EXPERIMENTAL STUDY ON PYROLYSIS OF A HEPTANE POOL FIRE IN A REDUCED-SCALE COMPARTMENT

A. Nasr[*], S. Suard[*], H. El-Rabii[**], L. Gay[***] and J. P. Garo[*]
ayoub.nasr@irsn.fr
*Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
BP3, 13115 Saint Paul-Lez-Durance Cedex – France
**Institut Pprime, UPR 3346 du CNRS, ENSMA
1 rue Clément Ader, 86961 Futuroscope, Poitiers, France
***Electricité de France (EDF R&D),
6 Quai Wattier BP 49, 78401 Chatou Cedex, France

Abstract
Among all the experimental works performed earlier for the purpose of determining the energy balance at the pool fire surface in compartments, no study has been reported yet dealing with the measurement of total heat flux received by the fuel surface taking into account heat transfer enhancement due to hot gases and compartment surfaces. This paper presents experimental results of the burning behaviour of a heptane pool fire in a reduced scale compartment equipped with a mechanical ventilation network. The objective of this work is to study heat flux of the flame at the heptane surface in a vitiated environment formed with air and combustion products gases. Measurements of heat fluxes, fuel mass loss rate, oxygen concentration and temperature are performed for a 0.3 m diameter pool fire for different ventilation flows rate. An original method to separate effects of the radiant heat flux of the flame and of the external heat feedback to the fuel surface is developed by the way of using an additional heat flux measurement located under the pool fire. The results show that the fuel mass loss rate, flame temperature and heat fluxes to the fuel surface decrease as the oxygen concentration measured near the fuel decreases by varying the air refresh rate of the compartment. The flame radiation fraction shows similar behaviour whereas the convection fraction of the total heat flux received by the fuel increases when oxygen concentration decreases. It is also shown that the contribution of the radiant heat flux of the flame is not so small and cannot be neglected against the convective heat flux and external heat feedback from smoke and compartment surfaces even if oxygen concentration decreases and reaches a low value. Based on these experimental findings, it is discussed that any analytical approach conducted to predict the fuel mass loss rate in a similar confined compartment should consider variations of the total flame heat flux, including convective and radiant component, against oxygen concentration.

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 a key task for fire engineers and researchers. The heat release rate and fire duration are presumably the most important parameters in fire safety studies and it is now proven that the confinement of a compartment, like in nuclear industry for example, can have a major impact on these sensible parameters. This significant and complex research area has been investigated at IRSN (Institut de Radioprotection et de Sûreté Nucléaire) in order to provide sufficient data on the burning process in a confined and mechanically ventilated compartment. Thus, large-scale fire experiments, called PRISME-Source, involving a Hydrogenated Tetra-Propylene (TPH) pool fire were performed by the IRSN Fire Test Laboratory, in the DIVA facility [2, 3]. The effect of the pool surface area (0.2 and 0.4 m^2), the air change rate of the compartment and the position of the inlet opening on the fire duration and fuel mass loss rate were investigated. The main result of this experimental program has highlighted the influence of limited ventilation and oxygen depletion on the burning rate. Based on these experimental data, a theoretical study [4] using a well-stirred reactor approach, have compared with good agreements the measured fuel mass loss rate with the linear correlation of Peatross and Beyler [1].

A large-scale fire test of a simulated nuclear power plant cable room was also conducted by Hamins [5] to gain confidence in the accuracy of each of the component measurements that are considered in an energy balance. The experiment and the boundary conditions were fully defined and characterized for subsequent comparison with models. In addition, several experimental studies, which have considered small-scale apparatus and pool diameter around 0.2 or 0.4 m with liquid or solid combustibles were performed and concluded that the fire growth process is primarily due to environmental conditions such as oxygen concentration near the pool or external heat feedback from smoke or compartment surfaces to the fuel [6, 7, 8, 9, 10, 11, 12]. An experimental study, carried out by Utiskul et al. [10, 11], allowed to validate a theoretical work describing fuel mass loss rate based on the free burning and on the effect of oxygen depletion and external heat feedback. This theory assumes that the radiant flux of the flame can be neglected as the oxygen concentration decreases in the small enclosure and recovers the formulation given by [13] for the critical mass flux at extinction.

Among other works that have addressed the various phenomena related to pool fires, Weckman and Tieszen [14, 15] have studied both large and medium-scale pool fires to provide more insight into the complex physical phenomena which control development of the fire flow field. Their results have provided a comprehensive set of data useful in the assessment of the validation of numerical predictions of the pool fire flow field.

Some of the previous works have focused on the measurement of the fuel mass loss rate and flame radiation [8] or have determined convective and radiant heat fluxes by using a steady-state heat balance equation at the fuel surface with a radiation correction for the Spalding number [7]. The main conclusion concerns principally the decrease of flame radiation when oxygen concentration is decreased. Some observations about the convective flux have determined a slight increase when oxygen concentration decreases. More recently, an Advanced Flammability Measurements Apparatus was used to quantify the effect of enhanced ambient oxygen concentration to conduct fire experiments for three types of fuel [12]. The main objective of this work was to study the heat flux of the flame back to the fuel burning surface for 20.9 and 40 % ambient oxygen concentrations. It was inferred from measurements that the radiant and total components of the flame heat flux increase when enriching ambient oxygen concentration. The variation of the convective part against oxygen concentration seems to remain uncertain due to an important measurement uncertainty. Measurements of the surface radiant heat feedback were also performed during an experimental work published in [16, 17, 18], to study the effect of a water mist entering a flame in open atmosphere, regarding the energy balance at the fuel surface.

From this literature review, it appears that only few experimental works dealt with the study of fire growth process in enclosures, especially by the measurement of the heat feedback at the pool surface. 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. Based on these observations, the present study focuses on the determination of the total 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 convective and radiant heat flux from the flame as well as the external heat flux from hot gases and hot walls.

The outline of the paper is as follows. The experimental apparatus is described in the next section as well as the various measurements performed using specific gauges. The development of a new method for determining the components of the total heat flux received by the fuel surface is described. The section that follows presents results on heat flux distributions at the fuel surface for different oxygen concentrations.

Experimental apparatus

A serie of fire experiments was conducted in a reduced-scale compartment based on a single room of the DIVA facility (IRSN) [2, 3]. Scaling the model was achieved by considering scaling laws theory so that the reduced-scale tests were representative of those obtained for large scale. This methodology involves the use of dimensionless numbers such as Froude and Richardson numbers that must be conserved for each case with a Reynolds number not preserved but sufficiently large to make the flow turbulent. The length of the small compartment was scaled by 2/5 and scaling heat release rate imposes the preservation of the quantity $\dot{Q}^2/L^5$.

A. Test compartment and conditions

The pool burning tests were conducted in a reduced scale compartment (8 m^3) based on 120 m^3 compartment (PRISME room) as shown in Fig. 1. The compartment surfaces were built with non-combustible concrete of 200 mm thick and thermal conductivity (λ) of 0.12 $W.m^{-1}.K^{-1}$, offering great resistance to heat transfer via natural insulation. An insulating layer of 35 mm thick Promatect H with thermal conductivity of 0.175 $W.m^{-1}.K^{-1}$ was also fixed to the compartment surfaces. The ceiling was lined with 2 layers of 35 mm thick Promatect H. A glass window (0.16 m^2) with good thermal shock resistance and very low thermal expansion was installed on the behind wall to obtain a small gap allowing visualization of the fire growth using a video camera positioned outside the compartment. This reduced scale compartment was already used by Lassus [20, 21] to study the influence of ventilation on ignition risk in the extraction duct.

Experiments are performed with heptane (floating on water) pool fires of moderate scale. The fuel was burned in a circular stainless steel pan with diameter of 0.3 m and 0.1 m deep, located at the center of the compartment at a height of 0.38 m. Before each test, water was first added to protect the heat flux gauges positioned in the bottom of the pan followed by the fuel until it reached 1 mm below the pan lip. Pool combustion was initiated at ambient temperature using a propane gas burner.

Ventilation was supplied to the compartment in forced ventilation tests via a 0.2 m by 0.2 m air vent, in the lower part of the compartment at 0.3m high. Exhaust products exited the compartment through a similar vent located at the top of the compartment test at 1.7 high and extended to an exhaust fan. No supply fan was used during tests whereas air intake was achieved through the pressure difference in the compartment. The gas velocity in the small compartment was scaled by 2/3 and the number of Air Changes Per Hour [ACPH] was varied between 1 and 4. Each test was repeated three times.

B. Mass loss rate measurement

The fuel mass loss rate was determined by the rate of vaporized (or pyrolyzed) gas leaving the pool. A SCAIME load cell assembly positioned under the pan in the center of compartment was used to measure the fuel consumption as a function of time. The load cell has a response time of 60 ms, and the uncertainty of measurements is within 5%.

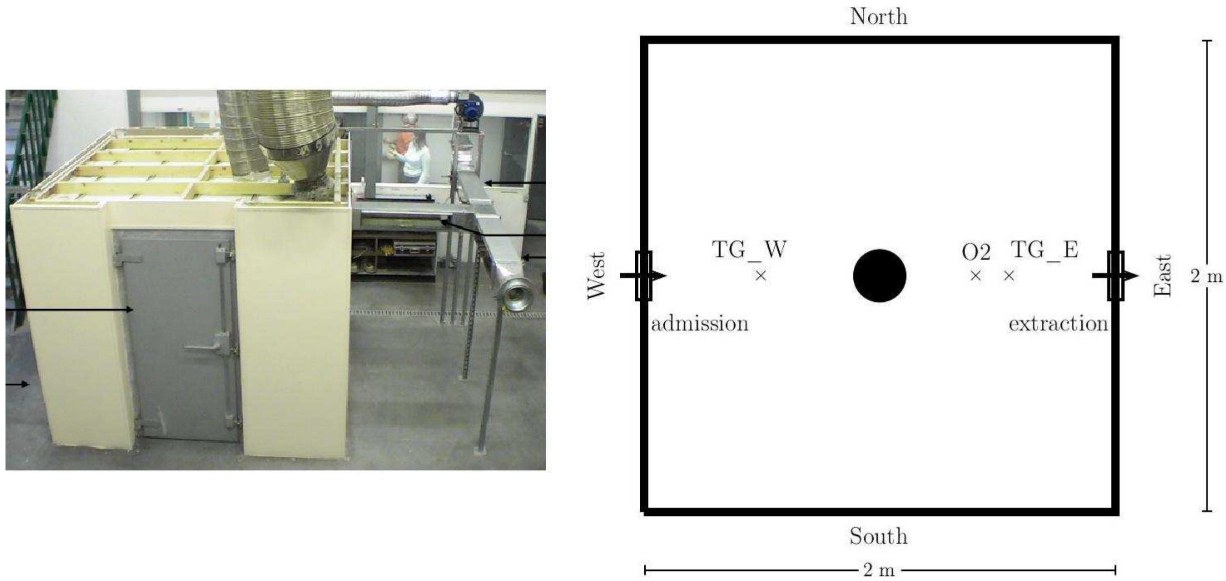

Figure 1. View of the reduced scale enclosure.

C. Gas temperature and concentration measurement

The temperature measurements in the compartment (see Fig. 2) were performed with three arrays of chromel-alumel thermocouples type K of 0.5 mm wire diameter that give values with an uncertainty of ±1.5°C. The first array of 13 thermocouples was located in the centre of the compartment. The first thermocouple was placed 0.55 m above the ground and the others were positioned at regular intervals of 0.05 m and 0.2 m over the height of the compartment as shown in Fig. 2. Fuel temperature was also measured using two K thermocouples placed 0.08 m and 0.07 m above the bottom of the pan respectively. The main purpose of this measurement was to estimate the time at which the fuel layer reaches its boiling point at a constant temperature rather than analysing the temperature history of the liquid phase. The second and the third array of 10 thermocouples on each were located 0.45 m from the left and right walls respectively; the first thermocouple was placed 0.1 m above the ground and the others were located 0.2 m apart from each other.

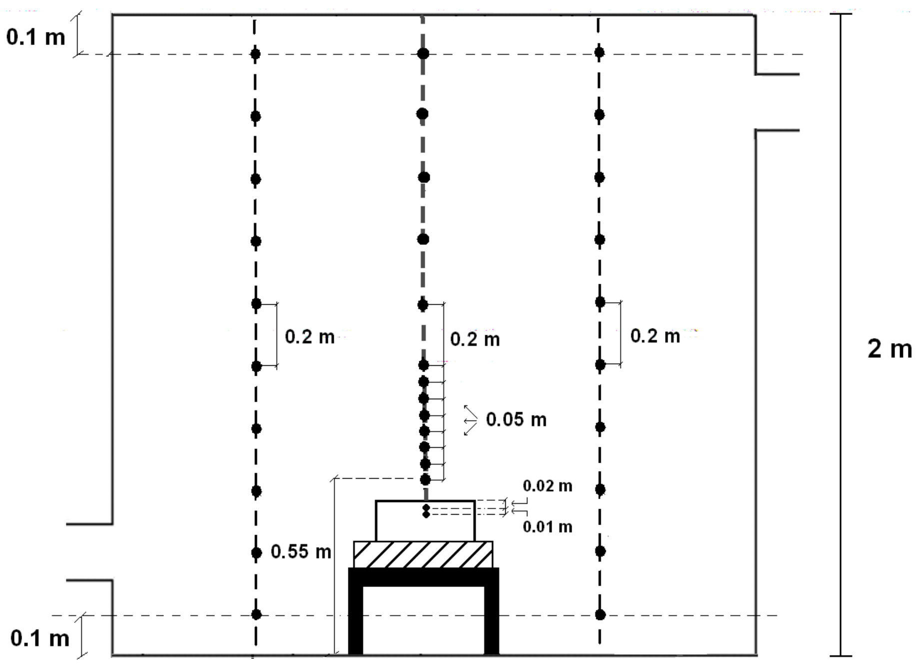

Figure 2. Schematic of the thermocouples position.

Molar concentrations of oxygen, carbon dioxide and carbon monoxide were measured near fuel. For this purpose, a sampling probe was fixed at 0.3 m from the pool edge at the level of the flame base and connected to a COSMA analyzer which controls the gas sampling.

D. Heat flux measurement

Based on the work of Richard [16, 18], radiant heat flux at the fuel surface was measured by means of three water-cooled Gardon-gauge-type radiometers MEDTHERM working in the range 0-2 $W.cm^{-2}$, for different radial positions (0, 1/3 and 2/3 of the radius of the pool). Each radiometer was water cooled and was equipped with a window to eliminate the conductive and convective components. The window used was in calcium fluoride, which offers a useful range of spectral transmittance between 0.3 μm and 11.5 μm (the spectral range from a luminous flame is between 0.5 μm and 5 μm). The field of view of these radiometers was 150 deg and the uncertainty in flux measurements was 3%. The radiometers were horizontally oriented and were submerged in water as shown in Fig. 3. In addition, the measured values were corrected to take into account the influence of the pan rim which partially masks the fields of view of the radiometers (method described in [16, 17, 18]). The flame convective heat flux was deduced using the energy balance equation at the pool fire surface:

$$\dot{q}''_{\mathrm{f,c}} = \dot{q}''_{\mathrm{total}} - \dot{q}''_{\mathrm{s,r}} \tag{1}$$

$$\dot{q}''_{\mathrm{total}} = \dot{m}''_F L_v + \sigma(T_s^4 - T_\infty^4)\,. \tag{2}$$

$\dot{q}''_{\mathrm{total}}$ is the total heat flux received by the heptane surface. $\dot{m}''_F$ represents the measurement of the fuel mass loss rate. $\sigma(T_s^4 - T_\infty^4)$ is the surface re-radiation heat loss. L_v is the heat of gasification of the fuel. $\dot{q}''_{\mathrm{s,r}}$ is the mean radiant heat flux determined by integration of the extrapolated radiant heat fluxes at the surface, along the pan radius:

$$\dot{q}''_{\mathrm{s,r}} = \frac{8}{D^2}\int_0^{D/2} \dot{q}''_{\mathrm{s,r}}(r)\, r\, \mathrm{d}r\,, \tag{3}$$

where $\dot{q}''_{\mathrm{s,r}}(r)$ is equal the radiant heat flux measured inside the pan $\dot{q}''_{\mathrm{in}}(r)$ multiplied by an attenuation coefficient C, which takes into account the radiation loss by absorption inside the pan through the water and the heptane layers above the radiometers. $C = e^{-\mu_{\mathrm{h}} \cdot z_{\mathrm{h}}} . e^{-\mu_{\mathrm{wa}} \cdot z_{\mathrm{wa}}}$, μ and z represent respectively the absorption coefficient and the depth for water (subscript wa) and heptane (subscript h) layers.

It is worth noting 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). To decouple the measurement of the flame and external heat feedback to the fuel surface, another radiometer MEDTHERM was positioned under the pool and headed towards the behind wall so that the external radiation was only captured (see Fig. 3).

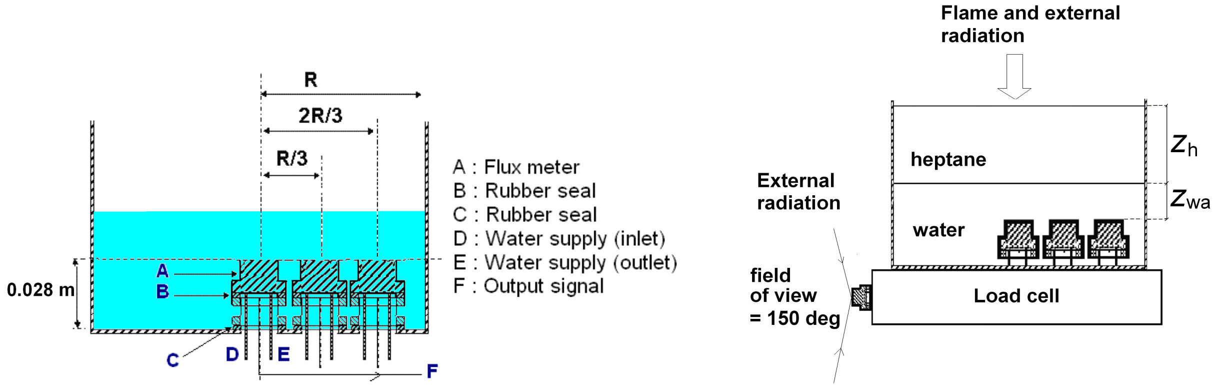

Figure 3. Schematic representation of the reduced-scale heptane pool fire.

E. A decoupling methodology for radiant heat fluxes at the fuel surface

This section deals with a new method investigating the radiant components of the heat transfer to the fuel surface in the case of a confined fire scenario. In an open-atmosphere system, Beaulieu and Dembsey [12] have used two methods to measure the radiant and convective components of the total heat flux to the fuel surface. The first was to use a heat flux gauge, placed at the sample surface, which measures the total and radiant heat fluxes from the flame where the convective component is the difference between them. The second method consisted of using a heat flux at the sample surface that indicates the total heat flux then this gauge is recessed 0.0064 m below the surface at the same location to obtain the radiant component. For free burning heptane pool fires, Richard and Garo [16, 17, 18] have measured the radiant heat flux of the flame to the fuel surface using the same measurement techniques described in the previous section. The radiant heat flux at the surface was obtained by extrapolating the measured heat flux evolution across the fuel.

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, an original method which considers external radiation under the pool is presented. Such measurement does not take into account radiation contribution from the flame because the radiometer located under the pool was positioned in such a way that its angle of view does not cover the flame area (Fig. 3). However, this measurement cannot be directly related to the external radiation received at the fuel surface because the radiometer positioned under the pool provides 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 hot smoky layer below the ceiling and one next to the floor which consists of cool uncontaminated air. Consistent with these observations, the radiometer located under the pool cannot be used in determining the external feedback at the fuel surface unless the effects of orientation are considered. The following method, described in detail in Appendix A, 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 $\dot{q}''_{\text{e, r}}$ and the radiant heat flux of the flame $\dot{q}''_{\text{f, r}}$ received at the fuel surface are then defined as:

$$\dot{q}''_{\text{e,r}} = (1-\varepsilon_f)\alpha\dot{q}''_{\text{un}} \tag{4}$$

$$\dot{q}''_{\mathrm{f,r}} = \dot{q}''_{\mathrm{s,r}} - \dot{q}''_{\mathrm{e,r}} \,, \tag{5}$$

where ε_f is the flame emissivity and α is a factor determined at fire extinction corresponding to the ratio of radiation measurements at the fuel surface and under the pool:

$$\alpha = \left.\frac{\dot{q}''_{\mathrm{s,r}}}{\dot{q}''_{\mathrm{un}}}\right|_{\mathrm{ext}} . \tag{6}$$

Results and discussion

F. Effects of oxygen concentration on fire parameters

The results in Figs. 4 to 6 clearly show a sharp decrease in fuel mass loss rate as the number of Air Changes Per Hour [ACPH] in the compartment is varied between 4 and 1. In each test, fire extinction is occurred due to lack of fuel since the oxygen concentration of the air surrounding the flame is always above the lower flammable limit. In addition, for a given amount of fuel, the fire duration varies between 24 min (ACPH=4) and 40 min (ACPH=1). This variation is governed by the rate of vaporization of fuel during the steady burning stage, which depends on the oxygen concentration measured near the pool, thereby, the greater the oxygen concentration the shorter the fire will last. These observations are in reasonably good agreement with the experimental tests conducted by Pretrel [2, 3] as part of the PRISME program.

The temperature distributions, along the flame axis, were measured using eight K thermocouples positioned at regular intervals of 0.05 m and covering a height of 0.42 m with respect to the pan lip (see Fig. 2). Few years ago, an experimental study performed by Richard *et al.* [16], used a heptane pool fire with a diameter of 0.23 cm in open atmosphere to investigate extinguishing properties of water mist system. Experimental measurements without water were performed in [18, 22] for calibration. Fig. 7 presents a comparison of the axial temperature profiles obtained during the steady-state phase, respectively, in a vitiated environment (ACPH varied between 4 and 1) and in free atmosphere [22]. A dimensionless variable Z/D, representing the ratio of the height Z above the pan lip to the pool diameter D, is also defined to allow comparison of experimental results for these fuel configurations with two different pan sizes (0.3 m and 0.23 m). 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 to 645°C. 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. Furthermore, the temperature variation in free atmosphere shows a rapid decrease when the dimensionless variable Z/D exceeds 0.6 as well as the temperatures tend to decrease below those measured in closed environment for Z/D>1. This behaviour can be explained by the fact that the temperature within a fire plume will decrease as smokes get diluted with fresh air in open environment.

Table 1 shows heat fluxes results transmitted to the fuel surface and the measured fuel mass loss rate per unit area in function of the oxygen concentration at the flame base. These values were obtained during a quasi steady-state phase of fire using equations (1-6) with a heat of gasification of 320 $kJ.kg^{-1}$. An average gas temperature T_g was determined from the measurements made by a vertical thermocouple tree on the left quadrant of the compartment.

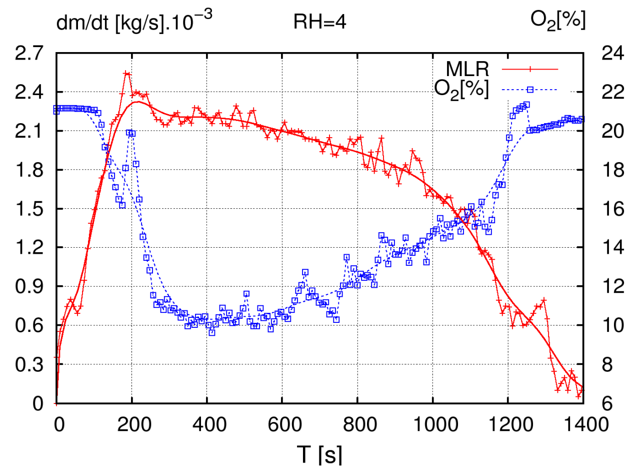

Figure 4. Fuel mass loss rate and oxygen concentration, ACPH=4.

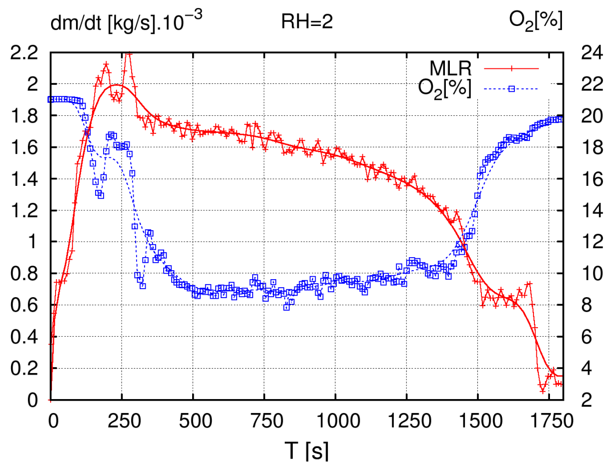

Figure 5. Fuel mass loss rate and oxygen concentration, ACPH=2.

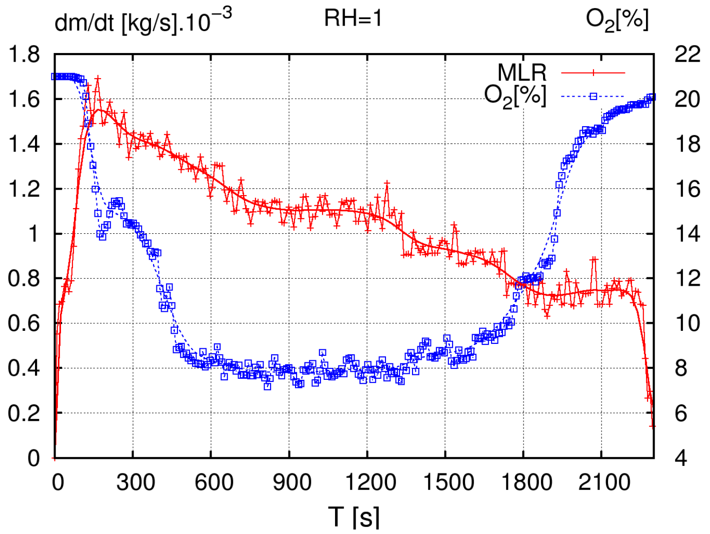

Figure 6. Fuel mass loss rate and oxygen concentration, ACPH=1.

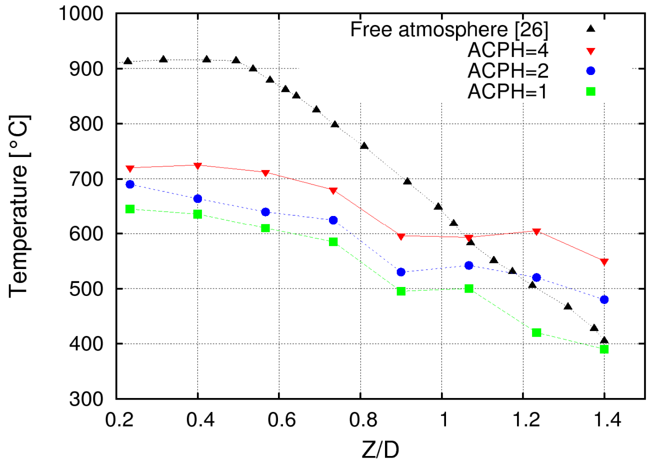

Figure 7. Temperature distribution along the pan axis during the steady-state phase.

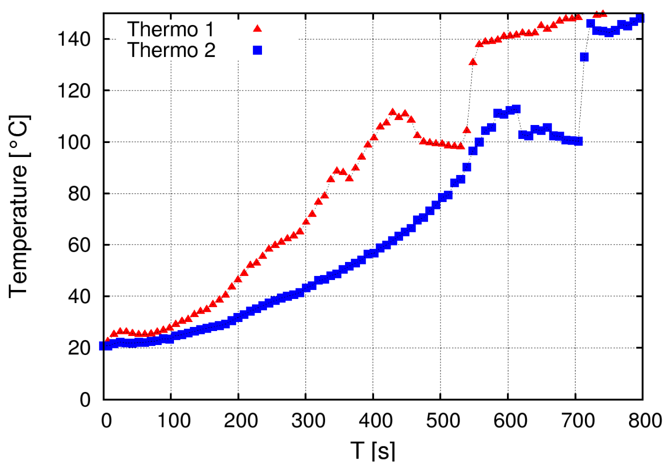

Figure 8. Temperature in fuel pan, ACPH=4.

We recall that heptane was contained in a circular pan of 10 cm deep in the absence of any fuel injection system used to maintain the liquid phase at ambient temperature and a fixed depth. Shortly after ignition, fuel temperature will increase and approaches the boiling point during the steady-state phase. Heat conduction through the fuel is then assumed to be negligible and the heat of gasification is given by the latent heat of vaporization of heptane (320 kJ.kg-1). This is further confirmed by the temperature distributions in fuel measured using two K thermocouples positioned 0.08 m (Thermo 1) and 0.07 m (Thermo 2) above the bottom of the pan. Considering the experimental test with ACPH = 4 (see Fig. 8), as soon as the fuel surface reaches the first thermocouple (t=500 s), the second thermocouple at 1 cm below, indicates a value of 80°C which is relatively high, confirming that the temperature of liquid phase is approximately constant and the energy required for heating fuel is negligible.
The flame emissivity in Eq. (4) can be determined experimentally using infrared thermography techniques as shown in [12, 23]. In the present work, it is fixed to its value in open atmosphere of 0.28, obtained using Babrauskas's formulation [24].

Table 1. Fuel mass loss rate, gas temperature, and heat fluxes measurements for various oxygen concentration, heptane pool fire with diameter of 0.3 m.

ACPH	O_2[%]	MLR	$\dot{q}''_{total}$	$\dot{q}''_{s,r}$	$\dot{q}''_{f,r}$	$\dot{q}''_{e,r}$	$\dot{q}''_{f,c}$	T_g	$\dot{q}''_{f,r}$	$\dot{q}''_{f,c}$
		$.10^{-3}$ kg/s			kW/m^2			°C	[%]	
4	10.5	2.2	10.16	5.5	4	1.5	4.66	215	39	46
2	9	1.75	8.12	4.26	2.9	1.36	3.86	195	36	48
1	7.8	1.15	5.4	2.7	1.6	1.1	2.7	160	30	50

As illustrated in Table 1 and Figs. 4 to 6, the fuel mass loss rate and the flame temperature decrease as the oxygen concentration measured near the pool, at the flame base, is decreased. The heat fluxes received at the pool surface show similar behaviour and reducing the oxygen concentration by 26 % (from 10.5 % to 7.8 %) lead to decrease the radiant heat flux of the flame by 60 % (from 4 kW/m^2 to 1.6 kW/m^2); in the same way, the flame convective heat flux is decreased by 42 %. On the other hand, the flame radiation fraction decreases when the oxygen concentration is decreased whereas the convection fraction of the total heat flux received by the fuel increases. This behaviour is in agreement with the experimental and theoretical work of Tewarson *et al.* [6].

The external heat feedback is proportional to the temperature of gas in the local T_g which depends on the heat release rate of fire (HRR). Consequently, the external heat flux tends to vary substantially when oxygen concentration near the pool is varied (see Table 1). It should also be highlighted that the radiant heat transfer from the flame is greater than the external heat feedback. This experimental result seems to disagree with the hypothesis made by Utiskul [9] concerning the fuel mass loss rate model which assumes that radiation from the flame may be neglected if oxygen concentration is decreased in the enclosure.

Concluding remarks

The basic aim of this paper was to study the burning process of a heptane pool fire in a reduced-scale compartment. From this experimental work, some results may be summarized as follow:

An original method is developed for decoupling flame and external flux measurements at the fuel surface. In this context, an approximation for a steady-state analysis was proposed, based on an additional heat flux measurement located under the pool fire. High under-ventilated combustion regime was studied with low oxygen concentration near the pool varied between 10.5 % and 7.8 %. Fire extinction was occurred due to lack of fuel and it was discussed that the greater the oxygen concentration near the pool the shorter the fire will last. It was also shown that the fuel mass loss rate, flame temperature and heat fluxes to the fuel surface are very sensitive to changes in oxygen concentration at the flame base. The radiant and convective heat fluxes of the flame and flame radiant fraction decrease as the oxygen concentration is decreased. On the other hand, the flame convective fraction increases when the oxygen concentration decreases.

As a perspective, these results will be used to validate a theoretical formulation developed earlier [25, 26] to determine the burning rate of fuels for pool fires in a closed environment. A similar experimental work will be also conducted at the Institut Pprime using heptane and dodecane pool fires with smaller pool fire diameter of 0.26 m in the aim to reach under-ventilated combustion regime with a higher oxygen concentration measured near the pool.

Acknowledgements
This work was financed by EDF and IRSN through a thesis conducted by the Institut Pprime.

Nomenclature listing

L	characteristic length (m)	**Greek**		
L_v	heat of gasification (kJ/kg)	μ	absorption coefficient (1/m)	
$\dot{m}''$	mass loss rate per unit area ($kg/m^2/s$)	σ	constant Stefan-Boltzmann ($W/m^2/K^4$)	
O_2[%]	oxygen concentration	**Subscripts**		
$\dot{Q}$	heat release rate (kW)	f	flame	
$\dot{q}''_{e,r}$	external heat flux (kW/m^2)	F	fuel	
$\dot{q}''_{f,c}$	convective heat flux from the flame (kW/m^2)	g	gas	
$\dot{q}''_{f,r}$	radiant heat flux of the flame (kW/m^2)	h	heptane	
$\dot{q}''_{in}$	radiant heat flux measured inside the pan (kW/m^2)	l	lower layer	
$\dot{q}''_{s,r}$	total radiant heat flux to fuel surface (kW/m^2)	s	pool surface	
$\dot{q}''_{un}$	external heat flux measured under the pool (kW/m^2)	u	upper layer	
T	temperature (°C)	w	wall	
z_h	depth of the heptane layer in the pan (m)	wa	water	
z_{wa}	depth of the water layer above the radiometer positioned in the pan (m)			

References

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

[2] Pretrel, H., Le Saux, W., and Such, J. M., "Experimental study of burning rate behaviour of pool fires in confined and ventilated compartments". In *Post-Conference Seminar III of the 18th International Conference on Structural Mechanics In Reactor Technology (SMIRT 18), 9th International Seminar on Fire Safety in Nuclear Power Plants and Installations*, Vienna, August 22-24 2005.

[3] Pretrel, H., Querre, P., and Forestier, M., "Experimental study of burning rate behaviour in confined and ventilated fire compartments", *Fire Safety Science – Proceeding of the Eighth International Symposium,* International Association for Fire Safety Science, 2005, pp 1217-1229.

[4] Mélis, S. and Audouin, L., "Effects of vitiation on the heat release rate in mechanically-ventilated compartment fires", *Fire Safety Science – Proceeding of the Ninth International Symposium*, International Association for Fire Safety Science, 2008.

[5] Hamins, A., Johnsson, E., Donnelly, M., and Maranghides, A., "Energy balance in a large compartment fire", *Fire Safety Journal* 43: 180-188 (2007)

[6] Tewarson, A., Lee, J. L. and Pion, R. F., "The influence of oxygen concentration on fuel parameters for fire modeling", *Symposium International on Combustion*, Combustion Institute, 1981, pp 563-570.

[7] Santo, G. and Tamanini, F., "Influence of oxygen depletion on the radiative properties of PMMA flames", *Symposium International on Combustion*, Combustion Institute, 1981, pp 619-631.

[8] Santo, G. and Delichatsios, M. A., "Effects of vitiated air on radiation and completeness of combustion in propane pool fires", *Fire Safety Journal* 7: 159-164 (1984)

[9] Andrews, G. E., Ledger, J. and Phylaktou H. N., "Enclosed pool fires in low ventilation enclosures : Flame temperatures and global heat loss using gas analysis", *Fire Safety Science – Proceeding of the Sixth International Symposium*, Interflam Committee, 2000, pp 591-602.

[10] Utiskul, Y., "Theoretical and experimental study on fully-developed compartment fires", University of Maryland (USA), Phd Thesis, 2006.

[11] Utiskul, Y. and Quintiere, J. G. and Rangwala, A. S. and Ringwelski, B. A. and Wakatsuki, K. and Naruse, T., "Compartment fire phenomena under limited ventilation", *Fire Safety Journal*, 40: 367-390 (2005)

[12] Beaulieu, P.A. and Dembsey, N.A., "Effect of oxygen on flame heat flux in horizontal and vertical orientations", *Fire Safety Journal* 43: 410-428 (2007)

[13] Quintiere, J. G. and Rangwala, A. S., "A theory for flame extinction based on flame temperature", *Fire and Materials* 28: 387-402 (2004)

[14] Weckman, E. J. and Strong, A. B., "Experimental investigation of the turbulence structure of medium-scale methanol pool fires", *Combustion and Flame* 105: 245-266 (1996)

[15] Tieszen, S. R., O'Hern, T. J., Schefer, R. W., Weckman, E. J. and Blanchat, T. K., "Experimental study of the flow field in and around a one meter diameter methane", *Combustion and Flame* 129: 378-391 (2002)

[16] Richard, J., Garo, J. P., Souil, J. M., Vantelon, J. P. and Lemonnier, D., "Addition of a water mist on a small-scale liquid pool fire: effect on radiant heat transfer at the surface", *Proceeding of the Combustion Institute*, 2002, vol 29, pp 377-384.

[17] Garo, J. P., Vantelon, J. P. and Lemonnier, D., "Effect on radiation heat transfer at the surface of pool fire interacting with a water mist", *Journal of Heat Transfer* 132: 023503.1-023503.9 (2010)

[18] Richard, J., "Interaction d'un brouillard d'eau avec un feu de nappe à l'échelle laboratoire. Effets physicochimiques et influence sur le rayonnement", Ecole Nationale Supérieure de Mécanique et d'Aérotechnique et Faculté des Sciences Fondamentales et Appliquées, Phd Thesis, 2001.

[19] Babik, F., Lapuerta, C., Latché, J. C., Suard, S., and Vola, D., "Modeling and numerical studies of fires in confined, ventilated environments: the ISIS code", Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Scientific and Technical Report - IRSN, 2007, vol 4, pp 173-180.

[20] Lassus, J., Studer, E., Garo, J. P. and Vantelon, J. P., "Influence of ventilation on ignition risk of unburnt gases in the extraction duct of underventilated compartment fire", *Combustion Science and Technology* 182: 517-528 (2010)

[21] Lassus, J., "Risque d'inflammation de gaz imbrûlés au cours d'un incendie en milieu confiné-ventilé'', Ecole Doctorale : Sciences pour l'Ingénieur et Aéronautique, Phd Thesis, 2009.

[22] Richard, J., Garo, J. P., Souil, J. M., Vantelon, J. P. and Knorre, V. G., "Chemical and physical effects of water vapour addition on diffusion flames", *Fire Safety Journal* 38: 569-587 (2003)

[23] Planas-Cuchi, E., Chatris, J. M., Lopez, C. and Arnaldos, J., "Determination of flame emissivity in hydrocarbon pool fires using infrared thermography", *Fire Technology* 39: 261-273 (2003)

[24] Babrauskas, V., "Estimating large pool fire burning rates ", *Fire Technology* 19: 251-261 (1983)

[25] Nasr, A., Suard, S., Garo, J. P., El-Rabii, H. and Gay, L., "Determination by a CFD code and a global model of the fuel mass loss rate in a confined and mechanically-ventilated compartment fire", *International Conference on Fire Research and Engineering*, Interflam Committee, 2010, pp 1775-1781.

[26] Suard, S., Nasr, A., Melis, S., Garo, J. P., El-Rabii, H., Gay, L., Rigollet, L. and Audouin, L., "Analytical approach for predicting effects of vitiated air on the mass loss rate of large pool fire in confined compartments", *Fire Safety Science – Proceeding of the tenth International Symposium*, International Association for Fire Safety Science, Maryland, USA, 2011.

Appendix A

A schematic diagram for the reduced scale compartment is presented in Fig. 9 to describe the distribution of radiant heat fluxes, reaching both the fuel surface and the radiometer positioned under the pool. The measured radiant heat flux at the fuel surface (position 1) in Fig. 9 is equal to the sum of radiant flux of the flame $\dot{q}''_{\mathrm{f,r}}$ and those transmitted by the hot gases $\dot{q}''_{\mathrm{g}}$ and compartment surfaces $\dot{q}''_{\mathrm{w}}$. Two subscripts ''u'' and ''l'' are also used to separate the radiant heat flux from the compartment surfaces into two components: $\dot{q}''_{\mathrm{w,u}}$ and $\dot{q}''_{\mathrm{w,l}}$, which denote the radiant heat fluxes transmitted by the compartment surfaces in the upper and lower layer respectively:

Position (1): $$\dot{q}''_{s,r} = \dot{q}''_{f,r} + \dot{q}''_{e,r} = \dot{q}''_{f,r} + \dot{q}''_{g} + \dot{q}''_{w,u} + \dot{q}''_{w,l}\,. \tag{7}$$

According to Utiskul [10], we can write

$$\dot{q}''_{g} = \sigma\varepsilon_{g}(1-\varepsilon_{f})F_{1-g}T_{g}^{4}, \tag{8}$$

$$\dot{q}''_{w,u} = \sigma\varepsilon_{w,u}(1-\varepsilon_{g})(1-\varepsilon_{f})F_{1-w,u}T_{w,u}^{4} \text{ and } \dot{q}''_{w,l} = \sigma\varepsilon_{w,l}(1-\varepsilon_{f})F_{1-w,l}T_{w,l}^{4}\,. \tag{9}$$

T_g and T_w represent respectively the gas and wall temperatures, σ is the Stefan-Boltzmann constant and ε is the emissivity. The term $F_{i\text{-}j}$ represents the view factor to take into account the fraction of the radiation leaving surface *i* and strikes surface *j*.

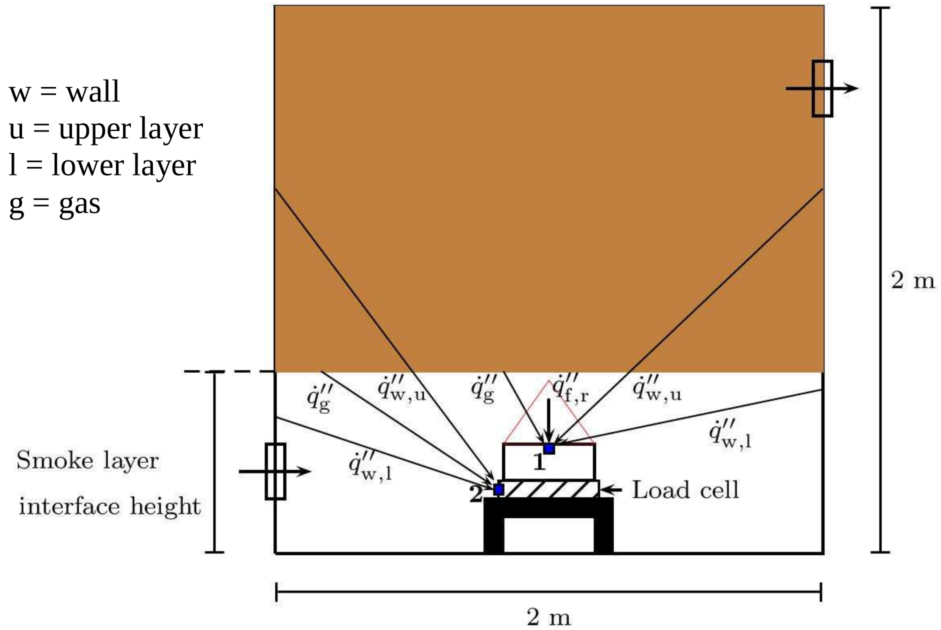

Figure 9. Distribution of radiant heat fluxes over the fuel surface (position 1) and under the pool (position 2).

The wall temperature in the lower layer (cold layer) is not high enough, thus $F_{1-w,l}T_{w,l}^{4} << F_{1-w,u}T_{w,u}^{4}$ and the radiant heat flux $\dot{q}''_{w,l}$ can be neglected. 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 $\dot{q}''_{w,u}$ is believed to be small. Hence, the measured radiant heat flux at the fuel surface reduces to

Position (1): $$\dot{q}''_{s,r} = \dot{q}''_{f,r} + \dot{q}''_{e,r} \approx \dot{q}''_{f,r} + \dot{q}''_{g}. \tag{10}$$

Similarly, the measured radiant heat flux at position (2) reads

Position (2): $$\dot{q}''_{\mathrm{un}} = \dot{q}''_{\mathrm{g}} + \dot{q}''_{\mathrm{w,u}} + \dot{q}''_{\mathrm{w,l}} \approx \dot{q}''_{\mathrm{g}}. \tag{11}$$

At fire extinction, the radiometers positioned at the fuel surface indicate a radiant heat flux which corresponds to the external heat feedback. A factor determined at this time and corresponding to the ratio of the radiation measurement at the fuel surface by the radiation measurement under the pool is defined as follow:

$$\alpha = \left.\frac{\dot{q}''_{\mathrm{s,r}}}{\dot{q}''_{\mathrm{un}}}\right|_{\mathrm{ext}} = \left.\frac{\dot{q}''_{\mathrm{e,r}}}{\dot{q}''_{\mathrm{un}}}\right|_{\mathrm{ext}} = \left.\frac{\sigma\varepsilon_{\mathrm{g}} F_{1-g} T_g^4}{\sigma\varepsilon_{\mathrm{g}} F_{2-g} T_g^4}\right|_{\mathrm{ext}} = \left.\frac{F_{1-g}}{F_{2-g}}\right|_{\mathrm{ext}} \tag{12}$$

During all the fire duration, we have

$$\frac{\dot{q}''_{\mathrm{e,r}}}{\dot{q}''_{\mathrm{un}}} = \frac{\sigma\varepsilon_{\mathrm{g}}(1-\varepsilon_{\mathrm{f}})F_{1-g} T_g^4}{\sigma\varepsilon_{\mathrm{g}} F_{2-g} T_g^4} = (1-\varepsilon_{\mathrm{f}})\frac{F_{1-g}}{F_{2-g}} \tag{13}$$

and by considering that the smoke layer interface height in the compartment is constant until the flame extinction thus the ratio F_{1-g} / F_{2-g} is also constant, the term in the left hand side of Eq. (13) becomes

$$\frac{\dot{q}''_{\mathrm{e,r}}}{\dot{q}''_{\mathrm{un}}} = (1-\varepsilon_{\mathrm{f}})\alpha . \tag{14}$$

Within this approximation, the external heat flux $\dot{q}''_{\mathrm{e,r}}$ and the radiant heat flux of the flame $\dot{q}''_{\mathrm{f,r}}$ received at the fuel surface can be written as

$$\dot{q}''_{\mathrm{e,r}} = (1-\varepsilon_f)\alpha\dot{q}''_{\mathrm{un}} \text{ and } \dot{q}''_{\mathrm{f,r}} = \dot{q}''_{\mathrm{s,r}} - \dot{q}''_{\mathrm{e,r}} . \tag{15}$$