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DETERMINING THE PATTERNS OF EXTINGUISHING POLAR FLAMMABLE LIQUIDS WITH A FILM-FORMING FOAMING AGENT

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An issue related to the use of foaming agents to extinguish fires involving flammable liquids is to ensure the efficiency of vapor insulation of flammable liquid and the foam stability during operation. Therefore, the object of research was a change in the insulating properties of the foaming agent film when interacting with a polar combustible substance. It has been proven that the presence of foaming agent on a flammable liquid leads to the formation of an insulating film on the surface resistant to the combustion temperature of the liquid, due to which re-ignition shifts towards longer time. A film of foaming agent was formed on the surface of the flammable liquid by leaking from the screen, which led to the insulation of the surface. The measured contact area of the foaming film with the electrode was more than $6.2\cdot10^{-3}$ m^2, which indicates the formation of a barrier for temperature, which collapses over time. According to experimental data on changes in electrical resistance, the critical contact area of the foaming film with the electrode was calculated, at which the film is destroyed. Based on the derived dependences, the change in the process of mass transfer of the foaming film to a flammable liquid was calculated, equal to about 800 s. The maximum possible mass transfer of the foaming agent into the flammable liquid and the reduction of insulation capacity were evaluated. The peculiarities of foam supply to the surface of alcohol through the screen are that the quenching time was about 156 s while the critical intensity of the supply of the working solution of the foaming agent was 0.054 dm^3/(m$^2\cdot$s). And the time interval before re-ignition was about 470 s, which is enough to cool the fire site. Thus, there is reason to assert the possibility of targeted control over the processes of extinguishing polar flammable liquids with a foaming agent

Keywords: foaming agent for extinguishing fires, foam inflow, foam resistance, isolating of flammable liquid

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1. Introduction

The elimination of fires of flammable liquids is directly related to the use of foaming agents that isolate the surface of burning liquids from the oxidizer (air), cool heated surfaces, and reduce the diffusion of vapors of flammable liquid.

However, the use of foaming agents has its own characteristics as the foam upon contact with a combustible substance loses its extinguishing efficiency and thus needs a larger quantity. Therefore, it is necessary to take into account both the properties of the flammable liquid and the type of foaming agent. In particular, when extinguishing flammable liquids, one of the destructions of the foam is its contact retraction into the fuel. This is especially true for polar flammable liquids such as alcohol, acetone, since they dissolve well in water, and the working solution of the foaming agent is composed of 94÷97 % water.

Countries' industries use significant volumes of ethyl alcohol and other polar flammable liquids. Therefore, for their extinguishing, it is necessary to use foaming agents that are able to perform these functions since during the contact of the foam films of the foaming agent with a flammable liquid, rapid desorption of surfactants occurs and, accordingly, the destruction of the foam. And there is a need to supply foam without immersing it, by smoothly flowing onto flammable liquid surface from the surface of the screen. Taking into account the requirements for the destruction of foaming agents in contact with polar flammable liquids, the question arises of assessing the possibility of using foaming agents in such systems.

This determines the need to study the conditions of insulation of the oxidizer due to the formation of a polymer film on the surface of a flammable liquid and the justification of the conditions for protecting the polar flammable liquid by inflow.

2. Literature review and problem statement

In work [1], it is noted that extinguishing fires of petroleum products during emergency spills at industrial capital construction facilities, transport, gas stations, and destruction of oil tanks is most effective when using foaming agents. A classification of foaming agents intended for extinguishing fires of petroleum products is given, which is based on the structure of the spreading coefficient of a water-forming foaming solution over the surface of hydrocarbons. The results of experimental studies using different foaming agents with different structure of spreading coefficient are given. It is determined which of the homologues of a number of primary sodium alkyl sulfates differ in foaming ability and fire extinguishing efficiency. It was revealed that a decrease in the value of interfacial tension leads to a decrease in the extinguishing time of the heptane flame. However, their interaction with polar flammable liquids is not given.

In study [2], a new gel-protein foam was produced. The microstructure, foaming, stability, and water-holding capacity of gel-like protein foam were systematically analyzed to determine the top three compositions. They were then used to evaluate extinguishing and anti-inflammatory efficacy compared to commercial film-forming fluor protein foam (FFFP). Experimental results showed that the gel-protein foam with the best extinguishing efficiency is a foam with a SA/$CaCl_2$ ratio of 9:1 and a concentration of 0.1 % by weight. The mean size and coefficient of water loss is 126.46 µm and 30.6 %, respectively, compared to 273.24 µm and 44.1 % for FFFP. Fire extinguishing tests have also confirmed that this gel-like protein foam has the best cooling and anti-inflammatory characteristics. The burnout time of 90 % of this foam is 454 s, which is 54.42 % more than that of FFFP, as it can float stably on the surface of the fuel to reduce the risk of re-ignition. The cited paper contains important data and guidance on the further development of gel foams for extinguishing fires in oil storage tanks but has not established their feasibility for fire safety of alcohol tanks.

To improve the extinguishing ability of protein foam (PF) in case of a diesel pool fire, a foam extinguishing device was used in [3]. Which investigated the effect of gas-to-liquid ratio, injection angle, motion pressure, and fluid flow velocity on the extinguishing efficiency of PF. When the gas-to-liquid ratio is 20, the foam has the shortest extinguishing time of 200 s and the lowest dose of extinguishing agent of 260 g among the samples. In addition, the extinguishing efficiency of the PF varies with changes in the injection angle and in the order of 90° (vertical injection)>45° (introduction with view)>−45° (upward entry)>0° (horizontal injection). In addition, with an increase in fluid flow and driving pressure, the extinguishing efficiency of the PF increases. In particular, the extinguishing time and dosing time of the extinguishing agent are reduced by 35.0 % and 11.5 % respectively at a flow rate of PF 50 l/h compared to 20 l/h, which are reduced by 25.0 % and 24.6 %, respectively, with a driving pressure of 0.5 MPa compared to a case of 0.3 MPa. The extinguishing efficiency factor of PF has been investigated from experimental aspects, which became the basis for the use of PF in extinguishing fires. But issues related to the extinguishing mechanism remain unresolved.

In [4], the efficiency of foaming liquids in subsurface applications largely depends on the stability and transport of foam bubbles in harsh environments with high temperature, pressure, and salinity. This inevitably leads to poor foam properties and thus limits the tearing efficiency. The aim of the cited work is to develop popular strategies for stabilizing foam in reservoir conditions. In particular, this review first discusses the three main mechanisms driving foam decay and summarizes recent advances in research on these phenomena. Since surfactants, polymers, nanoparticles, and their composites are popular options for foam stabilization, their stabilizing effects, especially synergies in composites, are also being considered. In addition to the experimental results report, the article also reports recent advances in surface properties using molecular-dynamic modeling, which provide new insight into gas/liquid surface properties under surfactant exposure at the molecular scale. The results of both experiments and simulations show that foam additives play an important role in foam stability, and the synergistic effects of surfactants and nanoparticles exhibit more favorable characteristics. However, it is not known how this additive affected the extinguishing of polar combustible substances.

Extinguishing foams are usually used to extinguish fires of flammable liquids, which uses their insulating and extinguishing effects [5]. In an attempt to curb gasoline fires, red palm oil was used to synthesize environmentally friendly fireproof foam that is less dense than petroleum motor alcohol (PMS). Transesterification of palm oil and ethanol in an acidic medium was carried out by boiling with a reverse refrigerator for 18 hours at 358 K to obtain palm oil ethyl ester (POEE), which was reduced with metallic sodium. The resulting sodium salts of POEE, which were highly viscous at room temperature, had a pH of 10.2. The optimal concentration of the foaming agent, obtained at a ratio of 1:8 moles of foaming agent to water, had foaming characteristics that persisted for about 29 days. Some physical properties of the foam obtained were checked, and the effectiveness of quenching with a foaming agent was confirmed. However, it is not specified how these formulations can be used in contact with water-soluble flammable liquids.

In study [6], aqueous film-forming foam, fluor protein foam, and synthetic foam were used to extinguish transformer oil fires. The extinguishing ability and resistance to reverse (repeated) combustion were investigated using a laboratory fire extinguishing system. In addition, emission products were analyzed to assess the characteristics of gas phase pollution. The results show that aqueous film-forming foam has the highest extinguishing efficiency, while fluor protein foam has the best flue gas burnout reverse efficiency and gas chromatography-mass spectrometer shows that the use of fluor protein foam results in significantly higher CO emissions than other foams. Pollutants mainly come from various hydrocarbons, which are formed as a result of incomplete combustion of transformer oil. Synthetic foam and aqueous film-forming foam lead to higher emissions of SO_2 and NO, and alcohols and esters predominate among pollutants. It should be noted that when using aqueous film-forming foam to extinguish the fire of the oil basin, a persistent organic pollutant perfluorooctanoic acid is detected in the gas phase.

Work [7] says that depending on the type of burning substance and the place of fire, appropriately prepared and developed solutions should be used. For this we can highlight, among others, materials, powders, or foaming agents. Modifications introduced into them, including those based on advances in nanotechnology, can increase the safety of their use and extend their service life. Such changes also reduce the cost of production and neutralization of the territory after a fire, increase the efficiency of fire extinguishing. The introduction of nanoparticles makes it possible, for example, to reduce the time of fire extinguishing, reduce the risk of smoke and toxic substances contained in it, as well as increase the specific surface area of particles and, thus, increase the sorption of pollutants. The development uses metallic nanoparticles, for example, NP-Ag, metal oxides such as NP-SiO_2, as well as particles of substances that are already present in extinguishing agents but processed and reduced to nanoscale. However, it should be noted that all changes should lead to the receipt of a tool that meets the relevant requirements of the legislation and has the appropriate permits.

In study [8], a round steel tank with a diameter of 1.5 m is used to simulate the fire of the full surface of a storage tank in an industrial park. To assess the effectiveness of various types of foam for extinguishing diesel fuel/methanol fires, a homemade fire extinguishing system was used, which gently releases foam at a speed of 11.4 l/min. Experiments were conducted to analyze the increase in fire temperature after isolating different types of foam. In the cited study, the dimensionless average temperature of 0.85 and 0.71 is considered as the fire extinguishing temperature of methanol and diesel, respectively. In the process of application, the increase in the length of the foam application over time still occurs according to the power law. The highest flow rate of 6 % FP/AR in a methanol fire and 6 % synthetic foam in a diesel pool fire was $0.0136\ m\cdot s^{-1}$ and $0.044\ m\cdot s^{-1}$, respectively, with a foam application rate of 11.4 l/min. The results show that in a methanol pool fire, the cooling effect of the foam is rated as FP/AR>AFFF>AFFF/AR>S>FP>S/AR. And the cooling effect of diesel foam is rated as S>S/AR>AFFF>AFFF/AR>FP>FP/AR. The cooling effect of the foam is especially noticeable during fires in the diesel pool. As for methanol fires, the foam extinguishing mechanism is mainly based on the effect of an "antisoluble film", which quickly forms a cover layer on the surface of the flammable liquid. At the same time, separating the flame from thermal feedback and preventing the formation of flammable vapors, isolating itself from the air and eventually suffocating the fire. However, it is not said about the intensity of supply.

Aqueous film-forming foam (AFFF) is a very important extinguishing agent for hydrocarbon fuel fires [9]. The effectiveness of the distribution of AFFF is one of the key factors determining the effectiveness of its extinguishing. There are many parameters that affect the effectiveness of AFFF distribution, but little research has been done on the mechanism of distribution. In the cited paper, a method for studying the expansion efficiency of surfactant solution on different oil surfaces is proposed. In addition, the kinetics of the equimolar system C4-Br/$CH_3(CH_2)_5NaO_3S$, C6-Br/$CH_3(CH_2)_5NaO_3S$ and C8-Br/$CH_3(CH_2)_5NaO_3S$ extends to the surfaces of cyclohexane, n-heptane, aviation kerosene; solvent oil and diesel fuel were investigated. Meanwhile, the ratio between spreading length and time at 25 °C was obtained, and experimental data were evaluated using a model of surface tension and viscosity mode. The values of standard deviation (RMSD), obtained as a result of correlation using the model of the surface tension and viscosity mode for all systems investigated, are lower than 3.41. Which indicates good consistency between experimental and theoretical values. This meant that a model of surface tension and viscosity mode could be used to predict the formation process of an aqueous film formed by a surfactant solution distributed over hydrocarbon oil. In addition, the theoretical spreading rate (R) and the average spreading velocity (R^{-}) from 0 to 50 s of C4-Br/oil, C6-Br/oil, and C8-Br/oil systems were also investigated. The results showed that R decreases with increasing time and the rate of descent gradually slows down. R^{-} increases with increasing fluorocarbon chains. In particular, the effect of the kinematic viscosity of the fuel on the spreading rate was also very obvious. The greater the kinematic viscosity of the fuel, the smaller the effect of surfactants on the spreading rate. However, the effect of foaming agent inflow and flame extinguishing has not been determined.

The properties of aqueous film-forming foam solutions (AFFF) of compositions containing different xanthan content were first investigated by varying the mass fraction of xanthan in the range of 0.1–0.5 % [10]. The foam properties and extinguishing capacity of AFFF compounds were then evaluated. The results showed that the xanthan content had little effect on the surface tension of the foam solutions. However, xanthan gum significantly influenced the viscosity of AFFF concentrates. Xanthan gum had practically no effect on foaming of AFFF compositions, but resistance to foaming compounds apparently improved with the addition of xanthan gum. The optimal xanthan content was determined to be 0.3 %, resulting in the shortest 90 % control time and extinguishing time. At the same time, foam burnout increased with the addition of xanthan gum due to increased stability.

In [11], a strategy for aqueous film-forming foam (AFFF) using mixtures of cationic-anionic surfactants with short fluorocarbon chains (<=C–4) in both cationic and anionic surfactants was proposed. Minimum surface tension (gamma (min)) of mixtures $C_4F_9SO_2NH(CH_2)_3N(CH_3)_3I$ (C_4FI) and $C_nF_{2n+1}COONa$ (n=1, 2, 3, 4) with different molar ratios (5:1, 2:1, 1:1, 1:2, 1:5) were measured at 25 °C. The gamma (min) for all C_4FI–$C_nF_{2n+1}COONa$ mixtures was significantly lower than that of pure C_4FI. Among these mixtures, an equimolar mixture C_4FI–C_3F_7COONa was chosen due to its low gamma radiation (min), qualified solubility, and relatively high fluorine efficiency. The spreading coefficients of its aqueous solution on n-heptane, toluene, benzene, cyclohexane, and gasoline were positive, indicating its potential in AFFF. Film spreading, tightness, and foaming were also checked. The effect of "green" additives was studied (alkyl glucose amide, xanthan gum, and sodium salt of carboxymethylcellulose) on foaming efficiency when a small dose of xanthan gum can significantly slow down foam drainage. It was confirmed that mixing oppositely charged surfactants that have short fluorocarbon chains was a valuable idea for the development of AFFF. In applications, quaternary ammonium-based surfactant can also be bromide or chloride rather than iodide for reasons of reduced cost and stability. But it is not said regarding their resistance to the effects of water-soluble flammable liquids.

In [12], experiments are given, the purpose of which was to quantify the degradation of foam caused by fuel by depositing foam on liquid fuels and water (for comparison) and measuring the thickness of the foam over time. The study included two fireproof foams, one fluorine-free (RF6-ICAO) and the other fluorinated (AFFF), as well as a foam made with a common surfactant SDS. To do this, they applied a layer of foam about 2 cm thick to three types of liquid fuels (n-heptane, methylcyclohexane, and isooctane) at room and elevated temperatures. The service life of the foam was reduced by 50 % and 75 % for AFFF and RF6, respectively, for foam on fuel compared to foam on water at room temperature. In all experiments, fluorine-free foams (RF6 and SDS) decomposed much faster than AFFF. In addition, the effect of fuel temperature was significant when the foam was placed on hot fuel: the life of extinguishing foam was reduced by 1–2 orders of magnitude between experiments conducted with fuel at room temperature and at 50 °C. Before the degradation of foam over fuel, fireproof foam has undergone a preliminary expansion (up to 50 % by volume). Degradation videos show that the expansion is the result of an increase in the size of bubbles near the partition boundary with accelerated enlargement due to coalescence. Based on observations, we propose and discuss the mechanism of degradation of foam caused by fuel. The results show that fluorine-free RF6 decomposes faster than AFFF (3 times at room temperature and 12 times at elevated temperatures compared to fuel), which may contribute to differences in their fire characteristics.

Thus, as a result of our review, it was established that during interaction with a water-soluble flammable liquid of the foaming agent, the process of its degradation takes place, which can lead to a repeated outbreak of a combustible substance. All this gives grounds for conducting research aimed at determining the parameters that increase the resistance to destruction of the foaming agent when interacting with a polar flammable liquid. Therefore, the establishment of conditions for insulation of the surface of a polar flammable liquid by a foaming agent and the substantiation of the technology of supplying a flammable liquid by inflow necessitated research in this area.

3. The aim and objectives of the study

The aim of this work is to identify patterns of insulation of polar flammable liquid by a film-forming foaming agent. This will justify the conditions for the use of film-forming foaming agents for extinguishing the flame of polar flammable liquids.

To accomplish the aim, the following tasks have been set:

– to simulate the process of mass transfer of foaming agent into a flammable liquid;

– to establish features of extinguishing the flame of ethyl alcohol with a film-forming foaming agent during full-scale tests.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the insulating properties of the foaming agent film when interacting with a polar combustible substance. The scientific hypothesis assumes a change in the insulating properties of the foaming agent film when interacting with a polar combustible substance.

To simplify the mathematical model of mass transfer for the purpose of its formal description, a number of assumptions are adopted that relate to the peculiarities of the flow of mass transfer and other types of processes at the modeling object. In particular, assumptions are accepted that determine the impact of changes in external conditions on the object and the lack of relationship between different implementations of the process, namely: the movement occurs in the vertical direction; the foaming solution and the polar flammable liquid are homogeneous; temperature, humidity, pressure are not variable.

4. 2. Investigated materials used in the experiment

To establish the ability of the foaming agent to flow onto a polar (water-soluble) combustible substance, samples of 6 % solution of foaming agent "S.F.P.M. 6/6" (Ukraine) were used. A solution of foaming agent with a flow rate of 0.02 kg/m^2 was applied to the surface of ethyl alcohol (pharmaceptyl), tests were carried out for spreading of the foaming agent.

4. 3. Procedure for determining the insulating ability of the foaming agent when interacting with a combustible substance

To conduct experimental studies to investigate the process of mass transfer of foaming agent into a layer of flammable liquid, special equipment was manufactured. For this purpose, a plastic cuvette [13] was used, which had metal electrodes and additionally had a screen for draining the foaming agent; an ohmmeter was used to measure electrical resistance during the tests (Fig. 1). A polar flammable liquid (alcohol) was placed in the cuvette, the surface of which was covered with a layer of foaming agent by inflow; for this purpose, a foaming agent was fed to the screen, and the resistance was measured. According to the criterion of absorption by the flammable liquid of the foaming agent, there was a decrease in electrical resistance.

The determination of the extinguishing efficiency of the foam was carried out according to [14, 15]. The essence is to determine the duration of extinguishing a cylindrical model fire at a given minimum intensity of supply of the working solution of the foaming agent, at which the extinguishing of the model fire source occurs. As well as the maximum feed intensity at which extinguishing does not occur or occurs in a period exceeding 300 s.

The model sample was installed horizontally on the test site. In a cylindrical mock hearth with a diameter of 518 mm, alcohol of about 100 g per 1 dm^2 of the surface was placed. Set on fire and kept for 60 s. A working solution of foaming agent with a feed intensity of 0.059 dm^3/(m^2·s) was fed to the screen of the model hearth for 300 s, the foam from which flowed to the surface of the fuel. We recorded the duration of extinguishing the flame. Then the burner was lit, which was installed in the center of the model focus and controlled the time of the re-flash.

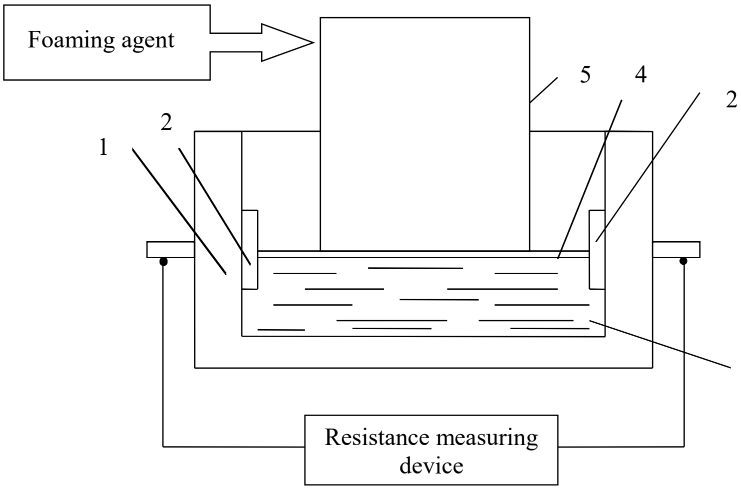

Fig. 1. Scheme for determining the electrical resistance of the foaming agent: 1 — cuvette made from plasic; 2 — electrodes; 3 — flammable liquid (alcohol); 4 — foaming solution; 5 — screen

Studies on modeling the process of mass transfer of foaming agent into a layer of flammable liquid were carried out using the basic provisions of mathematical physics.

5. Results of determining the mass transfer of the foaming film when interacting with a combustible substance

5. 1. Modeling of mass transfer characteristics for a foaming agent film on the surface of a polar combustible substance

In the interaction of the foaming agent with the combustible substance, we can assume that the foaming agent n is evenly distributed over the region $x\epsilon(-\infty, 0)$ (with an initial concentration of N). Starting from time $t=0$, substance n diffuses into the region $x\epsilon(\infty, 0)$, where it reacts with the combustible substance m (with the initial concentration M), which does not penetrate the partition boundary $x=0$. It is required to find the mass flow n across the boundary between regions $x=0$ at $t>\infty$ (Fig. 2).

The diffusion process describing the absorption process has the following form of the diffusion equation [16]:

$$\left(\frac{\partial}{\partial t}-D^{/}\frac{\partial^2}{\partial x^2}\right)N=0, \tag{1}$$

where N is the concentration of foaming agent on the surface of the combustible substance, kg/m^3;

D^* – diffusion coefficient of foaming agent into the layer of combustible substance, m^2/s;

t – residence time of the foaming agent on the surface of the flammable liquid, s.

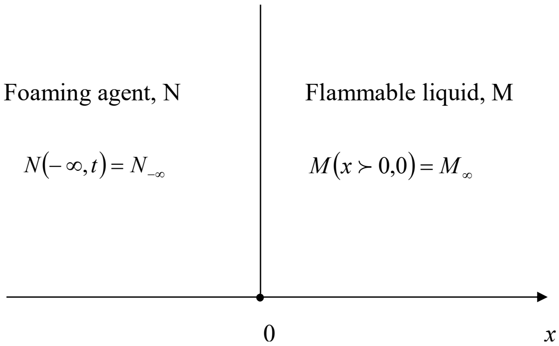

Fig. 2. Diagram of the process of mass transfer of the foaming agent into a flammable liquid

The system of initial and boundary conditions is as follows:

$$\begin{gathered}
N(-\infty,t)=N_{-\infty},\ N(\infty,t)=0,\\
N(x,0)=\{N_{-\infty},\text{at } x\prec 0; 0 \text{ at } x\succ 0\},\\
\left.\frac{\partial M}{\partial x}\right|_{x=0}=0,\ M(\infty,t)=0,\ M(x\succ 0,0)=M_{\infty},\\
N(-0,t)=\psi\cdot N(+0,t),\\
D^{/}\left.\frac{\partial N}{\partial x}\right|_{x=-0}=D\left.\frac{\partial N}{\partial x}\right|_{x=+0},
\end{gathered} \tag{2}$$

where ψ is the spreading coefficient (distribution) of the foaming agent.

For the foaming agent, the boundary condition according to equation (1) will take the form [17]:

$$-\sqrt{D^{/}}\left.\frac{\partial N}{\partial x}\right|_{x=-0}=\frac{N_{-\infty}}{\sqrt{\pi\cdot t}}-P^{1/2}\cdot N|_{x=-0}, \tag{3}$$

The relationship between boundary conditions will be as follows:

$$\left[N-M+\sqrt{D}\cdot P^{-1/2}\cdot\frac{\partial N}{\partial x}\right]_{x=+0}+M_{\infty}=0. \tag{4}$$

Given the condition of unambiguity (2), we can exclude left variables from equation (3) and we have the possibility for determining N, M, $\partial N/\partial x$ at $x=0$.

To simplify the solution, we change the scale of the coordinate and introduce the notation for boundary conditions:

$$\begin{gathered}
\xi=\frac{x}{\sqrt{D}},\ N|_{\xi=+0}=N_s,\\
M_{\infty}-M|_{\xi=+0}=S_s,\ \left.\frac{\partial N}{\partial \xi}\right|_{x=+0}=q_s,\ \delta=\sqrt{\frac{D}{D^{/}}}.
\end{gathered} \tag{5}$$

Then the equations at the distribution boundary take the following form [18]:

$$-\delta\cdot q_s=\frac{N_{-\infty}}{\sqrt{\pi\cdot t}}-\psi\cdot P^{-1/2}\cdot N_s, \tag{6}$$

$$-q_s=P^{-1/2}\cdot(N_s+S_s), \tag{7}$$

$$\begin{aligned}
-q_s={}&P^{-1/2}\cdot(N_s+S_s)+\\
&+\left(\begin{aligned}&P^{-1/2}+\frac{k}{2}(M_{\infty}-S_s)+\\&+\frac{k^2}{8}\left[N_s(M_{\infty}-S_s)-(M_{\infty}-S_s)^2\right]\cdot P^{-3/2}+\ldots\end{aligned}\right)\cdot N_s.
\end{aligned} \tag{8}$$

From (6) and (7), by excluding q and using the fractional differentiation operation, we derive the expression:

$$N\big|_{x=+0}=\frac{N_{-\infty}-\delta\left(M_{\infty}-M\big|_{x=+0}\right)}{\delta+\psi}. \tag{9}$$

At large time values ($t>0$), when the foaming agent flux n at the boundary becomes small, the concentration of the combustible substance m (M at $x=+0$) at $x=+0$ is reduced to the original value of M_{∞}. That is, the concentration of the foaming agent approaches zero. Thus, we can write:

$$N\big|_{x=+0}\approx\frac{N_{-\infty}}{\delta+\psi} \text{ or } N\big|_{x=+0}\approx\frac{N_{-\infty}\cdot\psi}{\delta+\psi}. \tag{10}$$

Then the diffusion flow through the distribution boundary at the final stage of the process of interaction between the foaming agent and the flammable liquid is described by the equation:

$$-\sqrt{D^{/}}\frac{\partial N}{\partial x}\bigg|_{x=-0}=\frac{\sqrt{D^{/}\cdot D}}{\psi\sqrt{D^{/}}+\sqrt{D}}\frac{N_{-\infty}}{\sqrt{\pi t}}. \tag{11}$$

As can be seen from equation (11), the mass transfer rate is determined by diffusion. In the case when the ratio of a flammable liquid to the concentration of the foaming agent is at the limit:

$$\frac{M_{\infty}}{N_{\infty}}\to\infty, \tag{12}$$

for $x>0$ values, we find an operator solution for the concentration of foaming agent in the form:

$$N\big|_{x=-0}=\frac{N_{-\infty}}{1+\left(\frac{\delta}{\psi}\right)\cdot\sqrt{1-N_{\infty}\cdot k\cdot P^{-1}}}, \tag{13}$$

or mass transfer intensity:

$$-D^{/}\frac{\partial N}{\partial x}\bigg|_{x=-0}=\frac{\sqrt{1+M_{\infty}\cdot k\cdot P^{-1}}}{1+\left(\frac{\delta}{\psi}\right)\cdot\sqrt{1-N_{\infty}\cdot k\cdot P^{-1}}}\frac{\delta}{\psi}\sqrt{\frac{D^{/}}{\pi\cdot t}}N_{\infty}. \tag{14}$$

At a considerable exposure time of this system, we obtain an expression for determining the mass transfer of the foaming agent into a flammable liquid:

$$N\big|_{x=-0}=\frac{\psi\cdot N_{-\infty}}{\delta\cdot\sqrt{\pi\cdot M_{\infty}\cdot k\cdot t}}, \tag{15}$$

or to calculate the mass transfer intensity of the foaming agent into a flammable liquid, the equation:

$$-D^{/}\frac{\partial N}{\partial x}\bigg|_{x=-0}=\sqrt{\frac{D^{/}}{\pi\cdot t}}N_{\infty}. \tag{16}$$

From this dependence, we can find the dynamics of absorption of the foaming agent by a flammable liquid by the values of the initial concentration, diffusion coefficient, and exposure time.

5. 2. Results of determining the change in the insulating properties of the foaming agent on the surface of a polar flammable liquid

The study of the process of mass transfer of the foaming agent film into a combustible substance has difficulties since the film has a thickness of several millimeters and changes over time. Taking into account the fact that the foaming solution contains 94÷97 % water and is an electrolyte. In electrolytic conductors, electricity flows, accompanied by decomposition of the substance. For foaming solution: the specific electrical conductivity is the electrical conductivity of the volume of solution enclosed between two parallel electrodes of area S at a distance l and is calculated by the equation:

$$\kappa=\frac{1}{\rho}, \ (\text{cm}\cdot\text{m}^{-1}), \tag{17}$$

where ρ is the resistivity of the foaming agent, which depends on the nature of surfactants, and is determined by dependence:

$$\rho=\frac{l}{S}\cdot R, \ (\text{Ohm}\cdot\text{m}), \tag{18}$$

where R is the foaming agent resistance, Ohm;

l – distance between electrodes, 0.02 m;

S – area of contact of the electrolyte with the electrode, m^2.

To establish the intensity of the mass transfer process of the foaming film into a flammable liquid, studies have been conducted on changes in electrical resistance during its decomposition. In this regard, the change in the contact area of the foaming agent (electrolyte) with the electrode was calculated (Table 1), for this the resistivity of the foaming agent according to [19] was 28.8 Ohm·m.

Fig. 3 shows the process of determining the intensity of mass transfer of the foaming agent film into a layer of flammable liquid.

It was established that the process of destruction of the foaming agent film on the alcohol surface took place within 800 s, when the thickness of the foaming layer became critical, which led to its destruction and disappearance of electrical conductivity.

Table 1

Results of determining the change in the contact area of the foaming film with the electrode

Exposure time, s	Electrical resistance value, Ohm	The contact area of the foaming film with the electrode, S, m^2
45	93	0.006194
90	146	0.003945
135	201	0.002866
180	260	0.002215
225	298	0.001933
270	346	0.001665
315	398	0.001447
360	458	0.001258
405	499	0.001154
450	558	0.001032
495	598	0.000963
540	649	0.000888
585	789	0.00073
630	851	0.000677
675	917	0.000628
720	962	0.000599
765	984	0.000585
810	>1001	0.000575
855	>1001	0.000575
900	>1001	0.000575

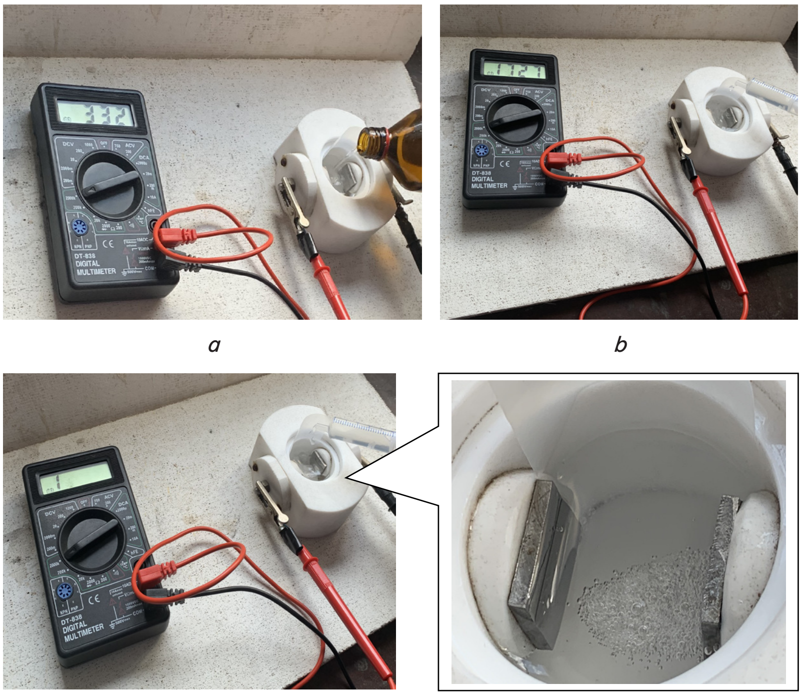

Fig. 3. The process of determining the intensity of mass transfer of the foaming agent film into the layer of flammable liquid: *a* – filling the cuvette with ethyl alcohol; *b* – inflow of foaming agent on alcohol; *c* – measurement of the electrical resistance of the foaming film; *d* – destruction of the foaming film

As shown by the results of our studies (Fig. 3), when foam is supplied to the surface of a flammable liquid containing 96 % (vol) of ethyl alcohol, its spreading and accumulation begin immediately after the start of feeding.

Taking into account the literature data, in particular, the value of the diffusion coefficient [20], which is $0.12 \cdot 10^{-6}$ m/s^2, the thickness of the foaming agent layer, which is 2 mm, the change in the process of mass transfer of the foaming agent film into a flammable liquid is calculated.

Fig. 4 shows the dynamics of absorption of the foaming agent by a flammable liquid, which is calculated by equation (16).

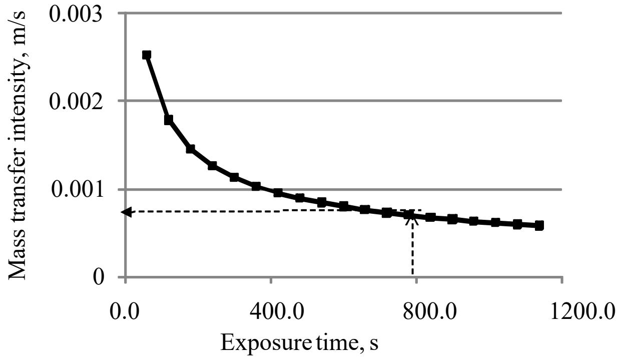

Fig. 4. The intensity of mass transfer of the foaming agent into a flammable liquid. The arrows show the time of formation of the critical value of the thickness of the foaming layer

According to the results of the foaming agent exposure on the alcohol surface, intensive mass transfer of water into a flammable liquid began at the beginning. This led to the destruction of the foaming film by 800 s and, accordingly, the destruction of electrical conductivity (resistance value >1000 Ohms).

To establish the effectiveness of alcohol quenching with a foaming agent, full-scale tests were carried out at facilities, in particular, model samples (Fig. 5).

The results of determining the duration of quenching and the critical intensity of the working solution are given in Table 2.

Table 2

Results of determining the effectiveness of alcohol flame quenching

No. of experiment	Duration of extinguishing, s	Time interval before re-ignition, s	Critical feed intensity of working solution, dm^3/(m^2·s)
1	159.8	453.2	0.054
2	153.6	487.4	
Mean	156.7	470.3	

As can be seen from Table 2, when applying foam to the surface of alcohol through the screen, the quenching time was about 156 s. The time interval before re-ignition was about 470 s, and the critical intensity of the supply of the working solution of the foaming agent was 0.054 dm^3/(m^2·s).

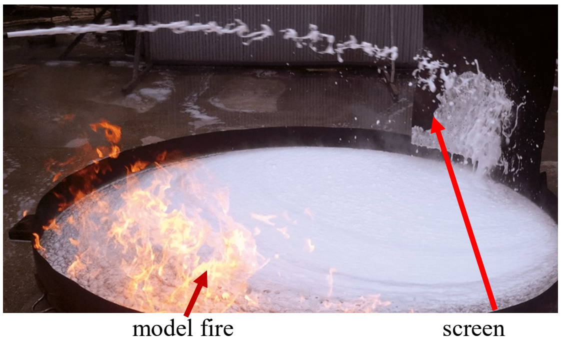

Fig. 5. The process of extinguishing a model fire by feeding foam on the screen and its inflow on alcohol

6. Discussion of results of studying the process of mass transfer of foaming agent when interacting with a polar combustible substance

When using foaming agents to protect flammable liquids from fire, as indicated by the results of research (Fig. 5, Table 2), the process of foaming agent inflow and insulation of flammable liquid is natural. This is due to the formation of a film of foaming agent on the surface of a flammable liquid, which slows down the processes of vapor escape of a flammable liquid and diffusion of the oxidizer and its combustion.

It should be noted that the presence of a foaming agent on a flammable liquid leads to the formation of an insulating film on the surface of a liquid resistant to combustion temperature. Obviously, such a mechanism of influence of the elastic film of the foaming agent is the factor regulating the insulation process, due to which re-ignition is shifted in a longer time frame. In this sense, the magnitude of the contact area of the foaming agent between the electrodes is important. Since the contact area of the foaming film with the electrode is destroyed, and, accordingly, the electrical resistance increases. This indicates the gradual mass transfer of the foaming agent into the polar flammable liquid and the destruction of the protective film, which can be identified by the method of electrical conductivity of the foaming agent.

This means that taking into account these facts opens up the possibility for effective regulation of the properties of foaming agents directly under the conditions of mass industrial production.

Comparison of experimental studies to determine the change in the electrical resistance of the foaming layer on the surface of a polar combustible substance and theoretical studies of the mass transfer of the foaming agent indicates the inhibition of the processes of destruction of the formed film. Since the process of destruction of the foaming agent film on the alcohol surface took place within 800 s, and the mass transfer intensity decreased to $0.7{\cdot}10^{-3}$ m/s (Fig. 4).

This does not diverge from practical data, well known from work [2, 5], the authors of which, by the way, also associate the effectiveness of extinguishing the flame of a flammable liquid with the formation of a layer of foaming agent on the surface of the burning liquid. In works [21, 22], the authors also associate the elimination of fire with the neutralization of the oxidizer in the system "combustible oxidizing substance", or neutralization of high temperature [23, 24]. But, unlike the results of studies published in [3, 7], the obtained data on the influence of the foaming agent on the process of inhibition of temperature transfer, allow us to assert the following:

– the main regulator of the process of extinguishing the flame of a flammable liquid is not only the stability of the foam under the action of temperature with heat absorption but also the formation of a film of foaming vapor, which insulates the exit of combustible vapors;

– a significant impact on the process of protecting a flammable liquid by a foaming agent is exerted in the direction of insulating combustion reactions by forming a stable film on the surface of a flammable liquid.

Such conclusions may be considered appropriate from a practical point of view since they allow a reasonable approach to determining the required amount of foaming agent for extinguishing the liquid. From a theoretical point of view, this makes it possible to assert the definition of the mechanism of the processes of inhibition of the flame of a flammable liquid, which are certain advantages of this study.

It is impossible not to note that the results of extinguishing the model source of alcohol fire (Fig. 5) indicate an ambiguous effect of the supply of foam to the screen and inflow on the flame of alcohol. This is manifested, first of all, in the duration of quenching and the value of the critical intensity of supply of the working solution of the foaming agent. Such uncertainty imposes certain restrictions on the use of the results obtained, which can be interpreted as shortcomings of this study. Inability to remove the named limitations in this study gives rise to a potentially interesting area for further research. In particular, studies can be focused on identifying the moment in time from which the fall in foam resistance begins and the ignition of a flammable liquid under the influence of high temperature. Such detection will allow us to investigate the structural transformations of the foaming film, which begin to occur at this time, and to determine the input variables of the process that significantly affect the onset of such a transformation.

7. Conclusions

1. Simulation of the process of mass transfer by foaming agent in its protection of polar flammable liquid was carried out, the insulating ability and obtained dependences were established, allowing us to obtain a change in the absorption intensity of the foaming agent. According to experimental data of changes in electrical resistance, the critical contact area of the foaming film with the electrode was calculated, at which the film is destroyed. Thus, with an electrical resistance of more than 984 Ohms, the contact area was $5.75{\cdot}10^{-4}$ m^2, and the mass transfer intensity dropped over $8{\cdot}10^{-4}$ m/s. And according to the obtained dependences, the change in the process of mass transfer of the foaming agent film into a flammable liquid, which is about 800 s, was calculated.

2. The peculiarities when applying foam to the surface of alcohol through the screen are that the quenching time was about 156 s while the critical intensity of the feed of the working solution of the foaming agent was 0.054 dm^3/(m^2·s). And the time interval before re-ignition was about 470 s, which is enough to cool the fire site.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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