The Numerical Implementation of the Method for Determining the Thermal Impact of Gas Blowout Fire, Considering the Wind Direction

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Abstract. The article provides a method for calculating the irradiation coefficient of a gas flame, inclined under influence of the wind, an arbitrarily located object in relation to the ground, the distance from the fire and the direction of the wind. The flame is brought to a circular inclined cone. A person was selected as a potential object of risk. The calculation of the irradiance coefficient was made by a numerical method. To check the adequacy of the adopted model, a calculation was made according to the well-known formula for approximating a flame by a vertical cylinder, considering it a particular case of a cone. When comparing the calculation by numerical integration method with calculation by formula, the match of results was found. We also provide directions for further research in this area.

1. Introduction
Conducting research work in the field of evaluation of the potential fire danger at gas and oil production facilities consists in a very limited use of experimental methods for studying the situation in case fires, the further evaluation of their development and assessing the consequences. This is due to the complexity and danger of carrying out large-scale fire experiments. The best research method for objects with high fire risks is the development of a mathematical model that makes it possible to determine the values of the thermal effect of a fire with its subsequent implementation in the program for computer simulation modeling of fires at fire hazardous facilities associated with the usage of hydrocarbons.

2. The relevance and scientific importance of the issue
The difficulty of extinguishing fires that occurs at these facilities, the need to ensure the safety of participants in the elimination of fire dictates the need to assess the real situation during a fire and predict its development [1, 2]. This points out the relevance of the development of a mathematical model and its numerical implementation in the modeling technique.

Earlier, foreign researchers and we carried out developments on modeling the situation during a fire in reservoirs with hydrocarbon fuel and determining safe distances for participants in the elimination of fire and other objects of risk [3, 4]. The novelty of these studies is based on a numerical implementation of mathematical model for determining the thermal effect in a gas blowout fire, taking into account the wind effect.
3. The theory and methods of experimental research

To ensure the safety of people during a gas blowout fire extinguishing, it is very important to assess the distribution of falling heat fluxes in the combat zone of firefighting brigades. This is a working area, in which, in addition to the employees of specialized emergency rescue units, there is also personnel of the facility and other specialists taking part in the elimination of emergency gushing. By the working area we mean the space of 2 meters high above the level of the zone, where working personnel usually operates.

The methodology for calculating the irradiance coefficient is based on Lambert's law.

\[
\frac{1}{\pi} \int_{F_1} \frac{\cos \psi_1 \cos \psi_2}{\pi S^2} \, dF_1 = \varphi
\]  

(1)

where, \( S \) – the distance between centers of elementary areas at \( F_1 \) and \( F_2 \);

\( \psi_1, \psi_2 \) - the angles between \( S \) and the normal to the areas at \( F_1 \) and \( F_2 \), respectively.

In order to carry out the integration, it is necessary, first of all, to express the quantities under the integral sign in equation (1) using the known parameters. Earlier, a mathematical description was made of the emitting object, in our case the flame of a gas blowout. We assume that the emitting object and the object of risk, for convenience, are described each in its own local coordinate system.

The goal of this work is the numerical realization of method for determining the thermal effect to the object of potential risk in a gas blowout fire, taking into account the direction and strength of the wind. For example, as an object of risk, let's choose a person in a work area.

To achieve this goal, it is necessary to solve the following tasks:
- bring the integrand expression (1) in relation to the working area,
- combine the coordinates of the flame and the object of risk into a single system,
- perform numerical integration, check the adequacy of the model.

The scheme for determining the irradiance coefficient in this area is shown in Figure 1.

The singular normal vector to the receiving area in the \( X_2 Y_2 Z_2 \) system has coordinates equal to:

\[
n_2 = \{-1, 0, 0\}
\]  

(2)

The coordinates of point A in the center of the receiving area are:

\[
X_A = 0 \\
Y_A = 0 \\
Z_A = 0
\]  

(3)

Thus, all coordinates associated with the emitting and receiving objects have been obtained. Before carrying out the integration process, it is necessary to bring out all parameters to one coordinate system.

Since we have two coordinate systems \( X_2 Y_2 Z_2 \) and \( X_1 Y_1 Z_1 \) whose origins do not match, it is necessary to make a replacement, a parallel transfer of the origin of one system to the origin of the other, leaving the direction of the axes unchanged. In this case, the transfer formulas will look like:

\[
X'_2 = X_2 + X_0
\]  

(4)

\[
Z'_2 = Z_2 + Z_0
\]  

(5)

where, \( X_0 \) and \( Z_0 \) are the coordinates of the old beginning in the new system \( X_2 Y_2 Z_2 \), m.

Mainly, the task is reduced to transforming coordinates associated with the receiving surface. Therefore, the coordinates of beginning of the \( X_2 Y_2 Z_2 \) system in the \( X_1 Y_1 Z_1 \) system can be determined by the formulas:

\[
X_0 = \ell
\]  

(6)

\[
Z_0 = H_2 - H_1
\]  

(7)

where, \( H_1 \) - is the height of the beginning of \( X_1 Y_1 Z_1 \) coordinate system from the ground level; 
\( \ell \) - distance from the wellhead to the risk object;
$H_2$ - is the height of the risk object (person).

Figure 1. The scheme for determining safe thermal zones for personnel.

$\vec{W}$ - direction of wind impact; $l$ - is the distance from the wellhead to the risk object; $\beta$ – is the angle of rotation of the flame; $\gamma$ - is the angle of inclination of blowout; $n$ - unit normal vector to the receiving area.

The transfer of the coordinate system of the irradiated object is shown in Figure 2.

Forasmuch now we have two coordinate systems $X_2' Y_2' Z_2'$ and $X_1 Y_1 Z_1$, the origins of which are equal, it is necessary to make an orthogonal transformation of the first system into the second. It can be said that we will consider the transformation of the space $(X_2' Y_2' Z_2')$ into the space $(X_1 Y_1 Z_1)$. This transformation has the feature - when a segment of length $S$ moves into a segment of the same length $S$, and two vectors emerging from one point with an angle $\psi$ between them follow into two vectors of the same length, with the same angle between them [5, 6].

Figure 3 shows orthogonal transformations of coordinate systems.
**Figure 2.** The transfer of the coordinates system of irradiated object.

**Figure 3.** Orthogonal coordinate system transformations.  
- a - rotation around the \(0Z_1\) axis through an angle \(\beta\);  
- b - rotation around the \(0Y_1\) axis by an angle \(\gamma\).

We make the transformation in two steps. First: \(X'_2\ Y'_2\ Z'_2\ \rightarrow\ X'_1\ Y'_1\ Z'_1\), i.e. rotation of the system around \(0Z'_2\) to the angle \(\beta\) (Figure 3 (a)) using the orthogonal matrix \(C_1\)

\[
C_1 = \begin{bmatrix} 
\cos\beta & \sin\beta & 0 \\
-sin\beta & \cos\beta & 0 \\
0 & 0 & 1 
\end{bmatrix}
\]  
(8)

The second step: rotation of the \(X'_1\ Y'_1\ Z'_1\) system around the \(0Y'_1\), axis by the angle \(\gamma\) using the orthogonal matrix \(C_2\) as shown in Figure 3 (b):

\[
C_2 = \begin{bmatrix} 
cos\gamma & 0 & sin\gamma \\
0 & 1 & 0 
-sin\gamma & 0 & cos\gamma
\end{bmatrix}
\]  
(9)

4. The practical importance, proposals for implementation, results of experimental research

So, we have received a number of mathematical expressions describing the emitting and receiving objects, and, therefore, allowing us to obtain an integral expression necessary to calculate the irradiance coefficient. At the same time, this method allows us to consider the location of the object of influence at any point in space around the burning gas blowout, as well as in any other configuration.
of the flame of an openly burning oil product. Knowing the integrand, you can carry out the process of calculating the slopes.

To check the adequacy of the model, it is necessary to make calculations according to well-known analytical formulas, bringing them to our model.

Let's consider the approximation of the flame by a cylindrical surface, as shown in Figure 4, rightly considering the cylinder to be a particular case of a cone, when the top and bottom are equal, while the radius of the torch is constant over the entire height.

Figure 4. Subdivision of the radiating surface when calculating the irradiance by the cell method.

\[
Y = \frac{B}{\pi} \arctg \frac{H}{\sqrt{1 - B^2}} + \frac{H}{\pi} \left[ \frac{1 + B^2 + H^2}{B_1^2 \sqrt{AC}} \arctg \frac{A(1 - B)}{C(1 + B)} - \arctg \frac{1 - B}{1 + B} \right]
\] (10)

At \( \gamma = 90^\circ \), using formula (10), the irradiance coefficient was calculated for the following initial data: relative height of the flame \( H_0 / d_r = 1.5 \), diameter of the flame base \( d_f = 22.8 \) m, a distance from the edge of the flame \( \ell = 0.5 \) \( d_r \). The result was 0.2450. The irradiance coefficient obtained by numerical integration by the method of cells at various intervals of the partition is shown in Table 1, from which it can be seen that the calculation results are quite accurate.

The implementation of the presented model in the form of a software product will improve the accuracy of calculations when solving problems of simulating fires, reduce labor costs, and take into account as much as possible when the calculations are made such important phenomena as a significant relationship between damaging factors, the features of hydrocarbons, combustion conditions and the state of environment (air temperature, wind direction and strength, humidity, etc.).

The research carried out forms the basis for the development of the algorithm and functional structure of the program for modeling the situation during a fire.
### Table 1. Numerical Integration Results for Cylindrical Flame Approximation.

| Number of partitions by height | Number of partitions by radius | Irradiation coefficient |
|-------------------------------|-------------------------------|-------------------------|
| 3                             | 2                             | 0.2440                  |
| 4                             | 4                             | 0.2479                  |
| 5                             | 4                             | 0.2484                  |
| 6                             | 5                             | 0.2451                  |
| 8                             | 7                             | 0.2406                  |
| 10                            | 12                            | 0.2450                  |
| 14                            | 11                            | 0.2450                  |
| 16                            | 12                            | 0.2454                  |
| 18                            | 16                            | 0.2456                  |

5. Conclusions

With the help of modern computer modeling technologies, it is possible to obtain a virtual picture of a fire in different periods of time, predict its further development, monitor the dynamics of the state and temperature of the irradiated object, i.e. an object located next to a burning one, its survivability in conditions of exposure to hazardous fire factors. The use of modern computer tools with the use of appropriate software for modeling complex fires of hydrocarbon blowouts can become an important tool in the practical part of the work of firefighters, in terms of working out possible scenarios for the development of fires, which in turn makes it possible to efficiently localize and extinguish them.

6. References

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