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MODELING OF SPILLING AND EXTINGUISHING OF BURNING FUEL ON HORIZONTAL SURFACE

Purpose. To construct a model of extinguishing a spill fire spreading on a non-smooth horizontal surface using water mist.

Methodology. A force balance equation for the forces influencing the spilled liquid spread has been worked out. The equation takes into account the change in the mass of the spilled liquid due to its burnout and possible inflow in the case of a continuous spill. Filling of the surface irregularities in the spill area has also been taken into account. There has been worked out a thermal balance equation for the fuel surface under sprayed water mist, based on the assumption that the water droplets completely evaporate before they reach the surface of the burning fuel.

Findings. The dynamics has been obtained for the radius change of the fuel spill for the spread and burnout on a non-smooth horizontal surface under the assumption of a circular shape of the spill. Relation has been determined between the time required to suppress a spill fire with water mist and the intensity of water feed.

Originality. The scientific originality consists in taking into account the surface irregularities and fuel burnout during the spill spread, as well as determining the time required to suppress a spill fire with water mist, depending on the intensity of the water feed.

Practical value. The proposed model for the fuel spill spread and fire extinguishing can serve as the basis for the design of a fire protection system for the processing equipment and, in particular, of an automatic water mist fire extinguishing system, at oil extracting and oil refining facilities.

Keywords: *burning fuel, spill fire, fuel spill dynamics, water mist, fire extinguishing*

Introduction. Flammable liquid spills stand among the most dangerous emergency scenarios that can occur during the extraction, transportation and processing of crude oil. The ignition of combustible liquid vapors can not only cause a spill fire, but also result in cascade fire propagation to the neighboring process facilities. Therefore, early elimination of the fire is of paramount importance. One of the options to increase the efficiency of the liquid fuel fire suppression is the use of water mist as an extinguishing agent. The main advantage of water mist is the potential to apply combined smothering and surface fire-fighting approaches, which would allow for quick elimination of the flame. The sprayed water is capable of cooling the burning fuel below its flash point and lowering the oxygen concentration in the combustion zone with water vapor below the level required for stable combustion.

Problem to be solved. In order to develop fire protection systems for processing equipment, and, in particular, automatic water mist fire extinguishing systems, it is necessary to determine the feed rate of the extinguishing agent, which in turn is impossible without an evaluation of the combustion parameters and a study into the interaction processes of the extinguishing agent with the burning fuel. One of the problems here is the lack of a mathematical model describing the change in the geometric parameters of the spill in the process of its spread and combustion, as well as the model of suppression of a spreading spill fire with water mist.

Literature review. A significant number of accidents in the chemical industry are associated with the spill of flammable liquids with their subsequent flare up [1]. The geometric parameters of flammable liquid spills are used as input data for the modeling of thermal impact of the spill fire on the processing equipment of oil extraction and oil refining facilities [2]. The dimensions of the spill depend on the duration and intensity of the liquid spread. All spills are conventionally divided into two categories by the time of their spread: instantaneous and continuous ones [3]. In [4], the spread and combustion of fuel on a glass horizontal surface is investigated. The peculiarity of spreading on a smooth surface is that the thickness of the liquid layer stays at several millimeters. In the experiment [5], the spread of fuel on a horizontal metal plate is considered. It was noted, in particular, that the theoretically calculated thickness of the liquid layer is consistent with the observed value. In the experiment [6], it was found that the heat flux from the flame on a film of fuel with a thickness of 6–15 mm does not depend on the thickness of the liquid layer and is constant in time, except for the period of flare-up and extinction. Direct application of the hydrodynamic approach to the analysis of the liquid drop spreading runs into serious difficulties [7]. The analysis of numerical models of the drop spreading is dealt with in [8]. Laboratory studies of the film front spreading along a smooth surface are given in [9]. In [10], models are given which take into account wetting of a surface by a liquid, namely, the contact angle θ

$$\delta=\sqrt{\frac{2\sigma}{\rho g}\left(1-\cos\theta\right)},\qquad(1)$$

where ρ is the liquid density; σ is the surface tension coefficient of the liquid, N/m; g is the acceleration of gravity.

The studies, in particular, presented in [11], indicate that the limiting thickness of the spill layer depends only on the type of liquid and its surface wetting behavior.

Evaporation of the water mist droplets during their movement in a high-temperature environment of the combustion plume of petroleum products was experimentally investigated in [12]. In the experiment [13], the extinguishing of fuel oil in a container with a diameter of 35 cm by pulverizing water at a rate of 25 l/min and the mechanisms of extinction with water mist were considered: cooling of the gas medium and reducing concentration of oxygen and of the combustible liquid vapor as the droplets evaporate in the combustion zone; cooling of the fuel surface as the droplets reach its surface. In [14], the efficiency of diesel fuel spill extinction was analyzed, depending on the diameter of the spill and the supply parameters of the water mist. In [15], the effect of multicomponent additives on the efficiency of combustible liquids extinction by water mist was experimentally studied.

Unsolved aspects of the problem. Existing models of a combustible liquid spreading deal with a smooth surface, as a result of which the given findings cannot be directly applied to the cases of fuel spread on the topsoil. Cooling is one of the least studied mechanisms of fire extinction action of the water mist on the burning fuel. In particular, there are no models for cooling the surface of the burning spill due to the heat removal by droplets of the water mist.

Purpose. The purpose of this research is to construct a model of fire extinction of a burning fuel spreading on a non-smooth horizontal surface using water mist.

The following is required to achieve this goal:

- to build a model of combustion of a fuel as it spreads on a horizontal surface;
- to build a model for suppressing a spill fire with water mist.

Results. To simulate the process of liquid spread on a horizontal surface, we will apply the principle of gravitational spread of a cylindrical liquid layer (Fig. 1) [10], which assumes that at each moment of time t the liquid is in a shape of a cylinder with the height of $h(t)$ and the radius of $R(t)$. In this case, we accept the absence of the liquid diffusion through the soil. Under the influence of gravity, the liquid flows out: $R(t_1) < R(t_2)$, $h(t_1) > h(t_2)$ at $t_1 < t_2$.

From (1), it follows that the maximum radius of the spill is equal to

$$R_{\max}=\sqrt{\pi\frac{V}{\delta}}=\sqrt[4]{\frac{\pi^2V^2\rho g}{2\sigma\left(1-\cos\theta\right)}},\qquad(2)$$

where V is the volume of spilling liquid.

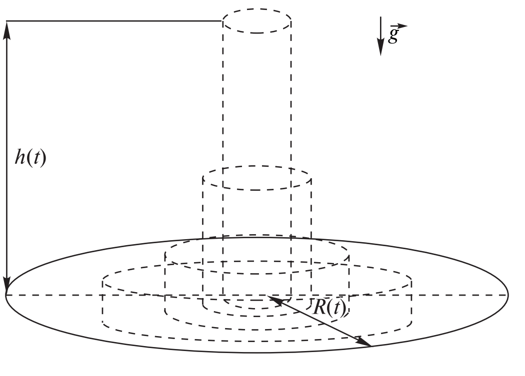

Fig. 1. Calculation principle of the gravitational spread of the cylindrical liquid layer

The peculiarity of spreading the liquid on a non-smooth surface is that it must fill the surface irregularities. This means that a certain volume V_d of the spreading liquid is used to fill the depressions

$$V_d=\pi R^2\delta,\qquad(3)$$

where δ is the average depth of surface irregularities. As a result, the expression (2) can be estimated as

$$R_{\max}=\sqrt[4]{\frac{\pi^2\left(V-\pi R_{\max}^2\delta\right)^2\rho g}{2\sigma\left(1-\cos\theta\right)}},$$

which leads to

$$R_{\max}=\sqrt{\frac{V}{\pi\delta+\frac{1}{\pi}\sqrt{\frac{2\sigma\left(1-\cos\theta\right)}{\rho g}}}}.\qquad(4)$$

Experimental studies [16] have shown that when water is spilled on dry soil $\delta\approx 1.7$ cm, which is approximately 5 times greater than the thickness of the water film on a smooth surface. Failure to take into account the surface tension of the liquid and the nature of the surface wetting $\sigma(1-\cos\theta)=0$ transforms (4) into

$$\tilde{R}_{\max}=\sqrt{\frac{V}{\pi\delta}},\qquad(5)$$

which results in the following relative error

$$\varepsilon=\frac{\left|R_{\max}-\tilde{R}_{\max}\right|}{R_{\max}}=1-\sqrt{1+\frac{1}{\pi^2\delta}\sqrt{\frac{2\sigma\left(1-\cos\theta\right)}{\rho g}}}.\qquad(6)$$

Fig. 2 shows the dependence of the relative error (6) on the value of $\varphi=\frac{\sigma\left(1-\cos\theta\right)}{\rho}$. The points on the horizontal axis are: $\varphi_1=1.5\cdot10^{-6}$ m^4/s^2 – gasoline; $\varphi_2=2.1\cdot10^{-6}$ m^4/s^2 – crude oil; $\varphi_3=6.7\cdot10^{-5}$ m^4/s^2 – water.

The plot analysis of Fig. 2 shows that even at an average depth of surface irregularities of $\delta = 1$ cm the relative error caused by the replacement of the expression (4) for (5) does not exceed 2 % in the range of parameter change φ inherent in liquids. For flammable liquids, this error does not exceed 1 %. Consequently, the maximum radius of liquid spill is determined primarily by the nature of the soil roughness, and not by the nature of surface wetting by the liquid and the strength of its surface tension.

The spreading process of the liquid on the horizontal surface is influenced by the following forces [10].

1. Pressure on the lateral surface of the cylindrical liquid layer (Fig. 1.)

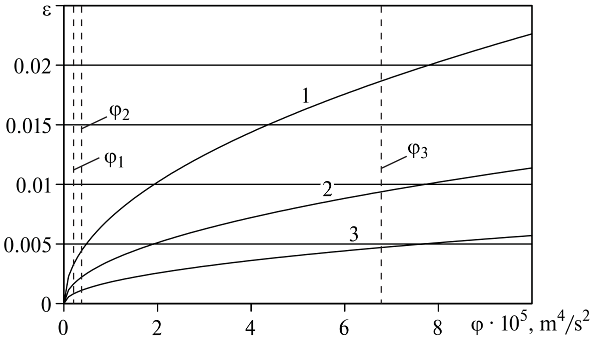

Fig. 2. Relative error for the estimation of the maximum spill radius without regard to surface tension and the nature of surface wetting depending on the value of the parameter φ:
1 – $\delta = 1$ cm; 2 – $\delta = 2$ cm; 3 – $\delta = 4$ cm

$$F_p(R) = \pi R \rho g h^2. \qquad (7)$$

2. Surface tension force

$$F_s(R) = -2\pi R \sigma (1 - \cos\theta). \qquad (8)$$

3. Viscous resistance force

$$F_{fr}\left(R\right) = 0.455\left(\lg\frac{wR}{\nu}\right)^{-2.58}\frac{\rho w^2}{2}\pi R^2, \qquad (9)$$

where w is the average horizontal speed of the liquid; ν is the kinematic viscosity of the liquid.

4. The resistance force due to the dissipation of the kinetic energy through the turbulent motion of the liquid

$$F_{turb} = -\frac{c_d c_1^3}{L_{\max}\sqrt{2}} m w \left|w\right|, \qquad (10)$$

where $c_d = 0.09$, $c_1 = 0.25$ are empirical constants; $L_{\max}$ is maximum vortex size $L_{\max} = h$; m is total liquid mass: $m = \rho V$; V is the volume of the cylindrical liquid layer.

In accordance with Newton's second law, under the influence of the forces listed above, the cylindrical liquid layer will move horizontally with acceleration a

$$F_p + F_{fr} + F_{turb} + F_s = ma. \qquad (11)$$

Combining the expressions (7–11) and taking into account the water consumption to fill the irregularities (3) allow us to obtain the differential equation of the second order for the spill radius

$$R'' = \frac{V(t) - \pi R^2 \delta}{\pi R^3} g - 0.455\left(\lg\frac{2R\left|R'\right|}{\nu}\right)^{-2.58}\frac{2\left|R'\right|R'}{V(t) - \pi R^2\delta}\pi R^2 - \\ - \frac{\sqrt{2}\pi c_d c_1^3 R'\left|R'\right|R^2}{V(t) - \pi R^2 \delta} - \frac{2\pi R\sigma\left(1 - \cos\theta\right)}{\rho\left(V\left(t\right) - \pi R^2\delta\right)}. \qquad (12)$$

Let us note that the right-hand side of equation (12) is uncertain with $R = 0$, therefore the initial condition is expressed as

$$R(0) = R_0; \quad R'(0) = 0, \qquad (13)$$

where R_0 is any initial radius that satisfies the following condition

$$0 < R_0 \le \sqrt{\frac{V\left(0\right)}{\pi\delta}}, \qquad (14)$$

that is, it does not exceed the maximum spill radius relevant to the volume of the liquid $V(0)$.

Let us assume that the flowing liquid ignites at the time $t = t_{ign}$, with the flare-up taking place in the center of the spill, and the flame propagates at normal speed w_n. Let us denote the radius of the burning liquid area $R_b \le R$ with R_b. Then, the change in the radius of the burning area can be represented as

$$R_b = \begin{cases} 0, & t < t_{ign} \\ \min\left(w_n\left(t - t_{ign}\right), R\left(t\right)\right), & t \ge t_{ign} \end{cases}. \qquad (15)$$

Volumetric change of the spilled liquid will be determined by the law of its outflow and the speed of its burning on the area $S_b = \pi R_b^2$

$$V' = V'_{total}\left(t\right) - \pi R_b^2\left(t\right) w_b, \qquad (16)$$

where $V_{total}(t)$ is the total volume of liquid spilled at the time t; w_b is the linear burnout rate of the liquid.

The equations (12, 15, 16) with the initial condition (13) form a system of nonlinear differential equations of the second order which describes the combustion of the liquid spreading over a horizontal surface.

Let us consider the following particular cases:

- instantaneous spill of combustible liquid;
- continuous liquid spill.

Instantaneous spill of flammable liquid with the volume V_0

$$V_{total}(t) = V_0 = \text{const}.$$

Then (16) is transposed into

$$V'\left(t\right) = -\pi R_b^2\left(t\right) w_b; \qquad (17)$$
$$V(0) = V_0.$$

If the volume of the liquid burned out during the time which it took for the flame to engulf the entire spill is short relative to the total liquid volume, then the equation (17) can be substituted with

$$V'(t) = -\pi R^2(t) w_b,$$

which after substitution $V(t) = \pi R^2(t)\delta$ is transposed into

$$R' = -\frac{R w_b}{2\delta}, \qquad (18)$$

with the initial conditions

$$R\left(0\right) = \sqrt{\frac{V_0}{\pi\delta}}, \qquad (19)$$

where the point $t = 0$ is the beginning of combustion. The solution for (18, 19) is

$$R\left(t\right) = \sqrt{\frac{V_0}{\pi\delta}}\exp\left(-\frac{w_b}{2\delta}t\right). \qquad (20)$$

As an example, Fig. 3 shows the result of simulation of the process of spread and combustion of crude oil with the total volume of $V_0 = 60$ l after an instantaneous spill.

Physical properties of oil: $\rho = 850$ kg/m^3; $\nu = 5 \cdot 10^{-6}$ m/s; $\sigma = 0.03$ N/m; $\theta = 19°$. Combustion of oil begins at the time $t_{ign} = 60$ s, the linear rate of burn-out of the liquid is $w_b = 6 \cdot 10^{-5}$ m/s, normal flame spread rate is $w_n = 0.4$ m/s.

The plot analysis of Fig. 3 shows that after an instantaneous spill of 60 liters of crude oil, the maximum radius of the spill is reached in about 20 seconds. The relative error at replacing the solution of system (12, 15, 17) with the approximate expression (20) does not exceed 4 %.

Continuous spill of a fuel with a volumetric flow rate $v(t)$

$$V_{total}\left(t\right) = V_0 + \int_0^t v\left(\tau\right) d\tau,$$

where $V_0 > 0$ is an arbitrary value of the initial volume, the necessity of which is caused by the condition (14). In this situation

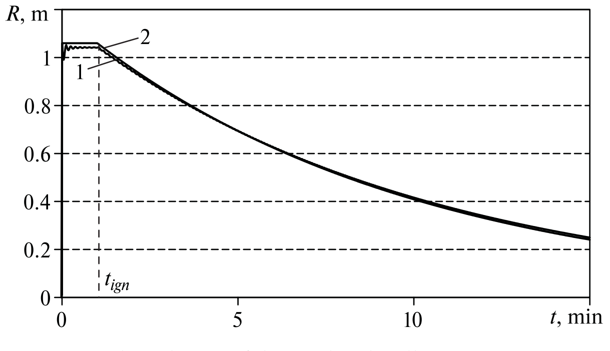

Fig. 3. Radius change of the crude oil spill over time:

1 is a solution of the system of equations (12, 15, 17); 2 is the dependence (20)

$$V'(t) = v(t) - \pi R_b^2(t) w_b; \quad (21)$$

$$V(0) = V_0.$$

If we assume that after the liquid ignition, the flame instantly spreads to the entire area of the spill, that is, $R(t) = R_b(t)$, $t \geq 0$, where the timing begins at the time of the liquid ignition, then the equation (21) is simplified to

$$V' = v(t) - Sw_b,$$

where S is the spill area. In addition, if we assume that the spill instantaneously reaches its maximum area consistent with the spilled liquid volume, $S = V/\delta$, we will obtain

$$S' = \frac{v(t)}{\delta} - S\frac{w_b}{\delta}, \quad t > 0; \quad (22)$$

$$S(0) = \frac{V_0}{\delta}. \quad (23)$$

Solving the equation (22) with the initial condition (23), we obtain

$$S = \exp\left(-\frac{w_b}{\delta}t\right)\left[\frac{V_0}{\delta} + \int_0^t \frac{v(t)}{\delta}\exp\left(\frac{w_b}{\delta}\tau\right)d\tau\right]; \quad (24)$$

$$R = \sqrt{S/\pi}. \quad (25)$$

Fig. 4 shows a change in the radius of crude oil spill over time at a stable volumetric flow rate of $v = 0.6 l/s$ for $t_{out} = 300$ s. The oil ignites at $t_{ign} = 100$ s.

The plot analysis of Fig. 4 shows that the relative error as a result of replacing the solution of the system of equations (12, 15, 21) with approximate expressions (24, 25) reaches 18 %.

Fire extinguishing of burning fuel with water mist. If we assume that the extinguishing process of a spill fire is done through heat removal from its surface by evaporating water droplets which do not reach the burning surface, the extinction process will be described by the following model

$$\frac{\partial\theta(x,\tau)}{\partial\tau} = \frac{\partial^2\theta(x,\tau)}{\partial x^2} + \frac{\partial\theta(x,\tau)}{\partial x}; \quad (26)$$

$$\theta(x,0) = 0; \quad \frac{\partial\theta(0,\tau)}{\partial x} = -\frac{raKI}{w_b\lambda(T - T_0)}, \quad (27)$$

where $\tau = w_b^2 a^{-1} t$; $x = w_b a^{-1} z$; $\theta = (T_k - T)(T_k - T_0)^{-1}$ are dimensionless variables; T, T_k are the surface temperature of the liquid and its boiling point, respectively; T_0 is the ambient temperature; a, λ are the coefficient of thermal diffusivity and heat conductivity of the fuel, respectively; r is the evaporation heat of water; K is the coefficient of water use; I is the rate of water supply.

Applying the Laplace transform to the differential equation (26) with the initial and boundary conditions (27), we obtain

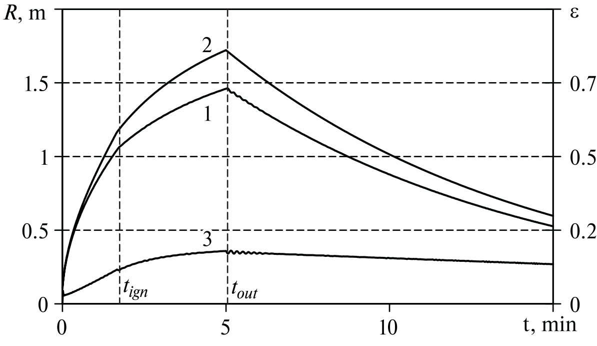

Fig. 4. Radius change of the crude oil spill over time:

1 is the solution of the system of equations (12, 15, 21); 2 is the dependence (24–25); 3 is the relative error (on the right axis)

$$\theta(x,p) = \frac{raK\exp\left[\left[-0.5 - (p+0.25)^{0.5}\right]x\right]}{w_b\lambda(T_k - T_0)\left[0.5 + (p+0.25)^{0.5}\right]}I(p), \quad (28)$$

where p is a complex variable.

For the fuel surface $x = 0$. In addition, let us suppose that $I = \text{const}$.

Then, after applying an inverse Laplace transform to expression (28), we obtain the following

$$\theta(x,\tau) = \frac{raKI}{w_b\lambda(T - T_0)}\left[1 + \left(\frac{\tau}{\pi}\right)^{0.5}\exp(-0.25\tau) - (1 + 0.5\tau)\,erfc\left(0.5\tau^{0.5}\right)\right]. \quad (29)$$

The time of extinction τ_e of the burning fuel is determined by the transcendent equation root

$$\theta_e - \theta(0, \tau_e) = 0, \quad (30)$$

where θ_e is the dimensionless fuel surface temperature at which its combustion stops.

The second summand in the equation (30) corresponds to expression (29) with $x = 0$ and $\tau = \tau_e$.

Solving the equation (30) for the spill of crude oil with the area $S = 3$ m^2 gives a dimensionless extinguishing time $\tau_e \approx 6 \cdot 10^{-2}$ which corresponds to $t_e \approx 12.0$. The values of the parameters included in the relations (26–29) were chosen as follows $\lambda = 0.12 W/m \cdot K$; $a = 8 \cdot 10^{-8}$ m^2/s; $r = 2.3 \cdot 10^6$ J/kg; $K = 0.08$; $I = 0.11$ kg/(m^{2}s); $T_e = 350$ K; $T_k = 400$ K.

The experiment provides the value for the extinction time $t_e = 14.1$ s.

Conclusions. A model was developed for spreading of a fuel on the soil surface and of its combustion taking into account the roughness of the surface. It is shown that the process of fuel spill is determined primarily by the nature of the soil irregularities, and not by the nature of the surface wetting. From a practical standpoint, this means that in order to determine the value of the parameter δ, which describes the average depth of surface irregularities and is included in the model of liquid spread, it is enough to define it experimentally through studying the spread of a certain volume of water.

A model has been built for the burning fuel surface cooling with droplets of water mist which completely evaporate before they reach the surface of the burning fuel. The model allows for determining the time of fire suppression depending on the rate of supply of the water mist.

The obtained expressions can be useful for the development of fire pre-plans at the oil extraction and refining facilities, design of process equipment fire protection systems, outlining of zones for safe positioning of the equipment and personnel, as well as for the design of automatic fire extinguishing systems [14].

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Моделювання розтікання й гасіння горючої рідини на горизонтальній поверхні

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Мета. Побудова моделі гасіння розпиленою водою горючої рідини, що розтікається на негладкій горизонтальній поверхні.

Методика. Побудовано рівняння балансу сил, що впливають на розтікання рідини. У рівнянні враховано зміну маси рідини в розливі, обумовлену її вигоранням і можливим надходженням у випадку неперервного витікання, а також ураховано заповнення рідиною заглиблень на поверхні, по якій відбувається розтікання. Побудовано рівняння теплового балансу на поверхні горючої рідини за умови подачі на неї розпиленої води, що спирається на припущення про повне випаровування крапель води до їх перетинання поверхні горючої рідини.

Результати. Отримана динаміка зміни радіуса розливу горючої рідини з часом при її розтіканні й горінні на негладкій горизонтальній поверхні у припущенні про кругову форму розливу. Знайдена залежність між часом гасіння горючої рідини розпиленою водою та інтенсивністю її подачі.

Наукова новизна. Полягає у врахуванні нерівностей поверхні й вигорання горючої рідини під час її розтікання, а також визначенні часу гасіння пожежі розливу розпиленою водою в залежності від інтенсивності її подачі.

Практична значимість. Запропонована модель розтікання й гасіння горючої рідини є основою для побудови системи протипожежного захисту технологічного обладнання і, зокрема, системи автоматичного пожежогасіння розпиленою водою на підприємствах нафтодобувної й нафтопереробної галузі.

Ключові слова: *горюча рідина, пожежа розливу, динаміка розтікання рідини, розпилена вода, гасіння пожежі*

Моделирование растекания и тушения горючей жидкости на горизонтальной поверхности

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Цель. Построение модели тушения распыленной водой горючей жидкости, растекающейся на негладкой горизонтальной поверхности.

Методика. Построено уравнение баланса сил, влияющих на растекание жидкости. В уравнении учтено изменение массы жидкости в разливе, обусловленное ее выгоранием и возможным поступлением в случае непрерывного вытекания, а также учтено заполнение жидкостью углублений на поверхности, по которой происходит растекание. Построено уравнение теплового баланса на поверхности горючей жидкости при условии подачи на нее распыленной воды, опирающееся на предположение о полном испарении капель воды до их пересечения поверхности горючей жидкости.

Результаты. Получена динамика изменения радиуса разлива горючей жидкости во времени при ее растекании и горении на негладкой горизонтальной поверхности в предположении о круговой форме разлива. Найдена зависимость между временем тушения горючей жидкости распыленной водой и интенсивностью ее подачи.

Научная новизна. Состоит в учете неровностей поверхности и выгорании горючей жидкости во время ее растекания, а также определении времени тушения пожара разлива распыленной водой в зависимости от интенсивности ее подачи.

Практическая значимость. Предложенная модель растекания и тушения горючей жидкости является основой для построения системы противопожарной защиты технологического оборудования и, в частности, системы автоматического пожаротушения распыленной водой на предприятиях нефтедобывающей и нефтеперерабатывающей отрасли.

Ключевые слова: *горючая жидкость, пожар разлива, динамика растекания жидкости, распыленная вода, тушение пожара*

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