Improving the approach to assessing and rationing the effects of heat flow in a fire on the human body

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Abstract. The purpose of this study is to improve the method of assessing the risk of damage from exposure to heat flow in accidents with the combustion of hydrocarbons. Modern methods of calculating fire risk values used in Russia are largely based on methods developed by foreign colleagues. However, there are a number of points that are not taken into account in any guide. In the course of the study, it is advisable to conduct an experiment, the results of which will determine the dependence of the degree of damage to living tissues on the intensity and time of exposure to radiation. This dependence is the basis for a mathematical model of human damage by waves of any spectrum, including radiation during the combustion of hydrocarbons. The results of mathematical modeling will be the basis for the development of an approach to the assessment of individual fire risk indicators, the normalization of human thermal injury with varying exposure duration and intensity of thermal radiation.

1 Introduction

The object of this study is the human body exposed to thermal radiation during the combustion of hydrocarbons during a man-made accident. The subject of the study is a method for assessing the risk indicators of human injury from exposure to heat flow in accidents with the combustion of hydrocarbons.

To date, it is possible to assess the effects of heat flow in fires, including the combustion of hydrocarbons, by following a number of techniques, for example, the methodology for determining the calculated values of fire risk at production facilities, approved by the order of the Ministry of Emergency Situations of Russia dated 10.07.2009 No. 404 [1]. This technique allows us to estimate both the dependence of the intensity of the heat flow incident on the target object on its distance to the hearth under various accident scenarios (a fire of a hydrocarbon spill, flare combustion, fireball) and the value of the individual fire risk indicator (the probability of fatal injury to people) [2-6].

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Methods for calculating the intensity of heat flow, as well as other values, within the framework of the methodology for assessing individual risk, are contained in many foreign sources [7-12]. In particular, the guidelines of the Netherlands Organization of Applied Scientific Research (The Netherlands Organization of Applied Scientific Research – TNO) are distinguished by a high degree of elaboration of this issue – the famous "color" books: the red book CPR 12E, the yellow book CPR 14E, the green book CPR 16E and the purple book CPR 18E [13-16].

These methods are mainly based on research materials carried out by a team of American scientists in the Japanese city of Hiroshima after its atomic bombing in 1945.

However, there are a number of points that are not taken into account in any manual, and taking into account which will improve the method of assessing the risk of human injury when exposed to heat flow:

1. It should be taken into account that the effect on a person of the heat flux emitted by a fireball of a nuclear explosion and the heat flux during the combustion of hydrocarbons is significantly different. This is due to the fact that the temperature of a fireball during a nuclear explosion is estimated at about 10000 K, and therefore the vast majority of the radiation energy is concentrated in the wavelength range of less than 1 microns, while the characteristic flame temperature during the combustion of hydrocarbons is significantly lower (about 1300 K), as a result of which a purely large part of the energy is concentrated in the infrared region of the spectrum.

It is known that long-wave radiation penetrates deeper into the tissues of the human body, therefore, the effect of thermal radiation from hydrocarbons is more dangerous. At the moment, the problem of assessing the response of human tissues to the effects of thermal radiation from a fire flame during the combustion of hydrocarbons has not been sufficiently studied, therefore, mathematical modeling of the coupled processes of radiation transfer and heat transfer in the upper layers of human body tissues is relevant.

2. Within the framework of the dose approach, the removal (escape) of a person from the fire source during the emergency combustion of hydrocarbons requires more correct accounting.

The effects of the heat flow of emergency combustion of hydrocarbons on living tissue can be successfully evaluated in the framework of mathematical modeling [17-21].

No matter how complete and accurate the developed mathematical model is, it must necessarily be validated by experiment.

Due to the impossibility of conducting an experiment on living beings, the task of conducting an experiment on an analogue of living tissue is urgent.

In the course of the study, it is advisable to conduct an experiment, the results of which will determine the dependence of the degree of damage to living tissues on the intensity and time of exposure to radiation, as well as its spectral characteristics. This dependence is the basis for a mathematical model of human damage by waves of any spectrum, including radiation during the combustion of hydrocarbons.

Tasks planned to be solved:

- mathematical modeling of the conjugate problem of the transfer of infrared radiation and heat exchange in the upper layers of human body tissues under the influence of heat flow in accidents with the combustion of hydrocarbons;
- conducting an experiment during which the dependences of the degree of thermal damage of the target object on the intensity of thermal radiation and exposure time will be obtained, taking into account the spectral characteristics of both the source and the target object;
- development of an approach to the assessment of indicators of individual fire risk, normalization of human thermal injury with varying exposure duration and intensity of thermal radiation.
2 Methods

The following methods were used in the study:

1. Analysis. It is necessary to analyze the effect of thermal radiation of hydrocarbons on human tissues, to identify the physical features of such radiation. The energy of thermal radiation during the combustion of hydrocarbons is concentrated in the visible and infrared parts of the spectrum.

2. Synthesis. Based on the experience of assessing human damage by thermal radiation, to improve the existing method taking into account the peculiarities of thermal radiation of hydrocarbons.

3. Mathematical modeling: carried out on the basis of the analysis and synthesis, in this case, a mathematical model is created that allows to evaluate the response of living tissue to thermal radiation during the combustion of hydrocarbons. Mathematical modeling is planned to be carried out in several stages: at the first stage, the simplest mathematical model is being built in the COMSOL Multiphysics software package, in which the radiation source is an absolutely black body, and the radiation of the entire spectrum falls on the target object in the form of a conditional living tissue. As a result, the calculated temperature distribution over the depth of the tissue will be obtained depending on the time.

   At the second stage of modeling, this model is planned to be improved taking into account the spectral characteristics of the target object imitating human skin (specially prepared rabbit skin, whose optical and thermophysical properties are close to those of human skin).

4. Verification of the model is carried out by checking its consistency and compliance with well-known physical laws, as well as robustness.

5. Validation of the model will be performed by comparing it with the results of the corresponding experiment.

3 Results and discussion

Mathematical modeling was carried out in the Comsol Multiphysics program, which allows modeling conjugate and separate physical processes. In particular, the capabilities of the heat transfer modeling module in solids were used.

Skin with a thickness of 1 mm stretched over muscle tissue with a thickness of 2 cm was used as a model for modeling. The intensity of the heat flux incident on the surface of the sample \( q = 5 \text{ kW/m}^2 \). The radius of the hole in the metal plate is 3 cm, the length of the sample is 6 cm.

The equation of thermal conductivity has the form:

\[
d_x \rho C_p \frac{\partial T}{\partial t} + d_x \rho C_p u \cdot \nabla T + \nabla \cdot q = d_x Q + q_0 + d_x Q_{ted}
\]

\[
q = -d_x k \nabla T
\]

\( q_0 \) – intensity of the thermal radiation source, 5 kW/m².

It is assumed that the heat in the target object spreads in different directions by means of conductive heat exchange:

\[
q_0 = h (T_{ext} - T)
\]

At the lower boundary, a thermal insulation condition is set, i.e., heat spreads throughout the sample in different directions, but does not spread downwards.

A stop simulation condition was set, according to which when the temperature reaches 51 °C (first-degree burn), the heating stops and the simulation stops. Under the given conditions, according to the calculation, a first-degree burn is achieved in 62.7 seconds (Figure 1).
Fig. 1. Dependence of temperature on time during irradiation of the sample $q = 5 \text{ kW/m}^2$ (first-degree burn).

Under similar conditions, a second-degree burn (temperature $55 \degree \text{C}$) according to the simulation results was achieved in 80.1 seconds (Figure 2).

Fig. 2. Dependence of temperature on time during irradiation of the sample $q = 5 \text{ kW/m}^2$ (second-degree burn).

Finally, a third-degree burn (tissue temperature $60 \degree \text{C}$) was achieved in 102.6 seconds (Figure 3).
Human skin and rabbit skin have similar thermophysical and optical properties. The absorption spectrum of two rabbit skin samples was obtained at the Resource Center "Optical and Laser Methods of Substance Research" of the Scientific Park of St. Petersburg State University using a Lambda 1050 spectrophotometer by Perkin Elme (Figure 4):

**Fig. 4.** Absorption spectrum of two rabbit skin samples.

### 4 Conclusion

As a result of the study, the following conclusions were made.

Using the Comsol Multiphysics program, mathematical modeling of the processes of heat radiation transfer and heat exchange in the upper layers of a target object simulating human skin was performed when exposed to a heat flux of 5 kW/m² intensity emitted by a completely black body at a temperature of 1000 K. As a result, the dependence of the
temperature of the sample on the time of its irradiation was obtained, the time marks corresponding to the receipt of burns of I, II and III degrees by the tissue were estimated. The absorption spectrum of two rabbit skin samples was obtained, which will be imitators of human skin during an experiment to validate the model.

References

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