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ABSTRACT

The objective of this work is to study the effects of air intake position on the burning behaviour of liquid pool inside a mechanically ventilated compartment formed with air and combustion products gases. Measurements of heat fluxes, fuel mass loss rate, oxygen concentration and temperature are performed for heptane fires with different pans diameter in a reduced scale enclosure with a length/height and width of 2 m at different Air Change Per Hour (ACPH). It is shown that when the air is admitted into the upper part, poor air circulation in the room is observed and the oxygen level in the vicinity of the fireplace is insufficient. This results in extinction of the fire due to lack of oxygen. On the other hand, when the air is admitted into the lower part, the fire is extinguished for lack of fuel and the fire has a sufficiently long steady state. The phenomenon of attenuation of the radiation of the flame by the smoke in the room was studied. With high air-inlet position, the heat flux from walls seems to be blocked by the smoke in the compartment, whereas with air intake in low position, the pool fire is subject to radiation from compartment surfaces together with heat fluxes from hot gases. This paper discusses a key issue relevant to the vaporization process at the fuel surface which is the effect of external heat feedback on the burning rate. Results indicated that this external flux, which is the sum of radiant heat fluxes from hot gases and compartment surfaces, can have a high contribution to the radiation transmitted to the pyrolysing surface depending on fuel parameters and on the characteristic length scale of the enclosure. Results show that the MLR is always greater when the air is admitted into the lower part of the room, regardless of the oxygen concentration around the flame. Influence of air intake position on MLR is attributed to the heat feedback into the liquid fuel and availability of sufficient oxygen for combustion to take place. Lowering the inlet duct enhances mixing in the compartment and disturbs the smoke layer structure, facilitating air supply towards the burning liquid pool. It results in an increase of MLR with a rise of ACPH. It is also showed that the contribution of the external heat feedback from smoke and compartment surfaces is not so small and cannot be neglected even if oxygen concentration decreases and reaches a low value.

Keywords: Enclosure fire, liquid fuel, air intake position, radiant heat flux.

NOMENCLATURE

Symbols

D Pan diameter [m]

$F_{\text{i-j}}$ View factor [-]

L Characteristic length of enclosure [m]

$\dot{m}''$ Surface mass loss rate [kg.m^{-2}.s^{-1}]

O_2 Oxygen concentration [%]

$\dot{q}''_{\text{e,r}}$ External heat flux [kW.m^{-2}]

$\dot{q}''_{\text{f,r}}$ Radiant heat flux of the flame [kW.m^{-2}]

$\dot{q}''_{\text{in}}$ Radiant heat flux measured inside the pan [kW.m^{-2}]

$\dot{q}''_{\text{s,r}}$ Total radiant heat flux to fuel surface [kW.m^{-2}]

$\dot{q}''_{\text{up}}$ External heat flux measured under the pool [kW.m^{-2}]

$\dot{Q}$ Heat Rate Release (HRR) [W]

T Temperature [K]

T Time [s]

z_h Depth of the heptane layer in the pan [m]

z_{wa} Depth of the water layer above the radiometer positioned in the pan [m]

Greek letters

α Key factor

μ Absorption coefficient [m^{-1}]

ε Emissivity [-]

Subscripts

f Flame

F Fuel

g Gas

h Heptane

l Lower layer

s Pool surface

u Upper layer

up Under pool

w Walls of the compartment

wa Water

I. INTRODUCTION

Over the past few years, fire safety is considered as first-priority and increasing the level of understanding of the behaviour of a compartment fire is nowadays the most important task for fire engineers and researchers. Fires taking place in a confined environment generally quickly become controlled by ventilation. Fires in enclosures equipped with forced (or mechanical) interconnecting ventilation remain one of the key issues for fire safety assessment [1, 2] as well as in the nuclear industry [3, 4]. Fire safety in nuclear installation is a concern that should be dealt with carefully as reviewed [3]. An accidental liquid fire would produce a non-negligible quantity of unburnt fuel because of inadequate air intake to sustain combustion [5-7]. Many fire scenarios especially in nuclear facilities, involve fires in confined spaces and generally in under-ventilated conditions [3, 4, 8].

The fire growth rates in confined spaces, possibly coupled with mechanical ventilation can be significantly different from the ones measured in open atmosphere [9]. These differences are caused by e.g. air vitiation and heat radiation from hot walls and the hot gas layer. Although there has been extensive studies on burning rate measurements for various liquid fuel pools [10, 11, 12, 13], effects of a change of air intake position from low to high in enclosure on fire dynamics are lacking. When air inlet is in low position in close proximity to fire source, they interact and ultimately behave like a fire under windy conditions. The presence of crossflow results in higher mass loss rates compared to cases with no windy [14]. This is attributed to the fact that in presence of a crossflow, the flame is deflected from the vertical, leading to an enhancement of heat feedback as a result of reduction in flame standoff distance. It is found that the fire growth rate remains moderate with high air inlet as a result of a restriction in air entrainment [11]. These analysis [11, 14] showed the presence of two competing fire interaction mechanisms : heat feedback enhancement and air entrainment restriction.

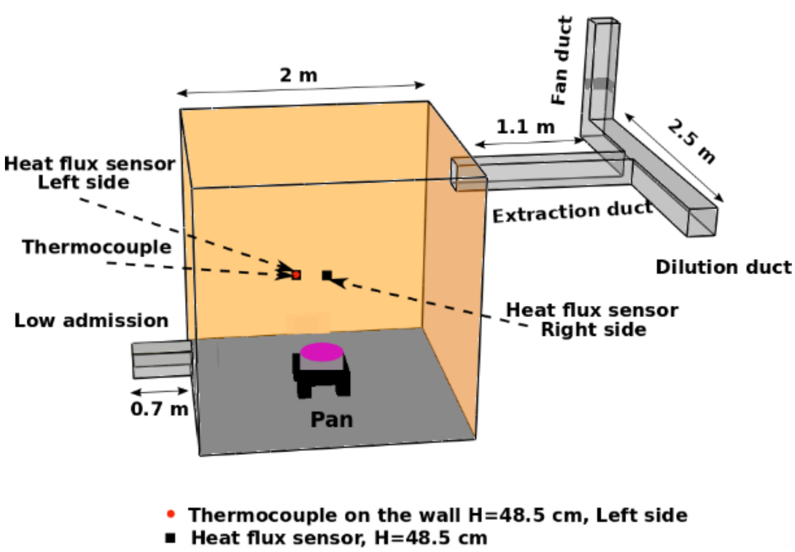
The effect of the radiative heat flux resulting from the hot gases and from the walls of the premises has been recognized as an important factor, leading to an additional heat flux contributing to the degradation of the fuel into pyrolysis gases [15]. The heat is therefore more maintained in the envelope favoring the release of pyrolysis gas [16]. Although the radiative flux of the flame constitutes the predominant heat transfer on a large scale, the work of Tewarson et al. [17] has shown that it can also be important on a small scale by varying the oxygen concentration at the focal point. The radiative flux of the flame increases with the oxygen concentration with the exception of certain fuels which have low production of soot. On the other hand, experimental tests have been carried out for different oxygen concentrations [18]. The results showed that varying the oxygen level at the local level modified certain properties such as the emissivity and the radiation of the flame. The direct change was a net change in the mass flow of fuel.

Concerning the behaviour of gases in the fire compartment, it is well known that the air-inlet position, located either in the upper or lower part of the room, influences the stratification of product gases concentrations and temperature [19-22]. In terms of oxygen concentration distribution, Peatross and Beyler [19] have shown that forced ventilation results in a well-mixed compartment regardless of the ventilation rate. Melis and Audouin [20] have studied the effect of air inlet position on the stratification of gases in the compartment. A set of a full scale compartment mechanically-ventilated pool fire experiments has been used as the basis of their study. The authors have shown that the compartment behaves as a well-stirred reactor when the ventilation inlet is in high position, whereas the oxygen concentrations in the compartment tend to be stratified when the inlet position is low. In this case, the well-stirred reactor approach breaks down. Therefore, the effect of the ventilation on the burning process enhancement is important and the understanding of the phenomenon is crucial because the modelling choices necessarily depend on the scenario studied.

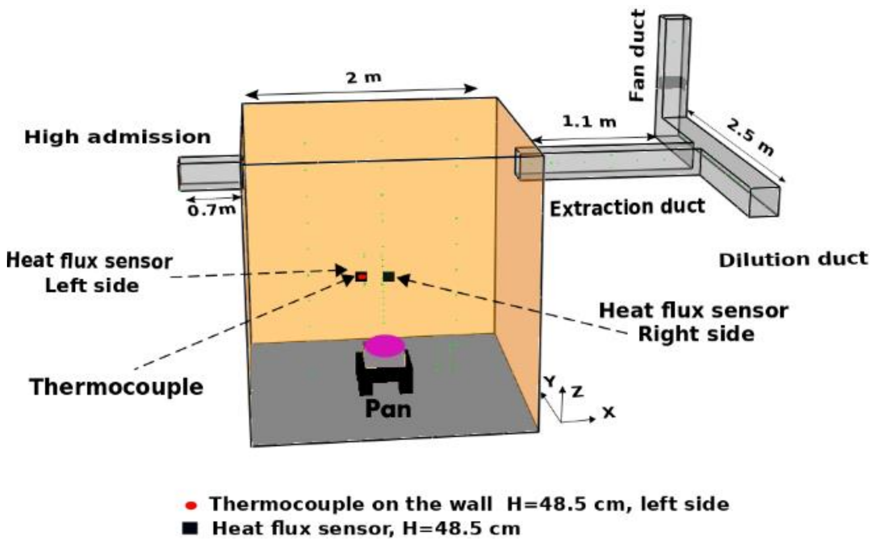
This study aims to understand the effects of air inlet position in enclosure to perform safe and successful prescribed confined fire. The low and high air intake positions with various global equivalence ratio are considered. Heat flux transmitted to the burning surface has not yet been measured taking into account heat transfer enhancement due to hot gases and compartment surfaces in function of the air-inlet position, located either in the upper or lower part of the room. Based on these observations, the present study focuses on the determination of the radiant heat flux components at the fuel surface for under-ventilated fires in a confined environment. Indeed, this work described measurement methods used to obtain the radiant heat flux from the flame as well as the external heat flux from hot gases and hot walls. The effect of ventilation or oxygen concentration in the local on the rate of vaporization of the fuel is discussed. The influence of the external heat feedback and the fuel surface on the development of the fire is also shown. As the heat flow is proportional to the mass flow of fuel, it is essential to understand the influence of ventilation on the phenomenon of loss of fuel mass. The effect of ventilation on the balance of heat transfers between the fuel surface is discussed in this paper.

II. EXPERIMENTAL SET-UP

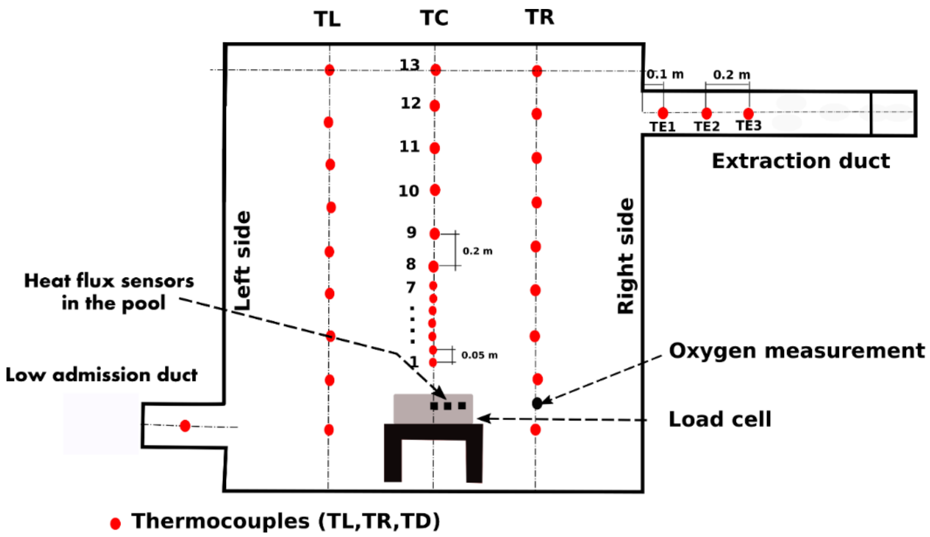
Fire experiments are often performed at reduced scale, for cost reason, to allow a sufficient number of tests. This is the case in the present study, where experiments are performed in the PERICLES fire platform of the PPRIME Institute (France), in a cubic 8 m^3 room test. This room is scaled from a 100 m^3 compartment.
In order to obtain a good similitude between various scale compartments, scaling relations are obtained maintaining the Froude number constant [23]. The reduced scale experimental device with a volume of 8 m^3 corresponds to a full scale 100 m^3 compartment with a HRR below 1 MW by preserving the ratio, $\dot{Q}^2/L^5$.
Fig.1 illustrates the experiment with the inlet branch in low or high position. The enclosure is 2 m in length/height and width. An external ventilation system consists of two intake ducts and an extraction duct. The ducts have a square section of 0.2x0.2 m^2. The extraction duct has a length of 1.1 m, and the dilution duct has a length of 2.5 m. The burnt gases can be directed into the extraction duct. The air intake was placed either in low position at a height of 0.3 m or in high position at a height of 1.7 m. The exhaust was placed always in the high position at a height of 1.7 m. In the case of a low air-inlet position, ventilation flow increases, a blowing out effect appears and flames are sloping all the more because ventilation flow is important ([10]). In order to avoid the sloping of the flame when air is admitted into the lower part of the room, a metal plate, which acts as an obstacle, has been positioned in front of the intake duct.



a) 3D view with air intake in low position



b) 3D view with air intake in high position



c) side (x, z) view for the measurement locations with low or high inlet position

Figure 1. Mechanically ventilated enclosure fire connected to an extraction duct

Walls of the enclosure are made of 20-cm-thick cellular concrete with a thermal conductivity of λ =1 W/m/K, a density of ρ =400 kg/m^3, and a specific heat of C_p=0.88 kJ/kg/K.
A mechanical extraction is carried out by using System-Air Euro S7440. This is a centrifugal fan with single-phase variable speed to select the desired airflow rate. As shown in Fig.1, the fan is placed at the outlet of a duct orthogonal to the dilution duct at a height of 2.6 m. The Air Change Per Hour (ACPH) of the enclosure is with a range from 1 to 4, corresponding to a volume flow rate of 24 and 40 m^3/h, respectively.
The liquid fuel pan with a pyrolysis area varying from 26 to 30 cm in diameter was placed in the middle of the enclosure, slightly elevated at a height of 0.3 m. The fuel mass was continuously monitored using a load cell, installed under the pan. The performed measurements include temperature and chemical species concentrations of gases sampled inside the enclosure. A good repeatability was obtained with a difference below 2% regarding the mass loss rate during fire tests. As shown in Fig.1, the gas temperature was analyzed from different vertical

profiles inside the enclosure. As shown in Fig.1, the temperature measurements in the compartment were performed with chromel-alumel thermocouples (type K) of a 0.5 mm wire with three arrays. The first array was positioned in the center of the compartment, the second and third array were located 0.45 m from the left and right walls, respectively.
For the tests, the liquid fuel was completed with 10 cm-height of water in the pool, and the depth of fuel added was 10 cm-height. Experiments were performed with heptane (floating on water) pool fires in a moderate scale. It was chosen because it has the advantage of a fixed boiling point (98°C) below that of water. As a consequence, it does not experience boil over, avoiding any serious splashing effect of water droplets striking the surface, which may disturb the measurements. Water is placed under the fuel to avoid heating effects. Without this heat sink due to this underlying water, it would result in a gradual heating of the tank which would cause the mass boiling of the heptane remaining at the end of the fire, thus accelerating its degradation and leading to an MLR (Mass Loss Rate) peak at the end of the fire.
Based on previous works [15], radiant heat flux at the fuel-water interface was measured by means of a water-cooled Gardon-gauge-type radiometer MEDTHERM with a range 20 kW/m^2, for different radial positions (0, 1/3 and 2/3 of the radius of the pool). This radiometers is equipped with a water cooled system and with a calcium fluoride window (to ignore the conductive and convective components). Water was added in the bottom of the pool to protect the radiometer. It should be noted that the measurement of the radiant heat flux in the pool can not be conducted for fuels with high boiling temperature since any protection of the gauges using water is not possible (boilover phenomena). The location of the radiometers was performed with a location accuracy of +/- 0.25 mm. To decouple the measurement of the flame and external heat feedback to the fuel surface, another radiometer was positioned under the pool and headed towards the behind wall so that the external radiation was only captured. The radiant heat flux to compartment surfaces was also measured at two heights (0.485 and 0.73 m from the ground) on the behind wall where two radiometers (their characteristics are cited above) were positioned at each height, located 0.075 m from the central axis of the wall (on the side of extraction (right) and on the side of admission (left)). The measured values would be the radiant heat flux of the flame and the external heat feedback from smoke and compartment surfaces. All of the experimental results obtained revealed good reproducibility of the MLR and the temperature of the gases in the room.

III. RESULTS AND DISCUSSION

This section presents the experimental results obtained using a heptane pan 30 cm in diameter, with an different ACPH varying between 1 and 4. For the heptane pan 26 cm in diameter, only the tests carried out 1 and 4 ACPH are presented in this section.

III.1 Effects on oxygen concentration on fire parameters

Results to the evolution of MLR (Mass Loss Rate) and measured oxygen concentration at proximity to fire source (cf. Fig.1) are presented in Figs.2 and 3 for cases where the air inlet is in low position or in high position for the heptane pan diameter of 30 and 26 cm at various ACPH. MLR in Figs. 2 and 3 present the three phases of fire development: a phase which corresponds to the ignition and growth of the fire, a phase where the fire is fully developed and a phase of decay of the fire. The results clearly show a sharp decrease in fuel mass loss rate (MLR) (see figs. 2 and 3) as the oxygen concentration measured near the pool, at the flame base, is decreased. It is well known [24] that oxygen concentration above 15% corresponds to a well-ventilated, the range of oxygen concentration from 10% to 15% implies an underventilated fire and when oxygen concentration is below 10%, implying a very under-ventilated fire.

During the fire development period, MLR increases as the oxygen amount surrounding the flame base, initially present in the compartment and supplied by ventilation flow, decreases until to about 15% (cf. Figs.2, 3) regardless of air intake position. The availability of sufficient oxygen allows the pyrolysis gases to undergo gas-phase combustion rapidly, releasing a large amount of energy in the forme of radiation. The heat feedback from the gaseous flame thus increases the burning rate, characterized by a rapid rise of MLR up to reaching the maximum.

For the fuel pan of 30 cm (cf. Fig. 2), the MLR reaches only a peak value of 1.52 g.s^{-1} by placing air intake in high position while changing air intake position from high to low leads to a peak value of 2.43 g.s^{-1}.

We find the same situation with a 26 cm diameter pan (cf. Fig. 3), with a peak value of MLR respectively from 1.34 to 1.89 g.s^{-1} for the change of the air intake in the high position to a low position. With a lower value of oxygen concentration measured at the flame base, the tests performed with a 0.3-m diameter pan show higher values of MLR, as compared to those performed with a 0.26-m diameter pan. Hence, in the present case, the effect of increasing the pool size on fire parameters is more important than the influence of reducing the oxygen concentration near the pool. These observations are consistent with the experimental data of Blinov and Khudiakov 0 and confirm that the burning rate of pool fires increases with scale and is dominated, at the larger scales, by thermal radiation from the flames.

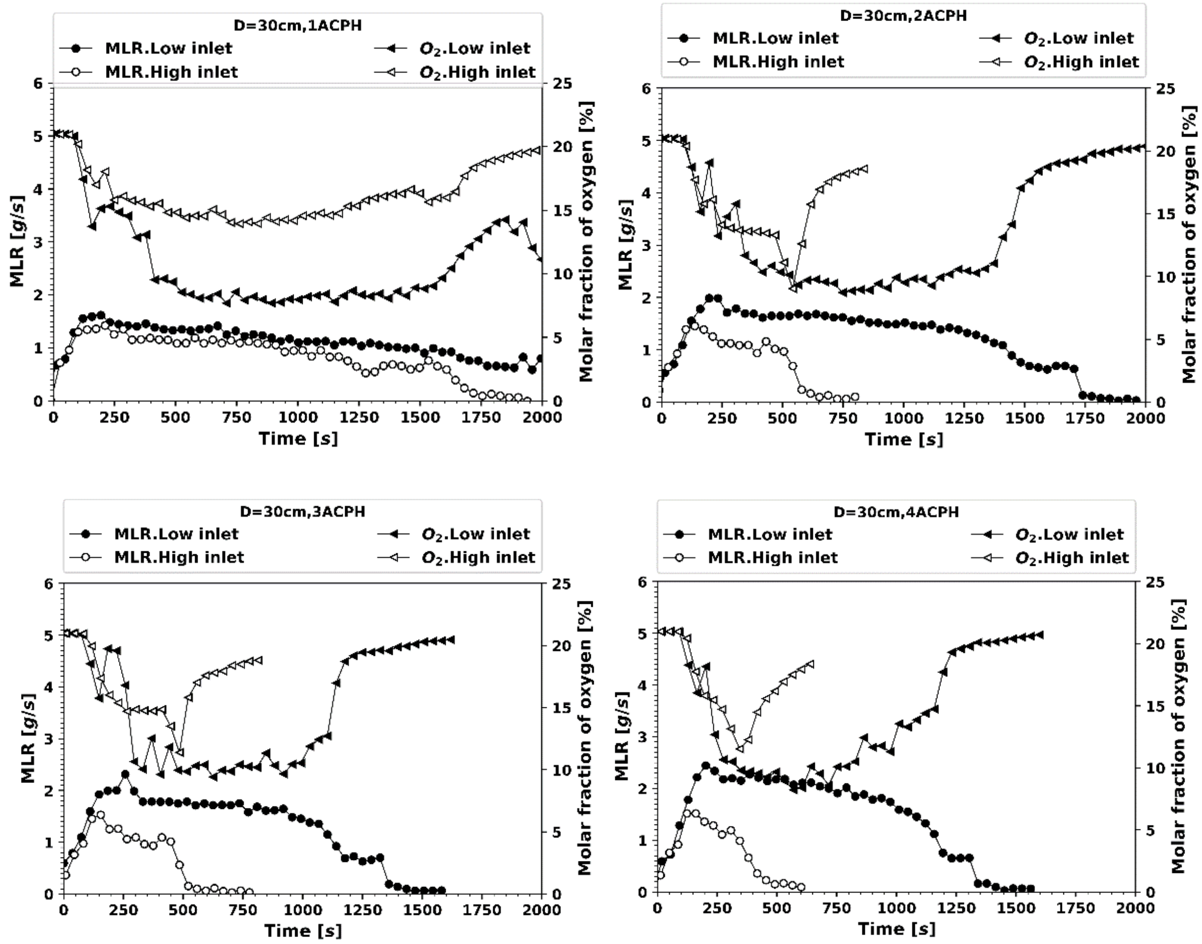


Figure 2. Impact of air intake position on evolution of Mass Loss Rate (MLR) and oxygen concentration at proximity to fire source with air admission in low and high position for pan diameter of 30 cm for different ACPH.

After the first period from about 150 s for a low inlet and 250 s for a high inlet, this is followed by a fully developed phase, in which fire in a very consistent manner becomes progressively oxygen limited. Particularly in under-ventilated conditions, changing air intake position from low to high change significantly the fire dynamics. For fuel pan of 30 cm at 1 ACPH, the MLR curves show a decreasing trend from a peak value of about 1.56 $g.s^{-1}$ for a low inlet and of 1.34 $g.s^{-1}$ for a high inlet. With an increase of ACPH from 1 to 4, the amount of oxygen supplied from a low inlet contributes to a rise of the MLR peak from 1.56 $g.s^{-1}$ to 2.43 $g.s^{-1}$ with an achievement of a quasi steady state period. However, a rise of ACPH in high position helps to generate the cooling effects on the ceiling hot smoke layer, and the fire growth rate is controlled by how fast the pyrolysis rate of liquid fuel via heat feedback. Thus the maximum MLR for a high inlet is practically insensitive to an increase of ACPH from 1 to 4 with a value from 1.34 $g.s^{-1}$ to 1.52 $g.s^{-1}$.
With a 26 cm diameter pan, with an increase of ACPH from 1 to 4, it is noted that the MLR is always greater when the air is admitted into the lower part of the room, regardless of the oxygen concentration around the flame.
It is found that fire dynamics become less sensitive to air intake position for well-ventilated fires due to sufficient quantity of oxygen for intensive combustion.

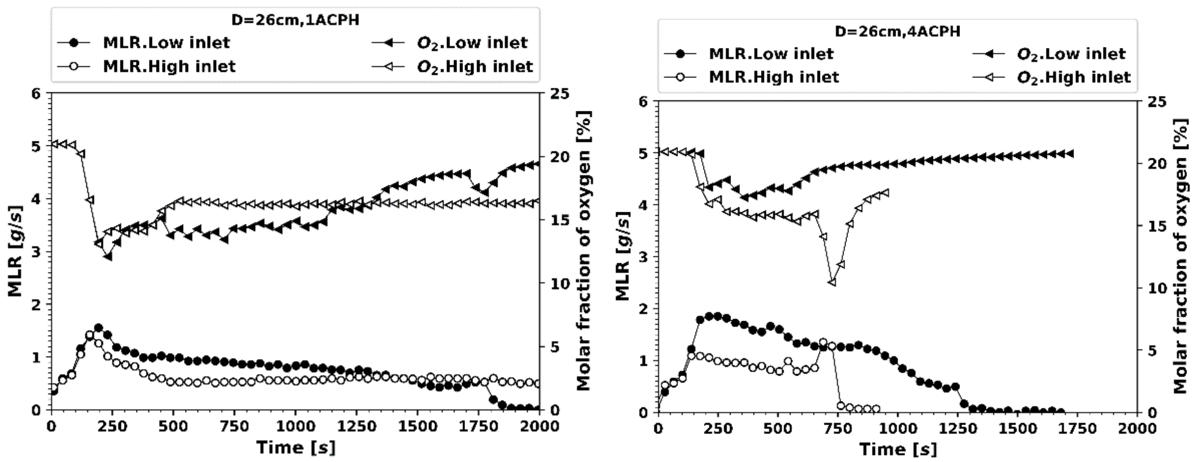


Figure 3. Impact of air intake position on evolution of Mass Loss Rate (MLR) and oxygen concentration at proximity to fire source with air admission in low and high position for pan diameter of 26 cm for 1 and 4 ACPH.

When air intake position is located in the lower part of the compartment, for the fuel pan of 30 cm in under-ventilation conditions, fire stops by lack of oxygen (cf. Fig.2). Note that, with these low oxygen concentrations (under-ventilation conditions), during the stationary phase of the fire), the flames were close to the extinction limit and significant fluctuations were observed. When the air admission is placed in high position (cf. Fig.2), fire exhaust occurs due to lack of fuel since oxygen concentration is above the Minimum Oxygen Concentration.
Occurrence of fire exhaust for the fuel pan below 26 cm is mainly due to burnout of the liquid fuel. Nevertheless, the fire exhaust happens earlier for high inlet position, resulting in a reduction in fire duration from 2000 to 750 s with an increase of ACPH from 1 to 4. This is

attributed to insufficient radiative heat feedback from flame and smoke to undergo thermal decomposition of the liquid fuel. Air intake position influences the balance of heat feedback to the liquid fuel and the oxygen available for efficient combustion, and as a result, the fire dynamics. In fact, these variations are governed by the rate of vaporization of fuel during the steady burning stage, which depends on the oxygen concentration measured near the pool.
By comparing these results, we note that the MLR is always greater when the air is admitted into the lower part of the room, regardless of the oxygen concentration around the flame. Indeed, the cold air admitted by the upper entrance descends by gravity, resulting in good homogeneity in the room so, the smoke fill almost the whole room and cover most of the flame. On the other hand, when the air is admitted through the lower entrance, a stratification is observed in the room and the smoke rises to fill the upper part. The presence of smoke around the flame leads to the absorption of part of the heat energy released by it, which lowers the MLR of fuel.

III.2 Effect of air-inlet position on gases stratification

Now, the experimental results present influence of air inlet position on the behaviour of gases in the compartment.

The temperature distributions, along the flame axis (TC), were measured with an arrays of 13 chromel-alumel thermocouples type K of 0.5 mm wire diameter. This array was located in the centre of the compartment and the first thermocouple was placed 0.55 m above the ground and the others were positioned at regular intervals of 0.05 and 0.2 m over the height of the compartment as shown in Figure 1.
For exemple, the fuel pan of 30 cm in diameter is selected for the analyse of influence of air intake position on thermal field along the flame axis (TC). A comparison of the axial temperature profiles obtained, in a vitiated environment (for 1 and 4 ACPH) at two instants of 250 and 500 s is shown. It appears that reducing the oxygen concentration from its normal value (i.e. 21 %) leads to decrease the temperature maximum along the flame axis from 910°C (flame temperature was measured by Richard et al. [26] in open atmosphere) to 750°C (Figure 4). The sharp decrease in flame temperature is mainly due to the decrease of oxygen concentration but also to an increase of heat capacity of the environment by the presence of hot combustion product gases.
Regardless of air intake position at 1 ACPH (cf. Fig.4), the temperature profiles at the two instants of 250 and 500 s are practically identical. This implies that a steady thermal stratification inside enclosure happens earlier starting from 250 s. A low or high inlet helps to maintain a hotter smoke layer near the ceiling with a temperature level of about 250°C as long as the air admission rate remains low at 1 ACPH. With the air inlet in low position, an increase of ACPH from 1 to 4 conducts to an increase of the smoke temperature near the ceiling from 250 to 350°C when the upper smoke layer is established at 500 s (cf. Fig.4). While as, for a high air intake at 4 ACPH, the compartment behaves as a well-stirred reactor at 500 s with a smoke temperature of about 50°C (cf. Fig. 4) due to fire exhaust (cf. Fig.2).
Note that accurate measurement of gas temperature above the flame base by using thermocouples is difficult by taking into account a multitude of potential errors, including thermal mass inertia, accumulation of soot particles, surface reactions and radiation. The uncertainty in the measurement of gas temperature by using thermocouples is estimated within 10%.

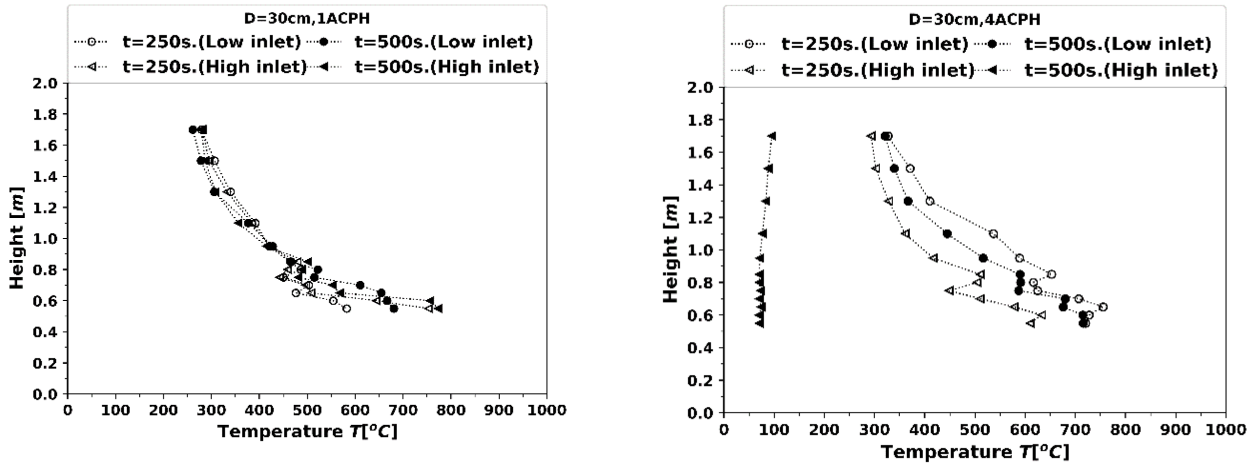


Figure 4. Influence of air intake position on the time history of gas-phase temperature in the centre of the compartment (TC) for pan diameter of 30 cm for 1 and 4 ACPH.

An another temperature distributions (TR) at two instants of 250 and 500 s for 1 and 4 ACPH for the fuel pan of 30 cm in diameter are shown in Figs.5. This array of 10 thermocouples was located at the right line and each thermocouple were located 0.45 m from the right walls; the first thermocouple was placed at a height of 0.1 m above the ground and the others were located at regular intervals of 0.2 m, as shown in Figure 1. We find a similar behavior that previously, a steady thermal stratification with a hotter smoke layer near the ceiling with a temperature level of about 250°C as long as the air admission rate remains low at 1 ACPH.

Indeed, with a low air intake, these profiles are indicative a cold and a hot layer near the flame base and ceiling respectively, consisting of the fresh air and exhaust hot gases. The gas in the compartment tends to be stratified and the fresh air fills the lower part when the air inlet position is near the floor. In fact, the cold air entering at the high inlet moves down by gravity, and hot buoyant combustion gases rise, causing better mixing and less stratification compared to low air inlet case. Indeed, with a low air intake, these profiles are indicative a cold and a hot layer near the flame base and ceiling respectively, consisting of the fresh air and exhaust hot gases. On the other hand, experiments with high air-inlet position only show a quasi-constant temperature gradient with respect to compartment height (Fig. 4). With a low inlet, the smoke temperatures about 250°C are high enough to enhance heat feedback for the thermal degradation of liquid fuel.

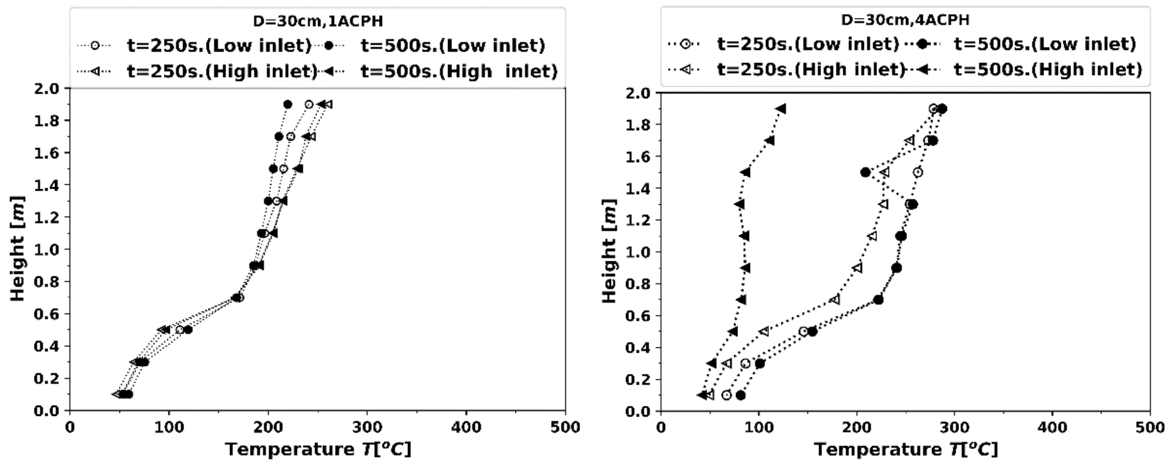


Figure 5 Influence of air intake position on the time history of gas-phase temperature in the centre of the compartment (TC) for pan diameter of 30 cm for 1 and 4 ACPH.

In a fire, the presence of smoke in the room causes the radiation transmitted by the flame to the environment to be attenuated. In order to correctly understand each fire test conducted in the small compartment, four heat flux gauges were placed at a wall surface at two different heights (0.485 or 0.73 m) with a separation distance of 15 cm in relation to the central axis of the behind wall (cf. Fig.1a, b).

An exemple of measurements of the radiant heat flux transmitted to the compartment surfaces at the left and right sides to a height of 0.485 m for pan diameters of 30 cm and 26 cm at various ACPH are presented in Fig. 6 and 7. The measured value is none other than the sum of the radiation fluxes from the flame and the hot gases in the room. The results in Figs. 6 and 7 illustrate that the radiative heat flux received by the walls decreases considerably after 150 s for a low inlet and 100 s for a high inlet, the time during which the smokes fill the room. For fuel pan of 30 cm at 1 ACPH, the wall heat flux level on the side of extraction (right) and on the side of admission (left) is independent of the air inlet position. On the side of extraction (right), with an increase of ACPH from 1 to 4, with the increasing of the the HRR (MLR) supplied from a low inlet, contributes to a rise of the wall heat flux level with an achievement of a quasi steady state period. However, a rise of ACPH in high position helps to generate the cooling effects on the ceiling hot smoke layer, and the fire growth rate is controlled by how fast the pyrolysis rate of liquid fuel via heat feedback. Thus it is found that the wall heat flux level on the side of admission (left) and on the side of extraction (right), is practically insensitive to an increase of ACPH from 1 to 4.

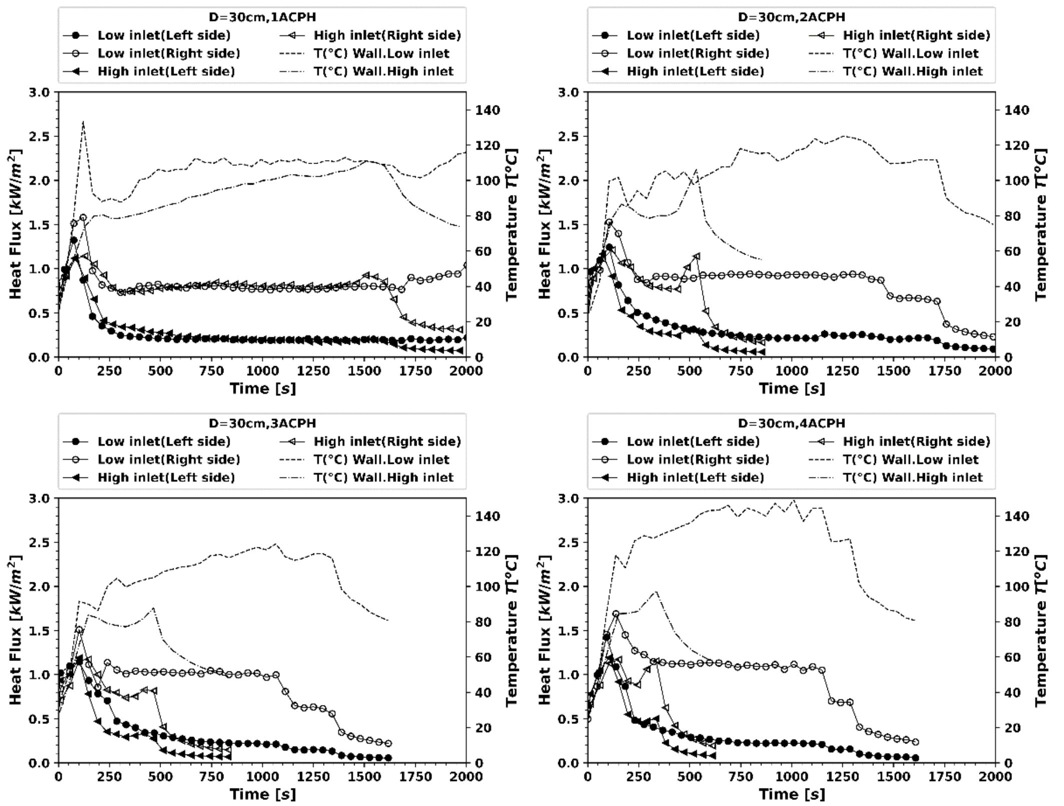


Figure 6. Radiant heat flux transmitted to compartment surfaces and surface temperature on the behind wall of the enclosure, measured at the left and right sides for pan diameter of 30 cm with air admission in low and high position.

With a 26 cm pan diameter, for an admission in the lower part, we find the same situation except for the left side which increases like the right side with an increase of ACPH from 1 to 4, (the HRR increases (MLR)).

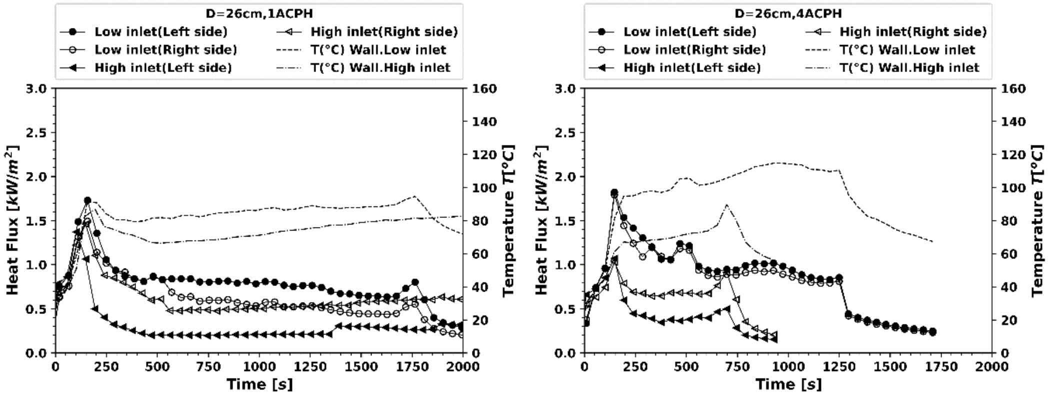


Figure 7. Radiant heat flux transmitted to compartment surfaces and surface temperature on the behind wall of the enclosure, measured at the left and right sides for pan diameter of 30 cm with air admission in low and high position.

With an increase of ACPH from 1 to 4, it is noted that the the wall heat flux level is always greater when the air is admitted into the lower part of the room, regardless of on the side of extraction (right) or on the side of admission (left).

Results to the evolution of radiant heat flux transmitted to the compartment surfaces at different height for which the radiometers are positioned on the wall (0.485 or 0.73 m) are presented in Figs.8 and 9 for cases where the air inlet is in low position or in high position for the heptane pan diameters of 30 and 26 cm at various ACPH. The results show that when the air-inlet position is high, radiation from flame is attenuated by the sootier gas mixture within the compartment regardless of the height at which the radiometer is positioned on the wall (0.485 or 0.73 m). When the air-inlet position is low, Figs. 8 and 9 suggest two different behaviours: the radiant heat flux measured at a height of 0.73 m decreases after 150 s as radiation from the flame is blocked by the smoke. For measurement located at a height of 0.485 m, a smaller effect is found of the smoke on flame radiation. These observations confirm that when the air is supplied in the upper part, the smoke would fill the entire compartment and radiation from the flame is absorbed. It is also found that the attenuation of the radiation of the flame by the smoke is more important than the radiative contribution of the smoke themselves.

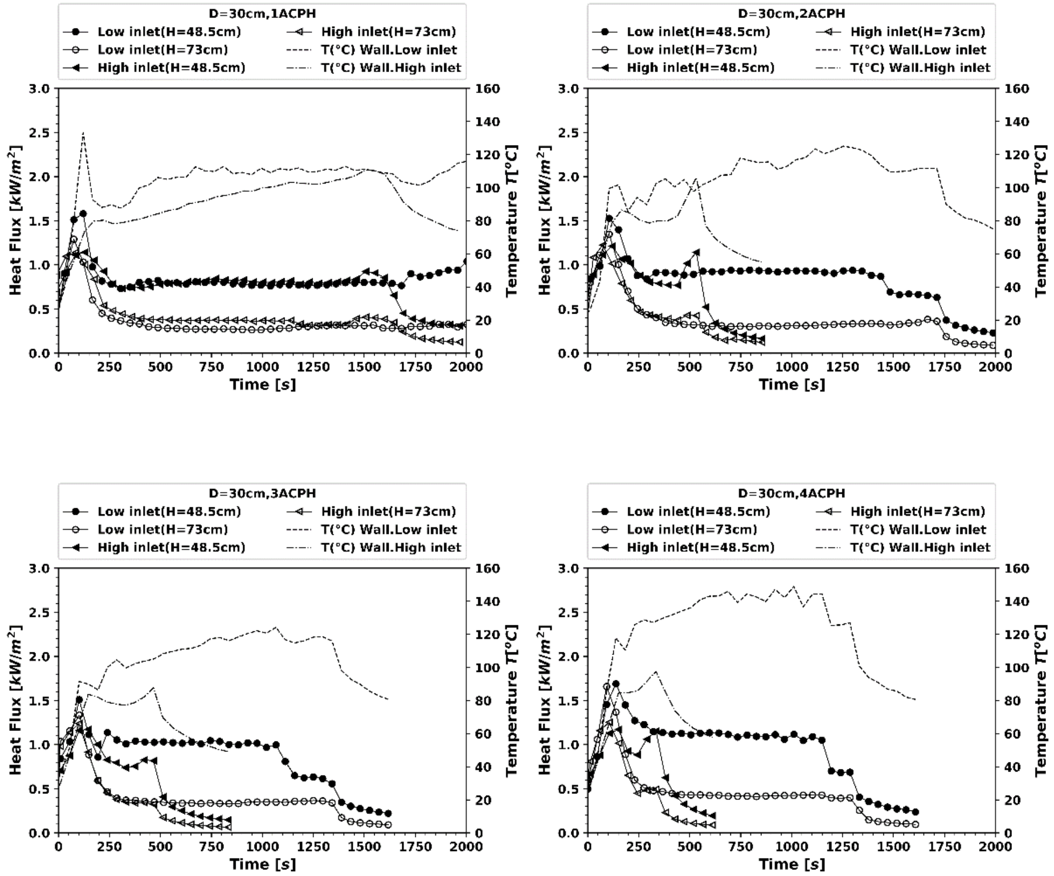


Figure 8. Radiant heat flux transmitted to compartment surfaces and surface temperature on the behind wall of the enclosure, measured at the left and right sides for pan diameter of 30 cm with air admission in low and high position.

The surface temperature on the behind wall of the enclosure was also measured using a K thermocouple located at 0.075 m from the central axis of the wall at a height of 0.48 m is shown in Figs. 8 and 9. Levels of heat flux allows to maintain a wall temperature of about 100-150 °C and 80-100°C respectively for the air inlet in low position and in high position for the heptane pan diameter of 30 cm and a wall temperature of about 80-110 °C and 70-80°C respectively for the air inlet in low position and in high position for the heptane pan diameters of 26 cm with a long time delay, except for high inlet position with an increase of ACPH from 1 to 4 due to rapid fire exhaust. Such wall temperature level seems not high enough for emitting a strong radiation heat flux over the liquid surface.

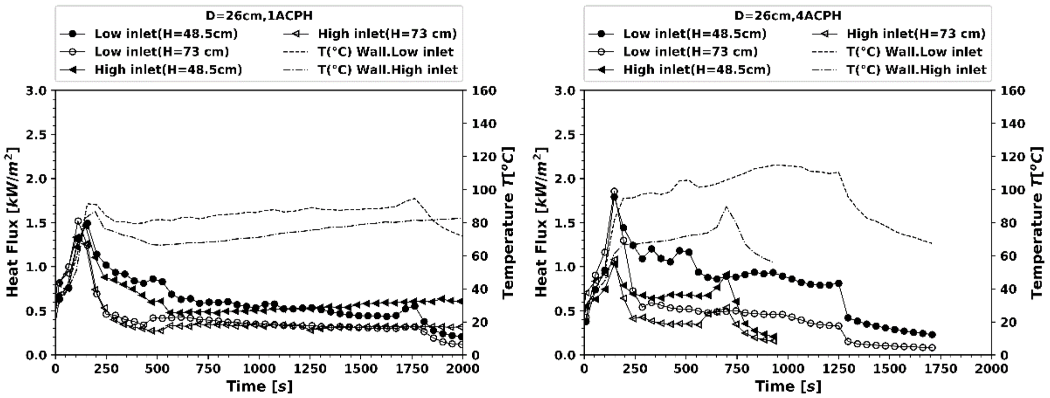


Figure 9. Radiant heat flux transmitted to compartment surfaces and surface temperature on the behind wall of the enclosure, measured at the left and right sides for pan diameter of 30 cm with air admission in low and high position.

III.3 Heat fluxes at the fuel surfaces

In the heptane pool fire, heat flux gauges are positioned in three radial positions under the water-fuel interface, thus making it possible to measure the net radiative flux received on the surface of the heptane. The mean radiant heat flux to the fuel surface is calculated by integrating radiation heat flux, $\dot{q}''_{\mathrm{s,r}}$ along the pan radius, as follows :

$$\dot{q}''_{\mathrm{s,r}} = \frac{8}{D^2} \int_0^{D/2} \dot{q}''_{\mathrm{s,r}}(r)\, r\, \mathrm{d}r \tag{1}$$

It is worth noting that a direct measurement of radiant heat flux over the heptane pool surface cannot be performed due to its regression. Knowing the accurate initial fuel level position, the location of the radiometer and the instantaneous burning rate, it is possible to deduce the evolution of the radiant heat flux in depth as a function of the distance from the sensitive surface of the radiometer. As a result, in the experiment, the radiant heat flux measured inside the liquid pan $\dot{q}''_{in}(r)$ as a function of time is divided by an attenuation coefficient C, varying with time, as follows :

$$\dot{q}''_{s,r}(r) = \dot{q}''_{in}(r)/C \quad \text{with} \quad C = (e^{-\mu_f z_f} . e^{-\mu_w z_w}) \tag{2}$$

where μ represents the absorption coefficient, and z_f the layer depth of liquid. The subscript f and w denote, respectively, fuel as heptane and water. z_f the layer depth of fuel is determined with time ($Z_f = Z_{f,0} - \frac{\dot{m}''t}{\rho_f}$).This treatment allows to take into account the radiation loss by absorption inside the pan through water and fuel (heptane) layers above the radiometers. The radiant heat flux at the surface was obtained by extrapolating the measured heat flux evolution from across the fuel (cf. Eq.2).

The radiant heat flux at the fuel surface $\dot{q}''_{\mathrm{s,r}}$ is equal to the sum of radiant flux of the flame $\dot{q}''_{\mathrm{f,r}}$ and the external heat flux $\dot{q}''_{\mathrm{e,r}}$.

$$\dot{q}''_{\mathrm{s,r}} = \dot{q}''_{\mathrm{f,r}} + \dot{q}''_{\mathrm{e,r}} \tag{3}$$

In the case of a confined environment, the knowledge of all radiation components at the pool surface requires the measurement of the radiant heat flux of the flame and the external radiation. In the present work, based on the work of [15], a method which considers external radiation under the pool is presented. So as not to take into account radiation contribution from the flame, a radiometer has been used, located under the pool and was positioned in such a way that its angle of view does not cover the flame area. However, this measurement cannot be directly related to the external radiation received at the fuel surface because the radiometer positioned under the pool provides only the measurement of a proportion of all that radiation from the hot gases and compartment surfaces.

In fact, the measured radiant heat flux takes into account a view factor ($F_{\text{i-j}}$) as well as it depends on the height of the interface separating the two layers in the compartment, a layer which contains hot combustion products and soot and one next to the floor which contains fresh air. In other words, such radiometer cannot be helpful in determining the external feedback at the fuel surface unless the effects of orientation are considered. Therefore, the following study provides a valid approximation for a steady-state analysis, which allows the determination of the radiation components at the fuel surface regardless of the view factor ($F_{\text{i-j}}$) or the smoke layer interface height in the compartment.

The external heat flux $\dot{q}''_{\text{e,r}}$ received at the fuel surface is specific to enclosure fires and takes into account the radiative flux coming from the hot gas layer and from the hot walls. It can be written as equal to the sum of radiant flux of those transmitted by the hot gases $\dot{q}''_{\text{g}}$ and the radiant heat flux from the compartment surfaces into two components: $\dot{q}''_{\text{w,u}}$ and $\dot{q}''_{\text{w,l}}$, which denote the radiant heat fluxes transmitted by the compartment surfaces in the upper and lower layer respectively:

$$\dot{q}''_{\text{e,r}} = \dot{q}''_{\text{g}} + \dot{q}''_{\text{w,u}} + \dot{q}''_{\text{w,l}} \tag{4}$$

As seen previously, such wall temperature level seems not high enough for emitting a strong radiation heat flux over the liquid surface. On the other hand, due to the high opacity of the gases caused by an important soot production inside the compartment (the smoke emissivity ε_{g} is significant), the radiant heat flux $\dot{q}''_{\text{w,u}}$ and $\dot{q}''_{\text{w,l}}$ can be neglected. The external heat flux $\dot{q}''_{\text{e,r}}$ and total radiant heat flux at the fuel surface $\dot{q}''_{\text{s,r}}$ received at the fuel surface are then defined as:

$$\dot{q}''_{\text{e,r}} \approx \dot{q}''_{\text{g}}.$$

With $\dot{q}''_{\text{g}} = \sigma \varepsilon_{\text{g}} (1 - \varepsilon_{\text{f}}) F_{in-g} T_g^4$ (5)

The external heat flux $\dot{q}''_{\text{e,r}}$ and total radiant heat flux at the fuel surface $\dot{q}''_{\text{s,r}}$ received at the fuel surface are then defined as:

$$\dot{q}''_{\text{s,r}} = \dot{q}''_{\text{f,r}} + \dot{q}''_{\text{e,r}} \approx \dot{q}''_{\text{f,r}} + \dot{q}''_{\text{g}}. \tag{6}$$

In the same way, the measured radiant heat flux under the pool $\dot{q}''_{\text{up}}$ can be expressed as follows:

$$\dot{q}''_{\mathrm{up}} = \dot{q}''_{\mathrm{g}} + \dot{q}''_{\mathrm{w,u}} + \dot{q}''_{\mathrm{w,l}} \approx \dot{q}''_{\mathrm{g}}. \tag{7}$$

With

$$\dot{q}''_{\mathrm{g}} = \sigma \varepsilon_{\mathrm{g}} F_{up-g} T_g^4 \tag{8}$$

Indeed, radiometers positioned in the bottom of the pan indicates at the flame extinction ($\varepsilon_{\mathrm{f}} = 0$) a radiant heat flux which corresponds to the external heat feedback from hot gases and compartment surfaces. A key factor determined at fire extinction and corresponding to the ratio of the radiation measurement at the fuel surface by the radiation measurement under the pool could be defined as follow:

$$\alpha = \left.\frac{\dot{q}''_{\mathrm{s,r}}}{\dot{q}''_{\mathrm{up}}}\right|_{\mathrm{ext}} = \left.\frac{\dot{q}''_{\mathrm{e,r}}}{\dot{q}''_{\mathrm{up}}}\right|_{\mathrm{ext}} = \left.\frac{\sigma \varepsilon_{\mathrm{g}} F_{in-g} T_g^4}{\sigma \varepsilon_{\mathrm{g}} F_{up-g} T_g^4}\right|_{\mathrm{ext}} = \left.\frac{F_{in-g}}{F_{up-g}}\right|_{\mathrm{ext}} \tag{9}$$

For a steady-state analysis, the smoke layer interface height in the compartment is believed to be constant until the flame extinction; thereby the ratio F_{1n-g} / F_{up-g} is also constant.

The approximation, considering that this factor remains constant during all the fire duration, allows to define the external heat flux $\dot{q}''_{\mathrm{e,r}}$:

$$\frac{\dot{q}''_{\mathrm{e,r}}}{\dot{q}''_{\mathrm{up}}} = \frac{\sigma \varepsilon_{\mathrm{g}} (1-\varepsilon_{\mathrm{f}}) F_{1-g} T_g^4}{\sigma \varepsilon_{\mathrm{g}} F_{2-g} T_g^4} = (1-\varepsilon_{\mathrm{f}}) \frac{F_{1-g}}{F_{2-g}} = (1-\varepsilon_{\mathrm{f}}).\alpha \tag{10}$$

$$\dot{q}''_{\mathrm{e,r}} = (1-\varepsilon_f)\, \alpha\, \dot{q}''_{\mathrm{up}} \tag{11}$$

The flame emissivity in Eq. (11) is fixed to its values in open atmosphere of 0.25 and 0.28 (with 0.26 and 0.3-m diameter pans respectively), calculated using Babrauskas's formulation **Erreur ! Source du renvoi introuvable.**. Fig.10 and 11 show the time histories of the radiant heat flux to the fuel surface and the external heat flux for low and high inlet positions for the fuel pan size from 30 to 26 cm for different ACPH. During the initial phase, the measured exaggerated spikes of the radiant heat flux to the fuel surface may be attributed to the uncertainty in the estimation of the values of radiant heat fluxes supplied by the flame. As explained above, the surface heat flux is obtained by extrapolation of the radiative heat fluxes measured at different depths in the liquid, and it is difficult to assess accurately its value (accuracy not better than 10%). We must be well aware that the deduced radiant heat fluxes at the fuel surface were only a rough approximation with an uncertainty up to 20% associated with the measured layer depth, Z_f.

The measurements of the the external heat flux can be considered after steady-state burning had been established (depending on pan size and ACPH) the same way as MLR. On the other hand, due to the high opacity of the gases caused by an important soot production inside the compartment, the radiant heat flux to the fuel surface decreases considerably the time during which the smokes fill the room (see figs 8-9). When combustion environment is steady-state, the heat feedback from the flame, smoke and wall to the liquid surface tends to provide a constant radiant heat flux and the contribution of the external heat flux increases substantially (eqs. 3-11). Placing the air admission in high position contributes to a sharply decreasing trend of radiant heat flux from about due to onset of fire exhaust.

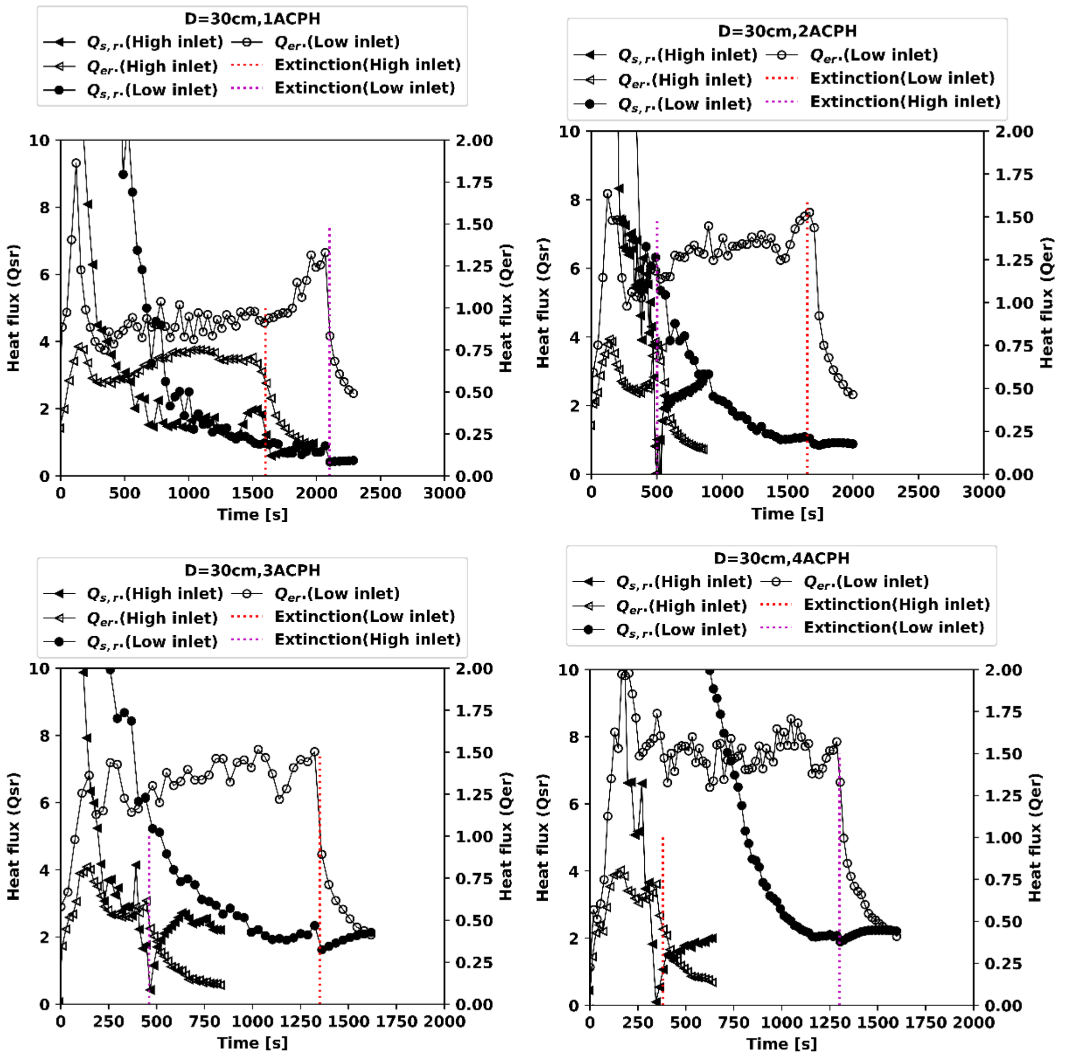


Figure 10. Influence of air intake position on heat flux over surface of the liquid fuel and the external radiant heat flux for pan diameter of 30 cm.

For fuel pan of 30 cm with a low inlet, an increase of ACPH from 1 to 4 with a hight MLR (HRR) contributes to a rise of the radiant heat flux to the fuel surface and the external heat flux, even when the under-ventilated condition takes place. As seen prevously, a rise of ACPH in high position helps to generate the cooling effects on the ceiling hot smoke layer, and the fire growth rate is controlled by how fast the pyrolysis rate of liquid fuel via heat feedback. Thus the radiant heat flux to the fuel surface and the external heat flux for a high inlet are practically insensitive to an increase of ACPH from 1 to 4. At 1 ACPH, whether the radiant heat flux on the surface of the fuel or the external heat flux, the gaits are comparable, for a low or a high inlet position.

As illustrated in Fig.11 for the pan diameter of 26 cm, a similar trend for the radiant heat flux to the fuel surface and the external heat flux is found, following its fire dynamics trend.

The comparison of the results leads to the conclusion that the ventilation of the room has an eff et on the behavior of hot gases and therefore on the external radiation received at the fuel surface. The external radiant heat flux is proportional to the temperature of gas in the local which depends on HRR of fire (MLR). Consequently, the external heat flux tends to vary substantially when oxygen concentration near the pool is varied. The effect of the under ventilation on the combustion parameters, including the MLR and the radiant heat flux received at the surface, means that the decrease in the oxygen concentration in the vicinity of the hearth leads to a decrease in the radiant heat flux from the flame and from external radiation. In fact, in the case of a low air-inlet position, the pool fire is subject to radiation from compartment surfaces together with heat fluxes from hot gases whereas in the second case, with high air-inlet position, the heat flux from walls seems to be blocked by the smoke in the compartment. Which means that the value of the external flux with a low air-inlet position is greater than the value obtained when the air-inlet has a high position.

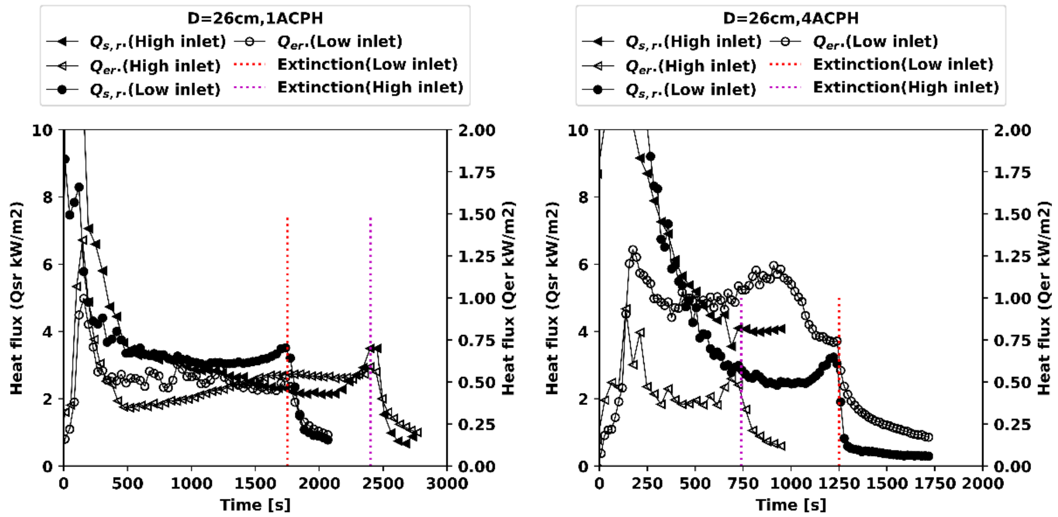


Figure 11. Influence of air intake position on heat flux over surface of the liquid fuel and the external radiant heat flux for pan diameter of 26 cm at different ACPH.

Indeed, some previous works have studied the influence of the position of the air intake on the behavior of gases in the room [19, 20, 22] and have shown that when air is admitted in the lower part from the room, a vertical stratification of oxygen is observed in the room, exhibiting two so-called upper and lower zones. The hearth is thus subjected to radiation from hot gases but also to radiation reflected by the walls. However, it was shown that the oxygen distribution in the room was relatively constant when the air was admitted in the upper part [19] thus, the height of the interface between the two zones in the room is not high from where the radiant flux reflected by the walls is absorbed by the smoke. It should also be highlighted that the external heat feedback from smoke and compartment surfaces cannot be neglected against the radiant heat transfer from the flame and the radiant heat flux to the fuel surface even if oxygen concentration decreases and reaches a low value.

IV. CONCLUSIONS

Experimental results obtained with fires for heptane pan diameters of 30 and 26 cm are studied with the air intake was placed in low or high position inside the compartment, providing a various Air Change Per Hour (ACPH) in a range from 1 to 4. It is shown that when the air is admitted into the upper part, poor air circulation in the compartment is observed and the oxygen level in the vicinity of the fireplace is insufficient. This results in extinction of the fire due to lack of oxygen. On the other hand, when the air is admitted into the lower part, the fire is extinguished for lack of fuel and the fire has a sufficiently long steady state. By comparing these results, we note that the MLR (ie. HRR) is always greater when the air is admitted into the lower part of the room, regardless of the oxygen concentration around the flame.

This is attributed to insufficient radiative heat feedback from flame and smoke to undergo thermal decomposition of the liquid fuel, with high air-inlet position. Air intake position influences the balance of heat feedback to the liquid fuel and the oxygen available for efficient combustion, and as a result, the fire dynamics. In fact, these variations are governed by the rate of vaporization of fuel during the steady burning stage, which depends on the oxygen concentration measured near the pool. In fact, the cold air entering at the high inlet moves down by gravity, and hot buoyant combustion gases rise, causing better mixing and less stratification compared to low air inlet case. The presence of smoke around the flame leads to the absorption of part of the heat energy released by it, which lowers the MLR of fuel. On the other hand, when the air is admitted through the lower entrance, a stratification is observed in the room and the smoke rises to fill the upper part.

In case where the air is admitted into the lower part of the compartment, the pool fire is subject to radiation from compartment surfaces together with heat fluxes from hot gases whereas in the second case, with high air-inlet position, the heat flux from walls seems to be blocked by the smoke in the compartment. In addition, the phenomenon of attenuation of the radiation of the flame by the smoke in the compartment was studied. This phenomenon depends on the configuration adopted for the ventilation of the room: when the air is admitted in the lower part, the attenuation of the radiation of the flame is observed only in the upper area of the room while the results show that when the air-inlet position is high, radiation from flame is attenuated by the sootier gas mixture within the compartment. It is also found that the attenuation of the radiation of the flame by the smoke is more important than the radiative contribution of the smoke themselves. It should also be highlighted that the external heat feedback from smoke and compartment surfaces cannot be neglected against the radiant heat transfer from the flame and the radiant heat flux to the fuel surface even if oxygen concentration decreases and reaches a low value.

The configuration adopted for ventilation in the room can also have an influence on the distribution of gaseous products and on the phenomenon of attenuation of the flame radiation. The work is continuing with this objectif to study this influence.

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