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MODEL FOR CHOOSING OPTIMAL WATER FLOW RATE FOR TANK WALL COOLING

In this paper, we have considered the problem of choosing the optimal water flow rate for cooling the tank wall with water in the event of a fire in the adjacent tank. The optimal water flow rate is understood as the minimal flow ensuring a sufficient level of cooling. The choice of the water flow rate is based on the solution of the thermal balance equation for the tank wall and the thermal balance equation for the water film. The model takes into account the radiant heat transfer between the flame, the tank wall, the environment and the internal space of the tank. The convective heat transfer from the tank wall to water and vapor-air mixture is also taken into account. Here, we have developed an algorithm for determining the optimal water flow for cooling the tank wall. Solving the problem of choosing the rate of the cooling water flow is reduced to the sequential solution of the problems to determine the temperature distribution along the tank wall and the water film. We have constructed the functional dependence of optimal water flow rate for tank cooling on the direction and velocity of the wind. The inclination of the flame by the wind towards the adjacent tank increases the relevant heat influx, which requires a greater intensity of cooling. On the contrary, when the direction of the wind is away from the adjacent tank, the heat flux decreases. At the same time, for wind velocity greater than a certain value, the heat flux decreases to such an extent that there is no more need to cool the walls of the adjacent tank. With the perpendicular direction of the wind, at certain velocity values, there is no need to cool the walls of the adjacent tank either. The obtained results can be used to determine the rate of water flow for cooling the tank wall in the event of a fire in an adjacent tank.

Keywords: tank fire, thermal influence of fire, heat transfer, water cooling, water flow rate

1. Introduction

Tanks and tank farms are the main facilities for storing oil and petroleum products. They make part of process flow designs for oil gathering and preparation facilities, trunk petroleum product pipelines, oil refineries, transshipment and distribution depots and other enterprises. The most common type of tanks are aboveground vertical steel tanks (VST) made of steel sheets. VSTs account for about 95 % of the global storage volume for oil and petroleum products in tank farms. Large amounts of combustible and flammable liquids accumulated on a relatively small area carry a high level of fire hazard. A fire in a tank or within its dike often leads to an escalating spread of fire [1]. According to [2], about 44 % of large-scale fires associated with a domino effect began with a fire in a tank or with a spill fire. Statistical analysis of domino accidents shows [3] that the most frequent causes are external events (31 %) and mechanical malfunctions (29 %). In total, 63 % of accidents are associated with large storage tanks, 35 % occurring at storage facilities, and 28 % at process plants. At the same time, accidents with a domino effect most often involved LPG and liquid hydrocarbons [4]. The reason for the escalating spread of fire is the heating of the steel structures of the adjacent tanks to the autoignition point of the stored product. This can lead to an explosion of the vapor-air mixture in the gas space of the tank or to fires at the breather vents. The situation of the first type occurs if the concentration of the petroleum product vapors in the gas space of the tank lies within the lower and upper concentration limits of flame propagation. The situation of the second type occurs if the concentration of vapors in the gas space exceeds the upper concentration limit of flame propagation.

Thus, the problem of the spread of fire to neighboring tanks as a result of the heat influx remains relevant.

2. Analysis of literary data and problem statements

In [5], turbulent combustion of heptane is simulated and compared against experimental data on its combustion in a 7,1 cm laboratory pool. Based on the fuel and the pool diameter, the inlet power is 4,0 kW. It is noted that under such conditions there is a significant radiant fraction of approximately 29 % caused by strong sooting propensity of the target pool fire. However, the influence of thermal radiation on the neighboring objects is not considered. In [6], an improved model of thermal radiation from a fire is introduced, based on the perception of a flame as a solid cylinder of fire. Based on experimental studies of oil burning in a tunnel and in an open space, an additional coefficient is introduced to align the predicted and test data. The disadvantage of the work is the binding of the coefficient to the specific experiment conditions and the difficulty of transferring it to other conditions. In [7], the effect of a 1 m crude oil pool fire and 30 m and 50 m diameter kerosene pool fires on adjacent tanks was investigated using a Fire Dynamics Simulator (FDS) environment. A conclusion was made about the possibility of a domino effect due to the heating of adjacent tanks to critical temperatures. The disadvantage of this research is the impossibility of generalizing the obtained results to other conditions.

A specific model is developed in [8], taking into consideration flame pulsations. The influence of the heat flux from the adjacent fire on the strength of the tank structures is studied. However, the consequences of heating steel structures to the self-ignition temperature of petroleum product vapors is not considered. In [9], a CFD model of a large LPG fire is built, the power of thermal radiation transferred to the liquid surface and to the environment is determined, which makes it possible to estimate the safe distances between the fire and adjacent objects. However, the protection of the objects exposed to thermal radiation is not considered in the paper. In [10], an FDS model of the thermal effect of a fire on an adjacent petroleum tank is built, and the zones of safe placement of fire-fighting assets are calculated. However, the obtained results are impossible to generalize to other cases.

In [11], an experimental and quantitative study is made of the liquid leaking from the tank and burning. However, the impact of the fire on the adjacent tank is not considered. In [12], the thermal effect of a fire in a tank on a similar adjacent tank with a petroleum product is studied. A model of the tank heating is built, taking into account the radiant heat transfer from the flame and the heated walls of the burning tank. The temperature distribution inside the tank wall is determined. However, the convective heat transfer is not studied in the paper. The model of thermal effect of the dike fire on the next tank is built in [13]. The model takes into account both the radiant and convective heat transfer. However, the paper does not address the case of a tank fire. The model of thermal effect of the tank fire on the adjacent tank is built in [14]. The model takes into account the inclination of the flame under the influence of the wind; however, the protection of the adjacent tank is not considered. In [15], a model of the thermal effect of a fire on a petroleum tank is built and the weakening of the shell material is studied. At the same time, the issue of protecting the tank is not addressed there as well. In [16], a two-zone model of the thermal effect of a flame on an adjacent petroleum is proposed. This paper takes into account the higher temperature of the lower part of the flame and lower temperature of its upper part. However, it also does not address the protection of the adjacent tank being heated by the fire.

In [17], a model of the tank cooling with a water film flowing down the tank wall is constructed. The model takes into account convective heat transfer between the wall and the water film, radiant heat transfer from the flame and the environment, as well as radiant and convective heat transfer from the gas space of the tank. However, the selection of the water flow rate for cooling is not studied. In [18], the cooling of the tank with the help of fire monitors is considered, resulting in the heat balance equation for the tank wall and the flowing water film. At the same time, the steady-state temperature distribution providing the basis to determine the adequacy of the cooling water flow rate was not considered in the paper.

The analysis of the thermal effect models of tank fires on adjacent tanks proves that the problem of cooling adjacent tanks with water remains insufficiently studied. This, in turn, can lead to errors in estimating the required water flow rates for cooling the tank walls.

Thus, we identified an unsolved part of the problem of fire spreading to adjacent tanks due to heat flux as the lack of data on the rates of water flow to the tank walls to ensure adequate cooling.

3. The purpose and tasks of the research

The purpose of this research is to develop a model of the optimal water flow rate for cooling the tank wall in the event of a fire in a adjacent tank.

To achieve this goal, the following tasks must be solved:

– set the problem of optimal flow rate selection for cooling the tank wall, based on the heat balance equations;

– develop an algorithm for solving the problem of optimal flow rate selection for cooling the tank wall;

– solve the problem of optimal flow rate selection for cooling the tank wall for typical petroleum products.

4. Research materials and methods

The object of the research is the process of the vertical steel tank wall cooling with a water film in the event of a petroleum product fire in a similar adjacent tank. The main premise of this research is the uniform movement and thickness of the water film along the tank wall. The finite difference method was used to numerically solve the system of heat balance equations. The dichotomy method was used to find the optimal value of the cooling water flow rate. The computational algorithm was constructed in the Delphi (Community Edition) software environment. The calculations were carried out on the example of the fixed – roof RVS-10000 tank (diameter 28,5 m, height 18 m).

5. Results of building a model for the optimal cooling water flow rate

5.1. Setting the problem of the optimal water flow rate selection for tank cooling

Let us consider a crude oil fire in the RVS-10000 tank in the absence of wind. At a standard distance (21 m), there is another tank filled with petroleum product up to a level of 9 m. Therefore, the height of the wall above the level of the petroleum product shall be L=9 m. To estimate the thermal effect of the fire on the tank, we will use the model built in [17]. Fig. 1 shows the temperature distribution along the height of the tank wall in the part facing the fire and above the petroleum product level. Fig. 2 shows temperature distribution along the water film flowing down the wall. The initial temperature of the water supplied for cooling is taken as T_0=20 ºC.

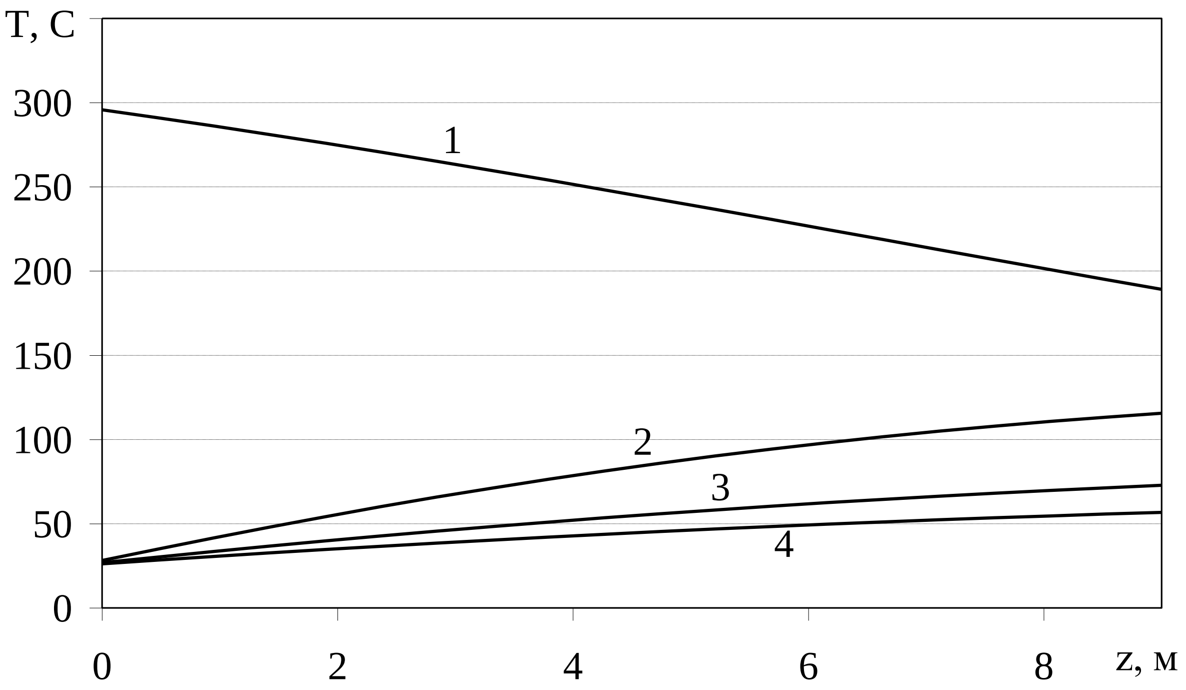

Fig. 1. Temperature distribution along the height of the RVS-10000 tank wall after 20 min. of exposure to the crude oil fire in a similar adjacent tank at different values of the cooling water flow rate: 1 – I=0; 2 – I=0,2 l/(m·s); 3 – I=0,4 l/(m·s); 4 – I=0,6 l/(m·s)

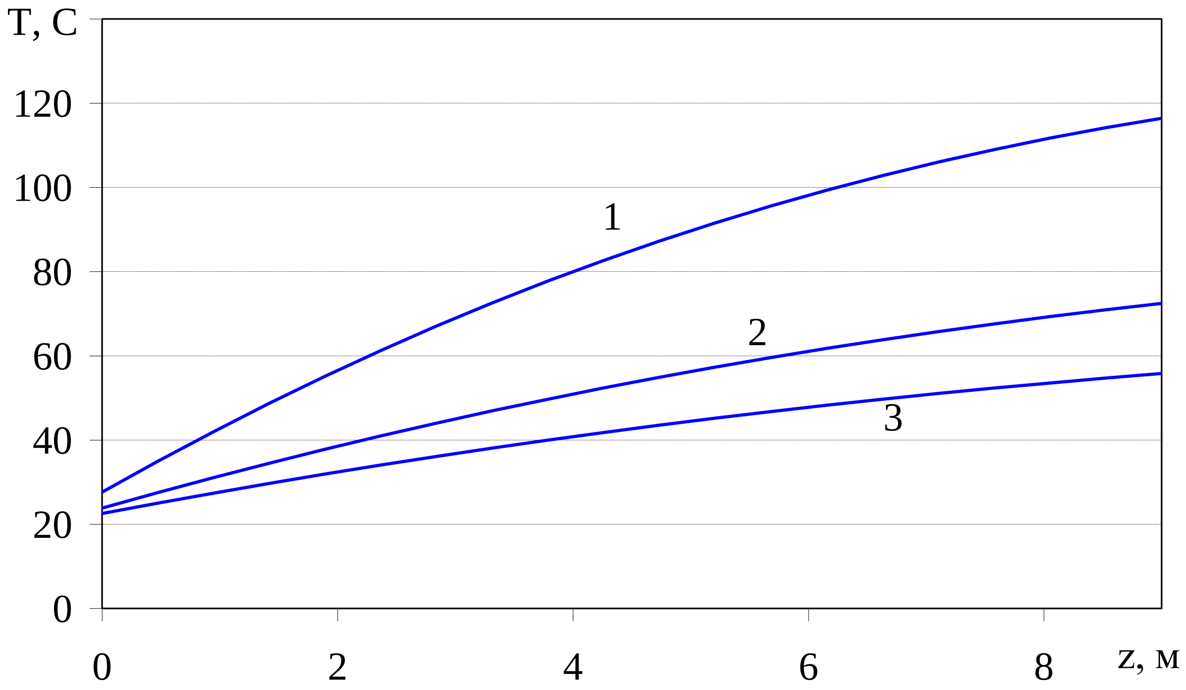

Fig. 2. Temperature distribution along the water film flowing down the wall of the RVS-10000 tank after 20 min. from the start of the crude oil fire in a similar adjacent tank at different values of the cooling water flow rate: 1 – I=0,2 l/(m·s); 2 – I=0,4 l/(m·s); 3 – I=0,6 l/(m·s)

The optimal water flow rate shall be understood as such a flow rate, which, on the one hand, ensures minimum water consumption:

$$I \to \min , \tag{1}$$

and on the other hand, ensures meeting the the following conditions:

- the wall temperature should not exceed the maximum permissible value $T_{out\ max}$

$$T^*_{out}(z_i) \le T_{out\ max}; \tag{2}$$

- the temperature of the water film should not exceed the maximum permissible value $T_{c\ max}$

$$T_c(z_i) \le T_{c\ max}. \tag{3}$$

The optimal water flow rate will be determined by the fulfillment of the conditions (2) and (3), which in turn depend on a number of factors:

- type of burning liquid;
- wind direction and velocity;
- petroleum product level in the heated tank.

The level of the product in the heated tank affects the height of the free wall above the level of the oil product. It is this part of the wall that needs cooling. The most challenging case in terms of cooling is a low level of the petroleum product, because then it is necessary to ensure the fulfillment of conditions (2), (3) along the entire height of the tank wall. According to the analysis made in [19], vertical steel tanks used to store crude oil and petroleum products with a volume of 1000 m^3 (RVS-1000) and more have a height of 12 m or 18 m.

The type of burning liquid determines the height of the flame, the temperature of the emitting surface of the flame and its emissivity factor. The inclination of the flame by the wind changes the irradiation coefficient between the flame and the adjacent tank, thereby affecting the heat flux density from the fire. The tank adjacent to the fire will need the most cooling when the wind is directed from the fire towards this tank.

In [14], it is shown that in a tank group of identical vertical steel tanks, with a capacity of up to 20,000 m^3, in dimensionless coordinates, the irradiation coefficient depends only on the type of burning liquid, direction and velocity of the wind, and does not depend on the capacity of the tanks. This means that for tank farms with the single tank capacity of up to 20,000 m^3, it is sufficient to carry out calculations for arbitrary tanks with heights of 18 m and 12 m.

Therefore, the input parameters for the problem of the optimal cooling flow rate selection are the following:

- type of burning liquid;
- height of the tank wall to be cooled (12 m or 18 m);
- wind velocity.

5.2. Algorithm for solving the problem of optimal cooling water flow rate selection

Let us denote as F(I) the difference between the maximum water temperature on the tank wall at a given flow rate I and the maximum permissible temperature $T_{c\ max}$ of the water flowing down the wall:

$$F(I) = \max_{z,\varphi} T_c(z,\varphi) - T_{c\ out}. \tag{4}$$

Then, the algorithm for solving the problem of optimal flow rate selection will be the following.

1. We set the maximum permissible error ε and the maximum permissible water temperature $T_{c\,max}$.

2. We choose such a value of the water flow I_b, which is guaranteed to provide cooling to the required level, for example, $I_b = 2$ l/(m·s).

3. We calculate the value

$$F_a = F(I_a);\; F_b = F(I_b).$$

4. If

$$|I_a - I_b| < \varepsilon,$$

then we go to step 9.

5. We calculate

$$I_c = \frac{I_a + I_b}{2};\; F_c = F(I_c). \tag{5}$$

6. If $I_c < 0$, then we suppose

$$I_b = I_c;\; F_b = F_c. \tag{6}$$

7. If $I_c > 0$, then we suppose

$$I_a = I_c;\; F_a = F_c. \tag{7}$$

8. If $I_c = 0$, then go to step 9, otherwise go to step 4.

9. The optimal flow rate is

$$I^* = \frac{I_a + I_b}{2}.$$

Thus, by executing the above algorithm we obtain the optimal value I^* for the water flow rate.

5.3. Solving the problem of optimal water flow rate selection for typical petroleum products

Fig. 3 shows the dependence of the optimal cooling water flow rate on the wind velocity for the crude oil fire in a similar adjacent tank. For the calculations, it was assumed that the tanks are at a distance of 0,75D from each other (D being the diameter of the tank); the wind is directed from the burning tank towards the adjacent one, which needs to be cooled. The temperature of the flame radiating surface and its emissivity factor were taken as T_f=1100 ºC, ε_f=0,85, respectively. The maximum permissible water temperature on the tank wall $T_{c\,max}$=95 ºC; the maximum error in determining the water flow rate is ε=0,001 l/(m·s). The decision about the need for cooling was made if the temperature of the tank surface exceeded $T_{out\,max}$=120 ºC.

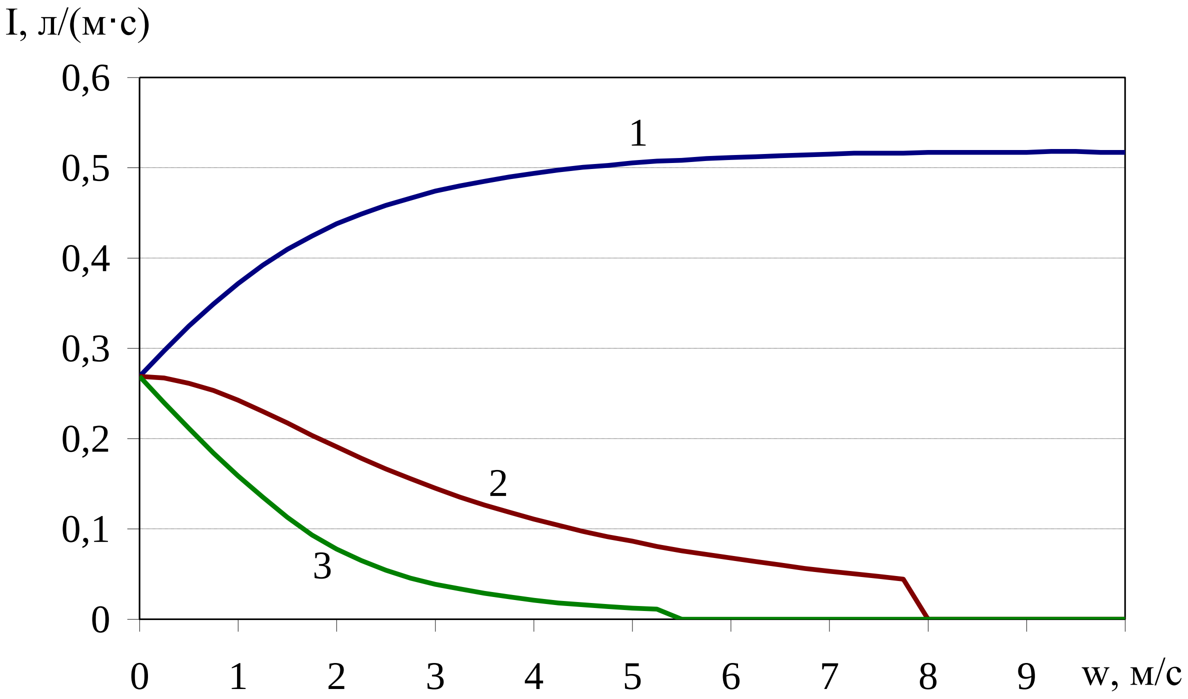

Fig. 3. Optimal water flow rate to cool the tank in the event of a crude oil fire in a similar adjacent tank, depending on the wind velocity: 1 – the wind is directed from the burning tank towards the adjacent one; 2 – the wind is directed perpendicular to the direction of the nearby tank; 3 – the wind is directed in the opposite direction from the adjacent tank

Fig. 4 shows the dependence of the optimal cooling water flow rate on the wind velocity for the gasoline fire in a similar adjacent tank. Here, the temperature of the flame radiating surface and its emissivity factor were taken as T_f=1200 ºC, ε_f=0,97, respectively.

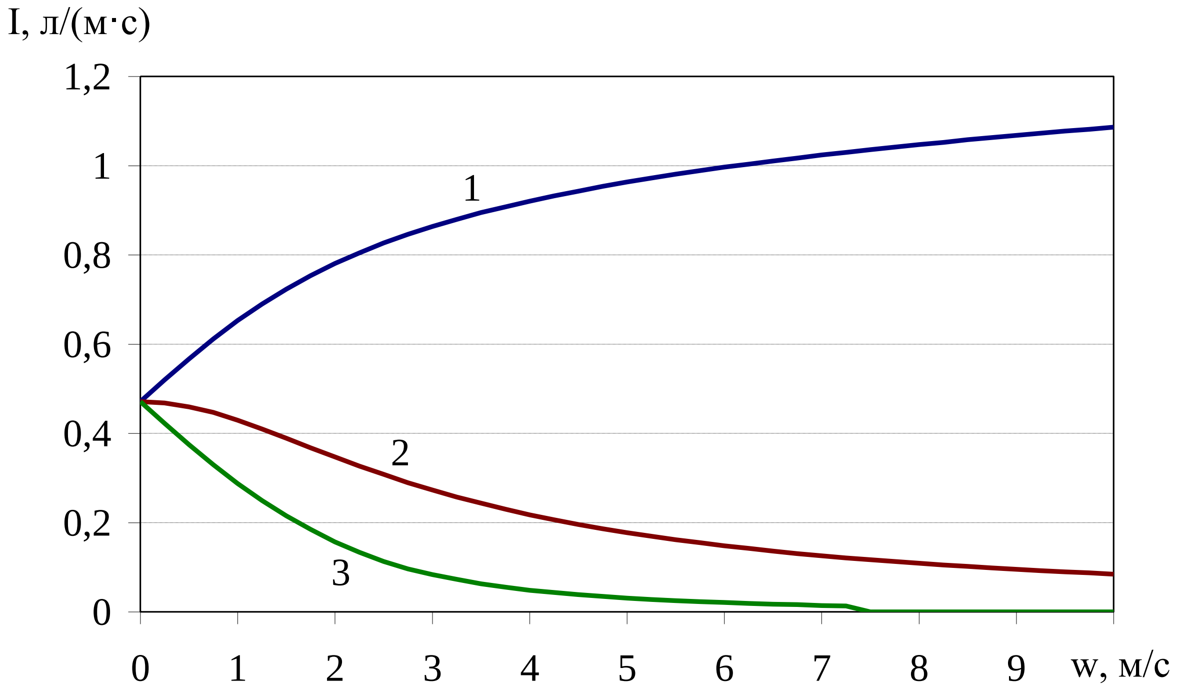

Fig. 4. Optimal water flow rate to cool the tank in the event of a gasoline fire in a similar adjacent tank, depending on the wind velocity: 1 – the wind is directed from the burning tank towards the adjacent one; 2 – the wind is directed perpendicular to the direction of the nearby tank; 3 – the wind is directed in the opposite direction from the adjacent tank

Fig. 5 shows the dependence of the optimal cooling water flow rate for the diesel fuel fire in a similar adjacent tank. The temperature of the flame radiating surface and its emissivity factor were taken as T_f=1100 °C, ε_f=0,95, respectively.

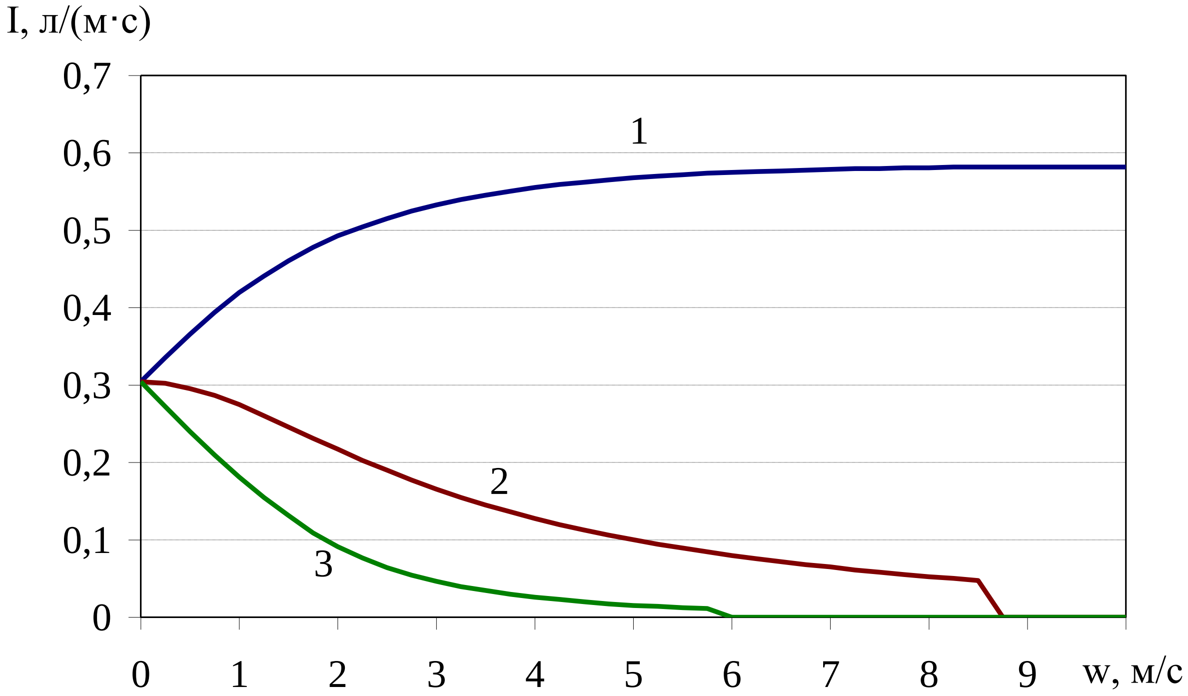

Fig. 5. Optimal water flow rate to cool the tank in the event of a diesel fuel fire in a similar adjacent tank, depending on the wind velocity: 1 – the wind is directed from the burning tank towards the adjacent one; 2 – the wind is directed perpendicular to the direction of the nearby tank; 3 – the wind is directed in the opposite direction from the adjacent tank

The lower temperature of the flame in a diesel fuel fire, as well as its shorter height compared to gasoline, result in a lower density of heat flux from the fire to the nearby tank. This, in turn, makes it possible to reduce the water flow rate for cooling the adjacent tank (Fig. 5).

6. Discussion of the results of building the optimal cooling water flow model

Equation (1) describes the temperature distribution at the midpoint of the tank wall exposed to the heat flux of a fire and being cooled by a water film flowing down the tank wall. Such a film can be formed by stationary cooling rings or by spraying water through a water cannon or fire monitors A, B. Boundary conditions (2), (3) together with the temperature distribution equation in the water film (4) take into account the radiant heat transfer from the flame and the environment, the convection heat transfer of the outer wall surface with the water film.

The analysis of graphical dependencies shown in Fig. 1 suggests that the greatest cooling effect occurs at the upper edge of the wall where the water enters. As water flows down the wall, its temperature rises (Fig. 2) and its cooling effect decreases. A comparison of the temperatures of the wall (Fig. 1) and of the water film on it (Fig. 2) shows the closeness of these values. From Fig. 2, it follows that at the flow rate of I=0,2 l/(m·s), the cooling water on the wall reaches the boiling temperature at a distance of $z_c\approx6{,}2$ m from the upper edge of the tank. Boiling leads to the repulsion of the water film from the surface of the tank wall. As a result, the cooling efficiency decreases sharply. This means that the lower part of the tank wall does not receive cooling and its temperature can reach the same values as in the absence of cooling – T_{out}=(190÷225) ºC (line 1 in Fig. 1). Therefore, water flow rate I=0,2 l/(m·s) is insufficient to cool this tank. At the flow rate of I=0,4 l/(m·s) or I=0,6 l/(m·s) such a problem is not observed – the water film does not reach the boiling temperature (lines 2, 3 in Fig. 2). Thus, cooling is sufficient in these cases.

It is advisable to choose the minimum value from the range of water flow rate values that are sufficient to meet cooling (conditions (6), (7)). Therefore, the optimization criterion takes the form of (5).

The problem of optimal water flow rate selection for tank cooling is the inverse of the problem of determining the temperature of the tank wall subjected to water cooling (8). This allows us to present the solution process as a sequence of direct problem solutions, leading to the water flow rate for cooling being obtained. The above algorithm is based on the dichotomy method. First, the temperature distribution is calculated in the absence of water cooling of the wall, and with a guaranteed sufficient flow rate (for example, 2 l/(m·s)). Then the temperature distribution at the average flow rate value (9) is calculated, which makes it possible to halve the search range – (10), (11). The process ends when the width of the range does not exceed the a priori given value ε. In particular, for the given conditions and ε=0,001, the execution of the given algorithm requires $\log_2 2000 \approx 11$ iterations.

The burning of gasoline is characterized by a higher flame, a greater emissivity factor of its surface, and a higher temperature compared to crude oil. This results in a higher heat flux density values to the adjacent tank. As a result, the required water flow rate for cooling the adjacent tank increases (Fig. 3, Fig. 4).

The inclination of the flame by the wind towards the adjacent tank increases the heat flux, which requires a greater intensity of cooling (Fig. 3 – Fig. 5). On the contrary, when the direction of the wind is away from the adjacent tank, the heat flux decreases. At the same time, for wind velocity values of any direction greater than a certain value (5,5 m/s for crude oil, 7,5 m/s for gasoline, 6 m/s for diesel fuel), the heat flux density decreases so much that the need to cool the walls of the adjacent tank disappears.

The inclination of the flame in a perpendicular direction from the adjacent tank leads to a decrease in the heat flux to the adjacent tank due to a decrease in the height of the flame and its deviation from the tank exposed to heating. This result qualitatively coincides with the conclusions given in [20]. At the same time, for wind velocity values greater than 8 m/s for crude oil and 8,5 m/s for diesel fuel, the heat flux density decreases so much that the adjacent tank does not need cooling.

The limitation of the constructed model is that it is based on the steady-state temperature behavior of the water film.

Prospects for further research are related to taking into account transient processes in the water film and building a non-stationary model of tank wall cooling.

7. Conclusions

1. We have formulated the problem of optimal flow rate selection for cooling the tank wall based on the heat balance equations. The optimal water flow rate is understood as such flow rate which minimizes water consumption, at the same time ensuring a sufficient level of tank cooling. In particular, in the event of a crude oil fire in steel tanks with a capacity of up to 20,000 m^3 and subject to regulatory distances between the tanks, with a cooling water flow rate of 0,2 l/(m·s), the water on the wall reaches the boiling temperature at a distance of 6,2 m from the upper edge of the tank, resulting in

sharp deterioration of the cooling performance. At flow rate of 0,4 l/(m·s), such a problem is not observed – the temperature of the water film and the walls does not exceed 80 ºC.

2. Here, we have developed an algorithm for determining the optimal water flow for cooling the tank wall. The above algorithm is based on the dichotomy method. For each iteration of the algorithm, the water flow range containing the optimal value decreases by a factor of 2. This means, that in order to determine the optimal flow rate with an error of no more than 0,001 l/(m·s), it is enough to perform 11 iterations, given that the width of the initial range does not exceed 2 l/(m·s).

3. The problem of choosing the optimal water flow rates for tank cooling has been solved on the examples of fires in adjacent tanks with crude oil, gasoline and diesel fuel. We have constructed the functional dependence of optimal water flow rate for tank cooling on the direction and velocity of the wind. The inclination of the flame by the wind towards the adjacent tank increases the relevant heat influx, which requires a greater intensity of cooling. On the contrary, when the direction of the wind is away from the adjacent tank, the heat flux decreases. At the same time, for wind velocity values of any direction greater than a certain value (5,5 m/s for crude oil, 7,5 m/s for gasoline, 6 m/s for diesel fuel), the heat flux density decreases so much that the need to cool the walls of the adjacent tank disappears. For the wind blowing at the perpendicular direction, and velocity values of more than 8 m/s for crude oil and 8,5 m/s for diesel fuel, there is no need to cool the walls of the adjacent tank either.

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МОДЕЛЬ ВИБОРУ ОПТИМАЛЬНОЇ ІНТЕНСИВНОСТІ ПОДАЧІ ВОДИ НА ОХОЛОДЖЕННЯ СТІНКИ РЕЗЕРВУАРА

Розглянуто оптимальний вибір інтенсивності подачі води на охолодження стінки резервуара водою в умовах пожежі в сусідньому резервуарі. Під оптимальною інтенсивністю подачі води розуміється така інтенсивність її подачі, яка мінімізує витрати води, забезпечуючи при цьому достатній рівень охолодження. Вибір інтенсивності подачі води спирається на розв'язання рівняння теплового балансу стінки резервуара і рівняння теплового балансу для водної плівки. Модель враховує теплообмін випромінюванням стінки з факелом, навколишнім середовищем і внутрішнім простором резервуара. Також враховано конвекційний теплообмін стінки з водою і пароповітряною сумішшю. Побудовано алгоритм визначення оптимальної інтенсивності подачі води на охолодження стінки резервуара. Розв'язання задачі вибору інтенсивності подачі води на охолодження зводиться до послідовного розв'язання задач визначення розподілу температур по стінці резервуара і водній плівці. Побудовано залежності оптимальної інтенсивності подачі води на охолодження резервуара від напряму і швидкості вітру. Нахил факела вітром в бік сусіднього резервуара збільшує щільність теплового потоку до нього, що потребує більшої інтенсивності охолодження. Навпаки, коли напрям вітру є протилежним напряму на сусідній резервуар, то щільність теплового потоку зменшується. При цьому для значень швидкості вітру більше певної величини щільність теплового потоку зменшується настільки, що зникає необхідність охолодження стінок сусіднього резервуара. При перпендикулярному напрямку вітру для певних значень швидкості необхідності в охолодженні стінок сусіднього резервуара також немає. Отримані результати можуть бути використані для визначення інтенсивності подачі води на охолодження стінки резервуара при пожежі в сусідньому резервуарі.

Ключові слова: пожежа в резервуарі, тепловий вплив пожежі, теплообмін, охолодження водою

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