Experimental Study of Burning Rate Behaviour in Confined and Ventilated Fire Compartments

HUGUES PRETREL[1], PHILLIPE QUERRE[2], and MARC FORESTIER[2]
[1] Laboratoire d'Expérimentation des Feux (SEREA/LEF)
[2] Laboratoire d'Etude et de Modélisation de l'Incendie (SEMIC/LEMI)
Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
Centre de Cadarache
13115 Cédex, St Paul-lez-Durance - France

ABSTRACT

This paper presents an experimental study dealing with the burning rate of pool fire in a confined and ventilated compartment within the framework of nuclear safety research. Based on full-scale pool fire experiments, it provides new information to improve understanding of burning rate mechanisms in confined and ventilated fire scenario. First of all, the paper describes the experiments conducted in both a free atmosphere and a compartment; the facility, instrumentation and fire source are detailed. Then, an analysis is made comparing free atmosphere and compartment burning rate for the same fire scenario (0.4 m^2 TPH pool fire). In compartment, burning rate versus time reveals three different periods: a first period when free atmosphere and compartment burning rate are identical, a second unsteady period, during which the burning rate is higher in a compartment than in a free atmosphere and a third steady period. From video-recorder and image analysis, a detailed description of the second unsteady region shows oscillating and periodic flame behaviour resulting in significant increase of the burning rate. The effects of the ventilation rate and the pool area on this phenomenon are demonstrated. The results provide new experimental information that contribute to improving understanding of burning rate in a compartment.

KEYWORDS: pool fire, burning rate, ventilation, industrial fires, compartment fires

INTRODUCTION

A confined and ventilated fire compartment is a widespread industrial fire scenario, which is studied extensively for fire safety issues in the nuclear industry. Indeed, buildings are often force ventilated and compartmentalized into a set of enclosures, so as to guarantee confinement and thereby stop radioactive materials or harmful products escaping from compartment. When addressing fire safety assessment, a key point is knowledge of the burning rate. For free atmosphere configurations, fuel burning rates are mostly known and do not cause too many difficulties when assessing fire hazard. On the other hand, in confined and ventilated fire compartments, fuel burning rates are barely known because of their complex dependency on the immediate environment. Indeed, confinement and the role of mechanical ventilation lead to two major effects that may modify burning rate: the change in chemical composition of the gas (reduction of oxygen concentration and air vitiation with combustion products) and the onset of induced flow (especially when the compartment volume is rather small compared to the fire's heat release rate). It is therefore a major issue in fire safety research to bring new experimental issues, which will improve our knowledge with the final aim of proposing guidelines when performing fire safety assessments.

FIRE SAFETY SCIENCE–PROCEEDINGS OF THE EIGHTH INTERNATIONAL SYMPOSIUM, pp. 1217-1228

This topic has been investigated at IRSN within the framework of a research project initiated to study the problem of smoke spreading in a multi-compartment fire scenario. The first step in this program is to characterize the burning rate of the pool fire in compartment by comparing it to its behaviour in a free atmosphere. The effects of the environmental conditions on the burning rate have been investigated from full scale fire test based on the specific compartment fire scenario. Pool fire is chosen because of the large amount of data available on its behaviour in free atmosphere (Babrauskas [1]).

Numerous investigations have clearly demonstrated (Blinov and Hottel [2]) or detailed through modelling proposals (Hamins [3]) that for industrial pool dimensions, the fuel burning mechanism is governed in free atmosphere by the flame radiation feedback on the surface of the liquid. In compartment, additional phenomena may modify the burning rate. The Babrauskas review [1] details how fire burning rate may be affected by the thermodynamics features of the gas surrounding the fire: its chemical composition (especially oxygen content and to a lesser extent, the gaseous combustion products), temperature and relative humidity. In addition to the gas properties effect, others mechanisms such as re-radiation of the wall enclosure, soot concentration and induced flows within the compartment, may modify the burning rate (Karlsson [4]). Typical examples of induced flows have clearly demonstrated their effects on burning rate through complex unsteady behaviour patterns of the flame structure (Pretrel [5], Bertin [6], Utiskul [7]). They illustrate how complex the burning rate in compartment can be when both effects of the gas characteristics and the flow induced within the compartment occur simultaneously.

The present work investigates the burning rate of pool fire in a confined and forced-ventilated compartment on the basis of full scale pool fire experiments representative of real scenarios encountered in the nuclear industry. It provides new information that improves understanding of the burning rate mechanisms and proposes subjects for modelling. To commence, the experiments conducted in a free atmosphere and in a compartment are presented. The facility, instrumentation and fire are detailed. An analysis is then made to compare burning rate versus time for a given pool area in a free atmosphere and in a compartment. Then the effect of ventilation rate on burning rate is presented. In conclusion the influence of the pool area is demonstrated.

DESCRIPTION OF THE EXPERIMENTS

Fire Studied and Experimental Facilities

The fire studied consists of a circular container (10 cm deep) filled with liquid fuel called TPH for Hydrogenated Tetra-Propylene ($C_{12}H_{26}$), a fuel used for nuclear reprocessing (similar to dodecane fuel). The container, positioned on a weighting device system, is 0.4 m above ground level (cf. Fig. 2). Two pool sizes were tested (0.2 and 0.4 m^2) with respectively 10 liters and 20 liters of fuel respectively. The initial liquid height before ignition is always 5 cm and during the experiment the fuel volume (and fuel height) decreases as fuel burns. The measured data comprises a vertical liquid fuel temperature profile at the centre of the pool with five K type thermocouples (1.5 mm diameter) and the fuel mass with a SARTORUS type weighing device, [0-300] kg range (with 2 g accuracy).

Tests were performed in two facilities at the IRSN Fire Test Laboratory at Cadarache. Free atmosphere tests have been conducted under the IRSN-SATURNE Hood (3 m diameter hood) in which combustion products are collected and transported through a 500 mm diameter exhaust duct connected to a ventilation system (cf. Fig. 1). The parameters measured in the hood exhaust are oxygen (O_2), carbon monoxide (CO) carbon dioxide (CO_2) and soot concentrations, gas temperature, pressure and gas flow rate.

Compartment tests have been conducted in the IRSN-DIVA facility, which is a large scale multi-room device comprising four rooms and a corridor in 0.3 m thick ferro-concrete walls equipped with a mechanical ventilation system (cf. Fig. 3). The facility is used in mono-local configuration for test purposes (using room 2 only behind closed doors) with the fire located at the centre of the room. Inlets and exhaust ducts are situated in the upper part of the room, near the ceiling (cf. Fig. 3). This scenario mimics a typical layout encountered in nuclear industry. Measurements inside the compartment are performed. Gas compositions (O_2, CO, CO_2) are measured continuously at three locations: near the pool and in the upper and the lower part of the compartment (cf. locations on Fig. 3). In both facilities videos are performed. Acquisition frequency for all measurement except video is 1 Hz.

Test Grid and Standard Test Procedure

The main test characteristics are given in Table 1 and Table 2. In a free atmosphere, tests have been repeated twice to check reproducibility. In the compartment, two (for 0.2 m^2) and three (for 0.4 m^2) compartment ventilation rates have been studied. The ventilation rate (labelled Tr in h^{-1}) is defined as the ratio between ventilation airflow rate before ignition (dv_{air}/dt) divided by the room volume (120 m^3).

Test procedures are as follows. For tests in free atmosphere, the fan is set to extract approximately 16,000 m^3/h. The fuel is then ignited with a propane burner and the flame spreads across the surface until the entire pool is burning. A fully developed fire stage is observed ending with extinction of the pool due to lack of fuel. A test with exhaust airflow of 8,000 m^3/h has been performed shows that this parameter has no influence on the burning rate.

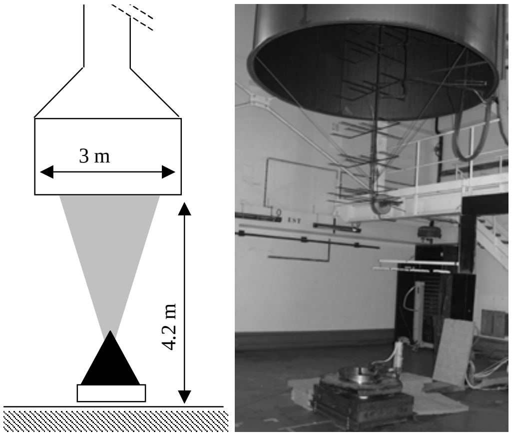

Fig. 1. Schematic representation and photograph of the SATURNE hood.

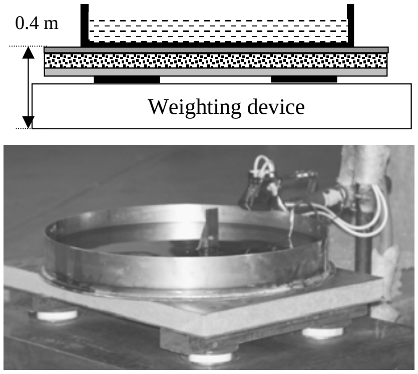

Fig. 2. Schematic representation and photograph of pool fire.

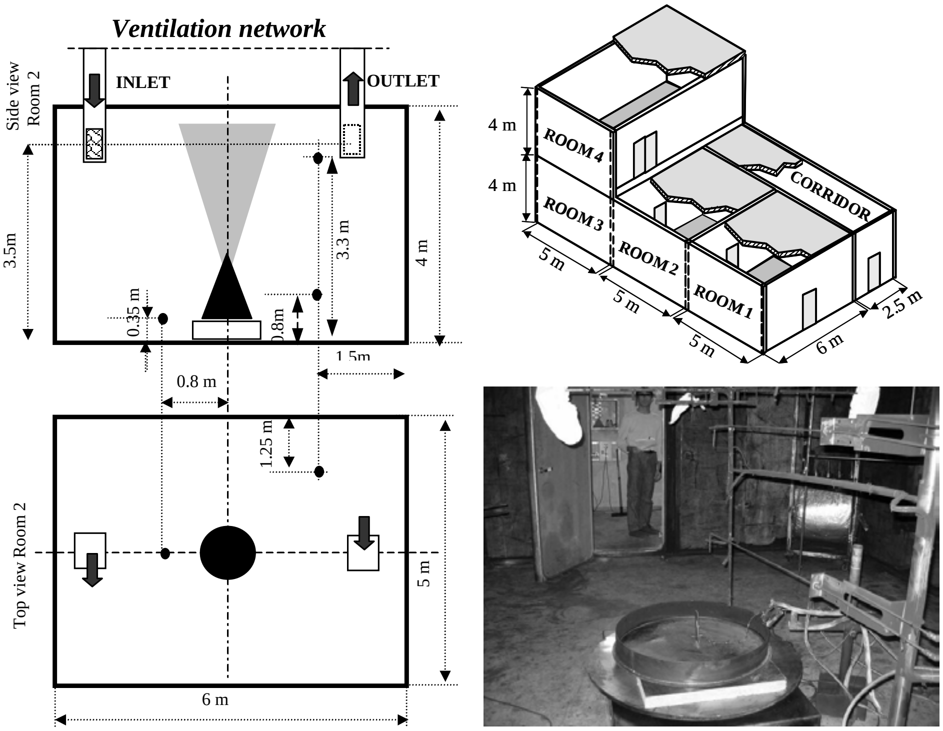

Fig. 3. Schematic representation and photograph of the DIVA facility.

Table 1. Test data in a free atmosphere.

	S	**D**	**M_f (t_o)**	**t_{ext}**	**M_f(t_{ext})**	**dm/dt**	**dm/dt/S**
Test name	m^2	m	g	s	g	$g.s^{-1}$	$g\ s^{-1}\ m^{-2}$
PRS-SI-S1	0.2	0.50	7752	1414	0	5.6	28.1
PRS-SI-S2	0.2	0.50	7702	1510	0	5.1	25.7
PRS-SI-S3	0.4	0.71	14902	1295	0	11.5	28.8
PRS-SI-S4	0.4	0.71	15088	1350	0	11.2	27.9

Table 2. Test data in a compartment.

	S	**D**	**Tr**	**dv_{air}/dt**	**M_f(t_o)**	**t_{ext}**	**M_f(t_{ext})**	**dm/dt**	**dm/dt/S**	**ϕ**
Test name	m^2	m	h^{-1}	$m^3\ h^{-1}$	g	s	g	$g\ s^{-1}$	$g\ s^{-1} m^{-2}$	-
PRS-SI-D1	0.4	0.71	4.7	560	14960	3190	1782	4.1	10.3	0.33
PRS-SI-D2	0.4	0.71	8.4	1010	15712	2580	0	6.1	15.2	0.27
PRS-SI-D3	0.4	0.71	1.5	180	15960	360	13080	8.0	20.0	2.02
PRS-SI-D5	0.2	0.50	4.6	555	7164	2552	0	2.8	14.0	0.23
PRS-SI-D5a	0.2	0.50	1.6	190	7842	1978	3336	2.3	11.4	0.54

For compartment tests, first the room ventilation rate is set to the required condition (*Tr* value). The fuel is then ignited as for tests under the hood. The pool fire develops until extinction occurs either due to either lack of fuel or oxygen starvation within the enclosure. One test (PRS-SI-D1) has been reproduced twice and demonstrated good reproducibility of the results.

The data given in Table 1 and Table 2 includes fuel mass before ignition $m_f(t_o)$, duration of the fire t_{ext}, fuel mass, if any, remaining after extinction in the container $m_f(t_{ext})$, average fuel mass loss rate (or burning rate) dm/dt defined as $[m_f(t_o)-m_f(t_{ext})]/t_{ext}$ and average fuel mass loss rate per unit of area $dm/dt/S$ defined as $[m_f(t_o)-m_f(t_{ext})]/t_{ext}/S$. In addition and only for the compartment tests, an equivalent ratio ϕ defined as $[(dm/dt)\ r]/[Y_{O2}.dm_{air}/dt]$ is calculated (r is the oxygen to fuel stoechiometric ratio, 3.48 and Y_{O2} the oxygen mass fraction in air 0.23). This parameter indicates how under-ventilated the tests are: the higher this parameter, the more the under-ventilated the test.

BURNING RATE VERSUS TIME FOR A GIVEN FIRE SCENARIO

Firstly, a comparison between the burning rate in a free atmosphere and in a compartment is investigated for the 0.4 m^2 pool fire.

In a Free Atmosphere

Burning rate versus time shows classic pool fire behaviour (cf. Fig. 4 and Fig. 5 grey curves). First, a propagation phase is observed, lasting approximately 30 s, during which the burning rate (dm/dt) increases from zero to about 4 g/s. Then the burning rate continues increasing until extinction due to lack of fuel. The stationary regime of the burning rate is obtained (about 14 g/s) for a very small period (between 600 s and 700 s) due to the very rapid appearance of border effects (due to fuel insufficiency in the pan) that leads to an increase in the burning rate before extinction. Some fluctuations are also observed and are attributed to uncontrolled airflow around the hood tending to push the flame from time to time. Nevertheless, good reproducibility is observed between the two tests (14.9 kg and 15.1 kg are burned in 1290 s and 1350 s respectively giving burning rates of 11.5 g/s and 11.2 g/s).

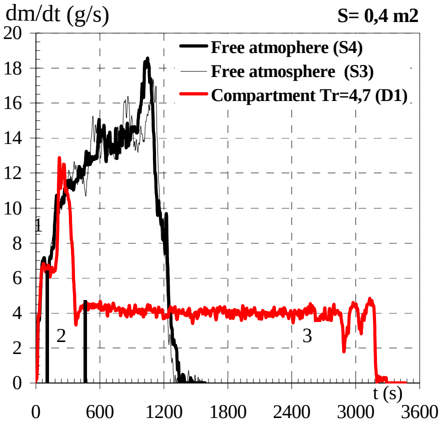

Fig. 4. Comparison between free atmosphere and compartment fire (S=0.4 m^2).

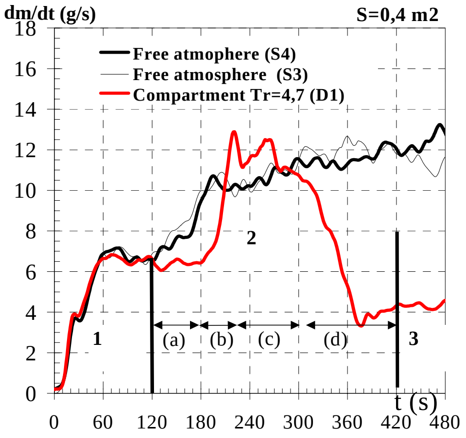

Fig. 5. Comparison between free atmosphere and compartment fire (S=0.4 m^2) (time scale reduced).

In the Compartment

A comparison of burning rates in a compartment and in a free atmosphere is discussed first at a ventilation rate of 4.7 h^{-1} (i.e., airflow rate before ignition of 560 m^3/h). Burning rate in the compartment shows three specific phases (cf. Fig. 4 and Fig. 5 which zooms in on the first 480 s of Fig. 4 during the first 480 s).

The first phase, lasting about 120 s, is a period during which the burning rate is remarkably identical to the rate in a free atmosphere. It consists of three sub-periods: the flame propagation period (30 s) followed by a phase of increasing to a maximum value (7 g/s) and a period of slight decrease for 60 s (cf. Fig. 5). The end of this period coincides with the appearance of vitiated air (increase of CO_2 and beginning of O_2 reduction) in the lower part of the vessel (cf. curves labelled (2) on Fig. 6 and Fig. 7 that show the time variation of oxygen and CO_2 concentrations for three positions) although there is still some rather “fresh air” in the incoming air close to the pool (cf. curves labelled (1) on Fig. 6 and Fig. 7). For this test, burning rates are identical in free air or compartment configurations for a duration similar to the time taken for the vessel to be filled with the combustion products and soot. Once the vitiated air reaches the flame level, the burning rate is affected.

A second phase then starts, characterized by a peak of burning rate. It is first initiated by a 60 s period (labelled “2a” in Fig. 5) , during which the burning rate remains constant and lower than the rate in a free atmosphere, even though the air close the pool is not yet vitiated (cf. curve (1) on Fig. 6 and Fig. 7). Then the burning rate increases significantly (period “2b”). This change takes place at the same time as vitiated air is detected very near the pool (decrease in O_2 yield and increase in CO_2 yield). The rate of increase (about 6 g/s in 30 s) is almost twice that observed at ignition (7 g/s in 60 s). The mass fuel loss rate then reaches a value (12 g/s) higher than in a free atmosphere (10 g/s) at the same time. The maximum value stabilizes on a plateau for about 60 s (period “2c”) and then gradually falls until its reaches a steady value (5 g/s) (period “2d”).

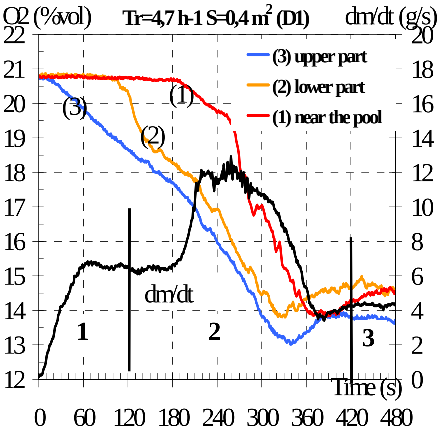

Fig. 6. Burning rate and O_2 yield versus time (Test D1 *S*=0.4 m^2 - *Tr*=4.7 h^{-1}).

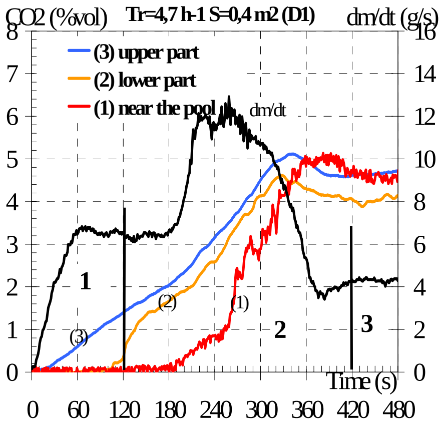

Fig. 7. Burning rate and CO_2 yield versus time (Test D1 *S*=0.4 m^2 - *Tr*=4.7 h^{-1}).

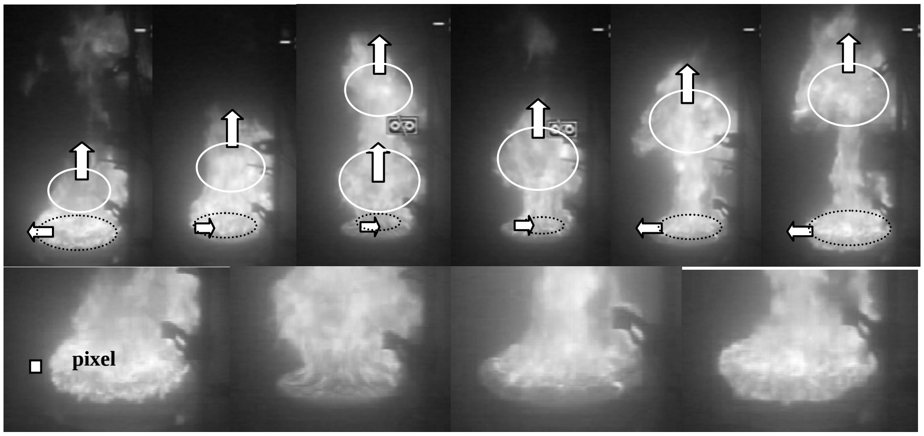

Fig. 8. Illustration of the periodic flame motion during phase 2a (Test D1): sequence of 6 images during one period, one image each 1/6 second (first line); zoom of 4 of those images (second line).

Analysis of the video recordings provides information on flame structure during the unsteady phase 2. During the first period (2a), the flame shape tends to stretch upwards, becoming narrower and longer; at the same time more and more soot is observed near the pool.

Then locally and from time-to-time, small flames appear around the pool as if they were “gasping for” oxygen. This phenomenon is amplified and leads to a periodic unsteady mechanism described as follow (cf. Fig. 8 that show pictures during one period). At the edge of the container and all around the pool, the flame front moves outwards in the pool in a sort of ring pattern, which expands radially and horizontally over time. This ring is then advected upstream in two sets of puffs. This sequence looks very similar to the puffing mechanisms commonly observed in a free atmosphere. However, the difference stems from the way the structure is created. In a free atmosphere, the structure is created above the pool, whereas in the compartment, it is created above and then around the pool due to horizontal motion of the flame front.

Analysis of the time variation of a pixel intensity located on one side of the pool (cf. first picture on Fig. 8) illustrates this effect (cf. Fig. 9). In a free atmosphere, intensity is stable (grey curve); in a compartment (black curve), intensity versus time shows clear fluctuations corresponding to the radial and horizontal flame motion passing periodically over this point.

Fast Fourier Transform analyses of the pixel intensity time variation signals are performed for three typical phases: one in a free atmosphere, one in a compartment during the first period when the burning rate is similar to that of a free atmosphere (phase 1) and one in a compartment during the period when the burning rate is increasing (phase 2b) (cf. Fig. 10). In a free atmosphere and during the phase 1 in a compartment, frequencies are about the same, 1.5 Hz, whereas the puffing mechanism during phase 2(b) displays a lower frequency of about 1.2 Hz. This result confirms that there are similarities between the two puffing mechanisms. However, the differences mainly affect flame motion that displays periodic horizontal outward motion in a compartment, which could explain the increase in burning rate.

The third and final phase is a steady phase that lasts until the fire is extinguished. The burning rate is constant (about 4 g/s) and much lower than in a free atmosphere (14 g/s). The oxygen and carbon dioxide concentration are also constant (14%vol of O_2 and 5%vol of CO_2) (cf. Fig. 11). This behaviour is typical of compartment fires in which equilibrium is reached between the amount of oxygen provided by the ventilation and the amount used by the combustion reaction. The fact that the CO yield falls continuously is probably the result of high CO production during the transition (phase 2b-2c) indicating the change in chemical reaction during this phase (cf. Fig. 12).

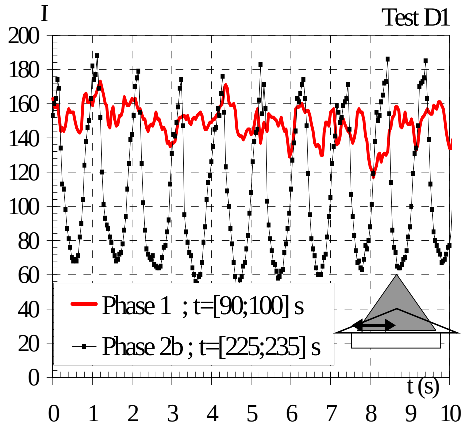

Fig. 9. Pixel intensity, I, versus time at a point located on one side of the pool (indicated on Fig 8).

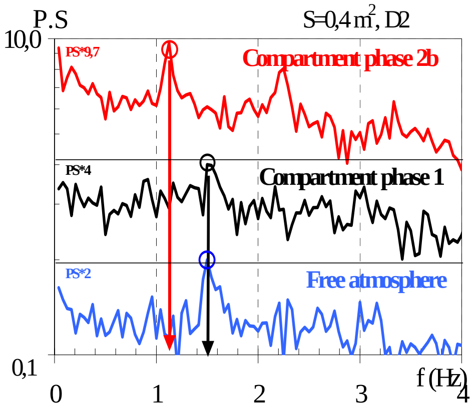

Fig. 10. Power spectrum (PS) in the frequency domain of the pixel intensity signal for three situations.

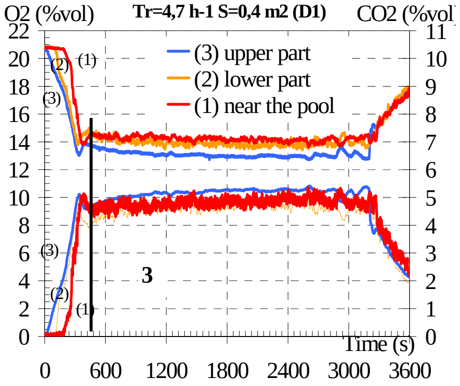

Fig. 11. O_2 and CO_2 yield versus time of 0.4 m^2 TPH pool fire in ventilated compartment.

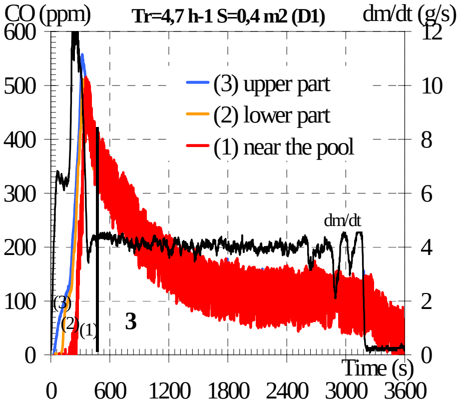

Fig. 12. Burning rate and CO yield versus time of 0.4 m^2 TPH pool fire in ventilated compartment.

EFFECT OF VENTILATION RATE ON BURNING RATE IN A COMPARTMENT

Compartment tests have been conducted for two other rates of ventilation: 1.5 h^{-1} and 8.4 h^{-1} (cf. Table 2). The three stages described above are clearly observed again (cf. Fig. 13 and Fig. 14). During the first stage, the change in ventilation rate does not modify the burning rate, which remains identical to that measured in a free atmosphere and for the same duration, about 120 s. This result is consistent with the previously proposed analysis that defines this duration as the time taken for the fire plume to fill the compartment in vitiated air. This result indicates that with this specific layout (inlet and outlet in the upper part of the compartment) ventilation contributes only to dilute the upper vitiated zone but has apparently no influence on the time this vitiated layer takes to reach floor level confirming the experimental results.

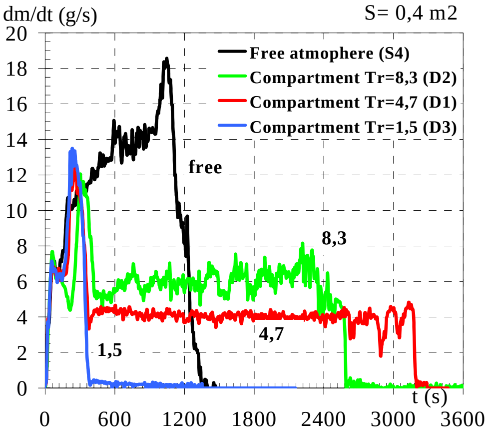

Fig. 13. Burning rate versus time of 0.4 m^2 TPH pool fire in ventilated compartment.

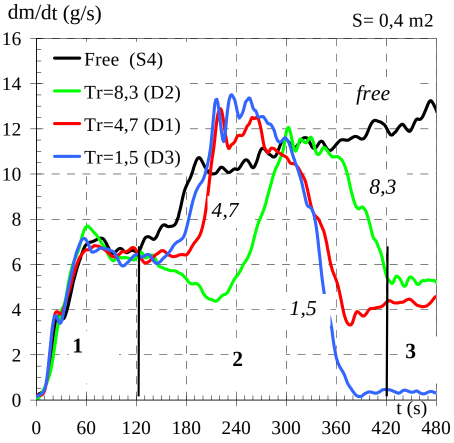

Fig. 14. Burning rate versus time of 0.4 m^2 in ventilated compartment (reduced time scale).

During the second stage, burning rates show similar behaviour whatever the ventilation rate: a stabilization period with a slight decrease, a significant increase up to a maximum value that is higher or similar to that of a free atmosphere followed by rapid decrease. The ventilation rate has no influence on the duration of the peak (about 180 s) although it delays the sequence timing; the lower the ventilation rate, the sooner the peak burning rate is reached. In addition, with the highest ventilation rate, the period (2a) (before the burning rate rises) is longer (100 s instead of 60 s for *Tr* = 4.6 h^{-1} and 30 s for 1.5 h^{-1}) and shows a slight fall in the burning rate. The ventilation rate also modifies the magnitude of the peak slightly: the lower the ventilation rate, the higher the maximum value. It changes the level at which burning rate stabilizes at the end of the second stage: the higher the ventilation rate, the higher the stable burning rate. For the lower ventilation rate, the burning rate is so low that combustion cannot be sustained and extinction occurs. In the range studied (1.5 and 8.3 h^{-1}), the ventilation rate does not really modify the unsteady mechanism observed during this second stage; it only seems to delay it. Analysis of the video-recordings and gas concentration (O_2, CO_2 and CO) shows very similar behaviour to that of test D1. It is worth noting that burning rate in a compartment scenario is higher than or at least equal to the rate in a free atmosphere, whatever the ventilation rate and for a specific period that nevertheless only lasts a few minutes.

The last steady stage is only observed for the two higher ventilation rate values. For the lower value (1.5 h^{-1}), extinction occurs at the end of the second phase due to lack of oxygen (cf. Fig. 13). The ventilation rate mainly alters the level of these steady conditions that are higher at a higher ventilation rate. These observations are consistent with conclusions obtained using simple theory of compartment fire. However, during this last stage, the test with *Tr* = 8.3 h^{-1} shows particular periodic oscillations of the burning rate around a mean value. Comparison of the burning rate with the gas temperature situated at 5 cm above the bottom of the pool (1.5 mm diameter K type thermocouple) shows that the change in burning rate is associated with gas temperature changes at the pool surface (cf. Fig. 15). The thermocouple signal shows that higher frequency oscillations that are not observed in burning rate (certainly due to the burning rate calculation method). Spectrum analysis shows the two frequencies of about 0.0055 Hz and 0.03 Hz that correspond to periods of about 180 s and 30 s respectively (cf. Fig. 16). The video analysis confirms that these higher frequency fluctuations correspond to periodic flame motion on and around the pool; the flame moves away from the pool.

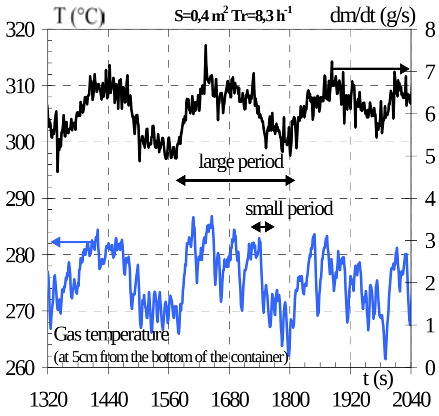

Fig. 15. Burning rate and gas temperature versus time (Test D2 *S*=0.4 m^2, *Tr*=8.3 h^{-1}).

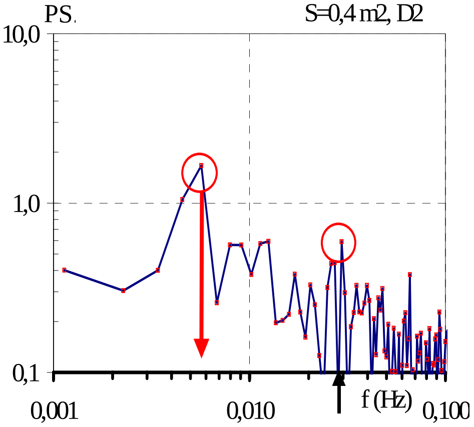

Fig. 16. Power spectrum (PS) in the frequency domain of the thermocouple signal.

EFFECT OF POOL AREA ON BURNING RATE IN A COMPARTMENT

The effect of pool area has been investigated in similar tests to those presented previously but with a 0.2 m^2 pool. The change in diameter produces different conclusions. Burning rate versus time shows an initial period during which its behaviour is identical to that in a free atmosphere (cf. Fig. 17). This period is longer (200 s) than that of a 0.4 m^2 pool confirming that it is governed by the magnitude of the fire plume flow-rate (lower for 0.2 m^2 pool fire) that fills the compartment. A change is then observed compared with the tests on a 0.4 m^2 pool, with the disappearance of the unsteady phase (phase 2). In the case of a 0.2 m^2 pool fire, the burning rate decreases progressively towards an almost constant value until the extinction. These observations indicate that the unsteady phase observed for a 0.4 m^2 pool fire could be a transition period between two “steady” situations: the free atmosphere situation and the steady compartment fire situation. A parameter that may affect the appearance of the transition period is the ratio between fire pool dimensions and compartment dimensions.

DISCUSSION AND CONCLUSIONS

The results clearly show that the fuel burning rate in a compartment can be higher, equal to or lower than the rate in a free atmosphere. Different types of behaviour have been encountered according to the period of the fire scenario. Four examples have been observed.

The initial typical behaviour concerns the very start of the fire. Burning rates in a free atmosphere or in a compartment are equal for any ventilation rate or pool diameter. This period actually corresponds to the time taken for the compartment to be filled with the combustion products, which depends on the fire heat release rate.

A second type of behaviour is observed immediately after the first initial period. The burning rate in a compartment differs from that in a free atmosphere. A first example is the occurrence of a flame puffing mechanism that occurs at low oxygen yield within the compartment, linked to a rapid increase in burning rate, which then exceeds the burning rate in a free atmosphere. This effect is not affected by the ventilation rate, but it disappears with the change in pool diameter. The most striking observation during this phenomenon is that, firstly the burning rate may be higher than in a free atmosphere, even with a lower oxygen concentration. Secondly it is also observed that an increase (or decrease) in burning rate in a compartment may be faster than in a free atmosphere, during the propagation phase for example. This observation is a significant result in the knowledge that the rise or reduction in burning rate are directly linked to pressure variations in the compartment (as shown cf. Fig. 18), which is a major concern when dealing with fire safety assessment in the nuclear industry. Analysis of this behaviour indicates that even with vitiated air close to the fire, an increase in burning rate may be observed, induced by unsteady mechanisms. It is a dynamic effect that modifies the burning rate.

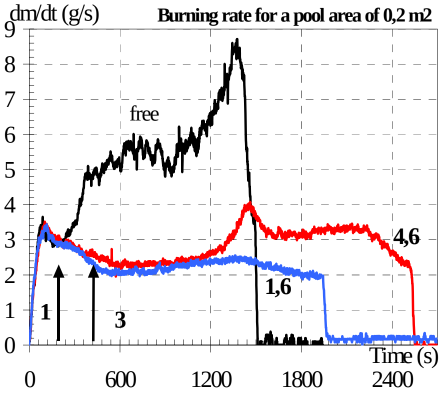

Fig. 17. Burning rate versus time (Tests S3, D5 and D5a).

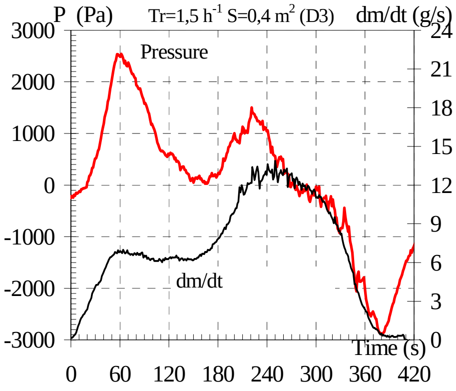

Fig. 18. Burning rate and pressure versus time (Test D3 S=0.4 m^2 - Tr=1.5 h^{-1}).

A third type of behaviour is observed during steady state evolution of the fire. In this case, the burning rate in a compartment is lower than in a free atmosphere mainly due to the low level of oxygen in the compartment. In this case, it is the low oxygen yield in the incoming air that modifies the combustion reaction thereby reducing radiation feedback on the pool. It is a chemical effect that modifies the burning rate.

A final example is the unsteady variation of burning rate, which may occur in a quasi-steady situation. The burning rate presents variations probably due to unstable and turbulent motion of the flame in an environment characterized by a low level of oxygen.

This study of burning rate in compartment fire illustrates how complex the flame structure can be, leading to very different types of behaviour (summary in Table 3). The understanding and thus the prediction of this parameter remain a key issue in fire safety assessment. This result brings up several issues that could be very challenging to model. Additional observations and experimental studies are needed to improve and refine definition of the mechanisms involved and propose new data for comparison with modelling proposal.

Table 3. Summary of observations made on the burning rate in compartment compared to the burning rate in free atmosphere.

Phases	**Initial period**	**Unsteady phase**	**Steady phase**
Duration	2 to 3 minutes	5 minutes	2 to 50 minutes
Main behaviour	Burning rate equal to the burning rate in free atmosphere	Significant changes, amplitude may overcome level in free atmosphere	Amplitude much lower than that in free atmosphere
Effect of ventilation	No effect	Delays the occurrence of the burning rate increase and modifies its level	Changes the stationary level
Effect of surface	Changes the duration of the period	May eliminate this period	Changes the stationary level

REFERENCES

[1] Babrauskas, V., *Heat Release in Fires*, V. Babrauskas and S.J. Grayson Edition, 1996.

[2] Hottel, H.C., "Review - Certain Laws Governing Diffusive Burning of Liquids by Blinov V.I., Khudiakov G.N.," *Fire Research Abstract and Reviews*, **1**, pp. 41-44, (1958).

[3] Hamins, A., Yang, J.C. and Kashiwagi, T., "A Global Model for Predicting the Burning Rates of Liquid Pool Fires," National Institute of Standards Technology, Report NISTIR 6381, Gaithersburg, MD, 1999.

[4] Karlsson, B., and Quintiere, J.G., *Enclosure Fire Dynamics*, CRC Press, 2001.

[5] Prétrel, H., Melis, S., Minétian, S., and Querre, P., "Experimental Observations of Pressure Instabilities during Pool Fire in Confined and Ventilated Enclosure," *Proceedings of the Fourth International Seminar on Fire and Explosion Hazards*, 2003.

[6] Bertin, G., Most, J.M. and Coutin, M., "Wall Fire Behaviour in an Under-ventilated Room," *Fire Safety Journal*, **37**, pp. 615-630.

[7] Utiskul, Y., Quintiere, J.G., Rangwala, A.S., Ringwelski, B.A., Wakatsuki, K., and Naruse, T., "Compartment Fire Phenomena under Limited Ventilation," *Fire Safety Journal*, **40**, pp. 367-390, (2005).