The object of this study is the process of liquid combustion in spillage, and the subject is the temperature distribution along the wall of a vertical steel tank when it is heated under the thermal influence of fire and cooled by water. A system of equations describing the water cooling of the wall of a vertical steel tank under the conditions of the thermal effect of a fire spilling a flammable liquid has been constructed. The system consists of a heat balance equation for the tank wall, a heat balance equation for the water film flowing over the wall, and a mass balance equation for the water film. The equations take into account the radiative heat exchange with the flame, the environment, the internal space of the tank, as well as the convective heat exchange with the surrounding air, the vapor-air mixture, and the liquid inside the tank, as well as between the water film and the wall. The joint solution to the system of equations makes it possible to determine the temperature distribution along the tank wall and the water film at an arbitrary time point, as well as to determine the thickness and flow rate of the water film at a certain point.

The finite difference method was used to solve the system of heat and mass balance equations. It is shown that the insufficient intensity of water supply for cooling leads to boiling of water from the film, as a result of which the wall temperature in such areas can reach 300 °C. A delay in the supply of water, even with sufficient intensity, could lead to the establishment of a film-like mode of boiling. In such a situation, the water film is thrown away from the wall, as a result of which the part of the wall below the film boiling zone remains without cooling. The practical significance of the built model is the possibility of determining the necessary intensity of water supply for cooling the tank and the limit time for the start of cooling

Keywords: flammable liquid spill, spill fire, tank heating, heat flow

UDC 614.84
DOI: 10.15587/1729-4061.2024.313827

BUILDING A MODEL OF OIL TANK WATER COOLING IN THE CASE OF FIRE

Oleksii Basmanov
Corresponding author
Doctor of Technical Sciences, Professor, Chief Researcher
Scientific Department of Problems of Civil Protection and Technogenic-Ecological Safety of the Research Center**
E-mail: oleksii.basmanov@nuczu.edu.ua

Volodymyr Oliinyk
PhD, Associated Professor, Head of Department*

Kostiantyn Afanasenko
PhD, Associate Professor, Deputy Head of Department*

Oleksandr Hryhorenko
PhD, Associate Professor*

Yaroslav Kalchenko
PhD, Associated Professor*

*Department of Fire and Technogenic Safety of Facilities and Technologies**
**National University of Civil Defence of Ukraine
Chernyshevska str., 94, Kharkiv, Ukraine, 61023

Received date 07.08.2024
Accepted date 14.10.2024
Published date 25.10.2024

***How to Cite:** Basmanov, O., Oliinyk, V., Afanasenko, K., Hryhorenko, O., Kalchenko, Y. (2024). Building a model of oil tank water cooling in the case of fire. Eastern-European Journal of Enterprise Technologies, 5 (10 (131)), 53–61. https://doi.org/10.15587/1729-4061.2024.313827*

1. Introduction

Tank farms are the main place of storage of oil products in the process of their processing and transportation. Extinguishing fires in tank farms is complicated by the danger of explosion of tanks adjacent to the fire, which occurs as a result of thermal effects on them. The threat of fire spread arises not only for nearby technological objects [1] but also for natural landscapes [2]. The main technique for storing oil and related products is the use of vertical steel tanks. The thermal effect of the fire threatens to heat the steel structures of the neighboring tanks to the self-ignition temperature of the liquid stored in them. Another danger is depressurization of flange connections and loss of strength of supporting structures [3]. The spread of the fire to the neighboring tanks leads not only to an increase in material losses but also poses a threat to the lives of the personnel involved in extinguishing the fire. In [4], 224 major accidents were analyzed, and it was noted that many of them were characterized by the “domino effect”, i.e., situations where one accident, even a relatively minor one, creates the basis for another. In [5], it is noted that fires cause almost 43 % of all “domino effects”, with the most common scenario being a fire in a tank or a spill of a flammable liquid. According to [6], about 44 % of large-scale fires, in which the “domino” effect was observed, started with a tank fire or a spill fire. Another negative consequence of large-scale fires is the emission of harmful substances into the atmosphere [7]. Spreading over long distances, they significantly affect the state of the air and create danger for people [8]. Spills of oil and oil products, which are not accompanied by fires, lead to soil, underground, and river water pollution [9].

Therefore, it is a relevant task to carry out studies aimed at devising methods for preventing the cascade spread of fire in tank farms.

2. Literature review and problem statement

In [10], data on 595 fires in tank parks with oil and oil products that occurred in the world were studied. Based on the analysis of statistics, the probability of the fire spreading to the neighboring tanks, the expected number of injured and dead were determined. But this approach does not provide an opportunity to determine the probability of fire spreading under specific conditions and to take measures that could prevent such a scenario. Paper [11] provides an overview of fire models when the spill of flammable liquid is limited by obstacles, in particular, collapse around the tank. Fires of this type account for about 42 % of all fires in tank farms. Flame pulsations, specific mass burning rate, flame height, radiation heat transfer were considered, but the heating of nearby technological facilities due to the thermal effect of the fire was neglected. In [12], the thermal effect of a fire on a tank in the form of a parallelepiped with a volume of 80 liters, filled by 18 % with diesel fuel, is experimentally investigated. Computational fluid dynamics (CFD) methods were used to determine the temperature distribution in the liquid poured into the tank. It follows from the model that the liquid in the reservoir is practically isothermal. Comparison of calculated and experimental data showed their satisfactory convergence. But the heating of the tank walls is not considered in the work.

An estimate of the convection component of the heat flow by radiation from a spill fire was given in [13]; however, the consequences of the thermal effect of the fire on the neighboring tanks were not considered either. In [14], the thermal effect on steel structures was investigated but the characteristics of the combustion chamber, which lead to a given value of the heat flow, were left out of consideration. In [15], a model of the thermal effect of a fire in a collapse on the part of the tank wall, which is above the level of the liquid poured into it, was built. The model takes into account radiation and convection heat exchange with the fire and the surrounding environment. At the same time, heat exchange with other parts of the wall and roof remains unaccounted for, both due to heat conduction and due to radiation. In [16], a model of the thermal effect of a fire on a tank with an oil product was built, which makes it possible to find the temperature distribution along the wall and roof of the tank at an arbitrary time point. This makes it possible to determine the areas on the wall of the tank that are subject to cooling, as well as the maximum time for the start of cooling. But the cooling effect of water is not considered in the work.

In [17], such a parameter as the time to failure of the tank under the conditions of the thermal effect of fire was investigated. Failure is understood as the heating of the steel structures of the tank to temperature values at which the strength of the structures may be lost. The model takes into account radiation and convection heat exchange of the surface of the tank with fire, liquid, and vapor-air mixture inside the tank. But the influence of the intensity of water supply on the cooling efficiency was not considered in the work. In [18], the heat flow from burning crude oil tanks was investigated. Using the simulation package FDS (fire dynamics simulator), the heat flow by radiation to the neighboring tanks was investigated. This makes it possible to determine the areas on nearby tanks that need to be cooled with water, the location of firefighting forces and means. But even here, the influence of the intensity of water supply on the cooling efficiency is neglected.

In [19], it was noted that there are no generalized correlations for determining the incident heat flow and the intensity of water supply for cooling, taking into account such parameters as wind speed, distance, and the type of burning liquid. In order to reduce water consumption, it is proposed to use its uneven supply depending on the amount of heat flow falling on a given section of the tank wall. A limitation of the study is that it was conducted using the FDS modeling package, which makes it difficult to generalize the results and use them under conditions different from those under study.

In [20], the cooling of the wall of a vertical steel tank by supplying water with the help of hydro monitors located outside the embankment was considered. But the constructed model of the cooling effect of the water film on the tank wall describes only the steady temperature distribution along the tank wall. The question under which conditions it is possible to enter such a regime remains out of consideration. The possibility of boiling water flowing down the heated tank wall is also not considered. At the same time, the boiling process significantly affects the heat exchange processes between the water film and the vertical wall [21]. In [21], the processes of heat exchange occurring in technological installations between the water film and the vertical surface were studied in detail. The heat exchange of a non-boiling water film, as well as a water film in bubble and film boiling regimes, is considered. But the issue of temperature distribution along the wall and water film has not been considered. In [22], the calculation of forces and means for localization and liquidation of a fire in a tank farm with petroleum products is given. But the disadvantage of the proposed approach is that it is based on the average indicators of the thermal effect of the fire and does not take into account such features as the direction and speed of the wind, the type of petroleum product that is burning.

Our review of the literature [15–20] shows that preventing the cascading spread of fire to neighboring tanks with petroleum products requires the cooling of tanks whose surface temperature reaches dangerous values, as well as the determination of the limit time for the start of their cooling. Methods from the theory of gravitationally flowing water films [21] can be used to build a cooling model of a vertical steel tank under fire conditions. This, in turn, creates the basis for calculating the necessary forces and means for fire localization and elimination [22].

All this gives reason to assert that it is expedient to carry out research aimed at building a model of cooling a tank with an oil product under the conditions of the thermal effect of a spilled flammable liquid fire.

3. The aim and objectives of the study

The purpose of our work is to build a model of water cooling of a tank with an oil product under the conditions of the thermal effect of a fire from a spill of a flammable liquid. A feature of the model is taking into account the radiation and convection heat exchange of the surface of the tank with fire, water, and the environment. In practice, this opens up possibilities for determining the necessary intensity of water supply for cooling tanks in case of fires at oil product warehouses.

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

– to build the heat balance equation for the surface of the tank and the water film flowing down the wall;

– to determine the coefficient of convection heat exchange of the tank wall with a water film;

– to solve the system of heat and mass balance equations.

4. The study materials and methods

The object of our study is the process of liquid combustion in spillage, 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 fire and cooled by water. The main hypothesis of the study assumes that the temperature distribution on the surface of the tank can be described by a two-dimensional heat conduction equation, which takes into account radiation and convection heat exchange with the fire, water film, and the environment. The main assumptions are the uniform temperature distribution over the thickness of the water film, the transparency of the water film for radiation from the fire and from the wall.

The two-dimensional heat conduction equation was used to determine the temperature distribution on the surface of the tank. Radial and convective components of heat transfer were calculated using the theory of heat transfer. The coefficient of convection heat exchange of the water film with the tank wall was estimated by methods from 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 11 (USA) programming environment.

5. Results of constructing a water cooling model of a tank with a petroleum product under fire conditions

5. 1. Construction of heat balance equations for the surface of the tank and the water film flowing over it

A common feature of all methods for supplying water for tank cooling (cooling rings, stationary fire water monitors, mobile equipment) is the formation of a water film that flows down the wall and thereby cools it.

In [16], the heat balance equation for the tank wall under the conditions of the thermal effect of fire is given:

$$\frac{\partial T}{\partial t}=a\left(\frac{\partial^2 T}{\partial z^2}+\frac{1}{R^2}\frac{\partial^2 T}{\partial \phi^2}\right)+\frac{q}{c_s\rho_s\delta};$$

$$0<z<H;\quad 0<\phi<2\pi, \tag{1}$$

where $T(\varphi,z,t)$ – temperature of the tank wall at the point (φ,z), given in cylindrical coordinates, at time t; R, H – radius and height of the tank; c_s, ρ_s – heat capacity and density of steel; δ – thickness of the tank wall; q – heat flux density falling on the wall:

$$q=q_1+q_2+q_c+q_4+q_5+q_6+q_7, \tag{2}$$

where q_1 – heat flux density by radiation from the fire; q_2 – heat flow density by radiation into the environment; q_c – heat flow density by convection heat exchange with the external environment, which is represented by a water film; q_4 – heat flux density by radiation from the inner surface of the wall through the gas space of the tank; q_5 – heat flux density by radiation from the inner surface of the tank roof; q_6 – heat flux density by radiation from the liquid surface; q_7 – heat flow density due to convection heat exchange with the steam-air mixture in the gas space of the tank. The formulas for determining the components of q_i, i=1,2,4,5,6,7 are given in [16]. The heat flux density due to convection heat exchange with the water film is determined by Newton's law:

$$q_c=\alpha_c\left(T_c-T\right), \tag{3}$$

where α_c is the coefficient of convection heat exchange between the wall and the water film flowing over it; $T_c(\varphi,z,t)$ is the temperature of the water film on the tank wall at the point (φ,z), given in cylindrical coordinates, at time t.

To determine the temperature distribution along the film, the elementary volume of water V flowing down the tank wall was considered (Fig. 1):

$$V=S\delta_c;$$

$$m=\rho_c V=\rho_c S\delta_c, \tag{4}$$

where S is the base area of the elementary volume of water V; m is the mass of this volume of water; ρ_c is the density of water.

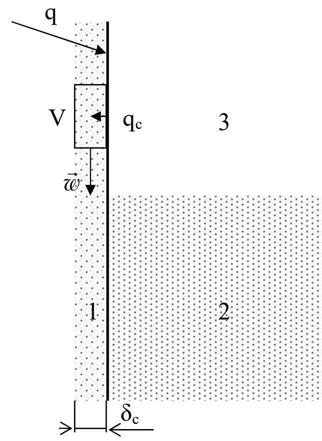

Fig. 1. Flow of a water film along the wall of a vertical steel tank: 1 – water film; 2 – oil product in the tank; 3 – gas space of the tank

Let q_w be the surface heat flux density received by the water film. Then the elementary volume of water V during a small time interval Δt will receive an amount of heat:

$$\Delta Q=Sq_w\Delta t, \tag{5}$$

where q_w is the total density of the heat flux received by the elementary volume of water. In this case, two cases are possible:

– the temperature of the water film is lower than the boiling temperature of water (T_c<100 °C) or the heat flow is directed from the film to the wall (q_w<0). Water is heated (or cooled);

– the temperature of the water film is equal to the boiling temperature of water (T_c=100 °C) and the heat flow is directed from the wall to the water (q_w>0). Water boils on the tank wall.

In the first case, the received heat ΔQ is used to heat this volume of water by the amount ΔT_c:

$$\Delta Q=c_c m\Delta T_c, \tag{6}$$

where c_c is the specific heat capacity of water. Combining expressions (4) to (6), we obtain:

$$\frac{\Delta T_c}{\Delta t}=\frac{q_w}{c_c\rho_c\delta_c}.$$

By moving to the limiting value at $\Delta t\to 0$ and taking into account the movement of water at a speed w in the direction opposite to the direction of the OZ axis, the differential equation was derived:

$$\frac{\partial T_c}{\partial t}=\frac{q_w}{c_c\rho_c\delta_c}+w\frac{\partial T_c}{\partial z}, \tag{7}$$

under boundary condition:

$$T_c(H,t)=T_{c0}, \tag{8}$$

where T_{c0} is the temperature of water supplied for tank cooling.

In the second case, the received heat ΔQ is spent to evaporate the mass of water Δm:

$$\Delta Q = r_c \Delta m, \tag{9}$$

where r_c is the specific heat of vaporization of water. Combining expressions (4), (5), (9), we get:

$$\frac{\Delta\delta_c}{\Delta t}=\frac{q_w}{r_c\rho_c},$$

where $\Delta\delta_c$ is the decrease in the thickness of the water film due to the evaporation of water by a mass of Δm. By multiplying the left and right parts of the equality by the flow rate, we obtained:

$$\frac{\Delta V_s}{\Delta t}=\frac{q_w}{r_c\rho_c}w,$$

where ΔV_s is a decrease in the volume intensity of irrigation due to water evaporation. Moving to the limit value at $\Delta t\to 0$, replacing the decrease in irrigation intensity with its increase, and also taking into account the movement of water with a speed w in the direction opposite to the direction of the OZ axis, we built the differential equation:

$$\frac{\partial V_s}{\partial t}=w\left(-\frac{q_w}{r_c\rho_c}+\frac{\partial V_s}{\partial z}\right), \tag{10}$$

under boundary condition:

$$V_s(H,t)=V_{s0}, \tag{11}$$

where V_{s0} is the initial volume intensity of irrigation.

By combining cases of heating and boiling of the film, the equation of temperature and thickness distribution over the water film was obtained in the form:

$$\frac{\partial T_c}{\partial t}=\frac{q_w}{c_c\rho_c\delta_c}f(T_c,q_w)+w\frac{\partial T_c}{\partial z}; \tag{12}$$

$$\frac{\partial V_s}{\partial t}=w\left[-\frac{q_w}{r_c\rho_c}\left(1-f(T_c,q_w)\right)+\frac{\partial V_s}{\partial z}\right], \tag{13}$$

where:

$$f(T_c,q_w)=\begin{cases}0, T_c=100\,^\circ\mathrm{C}\wedge q_w\geq 0;\\ 1, T_c<100\,^\circ\mathrm{C}\vee q_w<0.\end{cases}$$

Therefore, the temperature distribution along the tank wall and water film is described by differential equations in partial derivatives (1), (12), (13) under boundary conditions for the water film (8), (11) and initial conditions:

$$V_s(z,0)=0;\;\; T_c(z,0)=T_0. \tag{14}$$

The heat flow to the water film q_w is determined by the convection heat flow from the tank wall q_c, the convection heat flow into the surrounding air q_a, and the radiation heat flow into the environment q_0:

$$q_w=-q_c+q_a+q_0. \tag{15}$$

The heat flow density due to convection heat exchange with the surrounding air is determined by Newton's law:

$$q_a=\alpha_a(T_a-T_c), \tag{16}$$

where α_a is the coefficient of convection heat exchange between the water film and the surrounding air; T_a is the ambient air temperature. It can be both the value of the ambient temperature T_0 and the value of the temperature of the heated air and combustion products rising above the combustion chamber.

5. 2. Determining the coefficient of convection heat exchange of the tank wall with a water film

The water film flowing down the tank wall can be in two main states:

– boiling (if its temperature is 100 °C, and the wall temperature exceeds this value);

– non-boiling (if the water temperature or the wall temperature is below 100 °C).

The heat exchange between the wall and the water film depends significantly on the state in which it is. In the absence of boiling, the heat exchange of the flowing water film with the wall is determined by the following dependences [21]:

– wave mode ($5<\eta_t<30$):

$$\mathrm{Nu}=\frac{\mathrm{Pr}\,\eta_t^{1/3}}{5\mathrm{Pr}+5\ln\left(1-\mathrm{Pr}+0.2\mathrm{Pr}\,\eta_t\right)}; \tag{17}$$

– turbulent mode ($\eta_t>30$):

$$\mathrm{Nu}=\frac{\mathrm{Pr}\,\eta_t^{1/3}}{5\mathrm{Pr}+5\ln\left(1+5\mathrm{Pr}\right)+2.5\ln\dfrac{1-\mathrm{Pr}+0.4\mathrm{Pr}\,\eta_t}{1+11\mathrm{Pr}}}, \tag{18}$$

where η_t is the dimensionless film thickness:

$$\eta_t=\frac{\sqrt{\delta_c^3 g}}{\nu}, \tag{19}$$

ν is the kinematic viscosity of water; g is the acceleration of gravity; Pr is the Prandtl number of water; Nu is the Nusselt criterion of the water film:

$$\mathrm{Nu}=\frac{\alpha_c}{\lambda}\left(\frac{\nu^2}{g}\right)^{\frac{1}{3}};$$

α_c is the coefficient of convection heat exchange between the wall and water; λ is the coefficient of thermal conductivity of water.

The dimensionless thickness of the film is determined by the ratio [21]:

$$\begin{cases}\dfrac{V_s}{\nu}-12.5=5\eta_t\ln\eta_t-8.05\eta_t, 5<\eta_t\leq 30;\\ \dfrac{V_s}{\nu}+64=3\eta_t+2.5\eta_t\ln\eta_t, \eta_t>30.\end{cases} \tag{20}$$

The formula for determining the convection heat transfer coefficient follows from the expression for the Nusselt number:

$$\alpha_c=\mathrm{Nu}\,\lambda\left(\frac{g}{\nu^2}\right)^{\frac{1}{3}}. \tag{21}$$

The dependence of the coefficient of convection heat exchange of the water film and wall α_c on the intensity of irrigation V_s and water temperature T_c is shown in Fig. 2.

When bubbling in a large volume of liquid, the coefficient of convection heat transfer from the wall to the water is described by the dependence:

$$\alpha = 38.7\Delta T^{2.33} p^{0.5}, \qquad (22)$$

where q is the heat flux density; ΔT is the overheating of the wall relative to the boiling temperature of water; p is the pressure of saturated water vapor in bars. Formula (22) is valid for the range of values ΔT=(5÷20) K. As the wall temperature continues to rise and ΔT approaches the critical value ΔT_{cr1}≈25 K, the growth of the convection heat exchange coefficient slows down, reaching the maximum value α_{cr1}≈46.5 kW/(m²·K). On the other hand, the value of the convection heat transfer coefficient during bubble boiling is not less than when there is no boiling. Taking this into account, (22) will become:

$$\alpha = \max\left\{\min\left\{38.7\Delta T^{2.33} p^{0.5}, \alpha_{cr1}\right\}, \alpha_{100}\right\}, \qquad (23)$$

where α_{100} is the coefficient of convection heat exchange, provided there is no boiling, and the water temperature is 100 °C.

When the water temperature reaches the value T_{cr1}≈125 °C, boiling takes on a film regime. At the same time, there is a sharp drop in the convection heat exchange coefficient to the value α_{cr2}≈2.35 kW/(m²·K). With a further increase in the temperature pressure ΔT, the convection heat transfer coefficient remains approximately constant and begins to grow slowly at ΔT>50 K due to radiant heat transfer from the wall to the liquid. In view of this, it was assumed that the coefficient of convection heat transfer from the wall to the water film under conditions of film boiling takes the following form:

$$\alpha = \alpha_{cr2}.$$

The return to bubbling mode of boiling takes place when the water temperature drops to T_{cr2}≈114 °C. Therefore, under boiling conditions, the coefficient of convection heat transfer depends not only on the temperature difference between the wall and the water film but also on the boiling mode.

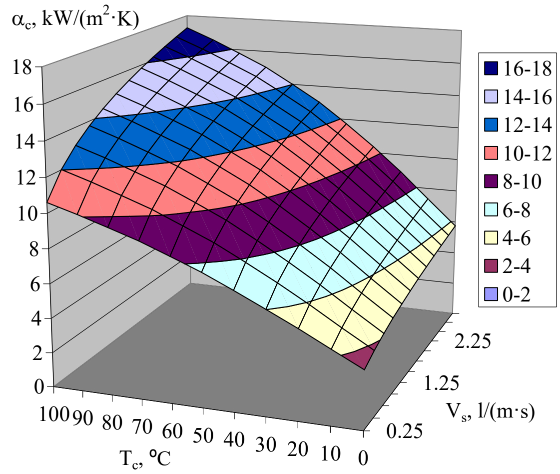

Fig. 2. Value of the coefficient of convection heat exchange of the water film α_c and the wall depending on the volume intensity of irrigation V_s and water temperature T_c

5. 3. Solving the system of heat and mass balance equations

As an example, the burning of spilled diesel fuel flowing with a volume velocity of 15 l/s onto a surface with an angle of inclination of 0.5° was considered. At the same time, the direction of inclination coincides with the X axis, and the origin of coordinates is located at the point of liquid leakage (Fig. 3). The RVS-5000 reservoir (height H=12 m, diameter D=23 m) is located at a distance of 6 m from the liquid leakage point in the direction of the Y axis. There is no wind. To determine the shape and size of the spill, the liquid spreading and impregnation model was used [23]. The following parameter values were chosen: hydraulic conductivity of wetted soil 1.68·10⁻⁷ m/s; capillarity index (suction head) 0.95 m; soil porosity 0.31; the average depth of irregularities is 1.7 cm.

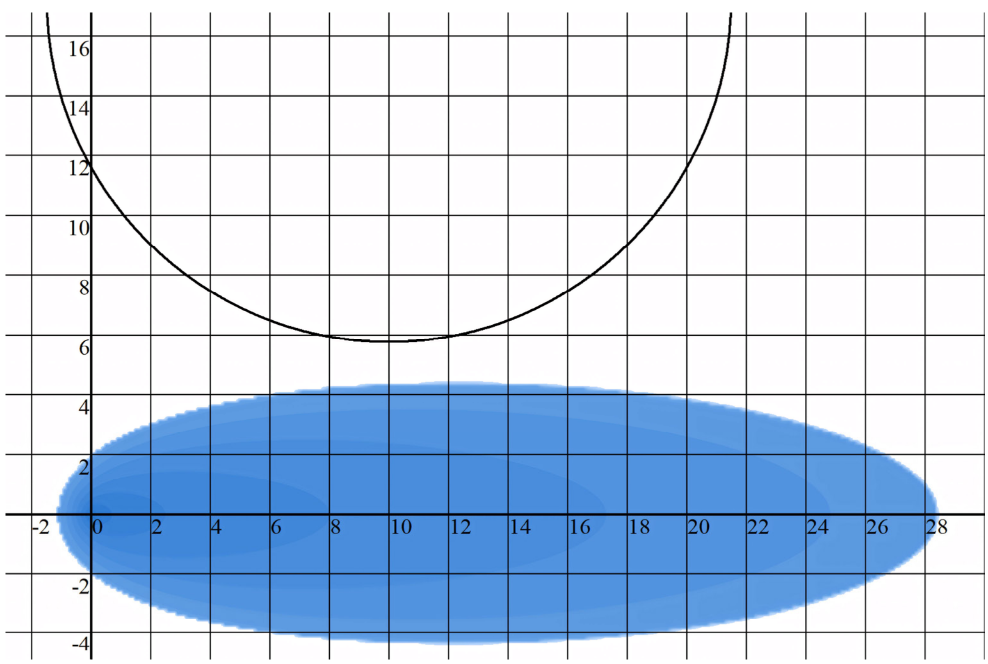

Fig. 3. Mutual location of the diesel fuel spill and the RVS-5000 tank

Fig. 4 shows the temperature distribution along the tank wall under the condition of cooling with water with a volumetric irrigation intensity of 0.5 l/(m·s). This intensity is insufficient: boiling occurs almost along the entire height of the wall, and its lower part remains unprotected due to the complete boiling of water.

Fig. 5 illustrates the temperature distribution along the tank wall if the volumetric intensity of irrigation of the wall is 1 l/(m·s). Analysis of the graphic image in Fig. 5 reveals the presence of an almost horizontal area (area 2), which corresponds to the wall temperature values in the range (100÷104) °C.

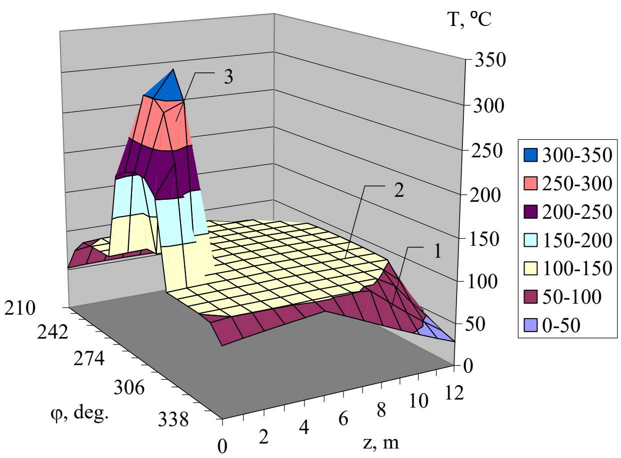

Fig. 4. Temperature distribution along the wall of the RVS-5000 tank filled with diesel fuel to a level of 4 m, depending on the vertical coordinate z and the angular coordinate φ after 20 min after the start of the fire, provided that water is supplied for cooling with a volumetric irrigation intensity of 0.5 l/(m·s)

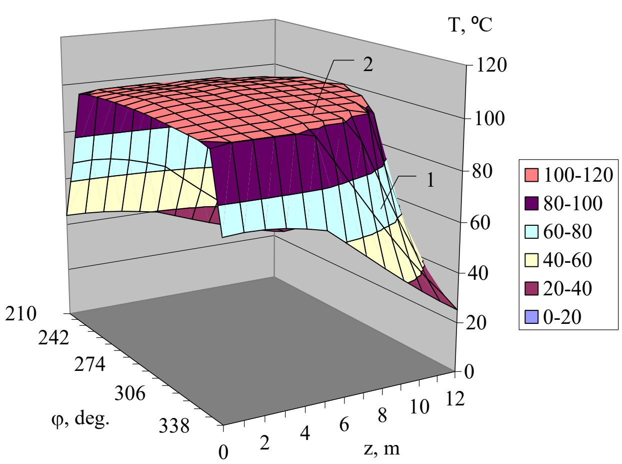

Fig. 5. Temperature distribution along the wall of the RVS-5000 tank filled with diesel fuel to a level of 4 m, depending on the vertical coordinate z and the angular coordinate φ after 20 min after the start of the fire, provided that water is supplied for cooling with a volumetric irrigation intensity of 1 l/(m·s)

In addition to the intensity of irrigation of the wall, the time of its initiation is also important. As an example, Fig. 6 shows the temperature distribution along the tank wall under the same conditions as in Fig. 5, but cooling started after 3 min after the fire started. A section corresponding to the film boiling mode appears on the temperature distribution chart (region 3 in Fig. 6). On this part of the wall, the water film is pushed away from the wall, as a result of which this part of the wall is unprotected, and its temperature reaches dangerous values.

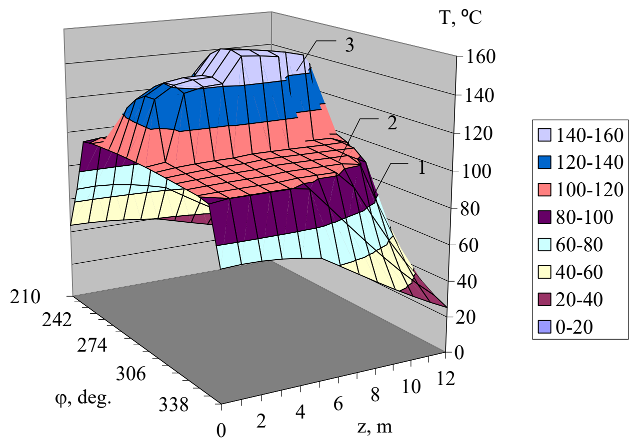

Fig. 6. Temperature distribution along the wall of the RVS-5000 tank filled with diesel fuel to a level of 4 m, depending on the vertical coordinate *z* and the angular coordinate φ after 20 min after the start of the fire, provided that water is supplied for cooling with a volumetric irrigation intensity of 1 l/(m·s) after 3 min after the fire started

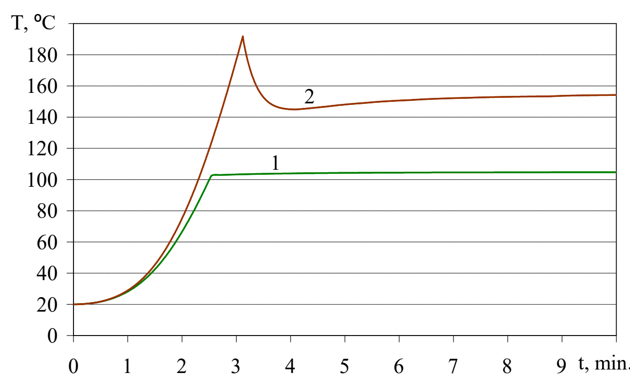

Fig. 7. Dynamics of changes in the temperature of the tank wall facing the fire for different cooling start times:
1 – cooling starts simultaneously with the start of the fire;
2 – cooling starts after 3 min after the fire started

Fig. 7 shows the dynamics of changes in the temperature of the wall facing the fire for different delay times between the start of the fire and the start of the cooling water supply.

In the case when water for cooling the wall begins to be supplied at the same time as the fire starts (line 1 in Fig. 7), boiling occurs under a bubble mode. At the same time, the wall temperature is about 104 °C. If cooling begins after the wall temperature exceeds 125 °C, boiling occurs under the film mode (line 2 in Fig. 7). Due to the fact that the heat transfer under this mode is an order of magnitude lower than under the bubbling mode of boiling, the cooling effect of water is not enough for the wall temperature to drop to the same level as in the first case.

Therefore, the efficiency of cooling is determined not only by the volumetric intensity of water supply for irrigation of the wall but also by the timing of the start of this supply.

6. Discussion of results based on the construction of a model of cooling a tank with an oil product under fire conditions

The small thickness of the walls of the tank (10 mm) relative to its linear dimensions (more than 10 m in diameter and height) makes it possible to consider the two-dimensional equation of thermal conductivity (1) instead of the three-dimensional equation of general form. This equation contains term (2), which takes into account the heat flow from the external environment to a point on the surface of the tank. This heat flow is due to the radiant and convective heat exchange of the wall with the external environment and, in particular, with the water film flowing down the wall of the tank. At the same time, the heat flow density from the water film to the tank wall is determined by Newton's law (3) and depends on both the water temperature and the wall temperature.

The processes occurring in the water film upon receiving a certain amount of heat (5) depend significantly on its temperature. If the temperature of the water is lower than its boiling point, then the received heat is spent on heating the water by amount (6). In this case, the heat balance equation for the water film takes form (7). The first term in its right-hand part corresponds to the increase in temperature due to heat exchange with the external environment, and the second – to the increase in temperature due to the movement of water along the tank wall.

If the temperature of the water is equal to the boiling temperature, then the received heat is spent on the evaporation of water from the water film (9). In this case, the temperature of the water film remains unchanged (100 °C), and the volume intensity of irrigation is determined by differential equation (10). The first term in brackets corresponds to the loss of water due to its boiling, and the second to the increase in the volume of water due to its movement along the wall. Combining the cases of heating and boiling of water gives a system of differential equations (12), (13) with boundary conditions (8), (11), and initial conditions (14). Its solution together with the heat balance equation for the tank wall (1) makes it possible to find the temperature distribution along the tank wall and the water film at an arbitrary time point. It should be noted that the rate of runoff of the water film in equations (12), (13) is a function of the volume intensity of irrigation at a given point. Differential equations (12), (13) make sense only under the condition of positive values of the volume intensity of irrigation, i.e., in the presence of a water film. The heat flow to the water film (15) is due to the heat flow from the tank wall, convection heat exchange with the surrounding air (16) and radiation heat exchange with the environment.

The volumetric intensity of wall irrigation with water determines the dimensionless thickness of the water film (20). In turn, the dimensionless thickness of the water film (19) characterizes the flow mode of the water film along the vertical wall: laminar, wave, and turbulent. From a practical point of view, only wave and turbulent flow regimes are important. Under the laminar mode, the film is unstable and the roughness of the surface of the tank leads to the fact that the solid film breaks up into separate jets. As a result, cooling is ineffective.

The Nusselt number of the water film is a function of its dimensionless thickness and, depending on the flow regime, is described by formulas (17) or (18). This makes it possible to determine the coefficient of convection heat exchange between the wall and the water film according to formula (21). It should be noted that the Prandtl number included in formulas (17), (18), as well as the coefficient of thermal conductivity of water in formula (21) are functions of temperature.

Analysis of the dependence of the convection heat exchange coefficient on the volume intensity of irrigation and water temperature (Fig. 2) reveals that for the given ranges of values of the intensity of water flow along the wall and its temperature, the value of the convection heat exchange coefficient is within (3.3÷17.2) kW/(m^2·K). The value of the convection heat transfer coefficient (Fig. 2) for the water film is an order of magnitude higher than the corresponding value for gasoline in the tank [16]. This is due to the forced nature of convection when water flows down the wall of the tank.

When water reaches a temperature of 100 °C, its boiling begins, provided that the wall temperature exceeds this value. As the density of the heat flux from the wall increases, the local chains of bubbles disappear, the entire surface of the water is covered with bubbles. At a surface temperature of 105 °C, the boiling becomes so intense that a water film is shed, unwetted areas are formed, and wedge-shaped jets appear [21]. The value of the coefficient of convection heat exchange under the bubbling mode of boiling is limited from below by the value for convection heat exchange in the absence of boiling and a water temperature of 100 °C. And the upper limit is α_{cr1}≈46.5 kW/(m^2·K) – formula (23). The transition to the film boiling regime is characterized by a sharp decrease in the convection heat exchange coefficient – to α_{cr2}≈2.35 kW/(m^2·K). Another negative consequence of the transition to the film boiling mode is the rejection of the water film from the tank wall, as a result of which its cooling effect is lost.

Fig. 4 shows the temperature distribution along the tank wall, in the case of burning diesel fuel spillage next to the RVS-5000 tank (Fig. 3). Analysis of the temperature distribution (Fig. 4) indicates the existence of three regions on the surface of the tank wall:

– in area 1, the wall surface temperature does not exceed 100 °C, water does not boil;

– in region 2, bubble boiling of the liquid occurs, and the temperature of the wall slightly exceeds the boiling temperature of water. As a result of intensive heat exchange between the wall and the water film under the bubbling boiling mode, this area has a horizontal appearance;

– in area 3, there is no water film due to complete boiling of water. Because of this, the wall temperature reaches a value of 300 °C, turning into a source of ignition for diesel fuel vapors.

Increasing the volumetric intensity of water supply to 1 l/(m·s) prevents both the complete boiling of water and the transition to the film boiling mode (Fig. 5). Boiling takes place under the bubbling mode on the part of the wall located on the side of the fire. Intensive heat removal due to boiling prevents further heating of the wall surface. This means that irrigation of the wall with a volumetric intensity of 1 l/(m·s) is sufficient to protect it from the thermal effects of this fire.

In addition to the volumetric intensity of water supply, an important factor is the time of the start of its supply. The consequences of a delay in the supply of water for cooling (in 3 minutes after the start of the spill burning) are shown in Fig. 6. In the region there is a film mode of boiling. The coefficient of convection heat exchange between the wall and the water film decreases by an order of magnitude compared to the bubbling boiling mode. As a result, the wall temperature reaches 150 °C or more. This situation is due to the fact that at the time of water supply, the wall has heated up to a temperature above 125 °C (Fig. 7) and boiling occurs under the film mode. As a result, the coefficient of convection heat exchange turns out to be an order of magnitude smaller than in the case in Fig. 5, and the cooling turns out to be insufficient. In the region of film boiling (region 3, Fig. 6), the part of the wall in contact with the liquid in the tank has a lower temperature (140 °C) than the part of the wall above the liquid level (160 °C). This is consistent with the results reported in [24], in which the cooling effect of the liquid contained in the tank was noted.

The advantage of the constructed model of tank cooling under the thermal effects of a spill fire is that it makes it possible to find the temperature distribution along the wall of a vertical steel tank and determine whether cooling is sufficient.

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

The disadvantage of the built model is that the question of the optimal choice of the intensity of water supply for cooling the wall and roof of the tank remains unanswered. Thus, the prospects for further research are related to determining the optimal intensity of water supply using mobile equipment or stationary cooling systems.

The proposed model of cooling a tank with an oil product under fire conditions could be used to predict fire development scenarios, make a decision on tank cooling, determine the limit time for the start of cooling, and design tank cooling systems [22].

7. Conclusions

1. A system of equations describing water cooling of a vertical steel tank with an oil product under the conditions of the thermal effect of a fire has been constructed. The system consists of a heat balance equation for the tank wall, a heat balance equation for the water film flowing over it, and a mass balance equation for the water film. Their joint solution makes it possible to determine the temperature distribution along the tank wall and the water film at an arbitrary time point. The equations are based on the assumption about a small thickness of the wall and the water film relative to their linear dimensions. The equations take into account radiative and convective heat exchange with the fire, the environment, the liquid, and the vapor-air mixture inside the tank.

2. Convection heat transfer coefficients of the water film with the tank wall under the boiling mode and in its absence have been determined. It is shown that in the absence of boiling, the value of the convection heat exchange coefficient increases with the increase in water temperature and volume intensity of water supply. At the same time, the value of the convection heat exchange coefficient belongs to the range (3.3÷17.2) kW/(m^2·K). The value of the coefficient of convection heat exchange of the wall with a water film is an order of magnitude higher than the corresponding value for the liquid stored in the tank. This is due to the forced nature of convection when water flows down the wall of the tank. The transition to the bubbling boiling mode leads to an increase in the convection heat exchange coefficient – its value can reach 46.5 kW/(m^2·K). But further heating of the wall leads to a transition to the film boiling regime, as a result of which the value of the convection heat exchange coefficient decreases to 2.35 kW/(m^2·K).

3. It has been shown that insufficient intensity of water supply for cooling leads to boiling of water from the film, as a result of which the wall temperature in such areas can reach 300 °C. A delay in the supply of water, even with sufficient intensity, can lead to the establishment of a film-like mode of boiling. In such a situation, the water film is thrown away from the wall, as a result of which the part of the wall below the film boiling zone remains uncooled and could turn into a source of ignition for petroleum product vapors.

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.

Funding

The study was conducted without financial support.

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.

References

1. Yang, R., Khan, F., Neto, E. T., Rusli, R., Ji, J. (2020). Could pool fire alone cause a domino effect? Reliability Engineering & System Safety, 202, 106976. https://doi.org/10.1016/j.ress.2020.1069761
2. Migalenko, K., Nuianzin, V., Zemlianskyi, A., Dominik, A., Pozdieiev, S. (2018). Development of the technique for restricting the propagation of fire in natural peat ecosystems. Eastern-European Journal of Enterprise Technologies, 1 (10 (91)), 31–37. https://doi.org/10.15587/1729-4061.2018.1217272
3. Vasilchenko, A., Otrosh, Y., Adamenko, N., Doronin, E., Kovalov, A. (2018). Feature of fire resistance calculation of steel structures with intumescent coating. MATEC Web of Conferences, 230, 02036. https://doi.org/10.1051/matecconf/2018230020363
4. Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., Abbasi, S. A. (2011). Domino effect in process-industry accidents – An inventory of past events and identification of some patterns. Journal of Loss Prevention in the Process Industries, 24 (5), 575–593. https://doi.org/10.1016/j.jlp.2010.06.0134

5. Amin, Md. T., Scarponi, G. E., Cozzani, V., Khan, F. (2024). Improved pool fire-initiated domino effect assessment in atmospheric tank farms using structural response. Reliability Engineering & System Safety, 242, 109751. https://doi.org/10.1016/j.ress.2023.1097515
6. Reniers, G., Cozzani, V. (2013). Features of Escalation Scenarios. Domino Effects in the Process Industries, 30–42. https://doi.org/10.1016/b978-0-444-54323-3.00003-86
7. Kustov, M. V., Kalugin, V. D., Tutunik, V. V., Tarakhno, E. V. (2019). Physicochemical principles of the technology of modified pyrotechnic compositions to reduce the chemical pollution of the atmosphere. Voprosy Khimii i Khimicheskoi Tekhnologii, 1, 92–99. https://doi.org/10.32434/0321-4095-2019-122-1-92-99 7
8. Popov, O., Iatsyshyn, A., Kovach, V., Artemchuk, V., Kameneva, I., Taraduda, D. et al. (2020). Risk Assessment for the Population of Kyiv, Ukraine as a Result of Atmospheric Air Pollution. Journal of Health and Pollution, 10 (25). https://doi.org/10.5696/2156-9614-10.25.2003038
9. Loboichenko, V., Strelec, V. (2018). The natural waters and aqueous solutions express-identification as element of determination of possible emergency situation. Water and Energy International, 61 (9), 43–50. Available at: http://repositsc.nuczu.edu.ua/handle/123456789/101569
10. Paula, H. M. (2023). Insights from 595 tank farm fires from around the world. Process Safety and Environmental Protection, 171, 773–782. https://doi.org/10.1016/j.psep.2023.01.05810
11. Guo, Y., Xiao, G., Wang, L., Chen, C., Deng, H., Mi, H. et al. (2023). Pool fire burning characteristics and risks under wind-free conditions: State-of-the-art. Fire Safety Journal, 136, 103755. https://doi.org/10.1016/j.firesaf.2023.10375511
12. Wang, M., Wang, J., Yu, X., Zong, R. (2023). Experimental and numerical study of the thermal response of a diesel fuel tank exposed to fire impingement. Applied Thermal Engineering, 227, 120334. https://doi.org/10.1016/j.applthermaleng.2023.12033412
13. Abramov, Y., Basmanov, O., Oliinik, V., Khmyrov, I., Khmyrova, A. (2022). Modeling the convective component of the heat flow from a spill fire at railway accidence. EUREKA: Physics and Engineering, 6, 128–138. https://doi.org/10.21303/2461-4262.2022.00270213
14. Kovalov, A., Otrosh, Y., Rybka, E., Kovalevska, T., Togobytska, V., Rolin, I. (2020). Treatment of Determination Method for Strength Characteristics of Reinforcing Steel by Using Thread Cutting Method after Temperature Influence. Materials Science Forum, 1006, 179–184. https://doi.org/10.4028/www.scientific.net/msf.1006.17914
15. Abramov, Y. A., Basmanov, O. E., Salamov, J., Mikhayluk, A. A. (2018). Model of thermal effect of fire within a dike on the oil tank. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 95–101. https://doi.org/10.29202/nvngu/2018-2/1215
16. Oliinyk, V., Basmanov, O., Romanyuk, I., Rashkevich, O., Malovyk, I. (2024). Building a model of heating an oil tank under the thermal influence of a spill fire. Ecology, 4 (10 (130)), 21–28. https://doi.org/10.15587/1729-4061.2024.30973116
17. Wu, Z., Hou, L., Wu, S., Wu, X., Liu, F. (2020). The time-to-failure assessment of large crude oil storage tank exposed to pool fire. Fire Safety Journal, 117, 103192. https://doi.org/10.1016/j.firesaf.2020.103192
18. Elhelw, M., El-Shobaky, A., Attia, A., El-Maghlany, W. M. (2021). Advanced dynamic modeling study of fire and smoke of crude oil storage tanks. Process Safety and Environmental Protection, 146, 670–685. https://doi.org/10.1016/j.psep.2020.12.00217
19. Saber, A., El-Nasr, M. A., Elbanhawy, A. Y. (2022). Generalized formulae for water cooling requirements for the fire safety of hydrocarbon storage tank farms. Journal of Loss Prevention in the Process Industries, 80, 104916. https://doi.org/10.1016/j.jlp.2022.10491618
20. Abramov, Y., Basmanov, O., Salamov, J., Mikhayluk, A., Yashchenko, O. (2019). Developing a model of tank cooling by water jets from hydraulic monitors under conditions of fire. Eastern-European Journal of Enterprise Technologies, 1 (10 (97)), 14–20. https://doi.org/10.15587/1729-4061.2019.154669 19
21. Vorontcov, E. G., Tananaiko, Iu. M. (1972). Teploobmen v zhidkostnykh plenkakh. Kyiv: Tekhnika, 194. 20
22. Shafiq, I., Hussain, M., Shafique, S., Hamayun, M. H., Mudassir, M., Nawaz, Z. et al. (2021). A comprehensive numerical design of firefighting systems for onshore petroleum installations. Korean Journal of Chemical Engineering, 38 (9), 1768–1780. https://doi.org/10.1007/s11814-021-0820-621
23. Abramov, Y., Basmanov, O., Oliinik, V., Khmyrov, I. (2022). Justifying the experimental method for determining the parameters of liquid infiltration in bulk material. Eastern-European Journal of Enterprise Technologies, 4 (10 (118)), 24–29. https://doi.org/10.15587/1729-4061.2022.262249
24. Ramsden, N., Abusaieda, K. A. M. (2017). A study of water cooling using different water application techniques to protect storage tank walls against thermal radiation. Process Safety and Environmental Protection, 109, 577–598. https://doi.org/10.1016/j.psep.2017.04.00922