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ABSTRACT

The calculation of the consequences associated with a pool fire consists in a stepwise procedure where a number of parameters must be characterized, which depend on the geometrical size and shape of the flame. A number of calculation models exists in the literature, characterized by different levels of accuracy and complexity.

In the present work we will focus on the characterization of the geometrical configuration of the flame generated from a pool fire: some of the most commonly adopted models will be shortly recalled, and compared against experimental data taken from the literature. It is expected that this would provide useful information about the range of applicability and the level of accuracy of these models. Also, it will help improve the quality of the results, and reduce the time required for carrying out important applications such as consequence assessment and risk analysis, where a large number of calculations must be run.

1. Introduction

Pool fire represents one of the most common accidental events which can occur within an industrial installation (Vilchez et al. 1995), however, since it is generated by the ignition of the release of any flammable liquids, it can actually happen in a wide range of situations, like during the transportation of traditional liquid fuels from storage or production sites to the final destination, and in other everyday-life conditions.

Unless a very large release has occurred, the consequences of such an event are usually limited to a relatively small area surrounding the location of the leak, compared with other more harmful accidents characteristic of the process and power industry, like VCEs and fireballs. Nonetheless the estimation of the impact area of pool fires is of great importance, especially when the possibility of generating accidents characterized by larger impact areas and more serious consequences (domino effect), is present.

The damages caused by a liquid fire are mainly connected with the heat radiated in the surrounding area, which depends on a number of parameters: the energy per unit time emitted by the flame, the distance from the fire, the characteristics of the target surface receiving the radiated heat (e.g. shape and size), and a number of other environmental conditions (atmospheric transmissivity, wind intensity, etc.).

At least in theory, the heat received by a given target might be calculated by means of the classical Stefan-Boltzmann equation, but due to the wide range of variability of the involved parameters, and to the uncertainty in their quantitative assessment, a number of theoretical and semi-empirical models have been proposed over the years and are still commonly adopted by safety engineers. Since they do not require the knowledge of many specific input parameters, another advantage of these correlations, lies in the fact that they can be easily applied in a number of applications where a great amount of quick calculations have to be carried out, such as in Risk Analysis. Nonetheless, because of the lack of experimental data, uncertainties are still present about their practical applicability. In this view, and with reference to other dangerous phenomena like explosions, it has already been shown that an assessment of the reliability and of the range of applicability of these models is of the higher importance (Bubbico and Mazzarotta, 2013). Consequently, a similar analysis will be repeated here with reference to some of the most widely known and adopted pool fire models.

2. Literature background

Assessing the damages caused by a pool fire is a stepwise procedure: following a backward sequence it can be observed that the heat received by a given target depends on a number of factors, such as the heat actually radiated by the fire, the fraction of heat "lost" along the travel from the emitting (the flame) to the receiving surface, the distance and the relative exposure of the receiving surface with respect to the emitting one (all of them summarized in the so-called geometric view factor). Most of these factors depend either on the geometrical size and shape of the flame and/or on the heat produced by the fire. The geometry of the fire is in turn a function of different parameters: some of them are intrinsic with the fuel involved in the fire (e.g. the physical properties, the heat of combustion, etc.); other parameters are somehow accidental, like the release rate, the size of the pool at the base of the fire (whether confined or not), the properties of the surface on which the liquid pool is formed (physical and thermal properties, whether flat or inclined terrain, etc.), the wind velocity and direction, and many others. Similarly, the heat produced by the fire is a function of the combustion rate and the heat of combustion of the fuel.

As might be expected, for each of the above parameters a number of calculation models exist, characterized by different levels of accuracy and complexity. Frequently, a higher accuracy is associated with a higher complexity of the model, which, in turn, often implies a larger number of input parameters for the model and longer calculation time. A higher accuracy is usually required when a specific case is under investigation, for example when at least some the parameters involved are already known in advance (e.g. pool size, wind velocity, distance from the target, etc.). In other cases, a lower accuracy can be tolerated, provided that shorter calculation times are obtained; this is the case of risk analysis, for example, where *all* the possible accidental scenarios have to be taken into consideration and simulated (different pool sizes, fuel and/or ambient temperatures, wind velocity and direction, distances, and so on). In these cases, an accurate analysis of all these scenarios would require an unacceptable calculation time; as a consequence, an optimum between results accuracy and calculation time is here sought, and a number of simplified models and correlations are thus available in the literature.

As stated above, the present work will focus on the characterization of the geometrical configuration of the flame generated from a pool fire: some of the models most commonly adopted in risk analysis will be shortly recalled in this section, and they will then be compared against experimental data obtained from the literature in the next section.

2.1 Burning rate

The first step in calculating the consequences of a pool fire consists in the calculation of the burning rate, that is the velocity of consumption of the fuel from the liquid pool. Three of the most common models will be used here.

Zabetakis and Burgess (1961) proposed the following relation for the calculation of the burning rate from hydrocarbon liquid pools:

$$m" = m"_{\infty}\left(1 - e^{-k\beta D}\right) \quad (1)$$

where $m"_{\infty}$ is the specific mass burning rate at "infinite" diameter (kg/m^2/s) to be experimentally determined, k is the absorption-extinction coefficient of the flame (m^{-1}), β is a correction coefficient for the beam length, and D is the pool diameter (m). According to this equation, the pool diameter has an explicit influence on the burning rate of the fuel, at least at low diameter values. A significant drawback of this equation is that all parameters are fuel-dependent and have to be determined experimentally: reliable measurements are available in the literature for a few substances, only, and in some cases different values are provided for the same fuels (Babrauskas, 1983; Rew and Hulbert, 1995; Munoz et al., 2004). Babrauskas (1983) also suggests deriving the combination kβ and not separated into k and β.

At larger scales (i.e. around 1 m diameter), the influence of the pool diameter vanishes and Burgess et al. (1961) correlated the burning rate of a number of liquid fuels (specifically, liquid hydrogen, liquid natural gas, butane, methanol, hexane, benzene, and xylene) by the simple relationship:

$$m" = 1.27 \cdot 10^{-6} \rho_L \frac{\Delta H_c}{\Delta H^*_v} \quad (2)$$

where ρ_L is the density of liquid fuel at boiling point, ΔH_c is the heat of combustion (kJ/kg), and ΔH^*_v is the modified heat of vaporization at the boiling point of the liquid given by

$$\Delta H_v^* = \Delta H_v + \int_{T_a}^{T_b} c_p dT \quad (3).$$

In Eq(3) ΔH_v is the heat of vaporization of the liquid at the boiling temperature (kJ/kg) and c_p is the heat capacity of the liquid (kJ/(kg°C)).
Eq(2) has been recognized as not accurate enough for liquefied gases (Mudan, 1984), and a more general, though less accurate, fitting equation has been proposed:

$$m" = 1 \cdot 10^{-3} \frac{\Delta H_c}{\Delta H^*_v} \quad (4).$$

An advantage of equations (2) and (4), with respect to Eq(1), is that they only need the heat of vaporization and heat of combustion of the involved fuel, which are much more easily available than the experimental parameters required by Eq(1).
Many other theoretical or empirical correlations are available in the literature (see for example Joulain, 1997; De Ris et al., 2000; Raj, 2007), however they will be not adopted here either because of their limited range of validity or because of the time required to get the input data or to run the calculations, which are not always acceptable during a full risk analysis.

2.2 Flame height

The flame height is a fundamental parameter to assess the consequences associated with a pool fire, and a large number of models have been proposed over the years for its quantification (just to name a few, see Rew et al., 1997; Mudan and Croce, 1986; Mudan, 1984; Raj, 2007; Munoz et al., 2007).
The best known and most widely adopted correlation for calculating the ratio between the flame height and the diameter of a circular pool is the one by Thomas (1963):

$$\frac{H}{D} = 42 \cdot \left(\frac{m"}{\rho_a \sqrt{gD}} \right)^{0.61} \quad (5)$$

where m" is the specific mass burning rate (kg/m^2/s) calculated by Eq(2), ρ_a is the air density (kg/m^3), and g the gravitational acceleration (m/s^2). Thomas also suggested an improved correlation to take into account the influence of the wind, however the value of the wind speed is rarely known from the available experimentations, and therefore this version will not be considered here. Other correlations have been put forward by different Authors, however they are either specific for particular fuels (see for example Moorhouse, 1982), or they proved to be less accurate than Eq(5) (Mudan, 1984).
Based on a variety of experimental measurements (even from jet fires), Heskestad (2002) proposed a correlation where the height of the flame is dependent on the heat produced by the fire, instead of the burning rate as in Eq(5):

$$\frac{H}{D} = \frac{0.235 Q^{2/5}}{D} - 1.02 \quad (6)$$

with Q (kW) the heat release rate.
Differently from Eq(5) and Eq(6), where the size of the flame is a function of the burning conditions, represented by either the mass burning rate m" or the heat release rate Q, the BrLtz correlation (Zhang et al., 2014) represents an even simpler approach, since the height of the flame is dependent on the diameter of the pool only:

$$\frac{H}{D} = 1.73 + 0.33 D^{-1.43} \quad (7).$$

3. Results and discussion

The above equations have been applied to a number of experimental data obtained from the literature. Unfortunately literature data are scarce in quantity and often incomplete (missing information on weather data, like temperature and wind velocity, on the physical properties of the fuels, and so on). As a consequence it is usual making reference to well known and often referred to experimental campaigns. Some of these data have already been summarized in previous papers, so, for the sake of simplicity, the data used in the present work have been directly derived from them, and in particular from Babrauskas (1983) and Rew and Hulbert (1995).

3.1 Burning rate

In order to check the accuracy of the above models, in Figure 1 the experimental values of the burning rate of hexane pool fires are reported along with the calculations provided by Eqs (1), (2) and (4). It is apparent that, while Eqs (2) and (4) provide rather good (constant) values of the infinite diameter burning rates, only Eq (1) is able to predict accurate values of the burning rate in the whole range of diameters investigated, and in particular for small pools (i.e., in the case of hexane, for D less than about 1.5 m). The same behaviour is

observed for most of common hydrocarbons and conventional liquid fuels (e.g., heptane, gasoline, JP4, etc.). Conversely, none of the adopted equations is able to reliably predict the burning rate for liquefied gases (LNG and LPG), as shown in Figure 2. This is in agreement with similar observations by Babrauskas (1983).
The above results demonstrated that Eq (1) provides better estimates of the burning rate of most hydrocarbons, with respect to Eqs (2) and (4). However, two considerations should be highlighted: the use of Eq(1) requires the knowledge of specific parameters strictly linked to the investigated fuel, which have to be experimentally determined and are not easily found in the literature; furthermore, from a practical point of view, in many cases pool fires generated by relatively large pools are of interest (which often means larger than 1 m), and in these cases the infinite diameter burning rates could suffice. On the other hand, it is worth saying that even in the case of Eqs (2) and (4), when mixtures of hydrocarbons are involved, which are not always very well characterized in terms of composition, their physical properties, such as the heat of evaporation and the heat of combustion which appear in Eq (3), cannot be accurately calculated, and consequently a significant uncertainty can be found in the estimation of the mixture burning rate.

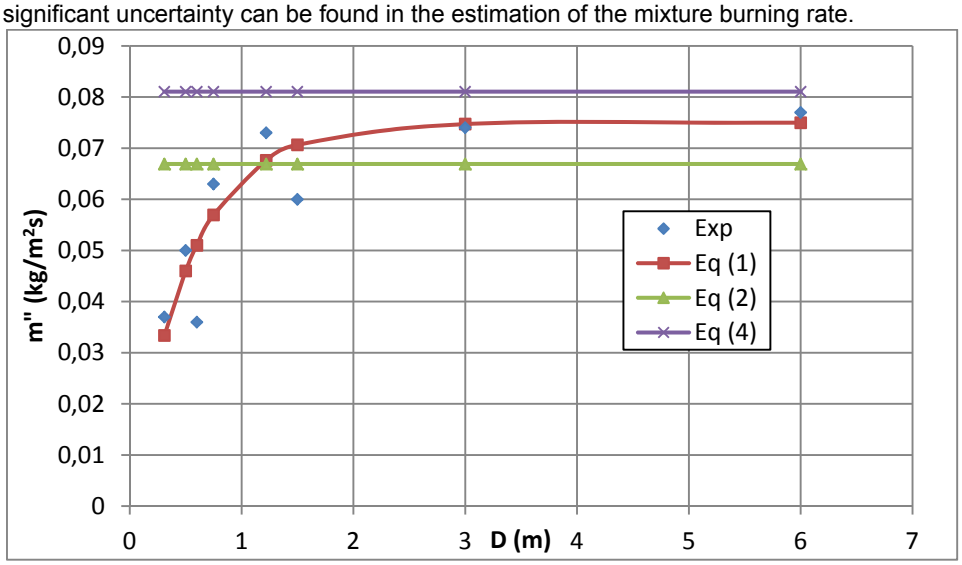

Figure 1: Burning rates for hexane. Experimental data and models predictions.

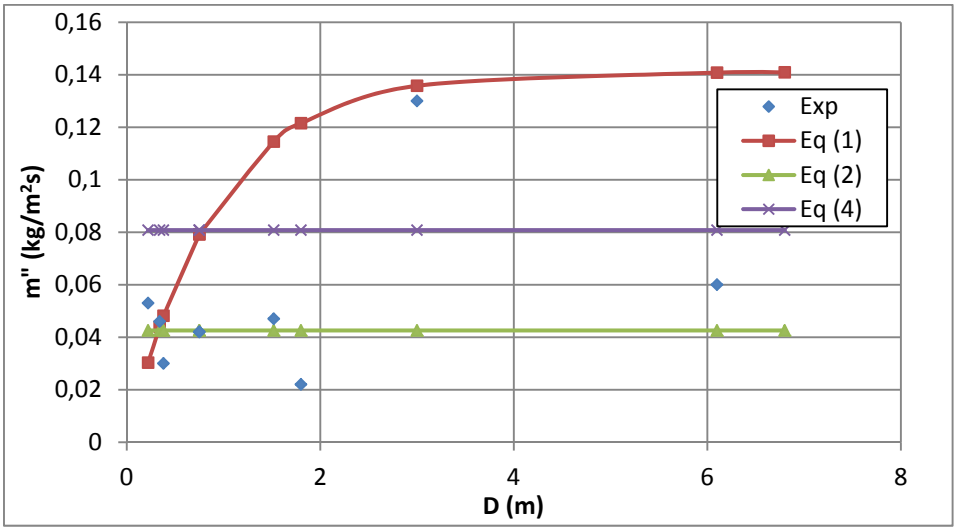

Figure 2: Burning rates for LNG. Experimental data and models predictions.

3.2 Flame height

In Figure 3 the experimental values of the flame height of hexane and heptane pool fires are reported along with the values calculated with Eqs(5) to (7); the curves are on a log-log scale for a better understanding of the trends. In the case of Eq(6), the heat production rate is required, which is linked to the burning rate of the fuel; since, as shown in section 2.1, this latter parameter can be calculated with different equations, different

versions of Eq(6) can be correspondingly derived. In the present case Eqs(1) and (4) have been adopted, giving rise to Eqs(6a) and (6b), respectively.

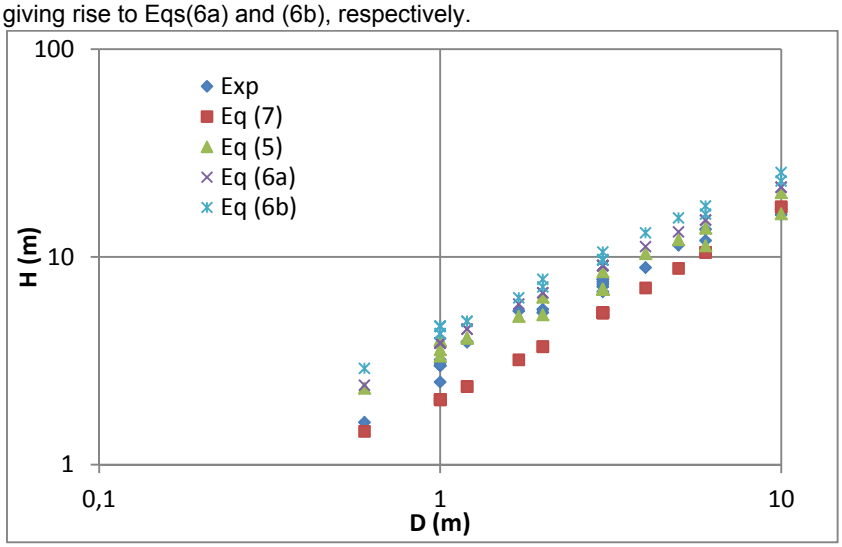

Figure 3: Flame height for hexane and heptane. Experimental data and models predictions.

It can be seen from Figure 3 that the Thomas correlation (Eq(5)), better fits the experimental data, with a very narrow spread of the estimates: an average ratio between calculated and experimental height (H_{calc}/H_{exp}) of 1.11 with a variance of 0.03, is obtained. Also Eq(6a) gives accurate results with a slightly larger overestimation of the flame length with respect to Eq(5): average ratio H_{calc}/H_{exp}=1.25 and var=0.01. In Table 1 the correlation parameters for the other equations are also reported.

Table 1: Statistical parameters for hexane and heptane pool fires

	Eq (5)	Eq (6a)	Eq (6b)	Eq (7)
Average H_{calc}/H_{exp}	1.11	1.25	1.41	0.75
Variance	0.03	0.01	0.03	0.02

In the case of hydrocarbon mixtures, like gasoline and kerosene (see Figure 4), rather different results are obtained, with the Thomas correlation showing a larger overestimation of the calculations with respect to the experimental values (H_{calc}/H_{exp}=1.23 average and variance 0.23), and the BrLtz correlation (Eq(7)) providing an excellent agreement with the measured data (H_{calc}/H_{exp}=0.99 with var=0.10). This is an interesting result, since, as highlighted in the previous section, this correlation does not require any additional input parameter, except for the pool diameter. Similar results are obtained with other mixtures (data not shown).

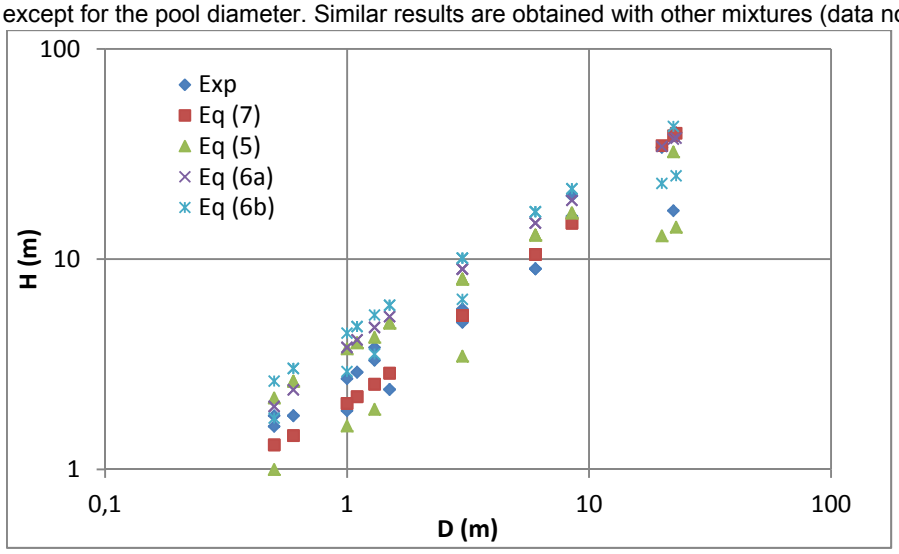

Figure 4: Flame height for gasoline and kerosene. Experimental data and models predictions.

4. Conclusions

Based on the above results, some interesting summarizing conclusions can be drawn.
As far as the burning rate of hydrocarbon liquids different than liquefied gases is concerned, when the fuel-specific data are available, the best predictions can be obtained with the Zabetakis and Burgess equation; however, when relatively large pools are taken into consideration (which often means larger than just 1-2 m), the classical correlations by Burgess and co-workers (Eqs (2) and (4)), can be reliably adopted, provided that accurate values of the physical properties of the involved substances are available. In the case of liquefied gases a high level of uncertainty still exists, unless more complex models are adopted which is often difficult to do in a number of application, like preliminary risk analysis.
In the case of the height of the flame generated by a circular pool fire, the Thomas equation has proved to give accurate predictions when the physical properties of the fuel are available. Quite interestingly, for a large variety of liquid mixtures, the very simple BrLtz correlation was able to accurately predict the flame height based only on the pool diameter. This is a very useful advantage when a large number of rapid calculations are required, or when a large uncertainty around the physical properties of the involved hydrocarbon mixture is present.

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