MATHEMATICAL MODELING OF DETERMINING THE SAFE DISTANCE FROM A GAS FOUNTAIN TORCH FLAME

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Abstract

Natural gas fountains are considered very dangerous due to their size and the effects they cause, and are therefore difficult to prevent. A gas fountain is a stream of gas or liquid flowing into the environment under pressure. They are formed as a result of accidents during the drilling and operation of wells in gas and oil fields, accidents in gas storage facilities, and local collapses of technological pipelines. If an ignition source is present (e.g. a mechanical spark or static discharge), the fountain will ignite and a fire will occur. To prevent these fires, mathematical calculations based on certain scenarios have been performed to determine the distance at which the firefighting team can safely operate from the source of the fountain.

Keywords: fountain fire, fire, torch flame, heat radiation, gas fountain

I. Introduction

In connection with the development of modern industry, the designs of the equipment used are adapted to new requirements. Despite this, the problems arising during the extraction and transportation of oil and gas, the danger of possible emergencies remain at the same level. Moreover, since new technologies are highly efficient, the consequences of accidents that occur are more severe than in the past [5].

Fires in open-pit gas and oil wells with gushing gas are among the most complex types of industrial accidents. The probability of a gas gushing fire is high. Some considerations about a gushing fire include. The flow of gas emitted in a powerful fountain can reach 10-20 million cubic meters per day or more, the height of the burning torch can reach 80-100 m, and the intensity of heat release in the torch can be several million kilowatts. [3, 4]. Its main component is methane. According to statistics, about 40% of accidents in gas and oil fields result in fires. Such fires are characterized by their large scale, are difficult to extinguish, and cause enormous economic and environmental damage [2]. Extinguishing fires in oil and gas fields, which are often located in hard-to-reach areas, requires very large logistical resources and such fires can last for weeks. It can be noted that gas fountains are considered to be gas fountains that are not less than 95% flammable by mass.

II. The setting of the issue.

Thus, it can be shown that in order to prevent emergencies arising during the uncontrolled combustion process associated with a gas fountain as a result of an accident and successfully eliminate its negative consequences, a comprehensive study of such events is one of the urgent issues. In this aspect, mathematical modeling of the combustion process of a natural gas fountain and measures to prevent it can allow solving a significant part of the problem posed. The presented article presents the results of some of the relevant studies. For this purpose, a mathematical model was used to estimate the safe distance from the flame of a gas fountain during an accident. Modeling of large-scale fires is based on the assumptions about such physical phenomena as the transfer of heat and mass of a fire under appropriate conditions of its development [1]. For example, in [6], a comparative analysis of mathematical models for calculating the dynamics of fire hazard factors was conducted, and proposals were made for their use in terms of application to oil and gas facilities.

III. Research method

During modeling, it was assumed that the source from which the fountain flame radiates heat is located at its geometric center, that is, at a height of $H_f/2$ from the well mouth (Figure 1).

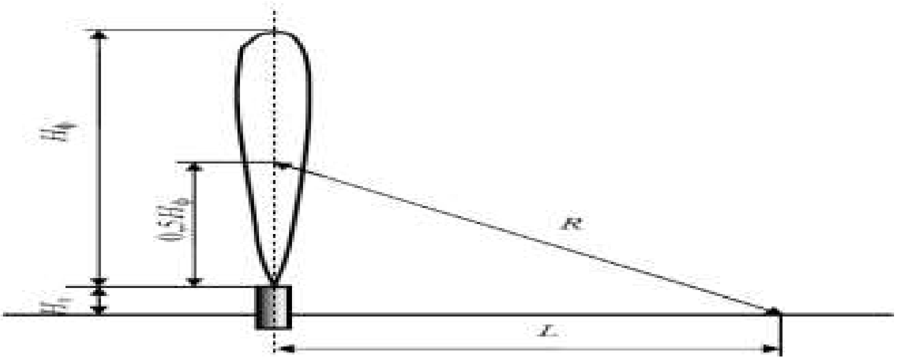

Fig. 1. *Scheme for calculating the safe distance from the flame of a gas fountain*

The radiation intensity (q_l) of a compact vertical gas fountain in still air can be calculated using the following formula [3, 4]:

$$q_l = \frac{\eta_l \cdot q_f}{4 \cdot \pi \cdot R^2} \tag{1}$$

Where, R is the distance from the center of the fountain to the observed point on the earth's surface, m.

It is clear from Figure 1 that the distance R can be calculated by the following formula:

$$R^2 = L^2 + (0{,}5 \cdot H_f + H_T)^2, \tag{2}$$

where L is a certain distance from the mouth of the gas well, m; H_f is the height of the gas fountain torch, m; H_T is the height of the gas well above the ground surface (1 m can be taken) (Fig. 1). Then:

$$q_l = \frac{\eta_l \cdot q_f}{4 \cdot \pi \cdot \left[L^2 + \left(0{,}5 \cdot H_f + H_T\right)^2\right]} \tag{3}$$

where η_l - coefficient of heat loss by thermal radiation of the torch flame; q_y - heat released by the fire, kW.

The heat loss coefficient (ηl) of the torch flame by thermal radiation will be calculated as follows:

$$\eta_l = 0{,}05 \cdot \sqrt{M}\ , \tag{4}$$

where M is the average molar mass of the components of the combustible mixture and will be calculated as follows:

$$M_l = \sum M_i \cdot a_i\,, \tag{5}$$

where M_i - is the molar mass of the i-type component of the combustible mixture; a_i – is the volume fraction of the i-type component of the combustible mixture.

The fountain flame is a source of thermal radiation, which is one of the most serious obstacles in the fight against fountain fires. Therefore, it is important to estimate the heat released by the fire (q_f, kW). This indicator can be determined by the following formula [4]:

$$q_y = \beta \cdot V_q \cdot Q_H^{sm} , \tag{6}$$

where Q_H^{sm} - total combustion heat during combustion of the gas mixture; β - incomplete combustion coefficient; V_q - gas flow rate per second during the fountain, m³/sec.

Since $\beta \approx 1$ for a gas fountain, the combustion rate will be equal to the gas consumption per second, so:

$$q_y = V_q \cdot Q_H^{sm} , \tag{7}$$

$$V_q = \frac{D \cdot 10^6\, m^3/day}{24 \cdot 60 \cdot 60 sec}, \frac{m^3}{sec} \tag{8}$$

where D – is the daily consumption of the gas fountain, million m³/day.

The daily consumption of a gas fountain can be expressed by a simple relationship:

$$D = 0.0025 \cdot H_f^2 , \tag{9}$$

Q_H^{sm} - can be determined by this formula:

$$Q_H^{sm} = \sum Q_i \cdot a_i , \tag{10}$$

where Q_i - the total heat of combustion of the i-type combustible component in the gas mixture; a_i - the volume fraction of the i-type combustible component.

$$Q_i = \frac{1000 \cdot Q_{Hi}}{24{,}45} , \tag{11}$$

where Q_{Hi} - is the lowest heat of combustion of the i-type combustible component in the gas mixture; 24,45 liters is the volume of 1 mole of gas at a temperature of 298 K.

With the help of the considered mathematical model, the calculation and assessment of the temperature of the fire in the gas fountain consisting of a gas mixture during an accident, the intensity of the heat radiation flow depending on the distance from the gas fountain source, and the distance at which the firefighting crew can work for a long time in combat uniforms and helmets with protective shields without special heat protection equipment, and the distance at which they can carry out fire extinguishing work in special heat protection equipment for no more than 5 minutes under the protection of a scattering water stream were carried out. The calculation was carried out based on the following fire scenario.

Suppose that a fire broke out in a gas pipeline due to an accident, when a compact gas jet was thrown into the surroundings. The composition of the compact gas jet was as follows: 85% methane (a_1=0,85), 9% ethane (a_2=0,09), 3% propane (a_3=0,03) and 3% nitrogen (a_4=0.03). The gas jet flows into the surroundings through a hole in the pipe with a diameter of d=150 mm. The height of the leak is -1 m. The coefficient of chemical incomplete combustion in the combustion zone is 8% of the lowest heat of combustion, which can be expressed as η_x=0,08.

It has been shown in the scientific literature that the values of the lowest combustion heats of methane, ethane, propane, and nitrogen can be calculated based on the result of Hess's law. The calculated values (Q_{Hi}) of the indicators considered here were taken from the literature sources given in [2, 4]: the values of the lowest combustion heats are Q_{H1}=802,29 kJ/mol for methane; Q_{H2}=1427,78 kJ/mol for ethane; Q_{H3}=2043,92 kJ/mol for propane; Q_{H4}=843,55 kJ/mol for nitrogen.

The values of the combustion heats (kJ/m^3) of 1 m^3 of the i-type gas component were taken as follows: $Q_{methane}$ =32813.50; Q_{ethane} =58395.91; $Q_{propane}$ =83595.91; $Q_{nitrogen}$ =34501.02. To calculate the thermal radiation coefficient (η_l) of the flare flame (see formulas (4) and (5), the molar mass of methane (M_1) is 16 g/mol, that of ethane (M_2) is 30 g/mol, that of propane (M_3) is 44 g/mol, and that of nitrogen is 28 g/mol. The height of the flare flame (H_f) varies between 10-50 m, increasing every 5 m.

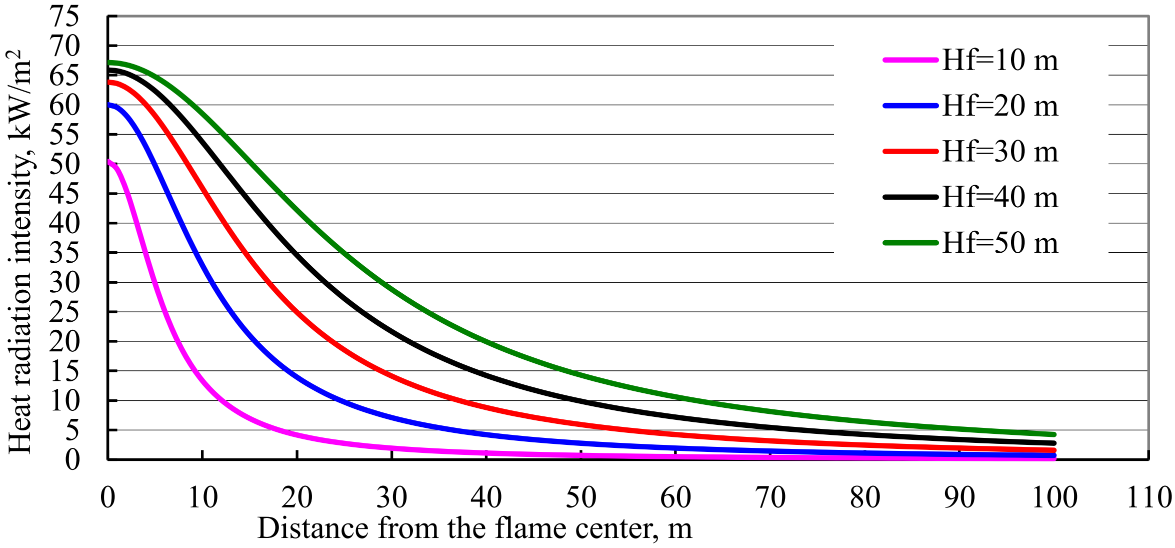

Fig. 2. *Dependence of the power of thermal radiation of a gas fountain flame on the distance from its source*

According to formula (10), the total heat of combustion during the combustion of a gas fountain is 36690.0 kJ/m^3. According to formula (5), the average molar mass of the gas components is 16.82 kg/kmol, so the thermal radiation coefficient of the torch flame is η_l=0.205.

Finally, a graph of the dependence q_l = f(L) was constructed using equation (7). As mentioned above, for this, the values of L = 0-50 m (every 5 m) were given, and the results of the calculations were presented in the form of a graph (Figure 2) and a table (Tables 1 and 2).

Table 1: *The distance at which firefighters wearing special heat-protective equipment can carry out firefighting operations in no more than 5 minutes, depending on the height of the flame, under the protection of a spray water stream.*

H_f, m	10	15	20	25	30	35	40	45	50
L, m	10	15	20	25	30	35	40	45	50

Table 1 shows that the distance at which personnel in special heat-protective equipment can carry out fire-fighting work in no more than 5 minutes under the protection of a sprinkler water stream increases significantly with the height of the torch flame, and this dependence is linear.

Table 2: *The distance from the source of the flame at which personnel wearing protective clothing and helmets with protective shields without special heat protection devices can work for a long time, depending on the intensity of the flame.*

H_f, m	10	15	20	25	30	35	40	45	50
L, m	21	31	42	52	61	71	81	90	100

IV. Conclusion

Based on the given scenario, with the help of a mathematical model, the temperature of the fire in the gas fountain consisting of a gas mixture during an accident, the intensity of the heat radiation flow depending on the distance from the gas fountain source, and the distance at which the firefighting crew can work for a long time in protective clothing and helmets with protective shields without special heat protection equipment, and the distance at which they can carry out fire extinguishing work in special heat protection equipment for no more than 5 minutes under the protection of a scattering water stream, were estimated.

It has been established that the distance from the source of the fountain, at which firefighters in protective clothing and helmets with protective shields without special heat protection devices can work for a long time, increases significantly, and this dependence is linear.

Thus, by plotting the graph of the dependence q_l = f(L), the following can be determined [2,3,4]:

1) The distance from the source of the fountain, at which personnel in protective clothing and helmets with protective shields without special heat protection devices can work for a long time, will be the distance at which the heat flux power is 4.2 kW/m^2. This can also be called the safe distance for extinguishing the fire.

2) The distance from the fountain source mouth at which personnel wearing special heat-protective equipment can carry out fire-fighting operations in no more than 5 minutes under the protection of a sprinkler water stream will be the distance at which the heat flow power is 14 kW/m^2.

CONFLICT OF INTEREST.
Authors declare that they do not have any conflict of interest.

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