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Predicting the emissive power of hydrocarbon pool fires

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Abstract

The emissive power (E) of a flame depends on the size of the fire and the type of fuel. In fact, it changes significantly over the flame surface: the zones of luminous flame have high emittance, while those covered by smoke have low E values. The emissive power of each zone (that is, the luminous or clear flame and the non-luminous or smoky flame) and the portion of total flame area they occupy must be assessed when a two-zone model is used.

In this study, data obtained from an experimental set-up were used to estimate the emissive power of fires and its behaviour as a function of pool size. The experiments were performed using gasoline and diesel oil as fuel. Five concentric circular pools (1.5, 3, 4, 5 and 6 m in diameter) were used. Appropriate instruments were employed to determine the main features of the fires. By superimposing IR and VHS images it was possible to accurately identify the luminous and non-luminous zones of the fire.

Mathematical expressions were obtained that give a more accurate prediction of E_{lum}, E_{soot} and the average emissive power of a fire as a function of its luminous and smoky zones. These expressions can be used in a two-zone model to obtain a better prediction of the thermal radiation. The value of the radiative fraction was determined from the thermal flux measured with radiometers. An expression is also proposed for estimating the radiative fraction.

Keywords: Pool fires; Emissive power; Thermal radiation; Solid flame model; Radiative fraction

1. Introduction

Of all potential accidents in the process industry, fires are the most frequent type. They can be divided into pool fires, jet fires and flash fires. Pool or tank fires are the most common, and may be present in a large number of the accident scenarios that arise in the process industry and in related activities.

When such fires occur, the area subject to the thermal effects is relatively small compared to areas affected by other accidents such as explosions or toxic spills. Nevertheless, the thermal radiation in this area can affect other equipment (for example, storage tanks), leading to a significant increase in the scale of the accident due to a domino effect. As a result, the predictive estimation of the intensity of thermal radiation on a given target is essential for emergency planning and for setting up safety measures.

The thermal radiation emitted by fires is estimated using semi-empirical models in which a series of parameters describing the characteristics of the fire must be assessed. These parameters can either be derived from empirical correlations or, alternatively, values from experimental measures can be used.

The solid flame model (SFM) is currently the preferred method for estimating thermal radiation from large fires, and is accepted in current regulations and legislation as a valid technique for assessing the thermal hazard of pool fires [1]. It may be used when the thermal radiation heat transfer is significantly greater than other heat transfer mechanisms. In the SFM the flame is usually represented by an emitter surface with a stable shape and constant emissive power distribution. The solid flame model is based on the following general equation:

$$q'' = \sum_i \tau_i F_i E_i \tag{1}$$

It is generally assumed that the entire surface of the flame has the same E value (one-zone model) and i is equal to one. This introduces a certain error, which can be reduced by using two-zone (or i-zone) models. In a two-zone model ($i = 2$) the solid flame is considered in two zones: the lower zone is luminous flame (high value of E) and the upper one consists of flame/smoke (lower value of E).

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Nomenclature

D	pool fire diameter (m)
E	average flame emissive power (kW m^{-2})
E_{lum}	luminous flame emissive power (kW m^{-2})
E_{soot}	smoky flame emissive power (kW m^{-2})
F	view factor
L	flame length (m)
m''	mass burning rate (kg m^{-2} s^{-1})
q''	radiant heat (kW m^{-2})
x_{lum}	fraction of luminous flame (−)
Greek symbols	
η_{rad}	radiative fraction
τ	atmospheric transmissivity
ΔH_{c}	net heat of combustion (kJ/kg)

Circular pool fires are usually modelled using a cylinder or a tilted cylinder when the flame is tilted by the wind. To apply the solid flame model it is necessary to know or calculate the flame size (height and diameter), the flame emissive power, the view factor between the flame and the target and the atmospheric absorption of radiation.

Among other studies concerned with the definition of models for predicting thermal radiation, Rew and Deaves [2] and Rew et al. [3] analyzed the accuracy of the various correlations which are generally used in the SFM, selecting those which gave the best results. However, these authors did not analyze the expressions available for calculating the emissive power, even though this parameter is essential in the estimation of thermal radiation from a fire using the solid flame model.

Therefore, while relatively consolidated methods exist for estimating the flame size, the view factor and the atmospheric absorption coefficient, predicting the emissive power of a large fire is still subject to a significant degree of error. An effort was made to improve the accuracy of the estimation by using experimental data from large pool fires. The aim of this work was to study the brightness of the flame surface, to evaluate and quantify the contribution of the luminous and non-luminous parts of the flame and the average E value for the whole flame, and to assess the radiative fraction.

2. Experimental set-up

In this article data from three series of outdoor large-scale pool fire experiments were used. The tests were performed using gasoline and diesel oil as fuels lying on top of a layer of water. Five concentric circular pools made of reinforced concrete (1.5, 3, 4, 5, and 6 m in diameter) were employed.

The flame temperature was measured by a set of thermocouples fixed at different positions on a metal structure and on a series of wires crossing the pools at different heights. The burning rate was measured with a system of communicating vessels. The weather conditions were recorded using a meteorological station located on a tower at a height of 10 m.

The experiments were filmed using two video cameras, which registered visible light (VHS), and a commercial thermographic camera (IR). The thermographic camera and one VHS camera were placed side by side, perpendicular to the predominant wind direction during the experiment. The distance between the pool fire and the cameras varied according to the size of the pool fire and was such that all flames were viewed in their entirety by the infrared camera.

In some experiments one or two wide-angle radiometers were used to measure the incident external radiation. The radiometers were placed at distances equivalent to three and five times the pool diameter, measured from its centre, and at heights ranging from ground level to 1.5 m.

Data were recorded on two computers using *ad hoc* software. The acquisition system also contained special hardware for the collection of data measured by the sensors and devices used in the test. In order to synchronize the data logging, the computers were connected via an Ethernet network. A detailed description of the installation and procedures can be found elsewhere [4].

3. Experimental results

Experimental data were processed to obtain the values of the main variables: burning rate, flame shape and size (diameter, length), emissive power and luminous/non-luminous zones. Mathematical expressions were then obtained for calculating burning rate and flame length (maximum and average) [4].

The emissive power of flames is closely related to the appearance (brightness) of their surface. In the accidental burning of liquid hydrocarbons, a large amount of smoke is formed due to the poor combustion. Thus, the surface of the flames consists of different zones according to their brightness, which can be separated for simplicity into two categories: luminous and non-luminous. Furthermore, the position of these zones is variable, due to the high turbulence involved. Their respective contribution to the overall emissive power of the fire will be fairly different and must therefore be taken into account in order to obtain a more accurate value of E.

The existence of these zones can be clearly seen in Fig. 1. This figure corresponds to a diesel oil fire with a diameter of 6 m. The IR contours have been superimposed over the visible image. The luminous and smoky zones are clearly visible.

Superimposing the IR contours over the visible images made it possible to divide the flame surface into luminous and non-luminous zones. The procedure – which is relatively complex – consists essentially of the following steps: (a) digitalization of VHS images; (b) determination of synchrony; (c) determination of scaling factors; and (d) alignment and superimposition of IR images. A detailed explanation can be found elsewhere [4]. Following these steps, the average values of E for each zone were calculated.

Analysis of the energy distribution shows that the average emissive power of the non-luminous part of the flame is $E_{\mathrm{soot}} = 40\ \mathrm{kW/m^2}$; this value is not dependent on either the pool diameter or the type of fuel. The average emissive power of the

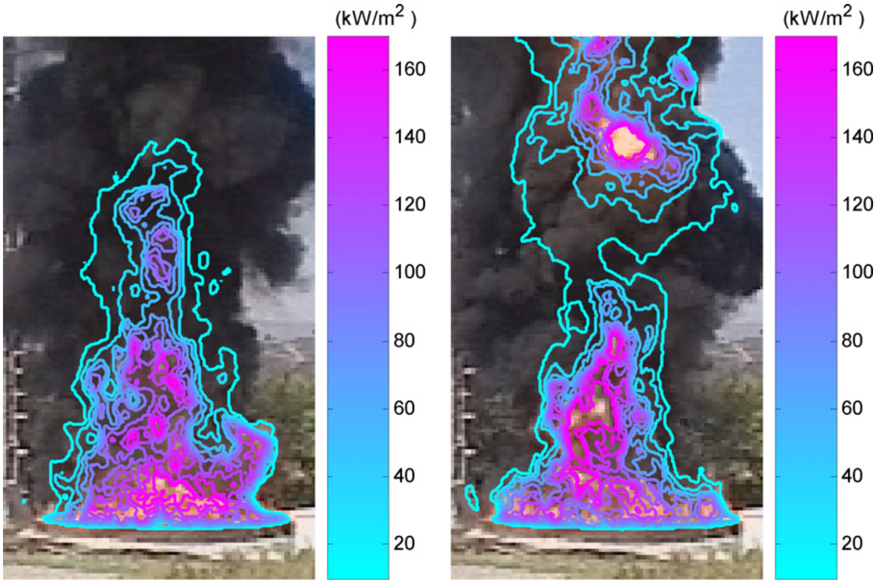

Fig. 1. Luminous and non-luminous zones in a pool fire (diesel oil, 6 m diameter).

luminous zone is approximately $E_{lum} = 80–120\,kW/m^2$, depending on the type of fuel and pool diameter. Moreover, the analysis also revealed the fraction of the flame surface occupied by the luminous zone, x_{lum}, for pool fires with $D \leq 5$ m: 0.45 for gasoline and 0.30 for diesel oil.

The overall average value of E was found to increase as a function of diameter up to approximately $D = 5$ m. According to different authors [5], the overall emissive power starts to decrease with larger diameters; the only results obtained in this range (at $D = 6$ m) seem to confirm this trend. Fig. 2 plots the data from this study together with those from Koseki [6] and Moorhouse and Pritchard [7]. The correlation proposed by Mudan [5] is also plotted: the predicted values are significantly higher than the experimental ones.

In fact, the existing models overpredict the value of E for pool fires with diameters of up to 10 m and give relatively low values for large pool fires (more than 20 m in diameter).

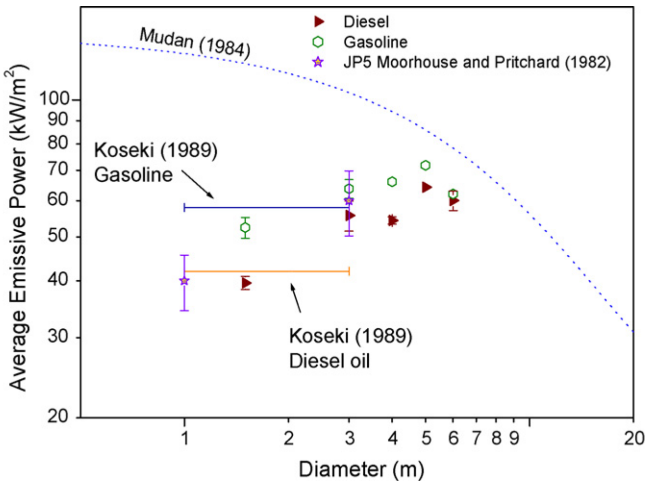

Fig. 2. Values of average emissive power obtained from IR images, together with data obtained by other authors.

4. Prediction of the emissive power

The experimental results were analyzed as a whole in order to obtain a model that would combine the calculation of E as used in a one-zone solid flame model and the parameters used in a two-zone SFM, that is, the values of E for the lower and upper parts of the flame and the fraction of the flame surface occupied by the luminous zone.

From the values of E_{lum}, E_{soot} and the fraction of the luminous flame, x_{lum}, the flame average emissive power can be calculated with the following expression:

$$E = x_{lum} E_{lum} + (1 - x_{lum}) E_{soot} \tag{2}$$

The increase in average emissive power as a function of fire diameter can be explained by the behaviour of E in the luminous zone, determined by the superimposition of IR-VHS images, and by the distribution of E as a function of flame height (obtained from the analysis of IR images [4]). Furthermore, the decrease in average emissive power at $D > 5$ m can be attributed to the generation of smoke near the lower part of the flame, which decreases the area of luminous flame.

In order to develop a model that explains this behaviour, the following assumptions are accepted:

- The range of the increase in E ($D \leq 5$ m) is dependent on two facts: (a) the ratio between the luminous and non-luminous surfaces is essentially constant; and (b) the value of the emissive power for the luminous flame, E_{lum}, increases with D.
- The range of the decrease in E at higher diameters is caused by the reduction of the fraction of the flame surface occupied by the luminous zone, while E_{lum} is essentially constant.

The E_{soot} parameter is taken as a constant value of $40\,kW/m^2$ for any pool diameter and fuel type (experimental data). For the range in which E increases with diameter ($D \leq 5$ m), the values taken for the x_{lum} parameter are 0.45 and 0.30 for gasoline and

Table 1
Values of the parameters in Eq. (3) and (4)

Variables	$D < 5$		$D \geq 5$	
	Gasoline	Diesel oil	Gasoline	Diesel oil
x_{lum}	0.45	0.30	$cD^d - f$	$cD^d - f$
E_{lum}	aD^b	aD^b	115	115
E_{soot}	40	40	40	40
a	53.64	28.03		
b	0.474	0.877		
c			1.80	1.26
d			−0.377	−0.257
f			0.533	0.533

diesel oil, respectively, as explained above. It is assumed that the E_{lum} parameter increases linearly with D in a log–log diagram, thus giving the following relationship:

$$E_{\mathrm{lum}} = aD^b \tag{3}$$

The values of constants a and b obtained from the experimental data are shown in Table 1.

For the range in which E decreases with diameter ($D > 5$ m), the x_{lum} parameter is considered to decrease steadily from 0.45 (gasoline) or 0.30 (diesel oil) to a value of 0.05 at $D = 20$ m. The following equation applies:

$$x_{\mathrm{lum}} = \begin{cases} cD^d - f & \forall 5\,\mathrm{m} \leq D < 20\,\mathrm{m} \\ 0.05 & \forall D \geq 20\,\mathrm{m} \end{cases} \tag{4}$$

The values of constants c, d and f obtained from the experimental data are shown in Table 1.

The exact situation for large diameters is not well known. As the diameter increases, the luminous surface of the flame will gradually decrease. At a certain pool fire diameter, most of the flame surface will be covered by smoke and the luminous zone will be very small; as a result, the average emissive power of the flame will be essentially equal to the emissive power of the smoke, E_{soot}. If it is assumed that E decreases linearly as a function of D (there are not enough experimental data on this range to establish the minimum value of x_{lum} and the rate of decrease of E) with the same ratio as observed when the pool fire diameter changes from 5 to 6 m, then when $D = 20$ m the entire flame surface would be covered by the smoke. Considine [8] indicates that the thermal radiation in pool fires with $D > 25$ m must be entirely attributed to the bursts of luminous flames which appear intermittently in the smoke.

Here, it has been assumed that a small part of the fire surface is luminous even in such large fires; thus, in the model we have considered that 5% of the flame surface is always luminous. E_{lum} in this range (decreasing E) has been assumed to have a constant value of 115 kW m^{-2} (average maximum value of E_{lum}) for the two liquid fuels used and any pool diameter.

The variation of the different variables as a function of pool diameter can be seen in Fig. 3 for a gasoline fire. The upper plot shows the variation of x_{lum}: constant up to $D = 5$ m, then decreasing steadily to a value of 0.05 at $D = 20$ m, as stated above. In the lower plot, E_{lum} increases with a pool fire diameter up to $D = 5$ m and takes a constant value for larger diameters. E increases up to $D = 5$ m according to Eq. (2), and decreases in the range 5 m < $D \leq 20$ m; at $D > 20$ m, it takes a constant value $E \approx 44$ kW m^{-2}. The average emissive power of the flame can be calculated with Eqs. (2)–(4).

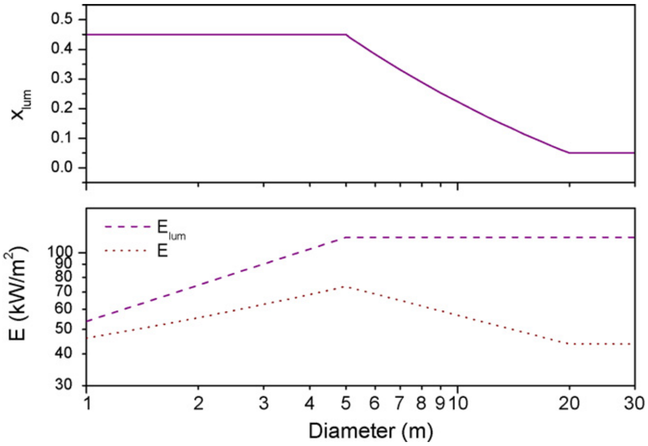

Fig. 3. Evolution of x_{lum}, E_{lum} and E as a function of pool diameter (gasoline).

The predicted values of average emissive power using this model were compared with the experimental values in Fig. 4. It can be seen that the agreement is fairly good for both fuels, following the aforementioned trend.

5. Radiative fraction

The fraction of energy radiated by the fire (η_{rad}) is frequently used to determine the average emissive power of the flame in the one-zone solid flame model [5]. The two parameters can be related using the following expression:

$$E = \frac{\eta_{\mathrm{rad}} \dot{m}'' \Delta H_{\mathrm{c}}}{(1 + 4L/D)} \tag{5}$$

Although there is a significant dependence between the value of η_{rad} and pool diameter [9], very few authors have analyzed it. Yang et al. [9] indicated that the radiative fraction was more or less constant, with a value of 0.35 for pool diameters of less

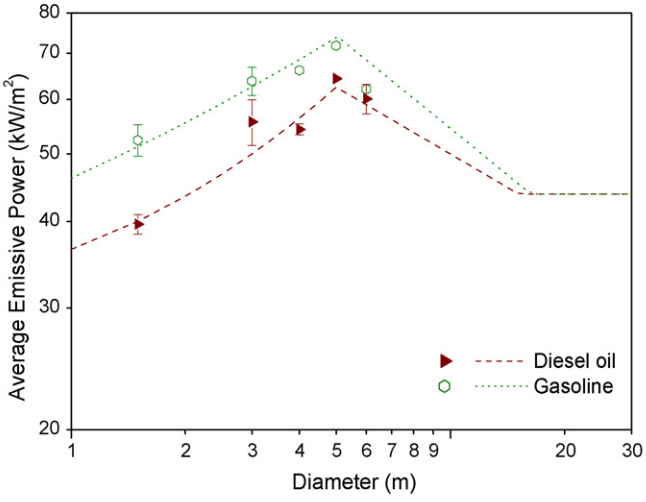

Fig. 4. Experimental results vs. values predicted by the model.

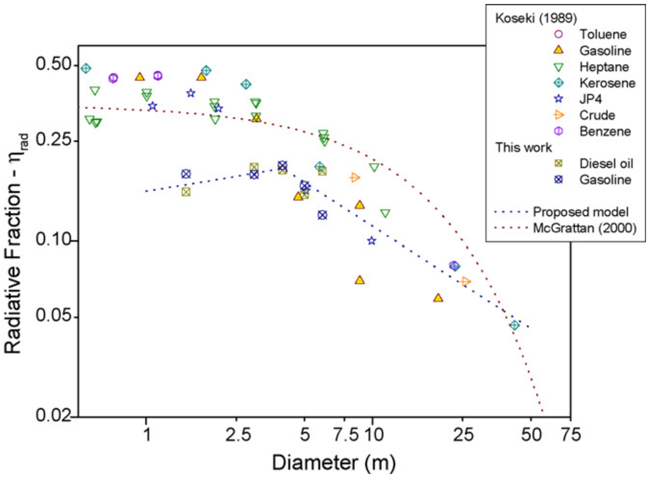

Fig. 5. Experimental results (this work and Koseki [6] data) vs. the proposed model and McGrattan [10] correlation.

than 2 m; for larger diameters, η_{rad} decreases proportionally to $D^{-0.5}$. However, McGrattan et al. [10] found an exponential relationship between η_{rad} and pool diameter:

$$\eta_{\mathrm{rad}} = 0.35e^{-0.05D} \tag{6}$$

The values obtained with this expression are significantly higher than those obtained experimentally in this study. Our results increase slightly with pool diameter up to $D = 4$ m and decrease for larger pool sizes. Even though there was a certain scattering in the experimental results, an attempt was made to obtain a correlation giving η_{rad} as a function of pool diameter for both fuels used:

$$\eta_{\mathrm{rad}} = \begin{cases} 0.158D^{0.15} & \forall D \leq 5\,\mathrm{m} \\ 0.436D^{-0.58} & \forall D > 5\,\mathrm{m} \end{cases} \tag{7}$$

The experimental results, together with those published by other authors, are plotted in Fig. 5; Eqs. (6) and (7) have also been plotted. As can be observed, the expression proposed by McGrattan et al. [10] is relatively close to Koseki [6] data for small pool diameters ($D < 3$ m), but does not agree with the data for larger diameters. Eq. (7) shows a fairly good agreement with our experimental results for the whole range of pool sizes and with the Koseki data for diameters larger than 5 m.

6. Conclusions

Emissive power is a key parameter in calculating the thermal radiation emitted by a fire. However, the different procedures that can be used to predict the value of this parameter show a significant lack of accuracy.

Using experimental data obtained from large pool fires, the superimposition of IR-VHS images made it possible to identify luminous and non-luminous zones. It was therefore possible to establish the distribution of E over the flame surface. Eq. (3) and (4) were obtained which, together with Eq. (2) and the appropriate values ($E_{\mathrm{soot}} = 40\,\mathrm{kW\,m^{-2}}$; when $D > 5$ m, $E_{\mathrm{lum}} = 115\,\mathrm{kW\,m^{-2}}$; when $D \leq 5$ m, $x_{\mathrm{lum}} = 0.45$ for gasoline and $x_{\mathrm{lum}} = 0.3$ for diesel oil), allow the calculation of the value of E. Since these equations take into account the respective contributions (x_{lum}, E_{soot} and E_{lum}) of the luminous and non-luminous surfaces of the flame, they can be used in a two-zone solid flame model, thus providing more accurate estimations of the thermal radiation intensity on a given target. The agreement between values obtained using these expressions and the experimental data is fairly good.

Finally, the thermal flux measured with radiometers gave the value of the radiative fraction. An expression for estimating the radiative faction was also proposed; it shows quite good agreement with experimental data for large pool fire diameters (up to 50 m) reported by other authors.

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