UDK 614.8

A.E. Basmanov, DSc, Prof., chief researcher, NUCDU,
A.A. Mikhailyuk, CandSc, Senior Researcher, head of postgraduate, NUCDU,
I.A. Gorpinich, head of rescue training department, NUCDU

WIND INFLUENCE TO THE FLAME SHAPE OF A CIRCULAR POOL FIRE

Mathematical model of the flame shape of a circular pool fire in the presence of wind is built. It is presented in parametric form.

Keywords: flammable liquids, flame, flame tilted by wind.

Problem formulation. Case histories have shown that oil spill fires belong to the most dangerous accidents on the railway. Estimating heat impact on rail cars in a railway accident requires mathematical description of radiating surface of the flame. Wind direction and velocity are factors influenced on the flame shape. Therefore mathematical description of these processes is very important for researches on pool fire in the presence of wind.

***Analysis of recent researches and publications*.** Mathematical model of radiating surface of the flame for a circular pool fire was built in [1]. It was supposed that flame shape is self-similar and there is no wind. Expressions for flame length and tilt angle for a circular pool fire were proposed in [2, 3, 4]. They take into account wind velocity. But the flame shape hasn't been studied yet.

***Statement of the problem and its solution*.** The main goal of the work is to build a model of the flame radiating surface for a circular pool fire which takes into account wind direction and velocity.

In general the surface of a flame can be represented in parametric form

$$\begin{cases} x = u + z_0 \cdot \sin\alpha \cdot \cos\varphi, \\ y = v + z_0 \cdot \sin\alpha \cdot \sin\varphi, \\ z = z_0 \cdot \cos\alpha, \end{cases}$$

where $(u, v) \in \Omega$; Ω is pool area; z_0 is flame height above point (u, v) of the pool in the absence of wind; α is angle of flame tilt; φ is wind direction.

The height of the visible flame is function of pool diameter and wind velocity [1, 3]

$$\frac{L}{D} = 55\left[\frac{v_m}{\rho_a \sqrt{gD}}\right]^{0,67} \left(u^*\right)^{-0,21}, \qquad (1)$$

where L is flame length; D is pool diameter; v_m is burning rate; ρ_a is the am bient density; g is the acceleration of gravity; u^* is dimensionless wind velocity:

$$u^* = w\left(\frac{g v_m D}{\rho_a}\right)^{-1/3}; \tag{2}$$

w is wind velocity. Combining (1) and (2) gives formula

$$L(D) = 55\left[\frac{v_m D}{\rho_a \sqrt{g}}\right]^{0,67}\left[w\left(\frac{g v_m D}{\rho_a}\right)^{-1/3}\right]^{-0,21}. \tag{3}$$

Analysis of expression (3) gives $L \sim \dfrac{D^{0,7}}{w^{0,21}}$.

Angle of flame tilt (deviation from vertical axis) is described by formula [1]

$$\cos\alpha = s(w) = \begin{cases} 1, & w\left(\dfrac{g v_m D}{\rho_a}\right)^{-1/3} \le 1, \\ w^{-0,5}\left(\dfrac{g v_m D}{\rho_a}\right)^{1/6}, & w\left(\dfrac{g v_m D}{\rho_a}\right)^{-1/3} > 1. \end{cases} \tag{4}$$

Applying expressions (3) and (4) to self-similar flame shape gives the flame surface in parametric form

$$\begin{cases} x = u + z_0 \cdot \sqrt{1 - s^2(w)} \cdot \cos\varphi, \\ y = v + z_0 \cdot \sqrt{1 - s^2(w)} \cdot \sin\varphi, \\ z = z_0 \cdot s(w), \end{cases} \tag{5}$$

$$z_0(u, v) = L(2r),$$

where r is the distance between the point (u, v) on the pool and border of the pool.

The vertical section of a circular pool fire with the center in the origin of coordinates and wind directed along the axis OX is defined by

$$\begin{cases} x = u + z_0(u)\sqrt{1 - s^2(w)}, \\ z = z_0(u) s(w), \end{cases} \tag{6}$$

$$z_0(u) = 55\left[\frac{v_m (D - 2|u|)}{\rho_a \sqrt{g}}\right]^{0,67}\left(u^*\right)^{-0,21}, \quad -\frac{D}{2} \le u \le \frac{D}{2}, \tag{7}$$

$$u^* = w\left(\frac{g v_m (D - 2|u|)}{\rho_a}\right)^{-1/3}. \tag{8}$$

Expressions (6), (7), (8) are function $z(x)$ in parametric form. Flame tilt is a reason why flame extends over the edge of the pool and elongates its base. This fact is in empirical qualitative agreement with empirical data [1, 2].

The equation of the surface of circular pool fire (5) and wind directed along axis OX can be simplified by transformation to polar coordinates on the pool area:

$$\begin{cases} u = r\cos\psi, \\ v = r\sin\psi. \end{cases}$$

In this case

$$\begin{cases} x = r\cos\psi + 55\left[\dfrac{v_m(D-2r)}{\rho_в\sqrt{g}}\right]^{0,67}\left[w\left(\dfrac{g v_m(D-2r)}{\rho_a}\right)^{-1/3}\right]^{-0,21}\cdot\sqrt{1-s^2(w)}, \\ y = r\sin\psi, \\ z = 55\left[\dfrac{v_m(D-2r)}{\rho_a\sqrt{g}}\right]^{0,67}\left[w\left(\dfrac{g v_m(D-2r)}{\rho_a}\right)^{-1/3}\right]^{-0,21}\cdot s(w), \end{cases}$$

$$0 \le r \le D/2,\ 0 \le \psi \le 2\pi, \qquad (9)$$

where cosine of the angle of flame tilt $s(w)$ is evaluated by expression (4) which depends only from wind velocity and fuel parameters.

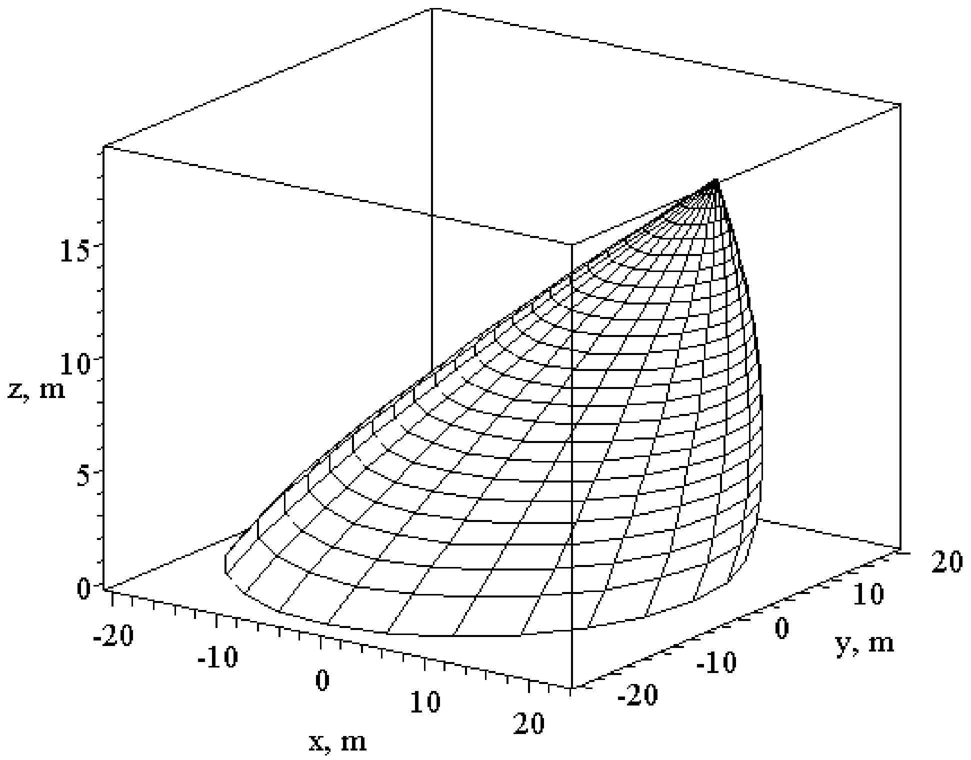

Fig. 1. The surface of a circular pool fire of gasoline of the diameter of 40 m and wind velocity of $w = 6\,m/s$

Fig. 1 demonstrates the surface of a circular pool fire of gasoline. Pool diameter is 40 m and wind velocity is 6 m/s.

There is a line on the flame surface where its normal vector is paralleled to the plane XOY. In this case border of area covered by flame is a projection of the line to plane XOY. Normal vector to surface in polar coordinates is

$$\vec{n} = \left(\frac{\partial y}{\partial r}\frac{\partial z}{\partial \psi} - \frac{\partial z}{\partial r}\frac{\partial y}{\partial \psi},\ \ \frac{\partial z}{\partial r}\frac{\partial x}{\partial \psi} - \frac{\partial x}{\partial r}\frac{\partial z}{\partial \psi},\ \ \frac{\partial x}{\partial r}\frac{\partial y}{\partial \psi} - \frac{\partial y}{\partial r}\frac{\partial x}{\partial \psi} \right).$$

Partial derivatives $\frac{\partial}{\partial r}, \frac{\partial}{\partial \psi}$ of the surface (9) are

$$\frac{\partial x}{\partial r} = \cos\psi + 55 g^{-0,265} w^{-0,21} \left(\frac{v_m}{\rho_a}\right)^{0,74} 0,74 \cdot (-2)(D-2r)^{-0,26} \sqrt{1-s^2(w)};$$

$$\frac{\partial x}{\partial \psi} = -r\sin\psi;$$

$$\frac{\partial y}{\partial r} = \sin\psi;$$

$$\frac{\partial y}{\partial \psi} = r\cos\psi.$$

Therefore expression for vertical component of normal vector of the flame surface is

$$\frac{\partial x}{\partial r}\frac{\partial y}{\partial \psi} - \frac{\partial y}{\partial r}\frac{\partial x}{\partial \psi} = r +$$
$$+ 55 g^{-0,265} w^{-0,21} \left(\frac{v_m}{\rho_a}\right)^{0,74} 0,74 \cdot (-2) r (D-2r)^{-0,26} \sqrt{1-s^2(w)} \cos\psi.$$

Equating this expression to zero gives an expression for variable r:

$$(D-2r)^{-0,26} = \frac{1}{81,4} \frac{g^{0,265} w^{0,21}}{\sqrt{1-s^2(w)}} \left(\frac{\rho_a}{v_m}\right)^{0,74} \frac{1}{\cos\psi};$$

$$r = \frac{D}{2} - 1,12 \cdot 10^7 \frac{\left(1-s^2(w)\right)^{1,92}}{g^{1,02} w^{0,81}} \left(\frac{v_m}{\rho_a}\right)^{2,85} (\cos\psi)^{3,85}.$$

Substituting r in the expression (9) gives border of area covered by flame.

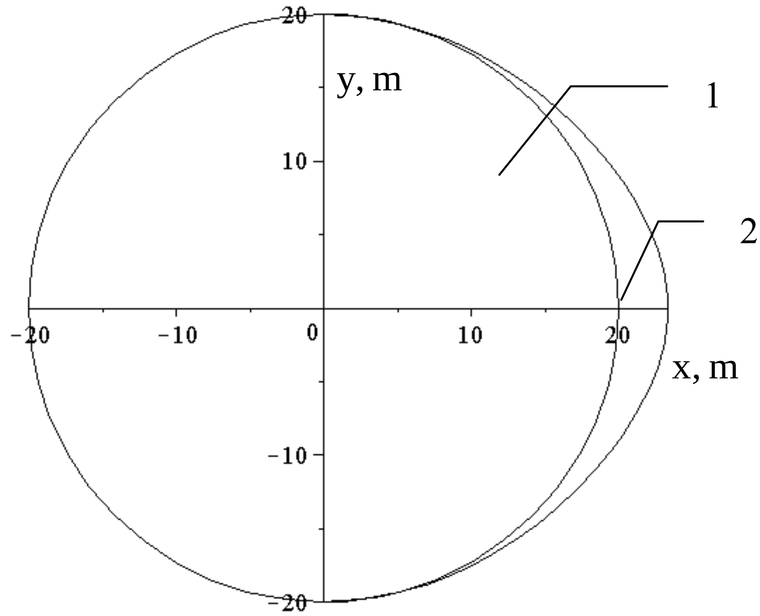

Fig. 2. Extended area covered by tilted flame: 1 – gasoline pool; 2 – area covered by the flame

***Conclusions*.** Mathematical model of the flame radiating surface of circular pool fire in the presence of wind is built. The model takes into account wind direction and velocity. It is presented in parametric form. The model can be used for evaluating of heat impact of fire to ambient objects.

REFERENCES

1. Basmanov A.E. Model of fire of round oil spill / A.E. Basmanov, I.A. Gorpinich // Problems of fire safety. – Kharkiv: NUCDU, 2015. – V. 37. – P. 27-31.

2. Less F. Loss prevention in the process industries / Frank P. Less. – Elseviesr. – 497 p.

3. Mudan K. S. Prog. Energy Combust. Sci. – 1984. – V. 10. – P. 59.

4. Schalike S. Flame Heights of Di-tert-butyl Peroxide Pool Fires – Experimental Study and Modeling / S. Schalike, K. Wehrstedt, A. Schonbucher // Chemical Engineering Transactions. – 2012. – V. 26. – P. 363-368.

О.Є. Басманов, А.О. Михайлюк, І.А. Горпинич

Вплив вітру на форму полум'я над розливом нафтопродукту

Побудовано математичну модель, що в параметричному вигляді описує форму полум'я над розливом нафтопродукту кругової форми.

Ключові слова: горюча рідина, факел, нахил факела вітром.

А.Е. Басманов, А.А. Михайлюк, И.А. Горпинич

Влияние ветра на форму пламени над разливом нефтепродукта

Построена математическая модель, в параметрическом виде описывающая форму пламени над разливом нефтепродукта круговой формы.

Ключевые слова: горючая жидкость, факел, наклон факела ветром.