ECOLOGY

Одним з найбільш безпечних способів гасіння пожеж в резервуарах з нафтою і нафтопродуктами є "підшарове" гасіння. Для цього способу використовують пінний концентрат з фторованими стабілізаторами, водний розчин якого здатен самовільно розтікатись і покривати поверхню нафти і нафтопродуктів тонкою плівкою. У роботі представлено математичну модель руху затопленого невільного пінного струменя в середовищі моторного палива, яка адекватно описує реальні фізичні процеси, що відбуваються при "підшаровому" гасінні пожеж у вертикальних сталевих резервуарах. Визначено параметри руху затоплених струменів піни низької кратності в резервуарі з моторним паливом, які будуть оптимальними для транспортування піни через товщу палива на його поверхню. Визначено, що рух затопленого пінного струменя характеризується значним згасанням (від 36 до 1,5 м/с) початкової швидкості із подальшим її зростанням завдяки дії сили Архімеда. Високі значення початкової швидкості струменя призводять до руйнування піни і відповідно гіршого гасіння пожежі. Зменшення початкової швидкості пінного струменя при заданій інтенсивності подачі слід здійснювати шляхом збільшення відповідної кількості пінних струменів із початковою швидкістю в діапазоні від 2 до 3 м/с. Пінні струмені слід розміщувати по колу радіуса, при якому зберігався б їх взаємний вплив, а швидкість збірного пінного струменя не перевищувала б рекомендованих для конкретного піноутворювача максимальних значень (3–5 м/с). Це призводить до покращення стійкості руху збірного струменя, зменшення руйнування піни в процесі її переміщення та недопущення виносу палива на поверхню горіння. Зроблені від реалізації математичної моделі рішення повністю узгодились з результатами, отриманими під час експериментальних досліджень з гасіння макетної пожежі класу В на спроектованій установці, яка є зменшеним варіантом резервуара "РВС-5000"

Ключові слова: нафтопродукти, пожежі в резервуарах, "підшарове" гасіння, піноутворювач

UDC 614.844.5

DOI: 10.15587/1729-4061.2020.206032

INFLUENCE OF FLOODED FOAM JETS' MOTION PARAMETERS ON SUBSURFACE EXTINGUISHING OF FIRES IN TANKS WITH PETROLEUM PRODUCTS

T. Voitovych
Adjunct
Department of Emergencies Recovery*
E-mail: voitovych.tm@gmail.com
V. Kovalyshyn
Doctor of Technical Sciences, Professor, Head of Department
Department of Emergencies Recovery*
Y. Novitskyi
PhD, Associate Professor
Department of Technical Mechanics and Dynamics of Machines
Lviv Polytechnic National University
S. Bandery str.,12, Lviv, Ukraine, 79013
D. Voytovych
PhD, Associate Professor
Department of Fire Tactics and Emergency Rescue Operations*
P. Pastukhov
PhD, Researcher
Laboratory of Fire Safety Research*
V. Firman
PhD, Associate Professor
Department of Life Safety
Ivan Franko National University of Lviv
Universytetska str., 1, Lviv, Ukraine, 79000
*Lviv State University of Life Safety
Kleparivska str., 35, Lviv, Ukraine, 79007

Received date 22.04.2020
Accepted date 17.06.2020
Published date 30.06.2020

1. Introduction

Extinguishing fires at storage facilities for petroleum and petroleum products is an extremely complex process that requires significant efforts and resources.

It is known that a number of water properties complicate or prevent using it to extinguish certain combustible liquids and solid combustible materials. In particular, water supplied in the form of compact jets cannot extinguish water-insoluble combustible liquids the density of which is less than the density of water (these liquids float to the water surface and continue to burn) [1]. Therefore, other fire extinguishing substances are used to extinguish them; in particular, foam concentrates are applied to produce aqueous film-forming foam (AFFF) from aqueous solutions with the help of special equipment [2].

An important indicator characteristic of fire-fighting foam is the combination of a specific mode of foam concentration with the possibility to change the foam composition. This makes it possible to regulate the physicochemical properties of the foam both by changing the mode of foam formation and by varying the composition of the foam concentrate [3].

Foam concentrates for fire extinguishing, depending on their properties and conditions of application, are divided into two classes: for general and special purposes. The components of foam concentrates for special purpose are designed to give them the desired and necessary properties. This may be a decrease in the rate of the foam destruction under the effect of thermal radiation, increased frost resistance, the possibility of using sea water, the ability to form a film on the surface of flammable liquids, etc. [4].

In the 1960s, fluorine-containing surfactants such as AFFF and FFFP were synthesized; their use in foaming compositions dramatically increased their fire-extinguishing efficiency due to the formation of water films on the surface of petroleum products [3]. Moreover, foams based on such foam concentrates are inert to the influence of hydrocarbons in the process of their rise to the surface of the petroleum product (with subsurface extinguishing).

The aqueous film-forming foam (AFFF) can spread rapidly on the surface of flammable liquids and form a layer of foam that acts as a physical barrier against heat and mass transfer, exhibiting an excellent cooling and insulating effect when burning hydrocarbons [5].

AFFF easily adheres to the surface of the fuel, thus forming a dense layer of foam due to the high viscosity (Fig. 1). This forms an aqueous film between the foam and the fuel, which covers the surface of the fuel fluid together with a dense layer of foam. Meanwhile, the evaporation of water reduces the oxygen concentration and combustion intensity, having a suffocating effect on the burning substance [6].

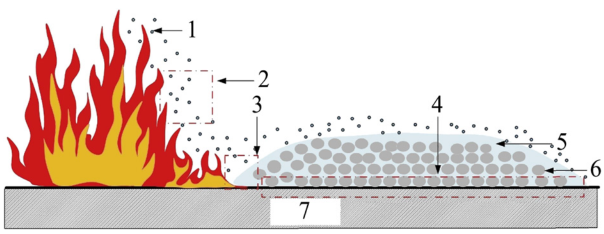


Fig. 1. A schematic diagram of the fire extinguishing mechanism by AFFF during the combustion of diesel fuel: 1 — water vapour; 2 — a rarefaction effect; 3 — cooling; 4 — an insulating effect; 5 — an aqueous film; 6 — a foam layer; 7 — diesel fuel

The use of film-forming foams to extinguish fires in tanks where petroleum and petroleum products are stored makes it possible to eliminate combustion even in cases when the tank structures are partially destroyed and closed areas (pockets) are formed. This is due to the ability of the film-forming foam to spread over the surface of the liquid stored in the tank and to flow around the structures partially immersed in it. AFFF concentrates can be used to extinguish water-insoluble combustible liquids by applying low-density foam both to the surface and under the layer of the liquid stored in a tank (subsurface extinguishing) [7, 8]. In the latter case, to obtain low-density foam, it is necessary to use high-pressure foam generators [9].

Study [10] presents the results of a literature review aimed at collecting information on tank fires, in particular on extinguishing them. As a result of the analysis, it was found that until 2003, the United States of America had most often applied the subsurface extinguishing mode.

The subsurface mode of injecting film-forming foam concentrates to extinguish fires of petroleum and petroleum products in vertical steel tanks is the safest for personnel who are not in close proximity to the fire. Besides, this method does not depend on weather conditions and is characterised by lower consumption of the extinguishing agent because all the foam is fed directly into the tank.

There are many options how to locate devices for injecting foam. It would be important to develop the most effective, which would preserve the mutual influence of the jets with the least destruction of the foam.

2. Literature review and problem statement

The issue of extinguishing fires of petroleum and petroleum products has been studied in many works. In [11], it is indicated that the current fire extinguishing systems for petroleum storage facilities cannot meet the needs of extinguishing fires in large tanks with a floating roof. The results show that the efficiency of the existing fire extinguishing systems should be increased at least 6–10 times. Study [12] describes a solution of these problems with the help of compressed air foam systems (CAFSs) to extinguish fire by various fire extinguishing agents. The problem is the lack of scientifically proven data on the optimal ratios of components in the gas-filled foam for extinguishing fires of different classes (or these data are a trade secret of manufacturers) [13]. An option to overcome these difficulties may be to study subsurface extinguishing with AFFF concentrates as an effective means and, at the same time, the safest way to extinguish fire in tanks with petroleum and petroleum products.

The mechanism to extinguish fire of diesel fuel with the help of AFFF was carefully analysed in [6], but the issues related to the supply of this type of foam concentrates under the burning petroleum product layer remain unresolved. In research works [7, 8, 14–18], mechanisms and models of extinguishing tank fires of petroleum and petroleum products by the subsurface mode were developed.

While analysing the regulations in the field of fire safety of tank farms [19, 20], it should be noted that the methods are the same when it concerns determining the technical parameters of a fire extinguishing system for tanks with petroleum and petroleum products and the intensity of working foam solutions for both subsurface and surface extinguishing of a burning tank. It is advisable to consider and investigate each method of extinguishing fires in tanks with petroleum and petroleum products separately.

That is why study [21] described the method of calculating the main parameters of the subsurface injection system of extinguishing fire in tanks with petroleum and petroleum products with low-density foam. The technical parameters of the subsurface extinguishing system for different types of tanks, types of fuel, and foam concentrations were also calculated there.

However, the question of choosing the optimal feed intensity of the foam concentrate during the subsurface extinguishing of a fire in petroleum tanks remains unresolved. Document [22] indicates these normative values, and hydrocarbons have the same values of minimum intensity ($0.068\ l/s\cdot m^{-2}$). This problem is partially covered in [23], where experimental tests were performed to determine the intensity of injecting low-density aqueous film-forming foam in vertical steel tanks for extinguishing the combustion of gasoline (0.1 l/s·m^{-2}) and diesel fuel (0.08 l/s·m^{-2}).

In [24], the relationship is studied between the expansion ratio and the pressure at foam discharge outlets during subsurface foam injection. A large change in the flow rate causes a change in the concentration of the foam solution, which affects the quality of the foam and the effectiveness of fire extinguishing. Especially when the flow rate increases too much, a backflow may occur. This study also determined the flow rate of the foam solution of the foam generator, which depends on the pressure of the inlet. However, the question of the passage of foam through the layer of petroleum product, which also destroys the foam and leads to worse extinguishing, remains underresearched.

When analysing the results of experiments in [23], the following tendency is observed: an increase in the pressure in the system – i. e., an increase in the feed rate of the foam concentrate leads to faster extinguishing, but to a certain extent. With a further increase in pressure, no significant reduction in the extinguishing time is observed, and at high pressures, extinguishing of the flame does not occur at all.

Study [15], which is based on the analysis of full-scale fire experiments and comparison of the results obtained in them with model experiments, determined the optimal parameters of the system of subsurface extinguishing of fire in tanks with petroleum and petroleum products. It also considered the factors that influence the fire-fighting efficiency of such a system (reduction of the foam concentration in the process of preparation and storage of the working solution, maintenance of the optimal length of the pipelines, etc.).

The analysed literature sources have not investigated the turbulence of the foam jet that leads to destruction of the foam during the subsurface injection of the foam concentrate into the tank. The mutual influence of the jets during their movement through the petroleum layer has not been studied either, and the optimal velocity of foam movement has not been specified.

This suggests that it is advisable to conduct a study of the physical process of raising the foam jets of the AFFF concentrate through the petroleum layer. It is necessary to determine the optimal feed rates of the film-forming foam in the tank as well as the parameters of the system of subsurface extinguishing (the number of inputs of the foam concentrate and their location).

3. The aim and objectives of the study

The aim of the study is to increase the efficiency of extinguishing fires in vertical steel tanks with petroleum and petroleum products by reducing the foam destruction, which will be ensured by studying the parameters of the movement of foam jets and their mutual effect.

To achieve this aim, it is necessary to solve the following tasks:

– to investigate the parameters of motion and location of flooded foam jets by their mathematical simulation in the medium of petroleum products;

– to verify experimentally the hypotheses of the motion parameters of flooded foam jets formed by simulating the physical model of the tank with motor fuel.

4. Materials and methods of research

4. 1. Software

For theoretical research on the parameters of the motion of flooded foam jets using mathematical simulation of the motion of flooded foam jets in the motor fuel medium, we used the software product Solidworks Flow Simulation 2017 [25–27]. It is designed to solve applications in the field of aerohydrodynamics and heat transfer by modelling relevant physical processes. Solidworks Flow Simulation is a fully integrated application of the Solidworks CAD system. It can be effectively used to calculate the force interaction between solids and the flow of liquid (or gas) in the case of their mutual motion and the influence of various physical factors on the motion of the fluid.

The mathematical model was built by geometrically designing a real unit in the environment of Solidworks [28] with the subsequent automatic exchange of necessary information between Solidworks Flow Simulation and Solidworks. The motion of the fluid and the heat exchange between bodies were simulated using the Navier-Stokes equations, which describe the laws of conservation of mass, momentum, and energy in a non-stationary form.

For Newtonian fluids, the dependence of the stress tensor on the action of viscosity forces and the effect of gravity on the medium were taken into account.

Multicomponent currents were of considerable interest for our case. A change in the concentration of the components of the mixture in space due to diffusion was modelled by the corresponding equations [28].

To solve the problem, a continuous non-stationary mathematical model was sampled both in space and time. To do this, the entire calculation area was covered by a grid the faces of the cells in which were parallel to the coordinate planes of the Cartesian coordinate system. The grid was generated automatically with the possibility to influence the size of the cells to improve the accuracy of calculating. Calculations were performed using the finite volume method [27].

4. 2. Problem formulation

It was necessary to determine the parameters of the movement of flooded jets of low-density foam and the features of their location in a tank with motor fuel (gasoline), which would be optimal for transporting foam through the fuel layer to its surface.

In Solidworks [27], we designed the tank model with the following (typical) internal dimensions: 15,000 mm high, 21,000 mm in diameter, and with steel walls 25 mm thick (Fig. 2). At the bottom of the tank (concentrically), we placed the source of the foam jet(s), and the end of the foam line of the specific diameter was directed vertically upwards. The tank was open.

4. 3. Initial and boundary conditions

The initial temperatures of the walls and the medium were equal to 293.2 K (default). The atmospheric pressure was 101,325 Pa (default). The required source capacity was preset as Q=0.2 m^3/s. The diameter of the pipeline was 100 mm (SVP-12). The specific foam density of a low expansion ratio was ρ=10 kg/m^3; the dynamic viscosity of the foam was η=0.0135 PA·s; the specific density of gasoline was ρ=750 kg/m^3; and the dynamic viscosity of gasoline was η=0.00053 Pa·s.

In the general settings, the process was non-stationary and gravity was "turned on".

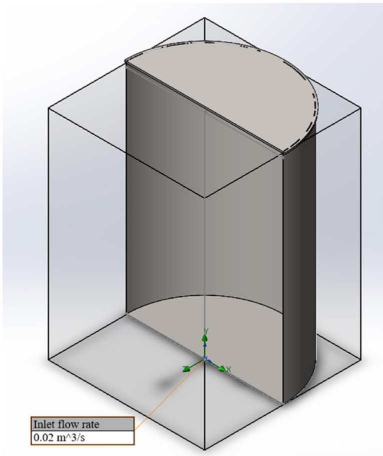
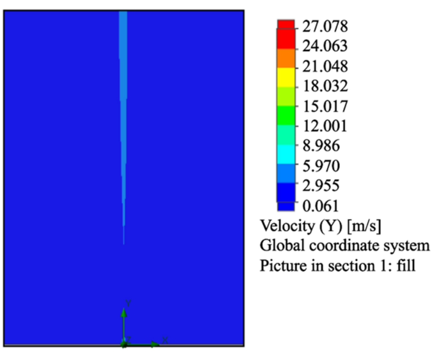


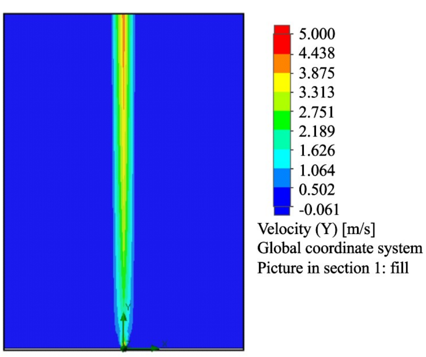
Fig. 2. A tank model with a vertical foam injection

5. Mathematical simulation of the movement of flooded foam jets in the medium of motor fuel

Fig. 2 shows the results of the research – chromatograms of the vertical velocity of a flooded foam jet. The process was stabilised for 180 s, which meant that further on everything would be unchanged.



a



b

Fig. 3. A chromatogram of the vertical medium velocity: *a* – unfiltered; *b* – filter 5 m/s

The chromatogram in Fig. 3, *a* is unfiltered and thus inconvenient to perceive, but it shows that the maximum value of the vertical velocity of the jet is 27.2 m/s. We used a velocity filter with a value of 5 m/s. This means that for velocities greater than 5 m/s the warmest colour of the chromatogram was used, and all smaller values received the appropriate shade, which is shown in Fig. 3, *b*.

As can be seen from Fig. 3, *b*, the velocity of the jet decreased sharply, and then, under the Archimedes action, increased. This fact is confirmed by known analytical and experimental studying of such cases [29].

For the possibility of the best analysis, we constructed a graphic dependence of the vertical velocity of a jet on a coordinate of its length (tank height coordinate). To do this, a vertical line was drawn from the centre of the jet to the surface of the tank on the plane of the chromatogram. The Solidworks Flow Simulation package built a graphical dependence of the specified parameter – in this case, the vertical velocity on this line (Fig. 4).

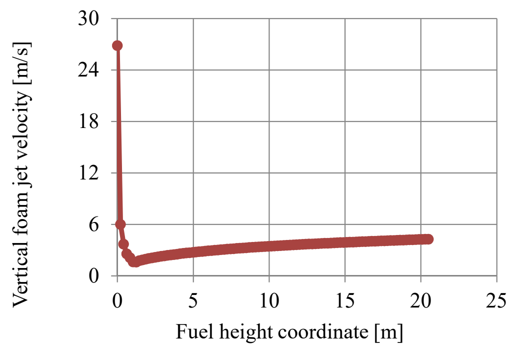


Fig. 4. Dependence of the vertical velocity of the foam jet on the tank height coordinate

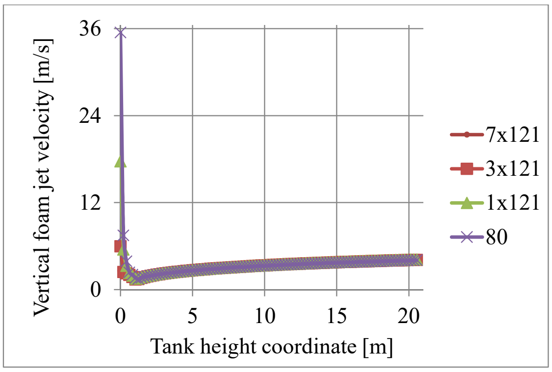
As can be seen from Fig. 4, the jet velocity faded from 27.2 m/s to 1.6 m/s at a length of 1.24 m, after which it began to increase to 4.27 m/s near the fuel surface.

The fact of the lack of velocity stabilization deserves special attention. As is known from the analysis of Stokes' formula [30], the motion of a body in a viscous fluid is stabilised due to the proportionality of the resistance force of the square (or other degree of velocity). The jet, stabilised with respect to the forces of resistance, is a body of infinite length that is not washed at the ends, so it is impossible to determine its velocity using Stokes' formula, as evidenced by the known provisions of the theory of flooded jets [29]. This fact indicates a good adequacy of the research results of the model.

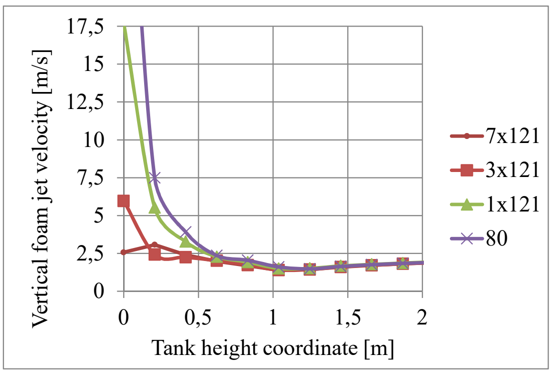
From the analysis of Fig. 4 it can be concluded that the initial velocity of the jet does not significantly affect its further movement. The motion parameters of such a jet are determined only by the difference between the densities of the media and their viscosity.

To confirm this hypothesis, we studied the motion of a jet with a capacity of 0.2 m^3/s at different initial velocities. To do this, we took different diameters of pipelines. Namely: one pipeline with a diameter of 80 mm, one pipeline with a diameter of 121 mm, three pipelines with a diameter of 121 mm, and seven pipelines with a diameter of 121 mm. The graphical dependence of the vertical velocity of such jets on their lengths (fuel height coordinates) is presented in Fig. 5.

As can be seen from Fig. 5, *a*, jets with different initial velocities are attenuated to a velocity with approximately the same value. In order to conduct a better analysis, Fig. 5, *b* presents the same dependence but in the extended velocity range, namely from 0 to 10 m/s.



a



b

Fig. 5. Dependence of the vertical velocity of the foam jet on the tank height coordinate and its initial velocity: *a* – in the normal range; *b* – in the range from 0 to 10 m/s

As can be seen from both figures, the velocities of the jets with different initial velocities at a length of 1,250 mm decreased to the same value of 1.5 m/s and then increased together to 4 m/s.

Thus, the hypothesis that the parameters of the motion of dependent flooded jets are affected only by the difference between the density of the foam and the medium in which it is flooded is correct. Of course, the influence of viscosity forces traditionally remains in force.

However, abrupt braking of the jet can lead to large values of turbulence energy, which in turn can cause destruction of the foam of the flooded foam jet. Therefore, subsurface extinguishing is recommended to be carried out by supplying foam in several foam jets, which, at a low initial velocity, provide the necessary intensity for effective fire extinguishing.

The location of the foam jets is recommended to be performed concentrically to the tank around its average radius [31].

Tests in this work indicate that the radius of the circle of the location of the jets should be made much smaller. This leads to the interaction of the jets and, as a consequence, an increase in their velocities due to a decrease in the area of interaction between the jets and the fuel (reduction of the impact of the viscosity forces). This factor reduces the destruction of the foam during its injection under the combustion layer.

We studied the model of a tank with ten vertical jets the foam lines of which were arranged in a circle with a diameter of 450 mm. All other parameters were the same as in the previous case.

The chromatogram of the vertical velocity of the foam jets is presented in Fig. 6.

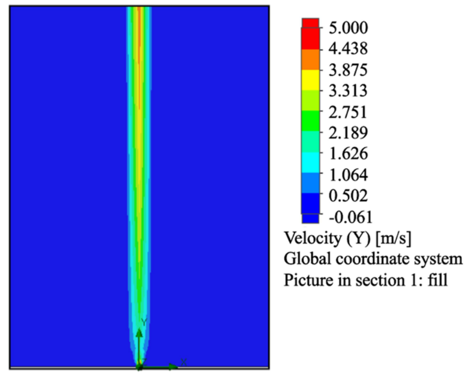


Fig. 6. A chromatogram of the vertical foam jet velocity

As can be seen from the chromatogram (Fig. 6), all the individual jets at the exit of the foam pipework merge into one combined stable jet with an obvious velocity increase in its centre.

Fig. 7 presents a graphical dependence of the vertical velocity of the combined foam jet that consists of ten vertical jets the foam lines of which are arranged in a circle with a diameter of 450 mm (no central jet) with a total capacity of 0.2 m^3/s.

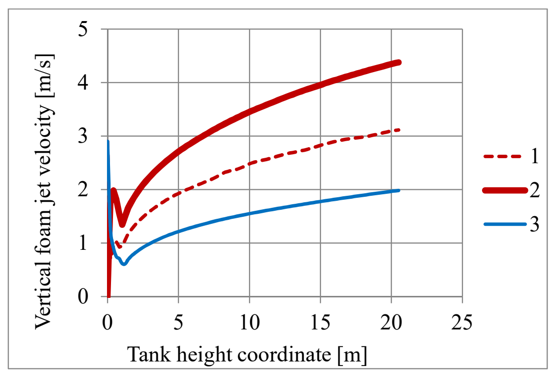


Fig. 7. Dependence of the vertical velocity of the combined foam jet on the fuel height coordinate (line 1 – in the centre of one of the ten foam jets; line 2 – in the centre of a jet comprised of the ten foam jets; and line 3 – in the centre of a separate single foam jet with similar output parameters)

As can be seen from Fig. 7, the braking intensity of the separate single foam jet 3 is the highest. The intensity of inhibition of the periphery of the foam jet combined of ten separate jets is slightly lower, so their velocity is higher. The value of the vertical velocity in the centre of the combined jet is the highest – i. e., the forces of viscous friction of the combined jet against the medium of the tank are the smallest.

On the other hand, there is a limit on the maximum value of the vertical velocity of the foam jet, an excess of which leads to the movement of the fuel to the combustion mirror. The value of this velocity is in the range of 3–5 m/s, depending on the brand of foam concentrate.

Therefore, the loss of foam during its injection under the layer depends on the number of jets and the value of the radius of the circle on which they are located. The number of jets and the diameter of their nozzles should be chosen so that the value of the initial velocity of one jet could not exceed 2–3 m/s, and the radius of the jet location must be such that the maximum vertical velocity of the combined foam jet could be in the range of 3–5 m/s, depending on the foam concentrate brands.

5. An experimental study of the parameters of the movement of flooded foam jets in the physical model of a tank with motor fuel

5. 1. Methods of testing to study the movement of foam through a layer of substance to extinguish a simulated fire in the physical model of a tank with motor fuel

Experimental tests of the parameters of the motion of a flooded foam jet in the medium of motor fuel were performed in a reduced physical model of a tank used for fuel storage (Fig. 8).

Let us establish the following similarity criteria and physical limitations:

– the turbulent nature of the movement of foam in the foam line and the foam jet in the medium of motor fuel;

– the value of the initial velocity of the foam jets should be in the range from 2 to 20 m/s;

– the boundaries of the foam jet area should not interact with the walls of the tank;

– the vertical velocity of the foam jet must be extinguished to the minimum value before the jet reaches the surface layer of fuel;

– the intensity of the foam concentrate must be effective to extinguish fire on the surface of the motor fuel;

– the value of the multiplicity of the foam should be in the range of 7–10.

The block diagram of the experimental setup is presented in Fig. 8.

The experimental unit comprised:

– manometer OBMV1-100 with a range of pressure measurements from –1 to 1.5 kgf/cm^2, accuracy class 2.5 [32];

– plastic tubes with an inner diameter of 10 mm and the following length values: $L1$=470 mm; $L2$=1,000 mm; $L3$=950 mm; $L4$=770 mm; $L5$=950 mm;

– fire extinguisher with a capacity of 2 litres;

– a metal tank with an inner diameter of 398 mm and a height of 440 mm.

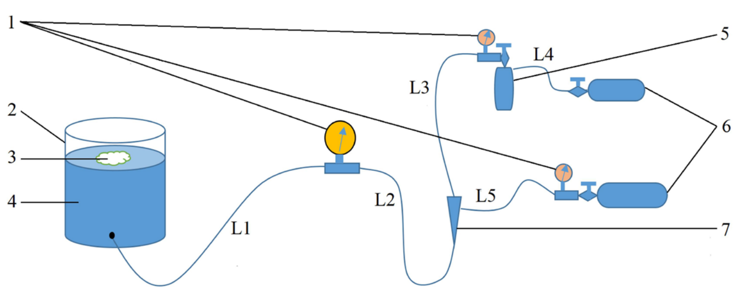


Fig. 8. A block diagram of the experimental unit: 1 — manometers; 2 — a metal tank; 3 — foam; 4 — motor fuel; 5 — a tank with a foam concentrate solution (fire extinguisher); 6 — a cylinder with compressed air or inert gas; 7 — an injector (glass)

5. 2. An experimental study of the motion of foam in the medium of motor fuel in the physical model of the tank

The experiments were performed outdoors. First, a 6 % solution of Bars AFFF concentrate in the amount of 2 litres (V_{FC}) was prepared, and the fire extinguisher 5 was filled with it.

The motor fuel 4 was poured into the metal tank 2. The height of the layer of the motor fuel was 180 mm and 360 mm, with the ambient temperature of +14 °C.

The required pressure values were set on the manometers 1.

The entire foam concentrate was fed to the bottom of the metal tank 2.

The thickness of the foam on the surface of the motor fuel was measured with a metal ruler after the completion of its supply at four points and the average value. The volume of the foam formed was then calculated as V_{foam}.

The foam expansion ratio was determined by the formula

$$K = \frac{V_{\text{foam}}}{V_{\text{FC}}}. \quad (1)$$

The test was repeated at different pressures.

During the works, videorecording was performed and the values of the following parameters were measured: the pressure at the outlet of the fire extinguisher, the pressure at the inlet to the tank and the supply time of the foam concentrate with the fixed amount of 2 litres.

The processed data of the experimental tests – the graphic dependence of the foam height throughout the fuel surface on the time of its leakage – are presented in Fig. 9.

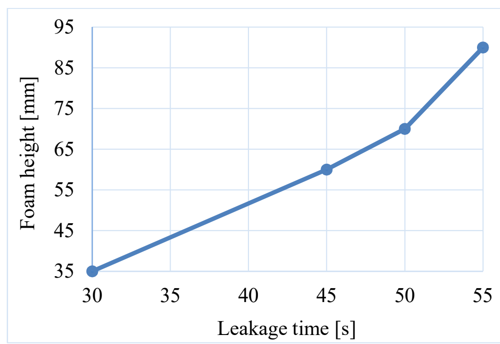


Fig. 9. Dependence of the foam height throughout the surface of the fuel on the leakage time

As can be seen from the graph in Fig. 9, an increase in the foam leakage time (decreasing its velocity) leads to an increase in the thickness of the foam on the fuel mirror.

Knowing the volume of the foam concentrate and the foam expansion ratio, we determined the maximum possible height of the foam on the surface of the fuel. The maximum height was 137 mm. Then, having experimental values of thickness, we determined the losses of the foam in the course of its supply (Fig. 10).

As can be seen from Fig. 10, the loss of foam is inversely proportional to the time of its leakage. That is, increasing the flow rate of the foam jet into the medium of the motor fuel leads to more intense destruction of the foam and hence to greater losses.

For a more complete study of this problem, as well as to confirm the basic assumptions in previous theoretical studies and to assess the adequacy of the results obtained there, we conducted similar theoretical research. We simulated the experimental setup in Solidworks Flow Simulation with similar parameters of foam motion that correspond to the minimum and maximum values of the experimental tests.

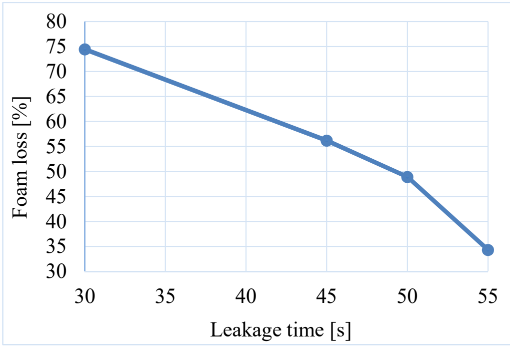


Fig. 10. Dependence of the foam loss throughout the fuel surface on the leakage time

The minimum volume flow of foam is 0.0003636 m^3/s= =21.2 l/min, which corresponds to the fourth point on the graph (time of 55 s, Fig. 10). The foam expansion ratio K=8.5 was established experimentally.

The results of the simulation (the obtained chromatograms and graphical dependences) of the movement of foam on the foam line and the foam jet in the medium of diesel fuel at an ambient temperature of 14 °C are presented in Fig. 10–14.

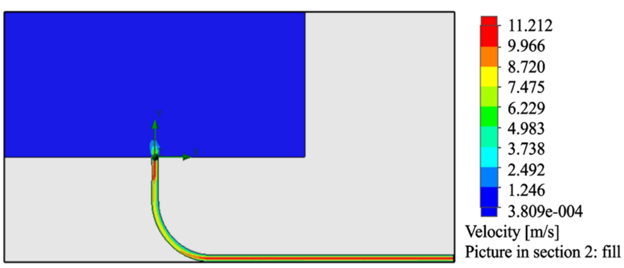


Fig. 11. A chromatogram of the foam and fuel velocity

As can be seen from Fig. 11, the maximum value of the velocity of the foam appears in the foam line (11 m/s). The movement of the foam is turbulent. The foam jet immersed in diesel fuel loses its velocity.

To better identify the parameters of the flooded foam jet, let us filter the chromatogram to more favourable values of its velocity, for example, set the upper value of the velocity at 1 m/s. This means that all velocities greater than 1 m/s will be displayed in one red colour and smaller values will have a colour gradation.

The results of filtering the chromatogram of the velocity of the foam are presented in Fig. 12.

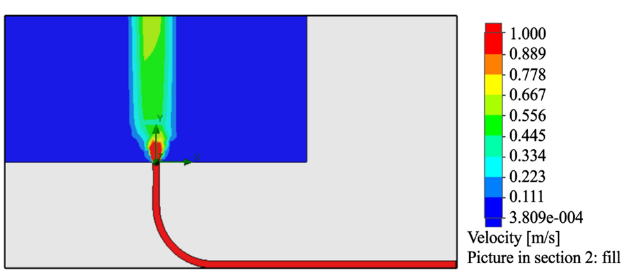


Fig. 12. A velocity chromatogram (V<1 m/s)

As can be seen from Fig. 12, the velocity of the foam jet immersed in diesel fuel faded sharply, which is confirmed by the theoretical and experimental research.

The middle of the expanded extinguishing foam jet is slightly shifted to the left of the centre of the foam line. Another visually noticeable consequence of the Archimedes action is an increase in the vertical velocity of the extinguished foam jet.

The displacement (to the left) of the axis of the foam jet relative to the axis of the foam line is explained by the presence of some residual horizontal foam velocity acquired during its movement on the horizontal section of the foam line.

Quantitative analysis of the parameters of the motion of the flooded foam jet can be performed using the possibility in the environment of Solidworks Flow Simulation to build a graphical dependence on the directly drawn line(s) on top of the studied chromatogram.

Let us draw a vertical line from the centre of the foam nozzle (Fig. 12) and construct a graphical dependence of the vertical velocity of the foam jet on the length of this line – i. e., the coordinate of the fuel height in the tank (Fig. 13).

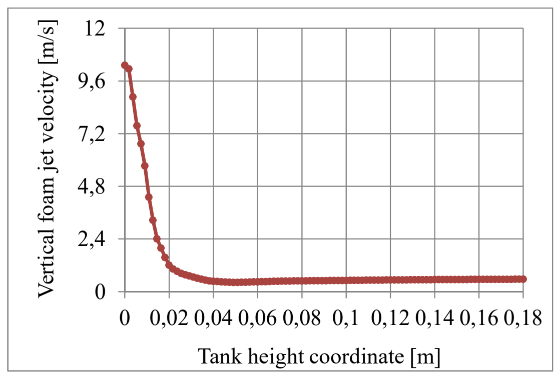


Fig. 13. Graphic dependence of the vertical foam jet velocity on the fuel height coordinate

As can be seen from Fig. 13, the velocity of the foam jet fades sharply (from 10.32 to 0.42 m/s) and then begins to increase slowly (up to 0.57 m/s), but this increase in velocity is limited by the height of the fuel in the tank (180 mm).

Therefore, one of the necessary conditions of the physical model is quite true, namely: the vertical velocity of the foam jet must be extinguished to the minimum value before the jet reaches the surface layer of the fuel.

To determine the motion of the whole medium, let us draw three horizontal lines on the chromatogram (Fig. 14) at different heights of the tank. The first line will be drawn at the bottom of the tank (5 mm above the bottom, to move away from the wall layer). The second line will be right in the middle of its height, and the third will be at the top, on the fuel mirror.

Thus, the graphical dependence of the vertical velocity of the medium on the width of the tank at different levels of fuel height is constructed in the way shown in Fig. 14.

As can be seen from Fig. 14, the vertical velocity of the injected foam at the bottom of the tank acquires maximum values; the jet at this point is narrow. With the height of the tank, the jet expands and its velocity decreases. The fuel adjacent to the jet area descends at a velocity of 0.009–0.014 m/s. Of course, there is a horizontal velocity of the fuel, which indicates its movement from the centre to the periphery, but for the lack of space and the unimportance of the factor, it is not considered in the study.

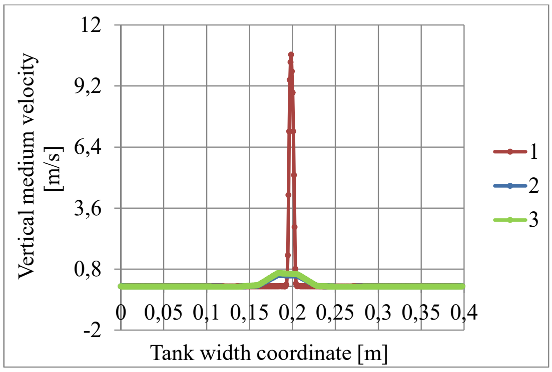


Fig. 14. Graphic dependence of the vertical velocity of the tank on its width at different levels of fuel height: 1 — the bottom of the tank; 2 — the middle of the fuel level; 3 — the top of the fuel

The graph confirms the veracity of another condition of physical modelling, namely: the boundaries of the foam jet should not interact with the walls of the tank.

Let us now consider the nature of the motion of the flooded foam jet in the diesel fuel medium.

The graphical dependence of the turbulence intensity on the fuel height coordinate in the tank is presented in Fig. 15.

For a better analysis of the graphical dependence, let us draw two vertical lines: one still from the centre of the jet and the other to the left, along with the displacement of the jet by 60 mm.

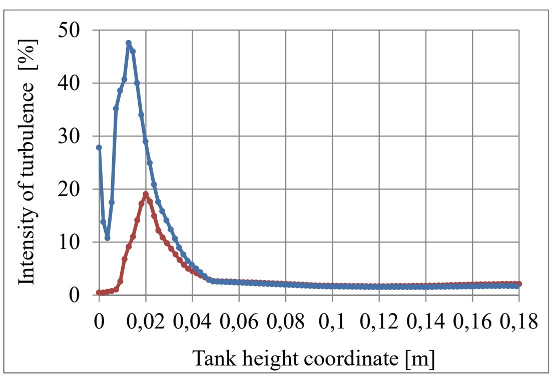


Fig. 15. Graphic dependence of turbulence intensity on the fuel height coordinate: the red line — in the centre of the jet; the blue line — 6 cm shifted to the left to the maximum value

Fig. 15 shows that the value of the intensity of turbulence in the immediate vicinity of the foam jet is 48 %.

The graph confirms the truth of another condition of physical modelling, namely: the nature of the movement of foam in the foam line and the foam jet in the medium of motor fuel is turbulent.

However, as noted above, of considerable practical interest for this case is the energy of turbulence as a force factor in the destruction of the foam jet.

To obtain a graphical dependence of the turbulence energy on the fuel height coordinate, let us use the same two straight lines (as in the previous case); we will only superimpose them on the corresponding chromatogram.

The graphical dependence of turbulence energy on the fuel height coordinate is presented in Fig. 16.

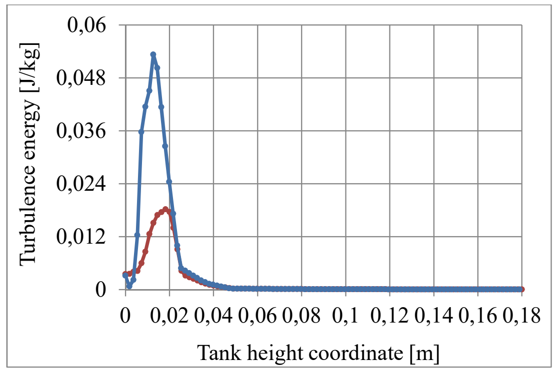


Fig. 16. Graphic dependence of turbulence energy on the fuel height coordinate

Fig. 16 shows that the maximum value of the turbulence energy is 0.053 J/kg.

Similar theoretical research of the model was conducted in the case of maximum volume flow of foam of 0.000667 m^3/s= =40 l/min, which corresponds to the first point on the graph (time of 30 s, Fig. 10). The foam expansion ratio K=8.5 was established experimentally.

The simulation results are processed in the same way as in the case of minimal spending, and for ease of analysis, they are superimposed on the previous ones.

Fig. 17 shows a graphical dependence of the vertical velocity of the foam jets with different volumetric flow rates on the fuel height coordinate.

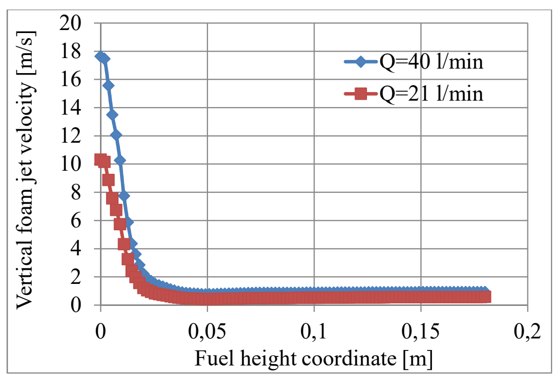


Fig. 17. Dependence of the vertical velocity of foam jets of different productivity on the fuel height coordinate

As can be seen from Fig. 17, the maximum value of the vertical velocity of the foam jet with twice the productivity is almost twice as high (17.64 m/s vs. 10.32 m/s). This discrepancy can be explained by the nonlinear dependence of the resistance of the foam line on the velocity of the foam in the case of turbulent motion.

Fig. 18 presents a graphical dependence of the intensity of turbulence of foam jets with different volumetric flow rates on the coordinate of the fuel height in the tank.

Analysis of the graphical dependence (Fig. 18) shows that the intensity of turbulence of both foam jets is proportional to their velocities.

The graphical dependence of the turbulence energy of foam jets of different productivity on the coordinate of the height of the fuel in the tank is presented in Fig. 19.

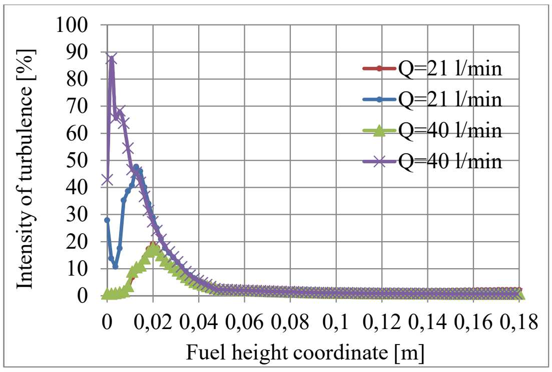


Fig. 18. Graphic dependence of the intensity of turbulence of foam jets of different productivity on the fuel height coordinate

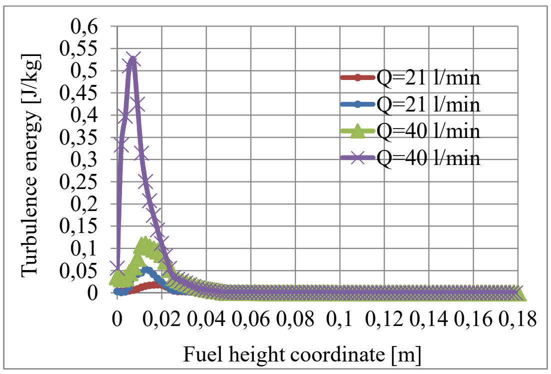


Fig. 19. Graphic dependence of turbulence energy of foam jets of different productivity on the tank height coordinate

As can be seen from Fig. 19, the maximum values of the turbulence energy of the flooded foam jets are not proportional to the maximum value of their velocities. The turbulence energy of a foam jet with twice the flow rate is almost ten times greater than the energy of a jet whose volume flow rate is twice as low.

From this we can conclude that the value of the turbulence energy of the flooded foam jet is the main factor in the destruction of the foam.

Given the fact that the ratio of the maximum values of the turbulence energy of the foam jets is close to 10 (9.88) and the ratio of the corresponding values of the thickness of the foam on the fuel surface in the tank is close to 3 (2.57), we can conclude that the value is nonlinear when it concerns the turbulence energy of the foam jet and the destruction of the foam in it.

Therefore, the effective foam intensity for fire extinguishing should be provided by the required number of foam jets of appropriate diameters at the lowest possible initial velocity.

5. 3. Experimental tests on extinguishing simulated fire of a B class in the physical model of a diesel fuel tank

Based on the hypotheses obtained from the mathematical model and the experiments described above, we conducted a study to determine the rate of extinguishing a fire in diesel fuel with the help of Bars AFFF concentrate by the subsurface mode in the designed unit (Fig. 8).

Experimental tests to extinguish the simulated fire were carried out in the same way as in the first stage (item 5. 1), but before the foam was supplied, the diesel fuel in the tank 2 was ignited by means of a lighted torch by hand. The time from the foam injection to the complete extinguishing of the fire was measured. We calculated the amount of the solution used, the foam expansion ratio, and the intensity of the foam concentrate.

As a result of the experimental tests, it was determined that when feeding the solution from several foam jets located in the middle of the bottom of the tank, extinguishing occurred faster than when feeding foam from the side of the tank at similar pressures in the line. Fire extinguishing is more effective when feeding foam from several foam jets, and the boundaries of the foam jet should not interact with the walls of the tank. Thus, we increased the intensity of extinguishing without increasing the pressure in the system and, accordingly, without destroying the foam. The results of extinguishing diesel fuel with foam jets supplied in the middle of the bottom of the metal tank are given in Table 1.

As can be seen from Table 1, when high pressure values are reached, extinguishing does not occur.

Fig. 20 shows a graphical dependence of the extinguishing time on the pressure in the pipework.

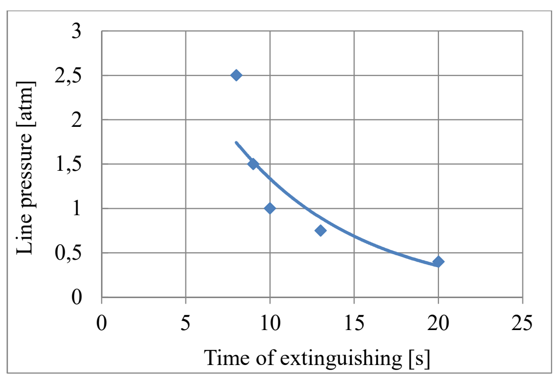


Fig. 20. Graphic dependence of the extinguishing time on the pressure in the line

Table 1

The results of extinguishing diesel fuel with foam jets fed in the middle of the bottom of a metal tank

No. of test	Foam concentrate	V_{FC}, 10^{-3}, m^3	H_{df}, m	T_{ext}, s	H_{foam}, m	V_{foam}, 10^{-3}, m^3	Foam expansion ratio	P_{fire}, atm	P_{line}, atm	Note
1	Bars AFFF	2	0.26	20	0.065	8.06	4.03	2.5	0.4	extinguished
2	Bars AFFF	2	0.26	13	0.06	7.44	3.72	4	0.75	extinguished
3	Bars AFFF	2	0.26	10	0.05	6.2	3.1	5	1	extinguished
4	Bars AFFF	2	0.26	9	0.045	5.58	2.79	6	1.5	extinguished
5	Bars AFFF	2	0.26	8	0.035	4.34	2.17	7	2.5	not extinguished

As can be seen from Fig. 20, the extinguishing time decreases with increasing pressure, and when the line pressure reached 2.5 atm, there was no extinguishing. The graph also shows that a strong increase in the line pressure from 1 to 1.5 atm slightly accelerated the extinguishing (from 10 to 9 seconds). The reason is the destruction of the foam due to the significant turbulence energy, which is a force factor in the destruction of the foam jet.

The graphical dependence of the height of the foam layer on the pressure in the line is presented in Fig. 21.

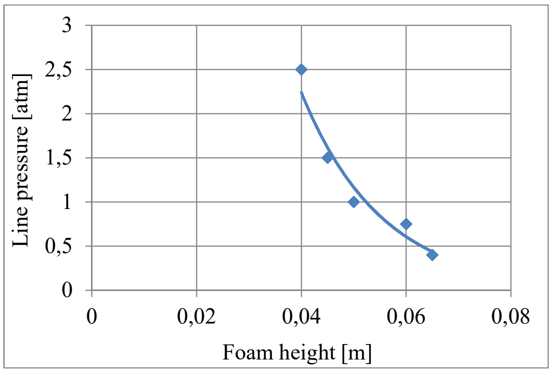


Fig. 21. Graphic dependence of the height of the foam layer on the pressure in the line

Analysis of the graphical dependence (Fig. 21) shows that with increasing pressure, the height of the foam layer formed on the surface of the combustible substance decreases. This also proves that at high pressure the foam is more destroyed due to the significant turbulence energy of the jets of the foaming solution.

6. Discussion of the results of research on the influence of the parameters of the movement of flooded foam jets on the subsurface fire extinguishing in the medium of petroleum products

The conducted theoretical and experimental research helped determine the optimal parameters of the subsurface mode of film-forming foam concentrate injection for effective fire extinguishing of petroleum and petroleum products in vertical steel tanks.

Analysis of the parameters of the motion of flooded foam jets by mathematical modelling in the environment of Solidworks Flow Simulation showed that the initial velocity of a jet has no significant effect on its subsequent movement (Fig. 3, 4). The motion parameters of such a jet are determined only by the difference between the densities of the media and their viscosity. The movement of the flooded foam jet in the tank with motor fuel is characterised by a significant attenuation (from 36 to 1.5 m/s) of its initial velocity (Fig. 5, *a*). Besides, these figures show that the velocities of jets with different initial velocities at a length of 1,250 mm decrease to the same value of 1.5 m/s and then increase together to 4 m/s due to the Archimedes action.

Abrupt braking of a jet can lead to large values of turbulence energy, which in turn can destroy the foam. Therefore, it is recommended to perform subsurface extinguishing by injecting foam by several foam jets, which at a low initial velocity provide the necessary intensity of effective extinguishing of fire.

As can be seen from the chromatogram (Fig. 6), all the individual jets at the exit of the foam pipework merge into one combined stable jet, with an obvious increase in velocity in its centre.

The tests (Fig. 7) indicate that a small diameter of the foam circumference (450 mm) leads to a mutual influence of the jets and, as a consequence, an increase in their velocities due to a decrease in the interaction of the jets and the fuel. This factor reduces the destruction of the foam during its transportation under the combustion layer. This allows us to conclude that the loss of foam in the process of supplying it under the layer depends on the number of jets and the value of the radius of the circle on which they are located. The number of jets and the diameter of their nozzles should be chosen so that the value of the initial velocity of one jet could not exceed 2–3 m/s and the radius of the jet location must be such that the maximum vertical velocity of the combined foam jet could be in the range of 3–5 m/s, depending on foam concentrate brands.

To study this problem in more detail, as well as to confirm the main assumptions of previous theoretical research and assess the adequacy of the results, the experimental setup (Fig. 8) was simulated in Solidworks Flow Simulation with similar parameters of the foam motion.

The graph in Fig. 15 confirms that the nature of the foam movement in the foam line and the foam jet in the medium of motor fuel is turbulent. The maximum values of the turbulence energy of the flooded foam jets are not proportional to the maximum values of their velocities (Fig. 19). The turbulence energy of a foam jet with twice the flow rate is almost ten times greater than the energy of the jet whose flow rate is twice as low. From this we can conclude that the value of the turbulence energy of a flooded foam jet is the main factor in the foam destruction. An increase in the initial velocity of a foam jet from 10 to 18 m/s leads to 50 % foam loss (Fig. 10).

The main restriction inherent in this method is the limited height of the model tank on which the experimental tests were conducted. Its height was 440 mm, as opposed to 15,000 mm in the real RVS-5000 tank, which was used for mathematical simulation. As a result, it is impossible to clearly verify the hypothesis that the initial velocity of the foam jet (respectively, the pressure) does not significantly affect its further movement (the increase in the vertical velocity of the foam jet occurs under the Archimedes action).

The limited height of the petroleum layer in the model tank prevented us from determining the velocity of the foam jet on the surface of the fuel or the maximum velocity that the foam can reach.

These limitations can be eliminated if in the future experimental research could be based on a real tank with petroleum products (for example, RVS-5000). This will also make it possible to track the effect of cooling the sides of the tank during extinguishing. The difficulty that we will face in this case is the high material costs of conducting the experiments.

The disadvantage of this study is that the cooling of the tank body was not taken into account when placing the foam jets closer to its walls.

Moreover, in the future, it is advisable to conduct theoretical and experimental research for other petroleum products, using different brands of foam concentrates.

7. Conclusion

1. The movement of a flooded foam jet in a tank with motor fuel is characterised by a significant attenuation (from 36 to 1.5 m/s) of its initial velocity. The value to which the velocity of the jet fades does not depend on the value of its initial velocity. High values of the initial jet velocity lead to destruction of the foam. An increase of the initial velocity of the foam jet from 10 to 18 m/s leads to 50 % foam loss.

2. Reduction of the initial velocity of a foam jet at a given feed rate should be carried out by increasing the appropriate number of foam jets with an initial velocity in the range from 2 to 3 m/s. Foam jets should be placed around a radius at which their mutual influence would be preserved, and the velocity of the combined foam jet should not exceed the maximum values recommended for a particular foam concentrate (3–5 m/s). This improves the stability of the combined jet, reduces the destruction of the foam during its movement, and prevents the movement of fuel to the combustion surface.

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UDC 614.841.45
DOI: 10.15587/1729-4061.2020.206373

THERMAL STATE OF STEEL STRUCTURES WITH A COMBINED FIRE PROTECTION SYSTEM UNDER CONDITIONS OF FIRE EXPOSURE

S. Novak
PhD, Senior Researcher*
E-mail: novak.s.fire@gmail.com
V. Drizhd
PhD
Scientific and Manufacturing Enterprise "Spetsmaterialy"
Telmana str., 12, Boryspil, Ukraine, 08304
E-mail: varvara.drizhd@gmail.com
O. Dobrostan
PhD*
E-mail: dob2009@ukr.net
*Scientific Testing Center
Institute of Public Administration and Research in Civil Protection
Rybalska str., 18, Kyiv, Ukraine, 01011

Враховуючи необхідність мінімізації масо-габаритних показників сталевих конструкцій, актуальним є питання про ефективність застосування для них комбінованої системи вогнезахисту. У статті досліджувався тепловий стан сталевих конструкцій з такою системою вогнезахисту в умовах вогневого впливу за стандартним температурним режимом згідно з ДСТУ Б В.1.1-4-98*. У експериментальних зразках використовували сталеві пластини квадратної форми зі стороною 500 мм і товщиною 5 мм та 10 мм. Проведеним дослідженням встановлено особливості залежностей температури сталевих конструкцій з пасивним і реактивним вогнезахисними матеріалами двох торгових марок від тривалості вогневого впливу.

Встановлено, що ці залежності для сталевих конструкцій з комбінованою, пасивною і реактивною системами вогнезахисту мають монотонно зростаючий характер. Максимальні значення тривалості вогневого впливу мають місце для експериментальних зразків, які мають товщину сталевої пластини 10 мм, для критичної температури сталі 600 °С. Вони становлять 111 хв, 101 хв, 55 хв відповідно для комбінованої, пасивної і реактивної систем вогнезахисту.

Встановлено, що для комбінованої системи вогнезахисту закономірним є підвищення тривалості досягнення критичної температури сталі порівняно до пасивної та реактивної систем вогнезахисту. Це обумовлене ефективним поєднанням фізико-хімічних властивостей пасивного і реактивного вогнезахисних матеріалів.

Для тривалості вогневого впливу до 79 хв значення тривалості досягнення критичної температури сталі для комбінованої системи вогнезахисту перевищує суму тривалостей її досягнення, які мають місце для пасивної і реактивної систем вогнезахисту. Це свідчить про ефективність комбінованої системи у цьому діапазоні тривалості вогневого впливу.

З підвищенням тривалості вогневого впливу має місце зниження ефективності комбінованої системи вогнезахисту.

Ключові слова: вогнезахисний матеріал, критична температура сталі, сталева конструкція, система вогнезахисту, вогневий вплив

Received date 20.03.2020
Accepted date 15.06.2020
Published date 30.06.2020

1. Introduction

According to EU Regulations No. 305/2011 [1], Technical regulations [2] and the state construction standards [3], one of the basic requirements for buildings is the preservation of the bearing capacity of structures during a fire within the specified period.

One of the ways to preserve this ability is to use fire protective materials applied for building structures of various types (for example, walls, floors, beams, columns) made of concrete, steel, wood, etc.

The types of fire-retardant materials for building structures were established in the instructions for technical approval of fire retardant materials in Europe ETAG No. 018-1 [4], ETAG No. 018-2 [5], ETAG No. 018-3 [6], ETAG No. 018-4 [7].

In accordance with these guidelines for steel structures (columns and beams), passive and reactive fire retardant