MODELLING OF THERMAL RADIATION FROM EXTERNAL HYDROCARBON POOL FIRES

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A review of literature and published full-scale measurements has been undertaken in order to assess the current status of the modelling of thermal radiation from hydrocarbon pool fires. Based on the review, a semi-empirical model was developed, in which the pool fire is assumed to radiate in two layers; a high emissive power, clean burning zone, at the base, with a smoky, obscured layer above. The choice and development of model correlations was made through comparison against a wide range of field-trial data, which was drawn together to form a validation database. The review also enabled a property database to be produced, containing burning rate and surface emissive power data for a broad range of liquid hydrocarbon fuels. The uncertainty in the application of semi-empirical pool fire modelling is discussed with regard to its use in assessing thermal radiation effects and estimating flame dimensions.

Keywords: hydrocarbon pool fire; thermal radiation; safety assessment.

INTRODUCTION

When a hydrocarbon liquid is accidentally released, for example due to the rupture of a process plant storage tank or a transportation incident, there is a possibility of ignition, resulting in a pool fire. A pool fire is a type of buoyancy-controlled turbulent diffusion flame which burns above a pool of vaporizing fuel, where the fuel vapour has negligible initial momentum. The consequences of such a fire may be immediate, if personnel are exposed to the incident radiation, or may be delayed, forming part of an escalation train leading to events of greater severity.

Consequently, the modelling of the hazards posed by pool fires is an important aspect of both onshore and offshore safety assessments. An extensive review of literature and full-scale measurements has been undertaken in order to assess the current status of the modelling of thermal radiation from pool fires. As a result of this review, a semi-empirical pool fire model, POOLFIRE6, was developed. This is a solid flame surface emitter model which uses a selection of sub-model correlations to derive a flame shape and the fire’s radiation characteristics, as functions of factors such as fuel type and wind speed. The pool fire is assumed to radiate in two layers; a high emissive power, clean burning zone, at the base, with a smoky, obscured layer above.

As a result of the review of full-scale measurements, a validation dataset was produced and used in the assessment of the POOLFIRE6 model. The review also led to the production of a property database containing burning rate and surface emissive power data for a broad range of liquid hydrocarbon fuels.

POOL FIRE CHARACTERISTICS

All luminous flames contain soot particles and it is their subsequent oxidation that produces a high proportion of the flame’s radiative power. The intensity of thermal radiation emitted from a pool fire is highly dependent on the level of obscuration of the incandescent soot particles within the flame by cold soot particles, or smoke, ejected from the flame. The quantity of smoke released depends on a number of effects including the air entrainment rate (controlling the fuel mass fraction within the flame), the turbulence generated in the flame (affecting the mixing rate and movement of smoke to the fire surface) and fuel type (unsaturated, large fuel molecules tend to last longer within the flame, resulting in heavily sooting flames).

The structure of an idealized, well-ventilated, hydrocarbon pool fire is outlined by Bull and Strachan and illustrated in Figure 1, where the fire development is divided into four phases. Firstly, fuel vaporizes from the surface of the liquid pool, with energy provided by feedback of thermal radiation from the combustion zones above. Immediately above the fuel surface, a clean burning luminous flame layer can be observed, characterized by a high mean radiative flux. Above this layer, an obscured flame zone develops, where smoke is ejected from the flame surface, masking the clean burning flame below. The clean burning flame intermittently appears in packets or ‘blumes’. As the height within the flame increases, the smoke obscuration gradually increases until no flame is visible, the combustion has ceased, and a plume of combustion products and unburned fuel is produced. Although this plume still contains heat generated by combustion lower down in the fire, it has a negligible contribution to the total radiative flux to external objects.

TYPES OF POOL FIRE MODEL

Two approaches are currently used in the assessment of hydrocarbon pool fires; field models and semi-empirical models. Field models (commonly known as Computational
Fluid Dynamics, or CFD, models solve the Navier-Stokes equations of fluid flow and, in order for them to predict fire behaviour, they must incorporate sub-models which describe the chemical and physical processes occurring in fires. Many of these sub-models are empirical and therefore validation of CFD codes is as important as it is for more simple modelling techniques. The advantage of field models is that they provide a more rigorous and flexible framework for solving combustion problems than semi-empirical models. Thus, once validated against data for typical pool fire configurations, more confidence can be attached to their results for less idealized scenarios. However, the disadvantage in using field models is that their use requires significant effort and expertise. Semi-empirical models are more frequently used in risk assessments due to their relative ease of use, and it is this level of modelling which this paper addresses.

Semi-empirical models characterize the geometry and radiative characteristics of a pool fire using correlations based on dimensionless modelling. They only incorporate simple descriptions of the physical processes which are required to describe the phenomena of interest and thus a semi-empirical model developed for predicting heat radiation from a fire is not designed to be used for predicting other phenomena. The correlations used in semi-empirical models are derived from a wide range of experimental data and give reasonable predictions provided that they are not used outside their range of validation. Various examples of semi-empirical models exist in the literature and this paper reviews such models and compares their correlations for flame shape and radiative power with full-scale data.

### FULL-SCALE DATA

**Validation Data**

There is a considerable volume of published data relating to the burning characteristics of pool fires; 81 datasets, from 36 separate trial series, were identified, full details of which are given by Rew and Hulbert. Although not all experiments provide complete sets of incident heat flux data, incomplete sets still provide a means of validating the flame shape correlations used within the pool fire model. The key data included in the validation dataset are summarized below:

#### LNG pool fires

Approximately 50% of the identified trial series include LNG fires. The scale of LNG pool fires conducted ranges from 1.8 m in diameter (Shell field trials), to the 35 m diameter Montoir field trials. Experimental pool fire data are also available for LNG releases on water, such as the China Lake field trials.

#### LPG pool fires

There is a reasonable quantity of data available for liquefied petroleum gas pool fires (propane and/or butane). Five series of trials have been identified, three of which provide incident heat flux data. The scale of the fires ranges from 2.7 m by 2.7 m square (Uehara et al.) to 28 m in diameter for the Shell Maplin Sands trials. In the latter trials, and in a series of trials conducted at China Lake, of approximately 10–20 m in diameter, the LPG was released onto water.

#### Heavy hydrocarbons (hexane, heptane and crude oil)

The heat flux data collected for this class of hydrocarbons are limited, with the maximum pool size under controlled experimental conditions being 6 m in a trial undertaken by the Japan FRI. However, limited data are available for a 52 m diameter iso-hexane tank fire incident (Lautkaski) and a 31 m diameter crude oil pool fire experiment (Koseki).

#### Commercial fuels (gasoline, aviation fuels, kerosene and diesel)

There is a large quantity of large-scale data for this class of fuel, but many of the data sets are incomplete; for example, incident heat flux levels are given, but, since no values of relative humidity are recorded, calculation of atmospheric transmissivity is not possible. The scale of the fires ranges from 0.6 m (Yumoto) to 28 m in diameter (China Lake field trials). Note that further trials of up to 75 m equivalent diameter are identified by Alger and Capener but insufficient data are supplied for their inclusion in the validation dataset.

#### Other fuels (toluene, methanol, liquefied ethylene gas and benzene)

A limited amount of data is available for these fuels. One or two datasets were identified for each, with the maximum pool size being 2.7 m by 2.7 m square.

The datasets encompass a wide range of input parameters and vary both in quality and in quantity of measurements. In order to produce a workable validation subset for incident
The review of full-scale data also allowed a fuel property database to be defined, giving parameters required as input to the model correlations discussed below. Although based on fuel properties presented by authors such as Mudan\textsuperscript{1} and Babrauskas\textsuperscript{13}, it has been enlarged to cover a wider range of hydrocarbon fuels and updated to encompass results of recent pool fire experiments. Table 2 gives the necessary properties for the fuels contained within the POOLFIRE6 database, noting that, where data is unavailable, conservative values have been used. For example, for LEG (liquefied ethylene gas), the only available data are for a 2.7 m by 2.7 m square pool fire, for which there was little smoke obscuration. Thus for LEG, $U_R$ is set to 1.0 for all fire diameters.

### Fuel Property Data

The review of full-scale data also allowed a fuel property database to be defined, giving parameters required as input to the model correlations discussed below. Although based on fuel properties presented by authors such as Mudan\textsuperscript{1} and Babrauskas\textsuperscript{13}, it has been enlarged to cover a wider range of hydrocarbon fuels and updated to encompass results of recent pool fire experiments. Table 2 gives the necessary properties for the fuels contained within the POOLFIRE6 database, noting that, where data is unavailable, conservative values have been used. For example, for LEG (liquefied ethylene gas), the only available data are for a 2.7 m by 2.7 m square pool fire, for which there was little smoke obscuration. Thus for LEG, $U_R$ is set to 1.0 for all fire diameters.

### SEMI-EMPIRICAL POOL FIRE MODELLING

Most semi-empirical pool fire models are solid flame surface emitters, where various correlations are used to define the dimensions of a simplified flame envelope and the mean emissive power of the flame surface. Point source models are rarely used, as they do not allow accurate prediction of radiation levels close to the flame surface. Correlations available for the prediction of flame shape and radiative properties of pool fires are reviewed below, with the choice of correlations for the POOLFIRE6 model being made through comparison against the validation data summarized above. The statistical measures used in the comparison (NMSE, FB and FTS) are defined in Appendix A.

### Flame Envelope

The two most common flame shapes used in semi-empirical pool fire models are a sheared elliptical cylinder and a tilted circular cylinder. A sheared elliptical cylinder tends to describe the real flame shape more accurately and can be used to give predictions of incident radiation to targets positioned laterally as well as downwind of the flame. Experimental work at Montoir on 35 m diameter LNG pool fires\textsuperscript{1} has shown that ground level radiation contours are egg-shaped rather than elliptical. Johnson\textsuperscript{4} has used the sheared elliptical flame shape to predict successfully the incident heat flux for these experiments. The disadvantage of a sheared elliptical cylinder flame shape is that computation of the view factors between target and flame cannot be done analytically and must therefore be performed numerically. However, contour integral techniques can be used to simplify the calculations, as outlined by Sparrow and Cess\textsuperscript{19}. Davis and Bagster\textsuperscript{20} present a method for identifying the area viewed by the receiver and Johnson\textsuperscript{4} has found that using the contour integral approach, rather than an area integral approach, reduces computation time by a factor of 10. Therefore, the POOLFIRE6 model uses a sheared elliptical cylinder envelope, split into two layers, with view factors calculated using contour integration.

Figure 2 shows the flame shape parameters which are

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**Table 2. POOLFIRE6 fuel property data.**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>$\dot{m}_{\text{eq}}$ $\text{kg m}^{-2}$ $\text{s}^{-1}$</th>
<th>$k_g$ $\text{m}^{-1}$</th>
<th>$E_{\text{avg}}$ $\text{kW m}^{-2}$</th>
<th>$k_{\text{eff}}$ $\text{m}^{-1}$</th>
<th>$C/H$</th>
<th>$U_R$ m$^2$ m$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone</td>
<td>0.038</td>
<td>2.238</td>
<td>130</td>
<td>0.500</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.085</td>
<td>2.700</td>
<td>130</td>
<td>1.000</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Butane</td>
<td>0.110</td>
<td>0.852</td>
<td>225</td>
<td>0.937</td>
<td>0.400</td>
<td>0.02</td>
</tr>
<tr>
<td>Crude oil</td>
<td>0.051</td>
<td>1.301</td>
<td>130</td>
<td>0.540</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.054</td>
<td>1.301</td>
<td>130</td>
<td>0.530</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.141</td>
<td>0.136</td>
<td>250</td>
<td>0.149</td>
<td>0.330</td>
<td>0.02</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.020</td>
<td>1.301</td>
<td>130</td>
<td>0.330</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>0.034</td>
<td>1.670</td>
<td>130</td>
<td>0.610</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Gasoline/petrol</td>
<td>0.067</td>
<td>1.480</td>
<td>130</td>
<td>0.430</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Heptane</td>
<td>0.081</td>
<td>1.394</td>
<td>200</td>
<td>0.438</td>
<td>0.23</td>
<td>0.12</td>
</tr>
<tr>
<td>Hexane</td>
<td>0.075</td>
<td>1.394</td>
<td>200</td>
<td>0.429</td>
<td>0.23</td>
<td>0.12</td>
</tr>
<tr>
<td>Hydrogen (liquefied)</td>
<td>0.161</td>
<td>6.741</td>
<td>70</td>
<td>7.415</td>
<td>0.000</td>
<td>1.00</td>
</tr>
<tr>
<td>JP4</td>
<td>0.056</td>
<td>1.962</td>
<td>130</td>
<td>0.460</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>JLS/kerosine</td>
<td>0.063</td>
<td>1.296</td>
<td>130</td>
<td>0.450</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>LNG/methane</td>
<td>0.140</td>
<td>265</td>
<td>0.500</td>
<td>0.77</td>
<td>0.69</td>
<td>0.55</td>
</tr>
<tr>
<td>LNG/methane (water)</td>
<td>0.141</td>
<td>0.136</td>
<td>265</td>
<td>0.149</td>
<td>0.250</td>
<td>0.02</td>
</tr>
<tr>
<td>LPG/propane</td>
<td>0.118</td>
<td>0.500</td>
<td>250</td>
<td>0.550</td>
<td>0.375</td>
<td>0.23</td>
</tr>
<tr>
<td>LPG/propane (water)</td>
<td>0.256</td>
<td>250</td>
<td>0.250</td>
<td>0.55</td>
<td>0.23</td>
<td>0.16</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.020</td>
<td>2.00</td>
<td>0.417</td>
<td>0.23</td>
<td>0.12</td>
<td>0.08</td>
</tr>
<tr>
<td>Naphtha/pentane</td>
<td>0.085</td>
<td>1.394</td>
<td>200</td>
<td>0.444</td>
<td>0.23</td>
<td>0.12</td>
</tr>
<tr>
<td>Octane</td>
<td>0.066</td>
<td>3.370</td>
<td>130</td>
<td>0.875</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.090</td>
<td>1.400</td>
<td>130</td>
<td>0.800</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

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required to define the flame envelope. The incident heat flux at a target is then calculated as follows:

\[ q = q_L + q_U = \tau_L F_L E_L + \tau_U F_U E_U \]  

(1)

Atmospheric transmissivity is determined using the method given by Wayne et al., which assumes that the flame can be modelled as a grey or black body emitter with a source temperature of 1500 K. Although this temperature is higher than that of the smoke which may obscure parts of the flame, most of the emitted radiation from a pool fire comes from the unobscured flame, which typically has a temperature of between 1200 K and 1500 K. This method requires the path length between the radiating body and the target to be defined. In the POOLFIRE6 model the path length is conservatively assumed to be equal to the minimum distance between the target and the pool fire envelope.

Other flame shapes have been used in the modelling of pool fires, such as a sheared conical ellipse or the realistic, normalized flame shape used in the British Gas FIRE2 model. The latter flame shape, combined with a two-layer surface emissive power model, has been used to predict heat flux from a wide range of fuel types. However, view factor calculations must be undertaken using an area integral method which is more time-consuming than the contour-integral or analytical methods which are available for simpler flame shapes, and the benefit of using a realistic flame shape is likely to be small in comparison with uncertainties in the surface radiative properties of the pool fire.

**Mass Burning Rate**

The parameters describing the flame geometry are dependent on both fuel type and ambient conditions. The key property used to characterize the fuel is its mass burning rate per unit area of pool surface, \( \dot{m} \). The mass burning rate for a particular fuel varies with pool diameter, as given by Babrauskas:

\[ \dot{m} = \dot{m}_b (1 - e^{-k_D}) \]  

(2)

It can be seen that the burning rate asymptotes to a maximum mass burning rate at large diameters. This can be explained by assuming that vaporization of fuel from the pool surface is due predominantly to radiation from the fire. As the flame grows, it reaches a characteristic size at which it is said to have become optically thick, and any further increase in size does not produce an increase in emitted radiation. The pool diameter at which this occurs varies with fuel type and thus \( k_D \) values are also fuel dependent.

**Flame Length**

Flame length can be defined in a number of ways. Cowley and Johnson make a distinction between maximum visible flame length and the average experimental value. The maximum visible flame length is the distance from the base of the flame to the highest point at which blumes of flame can be seen to emerge from the upper section of the flame. The average experimental value is the time-averaged height of these blumes of visible flame. As the soot production and obscuration of the flame increases, then the difference between the flame lengths measured in these two ways increases.

The Thomas correlation is widely used for models which use a mean surface emissive power over the entire envelope and is based on the dimensionless mass burning rate, \( \dot{m}^* \), of the fire under quiescent conditions:

\[ \frac{L}{D} = 42 \dot{m}^*^{0.61} \]  

(3)

Cowley and Johnson showed that, for the benchmark fires studied, models using the correlation gave good maximum flame length predictions for fires with little smoke obscuration, such as LNG or small flames, although the correlation tended to underpredict the maximum flame length for smoky flames. Pritchard and Binding have produced a two-layer surface emitter model, with a realistic flame shape, to be used for a wide range of hydrocarbons. This includes a new correlation to predict the maximum flame length:

\[ \frac{L}{D} = 10.615 (\dot{m}^*)^{0.305} (U^*_L)^{-0.03} \]  

(4)

This correlation takes into account the effect of wind causing improved air entrainment into the fire and thus lower flame heights, although the effect appears to be secondary as is evident by the small exponent of \(-0.03\) for \( U^*_L \). It should also be noted that the correlation has been developed for predicting the flame length for a model using a realistic normalized flame shape, as might be given by the dotted outline in Figure 2. Figure 3 compares the
Thomas\textsuperscript{22} and the Pritchard and Binding\textsuperscript{6} correlations with a least squares fit to large-scale pool fire data. The figure shows that the flame length data is very scattered, reflecting both the difficulty of measuring flame length and the different definitions of flame length used in different trials. Neither the Pritchard and Binding\textsuperscript{6} correlation nor the least squares fit provide significant improvement over the Thomas\textsuperscript{22} correlation, which is widely used in conjunction with cylindrical flame shapes and is therefore used in POOLFIRE6.

### Flame Tilt

A commonly used correlation for flame tilt is that given by the American Gas Association\textsuperscript{23}:  

\[
\frac{\tan \theta}{\cos \theta} = c (Fr)^a (Re)^b
\]

for \( U_{1.6}^* \leq 1.0 \)  

\[
\cos \theta = \frac{1}{U_{1.6}^*}
\]

This correlation has been criticized due to its prediction of zero tilt at low wind speeds, when experiments have shown that significant tilt may still occur. More recent studies\textsuperscript{3,4} have shown that flame tilt can be predicted using a correlation with a form given by Welker and Sleipcevich\textsuperscript{24}:

\[
\frac{\tan \theta}{\cos \theta} = a (Fr)^b (Re)^c
\]

The use of Froude, \( Fr \), and Reynolds, \( Re \), numbers in the modelling of flame tilt comes from consideration of the forces acting on the gases within the flame envelope. The Froude number can be considered to be the ratio of inertia to buoyancy forces and the Reynolds number the ratio of inertia to viscous forces, assuming that the inertia of the gas is dependent on the wind. The constants \( a \), \( b \), and \( c \) and the NMSE and FB values are summarized in Table 3 for correlations given by Johnson\textsuperscript{4} and Pritchard and Binding\textsuperscript{3}, as well as a least squares fit against the validation dataset. The Welker and Sleipcevich\textsuperscript{24} form appears to be insensitive to the Reynolds number of the pool fire; POOLFIRE6 uses the least squares fit, which is consistent with this lack of variation with \( Re \).

### Flame Drag

Moorhouse\textsuperscript{25} gives the following correlation for flame drag for LNG fires, which is similar to that developed by Johnson\textsuperscript{4}, also derived from LNG data.

\[
\frac{D'}{D} = 1.5 (Fr_{10})^{0.069}
\]

The Moorhouse correlation has been adapted by Mudan and Croce\textsuperscript{5} to model flame drag for other hydrocarbon fuels, by adding a density ratio term:

\[
\frac{D'}{D} = 1.25 (Fr_{10})^{0.069} \left( \frac{\rho_f}{\rho_t} \right)^{0.48}
\]

Pritchard and Binding\textsuperscript{6} give a correlation for flame drag with a reduced dependence on the density ratio:

\[
\frac{D'}{D} = 2.506 (Fr_{10})^{0.067} (Re)^{-0.03} \left( \frac{\rho_f}{\rho_t} \right)^{0.145}
\]

Table 4 compares the normalized mean square error (NMSE) and fractional bias (FB) values for the above correlations when compared against the full-scale pool fire dataset. It can be seen that, for drag ratio, the Moorhouse\textsuperscript{25} correlation represents the best fit to the data, although it should be noted that approximately half of the experimental data used in the comparison is that used by Moorhouse to develop his correlation. However, the additional data has been obtained from mainly non-LNG pool fire tests which implies that the density ratio term is not as significant as suggested by the Mudan and Croce\textsuperscript{5} modification. Therefore, in the absence of further experimental data, the density ratio term is omitted in the POOLFIRE6 model and the Moorhouse correlation is used.

### Flame Surface Emissive Power

The radiative output of a fire can be calculated either by assuming that a certain fraction of the combustion energy is released as radiation, or alternatively by using correlations to define the surface emissive power of the flame. Although the latter approach is that most commonly used for pool fires, care is required in its application. Different assumptions about the flame geometry can produce significant variations in flame surface area and therefore the surface emissive power of the flame needs to be matched to its surface area in order for its total radiative output to be modelled correctly.

The surface emissive power of a pool fire depends on the fuel type and the pool diameter. For LNG and LPG pool fires, a correlation of the following form is generally used:

\[
E = E_w (1 - e^{-k_0 D})
\]

For heavy hydrocarbon fuels, a smoky flame correlation is often used, as given by Mudan and Croce\textsuperscript{5}:

\[
E = E_{se} e^{-k_D D} + E_0 (1 - e^{-k_D D})
\]

The above correlations tend to be used within models which assume a constant mean surface emissive power over the full flame surface. However, a model which uses multiple layers of surface emissive power will give more accurate predictions of near-field incident radiation, especially downwind of the flame where the single-layer model can underpredict incident heat fluxes at ground level. The

<table>
<thead>
<tr>
<th>Table 3. Constants for flame tilt correlations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation</td>
</tr>
<tr>
<td>Johnson\textsuperscript{4}</td>
</tr>
<tr>
<td>Pritchard and Binding\textsuperscript{5}</td>
</tr>
<tr>
<td>Least squares fit</td>
</tr>
</tbody>
</table>
use of a multi-layer model arises from observations of large smoke-producing hydrocarbon fires, where a distinct base layer to the flame, which is almost unobscured by smoke and is emitting radiation at the maximum level for the fuel, can be seen. Above this layer, smoke is released from the fire, thereby obscuring the flame surface from the field of view of the target and heat is radiated in ‘blumes’. 

POOLFIRE6 uses a two-layer model. The base layer is assumed to emit thermal radiation at the maximum level for the fuel at the pool diameter, i.e. it is assumed that there is no obscuration of this layer by smoke, and its surface emissive power, \( E_u \), is calculated using equation (11). The upper layer is assumed to be obscured by smoke; the level of obscuration being defined for each pool fire using an unobscured ratio. Considine\(^2\) assumed that the portion of the fuel visible at any one time (unobscured ratio) is 30% and Pritchard and Binding\(^3\) use a database of values that depend on fuel type and pool diameter. In the absence of a suitable correlation for predicting obscuration, POOLFIRE6 also uses a database of unobscured ratios based on photographic data, mean surface emissive power data and on conversion of the Pritchard and Binding\(^3\) data to correct for flame length and flame shape. The surface emissive power of the upper layer, \( E_u \), is calculated from the unobscured ratio, \( U_R \), as follows:

\[
E_U = U_RE_L + (1 - U_R)E_S \quad (13)
\]

### Clear Flame Length

The modelling of the clear flame length has been addressed by Considine\(^2\), Pritchard and Binding\(^3\), and Ditali et al.\(^4\). Considine suggested that it varied from approximately 30% of the maximum flame length for fires up to 25 m in diameter to 0% for fire diameters of 50 m or more. As discussed above, the hydrocarbon fuel type has a large influence on the production of smoke within the fire, and, therefore, the clear flame length. The \((C/H)\) ratio can be used to describe the saturation of a hydrocarbon fuel and hence its tendency to produce soot. This ratio is the one used by Pritchard and Binding\(^3\) to characterize the effect of fuel type in their correlation for clear flame length:

\[
\frac{L_c}{D} = 11.404 (\dot{m}^*)^{1.13} (U^*_9)^{0.179} \left( \frac{C}{H} \right)^{-2.49} \quad (14)
\]

The air entrainment rate into a pool fire has a strong effect on the production of soot particles as is evident by the increase in soot production with increasing pool diameter (when the air entrainment rate to the centre of the pool is reduced). As discussed by Thomas\(^21\), the ratio of air entrained to fuel burned is characterized by the dimensionless mass burning rate of a pool fire, \( \dot{m}^* \), which accounts for its presence in the Pritchard and Binding\(^3\) clear flame length correlation. Increased wind speed also aids air entrainment into the pool fire and in the Pritchard and Binding correlation this is characterized using the dimensionless wind speed, \( U^*_9 \). Ditali et al.\(^4\) have produced a similar correlation, based on a separate set of experiments, with a lower dependence on \((C/H)\) ratio:

\[
\frac{L_c}{D} = 12.4 (\dot{m}^*)^{0.61} D^{-0.66} \left( \frac{C}{H} \right)^{-0.15} \quad (15)
\]

### Tank Fires

In the absence of full-scale tank fire data, it has been assumed in the POOLFIRE6 model that the correlations for flame shape and flame radiative power for ground level pool fires described above can also be used for tank fires. This seems a reasonable assumption provided that the liquid level of the liquid is close to the top of the tank. If the liquid level is significantly lower than the tank rim then the mass burning rate and flame characteristics may be affected.

A flame shape parameter peculiar to tank fires is flame sag; the flame from a tank fire ‘spills’ over the edge of the tank and drops, or sags, to a level below the tank lip, as illustrated in Figure 2. Observations suggest that the flame sag is approximately one third of the extension of the flame base due to flame drag. This is confirmed by the measurements by Lautkaski\(^1\) on a 52 m diameter iso-hexane tank fire; flame sag varied from 2.6 m to 6.8 m with corresponding flame drag extensions of 7.8 m to 20.8 m, i.e. approximately three times the flame sag. Therefore, in POOLFIRE6, it is simply assumed that flame sag, \( H_s \), is calculated as follows:

\[
H_s/D = \frac{1}{3}(D'/D - 1) \quad (16)
\]

### MODEL VALIDATION AND UNCERTAINTY

The full validation of the POOLFIRE6 model has been
detailed elsewhere\textsuperscript{1,28}. Figure 5 and Table 5 summarize the results of the validation exercise, from which the following key conclusions can be drawn:

1. Figure 5 shows that the POOLFIRE6 model predicts the measured thermal radiation to within a factor of two for 90\% of the validation dataset, the obvious exceptions being a methanol trial\textsuperscript{29} at 3 m and LNG trials\textsuperscript{30} at 6.1 m. POOLFIRE6, and similar semi-empirical models, will severely overpredict radiation from fuels which are non-sooting, such as methanol, where the majority of radiation comes from hot, gaseous combustion products, rather than from incandescent soot, for which the model has been developed. The LNG trials showed a wide variation between mean and maximum incident radiation and the pool fire model fitted to the trial data showed similar overprediction.

2. The POOLFIRE6 model tends to overpredict incident thermal radiation for diameters of greater than 3 m. Although no validation was undertaken for pool diameters greater than 35 m, the model is likely to be conservative for these scenarios, as the obscuration of the flame surface increases with pool diameter.

3. The model performed better for heavy hydrocarbon fuels than for LNG/LPG. Figure 6 illustrates the prediction of the model for a smoky, 10 m by 10 m square JP4 pool fire\textsuperscript{31}.

4. The model predictions improve as the distance from the fire increases, as illustrated in Figure 7 for LNG/LPG pool fires. This suggests that predictions of semi-empirical models of this type, which use idealized time-averaged flame envelopes, are uncertain at locations close to the flame.

5. The model predictions are poorer for water-based than for land-based fires, possibly due to uncertainties in defining the exact location of the fire centre with respect to receiver locations for fuel releases onto water. Although the statistics appear to suggest that the quality of the model is poorest for large diameter fires, it should be noted that this large diameter range is dominated by the water-based pool fire trials.

The breadth of the validation undertaken for the POOLFIRE6 model allows the model uncertainty to be defined for different fuel types and substrate conditions and for a range of ambient conditions and fire sizes. This uncertainty encompasses the stochastic nature of the problem, experimental errors and the inaccuracy of the model itself. In a semi-empirical model, the inaccuracy may arise from a lack of consideration of parameters such as substrate temperature (and its effect on mass burning rate) or over-simplification of the modelling of effects such as obscuration of the target from the flame by smoke. It should be noted that the validation has been undertaken for ‘ideal’ scenarios (well-ventilated, circular or low aspect ratio rectangular pool fires) only and further uncertainty may be introduced when attempting to use it for more realistic scenarios. Examples of ‘non-ideal’ conditions that may affect the radiation levels around a pool fire include reduced ventilation, obstructions within and around the pool, pool aspect ratio and temperature of the substrate. Uncertainty in experimental data may

---

**Table 5. Results of POOLFIRE6 validation.**

<table>
<thead>
<tr>
<th>Validation subset</th>
<th>NMSE</th>
<th>FB</th>
<th>FTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG/LPG</td>
<td>0.26</td>
<td>-0.42</td>
<td>0.79</td>
</tr>
<tr>
<td>Non-LNG/LPG</td>
<td>0.08</td>
<td>-0.06</td>
<td>0.98</td>
</tr>
<tr>
<td>Land-based circular</td>
<td>0.18</td>
<td>-0.29</td>
<td>0.90</td>
</tr>
<tr>
<td>Land-based rectangular</td>
<td>0.05</td>
<td>+0.04</td>
<td>1</td>
</tr>
<tr>
<td>Water-based</td>
<td>0.30</td>
<td>-0.33</td>
<td>0.75</td>
</tr>
<tr>
<td>$D &lt; 3$ m</td>
<td>0.12</td>
<td>+0.06</td>
<td>0.95</td>
</tr>
<tr>
<td>$3 \text{m} &lt; D &lt; 10$ m</td>
<td>0.10</td>
<td>-0.16</td>
<td>1</td>
</tr>
<tr>
<td>$D &gt; 23$ m</td>
<td>0.23</td>
<td>-0.36</td>
<td>0.83</td>
</tr>
<tr>
<td>Overall</td>
<td>0.17</td>
<td>-0.18</td>
<td>0.90</td>
</tr>
</tbody>
</table>

---

Figure 5. Comparison of POOLFIRE6 model with validation dataset.

Figure 6. Comparison with 10 m by 10 m square JP4 pool fire data\textsuperscript{31}.

Figure 7. Comparison with LNG/LPG circular land-based data.
relate to variation in ambient conditions (especially wind speed and direction) during a trial and the averaging time and field of view of radiometers. Generally, the low number of measurements taken for each trial precludes authors from defining the accuracy of their measurements. However, there are exceptions and, for example, Johnson\(^\text{et al.}\) provides standard deviations of measured flux data for a range of highly instrumented and well-controlled LNG pool fire trials. For the trials given, this standard deviation is approximately 10 to 25% of the average values and is related to both experimental uncertainty and the stochastic and fluctuating nature of the fire event.

The primary purpose of the POOLFIRE6 model is to predict the thermal radiation which is incident on targets external to the flame envelope. Thus, although the flame shape correlations have been compared against full-scale data, care is required in using semi-empirical pool fire models to predict flame impingement. Pool fires are unsteady and solid surface emitter models predict the visible steady-state dimensions of idealized flame envelopes. Additionally, the model does not allow prediction of heat fluxes to objects within the flame, where heat transfer is due to convection as well as radiation.

### CONCLUSIONS

The review of pool fire modelling and full-scale data has allowed the production and validation of a semi-empirical pool fire model, POOLFIRE6. The review showed that there is a large quantity of published large-scale data (especially for incident external radiation) which is of sufficient quality to be used to validate pool fire models, of whatever complexity. The validation dataset covers the majority of fuels, pool sizes and ambient conditions considered within risk assessments. However, two deficiencies that were identified are the lack of large-scale wind-blown tank fire data and measurements of incident radiation at locations close to the flame surface.

The validation exercise has defined the uncertainty in modelling thermal radiation from pool fires. The POOLFIRE6 model predicts thermal radiation within a factor of two for 90% of the validation subset, with better confidence for certain fuel types and sets of input parameters. The uncertainty in the modelling is likely to consist of two components; experimental error and model inaccuracy. Model inaccuracy may be reduced by improved modelling of smoke obscuration. There will also be uncertainty related to the use of the model within a hazard assessment which results from its use for non-ideal incidents, e.g. for obstructed pools, or where it is used outside its range of validation.

An alternative to semi-empirical modelling of pool fires is the use of field (CFD) models. However, these require sub-models for combustion, soot-production and radiative heat transfer. These sub-models will contain some level of empiricism and therefore CFD models also require validation. Once validated, CFD models have the potential to address effects such as enclosure of the fire and obstructions within the flame. These benefits must be balanced against the relative ease of use of semi-empirical models, which, within their range of validation, provide an efficient method of calculating heat fluxes for hazard assessment purposes.

### APPENDIX A—VALIDATION METHODOLOGY

There are various methods available for evaluating the quality of consequence models, including, for example, those used in the comparison of dense gas dispersion models against appropriate validation data (Hanna \(\text{et al.}\)\(^3\)). Britter\(^\text{et al.}\) has reviewed methods used to assess the fitness for purpose of technical models and suggests that two statistics used by Hanna \(\text{et al.}\)\(^3\), fractional bias and normalized mean square error, provide a useful comparison between models. If a quantity \(X\) has \(N\) predicted values, \(X_P\), corresponding to observations, \(X_O\), then these statistics can be calculated as follows:

**Fractional Bias (FB):**

\[
FB = \frac{1}{N} \sum_{i=1}^{N} \frac{X_O - X_P}{X_O + X_P}
\]

**Normalized Mean Square Error (NMSE):**

\[
NMSE = \frac{1}{N} \sum_{i=1}^{N} \frac{(X_O - X_P)^2}{X_O X_P}
\]

Fractional bias (FB) is a measure of the over- or underprediction of a model; a negative fractional bias indicates that a correlation is overpredicting experimental data. The normalized mean square error (NMSE) is a measure of the relative fit of a model to data and can be used in the comparison of correlations. Both the FB and NMSE measures have been used to assist in the process of choosing the correlations for the POOLFIRE6 sub-models and also in assessing the quality of the model for the prediction of thermal radiation for different fuel types and a range of input parameters.

A further statistical function used by Hanna \(\text{et al.}\)\(^3\) in the evaluation of hazardous gas models is the factor of two statistic.

**Factor of Two Statistic (FTS):**

\[
FTS = \frac{n}{n} \cdot \frac{X_O}{X_P}
\]

where \(n\) is the number of predictions within a factor of two of the corresponding observations. The FTS is an absolute measure of the quality of fit of a model and has been used to assess the POOLFIRE6 model predictions of incident thermal radiation.

### NOMENCLATURE

- \(a, b, c\) constants used in flame tilt correlation
- \(CH\) carbon to hydrogen atomic ratio in fuel
- \(D_f\) pool fire diameter, m
- \(D_{13}\) flame dragged diameter of pool fire, m
- \(E\) surface emissive power of flame, kW m\(^{-2}\)
- \(E_L\) surface emissive power of lower clean burning flame zone, kW m\(^{-2}\)
- \(E_m\) maximum emissive power of luminous spots, approximately 140 kW m\(^{-2}\)
- \(E_w\) maximum surface emissive power for the fuel, kW m\(^{-2}\)
- \(E_S\) emissive power of smoke, approximately 20 kW m\(^{-2}\)
- \(E_U\) surface emissive power of upper flame zone corrected for obscuration, kW m\(^{-2}\)
- \(F_L\) view factor between lower zone of flame and receiver
- \(Fr\) \(U^2/gD\) = Froude number of pool fire
- \(Fr_9\) Froude number of the pool fire based on wind speed at a height of 9 m
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