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METHOD TO OBTAIN LARGE SCALE BURNING RATE OF LIQUIDS WITH LAB SCALE TESTS

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Abstract

The aim of the study is to determine the burning rate of various flammable liquids at large-scales from small-scale experiments. However, it is not possible to carry out systematic tests on medium or large-scale to determine the fire properties of each product. The small-scale fire tests in laboratory offer many advantages in terms of cost and time in comparison with the large-scale experiments. But, the question remains the use of these experimental results in fire scenarios. Indeed, some measurements performed in laboratory scale, as the mass loss rate or the radiative fraction, cannot be directly extrapolated due to the scaling effects. It is well known that these latter modify the fire properties as the pool diameter rises from small cups to large pans ([6]).

According to Tewarson ([1], [2], [3]), fuel mass loss rates close to those measured at large-scale could be obtained from small-scale fire tests by increasing significantly the oxygen concentration of ambient air or by increasing the radiative heat flux to the combustible sample. Moreover, the former technique seems to show that an asymptotic value for mass loss rate is reached, as the oxygen concentration becomes more than 0.30 % ([2]). This asymptotic value would be comparable to the fuel mass loss rate measured in large-scale fires. In this work, these two experimental techniques are performed in a calorimeter apparatus ([8]) for eight liquids. Then, a way to use the small-scale experimental data is investigated in order to estimate the fire behavior at large-scale.

The analysis of experimental results allows us to propose a first classification on several liquids. This classification is based on the oxygen concentration or the radiative heat flux necessary to obtain the same burning rates as those measured in large-scale fire tests performed in the INERIS facility (fire gallery). A non-dimensional number, the ratio of the heat of gasification to the heat of combustion, is also introduced and seems to show that the fuel classification proposed here always holds. Finally, this approach (classification of fuel thanks to the non-dimensional number followed by one small-scale experiment) is tested with another liquid fuel (ethyl acetate), for which only the experimental data in the fire gallery are available. The conclusions of this study are very encouraging.

Keywords : large-scale, lab-scale, burning rate, heat flux, Tewarson calorimeter, oxygen concentration

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1. Introduction

Fire is a complex problem because of several interactions between physical and chemical processes, external environment and material properties of combustible. It is well known that the fire behavior observed in the small-scale fire tests in laboratory cannot be directly extrapolated to large-scale fire experiments. Nevertheless, determining the fire properties of various combustibles, and especially the heat release rate, is essential to predict the fire hazards in reality ([4]). Indeed, even if the fire modeling can often predict successfully the fire behavior in compartments, the knowledge of the initial heat release rate remains of first importance to simulate fire scenarios with a good confidence and to evaluate correctly the damages of fire on industrial facilities.

Nowadays, it is not possible to carry out systematically numerous experiments from small-scale to large-scale fire tests in order to determine the fire properties of any combustible available in industrial processes and in domestic materials. The main difficulty is due to the costs and the time associated with conducting large-scale fire experiments. Therefore, a great challenge for engineers is to investigate a way to use the small-scale data to predict the fire behavior of large-scale fires test, as previously written by Nam et Al ([11]): *“It would be very convenient if relatively simple and inexpensive bench-scale tests can be used in lieu of the full-scale test to assess the flammability of the materials”*.

The aim of the present work is to investigate a way to determine the large-scale burning rates of pool fire for liquid fuel from small-scale flammability tests performed in a Tewarson Apparatus ([8], [9]). To do this, this study relies on the Flame Radiation Scaling Technique (FRST) proposed by Tewarson ([1], [2], [3]). On another hand, small-scale fire experiments are also performed in the same apparatus by increasing the radiative heat flux to the fuel sample. Finally, the mass loss rates obtained from the two previous techniques at small-scale are compared with those measured in the INERIS fire gallery at large-scale. The experimental results of this work suggest that liquid fuels considered here could be classified according to their fire properties. Then, this classification allows to estimate with satisfaction their large-scale burning rate thanks to a simple small-scale fire test.

2. Previous investigations

In 1950s, Blinov and Khudiakov [6] performed an extensive study concerning the burning rates of liquid pool fires from small-scale and large-scale fire experiments. Typically, the pool fire diameters ranged from 3.7×10^{-3} to 22.9 m for various hydrocarbon liquids as gasoline, kerosene, diesel, petroleum, etc. Few years later, Zabetakis and Burgess ([7]) recommended first to fit these existing experimental data as the burning rate vs. the pool diameter. They have proposed the following relationship:

$$\dot{m}' = \dot{m}'_0 \left(k\beta D \right)^{-1} \quad (1)$$

With: \dot{m}'_0 : Mass loss rate of fuel per unit fuel surface area ($\text{kg/m}^2/\text{s}$).

$k\beta$: Empirical factor ($1/\text{m}$).

D : Pool fire diameter (m).

Finally, Babrauskas ([5]) compiled numerous experimental data available for estimating the burning rate and provided values of \dot{m}'_0 and $k\beta$ for more than 20 liquid fuels and one solid material (PMMA). But, the two parameters of the above correlation can be only estimated with confidence from fire experiments carried out from small-scale to large-scale. Thus, even if this approach is quite predictive, it requires to perform numerous fire tests, which are usually expensive and time consuming (especially for the large-scale fire experiments).

In order to limit the number of fire tests and to understand in depth the scaling effect, many researchers have attempted to develop a theoretical model for burning rate, such as the experimental parameters in the model could be easily obtained from the fire properties of materials and would not be dependent on the pool diameter considered. Very good reviews about different theoretical

approaches are available thanks to Hamins et Al [12] and De Ris et Al [13]. The older approach was developed in the 1960s and was based on the modeling of the fire by the Froude number. The Froude modeling is widely used and provides most of present correlations to estimate the characteristics of the fire and the plume. In 1970s, some experiments carried out by the Factory Mutual Center showed that the convective and radiative heat fluxes from the flame increased with the two-third power of absolute pressure. This would allow potentially for simulating large-scale fire tests from small-scale experiments performed in pressurized vessel. At the same time, “Pressure modeling” ([13]) has been developed to investigate the basic understanding of the pressure dependence of fire characteristics in diffusion flames. More recently, De Ris et Al ([13]) have proposed the concept of “Radiation Fire Modeling”, which has been designed to preserve the full-scale flame heat fluxes by increasing the ambient pressure a moderate amount as the scale is reduced. It has occupied an intermediate position between Froude and Pressure modeling. The main assumption of radiation fire modeling was that, by holding the product of a characteristic length scale by the square of the absolute pressure, the flame heat flux in the model have remained approximately the same as that at full scale. Nevertheless, De Ris et Al ([13]) concluded that this concept was confirmed by a limited set of pool fire experiments.

In the 1980s, Tewarson ([1], [2], [3]) proposed another empirical approach, named “Flame Radiation Scaling Technique” (FRST), to take into account the scaling effect from small-scale fire tests. Indeed, Tewarson ([1]) showed experimentally that, as the oxygen mass fraction is increased, the radiative heat flux from flame, \dot{q}'_r , is also increased. The increase in the \dot{q}'_r value with the oxygen mass fraction is mainly due to the increase in the flame temperature and soot formation, and the decrease in the residence time in the flame. The experimental results obtained by Tewarson seemed to show that the increase of oxygen concentration could increase the burning rate up to an asymptotic value, which was reached for oxygen concentration higher than 30% ([2]). According to Tewarson ([1], [2]), these asymptotic values seemed comparable with the values of burning rate obtained in large-scale fire tests. To illustrate this approach, Tewarson compared quite successfully the mass loss rates obtained from small-scale fire experiments under FRST with those obtained from large-scale fire tests for 5 fuels (N-heptane, two transform fluids, polystyrene, PMMA, methanol). Nevertheless, this technique is widely empirical and no theoretical modeling sustains its validity. The main advantages of the small-scale fire tests using FRST are to be easy to implement, flexible and less costly than large-scale fire experiments. For these reasons, some experimental results obtained in this study are based on the Flame Radiation Scaling Technique.

3. Experimental Apparatus

3.1. Tewarson Calorimeter

Experiments were carried out with the Fire Propagation Apparatus located at INERIS Fire Laboratory (Fig. 1). This apparatus, originally called “50kW lab-scale flammability apparatus” in the USA and Tewarson apparatus in Europe, is a polyvalent fire calorimeter. It has been recently described in two standard test methods, ASTM E 2058 ([8]) and NFPA 287 ([9]), under the final designation “Fire Propagation Apparatus” (FPA). The FPA is used to quantify material flammability characteristics including time to ignition, heat release rates, mass loss rate, and so on.

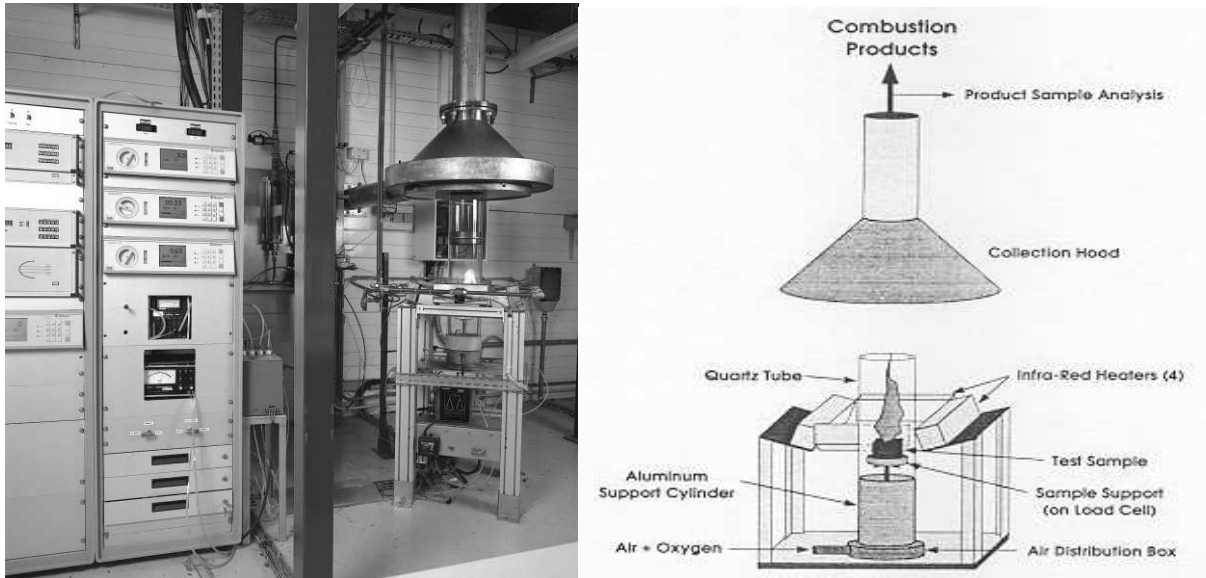


Figure 1: View of the Tewarson Calorimeter at INERIS

The air flow surrounding the fuel sample is controlled by means of two mass flow meters that allow the operator to set the desired mass flow rate of air of up to 300 Nl.min. Another mass flow meter allows mixing of various gases (as CO₂, N₂ or O₂) with the incoming air for non-ambient conditions. In this way, the incoming air in the apparatus can be enriched or depleted in oxygen. An oxygen analyzer measures the composition of oxidizing stream in order to know accurately the ambient condition. The sample probe is located just below the specimen holder in the combustion chamber. The upper part of the calorimeter is composed by the exhaust system, which recovers the combustion products before analyzing them in the test section. Four Infra-Red heaters are available to heat the sample with an external radiant heat flux coming from 0 to 60 kW/m².

The specimen holder is of 0.067 m in diameter and is insulated. During the small-scale fire tests, the thickness of the liquid fuel remains constant thanks to a fuel injection system.

Standard characterization of the composition of fire gases and smoke relies on the routine use of the on-line gas analyser. The heat release rate is measured from both oxygen consumption and carbon dioxide generation. The measurements performed during fire tests are the mass of the specimen, the concentration of various gases (O₂, CO₂, CO, NO, total unburnt hydrocarbons), the laser attenuation due to smoke at four monochromatic wavelengths, the gas temperature and the mass flow in the test section duct.

3.2. Fire Test Gallery

The large scale experiments were performed in the fire test gallery located at INERIS (Fig. 2). It consists of a horizontal tunnel of 50 m in length and having a semi-circular cross section of 10 m^2 in area. One end is directly opened to atmosphere and the other end is connected to a vertical fire compartment of 12 m in high and of 6 m^2 in area. This compartment is considered large enough to model the burning of a pool fire in open atmosphere: this point is discussed later. This first room is itself connected with a second compartment having nearly the same dimension. Both compartments are called “the tower” (Fig. 2). The second compartment is also connected to an installation equipped with gas sampling system and gas analysis instruments for various chemical products, and with water scrubbing system.

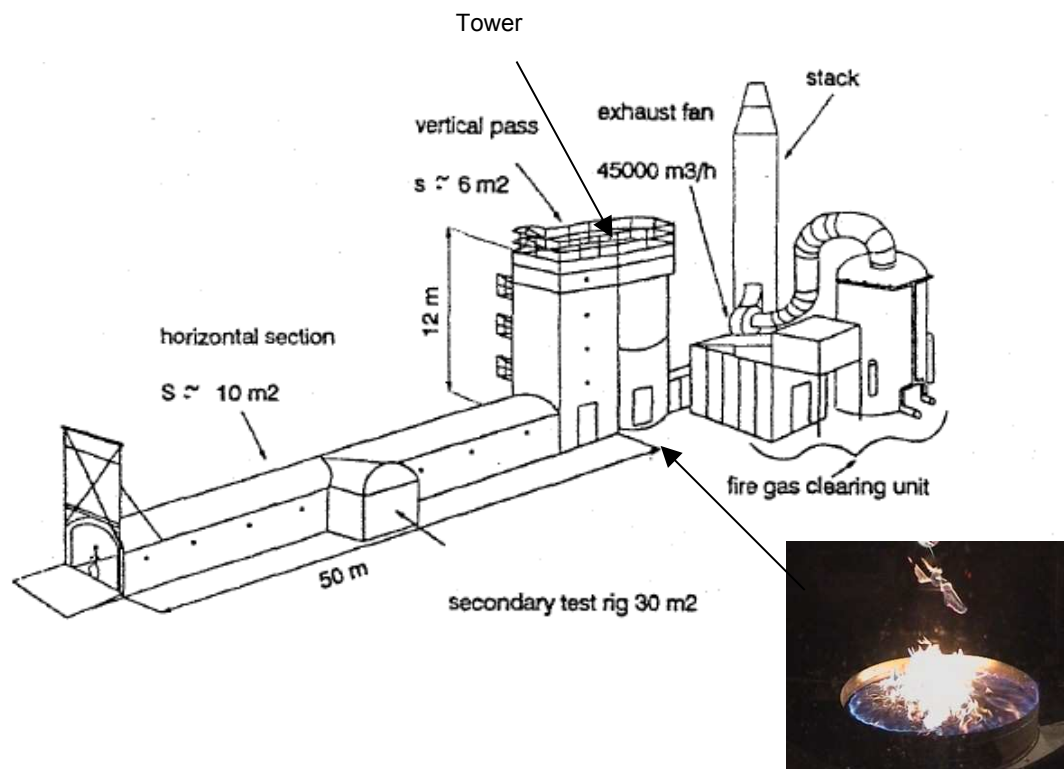


Figure 2: Fire gallery at INERIS

The liquid combustible was placed in a 1 m^2 circular pan located inside the tunnel at the middle of the first compartment in the tower. The mass loss rate of fuel was recorded during the fire tests by means of one balance placed below the pan. The combustible was ignited with a propane burner as shown in Fig. 2.

4. Liquid fuels

A campaign of several fire tests was performed on eight liquid combustibles in the INERIS fire gallery. The fire properties and experimental burning rates are presented in the table 1. The burning rates presented in this table are on one hand, the average values of burning rates at large-scale compiled by Babrauskas ([5]), and on the other hand the INERIS experimental data obtained in the fire gallery. These results are quite similar showing that: (1) the pool diameter is large enough to consider these experimental values as burning rates at large-scale ([5], [16]); (2) The fire compartment has minor effects on the burning rates.

Products	Formula	Molecular weight [g/mol]	Boiling Temperature [°C]	Heat of Combustion [MJ/kg]	Heat of vaporization [kJ/kg]	Calorific capacity [kJ/kg.°C]	Burning rate [g/m ² .s]	
							Babrauskas ([5])	INERIS
Acetonitrile	C ₂ H ₃ N	41.1	82 ⁽¹⁾	30.1 ⁽³⁾	736 ⁽¹⁾	2.2	-	50
Ethylene diamine	C ₂ H ₈ N ₂	60.1	117 ⁽¹⁾	28.6 ⁽³⁾	661 ⁽¹⁾	2.9	-	21
Acetone	C ₃ H ₆ O	58.1	56.3 ⁽¹⁾	29.7 ⁽⁴⁾	510 ⁽¹⁾	2.1	41	52
White spirit	-	-	135-205 ⁽²⁾	-	-	-	-	49
Heptane	C ₇ H ₁₆	100.2	98.4 ⁽¹⁾	44.6 ⁽⁴⁾	318 ⁽¹⁾	3.2	101	75
Pyridine	C ₅ H ₅ N	79.1	115.3 ⁽¹⁾	32.2 ⁽⁴⁾	446 ⁽¹⁾	1.7	-	65
Ethanol	C ₂ H ₆ O	46.1	78.3 ⁽¹⁾	27.7 ⁽⁴⁾	840 ⁽¹⁾	2.4	15	23
Kerosene	-	-	130-300 ⁽²⁾	43.2 ⁽⁵⁾	670 ⁽⁵⁾	-	39	44

⁽¹⁾ Component Plus (Pure components properties server; Editor: ProSim)

⁽²⁾ Material safety data sheet from supplier

⁽³⁾ European Program, “Mistral 2 Report”, INERIS, (Environment and climate research programme 1994-1998).

⁽⁴⁾ Technical Report Factory Mutual (confidential report).

⁽⁵⁾ Internal Report (2002), “Feux de nappe”, available from: ‘www.ineris.fr’

Table 1: Fire properties of the liquid combustibles used in this study

5. Results and Discussion

5.1. Burning rates as a function of oxygen concentration or external heat flux

Small-scale fire tests were carried out in the Tewarson calorimeter on different liquid fuels to investigate the effects of external heat flux and oxygen concentration on burning rates. Figure 2-a shows the evolution of burning rates as the oxygen concentration in air increases from nearly ambient (15%) to 80%, and Figure 2-b shows it as the external heat flux rises from 0 to 55 kW/m².

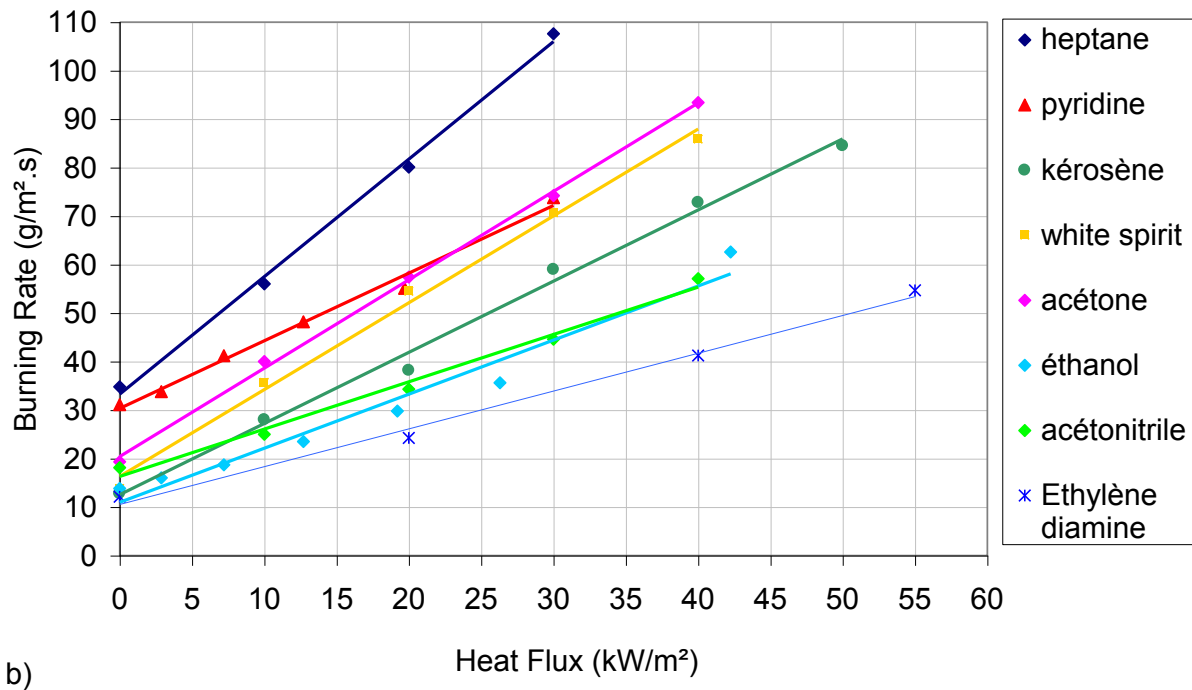
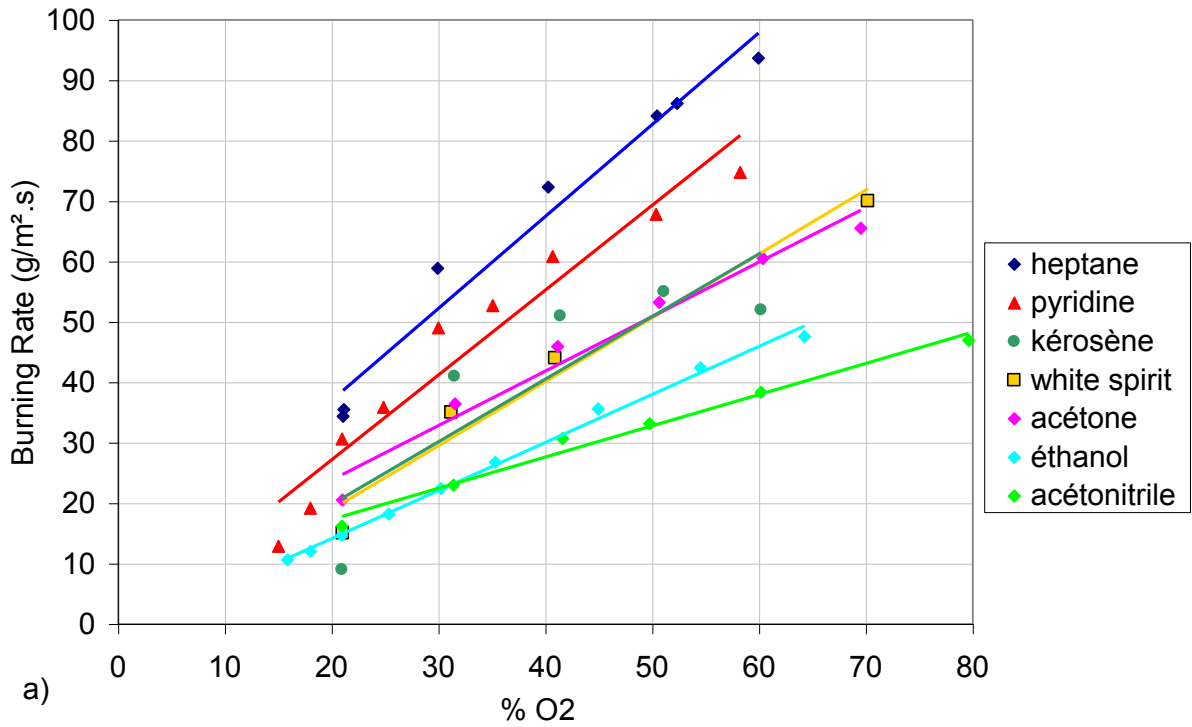


Figure 2: Evolution of burning rates according to
a) the oxygen concentration in air, b) the external heat flux

From Fig.2-a, the burning rate appears to be close to a linear function of the oxygen concentration, even for the highest oxygen concentration (> 30%). According to Tewarson ([15]), as the oxygen concentration increases to reach more than 30%, an asymptote limit for burning rate is expected and this value could be very close to the burning rate at large-scale for the combustible considered. Nevertheless, no asymptotic value expected for each fuel has been found in our experimental data. One deduces that the FRST approach proposed by Tewarson ([1], [2], [3]) doesn't work very well with the liquid combustibles studied here.

As previously, the experimental results show also a linear function of the external heat flux versus the burning rate (Fig.2-b). As shown by Tewarson ([15]), the mass loss rate can be broadly written as:

$$\dot{m}'' = \frac{\dot{q}_e'' + \dot{q}_f'' + \dot{q}_c'' - \dot{q}_r''}{\Delta H_g} \quad (2)$$

where: \dot{m}'' is the mass loss rate, \dot{q}_e'' is an external heat flux, \dot{q}_f'' is the radiative heat flux from flame to combustible, \dot{q}_c'' is the convective heat flux transferred to the combustible surface, \dot{q}_r'' is the surface re-radiation loss and ΔH_g is the heat of gasification.

If the external heat flux increases and becomes much higher than the other heat fluxes transferred to the fuel surface ($\dot{q}_e'' \gg \dot{q}_f'' + \dot{q}_c''$), the above relation is simplified as:

$$\dot{m}'' \approx \frac{\dot{q}_e'' - \dot{q}_r''}{\Delta H_g} \quad (3)$$

Thus, if the external heat flux is high enough, the mass loss rate of fuel become proportional to the inverse of the enthalpy of vaporization. As expected, our experimental results confirm this theoretical analysis.

5.2. Proposal to classify the liquid fuel and to define a way for determining burning rate at large-scale from small-scale experiments

In order to compare the experimental results obtained at small-scale and large-scale, it is proposed in the table 2 to summarize the values of heat flux or oxygen concentration necessary to obtain the same burning rates as those obtained for liquid fuels in fire gallery.

Liquid Combustibles	Φ [kW/m ²]	O ₂ [Vol %]	$\frac{\Delta T_v + \tau_p * \Delta T_c}{\Delta T_c}$
Ethanol, ethylene diamine	12 ± 1	31 ± ★	0.034 ± 0.001
White spirit, acetone, heptane, kerosene, Pyridine	20 ± 4	47 ± 4	0.018 ± 0.004
Acetonitrile	28	83	0.029

★ Not measured for ethylene diamine

Table 2: Classification of the liquids according to the external heat flux and the oxygen concentration necessary to obtain the value of the burning rate on fire gallery

It seems that three groups of liquid combustibles appear from this table corresponding respectively to 12, 20 and 28 kW/m² for external heat fluxes and 31, 47 and 83% for oxygen concentration. Moreover, The measured uncertainties around the averaged values are quite narrow. This finding allows us to

introduce an empirical classification of these liquids according to the external heat flux or the oxygen concentration. Moreover, a better idea will be to estimate this classification from fire properties usually available in the literature.

According to Hamins ([10]), the steady mass vaporization rate is related to the ratio of the heat of gasification (ΔH_g) to the ideal heat of combustion (ΔH_c). Here, the heat of gasification is defined as :

$$\Delta H_g = \Delta H_v + \rho_p * \Delta T \quad (4)$$

Then, Hamins defines the non-dimensional coefficient χ_s as $\chi_s = \Delta H_g / \Delta H_c$. This number is equal to the reciprocal of the diffusive transfer number, the usual B number ([16]). This value of χ_s is independent of the mass vaporization rate and depends only on intrinsic properties of the fuel. Calculating the coefficient χ_s for each liquid fuel considered, we note that the previous empirical classification always holds as shown in table 2. This result is potentially very important because, if the heat of gasification and the heat of combustion are known for a new liquid combustible, the non-dimensional coefficient χ_s can be evaluated from table 2 and only one small-scale experiment (using FRST or external heat flux technique) is necessary to determine its burning rate at large-scale.

5.3. Test of this new method on one liquid fuel

In order to test this new method, we used a liquid fuel (ethyl acetate) for which the burning rate at large-scale had been measured in the gallery fire facility, but no small-scale fire experiment with FRST or external heat flux technique was previously performed in the Tewarson apparatus.

Knowing the heat of gasification and the heat of combustion of this combustible, the first step was to calculate the ratio χ_s as :

$$\chi_s = \frac{\Delta H_g}{\Delta H_c} = 1.02 \quad (5)$$

The previous classification had pointed out that the liquid fuel is in the same range as white spirit, acetone, heptane, kerosene and pyridine.

Now, the second step was to perform small-scale fire experiments using the FRST in one hand and using the external heat flux technique in the other hand. The aim was to determine if the burning rate at large-scale is the same as the burning for an oxygen concentration of 47% or for a external heat flux of 20 kW/m².

Figures 3 and 4 show the burning rates of this liquid combustible (ethyl acetate) versus external heat fluxes or oxygen concentrations. For ethyl acetate, the average burning rate obtained from fire tests in gallery facility was measured as 45 g/m².s ± 10%.

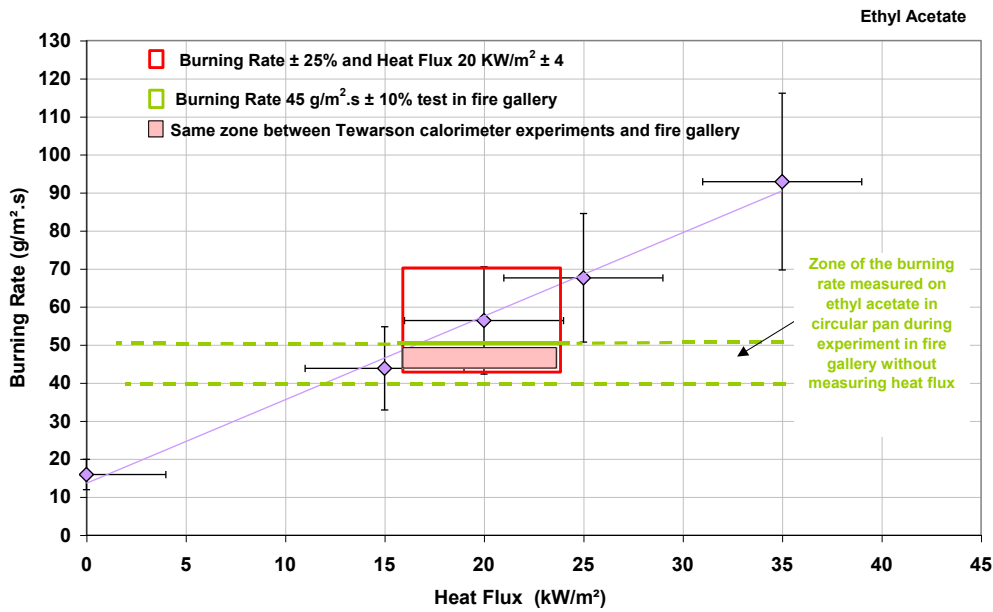


Figure 3: Evolution of the burning rate of ethyl acetate versus radiative heat flux

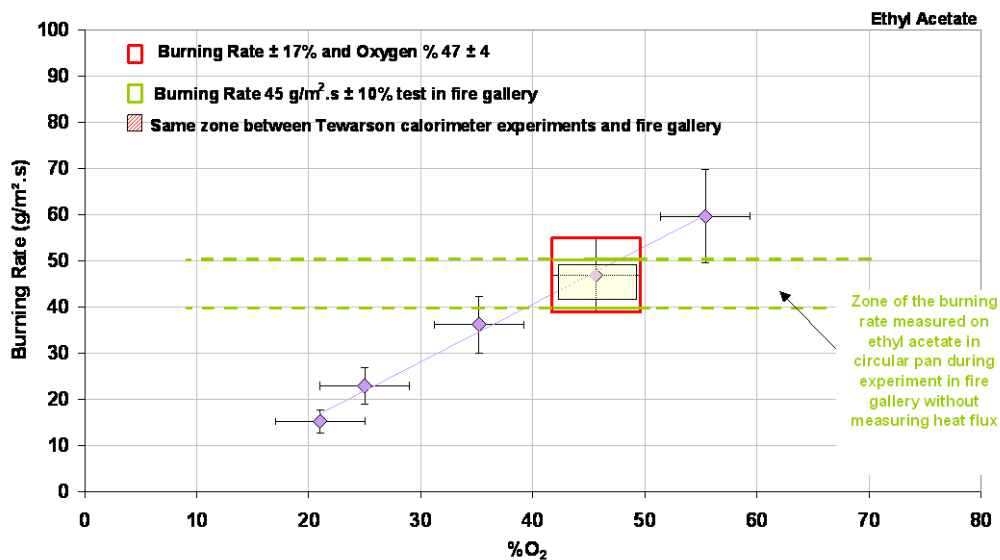


Figure 4: Evolution of the burning rate of ethyl acetate versus oxygen concentration

The objective was to find the burning rate measured during fire gallery experiment on ethyl acetate. According to table 2, the external heat flux (Fig.3) or the oxygen concentration (Fig.4) was fixed in Tewarson calorimeter to obtain the same burning rate as in the fire gallery experiment.

For external heat flux of $20 \text{ kW/m}^2 \pm 4$, the mean burning rate is measured at $56 \text{ g/m}^2/\text{s} \pm 25\%$, so it is ranged between 42 and $70 \text{ g/m}^2/\text{s}$. This mean value is quite high compared with the mean burning rate at large-scale but remains near $45 \text{ g/m}^2/\text{s} \pm 10\%$. However, these two measurements (small-scale and large-scale) overlap when taking into account the experimental uncertainties.

For FRST using oxygen concentration of $47\% \pm 4$, the mean burning rate is of $45 \text{ g/s} \pm 17\%$. This experimental value is very close to the mean burning rate obtained from large-scale fire tests. Furthermore, the uncertainty concerning the mean burning rate with the FRST is significantly lower than with external heat flux (respectively, 17% and 25%). This result seems to show that the FRST would be more accurate than the other method. But it is still very difficult to conclude only from this result.

6. Conclusion

The first conclusions from analysis of experimental results presented in this paper show that a classification for liquid combustible could be introduced. This classification is based on the oxygen concentration or the radiative heat flux necessary to obtain the same burning rates as those measured in large-scale fire. A non-dimensional number χ_S also seems to show that the classification for liquid fuel proposed here always holds. Thanks to this classification and the value of χ_S for a liquid combustible, it would be possible to estimate its burning rate at large-scale only from one experiment performed at small-scale using the FRST and the external heat flux method. This approach is tested with a liquid combustible and the first results are very promising. This new technique would be very interesting because it would be very cheap, easy to perform and request little time. Nevertheless, it is only a first step, mainly empirical, and it needs more experimental results in order to validate it furthermore.

7. Acknowledgements

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