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Combustion Rate of Medium Scale Pool Fire, an Unsteady Parameter

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Abstract: Pool fire is a classical dangerous phenomenon that can occur in various infrastructures and generates different consequences. Several investigations were achieved to improve the understanding of this phenomenon from theoretical to experimental. Experimental studies have lead to a classification of fuel as a function of combustion rate. These tests are generally based on constant level fire with fuel feed at the bottom of the sample. Theoretical studies have detailed the fire heat release distribution and the impact on the liquid fuel. Based on these results, the expected evolution of the fire includes three main parts: the fire increase, a constant maximal heat release period and the fire decrease. If this evolution suits with external pool fire, behaviour of the liquid can be impacted by contextual configuration. In confined infrastructures, such as building or tunnels, the liquid fuel combustion velocity becomes an unsteady parameter and the heat release rate from the fire varies, and often a runaway phase of the reaction is observed. Because such fires could be used for demonstrating the efficiency of a ventilation system, the power release must be controlled. This may have an important impact on the design of a mechanical ventilation system or the fire resistance of the infrastructure. To control the released power of such a fire, it is important to have a good understanding of this diffusion flame influenced by the environment. Then, understanding the phenomena that occur in the fire region means characterizing: the radiative fraction, the thermal exchanges and the impact of the flow on the fire. Using the results obtain along several experimental campaigns, both confined and unconfined, that were achieved in INERIS concerning pool fire, the different physical parameters are discussed and confronted with theoretical one. This paper proposed a physical characterization that finally leads to a power control strategy for pool fire.

Keywords: combustion rate; medium scale; pool fire

1 Introduction

Pool fire is not only an important dangerous phenomena but a useful one. Such a phenomenon can occur in different industries as petroleum, chemical plants and generate dramatic consequences. However, such a phenomenon is useful for fire safety because it can be used easily, for example to validate a tunnel ventilation system. Liquid pool fires were studied through different ways in the Literature, theoretical, numerical and experimental. However, most part of these studies refers to steady state pool fires that are not in accordance with long pool fires experiment in tunnels. In such a configuration, not only the physic of the pool fire governs the phenomenon but the tunnel specificities too. On top of that, the objective of long time pool fire adds some complexity.

On the one hand, accidental pool fires can occur in the retention pool of highly important fuel storage that means very long pool fire. On the other hand, because pool fire can be used for checking the ventilation design, the heat release must be controlled during a period as long enough as vehicle fire, for example. Consequently, studying long pool fire is a major interest for safety engineers.

This study is based on an experimental approach. Heptane pool fires were achieved in a third scale tunnel in order to determinate evolution of the heat release of such a fire during a long period that can reach more than one hour. This evolution shows that a runaway occurs instead of a constant heat release rate. Understanding the occurrence of such a runaway is crucial because it reveals that classical approach of constant heat release rate cannot be considered as an adjutant approach. The present study refers only to confined pool fire, i.e. it mainly concerns fire in tunnels, and cannot of course be extrapolated to atmospheric pool fire. In that second case, the heat exchanges are quite different.

This paper presents first the theoretical and experimental heat release curve for a heptane pool fire. Next, on the basis of temperature evolution in the liquid, the different phases that were observed are explained. Finally, some experiments enable to validate these explanations.

2 Experimental Heptane Pool Fire

2.1 Experimental Apparatus

Experiments were achieved in the INERIS fire gallery. This experimental device is a tunnel with a third scale section compare to a real one with 3 m in width and 1.85 m height. This tunnel is 50 m long and is equipped with ventilation and air treatment system, Fig. 1. The objective of this series of experiments was to understand long pool fire behaviour. Pool fire behaviour was experimentally studied but experiments are generally short pool fire, less than 10 minutes. The objective of the present campaign was to study more than 30 minutes pool fire. Pool fire was reproduced using heptane in a 0.25 m² round pool. This recipient contains around 22 kg of heptane for each test. The ventilation was forced in the gallery to represented longitudinal ventilation of road tunnel. The ventilation flow rate was about of 5.4 m^3/s during the fire tests. This forced ventilation of course can influence the fire development because the oxygen feed is limited by this ventilation system on the opposite of atmospheric fire that are feeding on requirement.

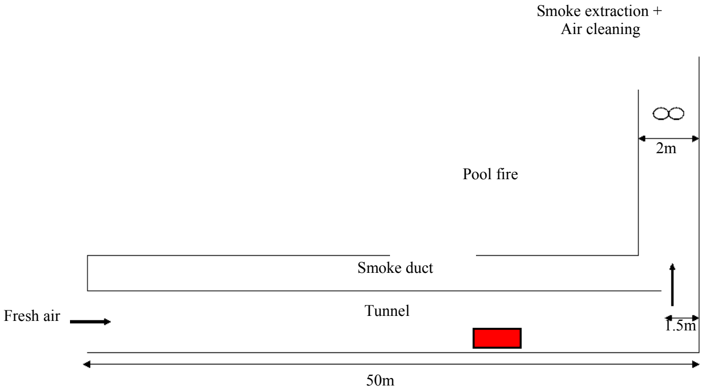

Fig. 1 Experimental apparatus schematic representation

2.2 Ideal Heptane Pool Fire

The apparatus used to generate the fire is a round container of heptane with a section of 0.25 m² and 0.20 m height. Such an installation may enable to obtain a constant power. Following theoretical knowledge about liquid pool fire, the fire power and duration can be evaluated using the combustion velocity and the heat of combustion. Using the classical values for heptane [1-2], i.e. a combustion velocity of 44 g/(m²·s) (i.e. 11 g/s for a 0.25 m² pool) and a heat release of 44.6 MJ/kg, the power that has to be reached by a 0.25 m² heptane pool fire is of about 500 kW. This correspond to the theoretical fire and, for such a theoretical approach, the initial power increase phase can be described using a t² law [3]. For a heptane pool fire, the corresponding phase is a very fast fire increase. This enables to evaluate the theoretical time for a 0.25 m² and the theoretical evolution in time of the fire power. The estimate time for this fire is about 40 minutes with a 20 minutes long period of steady state which corresponds quite to the standard curve for a vehicle in tunnel, as described in the first section. This theoretical approach predicts a three phases curve for heat release along time, Fig. 2.

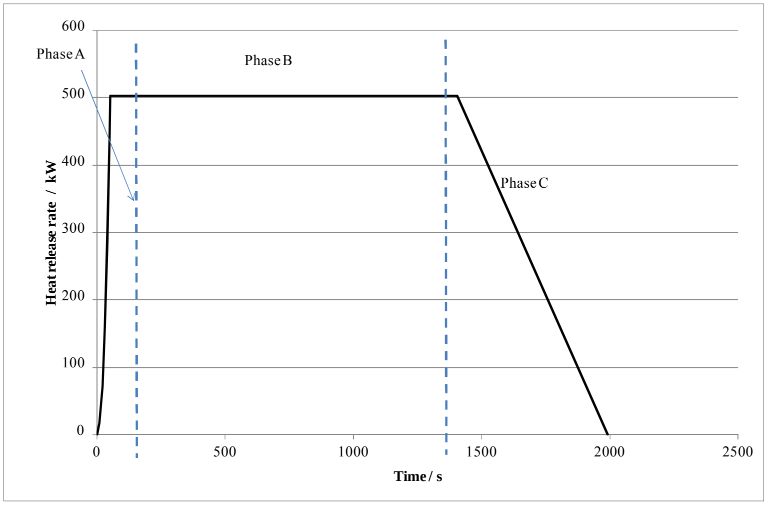

Fig. 2 Theoretical heat release curve for heptane pool fire

This theoretical approach shows that fire duration must be higher than half an hour with a very fast heat release rate increase and 22 minutes of constant heat release. On the basis of this approach, experiments were achieved for a 0.25 m² heptane pool fire.

2.3 Experimental Heptane Pool Fire

After this theoretical description of the heptane pool fire, it is important to check the compatibility between a theoretical pool fire and a real one. Long heptane pool fire were achieved, the total duration of the fire was longer than 30 minutes. This induces enough time to equilibrate the different thermal exchanges. The experimental release rate is reproduced on Fig. 3.

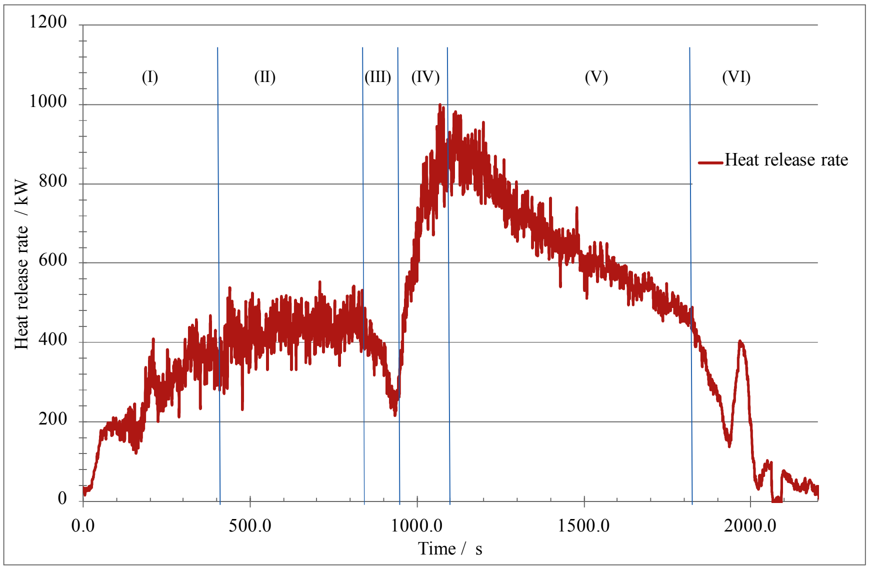

Fig. 3 Evolution of the power of a free heptane pool fire

As it appears on this figure, 6 different phases could be distinguished:

I. Initial fire growth period,

II. Steady power release phase,

III. Power decaying period,

IV. Rapid power increase,

V. Long power diminishing.

VI. Extinction.

Of course, this curve must be compared with the theoretical one. It appears that the heat release during phase II is in quite good accordance with theoretical value, around 500 kW. It however appears that this value is not the peak value reached by the fire. The heat release maximum value is quite the double of this theoretical value and the decrease phase, starting from this important peak value decrease to the theoretical maximum before the extinction phase. On top of that, it must be noticed that the second phase is quite longer than the first constant phase II. Finally, a surprising decrease appears in the middle of this heat release rate evolution before the important rise. Consequently, all these six phases must be explained and understood. Before going any further in the explanation for each phase, the physical behaviour of a pool fire must be described.

3 Liquid Fuel Pool Fire Physical Description

It must be first kept in mind that pool fire is nothing else than a self-sustaining diffusion flame. This implies two main characteristics: first, the flame position is governed by the mixing with air and second, the flame governs the combustible gas production. So, the above mentioned problem of obtaining a long steady fire means obtaining a steady exchanges between the flame and the liquid in order to feed the fire with a constant combustible flow rate.

3.1 Overview of Heat Exchanges

Several studies were achieved to improve the understanding of the pool fire behaviour. However, a large number of experimental tests were done at small scale either for space or in time. In both case, the involved phenomena are not representative of a large and long pool fire. Furthermore, the confined configuration in tunnel adds some complexity.

The thermal transfers were studied by different authors [4-5] and can be simplified to the scheme that represented this equilibrium, Fig. 4.

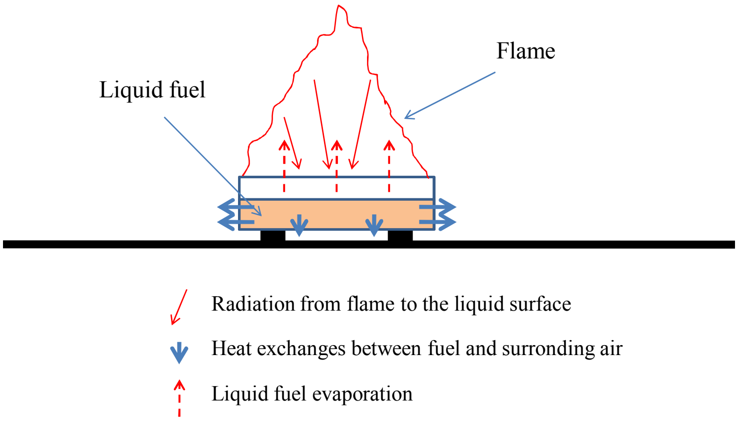

Fig. 4 Thermal exchange for a pool fire

This scheme represents a simple view of the thermal exchange between the air, the flammable liquid and the flame. It must be consider however that, in a tunnel configuration, the ventilation flow has an influence on the flame behaviour. The ventilation velocity will move the flame downstream the pool, as represented on Fig. 5.

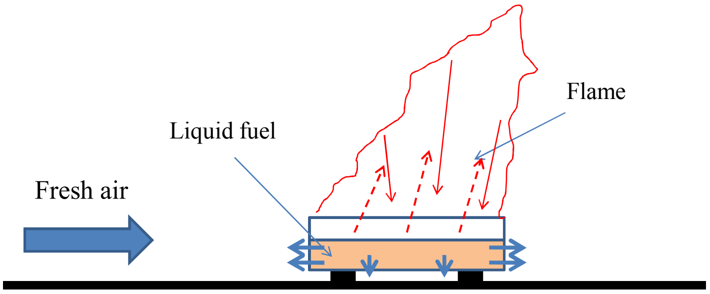

Fig. 5 Thermal exchange for a pool fire in tunnel configuration

The principle consists in heating the fuel by the energy emitted by the fuel combustion till it reaches a sufficient temperature to provide fuel vapour. Two cases should be distinguished. The first consists in a liquid boiling with emission of fuel without air. In that case, liquid behaviour will be quite chaotic because of the boiling effect. The second is equilibrium at a temperature that induces a high enough vapour pressure on the liquid surface. On that second case, some air will be present in the initial mixture. For the studied pool fire, the temperature seems to be of about 90°C (Fig. 6) that corresponds to a vapour pressure of $7.8.10^4$ Pa, which induces a fuel concentration of 78%.

The configuration of the heat reception and heat losses induces the creation of a temperature gradient inside the liquid. This means that keeping a steady evaporation rate requires a steady heat exchanges.

Having this behaviour in mind, analysis of the temperature evolution curves can be achieved.

4 Fire Phases Understanding

To improve the understanding of the six above described phases, thermocouples were introduced inside the pool to follow temperatures during the fire, Fig. 6.

This curve must be read keeping in mind the heat release rate evolution. This comparison between the two curves shows clearly that the beginning of rapid heat release increase corresponds to the instant when the liquid temperature at the pool bottom reaches the heptane boiling temperature. Based on these elements, an explanation of the heat release evolution is discussed in the following. The strong temperature rising on this graph reveals that the flame reaches the thermocouple.

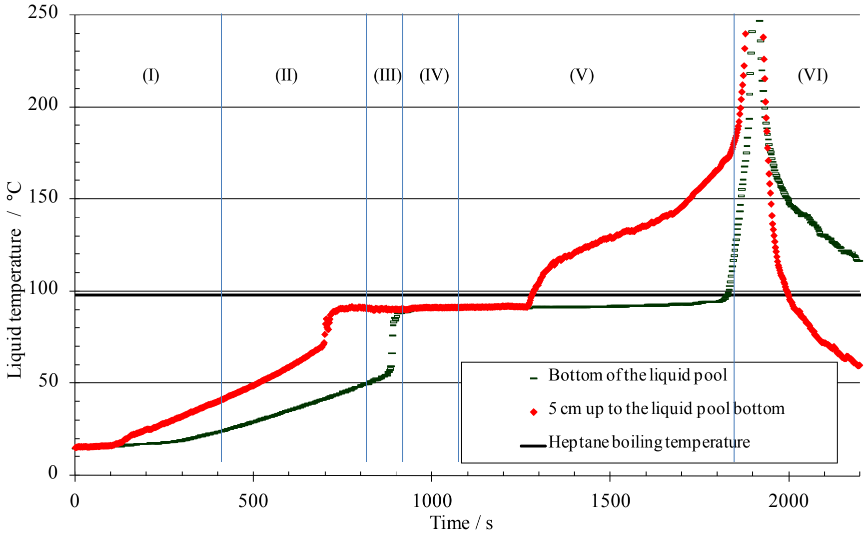

Fig. 6 Temperature evolution for the two thermocouples in the liquid

4.1 Initial Growth and Constant Phase – Phase I and II

The first two periods, i.e. the initial power growth and the steady period, are typical of pool fire. However, it must be noticed on the heat release rate that the increase is slower than expected. The rising curve does not follow a t^2 classical curve as discussed by [3]. The main consequence of this is that using a t^2 heat release rising is not realistic but induced an adjutant position for safety study. During the initial growth phase energy received by liquid heptane is used to produce more fuel vapour till equilibrium is reached. During this equilibrium phase, as discussed above, flame energy radiated to the liquid is divided into two parts:

- Evaporation of fuel,
- Energy conduction inside the liquid.

Considering that evaporated part of the liquid was previously preheated and knowing the mass loss rate, it is possible to evaluate the energy consumed for evaporation. The mass loss rate is around 10 g/s, which mean an energy consumption of 3.21 kW with a 321 kJ/kg for the evaporation enthalpy. Having assumed that this part of liquid was previously preheat, it imposes that the same quantity is preheat during this time from the ambient, around 10°C, to the boiling temperature, 99°C that corresponds approximately to 2 kW. This flux is distributed inside the liquid that generates the creation of the thermal gradient.

Then, the liquid temperature evolution is governs by the equation for energy conservation that can be written, for such a pool fire geometric configuration [6]:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\alpha \frac{\partial T}{\partial z}\right) + V_a \frac{\partial T}{\partial z} + \frac{k}{\rho C_p} q_r \exp(-kz) \tag{1}$$

where T is the temperature, t, the time, z, the vertical position, α, thermal diffusivity, V_a, regression velocity, k, radiative absorption coefficient, r, the density, C_p, specific heat and q_r the incident radiative flux. Solving this equation will enable determining the temperature evolution at the bottom of the pool.

In the a first approach, the steady thermal gradient thickness can be determined. Considering that this gradient is steady and moves with the regression velocity, i.e. a virtual z is attached with the liquid surface; it is possible to simplify this:

$$\frac{\partial}{\partial z}\left(\alpha\frac{\partial T}{\partial z}\right)=\frac{k}{\rho C_p}q_r\exp(-kz)+V_a\frac{\partial T}{\partial z} \tag{2}$$

$$\frac{\partial T}{\partial z}=-\frac{1}{\rho C_p\alpha}q_r\exp(-kz)+V_aT(z) \tag{3}$$

This theoretical basis will be used to develop a model to predict liquid fuel behaviour.

4.2 A First Decrease – Phase III

As mentioned above, a surprising decrease is observed in the middle of the heat release rate evolution curve. Considering that the fire is linked to both combustible and oxidant, it is legitimate to wonder about those two aspects: a modification of the heat exchange equilibrium or a transition to a ventilation control fire. Those two ways are developed and experimental validation configurations are proposed for each one.

(1) Fire controlled by heat exchange?

The first reason that can be developed concerns the fire itself or, more precisely, the heat exchange equilibrium between the fuel and the air. A rate decrease means that the evaporation fuel rate is diminishing which signifies that, one part of the energy is lost by the fuel due to a modification of the thermal exchanges equilibrium. Considering that this heat release reduction occurs just before the liquid reached its boiling temperature at the bottom of the pool, it is relevant to wonder about the heat transfer between the fuel and the surrounding air in this phase. To have a better understanding of these exchanges, photography of the experimental set up and a scheme of this installation are reproduced on Fig. 7.

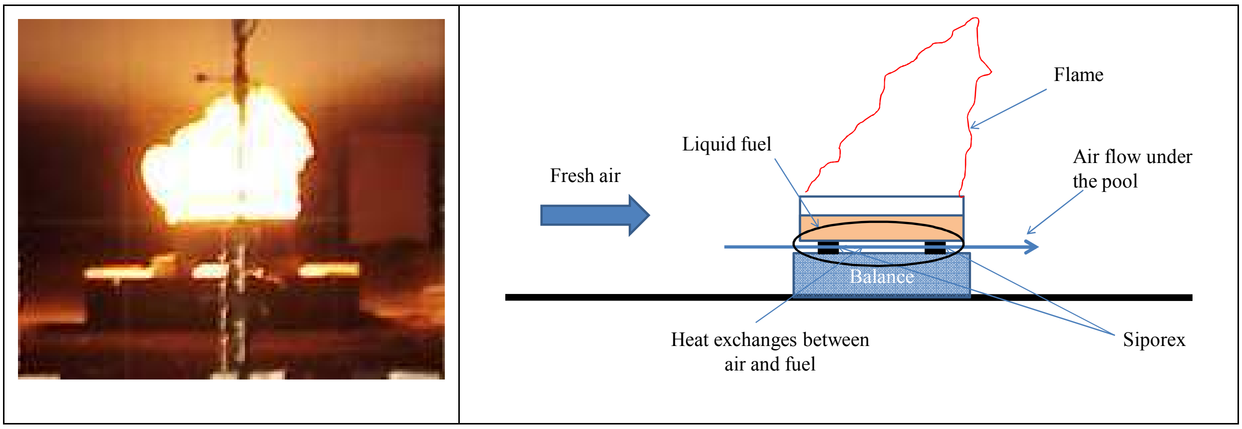

Fig. 7 Photography (left) and scheme (right) of the experimental set-up for fire

The heat exchange between the air flow under the pool and the liquid, or more precisely the steel at the bottom of the pool, is a convective exchange that can be written as follow, equation (2).

$$\mathrm{d}^2Q=h(T_p-T_{\mathrm{air}})\mathrm{d}S\mathrm{d}t \tag{4}$$

where d^2Q is the heat quantity that go through the surface element $\mathrm{d}S$ during $\mathrm{d}t$. T_p and T_{air} are respectively the steel and the air temperature. This equation shows that increasing the steel temperature will induce a heat exchange increase. To highlight this, the parallel evolution of bottom pool temperature and heat release rate is given on Fig. 8.

This figure clearly shows the quick increase of the temperature at the bottom of the pool due to the temperature gradient propagation inside the liquid. Consequently, this induces an increase of the heat exchange with the ambient air that flows under the pool and can consequently generate a decrease of the evaporation rate.

To check whether the heat exchange equilibrium modification influences the heat release or not, this experiment was achieved with insulation at the pool bottom, Fig. 9.

This figure shows that, for such a configuration, heat exchange are not possible at the bottom of the pool between incident air and the liquid. Then, the heat release rate for such a configuration was plotted on Fig. 10.

This figure clearly shows that introducing insulation at the bottom of the pool does not modify the heat release curve, including the heat release decrease that is kept for such a configuration. Such a result enables to reject the theory based on a modification of the heat exchanges.

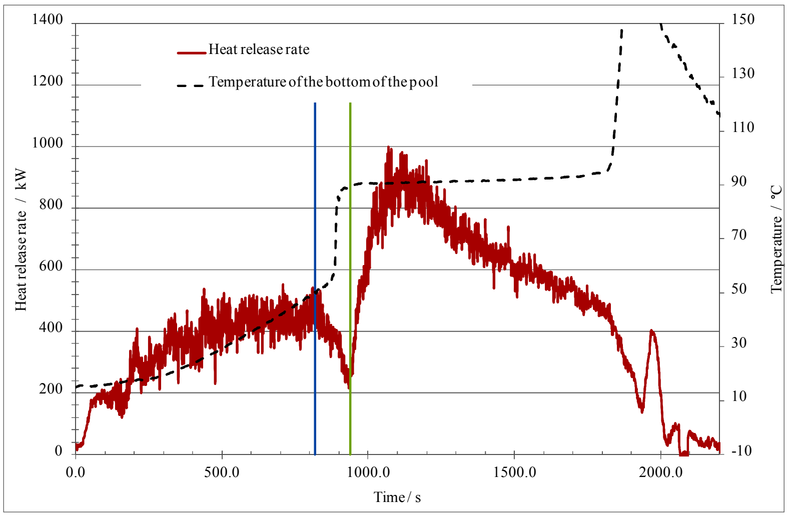

Fig. 8 Comparative evolution of heat release rate and temperature at the bottom of the pool

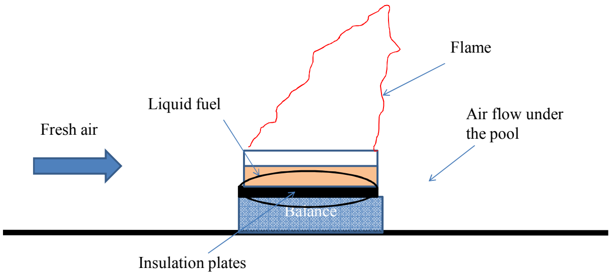

Fig. 9 Experimental configuration with insulation at the pool bottom

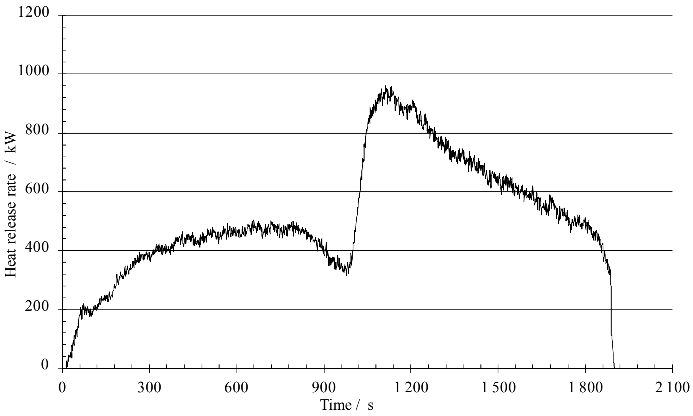

Fig. 10 Heat release rate for a heptane pool fire with thermal insulation at the bottom of the pool

(2) Fire controlled by the ventilation?

To evaluate the oxygen lack on the control of the fire, it is first necessary to consider the ideal reaction for heptane written as follow:

$$C_7H_{16} + 11\ (O_2+3.773\ N_2) \rightarrow 7\ CO_2 + 8\ H_2O + 41.5\ N_2 \quad (5)$$

This equation shows that, in ideal conditions, 11 moles of oxygen, i.e. 0,352 kg, are required to burn 1 mole of heptane, 0.100 kg. Considering the ideal value for specific heat of heptane at 44.6 MJ/kg, this implies that a 500 kW fire corresponds to an heptane consumption rate of 0,011 kg/s and consequently requires 0.04 kg/s of oxygen. This corresponds to an air flow of 0.2 kg/s to feed the fire. The forced ventilation in the fire galley is of about 6.5 kg/s for the whole 5.4 m² of the section of the fire gallery. Of course not all this air feed the fire but considering that the flame is located in the middle of the section, most of this air may be used. This of course, will be discussed. It is important however to consider the restriction due to the smoke layer than can reduced oxygen concentration by mixing with smoke, Fig. 11.

Fig. 11 Photography of the pool fire with the backlayering layer

To validate this, the fire was located at the entrance of the fire gallery to minimise the impact of the smoke layer. This experiment was achieved to minimise the influence of the backlayering layer on the fire. Consequently, its objective was to validate or not the theory based on the ventilation control. The heat release evolution obtained with this configuration is plotted on Fig. 12. This curve was obtained for a regulated fire; i.e. with water circulation at the bottom.

Fig. 12 Heat release rate for a fire at the entrance of the gallery.

This last curve shows that diminishing the effect of the backlayering induces an elimination of the decreasing phase which confirm the second developed approach that means a heat release controlled by the lack of oxygen.

4.3 A Rapid Increase – Phase IV

As discussed in the introduction of this paragraph, this rapid increase corresponds to the end of liquid preheat inside the pool. At the beginning of this phase, all the liquid is at the boiling temperature and all the energy received from the flame is used for heptane evaporation. Consequently, the gaseous fuel production increases and leads to an important rise in the heat release rate. Then this phenomenon is self sustained till a new equilibrium to be reached. This is shown on Fig. 8.

Of course, such a configuration must be fuel dependant. To evaluate this, an alcohol pool fire was achieved.

Properties of alcohol must be first compared with heptane ones. The boiling temperature is lower for alcohol with 79°C and the vaporisation enthalpy of 855 kJ/kg is higher. The heat of combustion for alcohol is only 28 MJ/kg[2]. Then, a 0.25 m² pool fire was achieved in exactly the same experimental conditions than heptane. The heat release rate evolution along time is plotted on Fig.13.

This curve shows explicitly differences with the heptane one. On this evolution, it appears the heat release rate to be constant along time on a very long period, longer than one hour. So, considering this heat release evolution, it is legitimate to wonder about the liquid temperature evolution inside the pool, Fig. 14. According the explanation developed in the previous paragraph, the temperature at the bottom of the pool stays lower than the boiling one.

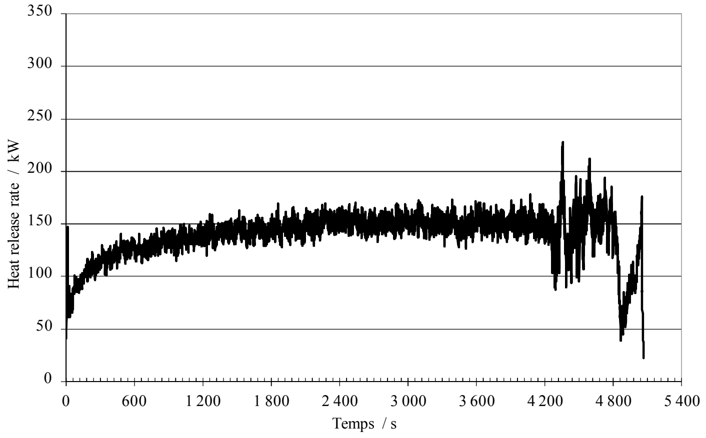

Fig.13 Heat release rate evolution for an alcohol 0.25 m² pool fire

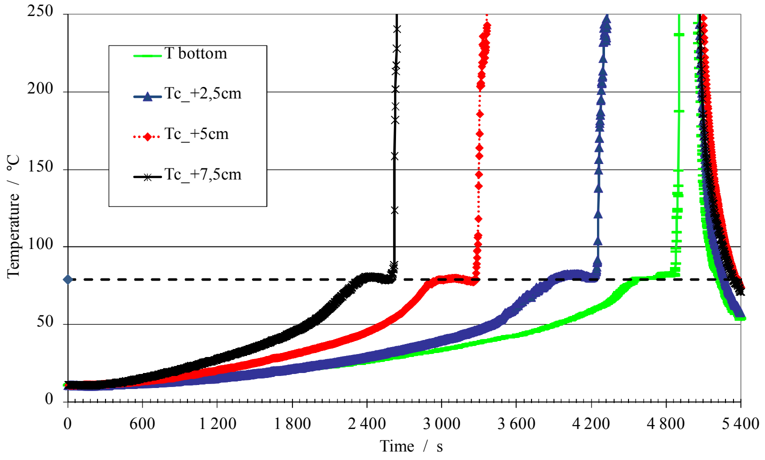

Fig. 14 Liquid temperature evolution along time for an alcohol pool fire

This curve clearly shows that the liquid temperature at the bottom does not reach the boiling temperature. Consequently, as discussed previously, the fire runaway cannot occur, which is demonstrated on Fig.13. This curve also shows that the heat propagation inside the liquid is limited for this product.

This fire seems indicating that there exists a criterion, based on some liquid properties as mainly heat of combustion, vaporisation energy, thermal conductivity and boiling temperature that governs the fire as mentioned by [7]. These properties are linked, not only with the combustion velocity, but with the transition to a runaway phase too.

To go any further, it is of course interesting to achieve a fire with a heat sink to prevent from boiling at the bottom of the pool. So, the second test case consists in a heptane pool fire with a heat sink at the bottom of the pool. A water cooling circuit was introduced at the bottom of the pool to prevent the liquid reaching its boiling temperature at the bottom of the pool. This method leads to the elimination of the runaway of the heat release, Fig. 15.

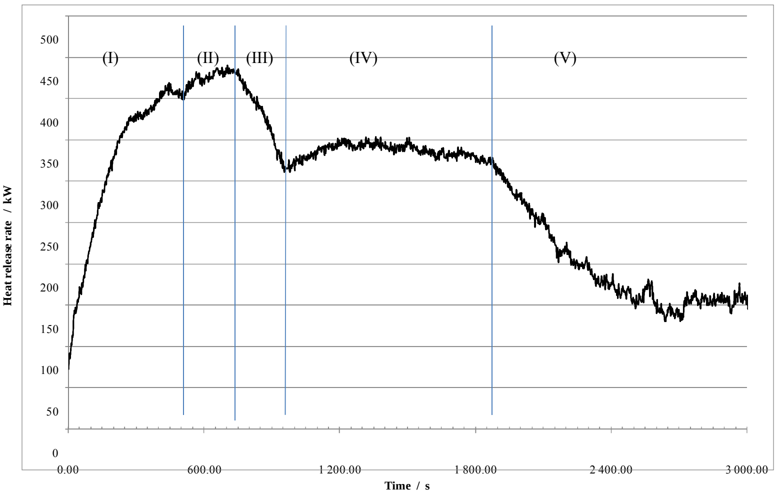

Fig. 15 Heat release rate from a regulated heptane pool fire

This figure lets appear 5 phases:

I. Initial fire growth period,
II. Steady power release phase,
III. Power decaying period,
IV. Second steady state,
V. Power diminishing.

Compared with the initial fire curve, Fig. 3, the runaway phase was replaced with a constant heat release phase. However, it can be noticed on this curve that the decaying period is still observed. It is however legitimate to wonder about the impact of the regulation system on this decaying period. A reduction of the regulation temperature should enable to maintain a constant heat release.

4.4 A Slow Decrease – Phase V and VI

After a short stability period at its maximum, some seconds, the heat release rate starts decreasing slowly. This short stability period signifies that the heat release run away is not a stable situation and the required energy to maintain it is higher than the energy received from the flame. Consequently, the energy received is used for evaporating a certain quantity of liquid lower than the required one to produce energy enough to evaporate this quantity. Consequently, the energy release by the fire is diminishing. On top of that, it is relevant to wonder about the combustion properties. Because of the fuel evaporation rising, the combustion will be modified and should become richer with the associated efficiency reduction and the increase of soot production. Of course those two phenomena will act simultaneously during this decrease phase.

It is important to note that this decrease phase follow a t^2 decreasing law with an asymptote with a value that correspond to the initial steady phase heat release.

4.5 Synthesis

This experimental sequence of four configurations has enabled not only to understand the different phases but to reach a configuration of constant fire as described by the theory. First, it was shown that, as mentioned by [7], physical behaviour of the fire is linked with heat of combustion, vaporisation energy and boiling temperature. Second, for a given fuel with an important enough heat of combustion that can leads to a runaway, it is possible to obtain a constant heat release with some adaptations. The first consists in introducing a heat well at the bottom of the pool and in ensuring a sufficient air feed to the fire.

5 Conclusions and Perspectives

This paper refers to liquid pool fire in confined spaces and their impact. It was first shown that, such a confined pool fire does not behave as theoretical predictions. . It must be first noticed that the first steady heat release value is close to the theoretical one but while three phases are waited, six can be distinguished including a runaway that induces the heat release to be doubled. Of course, this can have a major impact not only on the design checking but on consequences predictions too. On top of this runaway, a first decrease phase was observed just before this runaway. Those two phases are not classical and an explanation was proposed on the basis of temperature measurement inside the liquid.

Concerning the runaway, the explanation is based on the thermal exchanges equilibrium. When the whole liquid reach the boiling temperature, the evaporation rate increase rapidly because energy no more diffuses inside the liquid. That means that all the energy received by the fuel is used to generate vapour. This phase is however not a stable one and, just after this quick increase, a t^2 decrease is observed and the heat release tends to reduce to the theoretical value. Several reasons are proposed to explain this reduction based on heat exchanges equilibrium or on the combustion properties. Two reasons can explain the decrease phases; the first is based on heat exchanges while the second is based on a combustion control by the ventilation. Experiments were achieved to evaluate both configurations and show that this phase seems due to a transition from fuel control to ventilation control. Because the creation of a backlayering smoke layer, the air feed to the fire is reduced and consequently, the heat release is diminished.

In the last part of this paper, several experimental configurations are proposed for evaluate the explanation. The alcohol pool fire shows that the fire behaviour, not only in terms of combustion rate as proposed previously [7] but in terms of thermal gradient inside the liquid too. Considering that this gradient governs the runaway, such a correlation should be used to predict whether or not such a phenomena can occur.

This work was mainly based on experimental confined fires and cannot be generalised to all pool fires. This work must be extended to atmospheric fire in which thermal exchanges are quite different. The comparison between those two configurations of long fire will leads to a better understanding of this phenomena. On top of that, these experimental results will be coupled with numerical simulation to provide more information about the fire behaviour.

Finally, on the basis of the theoretical evolution of temperature inside the liquid, a model will be developed to predict liquid fuel behaviour. This model will be validated on the basis of the numerous experimental data available in INERIS. This model will mainly be based on the product characteristics, latent heat, vapour pressure as a function of temperature, heat of combustion and thermal conductivity in the liquid. The last will be used to predict thermal gradient thickness while the other will enable to have an estimation of the combustion rate for a given fuel.

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