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Brady Manescau, Léo Courty, Lahna Acherar, Bruno Coudour, Hui-Ying Wang, et al.. Effects of ventilation conditions and procedures during a fire in a reduced-scale room. *Process Safety and Environmental Protection*, 2020, 144, pp.263-272. 10.1016/j.psep.2020.07.035 . hal-03016835

HAL Id: hal-03016835

<https://hal.science/hal-03016835>

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journal homepage: www.elsevier.com/locate/psep

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Effects of ventilation conditions and procedures during a fire in a reduced-scale room

Brady Manescau^a, Léo Courty^{b,*}, Lahna Acherar^c, Bruno Coudour^c, Hui-Ying Wang^c, Jean-Pierre Garo^c

^a INSA-CVL, Univ. Orleans, PRISME EA 4229, 88 Bd Lahitolle, 18000, Bourges, France

^b Univ. Orleans, INSA-CVL, PRISME EA 4229, 63 Av. de Lattre de Tassigny, 18020, Bourges, France

^c Institut P, CNRS, ENSMA, Univ. Poitiers, 1 Av. Clement Ader, Téléport 2, BP 40109, 86961, Futuroscope Chasseneuil, France

ARTICLE INFO

Article history:

Received 26 March 2020
Received in revised form 19 July 2020
Accepted 20 July 2020
Available online xxx

Keywords:

Compartment fire experiments
Underventilation
Ignition risk assessment
Species concentration
Ventilation procedures

ABSTRACT

This paper deals with the consequences of applying ventilation procedures during confined fires. If the air intake duct is closed after the beginning of the fire, another risk may appear, namely the ignition of unburnt gases in extraction ducts. This configuration is typical of many industrial installations equipped with ventilation networks. Heptane and dodecane pool fires were performed in a reduced-scale compartment equipped with a mechanical ventilation network. Heat release rate, temperatures and unburnt species concentration were measured for different pan diameters, different ventilation flows, with and without closing the intake duct, to study fire development and the potential risk of ignition in the exhaust system. Empirical correlations to estimate unburnt species concentrations are given. Based on these correlations, lower flammability limit calculations and scaling laws, a risk assessment methodology is proposed and a decision support tool is provided. Experimental results clearly show that the auto-ignition of unburnt gases can happen near the extraction duct, with and without closing the intake duct.

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1. Introduction

Behavior of fires taking place in a confined and mechanically ventilated environment depends on the amount of oxygen available for combustion. Therefore, fires quickly become controlled by ventilation. If the oxygen concentration in the compartment decreases, flammable products due to incomplete combustion begin to accumulate in the room. A fire situation controlled by ventilation will lead to a greater production of flammable unburnt gases (Beyler, 1986; Tewarson, 2002; Morehart et al., 1990; Gottuk, 1992; Gottuk et al., 1992; Gottuk, 1995; Utiskul et al., 2005; Lattimer, 1994; Wieczorek, 2003; Lassus et al., 2014; Lassus, 2010; Lassus et al., 2016; Hostikka, 2017; Mowrer, 2016; Loo et al., 2016).

Three combustion regimes have been identified for confined fires, depending on the concentration of oxygen available for combustion (Lassus et al., 2014). If the concentration of oxygen is higher than the minimum oxygen concentration (MOC) of the burning fuel, sufficiently ventilated fires take place, i.e. almost complete combustion, the concentration of unburnt gases is almost zero. If

the concentration of oxygen ranges between the MOC of carbon monoxide and the MOC of the burning fuel, underventilated fires take place, i.e. the concentration of unburnt gases is moderate. If the concentration of oxygen is lower than the MOC of carbon monoxide, very underventilated fires take place, i.e. the concentration of unburnt gases is high, and the fire may extinguish due to lack of oxygen.

Most buildings, residential or industrial, are equipped with ventilation networks. The unburnt gases coming from the incomplete combustion can be transported to other premises, or even other buildings, through ventilation ducts. This accumulation of unburnt gases can create a flammable mixture that can ignite with an external ignition source or by self-ignition. The study of such phenomena requires a good characterization of the unburnt flammable gases produced by the fire. Given the role of carbon monoxide, several studies have been carried out over the past twenty-five years to understand the mechanisms of formation of this gas, its transport and the chemical reactions which may result from it.

The temporal evolution of dioxygen, carbon dioxide and carbon monoxide, during confined and ventilated fires have been studied in several works, like Beyler (1986); Tewarson (2002); Morehart et al. (1990); Gottuk, 1992; Gottuk et al., 1992; Gottuk et al., 1995) or Utiskul et al., 2005. The possible transportation of

* Corresponding author.

E-mail address: leo.courty@univ-orleans.fr (L. Courty).

<https://doi.org/10.1016/j.psep.2020.07.035>

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flammable unburnt gases to another compartment has been studied, by for instance Lattimer et al. (1994), Wieczorek Wieczorek, 2003; Lassus et al., 2014; Lassus et al., 2010; Lassus et al., 2016.

The risk of ignition of unburnt gas-rich fumes coming from a confined and ventilated fire has been studied by Lassus et al. (2010). Thus, it is possible to quantify the unburnt gases within the premises. Lassus et al. (2016) have also established an empirical relationship to determine the concentration of carbon monoxide, carbon dioxide, hydrogen and total hydrocarbon concentrations, depending on oxygen concentration. The pressure variation, representative of the dynamic confinement of an enclosure, has been studied Hostikka et al., 2017; Pretrel et al., 2012. It was found that fire development inside the compartment depends on the air tightness of the enclosure, and increased pressure can lead to a reverse flow in the supply ventilation system. However, there are few works investigating the effects of ventilation procedures (Pretrel and Such, 2005).

One strategy to stop a confined fire is to stop ventilation: the heat release rate will be lower, and the fire will stop due to a lack of oxygen (Pretrel and Such, 2005). However, with this strategy, the combustion will be incomplete, and many unburnt flammable species will be produced, increasing the risk of ignition in the ventilation system. Previous works considered the behavior of the fire for different ventilation velocities (Lassus et al., 2014), (Lassus et al., 2016). In this paper, fire behavior using ventilation procedures (closure or not of the air intake duct) are investigated, along with the issue of re-ignition of unburnt flammable gases in the extraction system.

Experimental pool fires were performed in an enclosure mechanically ventilated using two fuels, heptane and dodecane. Experimental results on the behavior of the fire with ventilation procedures are given. A risk assessment methodology is proposed for determining the effects on flammable unburnt gas production if the air intake duct is closed. Finally, a decision support tool is provided, consisting of an easy and practical criterion, allowing determination of the fuel storage amount that should not be exceeded to avoid any re-ignition of unburnt flammable gases in the extraction system.

2. Experimental section

Fire experiments are often performed at reduced scale, for cost reasons, to allow a sufficient number of tests. This is the case in the present study, where experiments were performed in a cubic 8 m³ room test. This room was scaled from a 100 m³ compartment. Scaling relations for compartment fires have been proposed by Heskestad (1973); Emori and Saito (1983); Quintiere (1989); Kayili et al. (2012) and Lassus et al. (2014). Scaling relations were obtained by keeping the Froude number constant Lassus et al. (2014).

This small-scale compartment was already used in previous works Lassus et al., 2014; Lassus et al., 2010; Lassus et al., 2016, without closing the air intake duct. Temperatures were measured with type K thermocouples. Relative pressures lower than atmospheric pressure (depression level even if values are positive) were measured continuously by a pressure sensor with a sensitivity of ± 2 Pa.

Continuous measurements of oxygen, carbon dioxide and carbon monoxide were performed by on-line analysis. Local samplings of oxygen, carbon dioxide, carbon monoxide, hydrogen and unburnt hydrocarbons were performed using a probe and analyzed by gas chromatography. All gas concentration measurements presented were performed at the entrance of the extraction duct.

The ventilation system consisted of an air intake duct located in the lower part of the room, and an extraction duct located in the upper part of the room. Ventilation velocities could be varied:

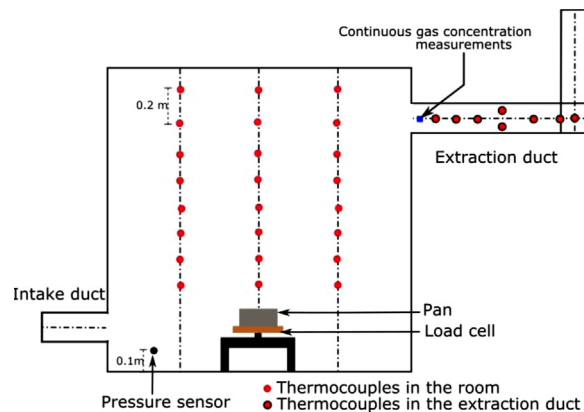


Fig. 1. Scheme of the experimental setup.

two rates of Air Change Per Hour (ACPH) were studied, 3 and 5. They corresponded to air flows of 24 and 40 m³·h⁻¹, respectively. Different ventilation procedures were investigated by closing the air intake duct for some experiments. For these experiments, the intake duct was closed as soon as the fire started.

Pool fires were performed using two fuels: heptane (CARLOERBA RECTIFS, technical-grade: 26.22 % pure n-heptane and 73.78 % other isomers of heptane) and dodecane (VWR-PROLABO, 98.971 % pure). Heptane is a liquid hydrocarbon commonly used in fire studies. Dodecane has a chemical formula similar to Hydrogenated Tetra-Propylene (HTP), which is a chemical solvent used in nuclear power plants. Note that these two fuels were also used by Loo et al. (2016) in a reduced-scale mechanically ventilated compartment.

Fires of different heat release rates (HRR) were performed by varying pan diameters: 0.10, 0.15, 0.23 and 0.30 m for heptane and 0.23, 0.30 and 0.40 m for dodecane. A load cell was placed under the pan to obtain the temporal evolution of the fuel mass and to calculate the HRR. Note that the oxygen consumption technique to measure HRR cannot be used here because the intake duct was closed in some experiments; it resulted in an overestimation of HRR. A scheme of the experimental setup is given in Fig. 1.

3. Experimental results

For each fire condition, three tests were made in order to check the repeatability of the main parameters. Fig. 2 presents HRR, depression, temperature and oxygen concentration for three different heptane fires (ACPH of 5, pan diameter of 0.3 m, intake duct open). These conditions correspond to a very underventilated fire.

The HRR as a function of time is presented in Fig. 3 for heptane (pan diameter of 0.3 m) and dodecane (pan diameter of 0.4 m) fires at 3 and 5 ACPH with and without closing the intake duct. One can note that for heptane fires, the HRR is decreasing faster and is stopping faster when the intake duct is closed. When the intake duct is open and the ventilation is 5 ACPH, the noisy evolution of HRR can be explained by the fast fire growth: the HRR is decreasing after 150 s, with a maximum of 150 kW (90 kW for the other studied conditions).

For dodecane fires, the trend is opposite. Fires last longer when the air intake duct is closed. In that case, the HRR obtained is moderate, around 50 kW. Fires with the intake duct closed last 8–12 min longer. This is due to the lower boiling point of heptane (98 °C) compared to dodecane (220 °C). Heptane fires growth are therefore faster than dodecane fires one. Heptane fires present a high HRR and a fast extinction. Dodecane fires last longer than heptane fires, leading to hotter walls of the enclosure and possibly allowing auto-ignition of unburnt species.

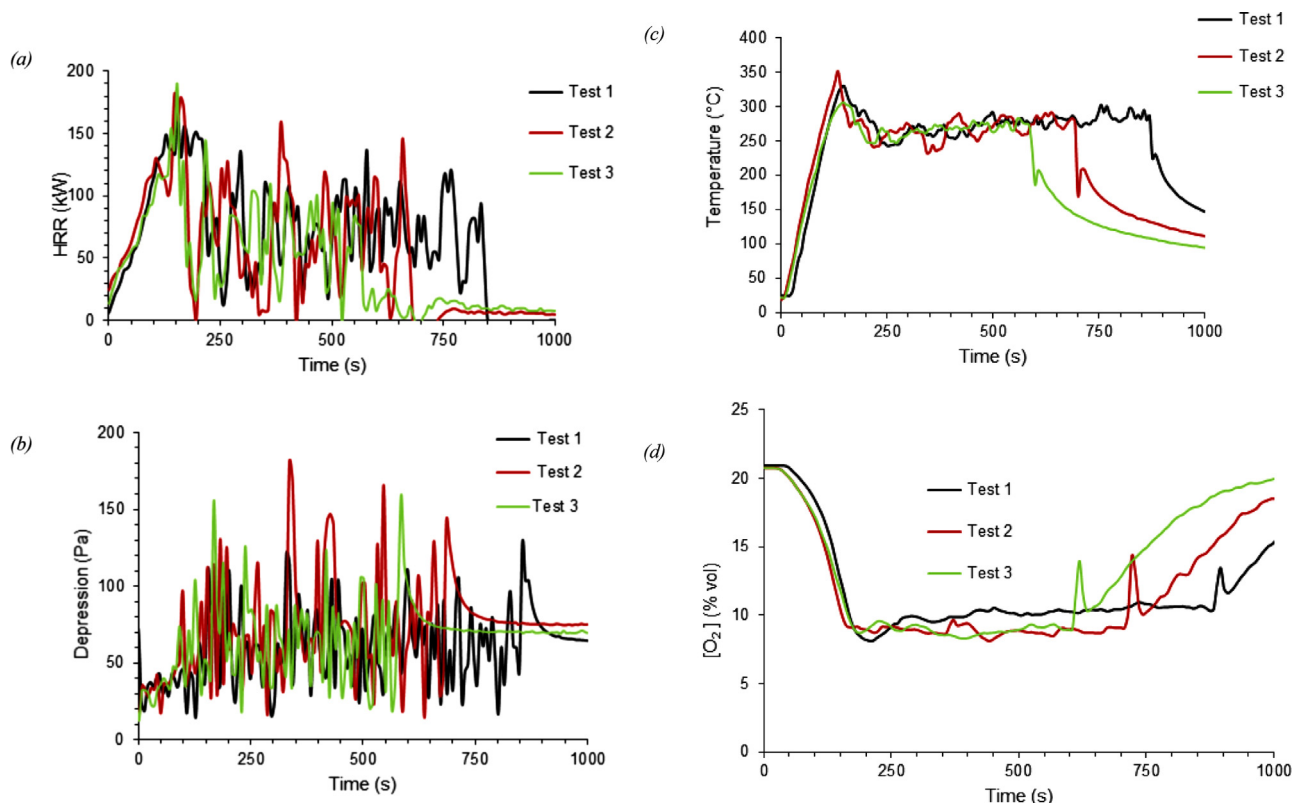


Fig. 2. Repeatability of heptane fires for a pan diameter of 0.3 m at 5 ACPH, intake duct open: (a) Heat Release Rates, (b) Depression, (c) Temperature, (d) Oxygen concentration.

Table 1

HRR (in kW) in different enclosures for three combustion regimes: sufficiently ventilated, underventilated and very underventilated.

$\frac{\dot{Q}^2}{L^5}$	3.13	7.03	12.50	29.1	116.28	261.63	465.13
Experimental setup (8 m ³)	10	15	20	30.5	61	91.5	122
Enclosure of 100 m ³	82	123	165	250	500	750	1000
Enclosure of 120 m ³	96	143	191	291	583	874	1165
Enclosure of 400 m ³	261	391	521	795	1589	2384	3178
Enclosure of 583 m ³ (ICFMP fire tests)	357	535	713	1088	2175	3263	4350
Combustion regimes	Sufficiently ventilated fires			Underventilated fires		Very underventilated fires	

At a given HRR, the analysis of the auto-ignition risk could be performed knowing the value of $\frac{\dot{Q}^2}{L^5}$. Results were similar for both studied fuels and are presented in Table 2 for the real scale (100 m³).

Table 2

Analysis of the ignition risk as a function of fire HRR for a 100 m³ installation.

HRR	$\frac{\dot{Q}^2}{L^5}$	Concentration of unburnt species (C)	Temperature T in the extraction duct	Auto-Ignition risk
Lower than 250 kW	Lower than 245	≤ 0,1 %	T ≤ 150 °C	No risk
Between 250 kW and 750 kW	Between 245 and 262	0,1 % ≤ C ≤ 1 %	150 °C ≤ T ≤ 250 °C	Minimal risk may exist
Higher than 750 kW	Higher than 262	1 % ≤ C ≤ 5 % Usually 3 % ≤ C	250 °C ≤ T	Strong risk

Results for other pan diameters were not plotted in this section, but the following conclusions could be drawn (cf. Tables 1 and 2). With pan diameters of 0.10 and 0.15 m for all the ventilation flows, the oxygen quantity initially present and supplied by mechanical ventilation allows a sufficiently ventilated fire to be obtained. Sufficiently ventilated fires with closed admission duct should therefore produce almost no unburnt gases. This is unlike fires with an open duct admission, where the evolution of the HRR for a given pan diameter depends on the extraction conditions (Lassus et al., 2014). With a pan diameter of 0.23 m, dodecane fires have a HRR comparable to that of heptane fires with a 0.15 m diameter pan. With a larger pan diameter (heptane fires with a 0.23-meter diameter pan, dodecane with 0.30 m pan diameter), the oxygen quantity initially present and supplied by mechanical

ventilation can become insufficient to obtain a complete reaction.

The oscillatory phenomena of the HRR are described in (Lassus et al., 2014; Lassus et al., 2010; Lassus et al., 2016). The noisy evolution is the consequence of fluctuations due to the underventilation. For sufficiently ventilated fires that stop by lack of fuel, fuel is burnt faster at high ACPH and therefore stop faster with high ventilation flows. HRR is therefore noisier for high ACPH. For very underventilated fires that stop by lack of oxygen, it is the contrary: noisier HRR are obtained for fires with low ACPH.

Unlike fires with opened air intake, the HRR hardly depends on the extraction conditions. ACPH has no effect on the fires with low and medium HRR (pan diameters of 0.10, 0.15 and 0.23 m). For very underventilated fires with high HRR (pan diameters of 0.30 m),

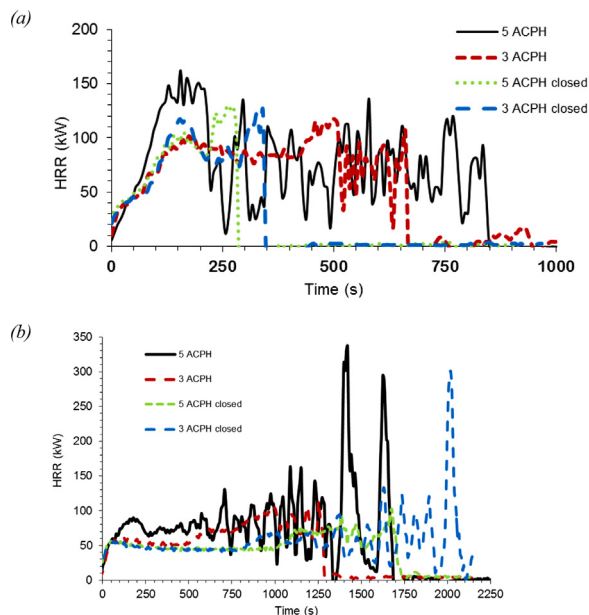


Fig. 3. Heat Release Rates of heptane (a, pan diameter of 0.3 m) and dodecane (b, pan diameter of 0.4 M) fires at different ACPH (air intake duct closed and open).

the effect of ACPH is more important. A stronger initial ventilation leads, after closing the intake duct, to a larger extraction rate at the level of the extraction duct. This mainly prevents fresh air to enter the compartment counterflow from the extraction duct.

Fire duration is longer at 3 ACPH than at 5 ACPH: this due to the fact that the extraction being less important, more oxygen remains present in the compartment.

The fire duration can be calculated from the oxygen mass conservation equation:

$$\Delta t = \frac{\rho_{air} \cdot V_{air} (Y_{O_2}(t_0) - Y_{O_2}(t_{ext}))}{r \cdot \dot{m}} \quad (1)$$

This equation corresponds to an idealistic approach (the parameter r , the fuel mass loss rate and gas density are assumed constant). The following values are chosen for the comparison: 0.233 ($= 0.21 \times 32/28.84$) for $Y_{O_2}(t_0)$; the average oxygen mass yield in the vessel at extinction is calculated using $Y_{O_2}(t_{ext}) (= MOC_{fuel} \times 32/29)$, V_{air} is the vessel volume of air, ρ_{air} the density of air, r the “oxygen to fuel” stoichiometric ratio and \dot{m} the average fuel mass loss rate. The MOC is calculated for a nearly complete reaction (Bodurtha, 1980):

$$MOC_i = LFL_i \cdot n_{O_2} \quad (2)$$

where LFL is the lower flammability limit of the given fuel (% vol.) and n_{O_2} is the mole number of oxygen required for a complete reaction (mol). MOC_{fuel} and $Y_{O_2}(t_{ext})$ of heptane and dodecane used for calculations are respectively 0.145 and 0.161, 0.132 and 0.146.

The fire durations calculated for heptane with a pan diameter of 0.3 m and closed intake duct are 284 s for 3 ACPH and 246 s for 5 ACPH, compared with the measured values of 347 s and 287 s. The measured heptane fire duration is higher than the theoretical one due to the additional air counterflowing from the extraction duct that is not considered in the calculations. Indeed, it was observed that there was a rise of fresh air coming from the extraction network in the lower part of the duct. This could not be quantified due to the rapid darkening of the windows by soot.

Fig. 4 presents the pressure as a function of time for different heptane fires. It can be noticed that pressure in the enclosure is slightly lower than atmospheric pressure: this is why fresh air is

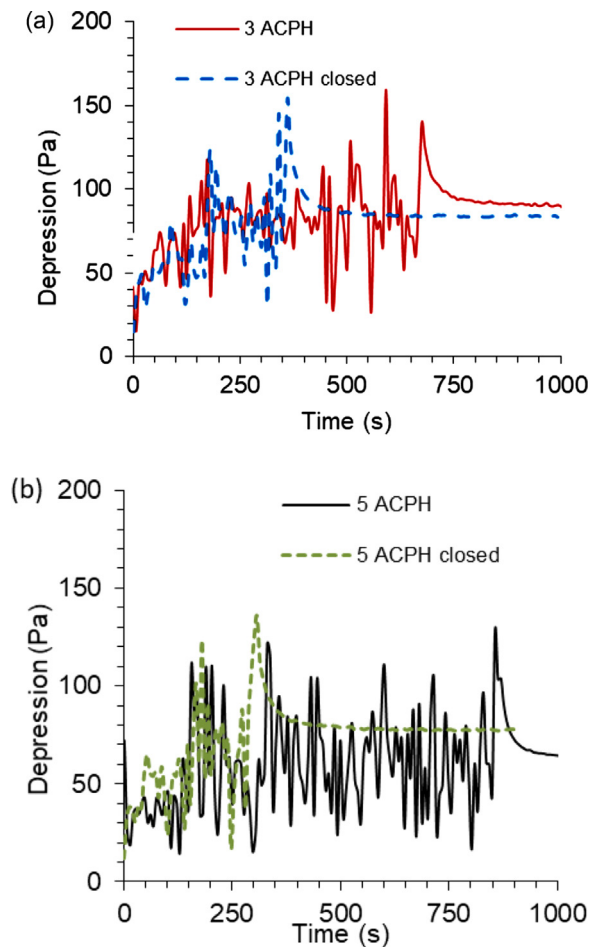


Fig. 4. Pressure as a function of time at the entrance of the exhaust duct (i.e. at the exit of the compartment) for heptane fires (pan diameter 0.3 m) at 3 (a) and 5 (b) ACPH (intake duct closed and opened).

entering the compartment via the extraction duct (Lassus et al., 2016).

The confined state can be disturbed by the pressure variation induced by the fire (Pretrel et al., 2012). Indeed, for an underventilated fire, these temporal variations in pressure follow a typical behavior characterized by a peak of overpressure when the fire starts and a peak of depression when the fire stops. During the ignition of a fire, the gas flow increases, resulting in a peak of overpressure. During the extinction a peak of depression is observed, resulting in the entrance of fresh air from the extraction duct as mentioned above. The same observations are also made for fires with the intake duct closed.

The magnitude of the pressure peaks depends mainly on the speed of heat release from the fire, the characteristics of the ventilation network (pressure losses of the different sections of the pipes (heat losses) and the thermal characteristics of the pipes (heat losses) and the compartment geometry. It has been shown through several tests that one does not necessarily need a significant HRR to have a significant increase in pressure (Pretrel et al., 2012). Indeed, a low HRR in a thermally insulated enclosure connected to a ventilation network with high pressure drop values can lead to a pressure increase. On the other hand, a high HRR in a metal enclosure (thermal losses) equipped with ventilation with pressure drops may not result in a significant increase in pressure. Thus, during a fire in a confined room mechanically ventilated, the pressure peaks can have different amplitudes for the same shape of the pressure behavior.

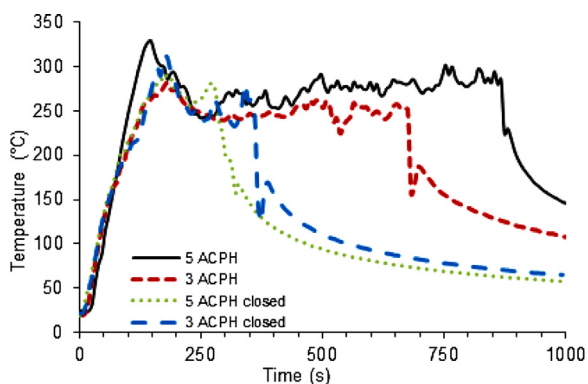


Fig. 5. Temperature as a function of time at the exhaust duct (i.e. at the exit of the compartment) for heptane fires (pan diameter 0.3 m) at 3 and 5 ACPH (intake duct closed and opened).

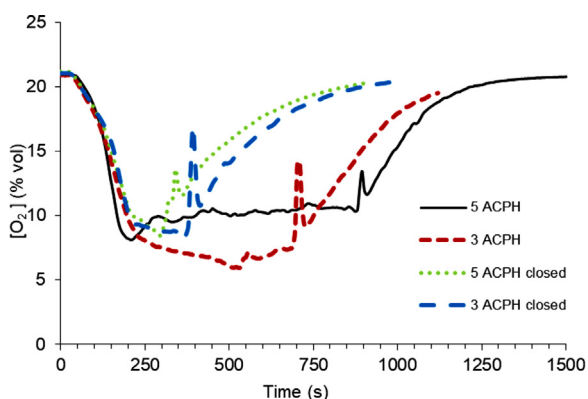


Fig. 6. Oxygen concentration as a function of time of heptane fires with a pan diameter of 0.3 m and at different ACPH (intake duct closed or opened).

The peaks described by (Pretrel et al. (2012)) can be observed in Fig. 4. In each of the cases, the presence of the peak of overpressure at ignition and the peak of depression at extinction is clearly observed.

Fires in this study were typical of enclosed fires where the ventilation is limited. This is the reason why the flame is perturbed. In order to avoid damage in the test room, only these two ventilation flows were tested.

Fig. 5 shows the evolution of the temperature at the inlet of the extraction duct for 0.3 m diameter fires, at 3 and 5 ACPH, with and without closing the intake duct. It can be seen that the temperature levels reached are fairly similar for the four tests. The gas temperature at the entrance of the extraction duct increases progressively during the fire growth period, reaching a plateau with a value of 250 °C in a quasi-steady period. Only the duration during which these temperatures were maintained varies.

At the end of the fire, a rapid temperature drop followed by a short rise is observed. The drop is caused by the entrance of fresh air in the duct during the depression.

Fig. 6 shows oxygen concentration at the entrance of the extraction duct as a function of time for the heptane fires (pan diameter 0.3 m) at 3 and 5 ACPH (inlet vent closed and opened).

It seems that during the initial growth phase, the oxygen concentration allows for a sufficiently ventilated fire. From 250 s, the under-ventilated regime starts and fires self-extinguish due to an insufficient amount of oxygen. After fire extinction, there is a significant peak in the oxygen concentration due to the inflow of oxygen in the extraction duct during the strong depression at the time of extinction. This entrance of fresh air (oxygen increase) at extinction also explains the carbon dioxide decrease (Fig. 7) due to dilution.

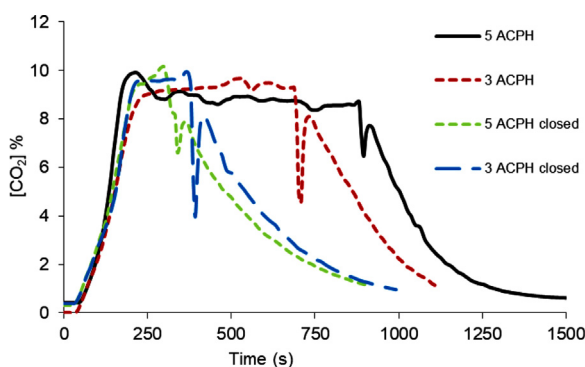


Fig. 7. Carbon dioxide concentration as a function of time of heptane fires with a pan diameter of 0.3 m and at different ACPH (intake duct closed or opened).

Fig. 7 presents the molar fraction of carbon dioxide as a function of time for heptane fires (pan diameter 0.3 m). CO₂ concentration shows a smooth trend during the fully developed fire and levels reached are fairly similar with and without closing the intake duct.

Small scale fire tests have shown a linear evolution of the carbon dioxide concentration as a function of the oxygen concentration (Lassus et al., 2016). Figs. 8a and 8b present carbon dioxide concentration as a function of oxygen concentration for heptane and dodecane fires under different conditions.

These evolutions of [CO₂] = f([O₂]), can be modeled by a straight line $y = -ax + b$, whose slope a is equal to n_{CO_2} / n_{O_2} , where n_{CO_2} and n_{O_2} are respectively the mole number of carbon dioxide produced and the mole number of oxygen consumed during the complete reaction of the fuel studied. This ratio is 0.64 in the case of heptane and 0.65 in the case of a dodecane. Coefficients b are 13.9 and 14.5 for respectively heptane and dodecane. It is therefore possible to estimate the CO₂ concentration knowing oxygen concentration.

It can be noticed that CO₂ concentrations are very similar for all studied conditions, meaning that they are not very dependent on the HRR. It is noted, however, that below the MOC of carbon monoxide at 25 °C (MOC_{CO} = 6.25 %), carbon monoxide is no longer oxidized to carbon dioxide. This is why the CO₂ concentrations do not exceed a value around 10 %. This corresponds to the phase where the fire becomes very under-ventilated: there is an increase in the production of unburnt materials, in particular carbon monoxide.

An empirical law was established by (Lassus et al., 2016) to obtain carbon monoxide concentration as a function of oxygen concentration. They have shown that, unlike carbon dioxide, carbon monoxide concentration as a function of oxygen concentration was not linear. Indeed, three distinct parts were noticed, corresponding to the different regimes of the fire: sufficiently ventilated, under-ventilated and very under-ventilated. Figs. 9a and 9b show [CO] as a function of [O₂] for respectively heptane and dodecane fires, at 3 and 5 ACPH, for different pan diameters, with and without closing the intake duct.

For oxygen concentration between MOC_{CO} and MOC_{fuel}, relation (3) is obtained. Note that at this stage, there is also production of CO₂ (still enough O₂ to oxidize CO).

$$[CO] = \frac{-c}{MOC} [O_2] + c \quad (3)$$

The coefficients c are of 1.96 and 1.98 for respectively heptane and dodecane, similar to k_{CO} , the maximum yield of CO species defined as:

$$k_{CO} = \frac{n_{CO} \cdot M_{CO}}{n_{fuel} \cdot M_{fuel}} \quad (4)$$

In the third phase, the fire is very under-ventilated: a very significant production of unburnt gases is noticed. The carbon monoxide

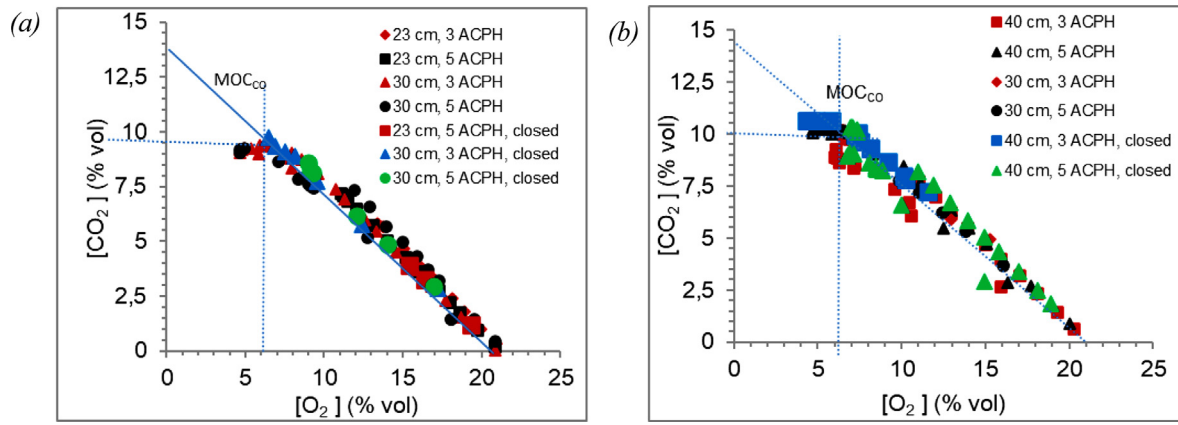


Fig. 8. Carbon dioxide concentration as a function of oxygen concentration: present measurements for different conditions of pan diameter at 3 and 5 ACPH (intake duct closed or opened), for (a) heptane fires and (b) dodecane fires.

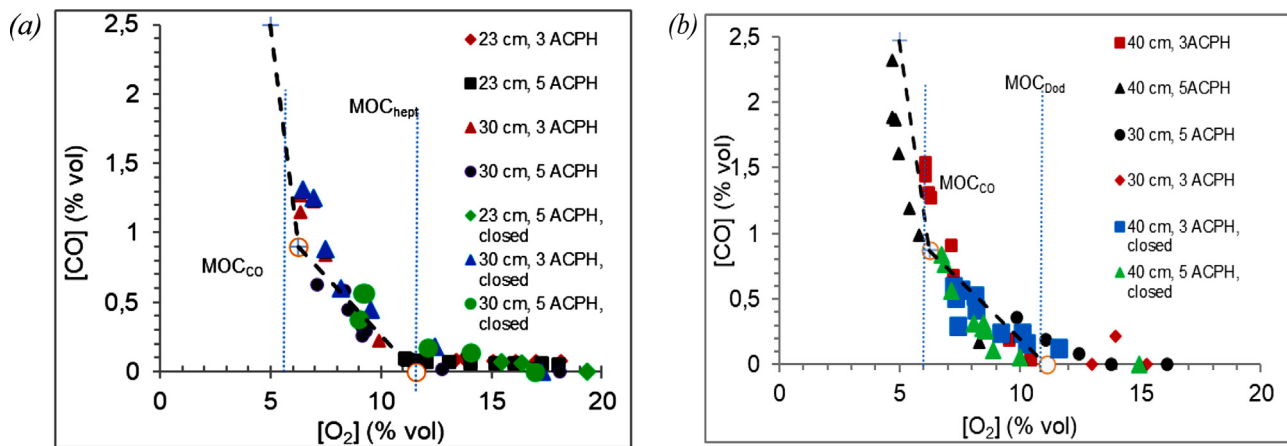


Fig. 9. Carbon monoxide concentration as a function of oxygen concentration: present measurements for different pan diameters at 3 and 5 ACPH (intake duct closed and opened), for (a) heptane and (b) dodecane fires.

concentration therefore increases strongly with the decrease in oxygen concentration. This phase is obtained for oxygen concentrations lower than MOC_{CO} and the following relation is obtained:

$$[CO] = \frac{-d}{MOC_{CO}} [O_2] + d + c \left(1 - \frac{MOC_{CO}}{MOC} \right) \quad (5)$$

where d is a coefficient depending on the fuel which is the same for heptane and dodecane and equal to 8 and c is the same coefficient as in the previous equation. At this stage, there is not enough O_2 to oxidize CO and for this reason there is a high production of CO and no production of CO_2 .

Similar carbon monoxide concentrations are obtained for all HRR and ventilation conditions studied.

The hydrogen concentration as well as concentrations of hydrocarbons that have a carbon chain length lower than or equal to four were measured by ten probes and are presented in Figs. 10 and 11, respectively for hydrogen and hydrocarbons. Trends are very similar to CO curves, with the presence of three distinct parts for all ACPH studied.

(Lassus et al., 2016) have shown that the sum of unburnt gases (hydrogen and total hydrocarbons) was equal to the concentration of carbon monoxide. It is therefore possible to estimate these unburnt gases concentrations knowing the CO concentration:

$$[CO] = [H_2] + \sum_{i,j=1}^{i=4, j \leq 10} [C_i H_j] \quad (6)$$

In order to study the validity of these relations, dodecane fires in a 0.4 m diameter pan at 3 and 5 ACPH closing the intake duct were executed. The CO concentration and the sum of the concentrations of unburnt gases (H_2 and $C_x H_y$) as function of time are presented in Fig. 12: experimental results are represented by dots and the dashed lines are correlations. One can note that experiments and calculations follow the same trend, with a slight overestimation of the calculated concentrations for some conditions. The relative gap between calculated and experimental values does not exceed 40 % for most of the conditions.

Note that the sufficiently ventilated regime is obtained before 350 s. The underventilated regime is obtained between 350 s and 700 s at 3 ACPH and between 350 s and 1050 s at 5 ACPH.

Production of CO is greater than the two other unburnt gases, which is similar to the observations made during Wieczorek's work (Wieczorek, 2003).

A too strong decrease at the end of the fire is predicted by the correlations. Since the combustion reaction is considered as complete during ventilated fires, estimated unburnt gas concentrations are equal to zero in the model if the oxygen concentration is higher than the MOC. Consequently, the decrease of unburnt gas concentration at the end of the fire is faster for the numerical results. For this reason, the relative deviation between correlated and experimental values can reach 60 %.

Some fluctuations can be noted in the species concentration predictions; they result from the evolution of O_2 concentration during this fire.

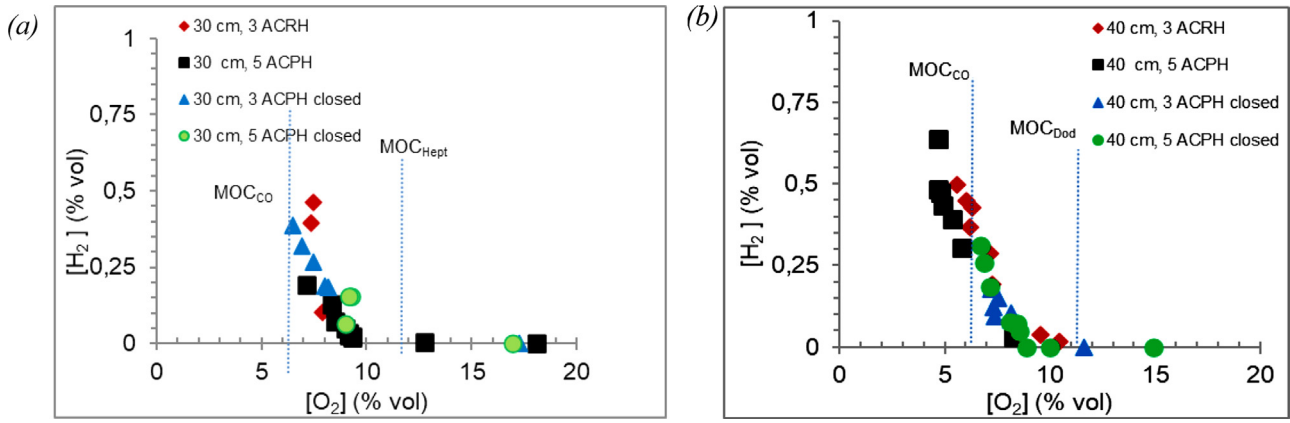


Fig. 10. Hydrogen concentration as a function of oxygen concentration for heptane (a) and dodecane (b) fires at 3 and 5 ACPH (intake duct closed and opened).

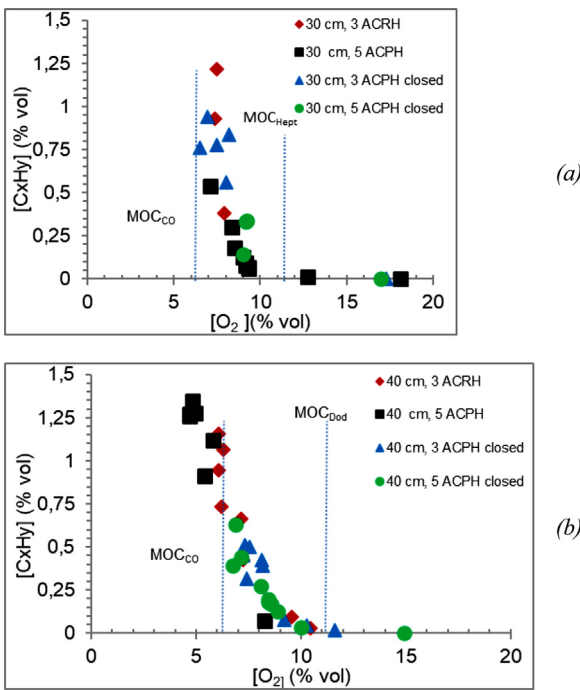


Fig. 11. Hydrocarbons concentration as a function of oxygen concentration for heptane (a) and dodecane (b) fires at 3 and 5 ACPH (intake duct closed and opened).

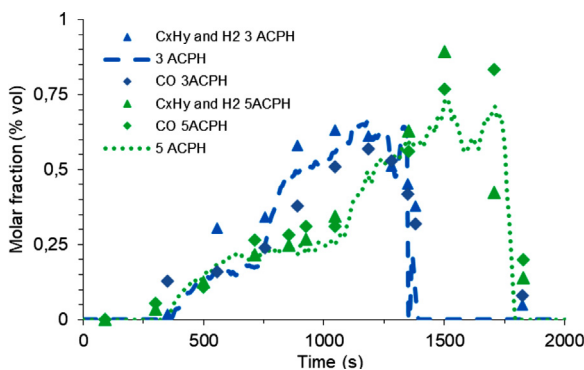


Fig. 12. Carbon monoxide concentration and the sum of the concentrations of unburnt gases (H₂ and C_xH_y) as function of time compared to the correlations for dodecane fires at 3 and 5 ACPH (pan diameter of 0.4 m, inlet vent closed).

Note that the admission duct is in the lower part of the setup. In some industrial cases, it can be in the upper part but that is not the case in the current test configuration. Species concentrations in a confined and mechanically ventilated enclosure are only valid for species concentrations in the extraction duct since concentrations are not homogeneously mixed in the enclosure.

The study of the risk of ignition of unburnt gases has shown that this can occur both by self-ignition and by controlled ignition. To assess this risk, it is necessary to know the composition of the mixture, as well as its temperature. In terms of composition of the mixture, it must have a proportion of fuel greater than the lower flammability limit (LFL) of the mixture.

LFL is influenced by the temperature of the ambient environment. (Zabetakis, 1965) observed that, for the majority of hydrocarbons, the LFL decreases of approximately 8 % with an increase of 100 °C.

Burgess-Wheeler's law (Burgess and Wheeler, 1911) describes the LFL of hydrocarbons as a function of temperature:

$$LFL_i(T) = LFL_i(T_0) \cdot \left[1 - \frac{T - T_0}{1300 - T_0} \right] \quad (7)$$

LFLs of the different fuels (except hydrogen) considered in this paper are determined at the mixture temperature. The LFL of hydrogen decreases more with temperature, and relation (8) is used:

$$LFL_i(T) = LFL_i(T_0) \cdot [1 - 0.00129 \cdot (T - T_0)] \quad (8)$$

In the case of a fuel mixture, the LFL of the fuel mixture is determined using the Le Châtelier law (Chatelier and Boudouard, 1898):

$$LFL(T) = \frac{100}{\left(\sum_i \frac{X_i}{LFL_i(T)} \right)} \quad (9)$$

Values of LFL at T₀ = 25 °C Babrauskas, 2003 for fuel species are respectively 12.5 %, 4%, 1.05 % and 0.6 % for CO, H₂, heptane and dodecane.

During gas sampling, some species with a long carbon chain were not identified. In this case, in a safety context, the LFL used for these species will be the lowest of the case considered. As the LFL decreases as a function of the carbon chain length, the LFL used will be the one of heptane in the case of heptane fires and the one of dodecane in the case of dodecane fires. The LFL of the mixture will vary since it decreases with temperature (Burgess and Wheeler, 1911): it will vary between 2.2 and 3 % for heptane and between 1.5 and 1.9 % for dodecane.

The auto-ignition temperature (AIT) is difficult to determine because it is sensitive to experimental conditions and is controlled by reactions of complex kinetics. The AIT is influenced by the nature

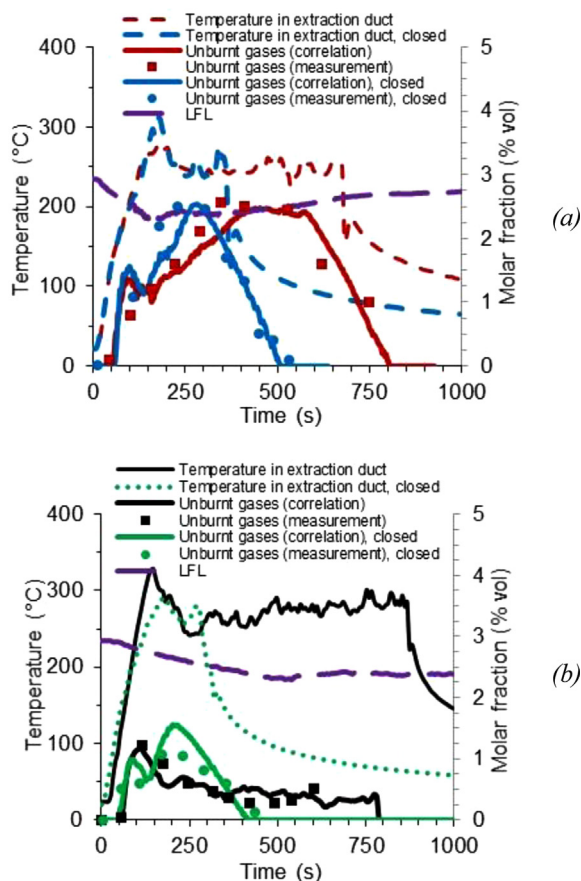


Fig. 13. Risk assessment of unburnt gas ignition at the entrance of the extraction duct. Heptane fires, pan diameter of 0.3 m, opened and closed inlet vent, (a) 3 ACPH and (b) 5 ACPH.

of the fuel. Whatever family of hydrocarbons is considered, the AIT decreases with the length of the carbon chain and becomes almost constant for long chains (Babrauskas, 2003).

Values of AIT for the fuel species considered here are 588 °C, 520 °C, 223 °C and 204 °C for respectively CO, H₂, heptane and dodecane.

There is currently no law to determine the AIT of a mixture. The AIT of a mixture is therefore taken equal to the lowest AIT present in the mixture: the one of heptane for heptane fires and the one of dodecane for dodecane fires.

In this study, the environment is dynamic and heterogeneous. Sudden variations in temperature and composition of the fuel mixture can occur when the flow of combustible gases meets the flow of air from the dilution duct. Assessing the ignition risk therefore relies on several hypotheses.

Figs. 13 and 14 present temperature and species molar fraction as functions of time for respectively heptane and dodecane fires. Heptane fires with a pan diameter of 0.1 m (HRR between 4 and 5 kW) do not present a risk of ignition for all ventilation procedures. Maximum temperatures reached at the entrance of the extraction duct do not exceed 70 °C, lower than the AIT. Concentrations of carbon monoxide are less than 0.08 % and those of total hydrocarbons and hydrogen are not measurable, less than 10⁻³ %, which is too low to generate an ignition risk.

Similarly, fires made with a 0.15 m diameter pan (HRR between 10 and 18 kW) do not present a risk of ignition: temperatures are below 140 °C and the total quantity of combustible gases does not exceed 0.3 %, which is lower than the LFL. These fires are therefore sufficiently ventilated. The same conclusions can be drawn for fires

with a 0.23 m diameter pan (HRR between 28 and 50 kW). Unburnt gases concentrations do not exceed 0.7 %. Closing the intake duct results in lower temperatures: 170 °C in the extraction duct against 200 °C.

On the contrary, for heptane fires with a 0.3 m diameter pan (HRR between 90 and 150 kW), temperatures at the entrance of the extraction duct are between 275 and 330 °C, high enough to lead to auto-ignition of long carbon chain hydrocarbons. The cumulative concentrations of unburnt species generated are between 1 % (5 ACPH) and 2.5 % (3 ACPH). A potential risk was therefore present for heptane fires in a 0.3 m pan diameter but not observed experimentally.

When it comes to dodecane, no risk of ignition in the extraction network was present for 0.23 and 0.3 m pan diameter fires. For the fires with pan diameter of 0.4 m (Fig. 13, HRR between 90 and 130 kW), temperatures were above 300 °C (i.e. above AIT), and concentrations above LFL. Auto-ignition in the extraction duct was observed experimentally for two conditions: 3 ACPH with closed intake duct and 5 ACPH with opened intake duct. At 3 ACPH and closed intake duct, it occurred at about 2020s (extinction at 1930s). At 5 ACPH and opened intake duct, it occurred at about 1370s (extinction at 1330s) and 1600s (extinction at 1500s).

It should be noted that such auto-ignitions, determined experimentally by visual identification of fire, is a random phenomenon varying for each fire test with a probability of 50 %. The empirical correlation is qualitatively promising for the risk assessment of unburnt gases ignition, but identification of the ignition time delay and location is within 15–30 % error.

4. Discussions

The experimental device is a model of a 100 m³ installation. From the scaling laws, a calculation of equivalent HRR can be performed. HRR is scaled by the preservation of the term $\frac{\dot{Q}^2}{L^5}$, where L is the characteristic length equal to the cubic root of the enclosure volume. Fire regimes can be obtained knowing the value of this term. Table 1 presents HRR obtained for different compartments (and therefore for different scales) for the three combustion regimes: sufficiently ventilated, underventilated and very underventilated.

A temperature criterion to prevent the risk of auto-ignition in the extraction ducts could be considered. The literature review showed that self-ignition was only possible with fuels with long carbon chains from 200 °C. Therefore, a minimum temperature of 200 °C was used to estimate the risk.

In order to validate results obtained in the reduced scale room, scaling effect is studied by comparing species concentrations and maximum temperatures measured in the reduced-scale enclosure and in the full-scale enclosure (Rowekamp et al., 2008) for heptane and dodecane fires.

At full scale, fires below 250 kW ($\frac{\dot{Q}^2}{L^5} \leq 29.1$), produce almost no unburnt gases. Fire tests performed in (Rowekamp et al., 2008) have shown that heptane fires generate almost no carbon monoxide (<10⁻² %) for 1 MW fires ($\frac{\dot{Q}^2}{L^5} = 24.5$). This is in agreement with the present results and shows that these tests were sufficiently ventilated in these conditions. A comparative study of the species generated by heptane fires with equivalent HRR between full and reduced scale is presented in Table 3.

Temperatures in the exhaust duct, maximum carbon dioxide and minimum oxygen concentrations are in good agreement for these two scales, despite the fact that thermal radiation from the walls is not considered in this comparison. This shows that for a given HRR, there is no scale factor for the concentrations of the species.

The difference between CO concentrations obtained during the reduced-scale experiments and experiments performed in

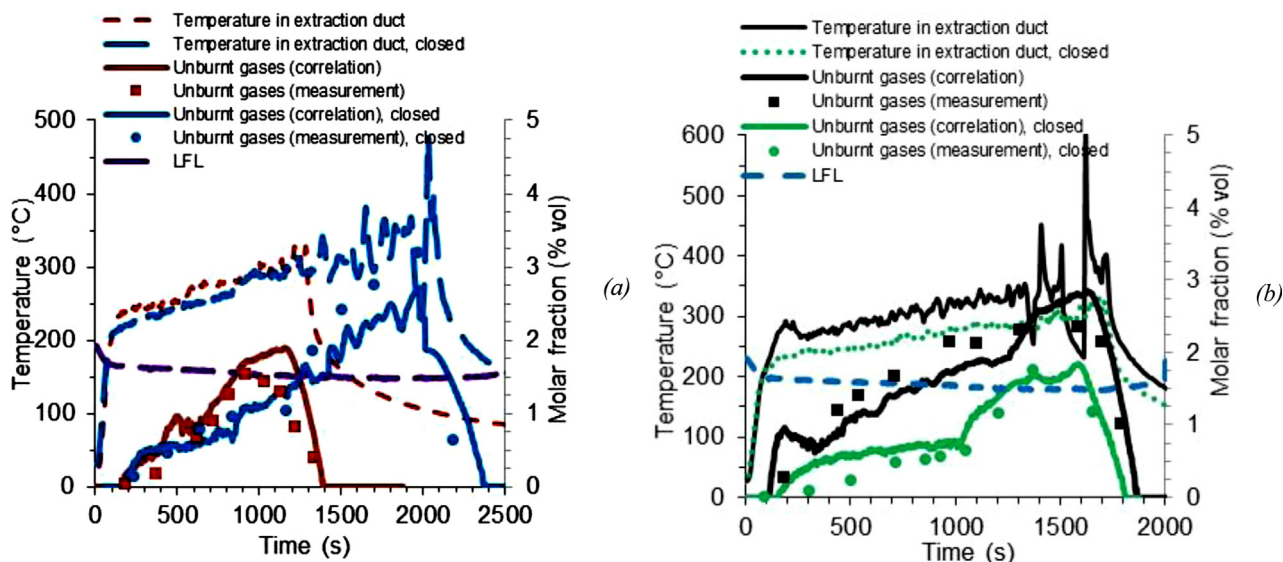


Fig. 14. Risk assessment of unburnt gas ignition at the entrance of the extraction duct. Dodecane fires, pan diameter of 0.4 m, opened and closed intake duct, (a) 3 ACPH and (b) 5 ACPH.

Table 3

Comparison between species concentrations and maximum temperature for heptane fires at full and reduced scales, equivalent HRR of $\frac{\dot{Q}}{V} = 24.5$, sufficiently ventilated fires.

Parameters	Full scale (Rowekamp et al., 2008)	Reduced scale compartment (present study)
\dot{Q}	1 MW	28 kW
[O ₂] (% vol.)	12	12.7
[CO ₂] (% vol.)	6.5	6.1
[CO] (% vol.)	0.01	0.07
T _{max} (°C)	255	235

Table 4

Comparison between oxygen concentrations and maximum temperature during full and reduced scale heptane fires of equivalent HRR of $\frac{\dot{Q}}{V} = 12.5$, sufficiently ventilated fires.

Parameters	Reduced scale compartment (present study)	Compartment of 120 m ³ (Melis and Audouin, 2009)	Compartment of 400 m ³ (Melis and Audouin, 2009)
\dot{Q} (kW)	20	190	520
[O ₂] (% vol.)	16	14.9	16.6
T _{max} (°C)	130	162	126

(Rowekamp et al., 2008) can be due to the differences in the sampling places in the extraction duct.

Results obtained for dodecane fire tests performed in the present study with HRR equivalent to 20 kW are compared to fire tests performed at larger scale (Table 4). Indeed, (Melis and Audouin (2009)) performed fire tests in a compartment of 400 m³ with a fuel composed of 70 v/v % of Hydrogenated Tetra-Propylene (HTP) and 30 v/v % of Tri-Butyl-Phosphate (TBP). HTP fire tests were also performed in a compartment of 120 m³. Note that HTP has a similar chemical formula as dodecane.

The same order of magnitude is obtained for the oxygen concentrations at the three scales. For the 120 m³ room test, the difference can come from the fact that the intake duct is located in the upper part of this room. This can also explain the difference for the temperature. Good agreement is obtained between the reduced-scale compartment and the 400 m³ compartment.

5. Conclusion

The behavior of pool fires using ventilation procedures (intake duct closed or opened) was experimentally studied. Closing the intake duct reduced heptane fires durations and extended dodecane fires durations. Intake duct closure had a non-significant effect on heat release rate, pressure, gases temperature and oxygen concentration in the extraction duct. Same conclusions were drawn regarding species concentrations (carbon dioxide, carbon monoxide, hydrogen and total hydrocarbons). It was also shown that for a fire established during a sufficiently long time (more than 20 min in the present study), there is significant risk of unburnt gases auto-ignition inside the extraction duct. Such auto-ignitions were observed for dodecane fires.

In the industrial environments, one of the ways to stop fires consists in cutting the ventilation after the beginning of the fire. Such procedures can therefore lead to another risk of auto-ignition of unburnt species in the extraction system. An easy and practical criterion to estimate this risk was proposed.

In future work, the auto-ignition phenomena are to be explained by studying flame propagations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the AREVA Company for its involvement in the project.

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