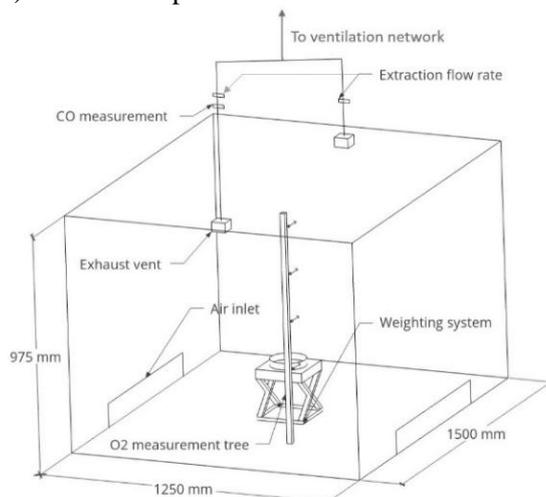


Figure 1: NYX reduced-scale experimental device and measurements.

The facility is instrumented with a SARTORIUS balance to obtain the fuel mass loss that is the time derivative of the fuel mass. Carbon monoxide production is measured at the exhaust from gas analyser. The emission factor of carbon monoxide is the ratio between the carbon monoxide flowrate in the extraction duct and the MLR. The volumetric flow rate of extracted air is measured in both extraction ducts using bidirectional Pitot probes. The total ventilation flow rate is therefore the sum of the volumetric flow rates measured in each of the duct. Finally, oxygen measurements are located on a vertical mast to get the oxygen concentration near the fire. To investigate the coupled effect of vitiation and elevation, fire test campaigns have been performed in varying the fire elevation and the ventilation flow rate for different pool diameters,  $D$  (0.09 m, 0.12 m, 0.15 m and 0.175 m). Test parameters are the pool elevation  $z_b$  ranged between 0.05 m and 0.80 m (the reference is the ground of the enclosure and the ceiling is at 1 m) and the initial ventilation flow rate before ignition  $\dot{q}_{ext}$  ranged between  $5 \text{ m}^3.\text{h}^{-1}$  and  $50 \text{ m}^3.\text{h}^{-1}$ . The ventilation flow rate of  $50 \text{ m}^3.\text{h}^{-1}$  characterised a well-ventilated situation for which nearly no smoke layer remains in the enclosure. This rate was chosen by Georges et al. [5] to only study the effect of fire elevation in a well-ventilated compartment. The present study investigates how the reduction of ventilation and the change of elevation affect the fire. Each test is performed as follows. First, the compartment ventilation flow rate is set to a given value. The pan is set at the given height then filled with the required quantity of fuel and igniter manually. The test ends by extinction by lack of fuel.

## 3. Results

### 3.1. Burning rate

Firstly, the influence of ventilation rate on the mass loss rate (MLR) evolution is shown in Figure 2-a. The temporal evolution of MLR shows an expected behaviour with a growth phase followed by a stationary phase and then the final extinction by lack of fuel. Varying the ventilation rate reduces the amplitude of the MLR. This effect is explained by the reduction in oxygen concentration near the fire as illustrated in Figure 2-b.

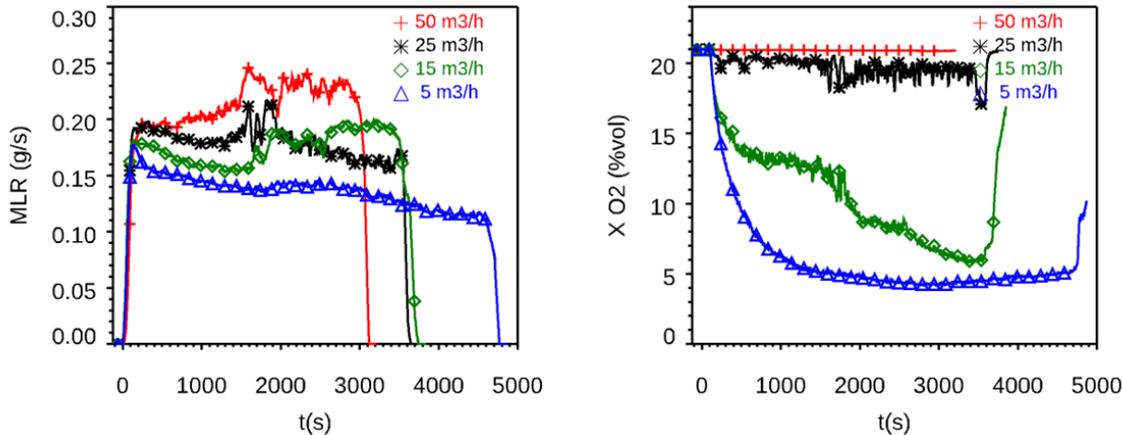


Figure 2: Effect of ventilation flow rate on the time variation of the MLR (a) and oxygen concentration at 0.55 from the ground (b) (pool fire of  $D=0.175$  m and elevation  $z_b/H = 0.41$ ).

This behaviour is confirmed on the analysis of the average MLR over the total fire duration. The Figure 3-a show the variation in MLR as a function of the ventilation flow rate for each pan diameter tested at a given elevation  $z_b/H=0.41$ . As the ventilation flow rate decreases, so does the MLR. This effect is more pronounced for higher pan diameter, the larger the pool fire, the more oxygen it consumes. For the same ventilation flow rate (and equivalent oxygen supply to the room), the larger fire source is then surrounded by a more polluted environment than the smaller one. The explanation attributed to oxygen reduction in the near-field of fire is confirmed in Figure 3-b that shows the evolution of the averaged oxygen concentration at the level of the fuel pans for tests carried out at different ventilation flow rate. As the ventilation flow rate decreases, the amount of oxygen close to the pool fire also decreases.

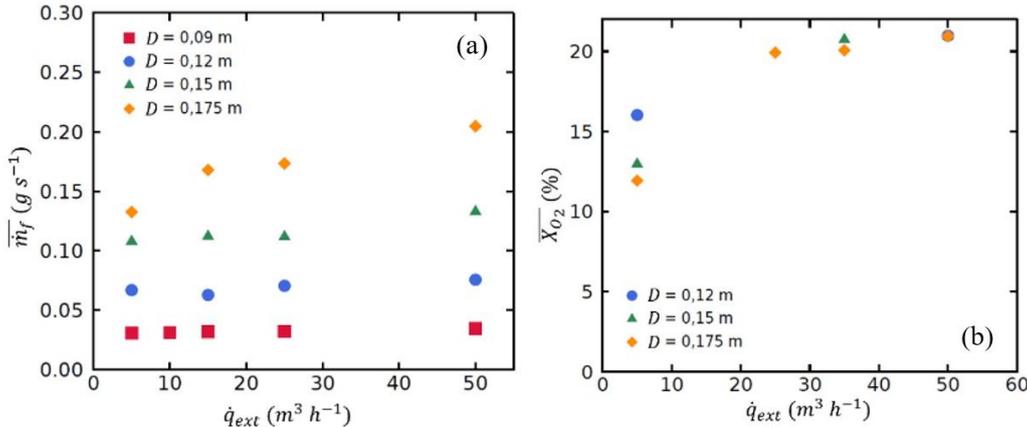


Figure 2: Global MLR (a) and mean oxygen concentration near the fuel pan (b) as a function of the ventilation flow rate for the different pan diameters (fire elevation  $z_b/H=0.41$ ).

The effect of the ventilation flow rate reported for a given elevation is also observed at different positions as indicated in Figure 4-a showing the global MLR as a function of the fire elevation for two ventilation flow rates and a given pan diameter. The behaviour reported by Georges et al. [5] in well-

ventilated environment ( $50 \text{ m}^3 \cdot \text{h}^{-1}$ ) characterised with two combustion regimes is also reported with lower ventilation flow rate ( $25 \text{ m}^3 \cdot \text{h}^{-1}$ ) but with lower amplitude of MLR. For the non-impinging flame elevations, the MLR remains constant while for the impinging flame heights, it increases with elevation, showing higher values of MLR than those of tests in the non-impinging flame regime. As long as the flame does not impinge over the ceiling, the predominant phenomenon on the fire dynamics is the lack of oxygen and when the flame impinges and spreads over the ceiling, the low-oxygen environment still affects the fire, but it is the increase in external heat fluxes that drives combustion and leads to an increase in MLR. The results also show that the transition between these two combustion regimes is not modified by the decrease in ventilation flow rate.

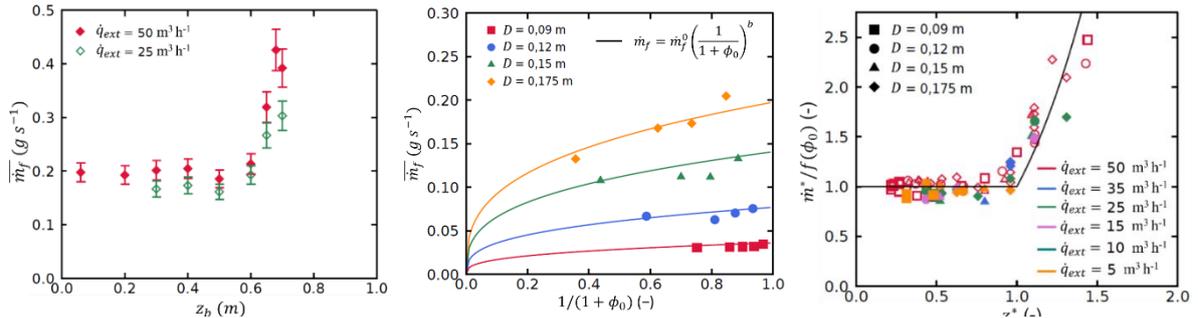


Figure 3: (a) Global MLR as a function of the elevation for two ventilation flow rates ( $D=0.175 \text{ m}$ ) (b), Global MLR as a function of the ventilation factor for four pool diameters ( $z_b/H=0.41$ ) (c) Dimensionless MLR as a function of the dimensionless elevation.

A normalised formulation of the MLR versus elevation and ventilation flow rate is proposed considering the dimensionless elevation,  $z_b^* = L_f / (H - z_b)$  with  $L_f$  the flame length at the ground level and the dimensionless mass loss rate  $\dot{m}^* = \dot{m}_f / \dot{m}_f^0$  as suggested by [5]. The ventilation flow rate is introduced through the ventilation factor (or global equivalent ratio)  $\phi_0 = r \cdot \dot{m}_f^0 / (y_{O_2}^0 \dot{q}_{ext})$  deduced from well-stirred reactor approach [9]. For a given elevation, the relation that best fit the data is in the form  $\dot{m}^* = f(\phi_0) = (1 + \phi_0)^{-1/3}$  as illustrated in Figure 4-b. Combining the two effects, elevation and ventilation flow rate, a general expression of the dimensionless burning rate is proposed as:

$$\dot{m}^* = \begin{cases} (1 + \phi_0)^{-b}, & z^* < 1 \\ (1 + \phi_0)^{-b} z^{*a}, & z^* \geq 1 \end{cases} \quad (1)$$

where  $a$  is 3 and  $b$  1/3 for the present data. An evolution law is then proposed for each combustion regime. In the first regime, only the ventilation flow rate through the parameter  $\phi_0$ , i.e. the lack of oxygen, influences the MLR. Above  $z^*$  equal to 1, the effect of elevation (and therefore external radiative heat fluxes) comes into play. In this second regime, the two antagonistic effects compete with each other but the increase in external heat fluxes is predominant. These results show an important finding that a fire is in the upper part of a room near the ceiling can be more intense even if the environment is poorly oxygenised.

### 3.2. Carbon monoxide production

While vitiation and proximity to the ceiling have an antagonistic effect on MLR, CO production should be favored by these two parameters, controlled by ventilation rate and fire elevation. Indeed, the Figure 5 shows the normalised CO emission factor (defined as the ratio between the emission factor at a given height and the emission factor of reference tests performed at the ground) as a function of the elevation  $z^*$  for tests carried out in a well-ventilated compartment. As for MLR, the production of carbon monoxide is also divided into two regimes. For non-impinging flames, the CO production remains quite constant at a low value. For impinging flame regime, the production

increases sharply with elevation. This phenomenon is related to the combustion reaction taking place in contact with the ceiling, deteriorating the reaction. The effect of the ventilation flow rate is reported in Figure 5-b. On the contrary to the MLR, the emission factor increases when the ventilation flow rate decreases: oxidation of CO into CO<sub>2</sub> is harder when there is less oxygen in the environment. For example, the emission factor for the 0.175 m diameter pan is multiplied by almost 10 between 50 m<sup>3</sup>.h<sup>-1</sup> and 15 m<sup>3</sup>.h<sup>-1</sup>. This increase is more pronounced than the decrease in MLR when the fire is poorly ventilated. In addition, the greater the pan diameter, the more important the CO production is.

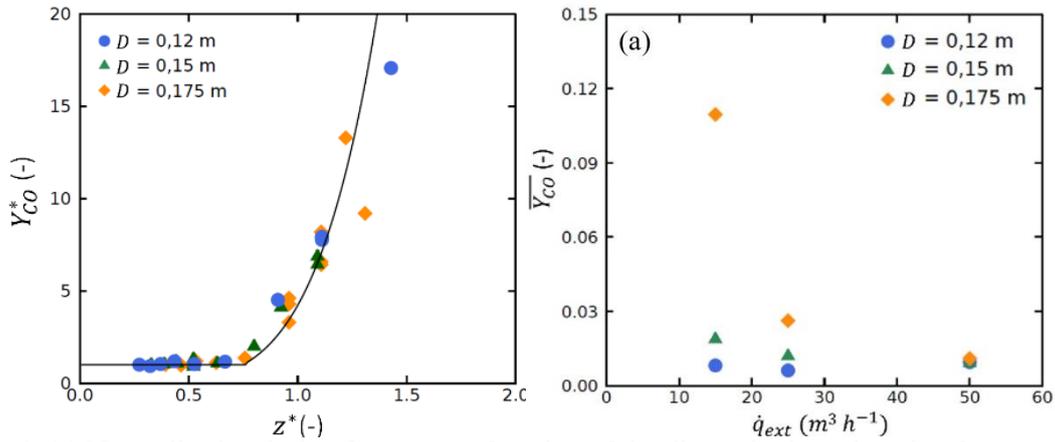


Figure 4: (a) Normalised emission factors as a function of the dimensionless elevation for tests carried out at 50 m<sup>3</sup> h<sup>-1</sup>, (b) CO emission versus the ventilation flow rate for 3 pool diameters and at elevation  $z_b/H=0,41$

In order to only highlight the effect of vitiation whatever the elevation, the CO emission factor normalised by the effect of the elevation specified with the function  $f(z^*) = z^{*a}$  is plotted versus the ventilation factor (Figure 6-a). The ventilation factor significantly influences the CO production whatever the elevation and the ventilation factor is an appropriate parameter to normalise the data. In addition on the contrary to the MLR, it demonstrates that both features, elevation and vitiation, have the same positive influence on CO production. Finally, the graph on Figure 6-b shows the CO emission factor as a function of the GER as defined by Gottuk et al. [9] for tests of the present study and others from the literature (Valoy et al. [10], Gottuk et al. [11], Beyler et al. [12]). This graph shows that the results of the present study are consistent with previous works with an increase in CO production as the GER rises.

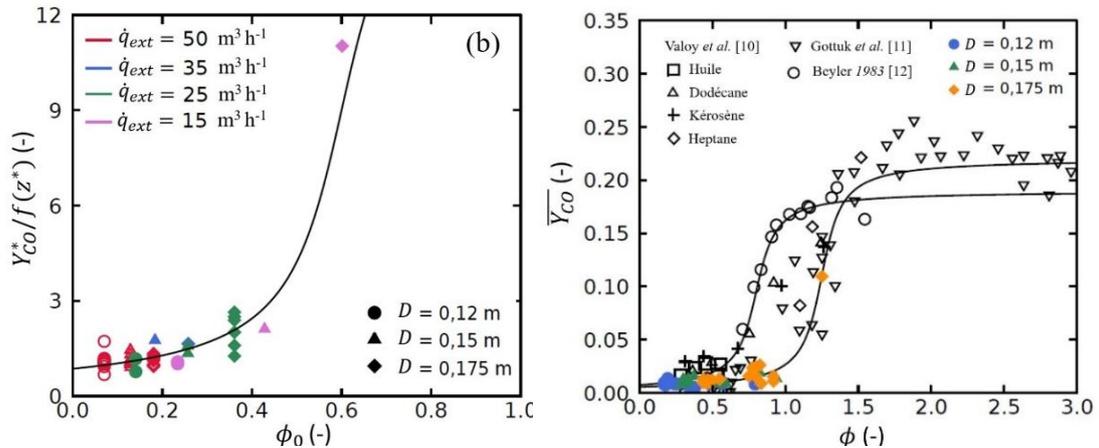


Figure 5: Emission factors as a function of the equivalence ratio for the tests of the present study but also Valoy et al. [10], Gottuk et al. [11] and Beyler et al. [12]. Laws of evolution proposed by Gottuk et al. [9].

#### 4. Conclusions

The aim of this work was to study the combined effect of fire elevation and ventilation flow rate on the characteristics of a fire in a mechanically ventilated enclosure. The analysis is based on a reduced-scale experimental study using dodecane pool fires of different diameters. The study parameters are fire elevation and enclosure ventilation rate. The fire characteristics studied are mass loss rate and CO production. The conclusions are the following.

Reducing the ventilation flow rate reduces the burning rate due to oxygen depletion in the environment surrounding the fire. This effect is observed whatever the fire elevation in the compartment. On the other hand, the fire elevation modifies the burning rate according to its position in the compartment; if the fire is located at an elevation such that the flame does not impinge on the ceiling, the burning rate remains insensitive to the elevation. If the fire is located at an elevation where the flame impinges on the ceiling, then the burning rate increases the closer it is to the ceiling. The effects of elevation and vitiation on the burning rate are opposite but lead to the predominance of the effect of elevation. In the upper part of a room, a fire is more intense than in the lower part, despite the negative effect of vitiation.

Concerning CO production, the effects of elevation and vitiation contribute to increase CO production. The proximity of a wall contributes to increasing the burning rate due to increased heat flux, and to degrading the chemical reaction by producing more CO. These results provide new data on compartment fires and help to better describe the behaviour of one of the most complex and difficult-to-predict scenarios.

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