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Flame Radiation Characteristics of Open Hydrocarbon Pool Fires

E. Ufuah and C. G. Bailey

***Abstract*— The fundamental subject of fire research with problems involving hydrocarbon pool fires focuses on thermal radiation from the flame surface. Smoke obscuration and pool fire size are parameters of influence. The object is to establish the temperature and heat flux profiles, and assess the hazard consequences that may arise from these fire actions. This investigation, therefore, provides a correlation for the surface emissive power of flame based on observed data taken from five different experimental studies. It is shown in this study that due to spatial and temporal variations associated with trials conducted at different times and locations on free-burning pool fires, model predictions for surface emissive power of flame can be very different. The present correlation provides a reasonable prediction for liquefied natural gas and aviation fuels compared to those of Shokri and Beyler, and Mudan and Croce. However, the investigation reveals that a coefficient of variation between 6 and 17 per cent can be found by separately adopting the flame height models of Heskestad and Thomas for fire diameters up to 120 m. This highlights the need to exclusively utilize a given methodology, which gives a clear description of all sub- models used in the derivation of surface emissive powers of free-burning hydrocarbon pool fires. It is noted that the significance of thermal radiation model also broadens the means by which the acceptable separation distances between radiation source and targets ‒ people and structures can be determined.**

***Index Terms*— Flame height, pool fire diameter, radiation model, soot.**

I. Introduction

The primary subject of research with problems involving hydrocarbon pool fires centres on thermal radiation from the pool surface. Over the last few decades there have been numerous experimental studies conducted to establish thermal radiation models from large pool fires [1]-[7]. To address the above subject, it is necessary to consider how big and fast the fire is burning as well as the consequent effect of smoke on radiation and wind on the resultant flame shape. Systematically, one may look at the operating fire regime that characterizes the scope within which radiation is seen to dominate in heat transfer. Babrauskas [1] explains that for diameters of pool fire, ($D > 0.2$m) heat transfer is dominated by radiation. Fuel type is known to be a single factor that characterizes the transition between optically thin and optically thick flame.

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Generally, for the range $0.2\text{m} \leq D \leq 1.0\text{m}$, the radiative mode of burning is said to be optically thin while for pool diameters greater than 1.0m the fire is known to have become optically thick and turbulent [1,5]. The object is to establish the temperature and heat flux distribution together with the hazard consequences deriving from such events. In this investigation, a correlation for thermal radiation from hydrocarbon pool fires is developed based on the methodology utilised by Shokri and Beyler [8]. The validity of the model is drawn from a set of data for pool fire radiation to nearby structures situated at ground level. A comprehensive algorithm for the computation including the relevant assumptions is presented, and the model is compared with those of Shokri and Beyler [8], Mudan and Croce [9] and McGrattan *et al*. [10].

An explicit account of wind effect on flame geometry has not been considered in the present model since the correlations on which a comparison is drawn are based on quiescent air conditions. However, if wind effect will be considered the flame height correlation of Heskestad [11] does no longer apply. An alternative geometrical characterization of the flame model can be made using the models proposed by Thomas [12] and Moorhouse [13]. Apparently, when developing the effective emissive power of a flame it is vital to exclusively adopt a given methodology. Table 1 summarises the discrepancies in the flame height model based on Heskestad [11] and Thomas [12] for the zero wind conditions using gasoline pool fuel in the diameter, D range of $1.0\text{m} \leq D \leq 120\text{m}$. The differences account for a coefficient of variation between 6 and 17 percent. This is sufficient to introduce errors in the prediction of flame behaviour if not correctly implemented, particularly for smaller pool diameters as depicted in Fig. 1. Fig. 2 illustrates various flame height models that can be utilized to compute radiant heat flux to nearby structures. The effect of wind has been included in the correlations of 'Thomas 2' and 'Moorhouse' as shown in Fig. 2.

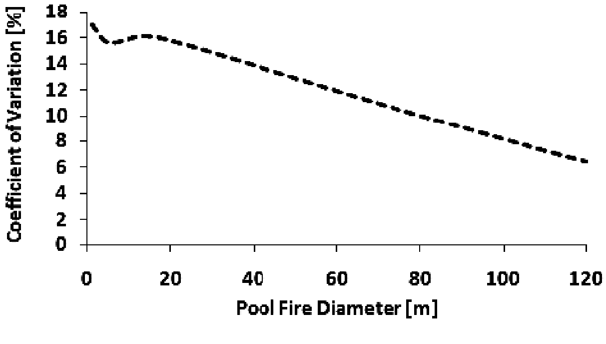

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Fig. 1 Degree of variation between Heskestad and Thomas flame height models for gasoline pool fire

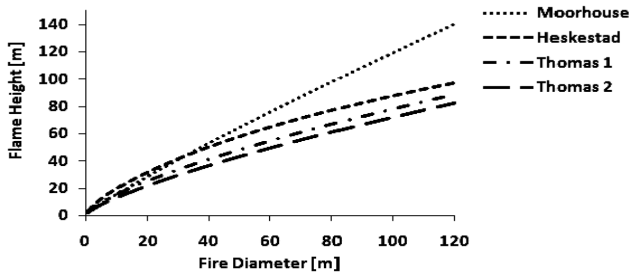

Fig. 2 Comparison of flame height correlations for gasoline pool fire

II. Pool fires and flame geometry

The properties of open pool fires are markedly different from those within enclosures. For pool fires, the spill could result from the rupture of a pipe or container as well as from possible overfilling of a storage tank [7]. When this happens, there is the likelihood of fire occurring subject to possible ignition sources. Different types of fire likely to occur in the offshore following accidental releases of flammable hydrocarbon fuels can be found in the handbook of society of fire protection engineers (SFPE) [14]. It is expected that a flammable liquid spill will continue to spread until it is bunded or at equilibrium when the burning rate of the fuel equals the spread rate. Moreover, the parameters that characterize the geometry of free pool fire flames include the flame height and the equivalent pool fire diameter. Fig. 3 illustrates the schematics of geometrical shapes of pool fire models. The tilt and drag of the pool flame are dictated by wind effect.

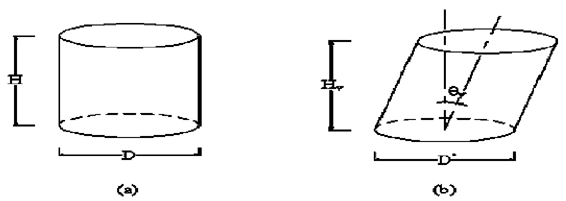

Fig. 3 Schematic of cylindrical flame models. (a) Still air flame model (b) Flame model under wind conditions

The most widely used flame height correlations are those of Heskestad [11], Thomas [12] and Moorhouse [13]. Equation (1) is used for still air investigation while that of (2) can be used under wind conditions as proposed by Thomas [12].

$$\frac{H}{D} = 42\left(F_r\right)^{0.61} \tag{1}$$

$$\frac{H}{D} = 55\left(F_r\right)^{0.67}\left(u_*\right)^{-0.21} \tag{2}$$

where H is flame height, D is fire diameter

$$F_r = \frac{\dot{m}''}{\rho_a\sqrt{(gD)}} \tag{3}$$

$$u_* = \left(\frac{u_w^3\rho_a}{gD\dot{m}''}\right)^{1/3} \tag{4}$$

Beyler [15] remarks that the Heskestad [11] correlation under quiescent air conditions best represents large diameter pool fires. The correlation of Moorhouse [13] based on several large scale test of liquefied natural gas (LNG) pool fires under wind conditions can be represented in the form:

$$\frac{H}{D} = 6.2\left(F_r\right)^{0.254}\left(u_{10}\right)^{-0.044} \tag{5}$$

Where F_r is the non-dimensional combustion Froude's number as given by equation (3) and u_{10} is the non-dimensional wind velocity of equation (4) with the wind speed measured at a height of 10m above the ground.

Heskestad flame height model for zero wind condition is commonly expressed as follows:

$$H = 0.23\dot{Q}^{2/5} - 1.02D \tag{6}$$

III. Thermal radiation characteristics

The flame spread rate for pool fires is considered to be liquid-controlled owing to its low initial momentum. The maximum liquid-phase spread velocity of pool fires is conservatively assumed as 0.1 m/s [14], [16]. Radiations from hydrocarbon fires come mostly from the glowing soot from within the flames. An exemption can be found for some clean burning pool fires such as methanol, in which thermal radiations come from the hot gases namely; carbon dioxide and water vapour. For large diameter soot-producing hydrocarbon pool fires, copious amount of soot can be produced thereby creating the tendency for the unburnt soot to escape from the flame. The soot then congregates and forms a film around the flame surface, thus limiting the radiation to external structures. Fig. 4 represents the classical and the modified cylindrical flame models for pool fires by the point source and surface emitter concepts. Most modellers have considered the following assumptions to characterize radiation models for soot producing flames [3], [7], [16]-[17]:

- Surface emissive power, *SEP*
- Radiative fraction of the total energy of combustion
- Atmospheric transmissivity and absorptivity

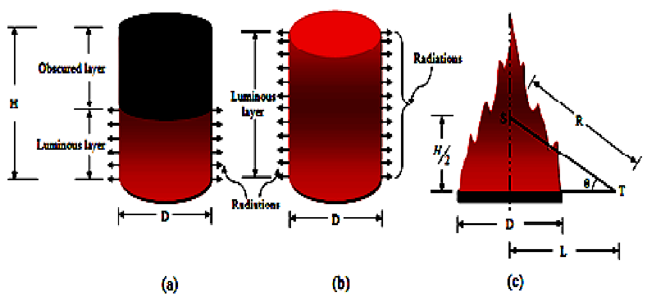

Fig. 4 Pool fire thermal radiation models (a) modified cylindrical flame model (b) classical cylindrical flame model (c) point source model

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The emissive power of a flame can be modelled based on the point source theory and the surface emitter theory. While point source concept appears to be overly conservative, the surface emitter theory averages the emissive power of the flame over the entire surface of interest. Cowley and Johnson [7] highlighted on three different ways by which the emissive power, *SEP* of a flame can be determined, namely;

- Spot measured emissive power
- Average measured *SEP*
- Model average measured *SEP*

The model average surface emissive power appears to be most commonly used in conjunction with the simplified geometrical shapes assumed for hydrocarbon fires. Using this concept, however, the surface areas of the model flame shapes seem to be larger than those of the visible flame surfaces [7]. The point source model of Drysdale [18] based on the narrow angle radiometer data for the radiant heat flux to external target can be expressed as follows:

$$q'' = \frac{\chi_r \dot{Q} \cos\theta}{4\pi R^2} \quad (7)$$

Where $\dot{Q}$ = the total combustive energy
χ_r = radiative fraction
θ = the angle between the normal to the external object and the line of sight between the object and the point source location
R = the sight distance between the fire point source location and the object.

For liquid hydrocarbon fuels, the heat release rate $\dot{Q}$ is a function of the fuel mass loss rate $\dot{m}''$, its lower heat of combustion Δh_c and the pool size *D* as follows:

$$\dot{Q} = \dot{m}'' \Delta h_c A \quad (8a)$$

$$\dot{m}'' = \dot{m}''_\infty \left[1 - \exp(-k\beta D)\right] \quad (8b)$$

Where $\dot{m}''_\infty$ = fuel maximum mass loss rate, $k\beta$ is a property of the fuel defined as the mean beam length corrector-flame attenuation coefficient product.

The surface area of a pool fuel can be determined using the correlation of Gottuck and White [14] for liquid pool and spill fires.

$$A_p = 1.4V; \quad \text{for pool} < 95\,\text{litres}$$
$$= 0.36V; \quad \text{for pool} < 95\,\text{litres} \quad (9)$$

In the case of an unconfined spill, Gottuck and White [14] proposed that the resultant pool size can be taken as 55 per cent larger than the corresponding confined pool fire size.

$$A_s = 1.55 A_p \quad (10)$$

An alternative correlation that can be used to determine fuel maximum mass loss rate and maximum regression rate can be found in [14].

IV. SHAPE FACTOR COMPUTATION

The amount of radiation reaching the surfaces of external targets from pool fire flames vary with shape and position of the fire relative to the target. These factors are commonly known as shadow and position effects. Generally, the shape factor F_{12}, between the flame source and the target can be determined from the following correlation [19].

$$F_{12} = \int\int_S \frac{\cos\theta_1 \cos\theta_2}{\pi R^2} dA_1 \quad (11)$$

where θ_1 and θ_2 are the angles between the normal to the surfaces and the line of sight for the emitter and the receiver respectively.
R = distance between the flame source and the target along the line of sight.
dA_1 = the elemental surface area of the emitter viewed by the receiver.

Using the mathematical form of (11), the following correlations have been derived to calculate the shape factors in still air for targets at the base or top level of the flame [20]. For horizontally placed targets, (12) is used whereas in the case of vertically positioned targets, (13) can be implemented.

$$F_{12,H} = \frac{B - \frac{1}{S}}{\pi\sqrt{(B^2 \_ 1)}} \arctan\sqrt{\frac{(B+1)(S-1)}{(B-1)(S+1)}} - \frac{\left(A - \frac{1}{S}\right)}{\pi\sqrt{(A-1)}} \arctan\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \quad (12)$$

$$F_{12,V} = \frac{1}{\pi S}\arctan\left(\frac{h}{\sqrt{(S-1)}}\right) - \frac{h}{\pi S}\arctan\sqrt{\frac{(S-1)}{S+1}} + \frac{Ah}{\pi S\sqrt{(A^2-1)}}\arctan\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \quad (13)$$

Where

$$S = \frac{2L}{D},\ h = \frac{2H}{D},\ A = \frac{h^2 + S^2 + 1}{2S},\ B = \frac{1+S^2}{2S}$$

L = distance between centre of pool fire and edge of target
H = flame height
D = equivalent flame diameter

V. THERMAL RADIATION MODEL

The thermal radiation model proposed in the present study adopts the Heskestad flame height correlation and uses the methodology for surface emitter models. Shokri and Beyler [8], Drysdale [18] and Mudan and Croce [9] present various algorithms to estimate the heat flux from flames to external targets. Shokri and Beyler [8] proposed the following correlation to calculate thermal radiation from hydrocarbon pool fires.

$$SEP = 58\left(10^{-0.00823*D}\right) \quad (14)$$

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Indeed, this correlation appears to under-predict the surface emissive power for liquefied natural gas fuel as demonstrated in Fig. 5. According to Mudan and Croce [9] a uniform surface emissive power of flames for smoky hydrocarbon fuels can be determined as follows.

$$SEP = E_{\max} . \exp(-kD) + E_s\left(1 - \exp(-kD)\right) \tag{15}$$

where E_{max} = equivalent ideal radiator emissive power of fuel, 140KW/m^2
E_s = maximum smoke emissive power, 20KW/m^2
k = flame extinction coefficient, 0.2m^{-1}
D = flame diameter

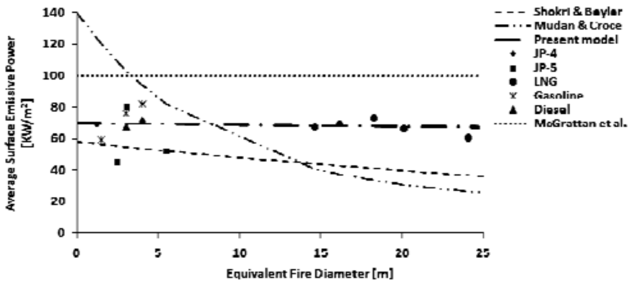

Fig. 5 Surface emissive power models as a function of fire diameter

The data set used to develop the present model comprises most of the results of trials utilized by Shokri and Beyler [8]. The motive for selecting this data set is to have a basis for acceptable comparison between the models. Table 1 summarises the data set used in the present formulation. A total of 15 trials and 59 data points are included with the pool diameter varying from 1.22 to 24.1m. The effective emissive power for each trial was based on the number of data points shown in Table 1. Using the method of least squares, the following model is proposed for the radiant heat flux to external targets.

$$\dot{q}'' = 20.7\left[\frac{L}{D}\right]^{-1.61} \tag{16}$$

The model of (16) accurately predicts the heat flux for LNG and aviation fuels fairly compared to that of Shokri and Beyler [8] as illustrated in Fig. 6. It may be used for initial fire design and evaluation. The proposed flame surface emissive power based on the studied fuels is given by the following expression.

$$SEP = 70\exp\left(-kD\right) \tag{17}$$

Where k = average flame extinction coefficient, 0.00165m^{-1}.
D = equivalent fire diameter, m

The incident heat flux can, therefore, be calculated from the following expression:

$$q'' = F_{12} * SEP \tag{18}$$

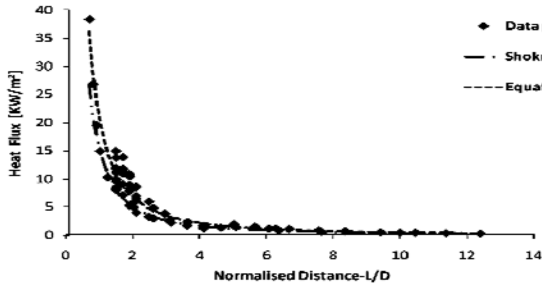

Fig. 6 Comparison of model predictions with measured data at ground level

The statistical correlations commonly considered appropriate for comparing observed data against predicted models were used according to [4],[21],[22]. These models are shown in the appendix and the computation is illustrated in Table 2. The assumptions made in formulating the present model include:

- The prevailing wind velocity is less than the critical velocity.
- The cylindrical flame geometry is based on Heskestad model.
- The spill fuel under consideration is confined.
- For the purpose of considering the effect of soot production on thermal radiation from the flame surface, the clear flame height can be taken as one half of the Heskestad geometric flame model.

The nomenclature - *gasoline 1* and *diesel 1* as given in Figs. 7 and 8 are used to characterise the flame envelope parameters based on measured data that were utilized to determine the angle factors. Similarly, *gasoline 2* and *diesel 2* characterise parameters based on the calculated flame height. The calculated flame height model over-predicts flame geometry compared with the observed data. However, it is shown in Fig. 7 that a similar trend is achieved in the prediction of radiant heat flux to external structures. Suppose the various models are extended to cover pool diameters up to 300m, it becomes obvious that the Shokri and Beyler correlation zeros out as can be seen in Fig. 10. For diameter approximately 50m, the Mudan and Croce model reduces to 20KW/m^2, which is the maximum surface emissive power of smoke. In a similar manner, McGrattan *et al.* proposes that the surface emissive power of the flame should be taken as 100KW/m^2 irrespective of the pool size. To account for the smoke obscuration effect, the Heskestad modified flame height model, H^* was used according to (19). The luminous factor is taken as 0.5. This concept is based on the fact that experiments have demonstrated that radiant heat fluxes at flame heights within pool fire diameters are relatively constant [3,5].

$$H^* = 0.12\dot{Q}^{2/5} - 0.51D \tag{19}$$

In order to further assess the radiative energy flux predictable from the various models, radiant heat flux from flame surface is plotted against pool fire diameter as illustrated in Fig. 11. It is the radiant heat flux per unit length of equivalent flame perimeter (calculated as *SEP* multiplied by the corresponding flame height). There are situations when it becomes necessary to limit the amount of radiation

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reaching external targets so that the acceptable separation distance can be reduced. When these barriers are constructed, the view from the targets is altered. McGrattan *et al*. [10] recommend that when analysing for thermal barriers, the *SEP* may be halved while the clear flame height is doubled so that a constant heat flux per unit length of flame is yet maintained.

In the present method, an evaluation of thermal barrier is addressed by considering the modified Heskestad flame height model using a luminous factor of 0.5 to calculate the angle factors. The results from this correlation are found to be reasonable when compared with those of McGrattan *et al*. [10] model.

Table 1 Summary of geometric and radiative properties of the studied fuel fires

Fuel Type	Fire Diameter [m]	Data Points	Average Emissive Power [KW/m^2]	Source
Gasoline	1.5	4	59.23	Muñoz et al.[4]
Gasoline	3.0	4	76.24	Muñoz et al.[4]
Gasoline	4	4	81.76	Muñoz et al.[4]
Diesel	3	4	67.57	Muñoz et al.[4]
Diesel	4	5	71.71	Muñoz et al.[4]
JP-4	1.22	3	69.06	Fu[5]
JP-4	2.44	5	44.63	Fu[5]
JP-5	2.44	3	46.47	Fu[5] /Dayan & Tien[3]
JP-5	3.05	6	79.99	Fu[5] /Dayan & Tien[3]
JP-5	5.5	4	53.31	Fu[5] /Dayan & Tien[3]
LNG	14.64	4	49.06	May & McQUEEN[6]
LNG	16.17	4	50.56	May & McQUEEN[6]
LNG	18.3	4	53.76	May & McQUEEN[6]
LNG	20.13	1	49.44	May & McQUEEN[6]
LNG	24.1	3	44.55	May & McQUEEN[6]

Table 2 Statistical matrix to compare the various models with observed data

Model	Fractional Bias	Normalised Mean Square Error
Present model	-0.059	0.0743
Shokri & Beyler [8]	0.223	0.144
Mudan & Croce [9]	-1.181	7.241

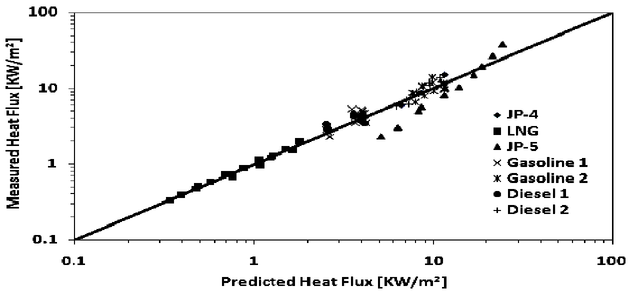

Fig. 7 Comparison of predicted radiant heat flux with experimentally measured data for the present correlation

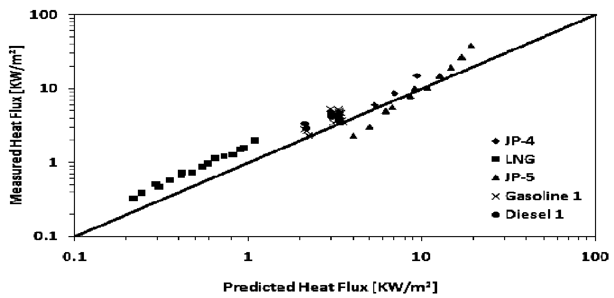

Fig. 8 Comparison of predicted radiant heat flux with experimentally measured data for the correlation of Shokri and Beyler

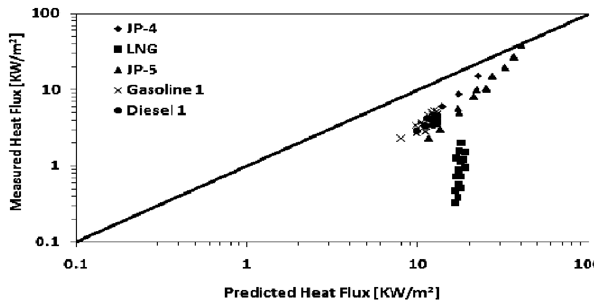

Fig. 9 Comparison of predicted radiant heat flux with experimentally measured data for the correlation of Mudan and Croce

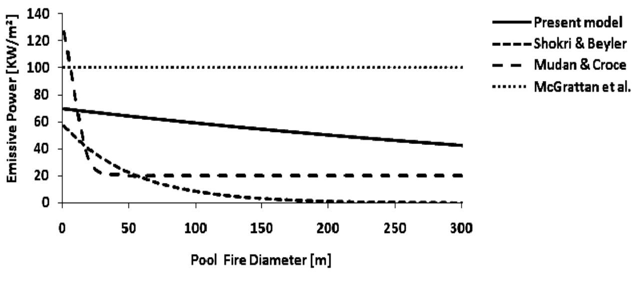

Fig. 10 Prediction range of surface emissive power models

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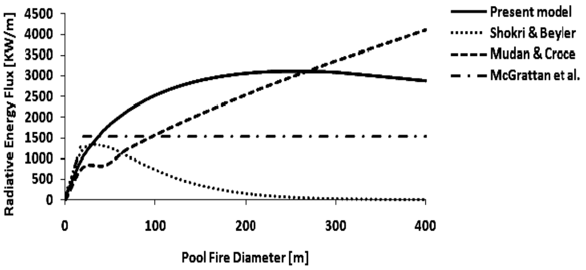

Fig. 11 Prediction range of radiant heat flux as a function of fire diameter for a gasoline pool fire

VI. Illustration

The example problem analysed by McGrattan *et al.* [10] is chosen to describe the use of the proposed correlations in evaluating the effectiveness of thermal barriers. It involves a gasoline tank farm separated from a shopping complex by a road. The following data are provided:
Dike width = 60m
Distance of target from the flame edge = 55m for personnel
Distance of target from the flame edge = 85m for building

It is proposed that a 7.3m vertical barrier will be built at the boundary of the tank farm to help screen the target from thermal radiation. The McGrattan *et al.* [10] model assumes that the maximum flame height is $6.4\text{x}10^{-3}q''$. Thermal radiation to external target is calculated to be $7.9KW/m^2$ with no thermal barrier, and $5.9KW/m^2$ when a thermal barrier of height 7.3m is constructed. The present method uses the modified flame height model of (19) to determine the luminous flame height, thus eliminating the conservatism inherent in the conventional model. Based on this concept, the heat flux incident on external targets has been calculated as $8.10KW/m^2$ with no barrier and $5.78KW/m^2$ when a barrier of height 7.3m is considered.

VII. Discussion and Conclusion

Thermal radiation from pool fire flames and the radiant heat flux to adjacent structures have been developed. For the fuel types considered in this study, the present model predicts fairly well compared to the correlations of Shokri and Beyler [8], and Mudan and Croce [9] particularly for LNG fuel. However, it should be noted that these models are exclusively dependent on the data used to calibrate them. Although, Figs. 7 and 8 appear to be similar it can be easily surmised from Fig. 5 that the present formulation presents a more precise prediction for thermal radiation from a flame surface.

Moreover, the fractional bias of Table 2 shows that the present model over-predicts the incident heat flux. The model of Shokri and Beyler [8], however, is shown to under-predict the heat flux. The over-prediction shown by the present model is negligible when compared with that of Mudan and Croce [9]. It is obvious in Figs. 5 and 9 that although the surface emissive power model of Mudan and Croce under-predicts the surface radiation for the LNG fuel, the incident heat flux to external targets is still over-predicted. This is due to the fact that LNG fuel data were not used to calibrate their correlation. Besides, one of the prominent assumptions behind McGrattan *et al.* [10] correlation is that no matter the size of the fire, the clear flame height will never exceed the numerical value of $6.4\text{x}10^{-3}q''$. This may not truly represent the flame behaviour because flames of fire diameters up to 50m can still produce thermal radiations at heights quite above that limit.

Remarkably, the Heskestad flame height model provides a sensible path to the prediction of thermal radiation for some cryogenic hydrocarbon pool fuels such as LNG and aviation fuels such as JP-5. The large deviation from observed data by the Mudan and Croce model suggests that most of the data used to calibrate their model and those analysed in the present model are quite different. The much over-prediction of the Mudan and Croce model, as revealed by the statistical measures, is contributed mostly by the LNG fuel since their correlation is only for a smoky flame. It can be concluded that thermal radiation prediction is spatially and temporally dependent, and also subject to uncertainties inherent in the modelling techniques and assumptions.

Appendix

$$FB = \frac{1}{N}\sum_{1}^{N} 2 * \frac{X_o - X_p}{X_o + X_p}$$

$$NMSE = \frac{1}{N}\sum_{1}^{N} \frac{\left(X_o - X_p\right)^2}{X_o X_p}$$

Where FB = Fractional bias
$NMSE$ = Normalised mean square error
X_0 = Measured value
X_p = Predicted value
N = Number of data points

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