Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 84 (2014) 514 – 523
Procedia Engineering
www.elsevier.com/locate/procedia

"2014 ISSST", 2014 International Symposium on Safety Science and Technology

Analysis for combustion properties of crude oil pool fire

CHEN Zhen, WEI Xiaolin*

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

Abstract

It is the fact that combustion properties of large-scale crude oil pool fire have great significance for security design and firefighting of current crude oil reserves. Burning rate, the flame shape and radiation intensity are the most important parameters for fires properties. According to two-zone theoretical model, there are many calculation models for different parameters. Based on crude oil pool fire experiments in Tomakomai, Japan, several common kinds of model are analyzed. Some conclusions are drawn: Babrauska formula is accurate around 10 m diameter; Thomas model is appropriate for the flame heighten of smaller scale(less than 5 m), while Heskestad model is appropriate for the flame heighten of larger scale (greater than 10 m); when the thermal radiation intensity is greater than 5 kW/m^2, Shokri Beyler model is more applicable; when the thermal radiation intensity is less than 1 kW/m^2, Point source model is more accurate.

Peer-review under responsibility of scientific committee of Beijing Institute of Technology
Keywords: crude oil pool fires; combustion properties; calculation models, burning rate; flame shape; thermal radiation intensity

1. Introduction

Pool fire accident is one of the common forms of disasters in petrochemical enterprises which have a longer duration and more derivative disasters of the characteristics. The mechanism of pool fire is very complex, including a lot of detailed processes of heat and mass transfer, and difficult to use only one reasonable physical model to describe[1,2]. The study of pool fire mainly analyzes the relationship between flame characteristics of fire environment based on the small scale pool fire experimental results. However, due to the limitations of experimental conditions, the correctness of Theoretical analysis and numerical simulation of large-scale pool fire have not been

* Corresponding author. Tel.: +86 10 82544231; fax: +86 10 82544231
E-mail address: xlwei@imech.ac.cn

Peer-review under responsibility of scientific committee of Beijing Institute of Technology
doi:10.1016/j.proeng.2014.10.463

fully verified. Therefore, the fire behavior characteristics of large-scale pool fire only be derived and estimated through some mathematical expressions of half theoretical and half empirical.

Blinov and Khudyakov[3] researched oil fires earliest with carried out a series of crude oil pool fires, and gained burning rates at small scale conditions. Koseki[4] consolidated and analyzed the results of some important oil pool fire experimental, and thought that the research of large-scale pool fire research has important significances. He also studied the radiation characteristics of smoke in large-scale pool fire. Current theoretical and experimental researches of pool fire also mainly focus on the determination of fuel burning rate and radiation intensity, the formation of visible flame area, the measurement of flame area, and the influence of wind speed on flame profile[5]. Researches show that, these characteristic parameters mostly relates to fuel type, the shape and size of fire pit , atmospheric environment and other factors[6,7]. Research carried out by Thomas[8] found the structure of the pool fire related to the movement of the flame plume, and the length of the visible flame was proportional to two-third of the Froude number. Steward found that the spectral radiative properties of high temperature flue gas particles had a major impact on the shape and thermal radiation intensity of luminous flame. In Heskestad's research[9] the flame was divided into two areas: combustion zone and plume zone, and the flame temperature were highest in the center line of the plume area, the temperature on both sides of center line decreased exponentially.

Flame size, combustion duration and thermal radiation intensity are not only main characteristic parameters of crude oil pool fire accident; they are main basics for fire risk assessment. This paper proved the rationality and precision of different heat radiation models of pool fire by experimental data of crude oil pool fire with different scales.

2. Introduction for crude oil pool fires in Tomakomai

Experimental data of pool fire is necessary for fire protection design, fire fighting and rescue at crude oil storage tank. In 1998, a series of different scales of pool fires experiment were carried out in Tomakomai crude oil reserve by JNOC (Japan National Oil Corporation), NRIFD (National Research Institute of Fire and Disaster) and University of Tokyo[10]. Considering the influence of the tanks area layout, the experimental was conducted in January in order to decrease the risk of boilover fire might occur in the process. Because there would be relatively stable north wind in January in Tomakomai, and the crude oil storage tank area was located on the north of experiment sites. At the same time, stable wind speeds contributed to reduce measuring error.

The scales of pool fire pans were set at 5 m, 10 m and 20 m, and the fuel was Arabian light crude oil, shown as Table 1. Measurement data included burning rate, flame height, internal temperature of fire, combustion product composition and flame radiation intensity. Level meters, which were set at the bottom of oil layer, could measure the speed of fuel combustion. And there were 12-16 radiometers around the fuel pans of every experiment, which were placed at 1.2 m from the ground, as shown in Fig. 1. In addition, the weather station was at 80 m east of the center of pool fires, which could measure ambient temperature, humidity, wind speed and direction, et al.

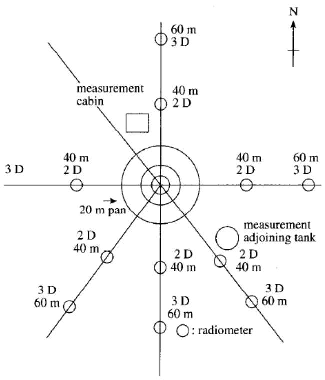

Fig. 1. Layout of oil pan and radiometers.

Table 1. Properties of Arabian light crude oil.

Density(g/cm^3)	0.84	Heat of combustion(kJ/kg)	42800
Viscosity(mm^2/s)	5.14	Flash point(K)	Lower than 273
Sulphur (%)	2.29	Carbon (%)	84.3
Hydrogen (%)	12.5	Nitrogen (%)	Less than 1

3. Theoretical analysis

The flame of crude oil pool fire is a kind of turbulent combustion flame controlled by buoyancy, and it is divided into two parts: fuel surface burning flame and the upper visible flame[11]. Supposing the burning face is circular, the heat and mass transfer process is shown in Fig. 2. Liquid fuels gasify constantly by the influence of thermal radiation, and rise to combustion region with the action of density gradient. Outside air is involved into central combustion region by the influence of flame buoyancy. The interface of air and fuel vapor fixes on a certain height above the fuel surface, which is depended on the chemical equivalent ratio of fuel burning. The combustion products continues to rise and it forms high temperature plume with ambient air.

Therefore, the flame of oil pool fire can be divided into two parts including lower burning region and upper plume region. In burning region the air and fuel mix and burn in stoichiometric ratio, and the momentum and heat of combustion products increase rapidly in vertical direction. In plume region the momentum and heat of mixture decline gradually as a result of no chemical reaction and the mixing of combustion products and ambient air. Consequently, the flame height is depended on heat release rate and mixing speed of combustion products and air.

In an ideal situation, combustible vapor burns completely in the interface of two regions. At this point, the flame temperature reaches a maximum. It is to say, there is maximal gradient of vapor concentration, air concentration and flame temperature in this surface, as shown in Fig. 3. In plume region, the relationship of the flame temperature, the axial velocity and the mass fraction of combustion products shows as formula 1[12].

$$\chi_P = \frac{T - T_a}{T_{ad} - T_a} \tag{1}$$

where, χ_p is the mass fraction of combustion products, T_a is ambient temperature, and T_{ad} is adiabatic flame temperature.

Due to the difficulties of carrying out large scale crude oil pool fire experiment, the shape features of large scale flame such as flame height, flame inclination are confirmed by empirical formula which obtained by small scale experiments. Then, the empirical correlation between flame height and burning rate is confirmed through reasonable simplification and assumption of distribution of combustion products, temperature distribution and heat radiation transfer model.

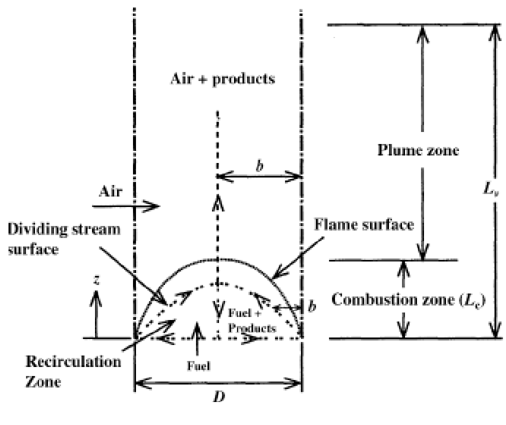

Fig. 2. Schematic of heat and mass transfer in pool fire.

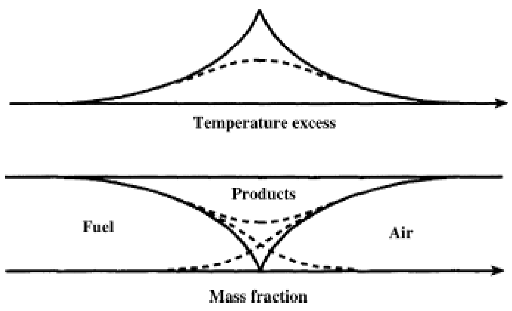

Fig. 3. Schematic of distribution of products, fuel, air and temperature.

All the flames of hydrocarbon fire have plentiful smoke particles, these particles have high temperature (exceed 1000K) and launch abundant spectrum located in visible spectrum, which determined visible flame profile[13]. Meanwhile, the thermal radiation of flame also has important relevance with the concentration and temperature of the smoke particles. The producing rate of smoke is related to air entrainment flux, fuel gasification rate and flame turbulence intensity[14].

4. Description of the model

4.1. Burning rate

The flame shape and radiative intensity of pool fire are closely related to the burning rate of fuels which is commonly represented by the mass loss rate per unit area[15]. The combustion rate of usual hydrocarbon fuels under different diameter of liquid pools can be calculated through the following formula put forward by Babrauskas [16].

$$m'' = m''_{\infty}(1 - e^{-k\beta D}) \qquad (2)$$

where m'' is the mass loss rate of the fuel, kg/(m^2·s); m''_{∞} is the maximum mass burning rate, kg/(m^2·s); k is the Flame attenuation coefficient, m^{-1}; β is correction coefficient of the light length; D is the pool diameter, m.

Fig. 4 shows that the actual combustion rate of fuels is gradually close to the maximum combustion rate with the pool diameter increases. This is because the heat transfer used for fuel surface gasification comes from heat radiation which is the mainly mode of thermal transmission in large pool fires.

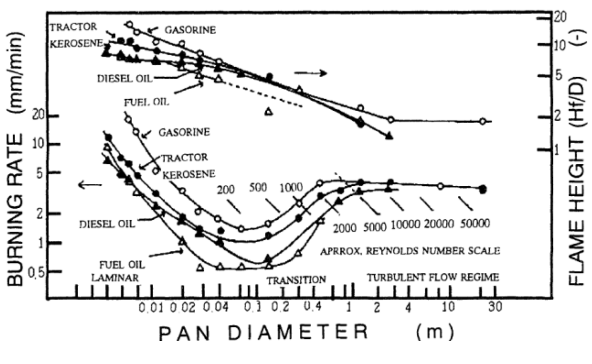

Fig. 4. Scale dependency of burning rate with pan diameter.

4.2. Flame shape

The flame shape of pool fire is generally represented by the three-dimensional cylindrical model with gray body radiation and the main parameters of which includes the flame chassis diameter, flame height and angle. In the actual pool fires, the flame chassis diameter is slightly larger than the pool diameter. However, in order to simplify the calculation, it is generally believed flame chassis diameter is equal to the pool diameter. And flame height as another important characteristic parameter, is directly related to the heat transfer process of pool fire and the influence of flame around environment.

Many researchers have studied flame height of pool fires in static environment and deduced some formulas based on a series of experimental data. For example, Thomas put forward the following formula to calculate flame height on the basis of wood crib fire test[17].

$$\frac{H}{D} = 42\left(\frac{m''}{\rho_a\sqrt{gD}}\right)^{0.61} \tag{3}$$

where, ρ_a is the air density, kg/m^3; H is flame height, m.

If consider the influence of wind speed, the flame height (H) and angle (α) can be expressed by the following equations that are deduced by Thomas[18].

$$\frac{H}{D} = 55\left(\frac{m''}{\rho_a\sqrt{gD}}\right)^{0.67} u^{*-0.21} \tag{4}$$

$$\cos\alpha = 0.7\left[\frac{u_w}{(gm''D/\rho_a)}\right]^{-0.49} \tag{5}$$

$$u^* = \frac{u_w}{(gm''D/\rho_v)^{1/3}} \tag{6}$$

Heskestad has correlated experiment results from a wide variety of sources includingbuoyant jets fires and pool fires, and derived the follow relation[19].

$$\frac{H}{D} = 0.235\frac{Q^{2/5}}{D} - 1.02 \tag{7}$$

where u_w is the local wind velocity, u^* is the dimensionless wind velocity, ρ_v is the fuel vapor density, Q is the heat release rate, *W*.

4.3. Heat radiation of flame

4.3.1. Radiative transfer theory

The main source of flame heat radiation is high-temperature smoke particles in the combustion production. Other gas productions can absorb and emit heat radiation with strong selective. When the radio of the diameter of the solid particles (d) to wavelength of thermal radiation (λ) is less than 0.25, the scattering process of carbon dioxide can be negligible according to Mie theorem[20]. Assuming that the flame is adiabatic, uniform, and in the state of thermodynamic equilibrium, it can be argued that the flame has the characteristics of gray body radiation.

Radiation spectrum rays in air transport, according to the Beer's law shows spectral radiation intensity passing away along decays exponentially. Beer's law is expressed as follows.

When the Radiation spectrum rays are transferring in air, its energy will be decays exponentially along with transmission distance according to the Beer's law.

$$I_{\lambda,\Omega,L} = I_{\lambda,\Omega,0}\exp(-\beta_\lambda L) \tag{8}$$

$$\beta_\lambda = \kappa_\lambda + \sigma_\lambda \tag{9}$$

where, $I_{\lambda,\Omega,0}$ and $I_{\lambda,\Omega,L}$ is the initial spectral radiant intensity and the one passing the length L, W/(m^2·μm·Sr); β_λ is spectrum attenuation coefficient, m^{-1}; κ_λ is spectrum absorption coefficient, m^{-1}; $\sigma_\lambda$is spectrum scattering coefficient, m^{-1}.

Assuming the air temperature is 300K and the pressure was 1atm around the pool fire, the temperature gradient between flame and ambient air is not considered. CO_2 and H_2O play a major role in absorption process, and the volume fraction of CO_2 and H_2O is normally 0.001 and 0.02. Without regard to the impact of scattering, the air attenuation coefficient is equal to sum of CO_2 and H_2O.

In the band scope of 1-5 μm, total radiation intensity of the flame is equal to sum of all spectrum radiation of different wavelength[25].

$$I(\Omega)=\int I(\lambda,\Omega)\mathrm{d}\lambda \tag{10}$$

For gray body, according to Lambert's law, total radiation intensity of hemi-sphere space is π times than directional spectrum radiation intensity.

When the temperature is 300 K and the pressure is 1atm, absorption coefficient of CO_2 and H_2O is shown in Fig. 5 and Fig. 6[21].

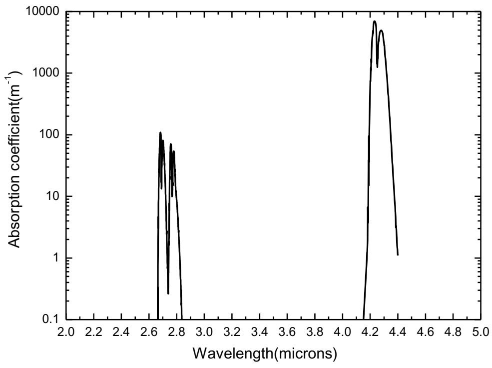

Fig. 5. Spectral absorption factor of CO_2 (at 300K, 1atm).

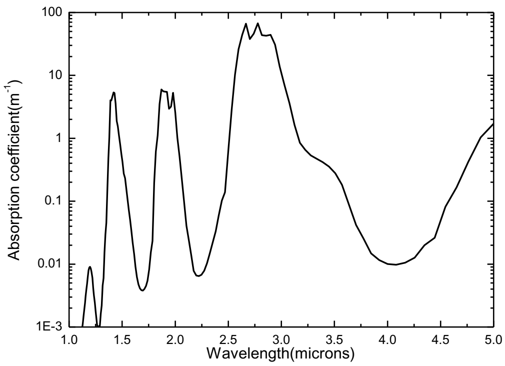

Fig. 6. Spectral absorption factor of H_2O (at 300K, 1atm).

4.3.2. Two methods for calculating thermal radiation

- Point source model

To predict the thermal radiation field of flames, it is customary to model the flame by a point source located at the centre of real flame and release heat to surrounding, as shown in Fig. 1. The point source model is the simplest configurationally model of a radiant source and provides a simple relationship that varies with the inverse square of the distance. The point source model is widely used in pool fires to estimate the radiation intensity, but the error is relatively large.

The incident radiative heat flux is given by[22].

$$I=\frac{Q\cos\theta}{4\pi L^2} \tag{11}$$

$$Q=(0.21\text{-}0.0034D)m''\Delta H_c \tag{12}$$

where Q is the total radiative energy output of the pool fire, kW/m^2; θ is the angle between the normal to the target and the line of sight from the target to the point source location; L is the distance from the point source to the target, m.

- The Shokri and Beyler model

Shokri and Beyler have described a method for prediction of radiation from pool fires based on the pool fire radiation data available in the open literature. They correlated experimental data of flame radiation to external targets in terms of an average effective emissive power of the flame. The flame is assumed to be a cylindrical, blackbody, homogeneous radiator with an average emissive power[23]. The diameter of the cylindrical radiation source is equal to the liquid pool diameter; the flame height is the visible flame length. Shokri and Beyler have treated radiant heat transfer from a source to a target and the incident radiative flux to a target outside the flame (I) is given by

$$I=EF_{12} \tag{13}$$

$$E=58(10^{-0.00823D}) \tag{14}$$

where, E is the emissive power of the pool fire flame, kW/m^2, and F_{12} is the view or configuration factor between the target and the flame. The configuration factor is a function of the target location, the flame height and diameter, and lies between zero and one[24]. The view factor in this article is provided by SFPE Handbook of Fire Protection Engineering, as shown in Fig. 7[24,25].

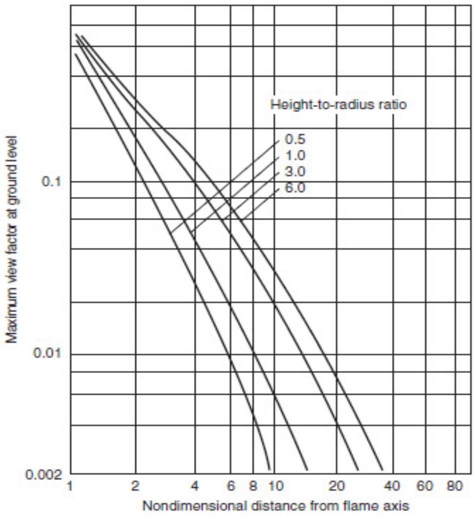

Fig. 7. Relation between maximum view factor and distance from flame axis at ground level.

5. Calculation and analysis

5.1. Burning rate and flame height

Burning rate is important parameter to describe fire intensity, which has a direct bearing on the height of the flames and heat release rate. It is connection with the fuel type, liquid pool size, fuel thickness and other factors. In the paper, the burning rate under different size is calculated by formula 2, and the flame heighten is calculated by Thomas and Heskestad experience formula. The results are shown in Table 2.

Table 2. The burning rate, flame heightens of experiment and calculated value.

Diameter of Pan	Experiments Value				Calculated Value		
	Fuel Thickness (mm)	Burning Time (min)	Burning Rate kg/(m^2•s)	Flame Heighten (m)	Burning Rate (kg/(m^2•s))	Flame Heighten (m) Thomas relation	Flame Heighten (m) Heskestad relation
D=20m	50	18.5	0.043	38	0.0466	32.2	38.7
D=10m	50	19.3	0.0364	18	0.037	15.9	19.8
D=5m	50	18.1	0.0365	9.1	0.0245	8.7	11.5

As shown in Table 2, the actual burning rate is approaching up the maximum value (0.05 kg/(m^2·s)), along with the rising of the burning pan diameter. When the pan diameter is more than 10 m, the results of calculation are close to experimental value. When the pan diameter is 5 m, the error is larger. Because the heat that fed back to fuel surface mainly come from flame thermal radiation at large scale condition; In small scale pool fire, heat conduction and thermal convection take larger proportion.

Considering the influence of wind, the height-diameter rate is 1.6–1.75 by Thomas formula at three groups of pool fire (*D*=20 m, 10 m, 5 m), which is less than experiment value (1.8–1.9) obviously. Only when the pan diameter is less than 5m, does Thomas formula calculation have good conformity. The height-diameter rate is 19-2.5 By Heskestad formula, and it is appropriate for condition of large scale pool fires.

5.2. Calculation of radiation intensity

In consideration of a mass of small-scale pool fire researches and relatively complete experimental data, the empirical formulas have been sufficiently validated at small-scale condition. Therefore, only the 20 m diameter pan is analyzed in the paper. Firstly, the spectral radiation intensity of carbon dioxide, water vapour and smoke particles is put together the experimental data, as shown in Fig. 8. In the band scope of 1-5 µm, the flue gas particles temperature is about 1450 K, and its spectral radiation intensity peak is higher than that of water vapour and carbon dioxide around 2µm band. There are five peaks of water vapour and carbon dioxide, 1.85 µm, 2.6 µm, 2.8 µm, 4.3 µm and 4.5 µm. In the band scope of 2.6-2.8 µm, water vapour and carbon dioxide plays a major role; and in the band scope of 4.3-4.5 µm band, carbon dioxide is dominant.

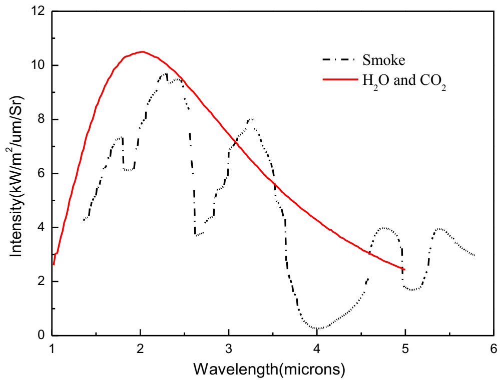

Fig. 8. The spectral radiant intensity result of pool fire experiment.

The radiation intensity accepted by the target position can be calculated by point source model and Shokri Beyler model. Then another result can be gained by Beer Law and Lambert law, based on experiment data. The comparison of different results of various scales pool fires is shown in Fig. 9.

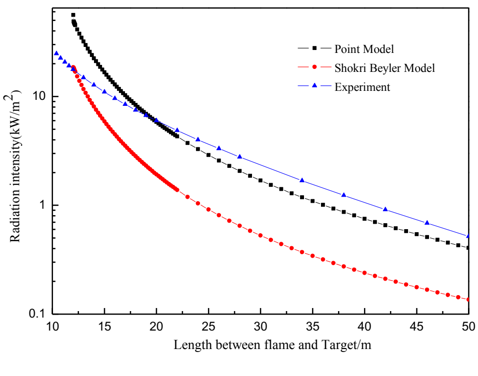

Fig. 9. Comparison of the results different models and experiment.

It can be seen from the Fig. 9 that with the increasing of the distance L, the logarithm of the radiation intensity in the target position appears linear downward trend approximately. Comparing with the calculation results based on the experiment, all the results obtained from the two models are reasonable as whole. However, in some particular situations, different models may have relatively large error.

The results of the point-source model are higher than others, when the radiation intensity is higher than 5kW/m^2. The reason is, in the point-source model the whole flame is assumed as a particle, which will lead large errors when the target position is near the fire. While the results of Shokri Beyler model match the experimental ones well. And the Shokri Beyler model results are a little smaller and larger than the experimental results respectively.

Because of the conservative derivation process in the Shokri Beyler model, the results are considered small in the case of the radiation intensity range is from less than 5 kW/m^2.The point-source model results are almost equal to the experimental values when the radiation intensity is less than 1kW/m^2. This shows that to assume the flame as a particle is plausible if the target position is far from the pool fire.

6. Conclusions

After processing and analyzing the data of crude oil pool fire experiments in Tomakomai, Japan. Some conclusions are drawn as following.

(1) Calculation model of burning rate proposed by Babrauskas is more accurate at the scale of 10m diameter; it requires further verification for larger scale pool fires.

(2) The heighten-diameter ratio is 1.6-1.75 by Thomas model, significantly less than the experimental value (1.8-1.9); when the pan diameter is less than 5m, the results is more accurate. The result is1.9-2.3 by Heskestad model, more than the experimental values (1.8-1.9); when the pan diameter is larger than 10m, the Heskestad model is more applicative.

(3) The results of Point source model and Shokri Beyler model results are quite reasonable.

When the thermal radiation intensity is larger (greater than 5 kW/m^2), Shokri Beyler model is more applicable; when it is smaller (less than 1 kW/m^2), Point source model is more applicable. Because it will not ignite surrounding combustible when the intensity is less than 5kW/m^2, Shokri Beyler response model can be used to analyze the thermal response of inflammable goods under fire environment. Meanwhile the Point source model is often used to judge the injuries, because people will feel pain and be burned with prolonged exposure, when the intensity is little than 5 kW/m^2.

Acknowledgements

The authors thank the National Natural Science Foundation of China (No. 91130028) for the financial support of this work.

References

[1] Drysdale D., An introduction to fire dynamics, 2th Edition. University of Edinburgh, UK, 1998.
[2] Koseki H, Natsume Y, Iwata Y, Takahashi T, and Hirano T. A study on large-scale boilover using crude oil containing emulsified water, J. Fire Safety Journal, 2(1997), 87-96.
[3] Blinov V.T and Kyudyakov G.N. Diffusion burning of liquids, Moscow, 1961.
[4] B. Zheng and G. H. Chen, Storage tank fire accidents, J. Process Safety Progress 3(2011), 291-293.
[5] W.C. Fan, J.S. Hua and G.X.Liao, Experimental study on the premonitory phenomena of boilover in liquid pool fires supported on water, J. Journal of Loss Prevention in the Process Industries, 4(1995).
[6] J.A. Fay, Model of large pool fires, J. Journal of Hazardous Materials, 2(2006), 219-232.
[7] Consalvi J.L, Demarco R, Fuentes A, Melis S, and Vantelon J.P,. On the modeling of radiative heat transfer in laboratory-scale pool fires, J. Fire Safety Journal, 8 (2012), 73-81.
[8] Thomas P.H., Modeling of compartment fires, J. Fire Safety Journal, 3-4(1983), 181–190.
[9] Heskestad G., Luminous heights of turbulent diffusion flames, J. Fire Safety Journal, 2(1983): 103-108.
[10] Koseki H and Iwata Y., Tomakomai large scale crude oil fire experiments, J. Fire Technology, 1(2000), 24-38.
[11] Riezel Y., Explosion and fire in a gas-oil fixed roof storage tank: Case study and lessons learned, J. Process Safety Progress 1(2002), 67-73.

[12] Fay J.A., Spread of large LNG pools on the sea, J. Journal of Hazardous Materials, 3(2007), 541-551.
[13] Klassen M and Gore J.P., Temperature and soot volume fraction statistics in toluene-fired pool fires, J. Combustion and Flame, 3(1993), 270-278.
[14] R. Morgan and P. Eric, Enhancing fire risk evaluations of plant structures using finite element analysis, J. Process Safety Progress, 4(2012), 411-412.
[15] Mishra K.B and Wehrstedt K.D., Decomposition effects on the mass burning rate of organic peroxide pool fires, J. Journal of Loss Prevention in the Process Industries, 1(2012): 224-226.
[16] Babrauskas V., Designing products for fire performance: the State of the art of test methods and fire models, J. Fire Safety Journal, 3(1995): 299-312.
[17] Yumoto T., Heat transfer from flame to fuel surface in large pool fires, J. Combustion and Flame, 1(1971),108-110.
[18] L. H. Hu, L. Wu, L. Liu, Flame length elongation behavior of medium hydrocarbon pool fires in cross air flow, J. Fuel, 111(2013), 613-620.
[19] Heskestad G. SPFE Handbook of Fire Protection Engineering, third ed.: Fire Plumes, Flame Height, and AirEntrainment, Quincy, 2002.
[20] Mudan K.S., Thermal radiation hazards from hydrocarbon pool fires, J. Progress in Energy and Combustion Science, 1(1984), 59-80.
[21] Ludwing C.B., Malkmus W. and Reardon J.E., Hand-book of infrared radiation from combustion.NASA-SP-3080, Washington D C, 1973.
[22] (Beyler C.L.(2002). SPFE Handbook of Fire Protection Engineering, third ed: Fire hazard calculation for large, open Hydrocarbon fires. National Fire Protection Association, Quincy.
[23] Shokri M & Beyler C.L.(1989). SFPE Journal of Fire Protection Engineering: Radiation from Larger Pool Fires.National Fire Protection Association.
[24] Mudan K.S., Geometric view factors for thermal radiation hazard assessment, J. Fire Safety Journal, 2(1987), 89-96.
[25] Rew P.J, Hulbert W.G and Deaves D.M., Model of thermal radiation from external hydrocarbon pool fires. Process Safety and Environmental Protection, 2(1997), 81-89.