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DEVISING TECHNOLOGY FOR EXTINGUISHING OIL TANKS USING COMPRESSED FOAM BY SUB-LAYER TECHNIQUE

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Tank facilities storing various combustible substances are a potential source of danger for the environment and human life. Fires in tanks can occur for various reasons: technical malfunctions, human factors, military operations, natural phenomena. One of the effective methods for extinguishing such fires is "sub-layer" extinguishing with the help of foam of low multiplicity. The possibility of "sub-layer" extinguishing with the help of compression foam, which has unique properties, has been considered. The object of this study is the processes of stopping combustion during fire extinguishing in steel tanks for the storage of petroleum products with the use of foaming agents of increased stability, which ensure the generation of compression foam in a "sub-layer" way. A mathematical model of the movement of a submerged non-free jet of foam in the medium of motor fuel is given, which adequately describes the real physical processes that occur during "sublayer" quenching of vertical steel tanks. According to the research, it was established that the use of foam with a multiplicity of 10 (K10) is 1.56 times more effective in serving time than the use of foam with a multiplicity of 5 (K5). From an economic point of view, K10 foam also has greater advantages as the costs of the foaming agent during its generation are 3.1 times lower than when using K5 foam. The simulations demonstrated that the foaming agent consumption of the K10 foam is lower than the foaming agent consumption of the K5 foam and results in a different amount of foam coming to the surface. The simulations also showed that the volume of K5 foam increases proportionally with the feeding time, while the volume of K10 foam increases disproportionally and starts to decrease after half the time. The results from the implementation of the mathematical model were fully consistent with the results from experimental studies on extinguishing a model fire of class B

Keywords: compression foam, fire extinguishing of petroleum products, "sublayer" extinguishing of tanks, fires in tanks

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1. Introduction

Fires in tanks, in most cases, begin with the explosion of a steam-air mixture. The physical and chemical properties of oil and petroleum products, the design of the tanks, the technological modes of operation, as well as climatic and meteorological conditions have a significant influence on the formation of explosive concentrations inside the tanks. An explosion in the tank leads to the collapse of the roof with subsequent burning on the entire surface of the oil product. At the same time, even in the initial stage, the burning of oil and oil products in the tank can be accompanied by strong heat radiation into the environment, and the height of the flame can be 1–2 diameters of the burning tank. The following techniques are mostly used to extinguish FSs and FL fires in tanks:

– by supplying foam of medium or low multiplicity in tanks from above with the help of medium expansion foam generator or air-foam barrels installed on fire trucks, equipment adapted for its supply, or stationary foam chambers in case of their efficiency;

– supplying foam of low multiplicity to the surface of the combustible liquid with the help of foam carriage barrels;

– sub-layer extinguishing using foaming agents of the AFFF type.

During the Russian military aggression against Ukraine, the enemy carried out massive shelling of petroleum storage warehouses both in the areas of hostilities and deep in the rear in the rest of the country. As a result of fire damage, tank farms are destroyed, large-scale fires occur, the territory of the objects is contaminated with explosive objects, there is a threat of repeated strikes. Under these difficult conditions, bodies and fire-rescue units of the State Emergency Service provide response to all fire incidents. Operational actions are organized in accordance with the requirements of regulatory acts with mandatory consideration of the specificity of the situation at the specific time at the site of the incident and the maximum possible observance of safety measures for extinguishing participants [1].

As a result of the rocket and artillery shelling of the oil product warehouse, destruction of and damage to a significant number of tanks, structures, and technological facilities occur, which is accompanied by large-scale fires.

During a fire in a tank park, the following is observed [1]:

– destruction of tanks as a result of fire, spillage and spread of oil products over a large area, including due to the lack of collapse of tank parks in individual cases;

– spillage of petroleum products from tanks due to heating and foaming; release from tanks of dark oil products due to heating;

– the formation of zones in damaged tanks that complicate the supply of fire-extinguishing substances due to the collapse of the roof;

– strong thermal radiation from the burning tank, powerful convective flows of combustion products and their direction changes depending on meteorological conditions;

– rapid development of fire and spread of fire through technological trays, sewage, and other systems;

– damage to the tanks due to the explosion of rocket fragments and leakage of oil products from them.

In addition to the conventional method of extinguishing tanks, the method of "sublayer" fire extinguishing is used. Extinguishing in this way can be carried out only if the tanks are equipped with a "sub-layer" fire extinguishing system.

Compression foam has been used for more than 30 years to extinguish fires of various classes. In the USA, compression foam is used to extinguish fires in residential buildings. This helps save fire-extinguishing substances and owing to the low content of the liquid phase in the compression foam, to reduce material damage from extinguishing. Despite this, in the USA and in European countries, no one has yet studied the extinguishing of tanks with oil products in the "sublayer" way using compression foam; there are no relevant regulatory documents.

Therefore, it is a relevant task to carry out studies on designing a system for "sublayer" extinguishing of tanks with oil and petroleum products, which could help fire departments to ensure faster and safer extinguishing of fires of this kind.

2. Literature review and problem statement

The authors of works [2, 3] propose to improve the technology of "sub-layer" fire extinguishing in tanks with petroleum products using air-mechanical foam of low multiplicity. It is also proposed to update the regulatory documents regarding the regulatory intensity of supplying working solutions of the foaming agent during "sub-layer" extinguishing and much more. In work [4], the authors describe methods of fire protection of tanks, including a system of "sublayer" fire extinguishing of oil products in tanks with increased capacity. The method of determining the fire-extinguishing efficiency of extinguishing petroleum products by a combined method based on the supply of solid granules of carbon dioxide and a foaming agent to reduce the extinguishing time and the amounts of fire-extinguishing substances was studied in [5] but the optimal ratio of fire-extinguishing substances for different amounts of petroleum products was not established. In [6], the properties of compression foam and the technological parameters of its generation were studied but the behavior of the foam in the petroleum product environment was not investigated. Compression foam has advantages in structure, uniform size, and high foam stability compared to traditional fire extinguishing foam because it can remain and accumulate on the surface, which obviously increases the effectiveness of fire extinguishing [7]. In Compressed Foam Fire Extinguishing Systems (CAFS), a foam concentrate is mixed with water in a specific proportion to form a foam solution that is mixed with gas at a fixed pressure. Study [7] investigated the influence of foam flow rate in pipelines, pipes, and bends, because it differs from the water model as foam is a gas-liquid two-phase flow with non-Newtonian fluid properties and compressibility. The studies focused on only two types of foam (1 % Class A and 3 % AFFF), which in turn limits the generalizability of the results and their application to different types of foam. Compression foam was also studied in [8], namely, its compressibility was investigated. This study needs further confirmation and development as there is insufficient information on comparisons with other foam types and different compression conditions. There is also the question of the calibration and reliability of the equipment that was designed specifically for the study and its comparison with already existing tools and methods. The authors studied the fire-extinguishing effect of compression foam in [9–11]. The model of fire extinguishing of petroleum products with film-forming compression foam (AFFF), which can be used for extinguishing fires, was studied in [9] but the issues related to the supply of compression foam under the layer of burning petroleum product remained unresolved. In [10], there is an assessment of the fire extinguishing efficiency of fire extinguishing systems with compression foam (CAFS) at different ratios: 5–12 parts of air to 1 part of the foaming solution. The authors of paper [11] conducted small-scale tests of the model to study the fire extinguishing effect of CAFS on a fire in an oil tank on the surface. The CAFS system supplies compression foam, as a rule, in multiples of 7. The foam has good adhesive properties, high resistance, more than 20 minutes on the surface of the combustion mirror.

All this gives reason to assert that it is expedient to carry out research into the physical processes of the rise of foam jets of compression foam through a layer of petroleum products, the determination of optimal pressures during the supply of foam, the study of fire-extinguishing properties of compression foam in the environment of petroleum products. Compression foam for "sub-layer" extinguishing is being used for the first time and is being researched at Lviv State University of Life Safety. It is also necessary to conduct a study to determine the optimal foam multiplicity that will provide the best extinguishing efficiency and establish the required performance of the foam supply. Particular attention should be paid to the behavior of compression foam in the oil product environment, its resistance to chemicals, compression and recovery of shape, as well as heat resistance.

3. The aim and objectives of the study

The purpose of our research is to devise the technology of extinguishing the tank with compression foam on the example of a tank with a volume of 5000 m^3. This will make it possible for fire departments to eliminate fires in tanks faster and thereby save the supply of fire-extinguishing substances.

To achieve the goal, the following tasks were set:

– to simulate the process of burning gasoline and supplying compression foam of different multiplicity in a tank of a certain volume;

– to determine the parameters of the compression foam supply in the “sub-layer” way.

4. The study materials and methods

The object of our study is the processes of stopping combustion during fire extinguishing in steel tanks for the storage of petroleum products with the use of foaming agents of increased stability, which ensure the generation of compression foam in a “sub-layer” way.

The main hypothesis of the study assumes that the compression foam will quickly cover the surface and stay for a long time on the surface without collapsing, thus preventing flammable vapors from entering the combustion zone and being a screen between the flame and the mirror of flammable substances (FSs) and flammable liquids (FL).

The software package SolidWorks Flow Simulations (France) is used for theoretical studies of the movement parameters of submerged foam jets, which is designed for solving applied problems in the field of thermohydrodynamics by simulating the relevant physical processes. SolidWorks Flow Simulations is a fully integrated SolidWorks CAD system application. It can be effectively used for calculations of force (stationary and non-stationary) interaction between solid bodies and fluid (gas) flow in the case of their mutual movement. It is also used to calculate the influence of various physical factors on the movement of the fluid medium; solving heat exchange problems; calculation of the movement of solid and/or liquid particles in a gas or liquid flow. A mathematical model is built by geometrically designing a real object in the SolidWorks environment, followed by automatic exchange of the necessary information between SolidWorks Flow Simulations and SolidWorks. The movement of the fluid medium and heat exchange between bodies is modeled using the Navier-Stokes equations, which describe the laws of conservation of mass, momentum, and energy in a non-stationary form.

This system of equations of conservation of mass, momentum, and energy of a non-stationary spatial flow in the Cartesian coordinate system (x_i, i=1, 2, 3) takes the form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_k}\left(\rho u_k\right)=0,$$

$$\frac{\partial\left(\rho u_i\right)}{\partial t}+\frac{\partial}{\partial x_k}\left(\rho u_i u_k-\tau_{ik}\right)+\frac{\partial P}{\partial x_i}=S_i,$$

$$\frac{\partial(\rho E)}{\partial t}+\frac{\partial}{\partial x_k}\left((\rho E+P) u_k+q_k-\tau_{ik} u_i\right)=S_k u_k+Q_H, \qquad (1)$$

where t is time, u is the speed of the fluid, ρ is the density of the fluid, S_i is the external mass forces acting on the unit mass of the fluid, E is the total energy of the unit mass of the fluid, Q_H is the heat released by the heat source in the unit volumes of the fluid medium, τ_{ik} – tensor of viscous shear stresses, q_i – diffusion heat flow, subscripts mean summation along three coordinate directions.

For Newtonian fluids, the stress tensor from the action of viscous forces is determined as follows:

$$\tau_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}+\frac{2}{3}\frac{\partial u_l}{\partial x_l}\delta_{ij}\right)-\frac{2}{3}\rho k\delta_{ij}, \qquad (2)$$

where μ is the coefficient of dynamic viscosity, δ is the Kronecker delta function, k is the coefficient of turbulent viscosity.

Diffusion heat flow is modeled using the equation:

$$q_i=-\left(\frac{\mu_i}{\Pr}+\frac{\mu_i}{\sigma_c}\right)c_P\frac{\partial T}{\partial x_k}, \quad k=1,2,3. \qquad (3)$$

For compressible media (gases), the equation of state in the following form is used:

$$\rho=\rho(P,T,y), \qquad (4)$$

where $y=(y_1, y_2, \dots y_N)$ is the vector of concentrations of components of the fluid medium. For gases, the equation of state of an ideal gas is used $\rho=P/(RT)$, where R is the gas constant of the modeled gas, which for a mixture of gases is defined as:

$$R=R_{\text{univ}}\sum_{i=1}^{N}\frac{y_i}{M_i},$$

where M_i is the molecular mass of the i-th component of the gas. To take into account the dependence on temperature, the following equation is used:

$$\rho=\left[\sum_{i=1}^{N}\frac{y_i}{\rho_{0i}}\left(1+\beta_{Ti}\left(T-T_0\right)\right)\right]^{-1}, \qquad (5)$$

where β_{Ti} is the volumetric thermal expansion coefficient of the i-th component, ρ_{0i} is the density of the i-th component at a certain temperature T_0.

The influence of gravity is modeled with the help of the term S_i, which is included in (1) as an external mass force:

$$S_i=-\rho g_i, \qquad (6)$$

where g_i is the i-th component (along the i-th axis of the coordinate system) of the gravitational acceleration vector.

Multicomponent flows are of considerable interest for research. The change in the concentration of the components of the mixture in space due to diffusion is modeled by the following equation:

$$\frac{\partial \rho y_i}{\partial t}+\frac{\partial}{\partial x_k}\left(\rho u_k y_i\right)=\frac{\partial}{\partial x_k}\left(\left(D_{ij}+D_{ij}^{'}\right)\frac{\partial y_j}{\partial x_k}\right), \quad i=1,2,\dots N, \qquad (7)$$

where y_i is the concentration of the ith component of the mixture, N is the number of components, D is the diffusion coefficient.

In addition, the equations of state of the fluid medium are used, and the dependence of the thermal conductivity of the components of the medium on temperature is described by known empirical formulas.

To solve the problem, a continuous non-stationary mathematical model is discretized both in space and in time. To this end, the entire calculation area is covered with a grid, the faces of the cells of which are parallel to the coordinate planes of the Cartesian coordinate system. The grid is generated automatically with the ability to influence cell sizes to improve calculation accuracy.

The parameters of the movement of foam jets in the gasoline environment were determined using the finite volume method, which was implemented in the SolidWorks Flow Simulations software environment.

Gasoline was treated as a liquid, and foam as a gas with the physical and mechanical properties of foam. Both media are insoluble in each other. In fact, air-mechanical foam is a two-phase medium, during the movement of which possible phase changes, such as foam destruction, were not considered. When switching from one foam to another, their generalized physical and mechanical characteristics were taken into account.

The effect of gravity and foam compression under the influence of gasoline pressure, as well as the effect of temperature on the physical and mechanical properties of both environments, were taken into account.

The movement of foam jets was considered only inside the gasoline, the release of foam on the combustion surface was stated as a fact, and the behavior of the foam on the surface was not modeled due to the limitations of the model.

The change of phases of the foam, namely its boiling due to the effect of temperature and pressure on it, was only stated as a fact, and the change in the physical and mechanical characteristics of the foam due to its boiling was not taken into account due to the limitations of the model.

5. Research results related to the technology of extinguishing the tank with compression foam in the "sub-layer" way using the example of a tank with a volume of 5000 m^3

5. 1. Simulating the process of burning gasoline and supplying compression foam of different multiplicity in a tank of a certain volume

In SolidWorks Simulations, a model of a tank with a volume of 5000 m^3 is designed with the following internal dimensions: Ø21 m, and a height of 16 m with steel walls 10 mm thick (Fig. 1). At the bottom of the tank (concentrically) we place the source of the foam jet – the end of a foam pipe of a certain diameter directed vertically upwards. It is assumed that the roof came off as a result of the explosion, so the tank is open from above. Further simulations were carried out in a tank with an open roof.

Design parameters of the model:
– outer diameter – 21000 mm;
– wall thickness – 10 mm;
– height (external) – 1610 mm;
– bottom thickness – 10 mm;
– tank material – steel;
– tank volume – 5531 m^3;
– the surface area of the tank mirror is 346 m^2.

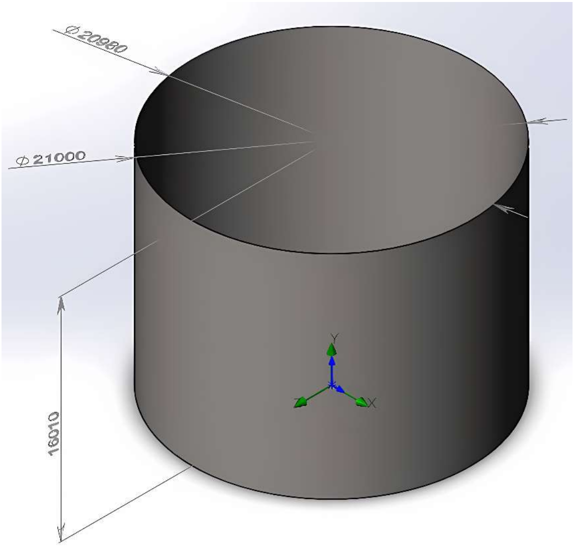

Fig. 1. A 5000 m^3 tank model in SolidWorks Flow Simulations environment

Fuel and tank heating was simulated for 30 minutes. This is the time needed by ARS units to prepare a foam attack. Let's take the temperature of the combustion mirror as 433 °K (160 °C). The temperature of the sides (walls) at the level of the combustion mirror is 650 °K (377 °C) [12, 13]. The ambient temperature is 293 °K (20 °C). Cooling of the tank walls is uniform convection, heat transfer coefficient – 20 W/m^2/K. The temperature above the combustion mirror is equal to the temperature of the mirror. The fluid medium is liquid (B70 aviation gasoline). We shall assume the initial temperature of the walls and the environment to be equal to 293.2 °K (20 °C) (by default). Atmospheric pressure is 101325 Pa (default). We choose the maximum duration of warm-up – 30 minutes.

The entire volume of the tank is 5531 m^3. It is divided into 1213824 elements, which is the value of the volume of one element of 0.004556 m^3, or 4.6 liters, which should ensure good accuracy of calculations [14, 15].

The chromogram of the medium temperature distribution on the plane passing through the vertical axis of symmetry of the tank (hereinafter simply the cross-sectional plane) is shown in Fig. 2.

Fig. 3 demonstrates that the tank has warmed up completely. The temperature of gasoline at the bottom rose by 27 °K from the initial temperature.

Fig. 2 demonstrates that the tank is heated uniformly, with some distortion of the spectrum near the combustion surface, which may be caused by the movement of the medium.

According to this chromogram, a graphical dependence of the temperature distribution of the environment at the end of the warm-up on the height of the tank was built, which is shown in Fig. 4.

Fig. 4 shows a chromogram of the vertical velocity of the medium on the cross-sectional plane.

Fig. 4 demonstrates that gasoline rises in the center to the top with a maximum speed of 5 cm/s, and falls down along the walls of the tank with a maximum speed of 2.5 cm/s. That is, in the process of heating, a laminar convective movement of gasoline was established, which additionally contributes to its heating from the fire and the distortion of the temperature distribution picture in Fig. 2.

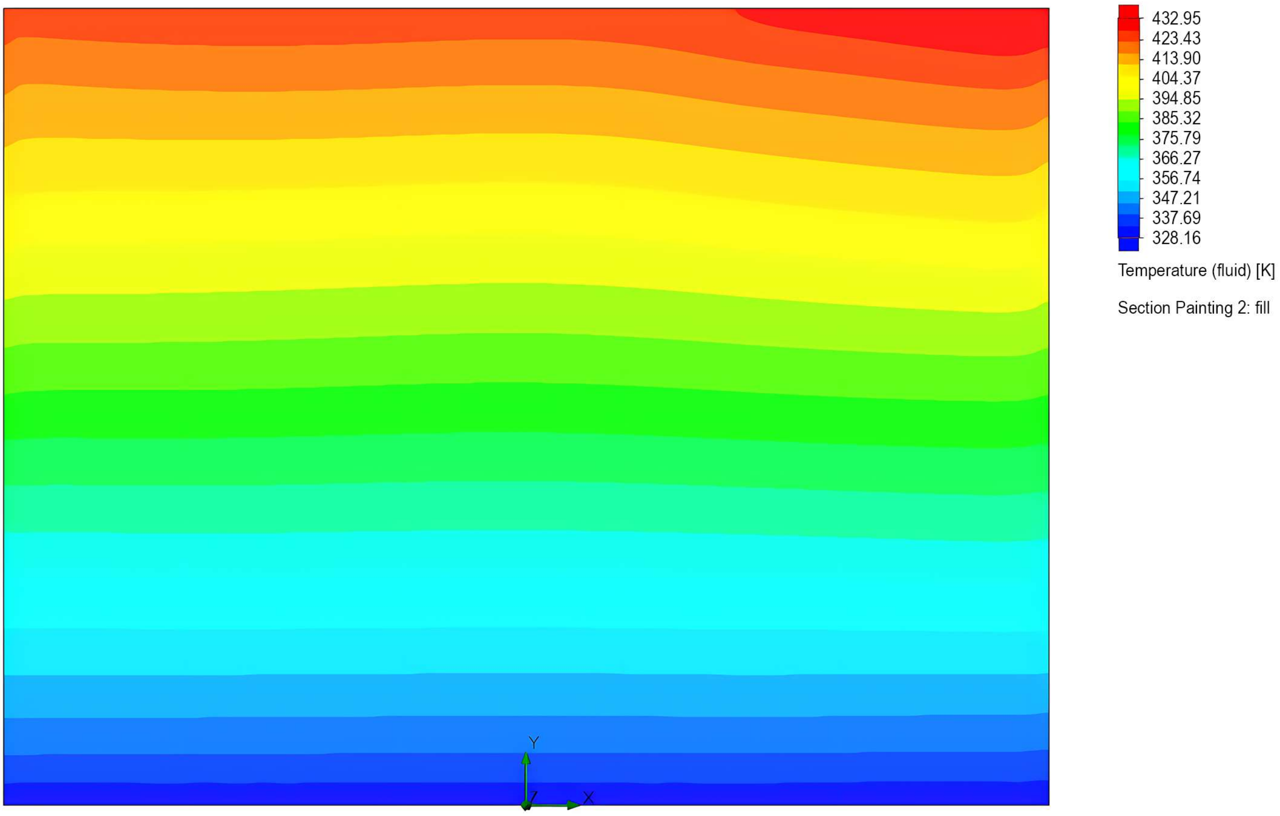

Fig. 2. The temperature of the environment at the end of warming up

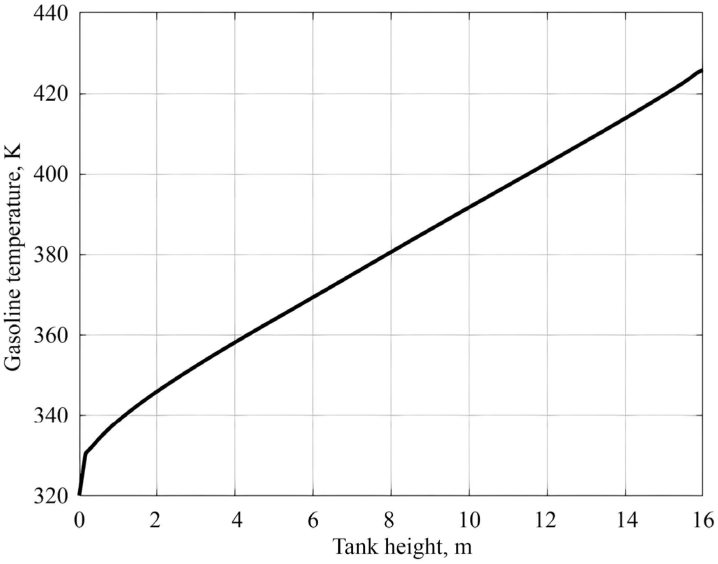

Fig. 3. Distribution of the temperature of the medium at the end of heating by the height of the tank

In the process of heating the medium of the tank as a result of its combustion, the tank itself, that is, the surface of the structure, is also heated.

The chromogram of the temperature distribution on the side surfaces of the tank walls is shown in Fig. 5.

Fig. 5 demonstrates that the walls do not heat up above the boiling temperature of gasoline, which indicates that the walls are well cooled by gasoline, that is, gasoline is heated not only from the combustion mirror but also from the walls, which have a much higher temperature.

As one knows, the density of a liquid medium (liquid) depends on temperature. Fig. 6 shows a chromogram of the dependence of gasoline density on its temperature, and Fig. 7 – graphical interpretation of this dependence along the vertical axis of symmetry.

Fig. 6 demonstrates that the density of gasoline decreases from the bottom to the top, that is, warmer fuel layers have a lower density and vice versa. This correlates well with the chromogram of the medium temperature, which is shown in Fig. 2. Fig. 7 demonstrates that the initial density of gasoline (750 kg/m^3) after heating changed from 722 at the bottom of the tank to 617 at the top – in the combustion zone. The average value of the density of gasoline is 668.5 kg/m^3 but the calculations based on numerical simulation results give a more accurate value – 671.1 kg/m^3. As you know, such a decrease in the density of a liquid leads to an increase in its volume. In the SolidWorks Flow Simulations environment [15], this increase in volume can be determined by the mass of gasoline displaced from the calculated volume, that is, the tank, since the volume of the tank in the model always remains unchanged.

Fig. 8 shows the graphical dependence of the mass of gasoline in the tank on heating time.

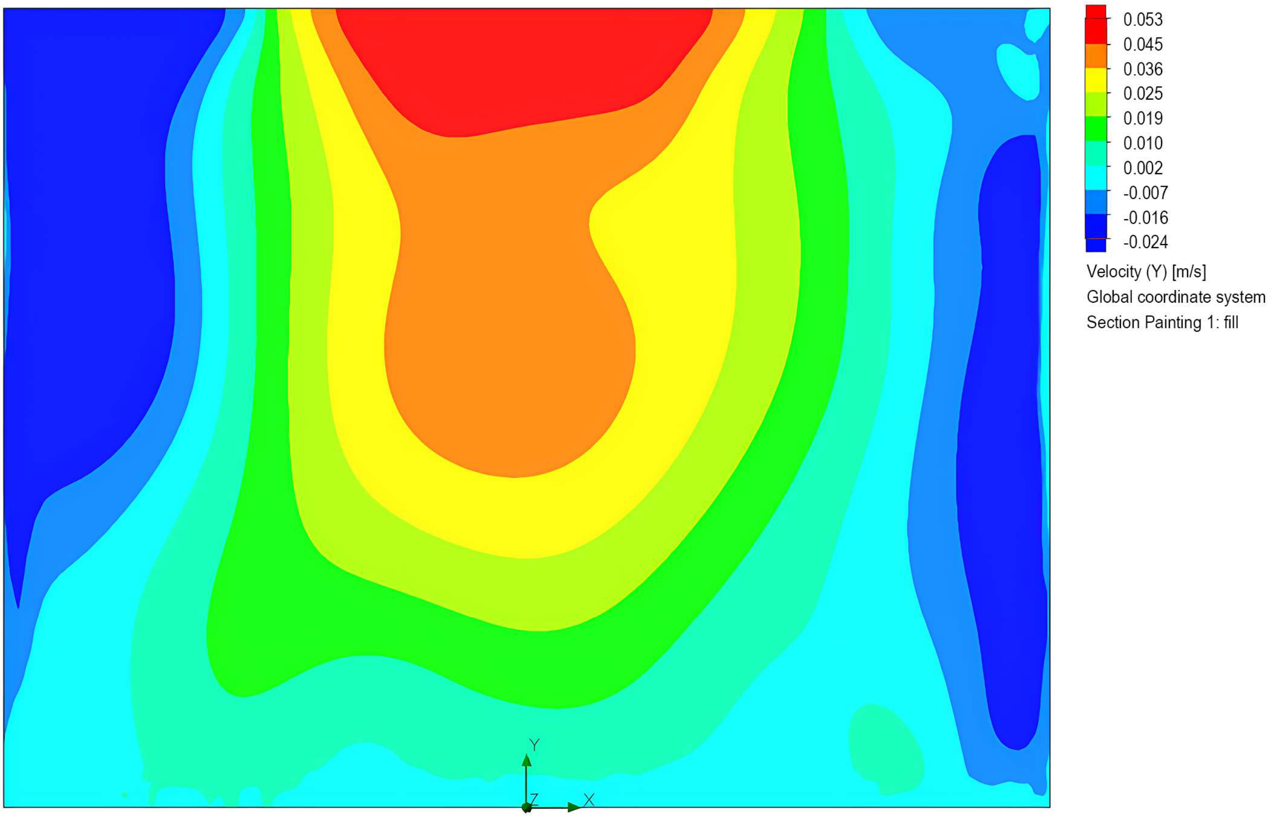

Fig. 4. Vertical velocity of heated gasoline

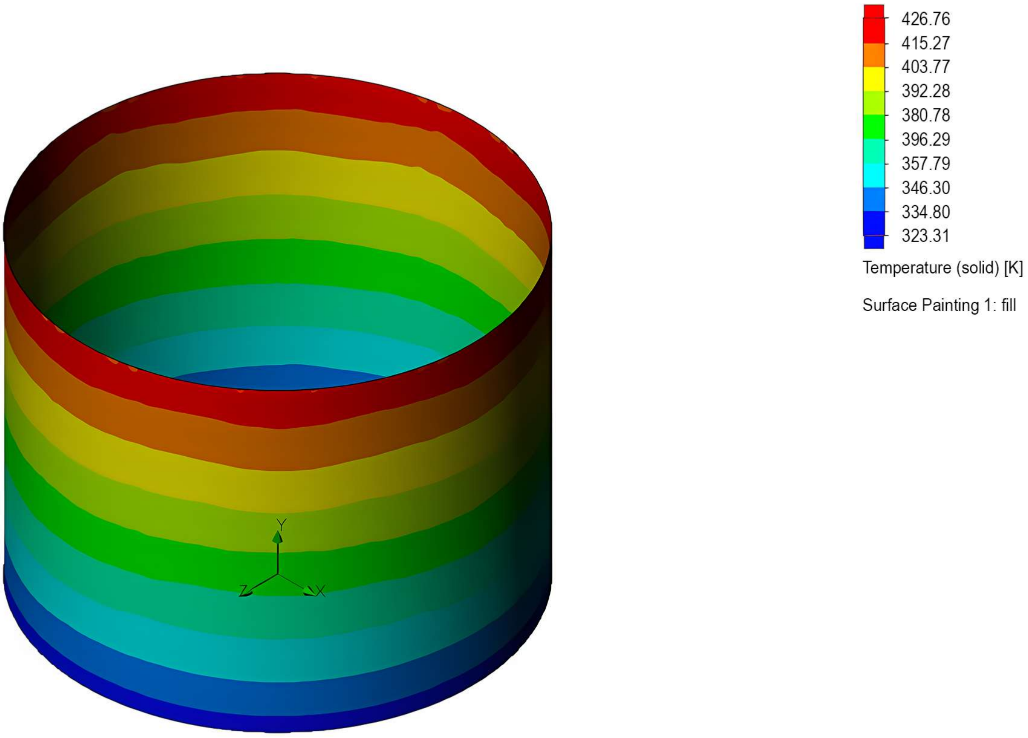

Fig. 5. Tank wall temperature after 30 min of heating

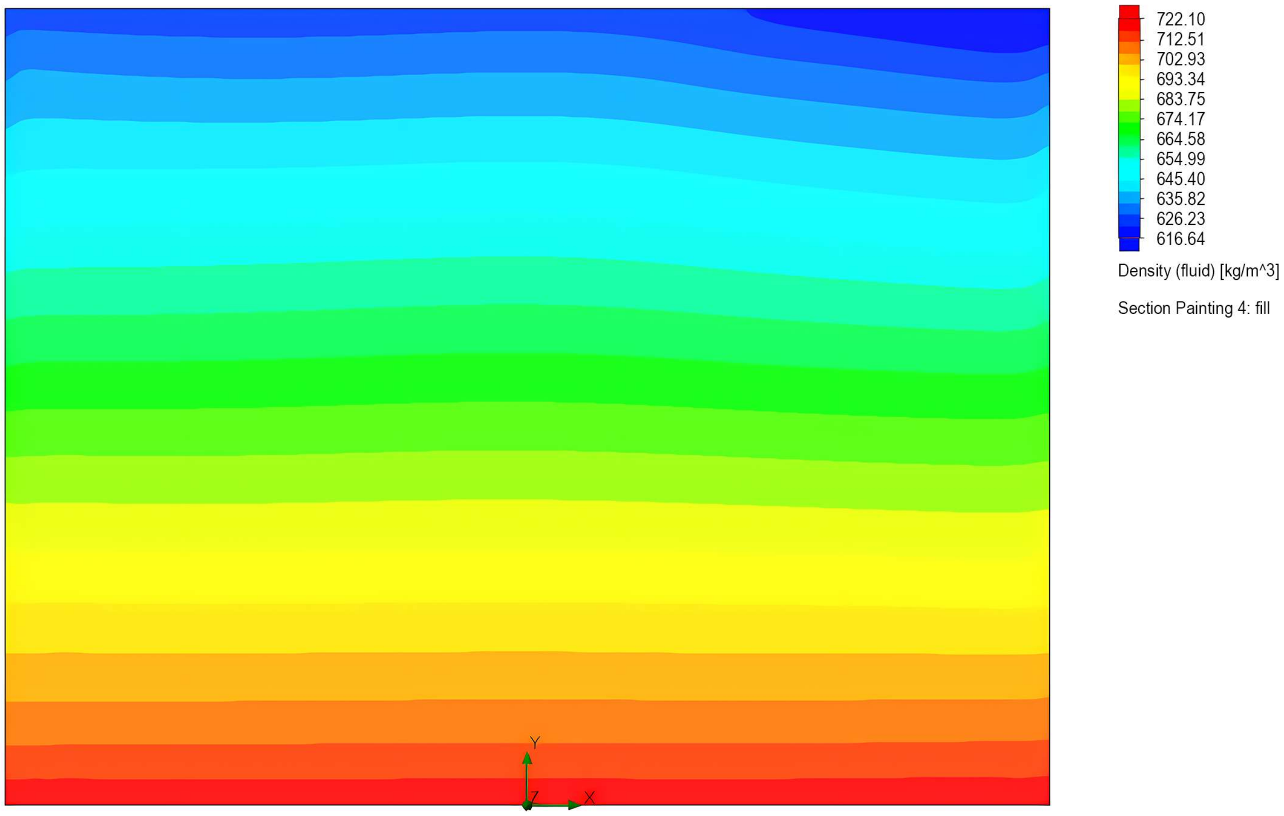

Fig. 6. Density of warmed gasoline at the end of warming up

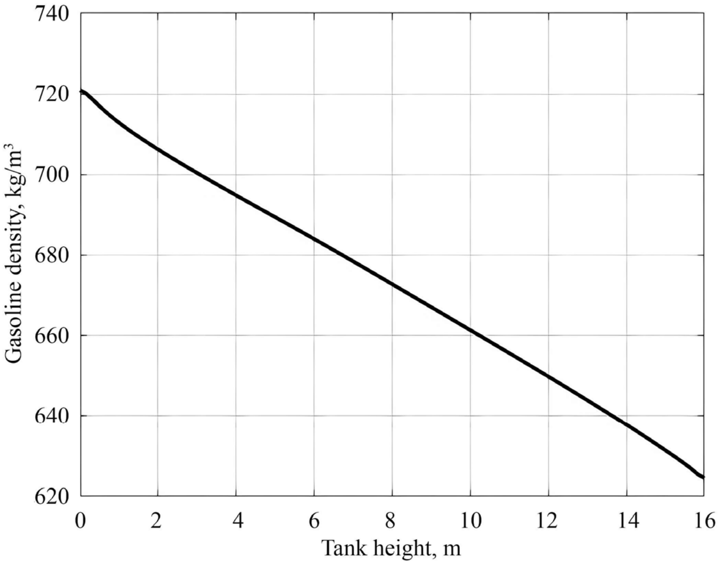

Fig. 7. Distribution of the density of heated gasoline by the height of the tank

Fig. 8 demonstrates that the mass of gasoline in the tank decreases in proportion to its heating, that is, gasoline is displaced from a completely filled tank, which can lead to an extremely dangerous emergency. To prevent this phenomenon, it is necessary to have a certain reserve volume in the tank, which will be filled with heated gasoline.

The volume of the tank in the model is determined as $V_p = \pi D^2 / 4H$ and is 5531 m^3.

The initial mass of gasoline in this volume:

M_1=4,147,970 kg at value ρ_1=750 kg/m^3.

The final weight of gasoline at the end of warm-up:

M_2=3,711,940 at value ρ_2=617 kg/m^3.

Mass of displaced gasoline:

$M=M_1-M_2$=436,030 kg.

The increase in volume at the average density ρ_{mid}=671 kg/m^3 is:

$V_{add}=M/\rho_{mid}$=650 m^3 (12 %).

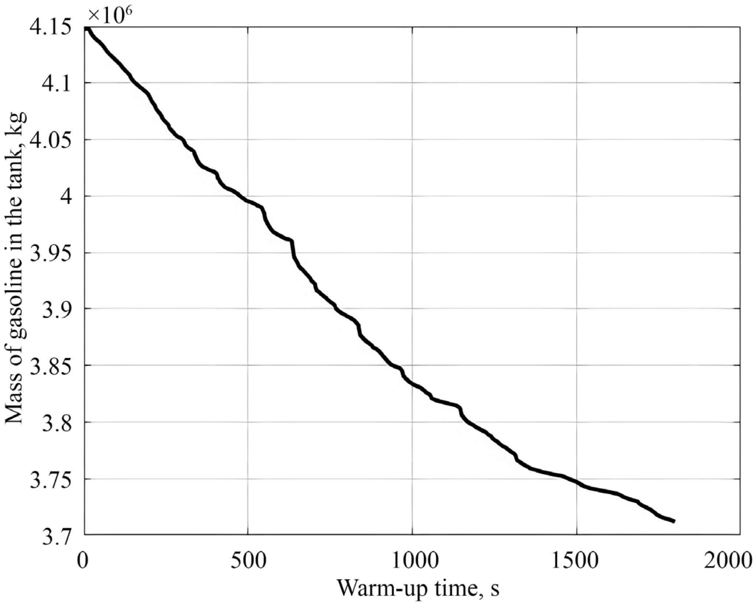

Fig. 8. Dependence of the mass of gasoline in the tank on the warm-up time

This is the volume of gasoline by which the volume of gasoline in the tank increases as a result of heating.

5. 2. Determining the parameters of supplying compression foam by the "sub-layer" technique

During the movement of foam jets in a tank with heated gasoline, the foam is modeled as a gas, which allows us to take into account the compression of the foam under the effect of gasoline pressure. To date, it is still impossible to model air-mechanical foam as a system of liquid and gas bubbles. Therefore, the two-phase inhomogeneous water-air system is replaced by a continuous medium – gas with the physical and mechanical parameters of foam. Hereafter, the liquid medium should be understood as a mixture of foam and gasoline.

The foam supply was carried out from the very bottom of the tank from 6 nozzles, which are evenly spaced along a ring pipeline of a medium radius with a diameter of 14 m. In reality, the barrels must be moved away from the bottom of the tank to a certain height, which was not established at the time of the study, so it was accepted to place them at the very bottom designs. In order for the jets to rise to the top as quickly as possible, they are spaced (6 pcs.) at a certain optimal [2] distance.

We determine the foam supply by a factor of 10 (K10) from the required intensity of 0.08 l/s*m^2 [2]. In terms of the area of the tank, this sets the value of mass supply Qm=28 kg/s, or Qv=0.14 m^3/s in terms of foam with a multiple of 5 (K5). These indicators are set because the foam with a factor of 10 will compress twice as much as the pressure at the bottom of the tank.

To verify the model, foam supply was considered for a short period of time (10 s, to avoid the mixing of flows and the influence of this process on the analysis of the state of the environment).

The chromogram of the speed of foam jets on the cross-sectional plane after 10 s of feeding K10 foam with a volumetric feed Q=0.14 m^3/s is shown in Fig. 9.

On the cross-sectional plane passing through the axes of the two jets, clearly formed jets are visible, and, importantly, the kinetic energy of these jets was transferred to the upper layers of the tank faster than the jets themselves. This is characteristic of an elastic environment and positively characterizes the adequacy of the model at the qualitative level. In order to facilitate the visual analysis of the chromogram, the maximum values of the speed of the jets were filtered to 1.5 m/s (this is the maximum in the area of the head of the jet, and everything above that merges in red).

In fact, the maximum is at the exit of the jets from the nozzle and is 11.8 m/s. The filter draws all speed values higher than 1.5 m/s in red. This allows one to better see (analyze) lower values of speeds.

As shown by theoretical studies of the process of feeding foam jets into the environment of heated gasoline, the laminar movement of the jets in the environment lasts only for a short period of time and becomes turbulent. The foam accumulates in the gasoline environment in the middle part of the tank and only after a certain period of time (55 s) comes to the surface in the form of separate parts. Before reaching the surface, the foam overheats, breaks down (boils) and reaches the combustion surface in the form of water vapor and air. At the same time, there is a local cooling of the areas of the combustion mirror in the steam exit zone.

To determine the effect of a change in the density of a heated fluid on the Archimedean force, consider the movement of foam jets in a cold and hot environment.

Fig. 10 shows the graphical dependence of the foam mass flow at the outlet of the tank (on the combustion mirror) on the duration of its supply and the temperature of the environment.

Fig. 11 shows the integrated dependence, which is shown in Fig. 10 – the amount of foam that came to the burning surface per unit of time.

As can be seen, in the case of a cold environment, the foam reaches the combustion surface after 20 s of supply, and reaches a maximum value of 20 kg/s after 35 s. In the subsequent time, the mass flow decreases, and their average value is close to half of the mass flow of foam at the inlet to the tank, namely 14 kg/s. That is, there is a certain accumulation of foam in the tank. In the case of a hot environment, the foam comes out at the 57th second and its mass flow rate is 0.9 kg/s, that is, all the foam that was supplied for 1 minute is in the tank.

Fig. 11 demonstrates that in the case of a cold environment, 450 kg of foam rose to the surface within 60 seconds, and in the case of a hot environment, only 3 kg, which is 150 times less. It should be noted that 1,680 kg was supplied within 60 seconds.

Therefore, the temperature of the fluid does not release the foam to the surface by reducing the lifting force due to the drop in the density of the medium.

The application of foam of different multiplicity during 1500 s was considered. Practical experience of "sub-layer" extinguishing indicates that the duration of foam supply is approximately 25 minutes. Based on this, we shall simulate the process of feeding foam of different multiplicity (K5 and K10) with the minimum necessary intensity of feeding. Foam K10 Q=0.14 m^3/s (28 kg/s) and Foam K5 Q=0.07 m^3/s (28 kg/s).

Fig. 12 shows the graphical dependence of foam flow rate on the combustion mirror on the time of its feeding; K10 foam as well as K5 foam rise to the surface of the combustion mirror unevenly, with significant fluctuations in productivity.

The flow rate of K10 foam is significantly higher than that of K5 foam, which leads to a different amount of foam applied to the mirror, which is shown in Fig. 13.

As can be seen from the chart in Fig. 14, the volume of foam 5 increases in proportion to the supply time.

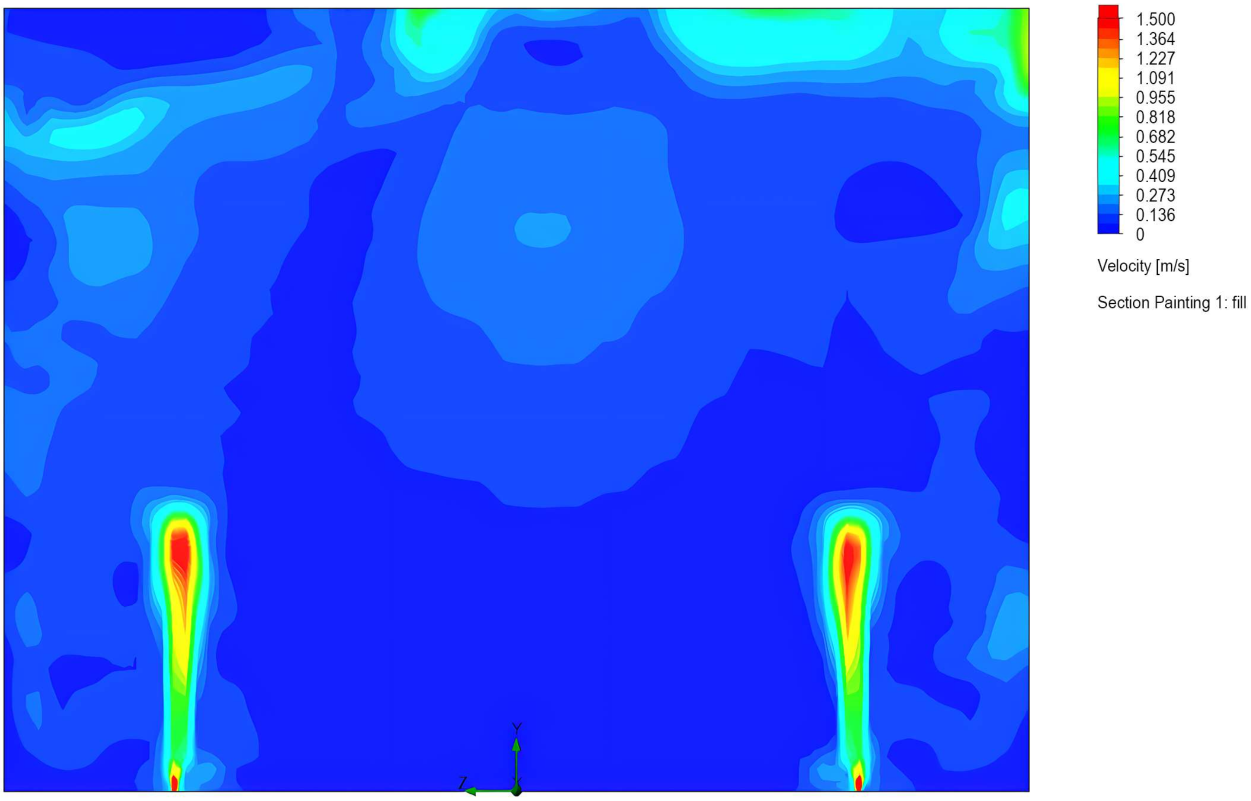

Fig. 9. Foam jet speed

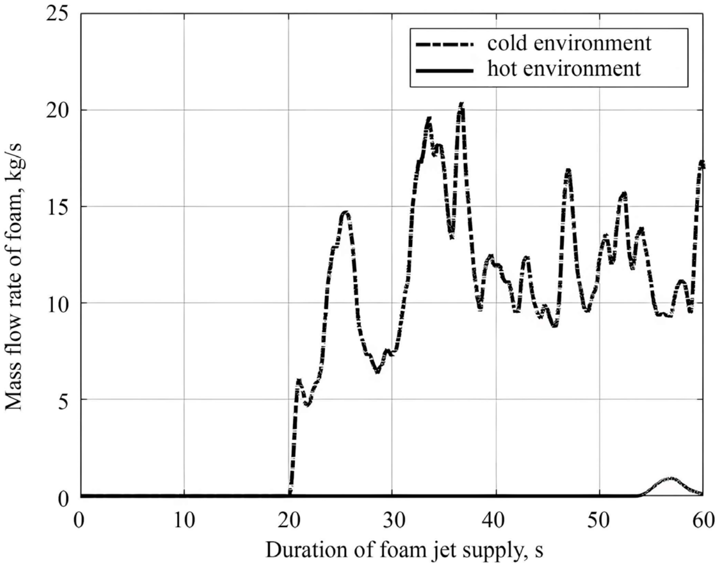

Fig. 10. Graphical dependence of the mass flow rate of foam at the outlet of the tank on the time of supply and the temperature of the medium

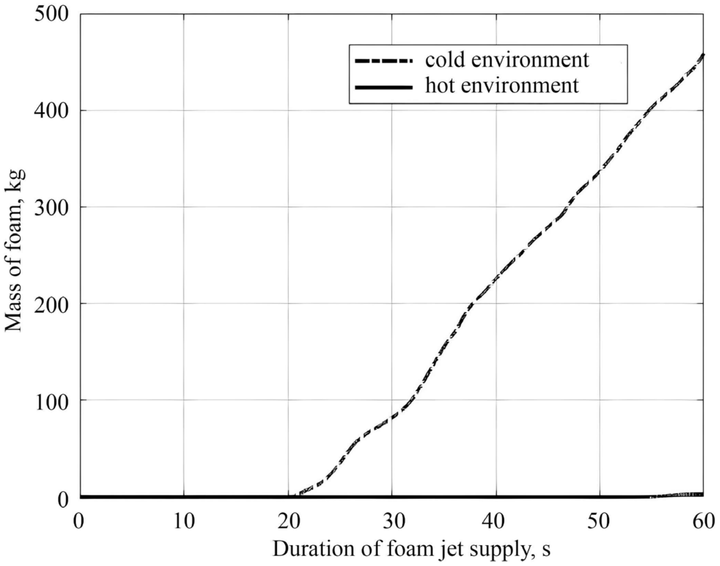

Fig. 11. Graphical dependence of the foam mass at the outlet of the tank on the time of supply and temperature

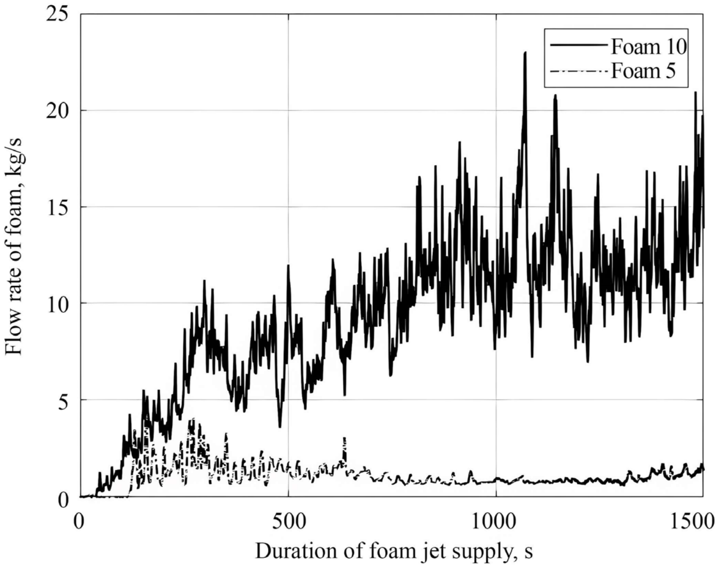

Fig. 12. Graphical dependence of the mass flow rate of foam on the combustion mirror on the time of supply

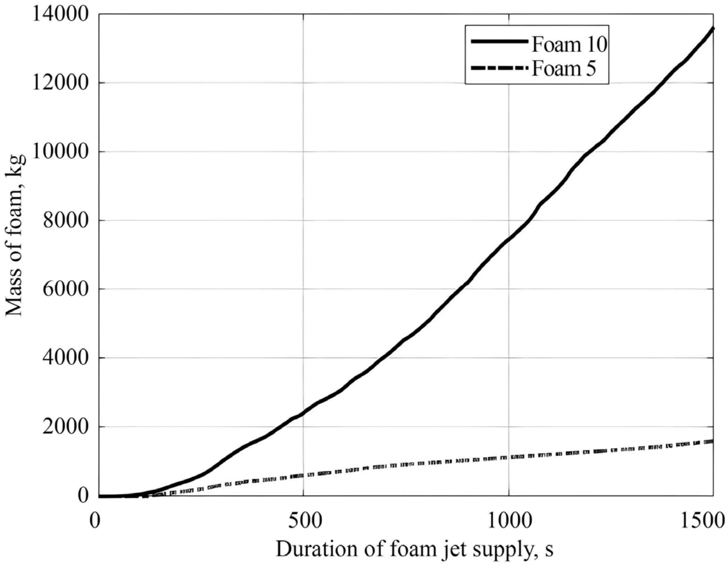

Fig. 13. Graphical dependence of the foam mass release on the combustion mirror on the time of feeding

Fig. 15, 16 demonstrate that foam K10 collects in a smaller cloud and its jets almost do not merge. K5 foam practically merges into one cloud.

Further suspension of the foam K5 is shown in Fig. 17.

As can be seen from the chromograms, the foam in all cases comes out on the surface of the burning mirror in separate fragments, and the fragmentation of the K10 foam output is much higher, which can also be seen in Fig. 12.

Fig. 18 shows the graphical dependence of temperature on the combustion mirror on the time of feeding foam jets (minimum values).

Fig. 18 demonstrates that the rapid rise of the K10 foam does not cool the combustion mirror (the temperature rises), and the suspension of the K5 foam leads to a good heat exchange with gasoline and the temperature on the combustion mirror drops.

In addition to cooling properties, the foam has insulating properties, preventing flammable vapors from penetrating to the reaction (combustion) zone. The insulating properties of the foam will depend on the accumulation of foam on the burning surface. Foam with a multiplicity of K5 hangs in the tank and does not cover the combustion surface for a long time. Accordingly, it stops the burning process 1.45–1.56 times worse (Table 1).

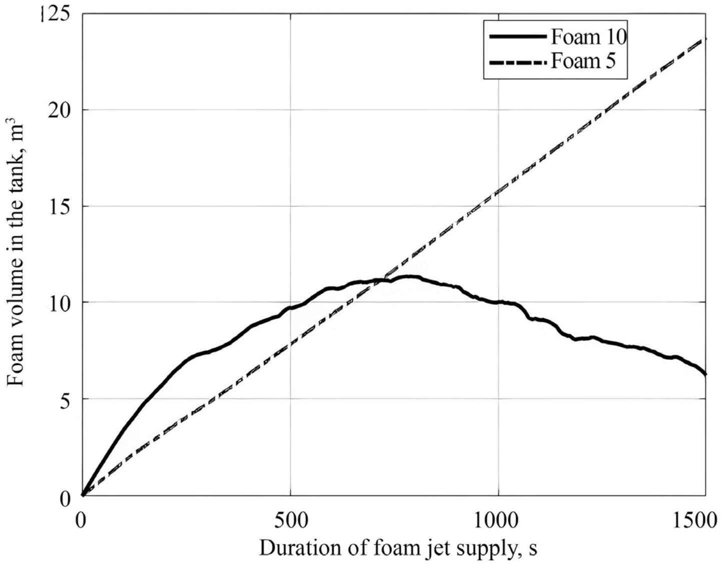

Fig. 14. Graphical dependence of the foam volume in the tank on the time of its supply

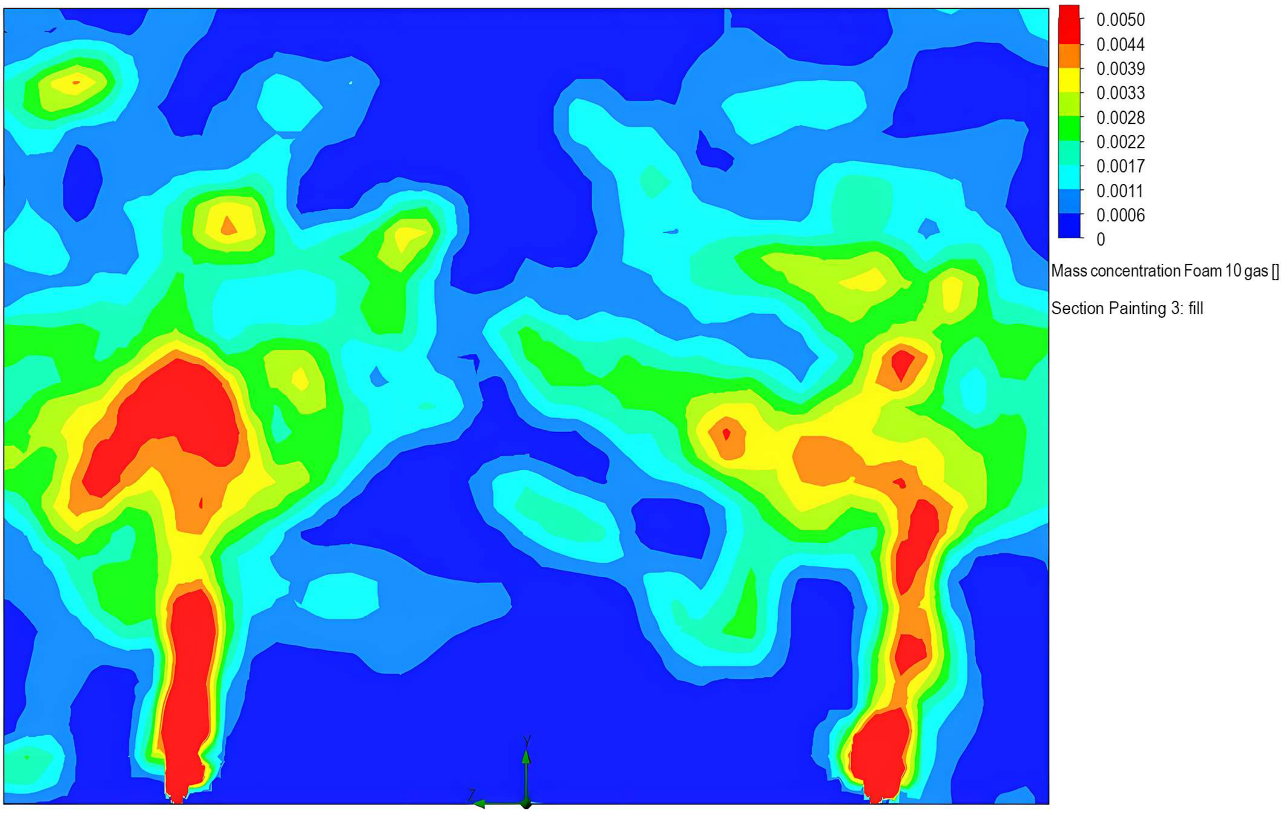

Fig. 15. Chromogram of foam 10 concentration per 600 s feed

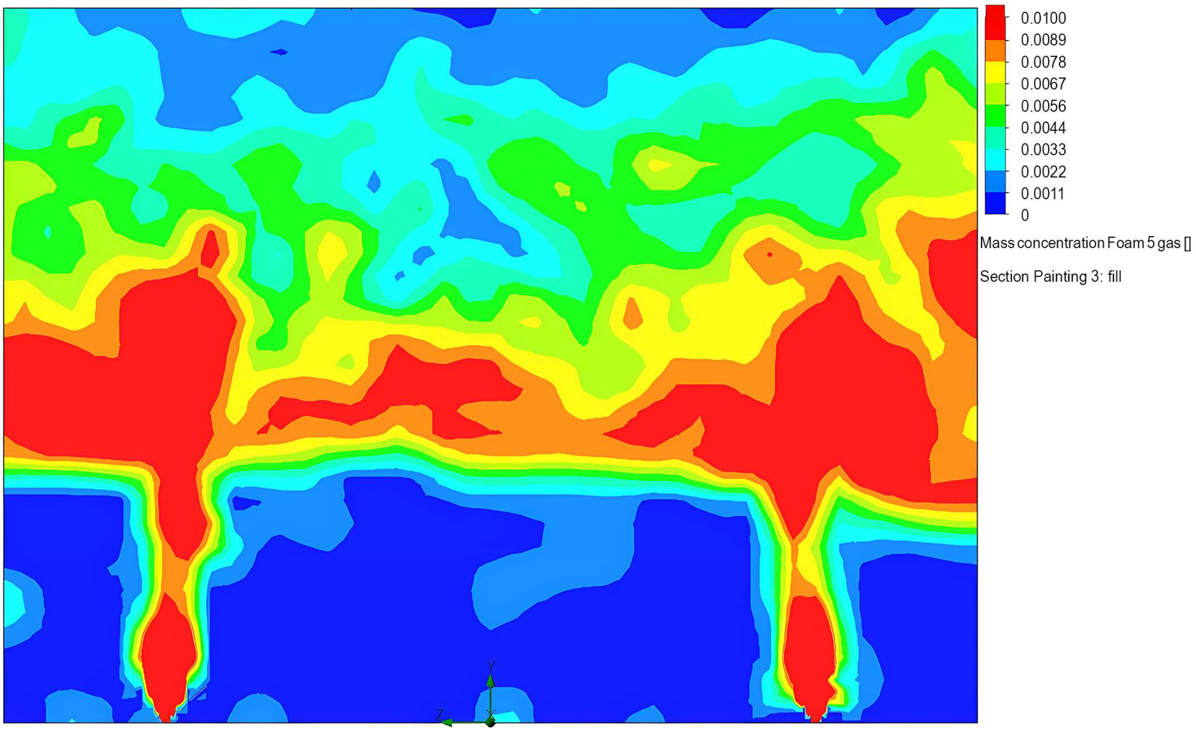

Fig. 16. Chromogram of foam 5 concentration per 600 s feed

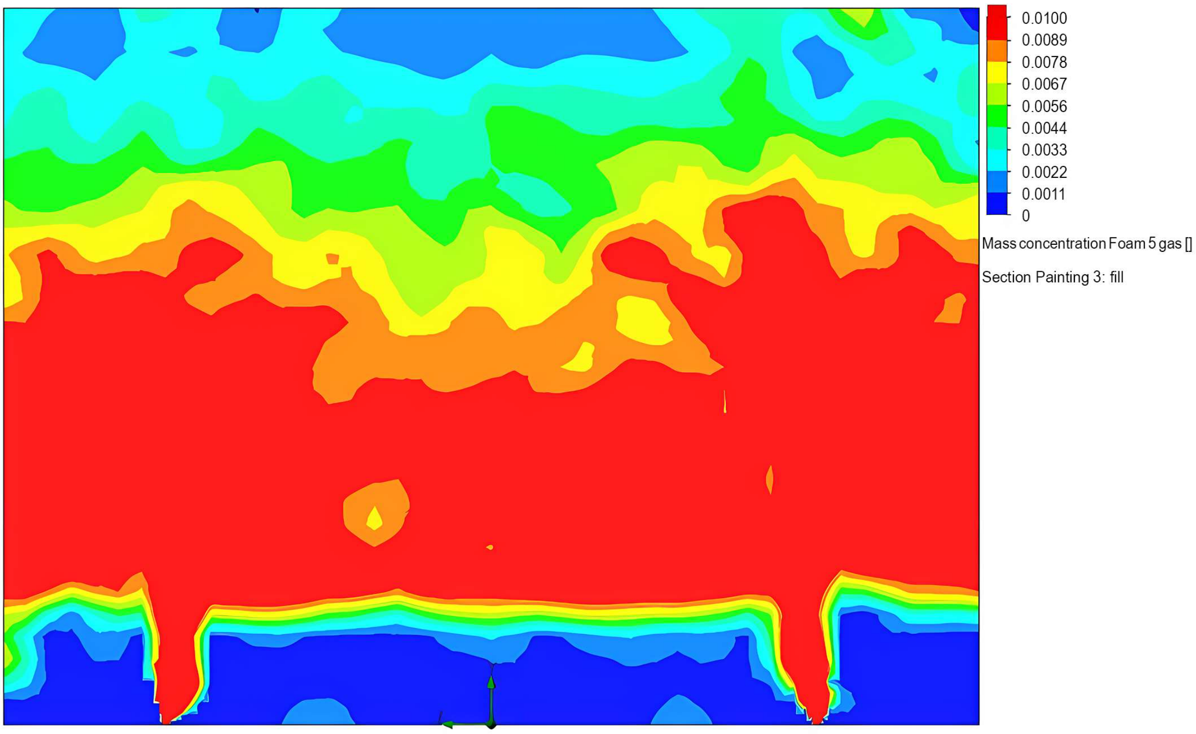

Fig. 17. Chromogram of foam 5 concentration per 900 s feed

Table 1

Results of the model study

Foam of different multiplicity at *P*, MPa	Foam supply time for quenching, s	Foam consumption, kg	Foam concentrate consumption, kg
K10 – 0.2	560	15,680	1,254
K10 – 0.3	410	17,220	1,377
K10 – 0.4	310	17,360	1,389
K5 – 0.3	598	25,116	4,019
K5 – 0.4	482	26,992	4,319

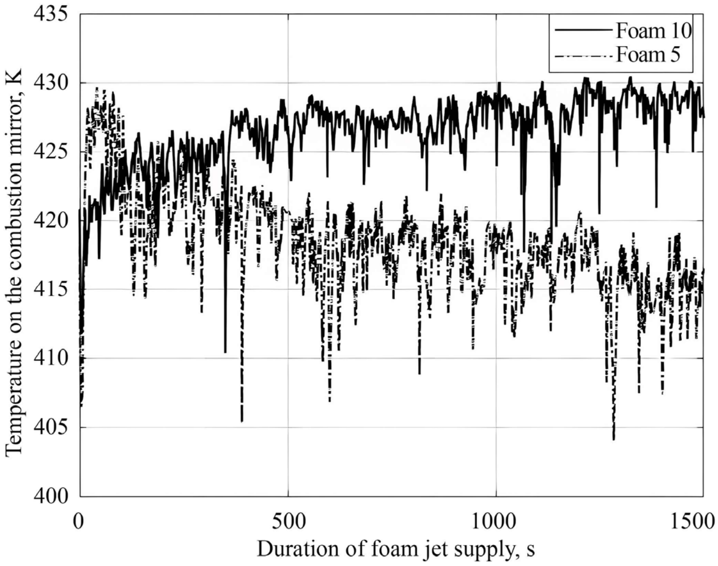

Fig. 18. Graphical dependence of the minimum temperature on the combustion mirror on the time of foam supply

6. Discussion of results of the simulation study on the supply of compression foam during the combustion of gasoline in the tank

As can be seen from Table 1, at a pressure of 0.2 MPa at the inlet to the tank, K5 foam does not come to the surface. The shortest time for the foam to reach the surface is 310 s for K10 foam at a pressure of 0.4 MPa. For K5 foam, this result at a pressure of 0.4 MPa is 482 s, which is 1.56 times longer. At a pressure of 0.4 MPa, 3.1 times more foaming agent is used for K5 foam than for K10 foam.

The research results are explained by the peculiarities of changes in the density of the petroleum product during combustion and its extinguishing. The behavior of compression foam in large tanks has not been studied. K10 foam, as well as K5 foam, rise to the surface of the combustion mirror unevenly (Fig. 12), with performance fluctuations. The flow rate of K10 foam is significantly higher than the consumption of K5 foam, which leads to a different amount of foam on the combustion mirror (Fig. 13). The mass of K10 foam on the combustion mirror is 8 times greater than the mass of K5 foam. That is, the K5 foam that did not reach the combustion mirror and is in the tank should be much more.

The graphical dependence in Fig. 14 shows how the volume of K5 and K10 foam accumulates in the tank from the time it is fed. The volume of foam 5 increases in proportion to the feeding time. At the same time, the volume of K10 foam increases disproportionately and after half the time (750 s), it begins to decrease, leaving the combustion mirror and partially turns into steam. Accordingly, K10 foam more intensively breaks through to the surface of the combustion mirror of the tank. At the end of the feed time, the K10 foam remains in the middle of the tank (in the gasoline itself) about 25 m3 for the 5000-tank extinguishing simulation case. The volume of K5 foam in the middle of the tank will be 95 m^3. That is, K10 foam more effectively participates in the extinguishing process (isolation of the combustion zone from flammable vapors, shielding ability). Foam with a multiplicity of K5 can hang in the middle of the tank (Fig. 15–17) and extinguish the tank fire more slowly.

Fig. 18 demonstrates that the rapid rise of the K10 foam does not cool the combustion mirror (the temperature rises), and the suspension of the K5 foam leads to a good heat exchange with gasoline and the temperature on the combustion mirror drops.

However, as shown by our results from the mathematical model research (Fig. 13), the foam does not rise to the surface during the first 2.5 minutes. From [13], the supply of foam to the surface is assumed to be 25 min. In 25 minutes, 1,900 kg of K5 foam and 14,000 kg of K10 foam came out on the burning mirror. A larger amount of K10 foam better isolates the combustible surface from the burning zone and facilitates extinguishing. With this amount (14,000 kg), it is possible to cover the combustion mirror of the 5,000 m^3 tank with a foam layer of more than 0.3 m, which is 3 times more than the required layer [13].

The disadvantage of the model is that the effect of water vapor on the flame is not taken into account. This leads to an inadequate model in which the foam does not break through to the surface of the combustion mirror within 25 min.

In reality, water vapor, making its way to the combustion surface, mixes with gasoline vapor, reduces the concentration of combustible vapors and oxygen, inerts the environment, which worsens its combustion. Also, the cooling of the environment on the mirror reduces the vaporization of gasoline, which also worsens the combustion process. That is, for successful modeling of the entire process of “underlayer” quenching, one more model is needed – a gas model behind a mirror. To compensate for its absence and improve the adequacy of the existing model, the following assumption was made: the supply of 28 kg/s of K10 foam for 5 min leads to a decrease in the temperature at the combustion mirror from 160 °C to 100 °C [12]. The shortcomings of the model, namely the impossibility of taking into account the phase transformations of foam and the influence of the mixture of water vapor and air on the process of gasoline combustion, do not affect the determination of the movement parameters of submerged foam jets. These shortcomings of the model affect the quantitative assessment of the "underlayer" quenching process as a whole, so this model needs further improvement.

The simulation results can be tested experimentally only on existing small tanks with a volume of 0.2 m^3. Therefore, we use simulation for compression foam, which is used for "sub-layer" extinguishing of large-volume tanks.

Failure to take into account the change in foam parameters during its boiling leads to an increase in the duration of foam exit to the combustion surface, which has experimental confirmation.

The model can be used for an approximate estimation of the movement parameters of air-mechanical foam in the environment of such liquids as gasoline, diesel fuel, fuel oil, etc. It allows one to evaluate the possibility of "sublayer" extinguishing of tanks and approximately determine such parameters as the required performance of foam supply, supply pressure, and time of foam exit to the combustion surface.

The adequacy of our results was assessed by their qualitative and quantitative comparison with data known from open sources regarding the processes of "underlayer" quenching, experimental studies [2, 3, 12, 13], and differs by up to 12 %.

Limitations of this study using the proposed model:

– quenching of tanks with oil product density less than 1000 kg/m^3;

– the size of the tank from 0.30 m to the size of real tanks 18 m and more in height. At a low height, the integrity of the foam layer is broken.

In further studies, it is necessary to pay attention to the techniques for supplying compression foam.

7. Conclusions

1. The model built in the SolidWorks Flow Simulations software environment adequately describes the movement of foam jets in a liquid fuel tank. The efficiency of "sublayer" extinguishing of a tank fire depends on the temperature of the heated gasoline; the sooner the extinguishing process (foam supply) begins, the higher the extinguishing efficiency will be. Another model is needed for successful modeling of the entire process of "sublayer" quenching – gas behind the combustion mirror.

2. The use of compression foam with a multiplicity of 10 for "sub-layer" fire extinguishing is much more effective than foam with a multiplicity of 5. The higher the multiplicity and productivity of foam supply, the higher the extinguishing efficiency will be: for K10, the time of foam supply is 1.55 times shorter, and the amount of used foaming agent in 3.1 times less than K5. The oil tank cannot be completely filled. Reserve volume of the tank is required. In the case of a burning duration of more than 30 minutes, the expansion of the oil product requires a reserve of the tank volume of at least 13 %. Under the condition of foam supply with a multiplicity of 10, the foam supply productivity is 56 kg/s.

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

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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