Analysis of the danger of thermal radiation of a spherical flame

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Abstract. A new mathematical model of spherical flame propagation during emergency emission and ignition of mixtures of hydrocarbon gases in an open space has been developed. A comparative analysis of the results of the study made it possible to establish the main mechanisms of heating of a combustible gas mixture as a result of radiation from gorenje products. As a result of mathematical modeling, the resulting radiation model meets the real gorenje conditions of gas-air mixtures.

1. Introduction
In emergency situations, the main mechanism of thermal effects of high-temperature sources capable of causing damage to people, destruction of related objects and the environment is thermal radiation. Sources of intense thermal radiation can occur during the extraction, processing, storage and transportation of hydrocarbon raw materials and energy-saturated materials, nuclear explosions, space and man-made disasters, terrorist acts and other emergency situations. Most of these sources are spherical in shape.

According to the data, the dangerous parameter of the impact of a spherical flame formed during an emergency release of liquefied hydrocarbon gases into an open space is the amount of radiation that causes ignition of wood or burns to a person. The calculation of this parameter is carried out at a constant diameter of the spherical flame. According to the classical theory of gorenje gorenje, stationary flame propagation is observed in an unlimited space at a constant rate of combustion. However, with a fixed initial volume of gas, the combustion of fuel will take place with a variable diameter of the spherical flame. In the theory of gorenje gas mixtures, the heating of the combustible mixture by flame radiation is neglected due to the diathermicity of gases and the relatively small width of the heated layer. Analysis of the literature data on radiation heat exchange in translucent media shows that, unlike solids in a gas, energy radiation occurs in volume both into the surrounding space and into the sphere [1-5]. To date, there are many works devoted to flame modeling [6-9].

In connection with the above, the theoretical and practical interest was the development of a mathematical model for the stationary propagation of a spherical flame and the assessment of the danger of irradiation of an object with an increased intensity.

2. Materials and methods
Numerical methods are used in the work.
3. Results
In case of emergency depressurization of liquefied petroleum gas storage tanks, a vapor-air cloud is formed under normal conditions. After reaching the lower or upper concentration limits, it is possible to ignite a combustible mixture and form a spherical flame with an initial diameter of up to a hundred meters. In the process of burning, the combustible mixture heats up and expands gorenje. In the quasi-stationary stage of gorenje, the diameter of the ball is 1.5 times larger than the initial one calculated for normal conditions. Consequently, the adiabatic heating conditions of the initial mixture are not preserved, and in addition to the thermal conductivity mechanism of heating the gas mixture from gorenje, there is an additional source. Such a volumetric source can be the radiation energy of gorenje products, which is absorbed by the initial mixture. This means that the dynamics of the volume of the combustible mixture will depend on three processes: heating from a spherical surface at gorenje temperature, expansion as a result of additional heating by radiation, volume reduction during the combustion of the combustible mixture.

A spherical flame can be considered as a space bounded by the combustion front gorenje. A quantitative description of complex phenomena and processes of heat exchange inside a sphere with a diameter of hundreds of meters and a temperature difference of up to a thousand degrees is not possible. Therefore, in the theory of heat transfer in a limited space, it is proposed to consider complex heat transfer as an elementary phenomenon of heat transfer by introducing a single coefficient of thermal conductivity $\lambda$.

In the gorenje infinitesimal front approximation, the unlimited area of integration of the equation is divided into two zones: the initial combustible mixture and the reaction products. A spherical flame can be considered as a space bounded by the combustion front gorenje. A quantitative description of complex phenomena and processes of heat exchange inside a sphere with a diameter of hundreds of meters and a temperature difference of up to a thousand degrees is not possible. The same heat source with a specific power of $q_v$ operates inside. With continuous fuel supply, we will consider the process stationary. In this case, we obtain the equation of thermal conductivity in a spherical coordinate system [10]:

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) = - \frac{q_v}{\lambda}$$  \hspace{1cm} (1)

Separating the variables, we get:

$$\frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) = - \frac{q_v}{\lambda} r^2$$  \hspace{1cm} (2)

Next, we integrate both parts of the equation:

$$r^2 \frac{dT}{dr} = - \frac{q_v}{3\lambda} r^3 + C_1$$  \hspace{1cm} (3)

Let's separate the variables again:

$$\frac{dT}{dr} = - \frac{q_v}{3\lambda} r + \frac{C_1}{r^2}$$  \hspace{1cm} (4)

Re-integrate both parts of the equation:

$$T = - \frac{q_v}{6\lambda} r^2 - \frac{C_1}{r} + C_2$$  \hspace{1cm} (5)

Due to the finite value of the temperature in the center, the constant $C_1 = 0$, then:
\[ T = -\frac{q}{6\lambda}r^2 + C_2 \]  

We find the constant \( C_2 \) from the boundary condition. On the surface of the flame, thermal interaction with the medium occurs due to radiation. According to the Stefan-Boltzmann law:

\[ -\lambda \frac{dT}{dr}_{r=R} = \varepsilon\sigma(T_c^4 - T_0^4) \]  

Where \( \varepsilon \) is the study coefficient, \( T_c \) is the flame surface temperature equal to:

\[ T_c = -\frac{q}{6\lambda}R^2 + C_2 \]  

Substituting (6) and (8) into (7), we get:

\[ \frac{q}{3}R^2 = \varepsilon\sigma \left[ \left(-\frac{q}{6\lambda}R^2 + C_2\right)^4 - T_0^4 \right] \]  

From where the integration constant \( C_2 \) is equal to:

\[ C_2 = \frac{q}{6\lambda}R^2 + \sqrt[4]{\frac{q}{3\varepsilon\sigma}R + T_0^4} \]  

Then the law of distribution of the temperature field will take the form:

\[ T = \frac{q}{6\lambda} \left( R^2 - r^2 \right) + \sqrt[4]{\frac{q}{3\varepsilon\sigma}R + T_0^4} \]  

4. Discussion

As follows from the obtained formula (11), the temperature field of the flame of a spherical shape depends on the size of the flame, on the thermal power and radiated ability. At the same time, the field itself inside the flame changes according to the parabolic law.

5. Conclusion

Thus, the analysis of the danger of thermal radiation of a spherical flame made it possible to identify and solve a number of important aspects of the problem of the gorenje of the damaging effect of a spherical flame when burning mixtures of hydrocarbon gases in an open space. The analysis of mathematical methods for modeling spherical flame radiation contributes to the improvement of existing and the creation of new methods for assessing the danger of thermal radiation.

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