Modeling an Ascending Flow over a Burning Oil Spill

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**Abstract.** A significant number of emergencies that occur in the chemical, process, and transportation industries begin with accidental spillage and ignition of combustible liquids. In such cases a special danger is the spread of fire to adjacent sites. As a rule, only the radiant heat transfer from the fire is taken into account when developing fire-fighting measures for combustible liquids storage facilities. However, in some cases, the convection component of the heat flux can make a significant contribution to the overall heat transfer. Ignoring it can lead to an incorrect safety assessment of an industrial facility. This paper proposes a model of the velocity and temperature distribution in the plume above a spill fire. The model is based on the Navier-Stokes equation and is a nonlinear second order parabolic differential equation. The properties of the combustion center determine the first-type boundary condition. The spillage of flammable liquid can have any shape. The presence of wind is taken into account by introducing a constant horizontal component of the flow velocity. The finite difference method is used to numerically solve the equation. The dependence of kinematic viscosity on the flow temperature is taken into account. An empirical relationship is used for correlation between temperature and velocity. It is shown that the presence of wind inclines the ascending flow. The angle of inclination is not constant and increases with distance from the combustion center due to the decrease in velocity and cooling of the flow.

**Keywords:** Navier-Stokes Equation, Spill Fire, Velocity and Temperature Distribution.

1. Background

A significant number of emergencies that occur in the chemical, process, and transportation industries begin with accidental spillage and ignition of combustible liquids [1]. Some of the catastrophic spill fire accidents that occurred in recent years are listed in [2]. The risks that arise when transporting dangerous goods by rail are analyzed in [3]. In [4], it is shown that one of the greatest dangers of derailment occurs when a train passes through railway turnout systems. Among all possible fire scenarios, flammable liquid spill fires are the most common and account for about 60% [5]. Thermal effect on steel structures leads not only to their loss of strength [6], but could also turn them into a source of ignition, if their temperature reaches the ignition temperature of the combustible liquid. Of particular danger is the spread of fire to adjacent facilities, including adjacent oil tanks (domino effect). Domino accidents lead to great losses of life and property [7]. In addition to causing damage to process facilities and natural landscapes [8], this leads to the release of pollutants into the atmosphere [9]. Spreading over long distances, they significantly affect the state of the air and pose risks to the population [10]. In this regard, one of the problems is to predict the thermal impact of a spill fire on neighboring facilities and prevent the domino spread of fire.

The main way to transfer heat from a spill fire is radiation. A model of tank heating from a pool fire was built in [11]. The model takes into account the following heat transfer mechanisms: heating by radiation, cooling by convection, cooling by radiation on the inside and outside of the tank. A model of a pool fire of a multi-component hydrocarbon mixture under semi-confined geometry was built in [12]. In [13], the spread and combustion model of burning fuel on a horizontal surface was built. Thermal effect of fire on steel structures is considered in [14], however, leaving aside the combustion center dynamics.

Combustion gases and heated air rise in a plume above the combustion center, capturing adjacent air masses. This means that in the event of a pool fire within the oil tank, there would be no transfer of heat by convection to an adjacent tank, and it is sufficient to consider only the radiation heat flux from the flame [15]. However in the case of a pool fire within the dike, the convection component of the heat flux from the fire can be significant, whereas wind blowing towards a tank could be an additional factor. In [16], it was shown that in some cases, ignoring the convection component of a fire heat transfer could lead to an error of up to 20% in forecasting the time it would take for the tank to heat up to a dangerous temperature. This means that it is necessary to take into account the convection component of the heat flux from a spill fire.

The calculation of the convection component of the heat flux requires estimates of the temperature and velocity of the combustion gases and heated air at the point of contact with the tank wall. Therefore, building of such estimates is a valid problem.

1. Modeling the velocity distribution in the flow over a burning spill
   1. Mathematical model

Let's consider a liquid spill fire occupying the area , located in the plane  (see Fig. 1). The plume of combustion gases and heated air rise vertically upwards from the combustion zone in the direction of the axis , pulling in adjacent stationary air masses. As a result, the flow expands, whereas its speed decreases. We will assume that the flow rate at a height  is:

, (1)

where  is the initial speed depending on the type of flammable liquid.

1

2

3

4











**Fig. 1.** Ascending flow over the burning spill: 1 – spillage of combustible liquid; 2 – ascending flow over the combustion center; 3 – distribution of velocities in the flow at the height ; 4 - distribution of velocities in the flow at the height 

We take air and combustion gases as a non-compressible Newtonian fluid. Thus their motion can be described by the Navier-Stokes equation:

 (2)

where *u(ux, uy, uz)* is the vector of air velocity at a certain point; *P* is the pressure;  is the kinematic viscosity of air, m2/s. We assume that the pressure is constant throughout the volume (*P = const*), and the flow is determined by the upward velocity *uz* and the wind blowing along the direction of the *X* axis. Thus,

*ux* = *const*; *uy* = *const*.

This simplifies the system of equations (2):

, , . (3)

The obtained equation (3) is a nonlinear second order parabolic differential equation, which together with the boundary condition (1) and the initial condition

 (4)

sets the distribution of velocities in the half-space  at any time .

In equation (3) we go over to new variables

.

We will consider the function

.

In this situation

; (5)

, ; (6)

, . (7)

Substituting (5)-(7) into (3), we obtain the equation

 (8)

with the initial and boundary conditions

, (9)

. (10)

In general, the kinematic viscosity depends on the temperature.

The temperature and velocity distributions in the ascending flow are related by the following ratio

, (11)

where

,

 is the ambient temperature. If a point  is selected as the point meeting the condition , then the expression (11) takes the following form

,

where  is the flame temperature. This allows for estimation of the flow temperature

. (12)

Note that the nonlinear differential equation (8) cannot be solved analytically.

* 1. Numerical simulation

To solve equation (8) we use the numerical method. We consider equation (8) for the parallelepiped confined space , supplementing the initial and boundary conditions (9), (10) with the first kind boundary conditions on the faces of the parallelepiped

;

;

.

Let's build a regular three-dimensional grid with the scale spacing of  in the space .

For all internal grid nodes, we replace the differential equation (7) by the finite difference equations. To do this, we approximate partial derivatives by the following expressions

;

where  is the scale spacing on the time axis.

;

;

;

;

;

.

Then equation (7) expressed as finite differences will take the following form

, (13)

It follows from (13) that the velocity increment (in time) *w* at an interior space point  is described by the following expression

, (14)

which allows for calculating the flow velocities at grid nodes at the next point in time

. (15)

Thus, formulas (14), (15) allow for finding the values of chemical concentrations at the grid nodes at an arbitrary point of time . Note that in any finite space there is a time independent solution for equation (13). The iterative process (14) resolves itself into this solution.

To determine the value of the kinematic viscosity coefficient, we use its approximation by a second degree polynomial

.

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

1. Results

Fig. 2 illustrates the distribution of velocities in a section that is perpendicular to the *OY* axis passing through the origin of coordinates. The combustion center has the shape of a circle, the center of which coincides with the origin. The initial velocity of the ascending flow from the combustion center is *u0* = 5 m/s, and the temperature is 1000 °С. The wind direction follows the direction of the *OX* axis having the velocity *ux* = 2 m/s. The iterative process (14) stops when the velocity distribution in the space shown in Fig. 2 reaches the steady state. The spacing along the spatial axes was chosen as *h* = 0.25m, and along the time axis Δ*t* = 0.01s.



-1.75 0 1.75 3.5 5.25 7 8.75

x, m

z, m

10

8

6

4

2

0

**Fig. 2.** Velocity distribution of air masses and combustion gases in the vertical section

For the same conditions, Fig. 3 shows the distribution of temperatures in the plume over the combustion center.



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

1. Discussion

The model of velocities distribution of combustion gases and heated air rising above the spill fire is based on the Navier-Stokes equations system. Assuming the constant nature of the horizontal velocity component allows for simplifying the system and obtaining a nonlinear differential equation with respect only to its vertical component. The velocity and temperature of the ascending flow in the combustion center determine the boundary condition.

The obtained differential equation contains the kinematic viscosity coefficient which significantly depends on the air flow temperature. In turn, temperature of the flow has a nonlinear relation to its velocity. Such a dependence rules out an analytical solution to the differential equation.

For practical application, the time independent solution of the equation is of interest, i.e., where ∂*w*/∂*t* = 0. But it is more convenient to solve the original time independent equation. The finite difference method is used for this purpose. By choosing the space wherein to consider the distribution of velocities and temperatures in the shape of a finite parallelepiped, the solution in finite differences resolves into a time independent solution.

Image analysis in Fig. 2, Fig. 3 shows that the wind inclines the ascending flow. But the angle of inclination is not constant. Due to the gradual decrease in the vertical velocity component, the inclination grows with distance from the combustion center. This allows for taking into account the convection component of the heat flux when planning firefighting measures at combustible liquids storage facilities. The results can also be used in the design of fire detectors [17].

The proposed approach offers an advantage of flexibility allowing for considering any shape of a spill fire, not just circular. Disadvantages include a simplified interpretation of the ascending flow in the plume above the combustion center and the steady state nature of the horizontal velocity component due only to wind.

Prospects for further research are related to the turbulent viscosity of the air, which is a function of flow velocity.

1. Conclusions

A mathematical model for the distribution of velocities and temperatures in the plume over the spill fire has been constructed. The model is based on a system of the Navier-Stokes equations and is a nonlinear second order parabolic differential equation. The influence of wind is taken into account as a constant horizontal velocity component. The application of the finite difference method allows for finding an approximate solution for a space bounded by a finite parallelepiped.

Analysis of the obtained solution shows that the wind inclines the ascending flow, but the angle of inclination is not constant. It increases with distance from the combustion center. This is due to the velocity loss and cooling of the plume.

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