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BUILDING A MODEL OF CHOOSING WATER SUPPLY RATE TO COOL A TANK IN THE CASE OF A FIRE

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The object of this study is the process of liquid burning in a spill, and the subject of the study is the temperature distribution along the wall of a vertical steel tank when it is heated under the thermal influence of a fire and cooled by water. The conventional approach to cooling vertical steel tanks with petroleum products with water during a fire is based on cooling the wall along the entire half-perimeter from the fire side. Instead, it is proposed to cool only that part of the tank wall that is heated above a certain limit value. In this case, the intensity of water supply for cooling is chosen so that the temperature of the tank wall does not exceed this value. The proposed approach is based on a system of equations consisting of a heat balance equation for the tank wall, heat and mass balance equations for the water film flowing down the tank wall. These equations take into account heat exchange by radiation and convection with the fire and the environment. An optimization problem has been constructed, the criterion of which is the minimum water consumption, and the restriction is not exceeding the wall temperature of the specified limit value.

An algorithm for determining the optimal intensity of water supply for cooling the tank wall has been developed. At the first stage, a reasonable intensity of water supply is determined, which ensures that the wall temperature does not exceed the limit value. At the second stage, the dichotomy method is used to determine the minimum possible intensity at which the specified condition remains fulfilled. The example of a diesel fuel spill shows that the application of the proposed approach makes it possible to reduce water consumption for cooling the tank by almost 3.5 times. This, in turn, means reducing the number of equipment and personnel involved for localization and elimination of the fire

Keywords: spill fire, tank heating, heat flow, water cooling, optimization

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1. Introduction

The development of the world economy is inextricably linked with the consumption of raw materials and energy. The main raw material for the chemical industry is oil, and one of the sources of energy is liquid fuel, which is also the result of oil refining. The processes of extraction, transportation, and processing of oil and oil products are accompanied by a number of risks, such as spills, fires, explosions. The main problem of such emergencies is the "domino effect", when one event creates the prerequisites for the next. An example is the thermal effect of a fire on neighboring oil tanks, as a result of which their explosion or ignition is possible.

A significant number of emergencies that arise during the transportation, processing, and storage of oil and oil products begin with an accidental spill of liquid [1]. The main technique of storing oil and oil products is the use of vertical steel tanks. The thermal effect of the fire threatens to heat the steel structures of neighboring tanks to the autoignition temperature of the liquid stored in them. Another danger is the depressurization of flange connections and the loss of strength of supporting structures [2]. According to [3], about 44 % of large-scale fires in which the "domino effect" was observed began precisely with a fire in the tank or a spill fire. A similar result is reported in [4]: fires are the cause of about 43 % of accidents in which the "domino effect" occurs. At the same time, the most common scenario is a fire in the tank or a fire of a spill of an oil product.

The spread of fire to neighboring tanks not only leads to increased material losses but also poses a threat to the lives of personnel participating in extinguishing the fire. Another negative consequence of large-scale fires is the release of harmful substances into the atmosphere [5]. Spreading over long distances, they significantly affect the air quality and pose a danger to people [6]. Oil and oil product spills that are not accompanied by fires lead to soil, groundwater, and river water contamination [7].

Therefore, research aimed at devising methods to prevent the cascading spread of fire in tank farms is relevant.

2. Literature review and problem statement

In [8], the influence of the angle of inclination of the surface on the process of spreading and burning of the liquid was experimentally investigated. However, glass is used as the surface, as a result of which the influence of surface irregularities and penetration into it is ignored. In addition, the volumetric flow rate of the flammable liquid did not exceed 2.63 l/min, which makes it difficult to extend the results obtained in the laboratory setup to the case of a real spill. In [9], the spreading and burning of n-heptane in steel gutters 3 m long and 10 cm, 15 cm, 22 cm wide were experimentally investigated. The main difference between spreading on a steel sheet and soil is the greater thickness of the liquid layer on the soil due to the presence of irregularities and porosity. This, in turn, leads to a higher rate of liquid burning on the soil. However, the influence of the heat flow from the fire on neighboring objects was not considered in those works.

The estimation of the convection component of the heat flux by radiation from a spill fire was given in [10]; however, the consequences of the thermal effect of the fire on neighboring tanks were not considered here either. In [11], the thermal effect on steel structures was studied, but the characteristics of the combustion site that lead to a given value of the heat flux were not considered. In [12], the heat flux by radiation from burning tanks to neighboring tanks was studied using the FDS (fire dynamics simulator) simulation package. This makes it possible to determine the zones on neighboring tanks that are heated to dangerous temperature values, the location of forces and means for extinguishing the fire. However, the protection of tanks by cooling them with water was left out of consideration.

In [13], a model of the thermal impact of a fire on a tank with an oil product was constructed. The model takes into account the radiative and convective heat exchange of the tank wall with the fire, the internal space of the tank and the environment. By solving the system of heat balance equations, the temperature distribution along the tank wall and roof is determined. This makes it possible to find the areas on the tank that require cooling with water, as well as the limit time for the start of cooling. However, cooling itself is not considered in the work. In [14], the cooling of the tank wall by a water film flowing down it is additionally taken into account. Such a film can be formed both by stationary cooling rings on the tank and by supplying water to the tank wall by fire hoses. The constructed model is based on the heat and mass balance equation for the water film and takes into account the boiling of water. The proposed approach makes it possible to determine the temperature distribution along the tank surface at a given volumetric water supply intensity. But the inverse problem, i.e., the choice of such an intensity of water supply that ensures cooling of the tank surface to safe temperature values, is not considered in the work.

In [15] it is noted that there are no generally accepted dependences for determining the consequences of the thermal effect of a fire on a tank with an oil product. This, in turn, complicates the construction of models of cooling tanks with water since such parameters as wind speed, distance, and type of burning liquid must be taken into account. In order to reduce water consumption, it is advisable to use its uneven supply depending on the heat flux density falling on a given section of the tank wall. The study was conducted using the FDS modeling package, which complicates the generalization of the results and their use under conditions different from the given data.

In [16], cooling of the wall of a vertical steel tank by supplying water using hydromonitors located outside the embankment was considered. A model of water film cooling was constructed under the condition of a steady-state temperature distribution along the wall and the film. However, the possibility of reaching a steady state and the estimation of the time required for this are ignored. Another limitation is the assumption of no boiling of the water film during its flow down the wall. In [17] it was shown that, depending on the type of burning liquid, variations in the heat flux density reached 77 %. Doubling the distance between the fire and the tank by 30 % reduced the heat flux density from the fire. Water supply with an intensity of 2 l/(m^2 min) in some cases reduced the heat flux density by 50 %. But even in this work, the question of choosing the intensity of water supply for cooling remains unanswered.

All this gives grounds to argue that it is advisable to conduct research aimed at building a model for choosing the intensity of water supply for cooling a tank with an oil product under the thermal effects of a fire caused by a spilled flammable liquid.

3. The aim and objectives of the study

The aim of our work is to build a model for selecting the water supply intensity for cooling a tank with an oil product under the thermal effects of a fire caused by a spill of a flammable liquid. The peculiarity of the model is to determine the minimum possible water supply intensity, which ensures that the temperature of the tank wall does not exceed a certain limit value. In practice, this opens up opportunities for reducing water consumption for cooling tanks during fires at oil product warehouses. This, in turn, makes it possible to reduce the number of equipment and personnel involved.

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

– to determine the minimum sufficient water supply intensity for cooling the tank wall;

– to develop an algorithm for solving the optimization problem;

– to evaluate the effect of optimization compared to the conventional approach to cooling tanks.

4. The study materials and methods

The object of our study is the process of burning liquid in a spill, and the subject of the study is the temperature distribution along the wall of a vertical steel tank when it is heated under the thermal influence of a fire and cooled by water. The basic hypothesis of the study assumes that the temperature distribution along the surface of the tank and the water film can be described by their heat balance equations, which take into account the radiation and convection heat exchange with the fire and the environment. The main assumptions are the formation of a continuous water film flowing down the wall under the influence of gravity, the small thickness of the film and the tank wall compared to their linear dimensions.

A vertical steel tank for petroleum products was considered, which has the shape of a cylinder with a circular base. To determine the temperature distribution along the surface of the tank and the water film, a system of equations was used, consisting of a two-dimensional heat conductivity equation for the tank wall, mass and heat balance equations for the water film. The radiative and convective components of heat transfer were calculated using the heat transfer theory. The convective heat transfer coefficient of the water film with the tank wall was estimated using the methods of the theory of gravitationally flowing water films. The finite difference method was used to solve the system of partial differential equations. The method was implemented in the Delphi 12 programming environment (USA).

5. Results of building a model for selecting the water supply intensity for cooling a tank in the case of fire

5. 1. Determining the minimum reasonable water supply intensity for cooling the tank wall

The following inequality was used as a condition for the adequacy of cooling:

$$T(\phi,z,t) \le T_{max}; \quad 0 \le \phi \le 2\pi; \quad 0 \le z \le H, \tag{1}$$

where $T(\varphi, z, t)$ is the temperature at point (φ, z) on the wall surface of a vertical steel tank with height H at time t; T_{max}=const is the maximum permissible temperature of the tank wall. T_{max}=105 °C was chosen as such a value. At higher values of the wall temperature, the boiling process intensifies, as a result of which the water film is thrown off, unwetted areas are formed, and wedge-shaped jets appear [18].

Conventionally, cooling should be carried out along the entire semi-perimeter of the tank facing the fire. In this case, both regulatory documents [19] and individual studies proceed from a certain intensity of water supply, the same for the entire semi-perimeter. However, given the need to reduce water consumption, it is advisable not to supply water for cooling evenly along the length of the semi-perimeter but such that ensures meeting condition (1).

So, the optimization criterion is:

$$I(\phi) \to \min; \quad 0 \le \phi \le 2\pi, \tag{2}$$

where $I(\varphi)$ is the volumetric water supply intensity (l/(m·s)) for cooling the wall at a point on the upper edge of the wall with angular coordinate φ (Fig. 1). Criterion (2) together with condition (1) represent a mathematical statement of the problem of optimal selection of the water supply intensity for cooling a vertical steel tank under fire conditions. The result of its solution is the function $I(\varphi)$, which describes the distribution of the water supply intensity for cooling along the perimeter of the wall of a vertical steel tank.

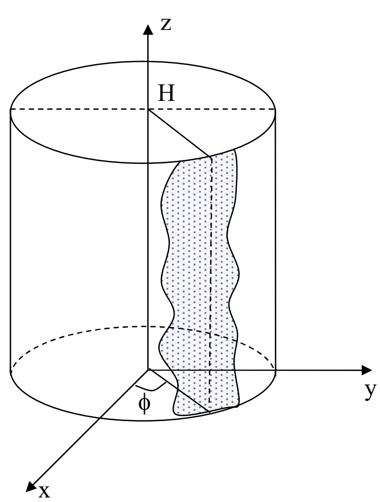

Fig. 1. Water supply to the wall of a vertical steel tank at a point with angular coordinate φ and its flow down the wall

The following function is introduced:

$$G(\phi,I) = \max_{\substack{0\le z\le H \\ 0\le t\le t_{max}}} \left(T_{max} - T(\phi,z,t,I)\right), \tag{3}$$

where $T(\varphi, z, t, I)$ is the temperature at point (φ, z) on the surface of the tank wall at time t under the condition of a constant water supply intensity I; t_{max} is the maximum time point up to which calculations of the temperature distribution along the wall are carried out. This time should be no less than the time for the wall temperature to reach a steady state. In the case of a fire caused by a spill of a flammable liquid, such a mode will occur after the spill reaches its maximum size. When calculating the values of $G(\varphi, I)$ it is assumed that the cooling of the wall with water begins simultaneously with the fire.

From the construction of the function $G(\varphi, I)$ it follows that at a fixed angle value $\varphi=\varphi_0$ the function $G(\varphi_0, I)$ is non-decreasing with respect to the water supply intensity I. In this case,

– $G(\varphi_0, I)<0$ corresponds to insufficient cooling water supply intensity;

– $G(\varphi_0, I)\geq 0$ corresponds to sufficient cooling water supply intensity.

From the above inequalities, as well as from the non-decreasing function $G(\varphi_0, I)$ in the variable I, it follows that the solution to the optimization problem (1), (2) is equivalent to solving the equation:

$$G(\phi,I) = 0; \quad 0 \le \phi \le 2\pi. \tag{4}$$

The solution to problem (4) is $I^*(\varphi)$ – the distribution of the water supply intensity along the perimeter of the tank. Problem (4) is the inverse of the problem of finding the temperature distribution along the surface of the tank wall at a given cooling water supply intensity.

5. 2. Construction of an algorithm for solving the optimization problem

The algorithm for determining the optimal water supply intensity for cooling the tank has the following form:

1. Choose the number of segments N into which the tank wall is divided along the perimeter.

2. Choose ε – the value of the permissible error in calculating the water supply intensity.

3. Choose the initial value of the water supply intensity I_0.

4. Calculate the temperature distribution over the tank surface in the absence of water cooling:

$$I_j^{(0)} = 0; \quad j = 0,1,\ldots,N-1; \quad I_j = I\left(\frac{2\pi j}{N}\right).$$

5. Using formula (3), calculate the value:

$$G_j^{(0)} = G\left(\frac{2\pi j}{N}, 0\right); \quad j = 0,1,\ldots,N-1.$$

6. For tank segments that require cooling, set the water supply rate I_0:

$$I_j^{(1)} = \begin{cases} 0, G_j^{(0)} \ge 0; \\ I_0, G_j^{(0)} < 0. \end{cases}$$

7. If all $I_j^{(1)} = 0$, j=0,1,..., N–1, then cooling is not required and the algorithm is completed.

8. Set k=1.

9. Calculate the temperature distribution over the surface of the tank at the selected cooling water supply intensity $I_j^{(k)}$.

10. Calculate the value from (3):

$$G_j^{(k)} = G\left(\frac{2\pi j}{N}, I_j^{(k)}\right); \quad j = 0,1,\ldots,N-1.$$

11. If:

$$G_j^{(k)} \geq 0, \quad j = 0,1,\ldots,N-1,$$

then the selected water supply intensities for cooling $I_j^{(k)}$ are sufficient; to select the optimal values, proceed to step 14.

12. Increase the water supply intensity for those segments where cooling was insufficient:

$$I_j^{(k+1)} = \begin{cases} I_j^{(k)}, G_j^{(k)} \geq 0; \\ 2 \cdot I_j^{(k)}, G_j^{(k)} < 0. \end{cases}$$

13. Set k:=k+1 and go to step 9.

14. Accept the limits for the cooling water supply rate:

$$I_{bj} = I_j^{(k)}; \quad j = 0,1,\ldots,N-1;$$

$$I_{aj} = \begin{cases} 0, I_j^{(k)} = I_0; \\ I_j^{(k-1)}, I_j^{(k)} > I_0; \end{cases} \quad j = 0,1,\ldots,N-1.$$

15. Calculate:

$$I_{cj} = \frac{1}{2}\left(I_{aj} + I_{bj}\right); \quad j = 0,1,\ldots,N-1.$$

16. Calculate the temperature distribution over the surface of the tank at the cooling water supply rate I_{cj}.

17. Calculate the value from formula (3):

$$G_j = G\left(\frac{2\pi j}{N}, I_{cj}\right); \quad j = 0,1,\ldots,N-1.$$

18. Narrow the limits of water supply intensity:

$$I_{aj} = I_{cj}, \text{ if } G_j < 0;$$

$$I_{bj} = I_{cj}, \text{ if } G_j \geq 0.$$

19. If $|I_{aj} - I_{bj}| < \varepsilon$ for all j=0,1,…,N–1, then go to the next step, otherwise proceed to step 15.

20. Accept as optimal:

$$I_j^* = I_{bj}; \quad j = 0,1,\ldots,N-1.$$

The presented algorithm for solving equation (4) makes it possible to determine the cooling water supply intensity $I^*(\varphi)$, which is the solution to the optimization problem (1), (2).

5. 3. Evaluating the effect of optimization compared to the conventional approach to tank cooling

As an example, Fig. 2 shows a spill of burning diesel fuel. The spill occurs on an inclined surface with an angle of inclination of 0.5° in the direction of the OX axis. The volumetric flow rate is 15 l/s. The flow of liquid is balanced by its burning and seepage into the soil, as a result of which the spill area asymptotically approaches its maximum value, which is about 200 m^2 (Fig. 3). The hydraulic conductivity of the wetted soil is taken to be 1.68·10^{-7} m/s; the capillarity index is 0.95 m; the soil porosity is 0.31; the average depth of irregularities is 1.7 cm [20].

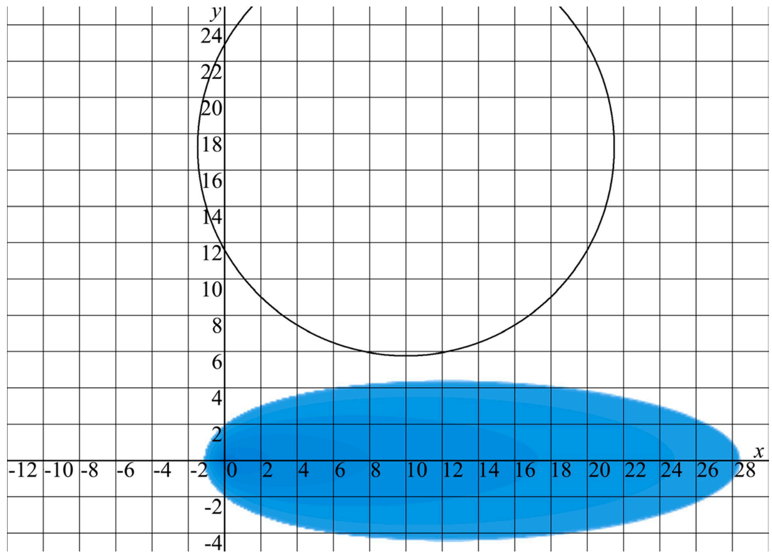

Fig. 2. Mutual location of the diesel fuel spill and the RVS-5000 tank 20 minutes after the start of the leak at a constant volumetric leak rate of 15 l/s

At a distance of about 4 m from the spillway, there is an RVS-5000 tank (diameter 23 m, height 12 m), filled with diesel fuel to a level of 4 m (Fig. 2).

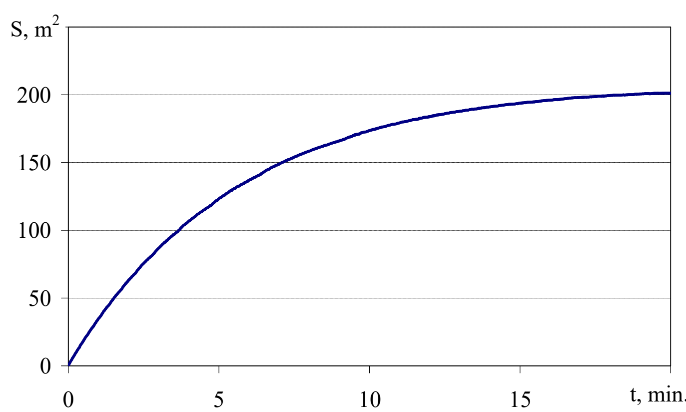

Fig. 3. Dynamics of change in spill area at a volumetric flow rate of diesel fuel of 15 l/s

Due to the thermal effect of the fire on the tank wall, its temperature in the absence of cooling exceeds 300 °C after 6 min. The results of solving the problem of optimal selection of the intensity of water supply for cooling the tank wall are shown in Fig. 4. The degree of blackness of the tank surface is taken equal to 0.5. In this case, the total water consumption for cooling the tank is 12.5 l/s.

In the event of a fire in a tank collapse, regulatory documents [19] recommend supplying water for cooling the tank wall with an intensity of 1.2 l/s. Figure 5 shows the distribution of the maximum temperature value along the tank perimeter when water is supplied with the regulatory intensity. In this case, the total water consumption for cooling is 42.4 l/s.

A comparison of the graphical dependences in Fig. 4, 5 shows that in both cases the maximum wall temperature was about 105 °C. But in the case of optimizing the supply intensity (Fig. 4), water consumption was almost 3.5 times lower compared to the case of standard intensity (Fig. 5).

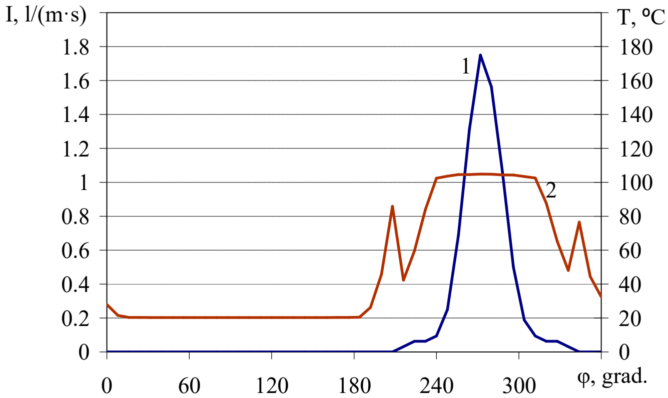

Fig. 4. Cooling of the RVS-5000 tank wall under the conditions of a diesel fuel spill fire: 1 — cooling water supply intensity along the tank perimeter; 2 — maximum wall temperature (on the right axis)

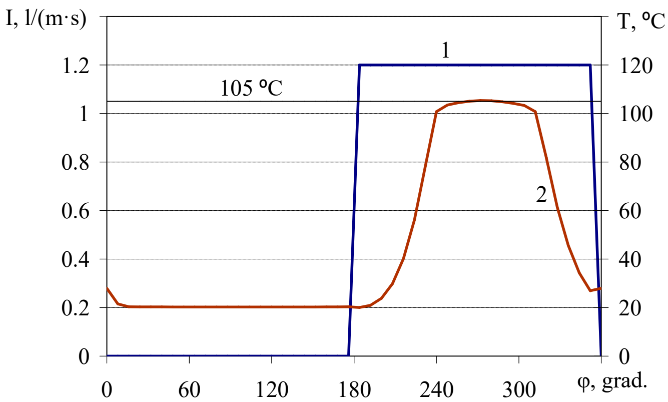

Fig. 5. Cooling of the RVS-5000 tank wall under the conditions of a diesel fuel spill fire in accordance with regulatory documents: 1 — cooling water supply intensity along the tank perimeter; 2 — maximum wall temperature (on the right axis)

Reducing water consumption is achieved by reducing the intensity of its supply in those areas of the tank wall that have a lower density of heat flux from the fire.

6. Discussion of results based on building a model for selecting the water supply intensity for tank cooling during a fire

The conventional approach to cooling vertical steel tanks with petroleum products with water during a fire is based on cooling the part of the wall facing the fire. In this case, cooling is carried out along the entire semi-perimeter with the same intensity, although the highest value of the heat flux density falls on the front part of the wall. Moving away from it, the heat flux density decreases. The same intensity of water supply to the entire wall, on the one hand, simplifies the design and implementation of tank cooling systems, but, on the other hand, it leads to excessive water consumption. In the case of using mobile equipment, excessive water consumption also means a larger number of equipment and personnel involved. This creates the prerequisites for determining the minimum possible water supply intensity that will ensure cooling the wall to a safe temperature value.

Inequality (1) corresponds to the condition that at any time the temperature at any point on the surface of the tank does not exceed a certain value $T_{\max}$. The temperature at which the steel surface of the tank can become an ignition source for oil vapors is about 200 °C and higher. But heating to much lower temperatures is also dangerous. Intensification of the boiling process when the wall temperature exceeds 105 °C leads to partial rejection of the water film and the formation of areas that are not covered with water. In such unprotected areas, the wall temperature can increase rapidly, reaching the autoignition temperature of oil vapors stored in the tank [13]. In the case when the wall temperature does not exceed 105 °C, unprotected areas on the wall do not occur [18].

Unlike the conventional approach to determining the intensity of water supply for cooling the tank [19], the solution to the optimization problem (1), (2) is not a single intensity value, but a function. This function depends on the angular coordinate φ (Fig. 1), i.e., the intensity of water supply is not uniform along the perimeter of the tank. The optimal intensity of water supply will be determined by the density of the heat flux from the fire, as well as the level of the oil product in the tank and its type. The effect of the oil product is associated with its cooling effect on the tank wall. The density of the heat flux from the spill fire, in turn, is determined by the geometric dimensions of the spill, the distance to the tank, the type of liquid, the direction and speed of the wind. All this makes it necessary to solve the optimization problem (1), (2) for specific conditions.

Function (3) for a given angular coordinate φ and water supply intensity I describes the difference between the maximum allowable temperature and its current value. If the cooling intensity is insufficient, the value of this function will be negative. Introducing function (3) makes it possible to move from the optimization problem (1), (2) to equation (4). Its solution gives the distribution of water supply intensity $I^*(\varphi)$ along the perimeter of the tank.

The proposed algorithm for solving equation (4) of water for cooling consists of four main modules:

– selection of model parameters (number of segments, permissible error value, initial value of cooling intensity – steps 1–3);

– determination of tank wall segments that require cooling (steps 4, 5);

– finding sufficient cooling intensity (steps 6–13);

– determination of the minimum possible water supply intensity that ensures cooling of the wall to safe temperature values (steps 14–20).

The value of the permissible error ε affects the number of iterations in steps 14–20, which makes it possible to estimate the complexity of the algorithm relative to it as O(–lnε).

The application of the proposed algorithm has been considered using an example of cooling a tank with oil product with water under the thermal impact of a spill fire (Fig. 2). Analysis reveals that optimizing the intensity of water supply for cooling makes it possible to reduce water consumption by almost 3.5 times compared to the regulatory intensity. This is due to the fact that meeting condition (1) only on a small area of the perimeter requires a high supply intensity – over 1.2 l/(m·s) (Fig. 4). On the other part of the perimeter, the cooling needs are much lower, or absent altogether. At the same time, regulatory documents proceed from a constant water supply intensity of 1.2 l/(m·s) (Fig. 5).

The advantage of the constructed model for selecting the intensity of water supply for cooling a tank under the thermal impact of a spill fire is that it makes it possible to minimize water consumption while maintaining cooling at a sufficient level. This, in turn, makes it possible to reduce the number of equipment and personnel involved.

The limitations of the model include the condition of a small thickness of the tank wall and water film compared to their linear dimensions.

The disadvantage of the constructed model is that it does not take into account the reflection of part of the water when the jet hits the tank wall. Thus, the prospects for further research are related to taking into account the water utilization factor and determining its dependence on jet parameters.

The proposed model for determining the intensity of water supply for cooling a tank with an oil product under fire conditions can be used both for making decisions about tank cooling and for designing tank cooling systems.

7. Conclusions

1. The minimum sufficient water supply intensity for cooling the tank wall under fire conditions has been determined. The proposed approach is based on the heat balance equation for the steel wall and the heat and mass balance equation for the water film flowing over it. The calculation of the water supply intensity is reduced to solving an optimization problem, the criterion of which is the minimum water consumption, and the restriction is that the tank wall temperature does not exceed a certain limit value. The value of 105 °C is proposed as such a value. At higher values of the wall temperature, boiling in the water film intensifies to such an extent that it leads to the destruction of a continuous film and the appearance of separate areas that are not cooled by water.

2. An algorithm for determining the optimal water supply intensity for cooling the tank wall has been developed. At the first stage, a reasonable water supply intensity is determined, which ensures that the wall temperature does not exceed the limit value. At the second stage, the minimum possible intensity is determined by the dichotomy method, at which the specified condition remains fulfilled. It is shown that the complexity of the algorithm depends on the permissible absolute error of determining the water supply intensity ε as $O(-\ln\varepsilon)$.

3. Using the proposed approach to cooling tanks makes it possible to increase the efficiency of the use of forces and means. Using an example of a diesel fuel spill fire, it is shown that at the optimal water supply intensity, its consumption is reduced by almost 3.5 times compared to the conventional approach. This, in turn, means a decrease in the number of equipment and personnel involved in the localization and elimination of the fire. This effect can be achieved due to a lower intensity of water supply to areas that are less exposed to thermal impact.

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, as well as 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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