Mathematical Modeling of the Thermal Effect During the Combustion of an Emergency Blowout of Hydrocarbon Fuel

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Abstract. The article demonstrates a reason for developing a scientifically based method for determining the falling heat steam from a fire flame of an emergency blowout of hydrocarbon fuel for liquid and gaseous product. In this case, the fire flame is taken in the form of a cone, inclined under the influence of wind, which will allow obtaining more accurate values. The method will help to identify the falling heat flow at any point in space around the burning flame, taking into account the direction and speed of the wind. The method is also applicable in assessing the thermal impact of a gas stream flame in accidents of gas transmission pipelines. The practical application of the methodology will provide an opportunity to determine safe distances for people involved in the elimination of the accident and fire-fighting, as well as to assess the safe distances for objects located in the heat affected zone.

1. Introduction
The social and economic situation of Kazakhstan today is largely determined by the state and development of the oil and gas industry. However, oil and gas production is the industry with the highest risk of emergency situations, the most frequent of which are fires.

Taking into account the high fire and explosion hazard of hydrocarbon raw materials at oil and gas production facilities, it is necessary to maintain a set of preventive measures to prevent fires and minimize their possible consequences. Although, fires occur in spite of taking preventive measures.

2. The relevance and scientific importance of the issue
The example of such fire is the emergency situation that occurred on March 25, 2019 at well № 8237 of the “Kalamkas” field in the Mangistau region of Kazakhstan. After the accident with the release of a gas-water mixture, an open combustion of a gas-water manifestation of a griffin took place on an area of about 900 m², the height of the flame reached 10-15 meters.

The elimination of that fire lasted for about five days. Special vehicles for gas-water extinguishing and fire pumping stations were involved (a total of 21 units of fire-fighting and special equipment, as well as 84 people). However, the presence of high temperatures in the emergency zone and constant winds changing their direction did not allow to provide the optimal placement of fire-fighting equipment for the effective introduction of fire extinguishing agents directly into the fire. [1].

According to the analysis of measures taken to eliminate and extinguish this fire, the leadership of the oil and gas industry and the firefighting service of the Republic of Kazakhstan noted the absence
of substantiated methods that allow assessing the real situation of the fire, as well as predicting its further development.

The relevance of this topic is as follows. Fires occurring at oil and gas facilities not only lead to enormous socio-economic damage, environmental pollution, but also cause irreparable environmental damage and can lead to climatic and biological disasters. When gas and oil gushers burn, millions of tons of hydrocarbons are burned per day, and fires can last for many months.

The extinguishing and liquidation of burning flames is protracted and requires the involvement of a large amount of manpower and resources. The work is associated with injuries, in some cases with the death of people, as well as with the failure of fire fighting equipment. The workers of emergency rescue services and maintenance personnel of facilities involved in the elimination of the accident and extinguishing the fire expose their lives and health to high risk, since work is carried out under the influence of extremely high values of heat flows, as well as other dangerous and harmful fire factors [2]. The development of solutions to reduce risks at gas and oil production facilities determine the relevance of the topic under consideration.

The issues of ensuring the safety of people in case of fires remain relevant, as evidenced by the studies of domestic and foreign scientists [3-6].

In case of fire in an open space, the greatest danger is caused by such a dangerous fire factor as the heat radiation of the flame.

In general, there are two models of heat sources of open fires of hydrocarbons: a point model and a model of a surface-volume source of radiation. The point model is used in cases where the dimensions of the radiation source are incommensurably small in comparison with the distance between the objects involved in heat exchange and the shape of the flame is not decisive.

Within safe distances between burning hydrocarbon fuels and nearby buildings and structures, a surface-volumetric emitter model must be used.

In this case, the heat flow from the fire perceived by an object located at a distance from the radiation source is equal to:

$$ q_n = \varphi \tau \varepsilon_1 \sigma_0 T_f^4 $$

Here $\varepsilon_1$ - characterizes the integral coefficient of radiation emission of the flame (reacting components), averaged over the surface, i.e. its integral emissivity.

As a rule, all researchers in this area introduce the following concept

$$ q_S = \varepsilon_1 \sigma_0 T_f^4 $$

Where, $q_S$ – an integral density of flame radiation, which characterizes the average emissivity of an equivalent optically "black" body with the same temperature ($T_f$) as the flame temperature;

$\sigma_0$ – Stefan-Boltzmann constant, equals to $5.67 \cdot 10^{-8}$ Br∙m$^{-2}$∙K$^{-4}$;

$\varphi$ – irradiation factor ("vision" factor), which depends on the location of the source and the object, characterizing the fraction of "hemispherical" radiation (in all directions of the half-space) that fell from the source to the object;

$\tau$ – absorption coefficient of radiation from a source by the atmosphere.

Then, the formula (1) takes the form as:

$$ q_n = q_S \varphi \tau $$

The formula (3) shows that the falling heat flow is a function of the thermal ($q_S$) and geometric characteristics of the flame ($\varphi$) and the object to which the thermal effect is directed, as well as the characteristics of the atmosphere between the objects involved in heat exchange ($\tau$).

In the model of a surface-volumetric emitter, it is assumed that the source of energy production is the entire volume of reacting gases, in which the processes of radiation and absorption take place simultaneously, and external radiative heat exchange occurs from the surface of a certain geometric approximation, while earlier modeling of fire was carried out under the assumption of burning in calm conditions. Later, foreign scientists obtained more complex formulas for determining the irradiance coefficient in the wind, but they also had a limited range of use.
The peculiarities of fires caused by spills of flammable liquids or combustion of tanks have already been comprehensively studied and there is a sufficient methodological base for their elimination. With regard to the fires of emergency blowouts, we have not come across engineering methods for predicting the situation that objectively reflect the real picture of the fire. And according to this, we formulated the purpose of the study: the modeling of situations during large open fires of emergency hydrocarbon blowouts, taking into account the wind direction.

The biggest danger is represented by fires of oil gushers. The study of such fires has shown that the shape of flame and the size of fire source will largely determine the oil product spilling over the ground surface. In other words, this fire can be considered as special case of spills and should not be singled out as a separate group.

We investigated the modeling of spill fires within the research work [7]. As a result of research, a methodology and program for modeling the situation during a fire at facilities related to the production, storage, processing and transportation of oil and oil products have been developed. Development allows:

- in accordance with the initial data, to calculate the values of the radiation density of the flame, the irradiance coefficient, the density of the incident heat flow, the safe distance from the fire source to the "risk object", draw a conclusion about the danger of thermal effects for potential risk object;
- to see a virtual picture of the dynamics of state of an object located next to the burning one (object of risk), evaluate the situation during the fire and predict the further development of it i.e. to represent the situation during the fire in different periods of time, the temperature regime of irradiated object and its survivability under the influence of hazardous fire factors.

To achieve this goal, it is enough for us to solve the problem of simulating a gas blowout fire, namely, to determine the irradiance coefficient for any ratio "flame-object of risk".

3. The theory and methods of experimental research

Consider the provisions of the classical theory of heat transfer by radiation between two surfaces randomly located in space.

The amount of energy that the elementary area $dF_i$ emits on the body surface $F_i(X, Y, Z = 0)$ per single area on the surface $F_2 \,(X, Y, Z) = 0$, is determined by the equation following from the Lambert and Stefan-Boltzmann laws:

$$dq_n = \varepsilon_i \sigma n T_i^4 \cos \psi_1 \cos \psi_2 \frac{1}{\pi S^2} \, dF_i \quad (4)$$

Where, $S$ – the distance between centers of elementary areas at $F_i$ and $F_2$;

$\psi_1, \psi_2$ – the angles between $S$ and the normal to the areas at $F_i$ and $F_2$, respectively

Integrating the equation (4) over the surface $F_1$ gives the following

$$q_n = \varepsilon_i \sigma n T_i^4 \left( \frac{1}{\pi} \right) \int \frac{\cos \psi_1 \cos \psi_2}{\pi S^2} \, dF_1 \quad (5)$$

Where, $F_1^*$ is part of $F_1$, for which $\psi_1$ and $\psi_2$ are less than $\pi/2$.

Equation (5) is the equation of radiant heat transfer between the radiating surface $F_i$, and the elementary area on the surface $F_2$.

In the expression (5), integral

$$\frac{1}{\pi} \int_{F_i} \frac{\cos \psi_1 \cos \psi_2}{\pi S^2} \, dF_1 = \varphi \quad (6)$$

is the coefficient of irradiation by the surface $F_i$ of an elementary area $dF_2$, which is a part of the total radiation energy $F_i$ falling on $dF_2$.

From the above it follows that the irradiance factor $\varphi$ is a purely geometric characteristic of the system and is determined by the shape of bodies and their location in space.

The reference literature on heat transfer contains a large number of formulas for calculating irradiance coefficients for the most common configurations [8, 9]. However, in relation to gas blowouts, the model
of a point radiation source was previously used. Although in practical application in regulatory documents, for example, in [10], due to lack of scientifically substantiated data on calculating the irradiance coefficient for a gas flame, it is recommended to use the formulas obtained for spill fires. Moreover, the same document notes that the flame has a cone shape with conicity factor of 0.15, i.e.

\[ H_0 = 0.15D \]

(7)

With a flame height:

\[ H_0 = k G^{0.4} \]

(8)

where \( H_0 \) – flame length along the axis, m;
\( D \) – flame tip diameter, m;
\( k \) – empirical coefficient;
\( G \) – product consumption, kg/sec.

In the literature [11, 12], there is a large amount of reference data on the account of these geometric relationships for the most common configurations. However, in previous studies of the thermal effect from a flame of a burning fuel, such factors as the direction and speed of wind, as well as changes in the geometric parameters of the flame under its influence, were not taken into account. Therefore, there can be so many such relationships that it will be possible to obtain analytical formulas for calculating the irradiance coefficients for all possible cases.

Based on the above it follows that the irradiance coefficient is purely geometric characteristics of the system and is determined by the shape of bodies and their location in space. This determines the need to develop a methodology for calculating the irradiance coefficient for any ratio "flame - object".

Under the influence of the wind, the flame tilted towards an object nearby. The design scheme is shown in figure 1.

![Figure 1. Calculation scheme.](image)

The calculation of irradiance coefficient is based on Lambert’s law [13]. In order to carry out the integration, first of all it is necessary to express the quantities under the integral sign in equations (6) through the known parameters.

For this it is required to connect \( \cos \psi_1 \) and \( \cos \psi_2 \) and \( S^2 \) with coordinates and other variables characterizing the shapes of surfaces of the flame and the irradiated object. In other words, the surfaces

\[ F_1 (X, Y, Z) = 0 \quad \text{and} \quad F_2 (X, Y, Z) = 0 \]

(9)

In addition, it is necessary to consider the mutual positioning of objects relative to each other.

We introduce two coordinate systems associated with the irradiating \((X_1, Y_1, Z_1)\) and irradiated \((X_2, Y_2, Z_2)\) objects.

In the system \((X_1, Y_1, Z_1)\) the unit normal vector \(n_1\) to the elementary area \(dF_1\) has coordinates:

\[ n_1 = \{Xn_1, Yn_1, Zn_1\} \]

(10)

and coordinates of point \(B\) in the center \(dF_1\):
Similarly, in the system \( X_2, Y_2, Z_2 \), the unit normal vector to the elementary area \( dF_2 \) on receiving surface \( F_2 \) will have the following coordinates:

\[
\hat{n}_2 = \{X_{n2}, Y_{n2}, Z_{n2}\}
\]  

and coordinates of point \( A \) in the center \( dF_2 \):

\[
A (X_{2A}, Y_{2A}, Z_{2A})
\]  

The distance between points \( A \) and \( B \) can be easily expressed in coordinates (11) and (13), passing first to any one coordinate system

\[
S = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2}
\]  

Here, under \( (X, Y, Z) \) we mean the coordinates of points in one selected system.

Introducing the unit vectors \( s_a \) and \( s_b \), which lie along the line connecting the elements and are directed \( s_a \) from point \( A \) to point \( B \), and \( s_b \) from \( B \) to \( A \). Then, considering the coordinates of the vector \( AB \)

\[
AB = \{X_B - X_A, Y_B - Y_A, Z_B - Z_A\}
\]  

We have

\[
s_a = AB / S
\]  

Similarly

\[
BA = \{X_A - X_B, Y_A - Y_B, Z_A - Z_B\}
\]  

Using these values, we can determine \( \cos \psi_1 \) and \( \cos \psi_2 \) from the dot product \( (n_1, s_a) \) and \( (n_2, s_a) \) \[8\]

\[
\cos \psi_1 = \frac{X_{s1}(X_A - X_B) + Y_{s1}(Y_A - Y_B) + Z_{s1}(Z_A - Z_B)}{\sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2}}
\]  

\[
\cos \psi_2 = \frac{X_{s2}(X_B - X_A) + Y_{s2}(Y_B - Y_A) + Z_{s2}(Z_B - Z_A)}{\sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2}}
\]  

The obtained expressions (14), (18), (19) connects the geometric characteristics of flame and the relative position of objects involved in heat exchange with their coordinates.

Thus, to solve the integral (6), it is necessary to choose a method for describing the geometry of emitting and receiving objects.

The flame is a tilted cone characterized by its height and diameter. Generally, in cylindrical coordinate systems, any point on the wall surface can be described by an angle \( \alpha \), with a height \( h \) and a radius.

Let us recall that for convenience, the emitting and irradiated objects are considered in different coordinate systems. Therefore, the coordinates of point \( A \) in the \( (X_1, Y_1, Z_1) \) system will be:

\[
X_{1A} = R_b \cos \alpha, \quad Y_{1A} = R_b \sin \alpha, \quad Z_{1A} = h,
\]  

where, \( R_b \) - is the radius of the cone at considered height of the flame, determined by (7).

The values of \( \alpha \) and \( h \) vary within the following limits

\[
0 \leq \alpha \leq 2\pi \quad 0 \leq h \leq H_l
\]  

where, \( H_{l} \) - is the height of flame.

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

So, we have obtained a mathematical model that allows us to build the model of thermal effect during the combustion of an emergency gusher of hydrocarbon fuel, namely: to select the local coordinate systems; obtain a mathematical description of the emitting object and the potential object of risk; align coordinate systems; calculate the irradiation coefficient of an object randomly located in the area around a burning gas flame by numerical methods, under any configuration of the flame of an openly burning product also considering the wind impact.

To check the input parameters for the developed mathematical model of a fire of bottling of oil products (modeling of an oil fire), experimental firing studies were carried out.

- burning of diesel fuel bottling on an area of 20 m²;
- burning of oil bottling on an area of 200 m$^2$;
- burning of diesel fuel bottling on an area of 100 m$^2$;
- burning of diesel fuel bottling on an area of 2000 m$^2$;
- burning of diesel fuel bottling on an area of 2.3 m$^2$

When processing the experimental data, empirical data were obtained on determining the geometric characteristics of the flame depending on the type of fuel, wind speed, and the size of the combustion center [7]. As a result of processing the experimental data, the values of the falling heat fluxes were obtained.

The results of the study can be used in the development of regulatory and methodological documents for the organization of liquidation and extinguishing of gas blowout fires, as well as ensuring the safety of employees involved in firefighting.

5. Conclusions
At present, all over the world, people are concerned about the problems of ensuring fire safety, saving people's lives, as well as protecting natural resources and material values in general.

One of the reasons for the difficult situation is an insufficiently formed system of social, legal and regulatory support for fire safety, as well as gaps in scientific and practical research on fire safety and, in particular, oil production facilities in the process of functioning of the fire safety system. Therefore, the existing system of requirements for ensuring fire and explosion safety should be constantly improved, and the system for assessing fire risks should be based on the results of scientific research.

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