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A MODEL OF COOLING A FLAT SURFACE WITH AN IMPACT JET OF EXTINGUISHING AGENT IN CASE OF A FIRE

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Abstract. Analysis of problems of cooling a roof of vertical steel tanks. The problem of the complex effect of the coolant flow mode, the distance from the cutoff of the fire barrel to the cooled plane, and the duration of the process at the braking point of an unsteady axisymmetric impact jet is posed. An analytical solution of the energy equation is obtained, formulated as a criterion equation. It is established that at significant distances between the nozzle section of the fire barrel, when $Fr < 1$, the intensity of heat exchange between a freely falling impact jet of extinguishing agent becomes more significant. It is established that at $Fr > 1$, the intensity of heat exchange does not depend on the magnitude of this distance, and in other cases it increases. It is stated that for a dispersed jet structure, the average heat transfer characteristics increase significantly for a short pulse duration.

Key words: impact jet, vertical steel tank, VST, heat transfer coefficient, criterion equation, Froude criterion

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Introduction

Industrial facilities with increased fire risk include, first of all, reservoirs of various designs intended for storing hydrocarbons (HC), and often such reservoirs are combined into so-called hydrocarbon parks. The consequences of fires in tank parks are characterized by significant material and environmental damage, and fire extinguishing technology requires the use of the most modern innovative solutions. This is due to the difficulties in the progression of such fires, when even at the initial stage there is a powerful heat flow generated by flare's high temperature, the height of which in some cases can reach 1–2 diameters of the burning tank [1].

The most common designs of hydrocarbon storage tanks at the moment are vertical steel tanks (VST), in order to increase the fire resistance of which it is necessary to ensure cooling of their side surfaces, and, if technically possible, their roofs (Fig. 1).

Fig. 1. **Training at the oil distribution base in Nalchik**

The organization of cooling of the external surfaces of both the burning and neighboring VSTs is considered to be of primary importance, while taking into account the wind direction, as well as the influence of thermal radiation from the flare and the external surface of the burning VST [2, 3]. Otherwise, the tank wall may lose its load-bearing capacity as early as 5–15 minutes after the start of HC combustion [4], therefore, it is necessary to provide for the possibility of cooling the external surface of the VST. At the same time, for cooling the side surfaces in the source [5], an estimate of water consumption in the range of 0,2–0,3 liters/sec is given, while modern sources do not reflect the problems of cooling the roof of the VST.

Currently, the facility fire departments have the technical possibility of cooling the roof of the VST in terms of using standard trunks of crank lifts and fire trucks (Fig. 1). It was shown in the source [6] that in this case a single circular jet with a free edge is observed having an impact. (Fig. 2).

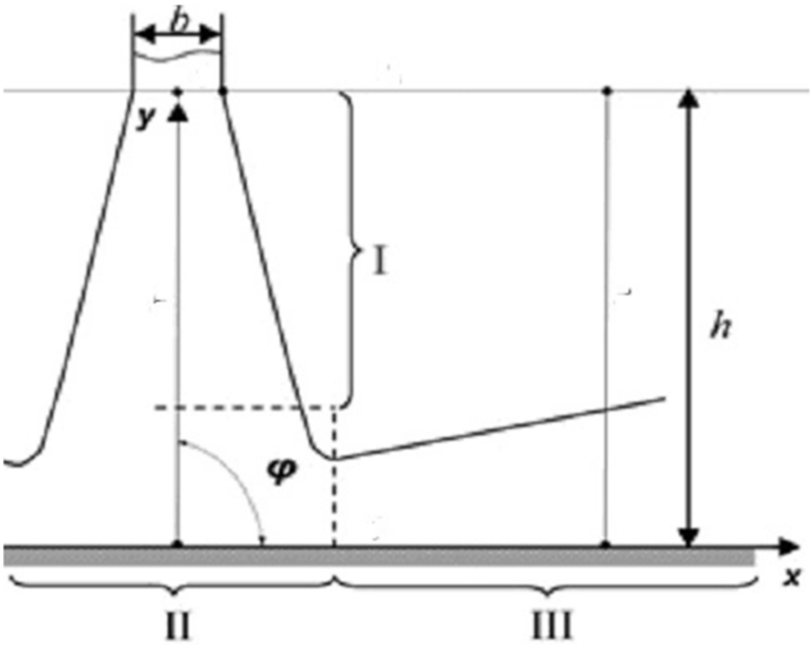

Fig. 2. **The impacting cylindrical jet falling on a flat surface**:
b – width of jet's compacted part; φ – jet's fall angle; *h* – height of jet's fall;
I – area of jet's free fall; II – area of jet's gradient flow in the impact and reversal zone on the cooling surface; III – area of near-wall cylindrical jet

The main achievements in the study of cooling processes of various surfaces by an impact of a droplet liquid jet are described in a number of reviews and monographs [7–15], however, it should be noted that a significant number of other works have been devoted to the study of the effects of flooded jets that move in a droplet liquid environment, which is irrelevant for cooling the roof of a VST in a fire.

The experimental results described in sources [7–11] do not fully describe the physical model of heat transfer processes, which is due to the short jet length, which is more typical for cooling microprocessors and other microelectronics element base products.

In the theoretical studies [12–15], the obtained models also do not take into account the influence of gravity on the nature of the formed jet, which, with significant distances between the nozzle section and the cooled surface, can be quite significant.

Thus, the purpose of the presented study was to analyze the complex influence of such factors as the movement mode of the coolant, the distance from the the fire barrel's cutoff to the cooled flat roof of the VST and the duration of the cooling process of the VST at the braking point of an unsteady axisymmetric impact jet of liquid extinguishing agent.

Task statement

Let us analyze the process of outflow of a droplet liquid in the form of an axisymmetric jet from a fire barrel with a spray diameter of d_o with an initial velocity of U_o followed by a vertical downward fall under the influence of gravitational forces (Fig. 2). When an impact jet of droplet liquid (for example, water) falls from a height of H the flow hits the flat surface of the roof of the VST, linear dimensions the wall area is commensurate with the size of the roof of the VST. We study the process of heat exchange between the coolant and the flat surface of the roof of the VST at the point of deceleration of the coolant flow on the axis of symmetry of the impact jet $r = 0$.

The flow pattern of a free-falling impact jet on a flat surface is shown in Fig. 3.

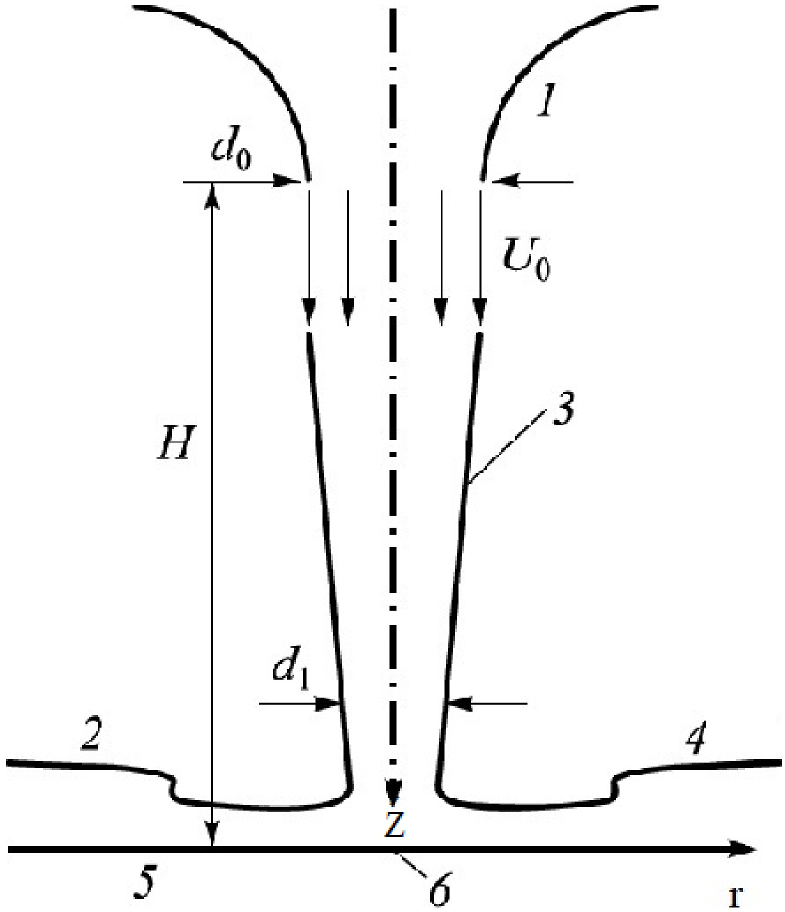

Fig.3. **Scheme of impact jet's free-falling extinguishing agent's flow pattern on a VST's flat roof surface** : 1 – nozzle; 2 – near-wall jet flow;
3 – impact jet stream edge; 4 – hydraulic surge; 5 – VST roof surface;
6 – dropping liquid's flow deceleration point

Taking into account the axisymmetry of the coolant flow, it is advisable to use a cylindrical coordinate system with the ordinate axis pointing downwards. Taking into account the operating flow rates of the coolant, the application of the ideal (Eulerian) fluid model makes it possible to construct a velocity field in the region of the flow deceleration point at $r = 0$, then

$$u = -2 \cdot a \cdot Z; \quad v = a \cdot r, \tag{1}$$

where u, v – the vertical and radial components of the flow velocity, respectively; α – the scale factor, the value of which is yet to be determined.

Considering expression (1) for the velocity field, the energy equation along the axis of symmetry of the coolant flow (with $r = 0$) can take the following form:

$$\frac{\partial T}{\partial t} - 2 \cdot a \cdot z \cdot \frac{\partial T}{\partial z} = a \cdot \frac{\partial^2 T}{\partial z^2} \tag{2}$$

To solve the differential energy equation (2), it is necessary to determine the initial and boundary conditions, which may look like:

$$T(t, \infty) = T(0, z); \quad T(t, 0) = T_o,$$

where T_∞ – the temperature of the coolant at the outlet of the barrel; T_o – temperature at the point of contact of the coolant and the outer surface of the cooling roof of a VST.

The solution of the problem will be significantly simplified if it is solved under boundary conditions of the first kind. It is also possible to use boundary conditions of the IV kind, but in this case, in relation to a process involving unsteady heat transfer between two bodies (the coolant and the outer surface of the roof of the VST), at the point of their contact at the initial moment of time, the temperature T_o can be determined as:

$$T_o = \frac{T_{1,o} \cdot K_\varepsilon + T_{2,o}}{1 + K_\varepsilon} \tag{3}$$

In equation (3), the number of conjugations K_ε is determined using expression (4):

$$K_\varepsilon = \sqrt{\frac{\rho_1 \cdot c_1 \cdot \lambda_1}{\rho_2 \cdot c_2 \cdot \lambda_2}} \tag{4}$$

where ρ_1, c_1, λ_1 – density, specific heat, and thermal conductivity of the coolant, respectively; ρ_2, c_2, λ_2 – density, specific heat capacity and thermal conductivity coefficient of the VST cover material are respectively; $T_{1,o}$ и $T_{2,o}$ –initial temperatures of the liquid and the VST roof material, respectively.

Thus, the temperature at the point of contact T_o remains constant, therefore, the temperature at $z = 0$ can be equated to the contact temperature and the methodology of boundary conditions of the I kind can be used, that is $T(t,0) = T_o$.

Mathematical model

To analytically solve the equation of the energy of the cooling process of the VST lid by an impact jet of liquid, it is necessary to introduce dimensionless variables:

$$\theta = \frac{T - T_\infty}{T_o - T_\infty}; \quad \tau = 2 \cdot a \cdot t; \quad \eta = z \cdot \sqrt{\frac{2 \cdot a}{\alpha}}.$$

Thus, the dimensionless form of the energy equation takes the form of:

$$\begin{cases} \dfrac{\partial \theta}{\partial t} - \eta \cdot \dfrac{\partial \theta}{\partial \eta} = \dfrac{\partial^2 \theta}{\partial \eta^2}; \\ \theta(\tau, \infty) = \theta(0, \eta) = 0; \quad \theta(\tau, 0) = 1. \end{cases} \tag{5}$$

It is proposed to simplify the form of the differential equation (5) in the source [16] by using a self-similar variable ξ:

$$\xi = \frac{\eta}{\sqrt{1 - e^{-2 \cdot r}}},$$

then the energy equation (5) takes the form of:

$$\frac{\partial^2 \theta}{\partial \xi^2} + \xi \cdot \frac{\partial \theta}{\partial \xi} = 0 \qquad (6)$$

conditions applied to the self - similar variable ξ can be defined as follows: $\theta(\infty)=0$; $\theta(0)=1$. In this case, the energy equation (6) is solved as follows:

$$\theta(\xi) = 1 - \sqrt{\frac{2}{\pi}} \cdot \int_0^{\xi} e^{-x^2/2} \cdot dx. \qquad (7)$$

The solution of the power integral (7) allows us to obtain the initial differential equation for the coefficient of heat transfer α_o from the liquid to the outer surface of the roof of the VST at the point of deceleration of the jet:

$$\alpha_o = \lambda_2 \cdot \frac{\partial T / \partial z_{z=0}}{T_\infty - T_o} \qquad (8)$$

Using equation (7), differential equation (8) for the heat transfer coefficient α_o takes on its integral form:

$$\alpha_o = \lambda_2 \cdot \frac{\sqrt{(4 \cdot \alpha) / (\pi \cdot a)}}{\sqrt{1 - e^{-2 \cdot r}}} \qquad (9)$$

For a sufficiently long process of cooling the roof of the VST in the limit when $\tau \to \infty$, the cooling process becomes stationary, and then:

$$\alpha_o = \lambda_2 \cdot \sqrt{\frac{4 \cdot \alpha}{\pi \cdot a}} \qquad (10)$$

The practical use of expressions (9) and (10) to evaluate the effectiveness of the cooling process by an impact jet of coolant is possible when determining the value of constant *a*, for which it is proposed to apply the jet continuity equation, which assumes equality of fluid flow in the section at the outlet of the fire shaft and in the section close to the outer surface of the roof of the VST:

$$d_o^2 \cdot U_o = d_1^2 \cdot U_1 \qquad (11)$$

where d_1 – diameter of the coolant jet at a distance *H* from the barrel.

For a freely falling jet of coolant, its velocity U_1 at a distance H from the fire barrel, and the velocity of movement of the liquid under the influence of gravitational forces is defined as:

$$|U_1| = \sqrt{U_o^2 + 2 \cdot g \cdot H} \tag{12}$$

where g – acceleration of free fall.

The ratio between the values of the velocity U_1 at a distance H from the fire barrel and the initial velocity U_o at the exit of the barrel is related to the Froude criterion, which characterizes the ratio of gravitational force to inertia force:

$$Fr = \frac{|U_o|}{\sqrt{g \cdot H}};$$

$$\frac{U_1}{U_o} = \sqrt{1 + \frac{2}{Fr^2}}.$$

Solving equations (11) and (12) together, we can obtain an equation that allows us to determine the diameter of the impact jet near the cooling outer surface of the roof of the VST:

$$d_1 = \frac{d_o}{\sqrt[4]{1 + \frac{2}{Fr^2}}}.$$

By solving the problem of the impact jet colliding with the plane of the cooling roof of the VST, it can be concluded that the size of the area in which the jet velocity drops from the maximum value U_1 to zero is commensurate with the diameter of the jet d_1. This statement allows us to determine the constant a in the heat transfer coefficient equation (9):

$$a = \frac{|U_1|}{2 \cdot d_1} = \frac{|U_1|}{2 \cdot d_o \cdot \sqrt[4]{\left(1 + \frac{2}{Fr^2}\right)^3}},$$

then finally the value of the heat transfer coefficient α from the liquid to the outer surface of the roof of the VST:

$$\alpha = \lambda_2 \cdot \sqrt{\frac{2 \cdot |U_o|}{\pi \cdot a \cdot d_o}} \cdot \sqrt[8]{\left(1 + \frac{2}{Fr^2}\right)^3} \tag{13}$$

The structure of equation (13) allows us to obtain a relationship with the main similarity criteria: Nusselt Nu, Reynolds Re, Prandtl Pr:

$$\frac{Nu}{\sqrt{\mathrm{Re}}} = \sqrt{\frac{2 \cdot \mathrm{Pr}}{\pi}} \cdot \sqrt[8]{\left(1 + \frac{2}{Fr^2}\right)^3}.$$

For small values of the Froude criterion applied to points adjacent to the cooled surface, and for its large values describing the process in the area of the barrel spray, the criterion equations of the heat exchange process between the impact jet and a flat horizontal surface take the form (14) and (15), respectively:

$$Nu \approx 1{,}035 \cdot \frac{\sqrt{Pe}}{\sqrt[4]{Fr^3}}, \quad npu \quad Fr << 1; \tag{14}$$

$$Nu \approx 0{,}798 \cdot \sqrt{Pe}, \quad npu \quad Fr >> 1, \tag{15}$$

where $Pe = Re \cdot Pr$ – the Pecle criterion.

Modeling results

Figure 4 shows the calculation results based on equations (14) and (15) with respect to the value of the Prandl criterion $Pr=7,6$, corresponding to ordinary water.

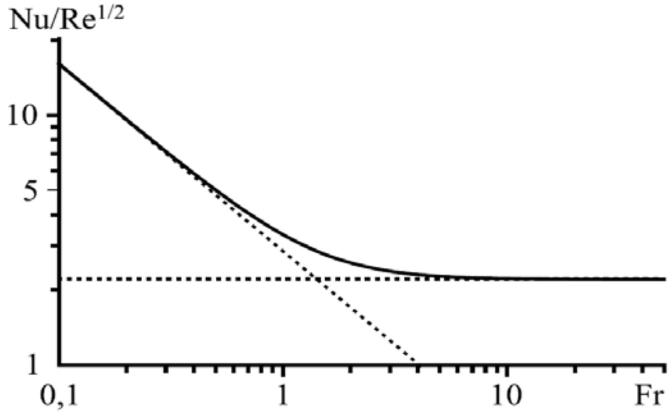

Fig. 4. **Impact jets's heat transfer dependence on the Froude number**

The study of the dependence of the Nusselt and Reynolds criteria on the values of the Froude criterion was carried out using a specially developed MS Basic macro as part of the MS Excel spreadsheet processor.

In the range of large values of the Froude criterion, the distance between the spray of the fire barrel and the cooled surface is small, therefore, the value of the Nusselt criterion is not affected by the Froude criterion and is practically unchanged, which is experimentally confirmed by the authors of the sources [7, 17].

On the contrary, in the range of insignificant values of the Froude criterion, gravitational forces prevail over inertial ones, which leads to an intensification of the heat exchange process with an increase in the height of the free fall of the impact jet onto the cooled surface. The numerical value of the Froude criterion, close to 1, is a natural point of transition from one regime to another, as illustrated in Fig.4.

With a sufficient increase in the height of the jet drop, the flow is dispersed into separate, sufficiently large droplets, which can have an impulse effect on a flat surface [18].

Let us define the average duration of the pulse action of a drop in a dimensionless form as $\sigma = \alpha \cdot t$, then the average value of the heat transfer coefficient α_m over the duration of the pulse action in accordance with (9) takes the form of:

$$\alpha_m = \lambda_2 \cdot \sqrt{\frac{2 \cdot |U_o|}{\pi \cdot a \cdot d_o} \cdot \sqrt[8]{\left(1 + \frac{2}{Fr^2}\right)^3}} \cdot \frac{1}{\vartheta} \cdot \int_0^{\sigma} \frac{d\theta}{\sqrt{1 - e^{-2 \cdot \theta}}}.$$

The solution of a certain integral is the hyperbolic arctangent function:

$$\alpha_m = \lambda_2 \cdot \sqrt{\frac{2 \cdot |U_o|}{\pi \cdot a \cdot d_o} \cdot \sqrt[8]{\left(1 + \frac{2}{Fr^2}\right)^3}} \cdot \frac{1}{\vartheta} \cdot arcth\sqrt{1 - e^{-2 \cdot \vartheta}},$$

the value of which can be decomposed into a row. And in the future, when calculating the average value of the heat transfer coefficient between a drop and a flat surface, only the first term of the decomposition should be taken into account:

$$\alpha_m = \lambda_2 \cdot \sqrt{\frac{2 \cdot |U_o|}{\pi \cdot a \cdot d_o} \cdot \sqrt[8]{\left(1 + \frac{2}{Fr^2}\right)^3}} \cdot \frac{1}{\sqrt{\vartheta}}.$$

Accordingly, the criterion equation of the heat exchange process for the case of an impulse impact flow on the flat surface of the roof of the VST takes the form of:

$$Nu_m \approx 1{,}128 \cdot \sqrt{\frac{\mathrm{Re} \cdot \mathrm{Pr}}{\vartheta} \cdot \sqrt[8]{\left(1 + \frac{2}{Fr^2}\right)^3}} \quad (16)$$

Figure 5 shows the calculation results based on equation (16) for various values of the Froude criterion.

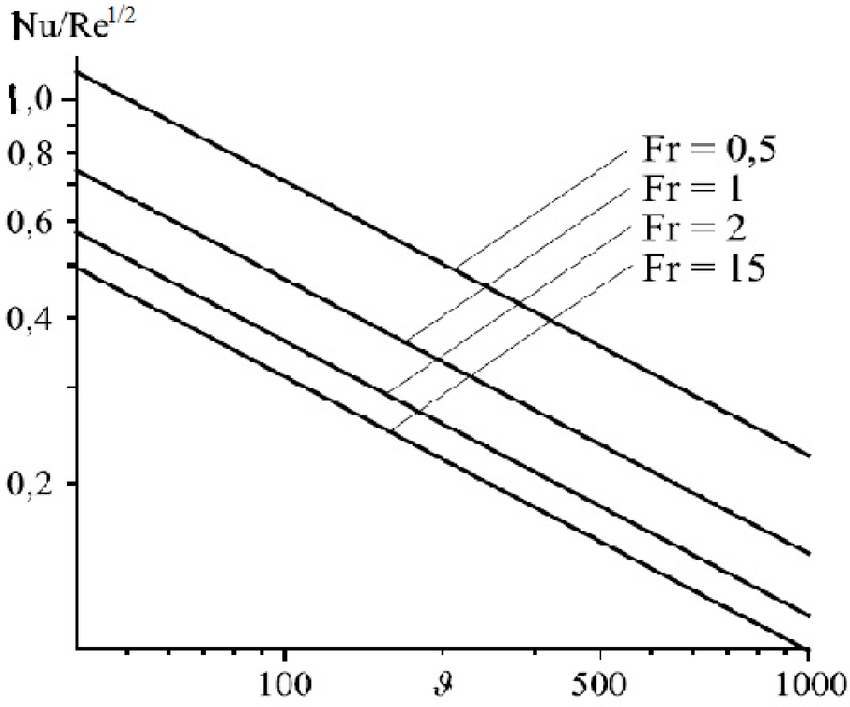

Fig 5. **Dependence of the heat transfer intensity on the Froude number under the pulsed action of an impact jet**

It follows from the analysis of Fig. 5 that the heat exchange intensity for the dispersed jet decreases as the distance from the nozzle section of the fire barrel to the cooled outer surface of the roof of the VST decreases. Approximately the same pattern can be traced with an increase in the duration of the pulse action of individual drops of coolant, which can be explained by a possible increase in the temperature difference.

Conclusion

Thus, a model of the heat exchange process between a freely falling impact jet of a fire extinguishing agent and the horizontal surface of the roof of the VST is presented in the form of a system of corresponding criterion equations representing the dependence of the Nusselt criterion on the Reynolds and Froude criteria characterizing the mode of movement of the coolant and the ratio of inertial and gravitational forces, respectively..

With small distances between the nozzle section of the fire barrel, when $Fr > 1$, the intensity of heat exchange between a freely falling impact jet of extinguishing agent and the horizontal surface of the roof of the VST does not depend on the magnitude of this distance.

With significant distances between the nozzle section of the fire barrel, when $Fr < 1$, the intensity of heat exchange between the freely falling impact jet of extinguishing agent becomes more significant

In the case of a dispersed coolant jet structure, the average heat transfer characteristics are significantly increased for a short pulse duration..

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