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Experimental study of thin-layer boilover in large-scale pool fires

Fabio Ferrero [a,*], Miguel Muñoz [a], Bulent Kozanoglu [b], Joaquim Casal [a], Josep Arnaldos [a]

[a] *Centre d'Estudis del Risc Tecnològic (CERTEC), Chemical Engineering Department, Universitat Politècnica de Catalunya, Diagonal 647, 08028-Barcelona, Catalonia, Spain*

[b] *Mechanical Engineering Department, Universidad de las Américas, Puebla, 72820-Santa Catarina Mártir, Cholula, Puebla, Mexico*

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Abstract

By performing a series of pool fire experiments, the authors attempt to apply knowledge of *thin-layer boilover* to the large scale (pool diameter from 1.5 to 6 m). Two commercial hydrocarbons were used: gasoline and diesel. As expected, only in the case of diesel did the phenomenon of *thin-layer boilover* occur. Data were used to analyze various features of *thin-layer boilover* in fires, particularly its intensity and onset time. A comparison with results published in the literature shows the importance of this study.

Keywords: Pool fires; Pre-boilover burned mass ratio; Boilover intensity; Onset time

1. Introduction

Fire accidents are a common threat in the process industry and in the transportation of hazardous materials. An accidental fire scenario often involves a hydrocarbon burning above a water layer. When the fuel layer is thin and its boiling temperature exceeds that of water, heat transfer from the flame can lead to a phenomenon known as *thin-layer boilover*. This event involves the eruptive vaporization of the water layer, which causes burning fuel to be ejected and increases the turbulence of the fire, thus giving rise to larger flames and radiation.

The phenomenon has mainly been studied in laboratories [1,2], and the results cannot be extrapolated to a real scenario. Thus, our research consisted of a series of outdoor large pool fire experiments, which enabled us to study the onset time, boilover intensity and thermal penetration rate.

Data analysis enabled us to derive a set of important parameters relevant to the thin-layer boilover phenomenon, such as onset time, boilover intensity (the effect on the burning rate) and the evolution of the temperature of the fuel and water layers. The influence of pool diameter and initial layer thickness on these parameters was studied. The onset time of thin-layer boilover was characterized by an increase in the sound level of the fire, which is associated with the explosion of fuel/water bubbles formed during the vaporization phase. Boilover intensity was calculated from the relationship between the burning rate during boilover and the burning rate during the stationary period.

Unless otherwise specified, hereinafter we use the word *boilover* to refer to thin-layer boilover.

2. Experimental facility and methods

Experimental tests were carried out in five concentric circular pools made of reinforced concrete (1.5, 3–6 m in diameter, respectively). In order to measure flame temperature, thermocouples were fixed at different positions on a metal structure built on a concrete base, 1 m from the outer pool. Furthermore, 10 K-type thermocouples, fixed at the pool's axis at a distance of 2 mm from one another, were used to determine the temperature of the two liquid phases and their interface. The burning rate was determined by measuring the variation in the fuel level using a system of communicating vessels. The tests were filmed with two video cameras, which enabled us to study flame height, and a thermographic camera (IR). The cameras were fixed at pre-calculated distances so that the flames could be viewed in their entirety. The sound level of the fire and the volume of the unburnt residue were measured. Two heat flux sensors were used to measure external radiation on targets at specified distances. Moreover, various

* Corresponding author. Tel.: +34 93 401 66 75; fax: +34 93 401 71 50.
E-mail address: fabio.ferrero@upc.edu (F. Ferrero).

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Nomenclature

A_R	area of the reservoir connected to the pool (mm^2)
D	pool diameter (m)
F	fuel level/weight loss conversion factor (mm g^{-1})
h_b	thickness of fuel layer at boilover on-set (mm)
h_0	initial thickness of fuel (mm)
I_b	boilover intensity (−)
k	burning rate extinction coefficient (m^{-1})
$\dot{m}$	burning rate (kg m^{-2} s^{-1})
$\dot{m}_{max}$	maximum burning rate during stationary period (kg m^{-2} s^{-1})
t_b	onset time of boilover (s)
$\dot{y}$	burning rate (mm s^{-1})
$\dot{y}_c$	thermal penetration rate (mm s^{-1})
$\dot{y}_{evap}$	rate of water evaporation (mm s^{-1})
R_C	regression coefficient (−)
Δh	level variation in the pool (mm)
ΔW	weight variation registered by the balance (g)
Λ	ratio between initial fuel layer and pool area (mm m^{-2})

Greek symbols

ρ	liquid density (g mm^{-3})
χ	pre-boilover burned mass ratio (−)

Subscripts

av	average
b	boilover
f	fuel
max	maximum
s	stationary
w	water

meteorological parameters, especially wind speed, were determined to provide further information. The data were stored in a computer by means of specially developed acquisition software. Two commercial hydrocarbons were used: unleaded Repsol 98 gasoline and Type-C Repsol diesel oil. In total, 22 experiments were performed.

Further details of the experimental facility and procedures are given in Planas et al. [3], Chatris et al. [4,5] and Muñoz et al. [6].

3. Results

3.1. Burning rate

The burning rate is a key parameter that is commonly used in correlations that define the characteristics of pool fires. It cannot be measured directly because of the presence of the fire. Thus, in our experiments the burning rate was calculated using a system of communicating vessels, which consisted of a small container (500 cm^3) connected to the pool fire by a flexible tube. A balance connected to a computer recorded the recipient's weight every 0.5 s [4]. The mass burning rate was then obtained by smoothing out the curve and multiplying the weight loss by the corresponding conversion factor, which had previously been determined. Fig. 1 shows the evolution of the burning rate for a 3-m gasoline pool fire and a 1.5-m diesel pool fire. Fluctuations in the burning rate were caused by changes in wind conditions. The final increase in the burning rate in the case of diesel fires was due to thin-layer boilover, which causes the eruptive vaporization of water, as explained in the introduction. This effect must be corrected to evaluate m during this period.

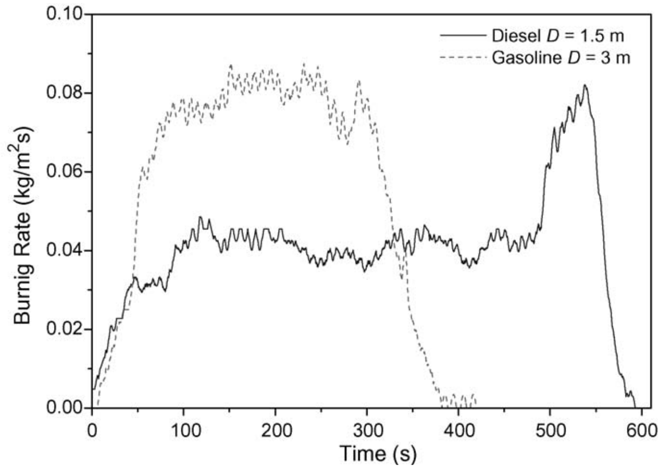

Fig. 1. Experimental burning rate for diesel and gasoline tests.

The data from the actual campaign were combined with the results of earlier experiments [4,6] to determine a correlation between the burning rate and the diameter of the pool in the steady period (i.e. the phase in which $\dot{m}$ is approximately constant). The influence of the wind on the mass burning rate during the stationary period was also evaluated by establishing a maximum threshold of acceptable wind conditions. It was concluded that the influence of the wind was limited for wind velocities lower than 1.6 m/s. The results that met that condition were averaged and correlated using Eq. (1), derived by Zebetakis and Burgess [7].

$$\dot{m} = \dot{m}_{max}(1 - \exp(-kD)) \qquad (1)$$

The final correlations were as follows:

$$\text{gasoline} \quad \dot{m} = 0.081(1 - \exp(-1.25D)) \qquad (2)$$

$$\text{diesel} \quad \dot{m} = 0.052(1 - \exp(-0.95D)) \qquad (3)$$

These correlations improved the results of the previous two series of experiments and were used in all further calculations involving the burning rate in the steady state (i.e. boilover intensity). The maximum burning rate was slightly higher than rates previously published [8,9]. However, the tendency for the maximum burning rate of gasoline to be much higher than that of diesel oil remained unchanged. Furthermore, as already shown in [6], the value of the constant k is lower for hydrocarbons with a wide range of volatilities (i.e. diesel oil).

3.2. Boilover onset time

In the event of an accident in which boilover may occur, it is essential to know when it will occur (i.e. its onset time). In fact, extinguishment should preferably be performed before then, because the fire becomes more dangerous after that time (the height of the flames and the radiation increase).

As is well known, boilover comes with a typical noise, normally referred to as a *crackling sound*, which is due to the water vapor bubbles exploding and entraining and ejecting fuel to the flames. Thus, the start of the phenomenon was determined from the sound level of the fire, as suggested by other authors [10]. Fig. 2 shows the behavior of the sound spectrum of the two fuels used in the experiments: Fig. 2(a) refers to gasoline (3 m pool diameter, 2 cm of initial layer thickness) and Fig. 2(b) to diesel (3 m pool diameter, 2 cm of initial layer thickness). Clearly, only in the diesel pool fires did boilover occur. The onset time was immediately identifiable: in the experiment in the example, boilover starts at around 360 s after the beginning of the fire. Other methods can be used to determine the start of the phenomenon, such as the instant in increase in burning rate, but the above-mentioned method was chosen for its simplicity and accuracy.

Fig. 3 shows the influence of the initial fuel layer in relation to the variation in pool diameter; this influence was determined from the experimental data gathered in the two last campaigns. Fig. 3 shows the regression lines determined from the correlation of the experimental results. The equations of the lines – all with a correlation coefficient of more than 0.98 – take the form shown in (4), where h_0 is expressed in mm:

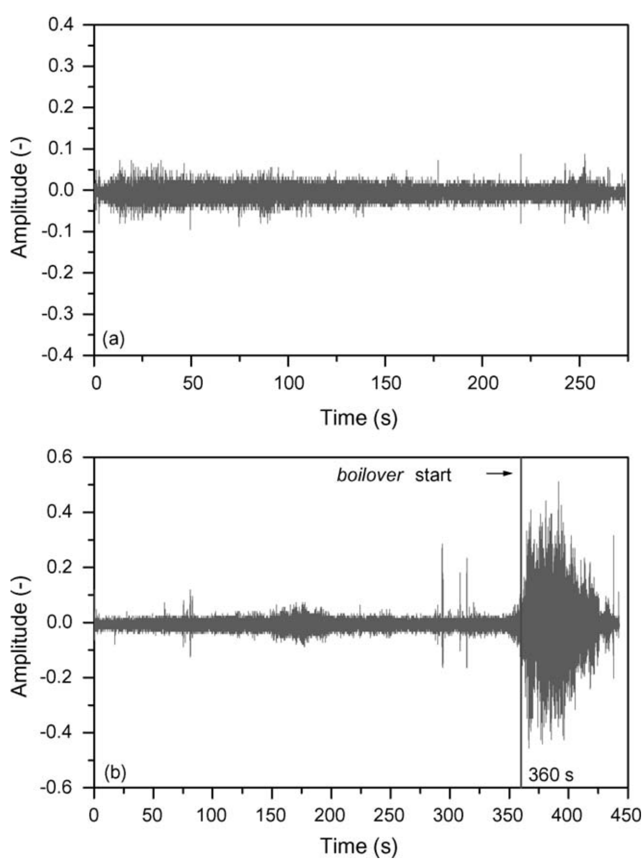

Fig. 2. Determination of onset time of boilover.

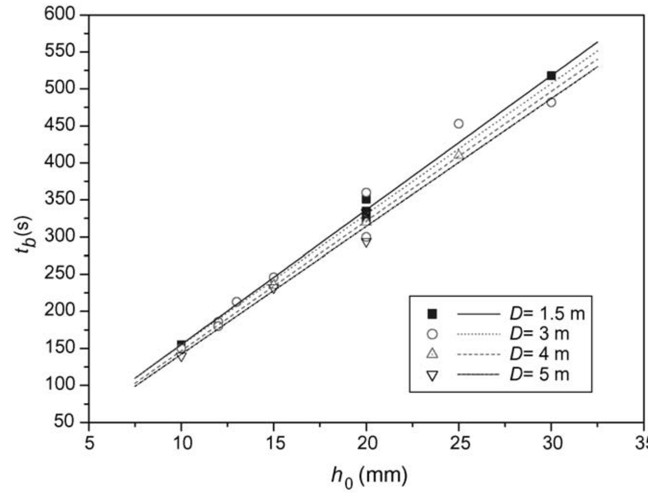

Fig. 3. Onset time boilover vs. initial layer thickness.

$$t_b = ah_0 - b \quad (4)$$

The regression coefficients (R_c) of the lines in Fig. 3 are shown in Table 1.

The graph shows that boilover onset time increases in a linear way with the initial thickness of the fuel layer. Furthermore, a slight decrease in onset time values as the pool diameter increases can be observed. The results agree with previous works for smaller pans, although in this study the decrease in the slope of the regression line with diameter was much greater [2].

Boilover occurs later if the initial fuel layer is thicker because of heat transfer: the thicker the layer, the longer the time needed for the fuel–water interface to reach the boiling temperature of water. For boilover to occur, the fuel–water interface temperature must be around 120 °C [2,11].

The fact that the slope of the regression lines decreases as the pool size grows (meaning that boilover occurs earlier the larger the diameter) is related to the increase in the velocity of heat propagation in the fuel layer (i.e. the thermal penetration rate), which is consistent with the increase in the burning rate with the diameter. The fuel is consumed more rapidly and more heat is generated, so the water reaches its boiling temperature faster. However, as discussed earlier on in this paper, the burning rate increases in an exponential way with the diameter and, for values higher than 2–3 m, the increase is reduced; this explains why the regression lines are closer to one another and confirms what is suggested in [2].

Table 1
Coefficients of the regression lines in Fig. 3

Diameter (m)	*a* (s/mm)	*b* (s)
1.5	18.15	26.4
3	17.7	22.6
4	17.5	28.3
5	17.25	30.6

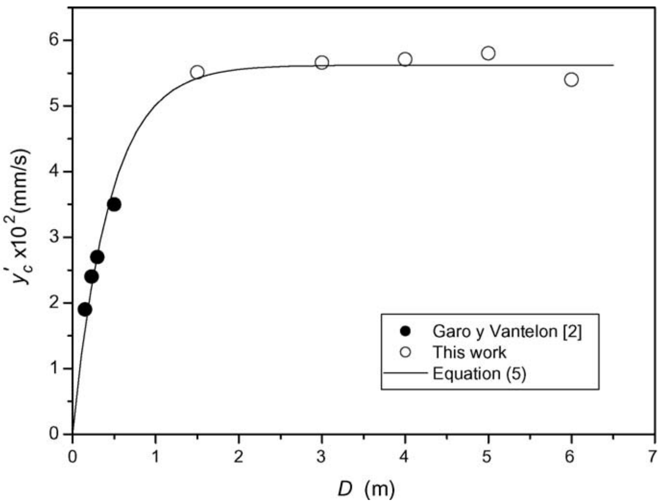

Fig. 4. Thermal penetration rate vs. pool diameter.

Values of thermal penetration rate $\dot{y}_c$, which represents the velocity of heat propagation in the fuel layer, are equal to the opposite of the slope of the regression rates [2]. Data from our experiments are compared graphically to the ones by Garo and Vantelon in Fig. 4, which shows the influence of diameter. All the results can be correlated with the same curve, which confirms, in a clearer way, the aforementioned statement that the effect of the diameter decreases as the pool size increases. The results are significant if we take into account the fact that Garo and Vantelon carried out their experiments with heating oil and ours were carried out with diesel oil. Therefore, Eq. (5), which presents a correlation coefficient of 0.99, can serve to predict the thermal penetration rate for hydrocarbon mixtures comprised between heating oil and diesel oil:

$$\dot{y}_c = 0.056(1 - \exp(-2.2D)) \quad (5)$$

Eq. (5) can be used to calculate how rapidly heat is transferred to the water–fuel interface. If a specific diameter is chosen, multiplying the value yielded by Eq. (5) for the initial layer thickness enables one to predict boilover onset time fairly accurately.

Table 2 compares the thermal penetration rate to the burning rate (in mm s^{-1}), which was obtained using Eq. (3).

Except for pool fires with a diameter of 1.5 m, the burning rate is higher than the heat front's propagation velocity (thermal penetration rate). This seems to indicate that a hot zone was not generated, or that this hot zone was consumed as soon as it occurred by combustion and the associated vaporization process that took place on the fuel layer's surface.

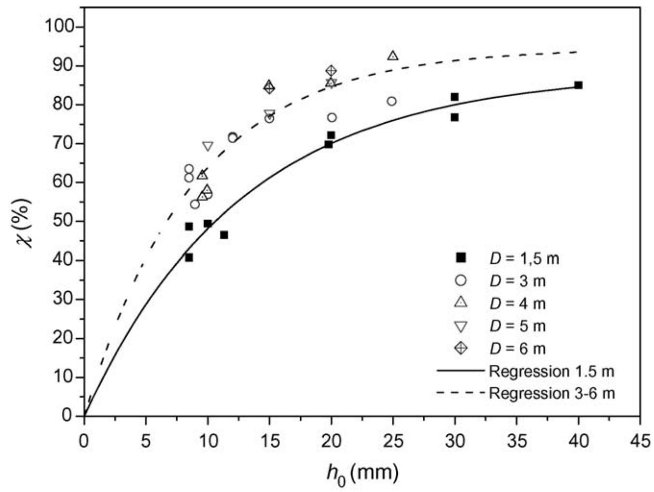

Fig. 5. Pre-boilover burned mass ratio vs. initial layer thickness.

3.3. Pre-boilover burned mass ratio

The quantity of fuel burnt before the occurrence of the phenomenon (pre-boilover burned mass ratio χ) is of great significance in boilover characterization. It provides information on the quantity of fuel still to burn that could be projected to the exterior of the pool during the boiling process. In Fig. 5, the quantity is represented as a function of the initial layer thickness: the data correspond to the three experimental series performed by the CERTEC. The results show how the pre-boilover burnt mass ratio increases with the initial thickness of the hydrocarbon layer with no clear dependency on the pool size. The behavior agrees with previous laboratory studies carried out by Garo and Vantelon [2]; these authors, however, registered a maximum value of 50% of the initial volume of fuel for thicknesses bigger than 10 mm, regardless of the pool size.

Fig. 5 shows that, in the present case, pool diameter had a certain influence on the parameter studied, in the sense that, the larger the pool, the bigger the pre-boilover burned mass ratio. However, for diameters larger than 3 m, this influence disappears, since a maximum burning rate is achieved. In view of these considerations, the experiments were divided into two groups: fires with a diameter of 1.5 m and the remaining fires. For each group, data were correlated with equations of the type shown in (6):

$$\chi = a(1 - \exp(-bh_0)) \quad (6)$$

where h_0 is expressed in mm. Table 3 shows the parameters of the correlation curves with their respective regression coefficients.

With respect to the study by Garo and Vantelon, the maximum values are achieved for initial fuel layers thicker than 4 cm, in comparison to 10 mm in [2]. Furthermore, the maximum is

Table 2
Experimental values of thermal penetration and burning rate

Diameter (m)	1.5	3	4	5	6
$\dot{y}_c \times 10^2$ (mm s^{-1})	5.51	5.66	5.71	5.80	5.40
$\dot{y} \times 10^2$ (mm s^{-1})	4.70	5.83	6.05	6.14	6.17

Table 3
Values of the parameter of Eq. (6)

Diameter (m)	a (−)	b (mm^{-1})	R_c
1.5	88.31	0.079	0.96
3–6	94.29	0.113	0.82

always more than 85–88% of the initial volume, in contrast to 50% as recorded in [2]. These differences are probably due to the type of fuel employed (heating oil is a less volatile fuel than diesel) and the different pool sizes, whose influence has been discussed.

In any case, the achievement of an asymptotic value is consistent with the start of boilover at a given fuel–water interface temperature and with the values for the thermal penetration rate ($\dot{y}_c$) and the burning rate ($\dot{y}$).

3.4. Amount of evaporated water

The amount of water that evaporates during boilover has not yet been accurately analyzed. Nevertheless, it is useful in evaluating the real burning rate during the boiling period and may be connected with an increase in the surface of the flame during boilover.

The method used to estimate the amount of evaporated water is briefly described below. As explained in the section on the burning rate, a system of communicating vessels between the pool and a container is used to determine fuel level variations in the pool, as defined by the following equation:

$$\Delta h = \Delta W/(A_R \rho_f) = F \Delta W \quad (7)$$

where F is the fuel level/weight loss conversion factor, which was evaluated experimentally during the filling process, and A_R is the area of the reservoir connected to the pool, which is used to determine weight loss ΔW. During boilover, Eq. (7) is not directly applicable, as ΔW also includes the evaporating water. However, in the boiling period, ΔW can be divided into two factors:

$$\Delta W = \Delta W_w + \Delta W_f \quad (8)$$

where ΔW_w is the weight variation due to the evaporation of water and ΔW_f the weight variation due to fuel consumption. Due to the linearity of the system, the two aspects can be considered separately, by means of the following equations, one for the fuel and one for the water:

$$\Delta h_f = \Delta W_f / A_R \rho_f = F \Delta W_f \quad (9)$$

$$\Delta h_w = \Delta W_w/(A_R \rho_w) = F \Delta W_w(\rho_f/\rho_w) \quad (10)$$

The volume of fuel still to burn at the onset of boilover can be determined by the difference between the initial amount and the burnt quantity given by (7).

By subtracting the residuum from the volume of fuel still to burn, the amount of fuel burnt during boilover is ascertained; by dividing this amount by the pool area, the variation in the level of fuel, Δh_f, is determined. Thus, from (9) the value of ΔW_f can be obtained. Moreover, ΔW was obtained from the difference in the weight measured by the balance from the beginning of boilover till its end. Although this quantity includes the residuum, the latter's contribution can be eliminated by means of Eq. (9), where Δh_f is the quantity of residuum measured experimentally. Thus, it is possible to determine ΔW_w as the difference between ΔW and ΔW_f, using Eq. (8). Then, from ΔW_w, the amount of evaporated water can be calculated. The results obtained in the last series of experiments are shown in Table 4.

Table 4
Experimental values of the amount of evaporated water

Experiment	Diameter (m)	Volume (l)	Initial layer thickness (mm)	Evaporated water (mm)
FOC3_22_D1.5	1.5	35	19.8	0.79
FOC3_01_D3	3	90	12.7	–
FOC3_02_D3	3	106	15.0	0.47
FOC3_04_D3	3	142	20.1	0.78
FOC3_05_D3	3	176	24.9	1.65
FOC3_18_D3	3	85	12.0	0.54
FOC3_20_D3	3	85	12.0	1.26
FOC3_14_D4	4	188	15.0	1.72
FOC3_15_D4	4	251	20.0	2.54
FOC3_16_D4	4	314	25.0	–
FOC3_09_D5	5	295	15.0	2.48
FOC3_10_D5	5	393	20.0	2.23
FOC3_11_D5	5	400	20.4	–
FOC3_07_D6	6	424	15.0	2.51
FOC3_12_D6	6	565	20.0	2.98

In the majority of fires, the estimated amount of evaporated water agrees with the visual observation of the decrease in the water level in the pool, taking the height of the thermocouple that is free at the end of the experiment as a reference. If the data for the same diameter is averaged, we can see that the amount of evaporated water in term of reduction in water depth grows approximately linearly with diameter, as shown in Fig. 6.

In order to evaluate an average evaporation rate, it is necessary to determine the duration of the boilover period. As explained previously, the start of the phenomenon is characterized by an increase in the sound level of the fire. The same criteria could be used to determine the final instant. Nevertheless, in the last moments of the fire, the sound spectrum evolves in a more irregular manner, which makes it harder to select a precise final instant. Therefore, the graphs showing the evolution of the burning rate and liquid temperature were used for this purpose (Figs. 7 and 8).

From the burning rate graphs (Fig. 7), the final instant of boilover was fixed at the moment in which the burning rate

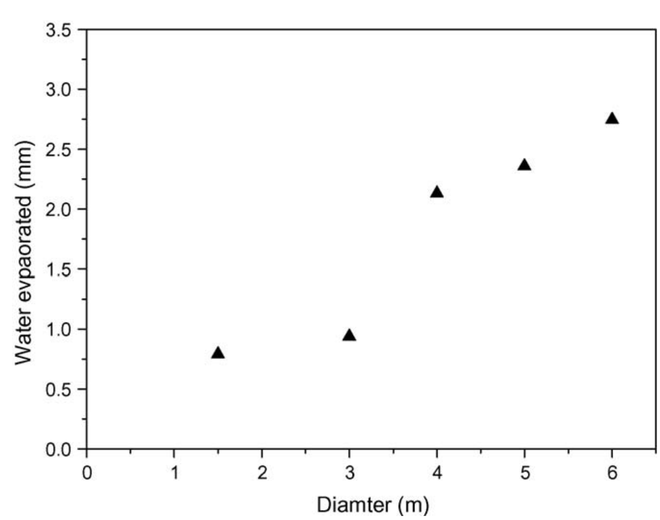

Fig. 6. Amount of evaporated water vs. pool diameter.

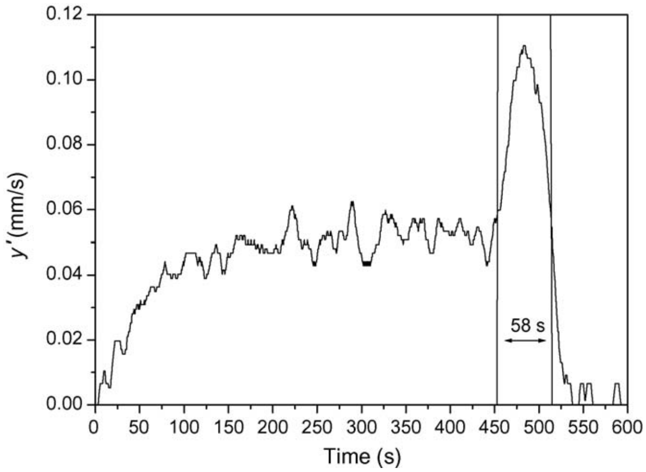

Fig. 7. Determination of boilover duration from burning rate evolution.

returns to the average value characteristic of the steady state. It has to be noticed that, after boilover onset, the balance variations include the contribution of the evaporating water. Even if, as it will be explained later, in some cases the burning rate during boilover is lower than during the stationary state, since the sum of the burning rate and of the water evaporation is always bigger than the burning rate during the stationary period, the methodology can also be applicable. From the temperature measured by the upper thermocouples, that is, the ones that had been directly in contact with fire due to the consumption of fuel (Fig. 8), the end of boilover was determined as the instant at which the temperature starts to increase abruptly, after the cooling caused by the evaporation of water (note that thermocouples are located every 2 mm. TL5 is at interface and TL1 and TL9 are 8 mm below and above it, respectively). As shown in Table 5, the values for the two estimations are in agreement.

By dividing the amount of evaporated water by boilover duration, the average water evaporation rate was obtained for every fire, as shown in Table 5. Since it is not possible to determine which method gives better results, the average value was used.

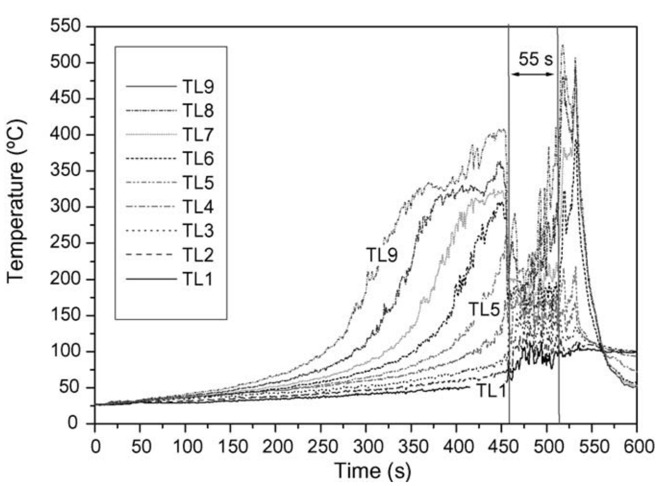

Fig. 8. Determination of boilover duration from temperature evolution (thermocouples are set every 2 mm, TL5 is at interface, TL1 is 8 mm below).

Table 5
Boilover duration and water evaporation rate values

Experiment	Boilover duration (s)		Average water evaporation rate ($mm\,s^{-1}$)	
	Burning rate	Liquid temperature	Burning rate	Liquid temperature
FOC3_22_D1.5	62	52	0.013	0.015
FOC3_01_D3	40	42	–	–
FOC3_02_D3	40	37	0.012	0.013
FOC3_04_D3	55	48	0.014	0.016
FOC3_05_D3	58	55	0.028	0.030
FOC3_18_D3	43	41	0.013	0.013
FOC3_20_D3	50	48	0.025	0.026
FOC3_14_D4	52	45	0.033	0.038
FOC3_15_D4	56	55	0.045	0.046
FOC3_16_D4	70	63	0.060	0.072
FOC3_09_D5	56	49	0.044	0.051
FOC3_10_D5	50	50	0.045	0.045
FOC3_11_D5	43	38	–	–
FOC3_07_D6	40	41	0.063	0.061
FOC3_12_D6	50	45	0.060	0.066

The average water evaporation rate can be subtracted from the apparent burning rate value during boilover, in order to obtain the real burning rate in that period.

No influence of diameter or initial layer thickness on boilover duration was observed. Generally, the boiling period lasted between 40 and 60 s. The water evaporation rate was not significantly affected by the initial layer thickness either. However, by averaging the data for the same diameter, a general trend can be detected: the water evaporation rate increases with pool size, as shown in Fig. 9.

While $\dot{y}_{evap}$ does not show any particular dependence on the initial layer thickness (h_0), it seems to be influenced by the fuel left to burn at boilover onset, in the sense that the larger the value of h_b, the smaller the value of $\dot{y}_{evap}$. In Fig. 10 Eq. (11), which describes the trend, is shown ($R_c = 0.8$):

$$\dot{y}_{evap} = 0.28\exp(-h_b/1.19) + 0.015 \quad (11)$$

An explanation for this might be that a greater thickness at boilover onset implies that more heat from the flame is absorbed

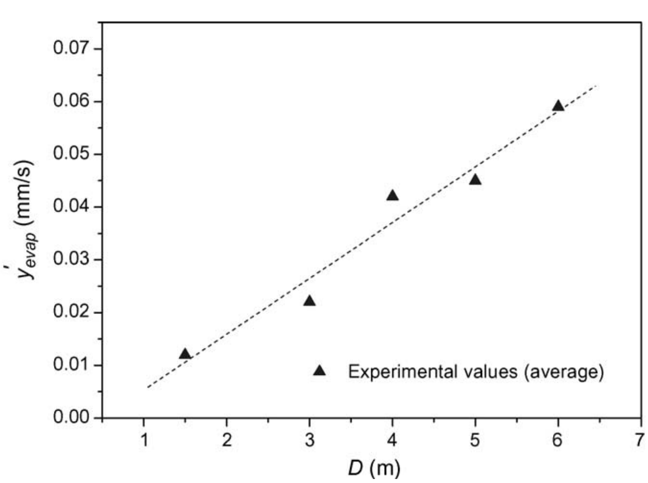

Fig. 9. Average water evaporation rate vs. pool diameter.

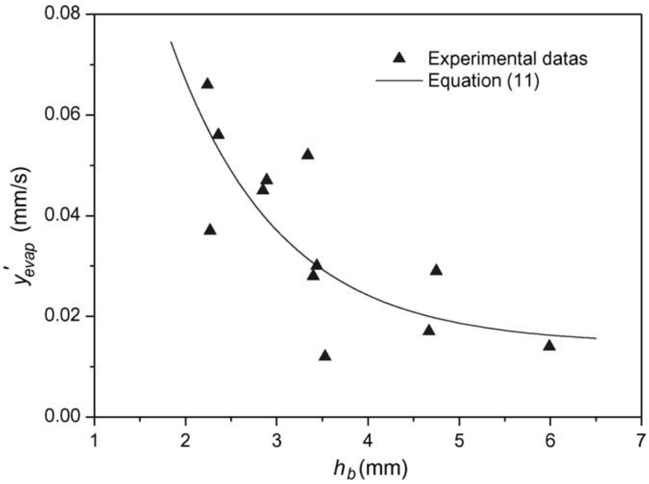

Fig. 10. Average water evaporation rate vs. thickness at boilover.

by the fuel layer. Thus, less heat reaches the water interface and so there is less evaporation.

Thickness at boilover is represented as a function of diameter in Fig. 11 and shows an exponential decrease. Once again, this behavior may be related to heat transfer from flame to liquid. An increase in the thermal penetration rate with diameter implies, in addition to boiling point being reached more quickly, a faster consumption of the fuel layer, which at boilover onset will be smaller.

Fig. 11 also shows the correlation of the experimental data ($R_c = 0.87$) with the following expression:

$$h_b = 8.70\exp(-D/2.37) + 1.50 \tag{12}$$

As there is less left to burn at boilover onset, less fuel can be carried to the flame during boiling. Therefore, it is reasonable to assume that boilover intensity decreases with pool diameter. In the following paragraph we confirm this hypothesis.

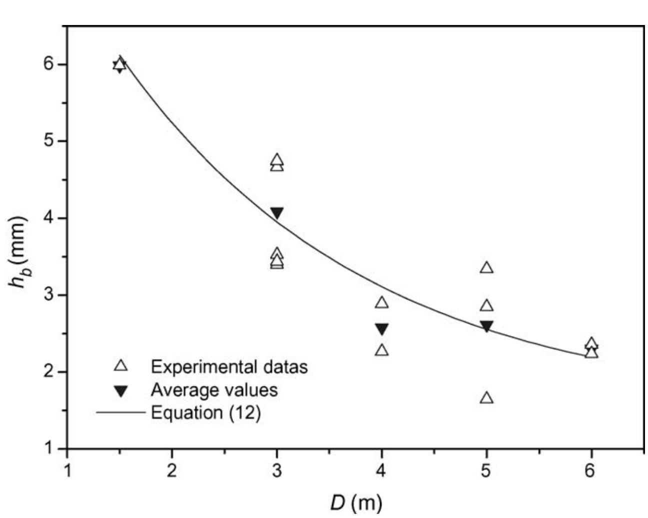

Fig. 11. Thickness at boilover vs. pool diameter.

4. Boilover intensity

The effect of boilover on the burning rate can be analyzed by defining boilover intensity as follows:

$$I_b = (\dot{m}_b - \dot{m}_s)/\dot{m}_s 100 \tag{13}$$

Thus, boilover intensity expresses the percentage increase (or decrease) in the burning rate during the boiling phase with respect to the stationary period.

The values of the burning rate in the steady state ($\dot{m}_s$) used in this analysis were obtained using Eq. (3). For each fire, two values for the burning rate during boilover were calculated.

- A medium burning rate, $\dot{m}_{b,av}$, which is obtained by dividing the quantity burnt during the boiling phase by the duration of the latter. For this reason, measurements of the unburnt residue at the end of the experiment were needed. Table 6 shows that the unburnt fuel is around 2–4% of the initial amount of fuel, and that it has a slight tendency to increase with pool fire diameter.
- A maximum burning rate, $\dot{m}_{b,max}$, which is determined by subtracting the amount of water evaporated from the peak of the burning rate measured during boilover. The quantity of evaporated water was determined experimentally by measuring the water level in the pool, and also estimated mathematically.

Thus, medium and maximum boilover intensities were calculated. For every value of Λ, which represents the fraction between the initial fuel layer and the pool area [4,5], Table 7 shows the results for the average and maximum burning rates during boilover, as well as the corresponding values for boilover intensity. In the same study, Eq. (14) was proposed to determine boilover intensity from the value of Λ:

$$I_b = 29.6\Lambda - 30.9 \tag{14}$$

Fig. 12 compares actual experimental data to Eq. (14) and shows that the data are unsatisfactory, as for large values of Λ the evolution may be asymptotical. It is difficult to carry out a complete analysis of the influence of Λ for big pools, because for diameters larger than 3 m the quantity of fuel needed would increase the cost of the experiments exponentially and could also lead to a hot zone boilover situation rather than to a thin-layer boilover process. Furthermore, for small pool fires, low values of Λ could lead to fuel layers too thin for combustion.

Table 6
Percentage of unburned fuel as a function of diameter

Diameter (m)	Unburned ratio (%)
1.5	2
3	2–3
4	3–4
5	2
6	4

Table 7
Burning rate results and boilover intensity

Experiment	Λ (mm m^{-2})	$\dot{m}_s$ (kg m^{-2} s^{-1})	$\dot{m}_{b,av}$ (kg m^{-2} s^{-1})	$\dot{m}_{b,max}$ (kg m^{-2} s^{-1})	$I_{b,av}$ (%)	$I_{b,max}$ (%)
FOC3_22_D1.5	11.21	0.047	0.106	0.113	125.92	139.81
FOC3_01_D3	1.80	0.06	0.106	–	77.65	–
FOC3_02_D3	2.12	0.06	0.086	0.108	44.75	80.64
FOC3_04_D3	2.84	0.06	0.085	0.084	42.7	40.88
FOC3_05_D3	3.52	0.06	0.073	0.074	22.03	23.25
FOC3_18_D3	1.70	0.06	0.074	0.108	23.15	80.14
FOC3_20_D3	1.70	0.06	0.064	0.077	6.68	28.96
FOC3_14_D4	1.19	0.062	0.036	0.066	−42.1	5.32
FOC3_15_D4	1.59	0.062	0.040	0.101	−35.66	61.74
FOC3_09_D5	0.77	0.064	0.059	0.061	−7	−4.28
FOC3_10_D5	1.02	0.064	0.048	0.055	−24.71	−13.03
FOC3_11_D5	1.04	0.0635	0.031	–	−50.84	–
FOC3_07_D6	0.53	0.0640	0.043	0.056	−32.3	−13.07
FOC3_12_D6	0.71	0.0640	0.032	0.051	−49.5	−20.57

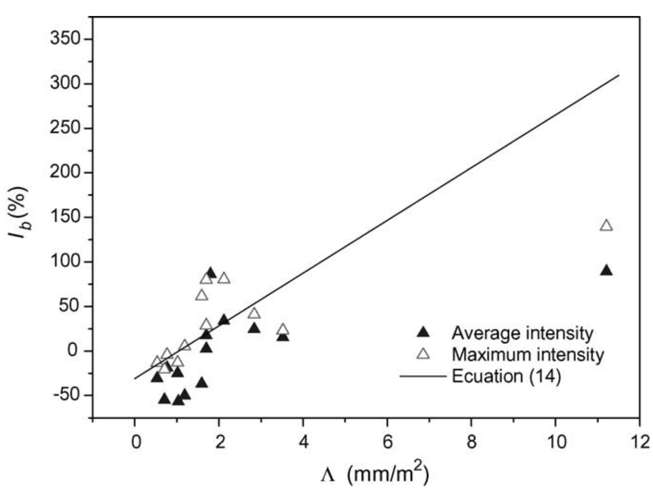

Fig. 12. Boilover intensity vs. Λ.

Based on these considerations, in the analysis performed the parameter that determines boilover intensity was investigated in other ways.

As a initial step, if we average the data with the same diameter a clear trend is observed, as shown in Table 8 and graphically in Fig. 13: both medium and maximum boilover intensities decrease with diameter. It should be noted that a negative value of boilover intensity does not mean a negative burning rate (which would have no physical meaning) but only a decrease in the burning rate during boilover with respect to the steady state.

The tendency observed agrees with previous experiments [2,12]. In contrast to the research carried out by Garo and Vantelon [2], in these experiments no clear influence of initial layer thickness on boilover intensity was observed, probably due to the lower percentage variations in the thickness with respect to the diameter.

Table 8
Average values of boilover intensity

Diameter (m)	$I_{b,av}$ (%)	$I_{b,max}$ (%)
1.5	89.5	140
3	30	51
4	−50	33.5
5	−33	−9
6	−42.5	−17

Fig. 14 shows how boilover intensity decreases as the water evaporation rate increases. The result might not seem logical, as a higher evaporation rate drags more fuel into the flame. However, as previously noted, the quantity left to burn at boilover is in this case smaller; thus, as the fuel that can be carried to the flame is just a small amount, boilover intensity does not increase.

From what has been discussed up to this point, the quantity left to burn at boilover onset would seem to be the parameter that controls boilover intensity. Fig. 15, which shows average and maximum boilover intensities as a function of the above-mentioned parameter, confirms the hypothesis and also shows a linear dependence. The fact that thickness at boilover decreases with pool diameter (Eq. (12)) explains why boilover intensity decreases with pool size. Taking into account this behavior, the following correlations are obtained:

$$I_{b,av} = -66.4 + 282.8 \exp\left(-\frac{D}{2.37}\right) \quad (15)$$

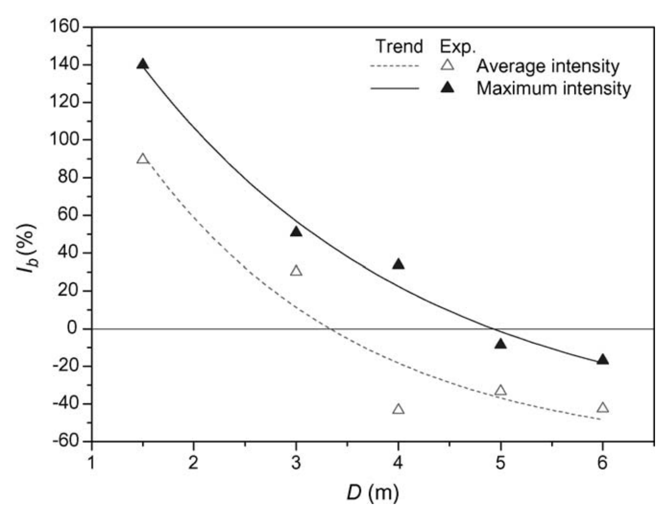

Fig. 13. Average and maximum boilover intensity as a function of pool diameter.

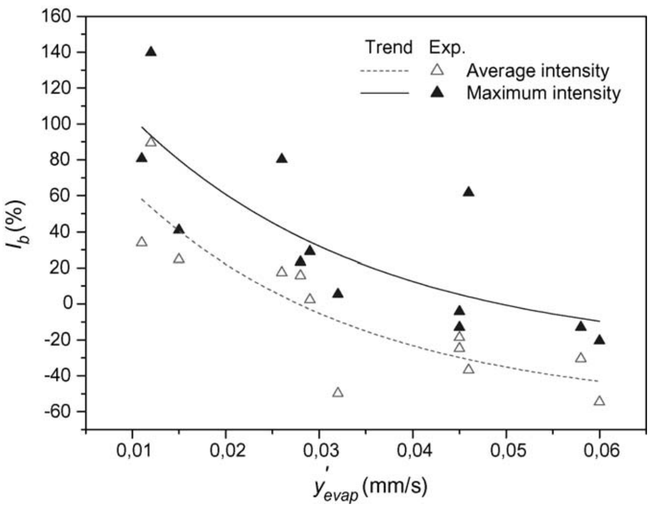

Fig. 14. Boilover intensity vs. evaporation rate.

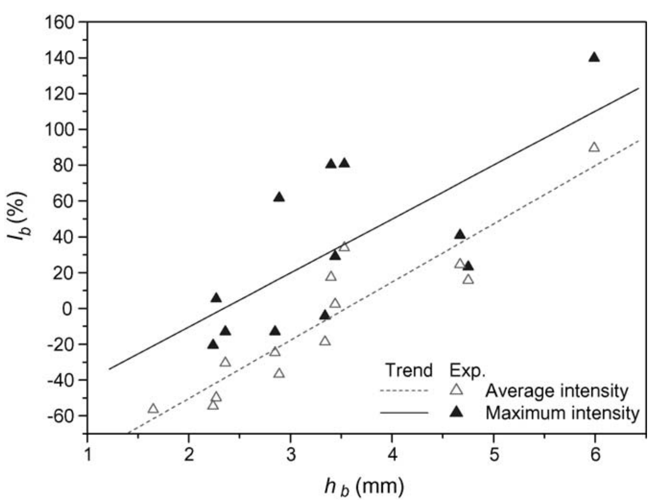

Fig. 15. Boilover intensity vs. thickness at boilover.

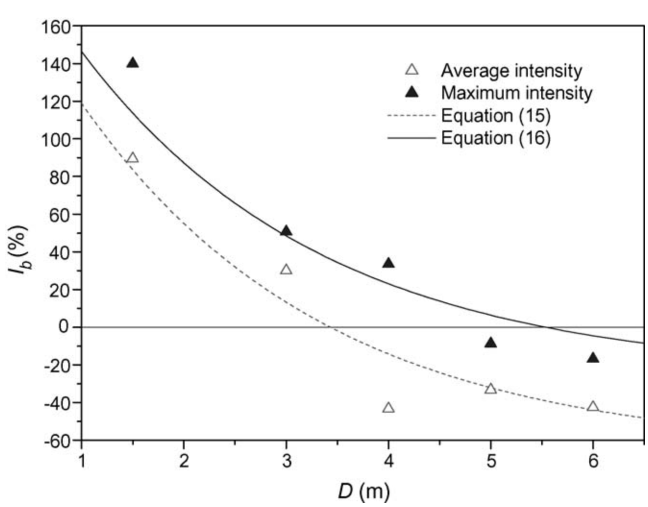

Fig. 16. Graphical overview of the predicted values of boilover intensity from Eqs. (15) and (16).

$$I_{\mathrm{b,max}} = -25.3 + 262.1 \exp\left(-\frac{D}{2.37}\right) \quad (16)$$

Eqs. (15) and (16), which are represented graphically in Fig. 16, fit the average boilover intensity values with regression coefficients of 0.95 and 0.99, respectively.

The good predictions obtained confirm that the fuel thickness at boilover onset is the limiting factor on the intensity of the phenomenon.

5. Conclusions

A series of large-scale pool fire experiments was carried out to improve knowledge of the thin-layer boilover phenomenon. Our analysis of these experiments brought forth the following conclusions.As in previous small-scale experiments [2], the pre-boilover burned mass ratio increases with the initial thickness of the hydrocarbon layer, until a maximum value is reached, which increases with diameter. This dependency on pool size disappears for diameters of more than 3 m, according to the burning rate values.Boilover onset time showed a linear dependency on the initial layer thickness. The influence of the diameter is much less significant than in small-scale experiments [2].

From the current and previous experimental data, a new equation was developed to determine the dependency of the thermal penetration rate on pool diameter. The correlation could prove useful for fuels ranging from diesel oils to heating oils.

No hot zone seems to appear within the fuel layer, as expected for thin-layer boilover. The values for the burning velocity and thermal penetration rate serve to explain this, as a hot zone would be systematically destroyed by the evaporation/combustion process.

Boilover intensity decreased with diameter. For values of more than 3–4 m, burning rate during boilover is lower than in the stationary period.

The limiting factor for boilover intensity was the residual fuel at the boilover onset.

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