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Experimental parametric study on low-frequency oscillating behaviour of pool fires in a small-scale mechanically-ventilated compartment

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ABSTRACT

The purpose of this work is to study the unstable oscillatory behaviour, with frequency in the order of few mHz, that has been occasionally observed in mechanically-ventilated compartment fires. To address this challenge, a series of experiments using a small-scale compartment was conducted using heptane and dodecane as fuels. Results show that, after the fire is fully-developed, unstable and stable combustion regimes can occur depending on the fuel type, the pool size and the air renewal rate of the compartment (ARR). A special regime of unstable oscillatory combustion with low frequencies (LF), accompanied by thermodynamic pressure and ventilation flow rate variations and displacement of the flame outside the pan, is observed. The occurrence and persistency of LF oscillations results from the competition between oxygen supply and fuel vapor supply due to the heat feedback from the flame and enclosure to the fuel tray. The LF oscillation period depends mainly on time required for storing enough fuel vapor for strong combustion. Whatever the fuel type, it is found that i) the range of ARR where LF oscillations appear and the oscillation amplitude increase with the pool size, and ii) the frequency increases, while amplitude decreases, with increasing ARR independently of the pool size. It is also found that the more flammable the fuel, i) the smaller pool size for which LF oscillations appear and the higher the frequency for the same ventilation conditions, and ii) the wider the range of ARR where LF oscillations appear for a given pool size.

KEYWORDS:

compartment fire; heat transfer; ventilation; low-frequency oscillations; unstable combustion; combustion regimes.

INTRODUCTION

The rate at which a compartment fire develops depends strongly on ventilation conditions (available oxygen). Most studies have focused on the effect of natural ventilation on compartment fire behaviour and fire extinction (see [1]-[6], to name but a few). For restricted air ventilation, unsteady under-ventilated fires can exhibit periodic oscillations and temporary flame quenching (e.g. [6]). In [4], Takeda conducted small-scale fire experiments, using poly-methyl-methacrylate as fuel. He showed that air vitiation results in a reduction of the fuel mass loss rate (MLR), with oscillations of ~1.33 Hz. Utiskul et al. [3] and He et al. [5] observed a similar flame oscillatory phenomenon, with different frequencies of around 1 Hz and 0.1-0.2 Hz, respectively. From small-scale experiments, Kim et al. [7] studied the effect of natural ventilation and fuel surface area on fire behaviour, using methanol as fuel. Oscillating combustion was observed before extinction, near the boundary between stable (beyond certain ventilation condition, combustion continues until the fuel was exhausted) and unstable (the balance between fuel vaporization and oxygen supply is broken, the fully-developed fire is not sustained, and extinction occurs) combustion regions, with frequency in the range of 0.02-0.2 Hz.
For fires in enclosures equipped with mechanical ventilation, such as in nuclear facilities, unstable low-frequency modes can be encountered, leading to pressure variations that can affect the confinement levels and hence the safety of the installation. Such a behaviour has been observed by Pretrel et al. [8] from experiments on heptane pool fires in the large-scale IRSN DIVA facility. Oscillations with frequency less than 10 mHz were recorded for a fire size (peak of heat release rate) of 0.5 MW fire and air renewal rate (ARR) from 12 to 17h^{-1}. During this oscillatory phase, a drastic change in flame behaviour was observed: the flame emission intensity decreased, and a weakly blue flame left the pool surface and moved slowly through the compartment, before coming back above the pan. This phenomenon has been also observed in naturally-ventilated compartment fires (e.g. [2],[5], [8]-[12]). To improve the understanding of the unstable low-frequency behaviour of mechanically-ventilated fires, experiments using a 1:4 scale reproduction of DIVA were carried out, varying the type of fuel, the pool size and the ARR.

EXPERIMENTS

Fire experiments were conducted in a 1.5m×1.25m×1m mechanically-ventilated compartment, called NYX (Fig. 1). This compartment is a 1:4 scale reproduction of a room of the DIVA facility of IRSN [2]. Froude similarity criterion was used for scaling gas flow rates between DIVA and NYX. The walls E, S, N, B and F (see Fig. 1) are composed of two layers, a 0.002 m-thick steel layer and a 0.045 m-thick calcium silicate layer. The west wall is made from heat-tempered glass allowing visualization of the fire growth using a CCD camera positioned outside the compartment. Unlike the DIVA facility which is fully mechanically-ventilated, the inlet air flow is free whereas hot gases are extracted mechanically. The air renewal rate (hereafter labelled ARR in h^{-1}) is defined as the ratio between the inlet air flow rate before ignition and the compartment volume. A vertical rake of 5 thermocouples (K type, 0.5 mm) was placed in each corner of the enclosure to measure gas temperatures. Molar fractions of O_2, CO_2 and CO molar fractions were measured by probes inserted into the exhaust branch. McCaffrey probes [13] were used to evaluate gas velocity inside the ventilation ducts to determine the inlet air flow and gas extraction rates. The pressure difference between the gases in the compartment and the air outside the compartment was measured using a differential pressure transducer (Emerson ROSEMOUNT). All measurements were recorded at a frequency of 1 Hz.

Fig. 1: Experimental set-up NYX. The letters W, E, S, N, and B refer to west, east, south, north and back faces of the compartment, respectively.

A circular pan was filled with fuel up to a height of 0.043 m whatever the pool size and fuel type. Ignition was provided by a propane burner. An electronic balance was placed at the centre of the floor to measure the mass of the fuel over time. A series of 31 experiments was performed using two types of liquid fuels, namely heptane and dodecane, and varying the pool size and ARR (Table 1). Although heptane and dodecane have similar heats of vaporization at 25°C (365 vs. 293 kJ/kg), heats of combustion (45.0 vs. 44.6 kJ/kg), and flammability limits (1-7 vs. 0.6-4.7 % in vol.), they strongly differ in boiling temperature (98 vs. 216 °C) and flashpoint (-4 vs. 72°C) [14]. Therefore, dodecane is less volatile and less flammable than heptane, leading to discrepancies in fire behaviour.

RESULTS AND DISCUSSION

LF Oscillatory behaviour

Time evolution of the mass loss rate (MLR) over several cycles of LF oscillations for the 18-cm diameter heptane pool fire, with a renewal rate of 12.5 h^{-1}, is shown in Figure 2, along with instantaneous video captured frames. The analysis reveals a strong correlation between the burning rate oscillations and those in the fuel burning area. When the flame is positioned vertically above the pan, the heat feedback from the flame to the fuel surface increases. The combustion heat release induces a rapid pressure and temperature rise due to the increasing burning rate. This leads to a reduction in the air inlet flow rate. The oxygen supply is not large enough to sustain a strong combustion. The flame is lifted and leaves the pool surface or occupies only a part of it (the flame changes in appearance, intensity and colour, from yellow to bluish-yellow). The heat feedback, and thus the MLR, decrease, which is followed by a reduction in pressure and temperature in the compartment. The admission flow rate increases, providing more oxygen to support combustion. The flame recovers its position above the pan. For this case study, the frequency of oscillations is approximately 18 mHz. Due to the configuration of ventilation, it is worth noting that the flame migrates to the F-E corner when it leaves the pool surface. Although not shown here, an inversion of ventilation causes the flame to move to the B-W corner. As demonstrated by Thomas et al [15], thermal feedback from the enclosure can also significantly contribute to the fuel gasification rate and thus to the oscillating fire behaviour. From fire experiments under natural ventilation conditions, Kim et al. [7] showed that the gas temperature in the compartment became higher as the oscillation repeated, increasing the temperature of the fuel tray and thus the emission of fuel vapor. The air supply was not large enough to balance the fuel vapor supply and extinction occurred.

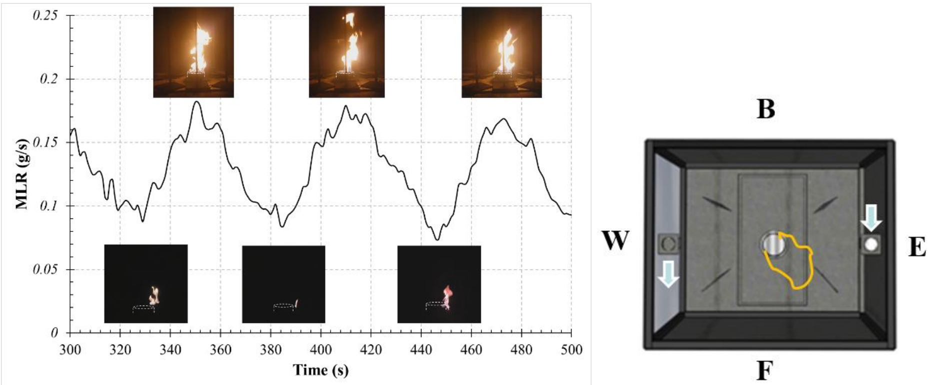

Figure 2: Left: MLR vs. time during the LF oscillatory phase for the 18-cm-diameter heptane pool fire with a renewal rate of 12.5 h^{-1}, and video captured frames after 329, 351, 385, 410, 447 and 473 s of fire; right: average position of the flame when it leaves the pool surface.

Regimes of combustion

Fig. 3 shows the time evolution of MLR for heptane and dodecane pool fires under forced ventilation conditions with different rates. In the first minutes, fire develops independently of the ARR (fuel-controlled fire). Subsequently, there are four distinct regimes of burning behaviour observed in the present study, depending on the fuel type, pool size and ARR. Three of them are unstable (extinction occurs before the fuel supply is completely exhausted) and one is stable (no extinction until burnout). Regime (1) corresponds to unstable combustion followed by rapid extinction due to filling. The compartment is filled nearly completely with smoke and the air renewal rate is not large enough to sustain a sufficient oxygen concentration (e.g. the red curve in Fig. 3b or the grey curves in Fig. 3e and Fig. 3f). In regime (2), where the fire is weakly ventilated, the flame stands upright, but it does not always occupy the entire fuel surface, which explains the decrease of MLR. A precarious balance is reached between air supply and fuel vaporization that can be broken at any time. The heat feedback from the flame and enclosure to the fuel tray is not sufficient to sustain combustion (not shown, gas temperatures remained relatively low and nearly constant throughout the test). Extinction occurs. This regime is observed for small pool diameters and ARRs (e.g. the orange and blue curves in Fig. 3a or the yellow curve in Fig. 3e). When the heat release rate of fire increases, the heat feedback is strong enough to sustain fuel evaporation. Unstable combustion, accompanied by low-frequency (LF) oscillations, takes place, which corresponds to regime (3). The oscillation period depends on time required for storing enough fuel vapor for strong combustion [7]. In this regime, extinction occurs due to an enhancement of the MLR resulting either from an increase of the heat feedback (e.g. the yellow curve in Fig. 3b) or from an increase of the heat transfer through the rim of the container, making easier the vaporization of the small quantity of liquid fuel remaining in the pan (e.g. the green, blue, red and black curves in Fig. 3c). Although not shown, a significant increase in gas temperature is observed over time. Regime (4) corresponds to stable combustion. This regime, marked by nearly steady burning, occurs for small pool sizes (e.g. the red, green and yellow curves in Fig. 3a or the black curve in Fig. 3e).

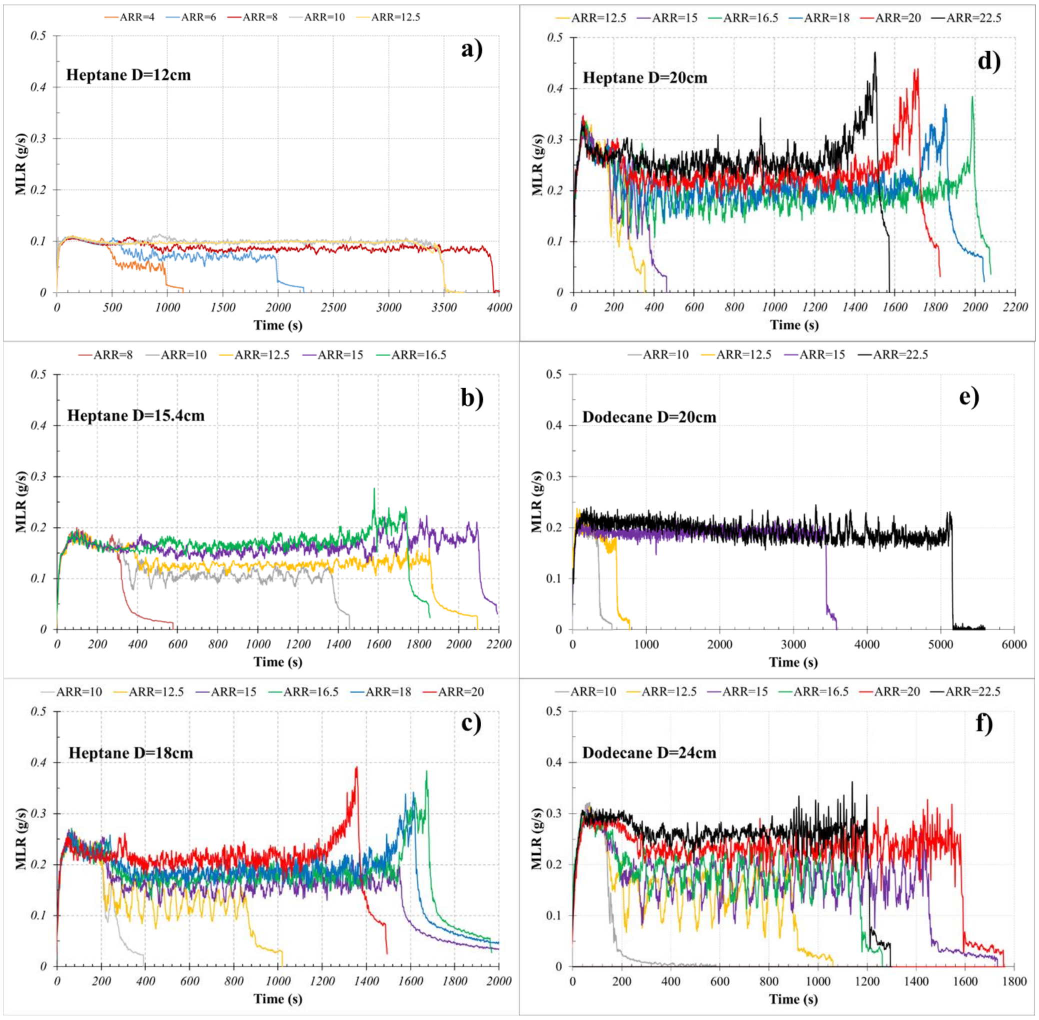

Fig. 3: MLR vs. time for heptane and dodecane pool fires and different ARR (h^{-1}).

Table 1 summarizes the results obtained from the experiments. The frequency of LF oscillations is calculated using a Fast Fourier transform (FFT).

For both fuels, some conclusions can be drawn. The frequency of LF oscillations increases, while amplitude decreases, with increasing ARR independently of the pool size (Table 1), as found by Pretrel et al. for large-scale experiments [8]. It is worth noting that the amplitude of LF oscillations increases with the pool size, as shown in Fig. 4 where the time evolution of MLR are plotted for heptane pool fires with ARR=12.5h^{-1}. Moreover, the range of ARR where LF oscillations appear and the oscillation amplitude increase with the pool size.

LF oscillation regime is strongly correlated to the flammability properties of the fuel used. For the same ventilation conditions, the more flammable the fuel, the smaller pool size LF oscillations appear and the higher the frequency. For example, for ARR=12.5h^{-1}, heptane pool fires exhibit LF oscillations (Regime (3)) from a diameter of 15.4 cm, whereas a larger diameter, i.e. 24 cm, is required for dodecane. Moreover, for the same pool size, the more flammable the fuel, the wider the range of ARR LF oscillations occurred.

All these results must still be confirmed by further experiments.

Table 1: Combustion regimes for heptane and dodecane compartment fires. D is the pool diameter. sf$\rightarrow$mf corresponds to a transition from single-frequency to multiple-frequencies oscillations during the test.

Fuel	D (cm)	ARR (h^{-1})									
		4	6	8	10	12.5	15	16.5	18	20	22.5
Heptane	12	2	2	4	4	4	-	-	-	-	-
	15.4	-	-	1	3 sf=12.4mHz $\rightarrow$mf	3 sf=16.5mHz $\rightarrow$mf	3 mf	3 mf	-	-	-
	18	-	-	-	3 sf=16.1mHz	3 sf=18.1mHz	3 sf=22.4mHz $\rightarrow$mf	3 sf=23.3mHz $\rightarrow$mf	3 mf	3 mf	-
	20	-	-	-	-	3 sf=18.0mHz	3 sf=20.9mHz	3 sf=22.8mHz $\rightarrow$mf	3 sf=26.0mHz $\rightarrow$mf	3 sf=33.3mHz $\rightarrow$mf	3 mf
Dodecane	20	-	-	-	1	2	3 mf	-	-	-	4
	24	-	-	-	1	3 sf=13.7mHz	3 sf=16.3mHz	3 sf=18.8mHz	-	3 mf	3 mf

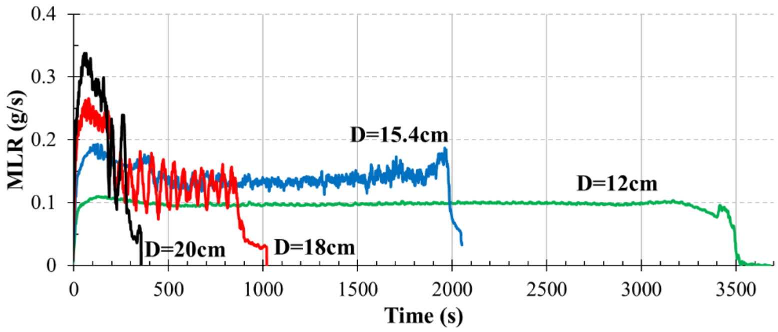

Fig. 4: MLR vs. time for different heptane pool sizes. Here, ARR=12.5 h^{-1}.

CONCLUSION

Small-scale experiments were conducted to investigate the low-frequency oscillating regime of hydrocarbon pool fires under forced ventilation conditions. This regime results from the competition between oxygen supply and fuel vapor supply due to the heat feedback from the flame and enclosure to the fuel tray. The influence of fuel type, pool size and air renewal rate on the occurrence and persistency of low-frequency oscillations is studied. However, further experiments are still required to complete the diagram of combustion regimes. It is found that, for both fuel types (heptane and dodecane): first, the range of ARR where the oscillatory regime appears and the oscillation amplitude increase with the pool size; and second, the frequency increases with the ARR, independently of the pool size, while the amplitude decreases. Results also show that the oscillatory regime is strongly dependent on the flammability properties of the fuel used, heptane fuel being more flammable than dodecane fuel. For a given ARR, the more flammable the fuel, the smaller pool size where LF oscillations appear and the higher the frequency. Moreover, for a given pool diameter, the range of ARR where LF oscillations appear is wider for heptane fires than for dodecane fires.

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REFERENCES

[1] Peatross, M.J., Beyler, C.L., "Ventilation effects on compartment fire characterization," *Fire Safety Science -- Proceedings of the Fifth International Symposium*, International Association for Fire Safety Science, 1997, 403-414.

[2] Audouin, L., Rigollet, L., Prétrel, H., Le Saux, W., Röwekamp, M. (2013) OECD PRISME project, fires in confined and ventilated nuclear-type multi-compartments, *Fire Safety Journal* 62:80-101.

[3] Utiskul, Y., Quintiere, J.G., "Generalizations on compartment fires from small-scale experiments for low ventilations conditions," *Fire Safety Science -- Proceedings of the Eighth International Symposium*, International Association for Fire Safety Science, 2005, 1229-1240.

[4] Takeda, H. (1985) Oscillatory phenomenon and inverse temperature profile appearing in compartment fires, *Combustion and Flame* 61:103-105.

[5] He, Q., Li, C., Lu, S., Huang, S. (2014) Experimental study of pool fire burning behaviours in ceiling vented ship cabins, *Procedia Engineering* 71:462-469.

[6] Hu, Z., Utiskul, Y., Quintiere, J.G., Trouvé, A., "A comparison between observed and simulated flame structures in poorly ventilated compartment fires," *Fire Safety Science -- Proceedings of the Eighth International Symposium*, International Association for Fire Safety Science, 2005, 1193-1204.

[7] Kim, K., Ohtani, H., Uehara, Y. (1993) Experimental study on oscillating behaviour in a small-scale compartment, *Fire Safety Journal* 20:377-384.

[8] Prétrel, H., Suard, S., Audouin, L. (2016) Experimental and numerical study of low frequency oscillatory behaviour of large-scale hydrocarbon pool fire in a mechanically ventilated compartment, *Fire Safety Journal* 83:38-53.

[9] Sugawa, O., Kawagoe, K., Oka, Y., Ogahara, I. (1989) Burning behaviour in a poorly ventilated compartment fire – ghosting fire, *Fire Science and Technology* 9:5-15.

[10] Wakatsuki, K., Low ventilation small-scale compartment fire phenomena: ceiling vents, *MS Thesis*, Department of Fire Protection Engineering, University of Maryland, College Park, 2001.

[11] Bertin, G., Most, J.M., Coutin, M., Wall fire behaviour in an under-ventilated room, *Fire Safety Journal*, 2002.

[12] Matsuyama, K., Okinaga, S., Hattori, Y., Suto, H., Experimental study on fire behaviour in a compartment under mechanical ventilated conditions: the effects of air inlet position, *Fire Science and Technology*, 11-119, 2015.

[13] McCaffrey, B.J., Heskestad, G., A robust bidirectional low-velocity probe for flame and fire application, *Combustion and Flame*, Volume 26, 125-127, 1976.

[14] *SFPE Handbook of Fire Protection Engineering (3rd ed)*, DiNenno P.J (ed), National Fire Protection Association, Quincy, MA 02269, 2002.

[15] Thomas, P.H., Bullen, M.L., Quintiere, J.G., McCaffrey, B.J., Flashover and instabilities in fire behaviour, *Combustion and Flame*, Volume 38, 159-171, 1980.