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MODELING THE CONVECTIVE COMPONENT OF THE HEAT FLOW FROM A SPILL FIRE AT RAILWAY ACCIDENCE

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Abstract

A significant number of emergencies that occur in the chemical, processing and transport industries begin with an accidental spill and ignition of a flammable liquid. In this case, the spread of fire to neighboring objects is of particular danger. When developing fire protection measures in areas where flammable liquids are stored, as a rule, heat transfer from a fire only by radiation is taken into account. But in some cases, the convection component of the heat flow can make a significant contribution to the overall heat transfer. Ignoring it can lead to an erroneous assessment of the safety of an industrial facility. In the paper, a model of the distribution of velocity and temperature in the upward flow, rising above the spill of a burning liquid, is constructed. The model is based on the system of Navier-Stokes equations, which, by means of simplifications, is reduced to a non-linear second-order differential equation of the parabolic type. The properties of the combustion site determine the boundary conditions of the first kind. In this case, the spill of a flammable liquid can have any shape. The presence of wind is taken into account by introducing a stable horizontal component of the flow velocity.

For the numerical solution of the equation, the method of completed differences is used. The dependence of the kinematic viscosity on the flow temperature is taken into account. An empirical formula is used as the relationship between temperature and speed. It is shown that the presence of wind leads to an inclination of the ascending flow. The angle of inclination is not constant and increases with distance from the combustion source due to a decrease in speed and cooling of the flow. An estimate of the coefficient of convection heat transfer convection of the tank wall with ascending flows over the combustion source is constructed. It is shown that the coefficient of convection heat transfer increases with increasing wind speed.

Keywords: Navier-Stokes equation, spill fire, flammable liquid, ascending flows, heat flow.

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1. Introduction

A significant number of emergencies that occur in the chemical, processing industry and transport begin with an emergency spill of flammable liquids [1]. In [2], cases of accidental spills of flammable liquids that caused fires were analyzed. In [3], the risks arising from the transportation of dangerous goods by rail are investigated, but the consequences of accidents are left without attention. In [4], an analysis of emergency situations associated with the spill of flammable liquids in railway transport was carried out. It is proposed to use statistical data to calculate the probability of accidents and the volume of spilled flammable liquid. This approach makes it possible to generalize the consequences of accidents, but does not allow analyzing a specific situation. In [5], it was found that one of the biggest derailment hazards occurs when a train passes a railroad switch. Among all possible fire scenarios, fire spills of flammable liquids are the most common and account for about 60 % [6]. The consequence of the thermal effect of a fire on neighboring objects is not only their loss of strength [7], but also their transformation into a source of inflammation if their temperature reaches the temperature of spontaneous combustion of a combustible liquid. This leads to the spread of fire to neighboring objects, in particular, to tanks or tanks with oil products. The cascading spread of a fire is characterized by significant material damage and loss of life [8]. In addition to causing damage to technological facilities and natural landscapes [9], there are also emissions of pollutants into the atmosphere [10]. Spreading over long distances, they have a significant impact on the state of the air and create risks for the population [11].

Radiation is the main mode of heat transfer from a spill fire. In [12], a model of tank heating from a spill fire was built. The model takes into account heat exchange by radiation with fire, the environment and the interior of the tank, as well as convection heat exchange with air. In [13], a combustion model for a multicomponent hydrocarbon mixture was constructed, but the heat flux from the flame is not considered in it. In [14], a model was constructed for the spreading and combustion of a combustible liquid on a horizontal surface. In [15], the thermal effect of a fire on steel structures was considered, but the dynamics of changes in the parameters of the combustion source was left without attention.

Combustion products and heated air rise above the combustion center, capturing neighboring layers of air. This means that in case of a fire in a tank with an oil product, there is no heat transfer by convection to the neighboring tank, and it is sufficient to consider only the heat flow by radiation from the flame [16]. But in the case of a fire in a landslide, the convection component of the heat flux from the fire can be significant. An additional factor is the presence of wind towards the reservoir. It was shown in [17] that in some cases the failure to take into account the convection component of heat transfer from a fire leads to an error of 20 % in predicting the time it takes for a tank to reach a dangerous temperature. This means that the convection component of the heat flow from the fire must be taken into account.

Thus, among the problems associated with the elimination of fires of spills of flammable liquids in railway transport is the problem of taking into account the convection component of the heat flow from a fire.

The main tasks in building a model of the convection component of the heat flow from a liquid spill fire include:

– construction of a mathematical model of ascending flows over a spill of burning liquid;

– finding the distribution of velocities and temperatures in the upstream;

– construction of an estimate of the coefficient of convection heat transfer of the tank wall with ascending flows over a spill of burning liquid.

2. Materials and methods

2. 1. Mathematical model of ascending flows over a burning liquid

Let's consider the combustion of a liquid spill occupying the region Ω located in the XOY plane (**Fig. 1**). The heated air and the combustion products formed in the combustion zone rise vertically upwards in the direction of the OZ axis, capturing the adjacent stationary air masses. As a result, the flow expands, and its speed decreases. Let's assume that the flow velocity at the height $z=0$:

$$u_z(x,y,0,t)=\begin{cases}u_0, & (x,y)\in\Omega,\\ 0, & (x,y)\notin\Omega,\end{cases} \tag{1}$$

where $u_0=\text{const}$ – the initial speed depending on the type of combustible liquid.

Let's consider air and combustion products as a Newtonian incompressible fluid. Then its motion can be described by the system of Navier-Stokes equations:

$$\begin{cases} \dfrac{\partial u_x}{\partial t}+u_x\dfrac{\partial u_x}{\partial x}+u_y\dfrac{\partial u_x}{\partial y}+u_z\dfrac{\partial u_x}{\partial z}=-\dfrac{1}{\rho}\dfrac{\partial P}{\partial x}+\nu\left(\dfrac{\partial^2 u_x}{\partial x^2}+\dfrac{\partial^2 u_x}{\partial y^2}+\dfrac{\partial^2 u_x}{\partial z^2}\right), \\ \dfrac{\partial u_y}{\partial t}+u_x\dfrac{\partial u_y}{\partial x}+u_y\dfrac{\partial u_y}{\partial y}+u_z\dfrac{\partial u_y}{\partial z}=-\dfrac{1}{\rho}\dfrac{\partial P}{\partial y}+\nu\left(\dfrac{\partial^2 u_y}{\partial x^2}+\dfrac{\partial^2 u_y}{\partial y^2}+\dfrac{\partial^2 u_y}{\partial z^2}\right), \\ \dfrac{\partial u_z}{\partial t}+u_x\dfrac{\partial u_z}{\partial x}+u_y\dfrac{\partial u_z}{\partial y}+u_z\dfrac{\partial u_z}{\partial z}=-\dfrac{1}{\rho}\dfrac{\partial P}{\partial z}+\nu\left(\dfrac{\partial^2 u_z}{\partial x^2}+\dfrac{\partial^2 u_z}{\partial y^2}+\dfrac{\partial^2 u_z}{\partial z^2}\right), \end{cases} \quad (2)$$

where $u(u_x, u_y, u_z)$ – the air velocity vector at a certain point; P – pressure; ρ – the air density; ν – the kinematic viscosity of air, m^2/s. Let's assume that the pressure is constant throughout the volume ($P = \text{const}$), and the flow movement is determined by the upward speed u_z and constant wind. In this way,

$$u_x = \text{const};\ u_y = \text{const}.$$

This allows to simplify the system of equations (2):

$$\frac{\partial u_z}{\partial t}=\nu\left(\frac{\partial^2 u_z}{\partial x^2}+\frac{\partial^2 u_z}{\partial y^2}+\frac{\partial^2 u_z}{\partial z^2}\right)-u_z\frac{\partial u_z}{\partial z}-u_x\frac{\partial u_z}{\partial x}-u_y\frac{\partial u_z}{\partial y},\ z>0,\ t>0. \quad (3)$$

The resulting equation (3) is a non-linear second-order differential equation of the parabolic type, which, together with the boundary condition (1) and the initial condition:

$$u_z(x,y,z,0) \quad (4)$$

specifies the distribution of velocities in the half-space $z > 0$ at a random time t.

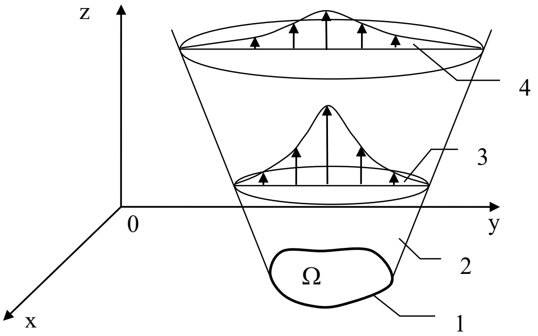

Fig. 1. Ascending flow on the spill of burning liquid: 1 – spill of combustible liquid; 2 – ascending flow above the combustion center; 3 – distribution of velocities in the flow at height z_1; 4 – velocity distribution in the flow at a height $z_2 > z_1$

In equation (3), let's pass to new variables:

$$\begin{cases} \xi = x - u_x t, \\ \eta = y - u_y t. \end{cases} \quad (5)$$

Let's consider the function:

$$w(\xi,\eta,z,t)=u_z(\xi+u_x t,\ \eta+u_y t\ ,z,t). \quad (6)$$

In this case:

$$\frac{\partial w}{\partial t}=\frac{\partial u_z}{\partial x}u_x+\frac{\partial u_z}{\partial y}u_y+\frac{\partial u_z}{\partial t}; \quad (7)$$

$$\frac{\partial w}{\partial \xi}=\frac{\partial u_z}{\partial x},\ \frac{\partial^2 w}{\partial \xi^2}=\frac{\partial^2 u_z}{\partial x^2}; \tag{8}$$

$$\frac{\partial w}{\partial \eta}=\frac{\partial u_z}{\partial y},\ \frac{\partial^2 w}{\partial \eta^2}=\frac{\partial^2 u_z}{\partial y^2}. \tag{9}$$

Substituting (7)–(9) into (3), let's obtain the equation:

$$\frac{\partial w}{\partial t}=\nu\left(\frac{\partial^2 w}{\partial \xi^2}+\frac{\partial^2 w}{\partial \eta^2}+\frac{\partial^2 w}{\partial z^2}\right)-w\frac{\partial w}{\partial z} \tag{10}$$

with initial and boundary conditions:

$$w(\xi,\eta,z,0)=0, \tag{11}$$

$$w(\xi,\eta,0,t)=\begin{cases}u_0,\ (\xi+u_x t,\eta+u_y t)\in\Omega,\\ 0,\ (\xi+u_x t,\eta+u_y t)\notin\Omega.\end{cases} \tag{12}$$

In general, kinematic viscosity depends on temperature. It is known from the theory of submerged jets that the temperature and velocity distributions in the flow are related by the relation:

$$\frac{\Delta T(\xi,\eta,z,t)}{\Delta T(\xi_1,\eta_1,z_2,t)}=\sqrt{\frac{w(\xi,\eta,z,t)}{w(\xi_1,\eta_1,z_1,t)}}, \tag{13}$$

where

$$\Delta T(\xi,\eta,z,t)=T(\xi,\eta,z,t)-T_0,$$

T_0 – the ambient temperature. If a point is chosen as a point (ξ, η, z, t) for which the condition ($\xi_1+u_x t$, $\eta_1+u_y t$)$\in\Omega$ is satisfied, then expression (11) takes the form:

$$\frac{\Delta T(\xi,\eta,z,t)}{T_f-T_0}=\sqrt{\frac{w(\xi,\eta,z,t)}{u_0}},$$

where T_f – the flame temperature. This makes it possible to estimate the flow temperature:

$$T(\xi,\eta,z,t)=T_0+(T_f-T_0)\sqrt{\frac{w(\xi,\eta,z,t)}{u_0}}. \tag{14}$$

Let's note that the nonlinear differential equation (10) cannot be solved analytically.

2. 2. Distribution of velocities and temperatures in the upward flow over the spill of burning liquid

To solve equation (10), let's use a numerous method. Let's consider equation (10) in the area bounded by the parallelepiped $\Omega=[a_x, b_x]\times[a_y, b_y]\times[0, b_z]$, supplementing the initial and boundary conditions (11), (12) with boundary conditions of the first kind on the faces of the parallelepiped:

$$w(a_x,\eta,z,\tau)=w(b_x,\eta,z,\tau)=0;$$

$$w(\xi,a_y,z,\tau)=w(\xi,b_y,z,\tau)=0;$$

$$w(x,\eta,b_z,\tau)=0.$$

Let's construct a regular three-dimensional grid with step h in the domain Ω. At all internal grid nodes, let's replace differential equation (9) with an equation in finite differences. To do this, let's approximate the partial derivatives by the expressions:

$$\frac{\partial w}{\partial t} \approx \frac{w(\xi_i,\eta_j,z_k,t_{m+1}) - w(\xi_i,\eta_j,z_k,t_m)}{\Delta t}; \tag{15}$$

where Δt – the step on the time axis;

$$\frac{\partial w}{\partial \xi} \approx \frac{\Delta_\xi w}{h} = \frac{w(\xi_{i+1},\eta_j,z_k,t_m) - w(\xi_i,\eta_j,z_k,t_m)}{h}; \tag{16}$$

$$\frac{\partial^2 w}{\partial \xi^2} \approx \frac{\Delta_{\xi\xi} w}{h^2} = \frac{w(\xi_{i+1},\eta_j,z_k,t_m) + w(\xi_{i-1},\eta_j,z_k,t_m) - 2w(\xi_i,\eta_j,z_k,t_m)}{h^2}; \tag{17}$$

$$\frac{\partial w}{\partial \eta} \approx \frac{\Delta_\eta w}{h} = \frac{w(\xi_i,\eta_{j+1},z_k,t_m) - w(\xi_i,\eta_j,z_k,t_m)}{h}; \tag{18}$$

$$\frac{\partial^2 w}{\partial \eta^2} \approx \frac{\Delta_{\eta\eta} w}{h^2} = \frac{w(\xi_i,\eta_{j+1},z_k,t_m) + w(\xi_i,\eta_{j-1},z_k,t_m) - 2w(\xi_i,\eta_j,z_k,t_m)}{h^2}; \tag{19}$$

$$\frac{\partial w}{\partial z} \approx \frac{\Delta_z w}{h} = \frac{w(\xi_i,\eta_j,z_{k+1},t_m) - w(\xi_i,\eta_j,z_k,t_m)}{h}; \tag{20}$$

$$\frac{\partial^2 w}{\partial z^2} \approx \frac{\Delta_{zz} w}{h^2} = \frac{w(\xi_i,\eta_j,z_{k+1},t_m) + w(\xi_i,\eta_j,z_{k-1},t_m) - 2w(\xi_i,\eta_j,z_k,t_m)}{h^2}. \tag{21}$$

Then equation (10) in finite differences takes the form:

$$\frac{\Delta_\tau w}{\Delta\tau} = \nu\left(\frac{\Delta_{\xi\xi} w}{h^2} + \frac{\Delta_{\eta\eta} w}{h^2} + \frac{\Delta_{zz} w}{h^2}\right) - w\frac{\Delta_z w}{h}. \tag{22}$$

It follows from (22) that the increment (in time) of the velocity w at an internal point (x_i, y_j, z_k) of the region is described by the expression:

$$\Delta_t w = \nu\frac{\Delta t}{h^2}\left(\Delta_{\xi\xi} w + \Delta_{\eta\eta} w + \Delta_{zz} w\right) - w\frac{\Delta t}{h}\Delta_z w, \tag{23}$$

which makes it possible to calculate the flow velocities at grid points at the next point in time:

$$w(\xi_i,\eta_j,z_k,t+\Delta t) = w(\xi_i,\eta_j,z_k,t) + \Delta_t w. \tag{24}$$

Thus, (23), (24) make it possible to determine the concentration of a chemical substance at the grid nodes at an arbitrary time τ. Note that in any finite region of space there exists a stationary solution of Eq. (22). The iterative process (23) coincides with this solution. To determine the value of the kinematic viscosity coefficient, let's use its approximation by a polynomial of the second degree:

$$\nu = \left(7\cdot 10^{-5}T^2 + 0.0964T + 13\right)\cdot 10^{-6}.$$

The relative error of this approximation does not exceed 2.2 % in the temperature range from 0 °C to 1200 °C.

2. 3. Estimation of the coefficient of convection heat transfer of the tank wall with ascending flows above the combustion chamber

The convection component of the heat flow from a fire spill of a flammable liquid has the form:

$$q_{conv} = \alpha(T - T_w), \tag{25}$$

where α – the coefficient of convection heat transfer; T – the temperature of the air masses; T_w – the temperature of the heated surface.

The coefficient of convection heat transfer α is determined by the relation:

$$\mathrm{Nu} = \frac{\alpha D}{\lambda},$$

where Nu – the Nusselt number; D – the diameter of the tank; λ – the coefficient of thermal conductivity of the air. The value of the Nusselt number averaged over the perimeter of the tank circumference is described by the dependence:

$$\mathrm{Nu} = 0.3 + \frac{0.62\mathrm{Re}^{0.5}\mathrm{Pr}^{1/3}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{2.82\cdot 10^5}\right)^{5/8}\right]^{4/5},$$

where Re – the Reynolds number:

$$\mathrm{Re} = \frac{w_f D}{\nu};$$

Pr – the Prandtl number; w_f – air flow speed:

$$w_f = \sqrt{u_x^2 + u_y^2 + w^2}. \tag{26}$$

Then the average value of the coefficient of convection heat transfer along the perimeter will take the form:

$$\alpha = \frac{\lambda}{D}\left[0.3 + \frac{0.62\mathrm{Re}^{0,5}\mathrm{Pr}^{1/3}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{2.82\cdot 10^5}\right)^{5/8}\right]^{4/5}\right]. \tag{27}$$

It was shown in [18] that in the temperature range $T = (273\text{–}1273)$ K, dependence (27) can be approximated by the expression

$$\alpha = 198T^{-0.7655}w_f^{0.9227}D^{-0.0773}. \tag{28}$$

The diameter of a railway tank car is about 3.2 m. Taking this into account, as well as relations (14) and (26), expression (28) takes the form:

$$\alpha = 181\left(T_0 + \left(T_f - T_0\right)w^{0.5}u_0^{-0.5}\right)^{-0.7655}\left(u_x^2 + u_y^2 + w^2\right)^{0.4614}. \tag{29}$$

3. Results and discussions

The constructed model of the velocity distribution of combustion products and heated air rising above the burning liquid is based on the system of Navier-Stokes equations (2). The assumption of constant pressure and the stable nature of the horizontal component of the air mass velocity makes it possible to simplify the system of equations and obtain a nonlinear differential equation with respect to its vertical component (3). This equation is a second-order parabolic type equation, which, together with the boundary condition (1) and initial condition (4), describes the distribution of velocities in the half-space $z > 0$ at an arbitrary time t. In this case, the speed and temperature of the ascending flow in the combustion source determine the boundary condition on the earth's surface.

The change of variables (5), (6) allows to pass to a simpler equation (10) with initial condition (10) and boundary condition (11).

The obtained differential equation contains the coefficient of kinematic viscosity, which significantly depends on the temperature of the air flow. The flow temperature is non-linearly related to its velocity (14). Such a dependence makes it impossible to analytically solve the differential equation (10). For practical application, the stationary solution of the equation is of interest, that is, $\partial w/\partial t = 0$. But it is more convenient to solve the original non-stationary equation. For this, the finite difference method is used, which is based on the replacement of partial derivatives by finite differences according to formulas (15)–(21). This makes it possible to pass from the differential equation (10) to the equation in finite differences (22). As the area in which the distribution of velocities and temperatures is considered, a finite parallelepiped is chosen. The step along the spatial axes was chosen to be 0.25 m, and along the time axis, 0.01 s. Let's note that the solution in finite differences coincides with the stationary solution if time goes to infinity.

Fig. 2 illustrates the distribution of velocities in a section perpendicular to the OY axis and passing through the origin. The combustion cell has the shape of a circle, the center of which coincides with the origin of coordinates. The initial speed of the upward flow from the combustion chamber is $u_0 = 5$ m/s, and the temperature is $T_f = 1000$ °C. The direction of the wind coincides with the direction of the axis OX, and the speed $u_x = 2$ m/s. The iterative process (14) stopped when the distribution of velocities in the region shown in **Fig. 2** went into stationary mode. The step along the spatial axes was chosen $h = 0.25$ m, and along the time axis $\Delta t = 0.01$ s.

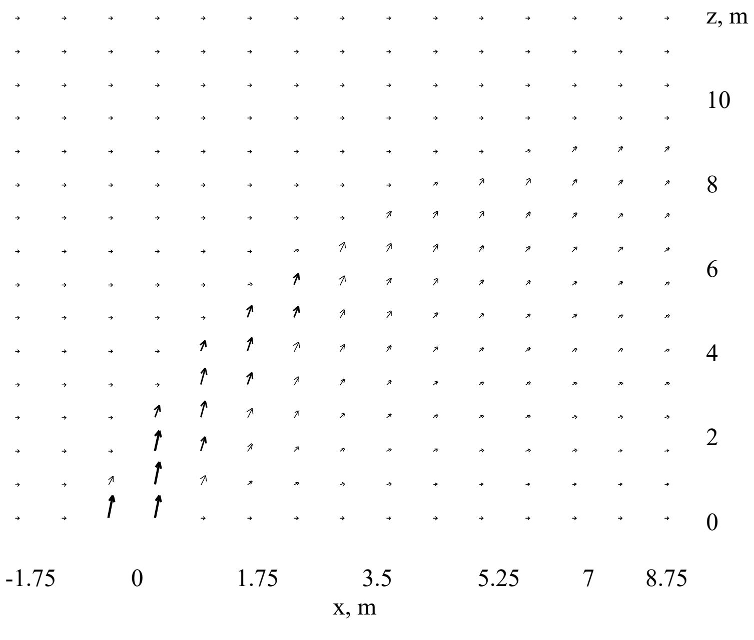

Fig. 2. Velocity distribution of air masses and combustion products in a vertical section

The temperature distribution in the ascending flow above the combustion chamber for the same conditions is shown in **Fig. 3**.

An analysis of the velocity distribution in the vertical section (**Fig. 2**) and temperature distribution (**Fig. 3**) shows that the wind tilts the ascending flow. The angle of inclination is not constant. As a result of a gradual decrease in the vertical velocity component, the slope becomes stronger with distance from the combustion source.

Based on the distribution of velocities and temperatures in the ascending flow, using the methods of the theory of similarity, an estimate of the coefficient of convection heat transfer of the ascending flow with the wall of a railway tank is found (27). Substitution of empirical dependences of thermal conductivity and Prandtl number on air temperature (27) allows to simplify this expression and obtain the convection heat transfer coefficient as a function of the velocity and temperature of ascending flows (29).

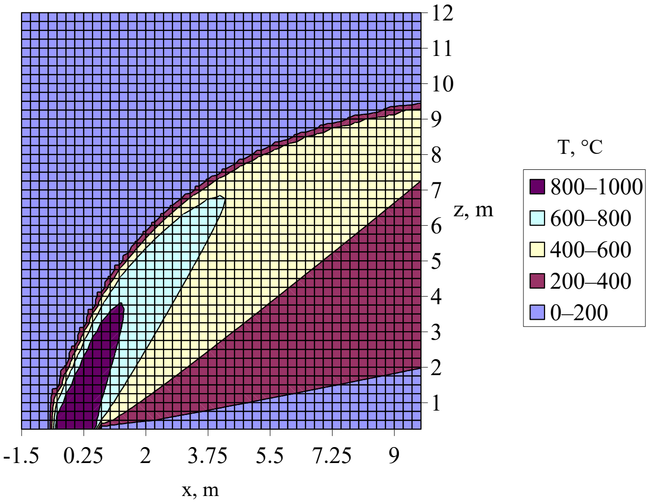

Fig. 3. Temperature distribution of air masses and combustion products in a vertical section

Fig. 4 illustrates the dependence of the convection heat transfer coefficient on the wind speed u_x and the vertical speed of the ascending flow w. In this case, the following values of the parameters were taken: $T_0 = 20$ °C; $T_f = 1000$ °C; $u_0 = 5$ m/s; $u_y = 0$.

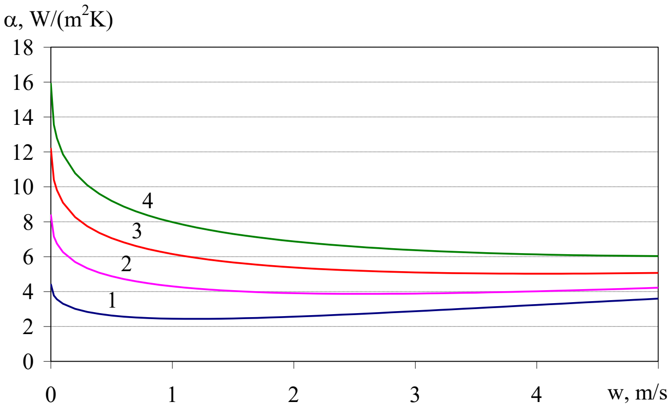

Fig. 4. Dependence of the coefficient of convection heat transfer on the vertical speed of the ascending flow w at different wind speeds: 1 – $u_x = 2$ m/s; 2 – $u_x = 4$ m/s; 3 – $u_x = 6$ m/s; 4 – $u_x = 8$ m/s

Dependence analysis in **Fig. 4** shows that the coefficient of convection heat transfer increases with increasing wind speed. If at wind speed $u_x = 2$ m/s its value lies in the range $\alpha = (2 \div 4)$ W/(m^2·K), then at speed $u_x = 8$ m/s $\alpha = (6 \div 16)$ W/(m^{2}K).

The coefficient of convection heat transfer makes it possible to estimate the convection component of the heat flow from a fire. The distribution of the convection component q_{conv} of the heat flux from a fire of a combustible liquid spill in a vertical section calculated according to (25) is shown in **Fig. 5**.

The calculation of the convection heat flux in **Fig. 5** is carried out under the condition that the temperature of the surface of the tank is equal to the ambient temperature. The analysis shows that depending on the distance of the tank to the fire, the density of the heat flow is (0.5÷2.5) kW/m^2.

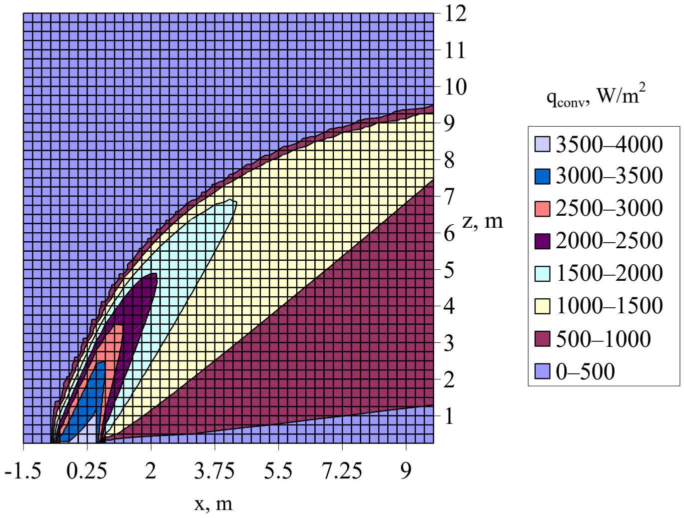

Fig. 5. Distribution of the convection component of the heat flux from a fire in a vertical section

This makes it possible to take into account the convection component of the heat flow when planning fire-fighting measures in places where combustible liquids are stored. The results can also be used in the design of fire detectors [19].

The advantage of the proposed approach is the ability to consider an arbitrary shape of the spill of a burning liquid, and not just a circular one. The limitation of this study is the need for a priori information about the value of the velocity in the boundary condition (12). The disadvantages include a simplified interpretation of the upward flow from the combustion source and the stable nature of the horizontal velocity component, due only to the wind.

Prospects for further research are related to taking into account the dependence of the density of the air medium on its temperature and the solution of the complete system of Navier-Stokes equations.

4. Conclusions

1. A mathematical model of the distribution of velocities and temperatures in the ascending flow over a spill of burning liquid has been constructed. The model is based on the Navier-Stokes system of equations with additional assumptions of constant pressure and no horizontal velocity component other than wind. Such simplifications make it possible to reduce the system of equations to one non-linear second-order differential equation of the parabolic type.

2. The application of the finite difference method allows one to find an approximate solution of the equation in the region of space bounded by a finite parallelepiped. The step along the spatial axes was chosen to be 0.25 m, and along the time axis, 0.01 s. An analysis of the obtained solution shows that the wind tilts the ascending flow, but the angle of inclination is not constant. It increases with distance from the source of combustion. This is due to the loss of speed and cooling of the ascending flow.

3. An estimate of the coefficient of convection heat transfer of the tank wall with ascending flows over the combustion source is constructed. It is shown that the coefficient of convection heat transfer increases with increasing wind speed. If at a wind speed of 2 m/s its value is in the range (2÷4) W/(m^{2}K), then at a speed of 8 m/s it is in the range of (6÷16) W/(m^{2}K). Depending on the distance of the tank to the fire, the density of the heat flow is (0.5÷2.5) kW/m^2.

Conflict of interests

The authors declare that there is no conflict of interest in this article, as well as the published results of the study, including the financial aspects of conducting the study, obtaining and using its results, as well as any non-financial personal relationships.

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Data availability

Data will be provided upon reasonable request.

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