

# Radiation thermal effect of a fire spilling fuel-air mixtures on a person

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**Abstract.** In the modern world, it is especially important to provide the population and industries with energy, which is necessary to maintain a consistently high quality of life. Often, the process of generating energy is associated with a certain risk to personnel and the public when using various types of fuel, often with fire hazardous properties. For each fire damaging factor, for example, for thermal radiation, toxicity of combustion products, smoke, and elevated temperature, the probability of human injury can be calculated. In this paper, the probability of a person being damaged by thermal radiation in a fire spilling a fuel-air mixture is calculated. A spill fire begins by igniting the vapors of spilled hydrocarbon fuel on an open surface. The calculation was carried out according to three methods, one of which takes into account the movement of a person away from the epicenter of the fire. The dependence of the heat flux density on the distance from the center of the fire is given. Based on calculations of the safe distance from the center of the fire and the values of thermal radiation using the Matlab software environment, the optimal method for determining the probability of human injury in case of a fire spill of an oil product was selected, and it was also concluded that it can be used in case of using high-energy fuel.

## 1 Introduction

The emergence and development of technologies in the field of energy, transport, information support, construction, etc. means the special need to ensure the safety of the population and personnel [1]. For this, risk assessment is carried out in different areas of human activity [2]. The probability of human damage or individual risk allows you to assess the possibility of damage when exposed to various harmful and dangerous factors [3].

At any stage of technological progress, the issue of fire safety has been and remains relevant: the use of a variety of fuels, the improvement of fire-fighting materials and the improvement of firefighting means reduce, but do not completely eliminate their risk [4-7]. One of the main damaging factors of a fire is thermal radiation [8-10]. In this work, the probability of damage by thermal radiation during a fire spillage of a fuel-air mixture will be determined.

Thus, at present there are a number of methods for determining the probability of human damage by heat exposure in case of ignition of vapors of a spilled fuel-air mixture [11, 12]. Moreover, almost all methods are limited to assessing the probability of damage based on only the intensity of the current heat flux, which is only true if the person remains stationary at a certain distance from the center of the fire. However, when calculating risk, the human factor and the possibility of making

different decisions should be taken into account [13, 14]. For example, the methods [15, 16] recommend determining the defeat of a person taking into account his movement, i.e. running away from the center of the fire, but the following circumstance is not taken into account. On the one hand, as the distance from the center of the fire heat flux density acting decreases, but on the other - the total accumulation of heat on the human body increases in proportion to the time of its stay in the thermal field.

The study was conducted with the following assumptions:

1. Combustion is considered as diffusion, i.e. directly dependent on the regime of air ejection into the combustion zone [17].

2. Combustion occurs from the open surface of flammable vapors of spilled hydrocarbon liquids.

3. The height (length) of the visible part of the radiating part of the flame is determined by hydrodynamic factors and can most reliably be calculated using empirical Thomas formulas [18].

4. The flame is considered as an optically "gray" monochromatic surface emitter. The complex, time-varying geometry of the flame is simplistically assumed to be a cylindrical surface while preserving the calculated height (length) of the flame and the equivalent spill diameter [19].

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## 2 Methods

The methods [15, 20], in addition to the intensity of the heat flux, suggest using a dose of heat radiation  $Q$ . The density of the heat flux affecting the human body is determined by the ratio [15]:

$$q(r) = E(d) \cdot F(r) \cdot \tau,$$

where  $q(r)$  – the intensity of thermal radiation of the human body (kW/m<sup>2</sup>),  $E(d)$  – the intensity of thermal radiation of a single flame surface (kW/m<sup>2</sup>),  $d$  – the equivalent hydrocarbon spill diameter (m),  $r$  – the distance from the center of the spill to the person (m),  $F(r)$  – the angular coefficient of irradiation,  $\tau$  – the air absorption coefficient.

The average surface density of the thermal radiation of the flame  $E(d)$  depending on the diameter of the source, and the specific mass burn rate for some liquid hydrocarbon fuels are given in [15, 20], but since the step of changing the diameter  $d$  is large (10 m), an approximation was made for the convenience of calculation at arbitrary values of equivalent diameter.

Criteria for human damage by the amount of heat received during exposure are shown in the Table 1, [20].

**Table 1.** The maximum permissible dose of thermal radiation when exposed to a "fireball" on a person.

The degree of damage	Dose of thermal radiation, J/m <sup>2</sup>
1st degree burn	$1.2 \cdot 10^5$
2nd degree burn	$2.2 \cdot 10^5$
3rd degree burn	$3.2 \cdot 10^5$
4th degree burn	$4.0 \cdot 10^5$

Table 2 shows signs of a person being affected by burns of various degrees and the likely consequences of such lesions. [20].

This article discusses the situation when a person, being at some distance from the center of the diameter of the oil spill, during his sudden outbreak, for some time (about 3-5 s) remains in shock (determined by the reaction time to the outbreak, turn, start of running), then begins to run away in the direction of decreasing the heat flux intensity to a safe distance determined by the

intensity of the acting heat flux of 1.4 kW/m<sup>2</sup> [21-25].

However, during the movement of a person to the border of the safe zone, the effect of thermal radiation continues on him.

In this case, the dose of heat exposure can be considered as an integral of the heat flux intensity [21]:

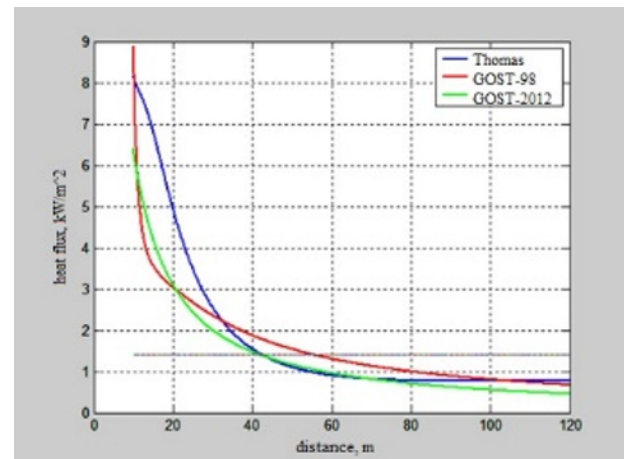
$$Q(r_1, r_2) = q(r_1) \cdot t_1 + \frac{r_2 - r_1}{v} \int_{r_1}^{r_2} q(x) dx \quad (1)$$

where  $r_1$  – the initial distance of a person from the center of the spill,  $r_2$  – the safe distance from hydrocarbon spill center.

The first term in (1) determines the dose of thermal energy received during the shock state of a person at a distance  $r_1$  from the center of the fire. The second term is the accumulated dose of thermal radiation during the movement of a person in a safe area with a speed of  $v$  (m/s).

## 3 Results and Discussion

The change in heat flux intensity  $q(r)$  calculated by various methods is shown in the Fig. 1.



**Fig. 1.** The change in the heat flux density (ordinate axis, kW/m<sup>2</sup>) depending on the distance from the center of the fire (m).

**Table 2.** Characteristic damages to humans by thermal exposure.

Degree of burn	Q kJ/m <sup>2</sup>	The nature of the defeat and the consequences	
1	to 120	Redness and swelling of the skin. Burns heal quickly.	Performance is not lost.
2	to 220	Formation of bubbles filled with liquid. Treatment is required.	Loss of performance. Sanitary losses.
3	to 320	Complete destruction of the skin, the formation of ulcers. Hospitalization is required.	Long-term loss of performance. Sanitary losses.
4	400 and more	Necrosis of the skin tissue, muscles and bones, carbonization. Mandatory hospitalization.	Lethal outcome is possible. Irretrievable losses.

**Table 3.** The probability of human damage in a diesel spill on an area of 20 m2.

Assessment methodology	The probability of a burn of 1st degree	The probability of a burn of 2nd degree	The probability of a burn of 3rd degree
Open body area 35%			
1	1.0	1.0	0.068
2	1.0	0.99	1.6·10 <sup>-4</sup>
4	1.0	1.0	0.99
Open body area 20%			
1	1.0	0.0362	0
2	0.9987	0.0014	0
4	1.0	0.6840	1.8·10 <sup>-8</sup>

The analysis of the calculation results shows that the safe distance value calculated by the methods of [15, 18] is  $R_{safe} = 42$  m, and by the method of [20]  $R_{safe} = 55.3$  m. At the edge of the flame (at a distance of  $\approx (6 \dots 10)$  m from the center), the calculated heat flux density will be according to the methods of [18, 20] and [15], respectively: 5.8 kW/m<sup>2</sup>, 6.0 kW/m<sup>2</sup> and 8.1 kW/m<sup>2</sup>. The calculations were carried out for the case of a spill of diesel fuel with a diameter of 20 m, with no wind.

To integrate the functions shown in Fig. 1, an approximation of the dependences  $q(r)$  is necessary, which is done by means of Matlab:

The Technique Of Thomas:

$$q1(r) = 3.3 \cdot 10^{-7} \cdot r^4 - 0.00011 \cdot r^3 + 0.013 \cdot r^2 - 0.7 \cdot r + 14;$$

The Technique of GOST R 12 3 047-2012:

$$q2(r) = 2.6 \cdot 10^{-7} \cdot r^4 - 8 \cdot 10^{-5} \cdot r^3 + 0.009 \cdot r^2 - 0.45 \cdot r + 9.3;$$

The Technique of GOST R 12 3 047-98:

$$4(r) = 3 \cdot 10^{-6} \cdot r^4 - 0.00053 \cdot r^3 + 0.034 \cdot r^2 - 0.98 \cdot r + 13.$$

The integration of functions of the heat flux intensity ranging from  $R_0$  to  $R_{safe}$  for the Thomas method  $Q_1 = 105.64$  kW for methods [15] and [20] the value of the thermal radiation dose will be  $Q_2 = 91.04$  kW,  $Q_4 = 96.35$  kW, respectively.

As a result, the dose of human thermal irradiation calculated by (1) will be at a time of shock 3s and the speed of movement to the safe zone  $v=5$  m/s:

- technique [1]:  $8,1 \cdot 3 + (42-10)/5 \cdot 105,64 = 700$  kJ/m<sup>2</sup>,
- technique [2]:  $5,8 \cdot 3 + (42-10)/5 \cdot 91,04 = 600$  kJ/m<sup>2</sup>,
- technique [4]:  $6,0 \cdot 3 + (55.3-10)/5 \cdot 96,35 = 890,9$  kJ/m<sup>2</sup>.

An important indicator of human damage to a dose of thermal radiation is the area of an open body exposed to radiation. According to K. Mudan, healthy people survive if second and third degree burns make up 20% of the surface of an unprotected body (head - 7%, hands from wrist to shoulder - 14%, hands - 5%). Accepting the uniform law of the distribution of thermal radiation

over the human body, the above dose values per one m<sup>2</sup> should be reduced in probability estimates to 35% of the body and up to 20% of the open part of the human body. Then, taking the burn part of the human body equal to 0.35 m<sup>2</sup> and 0.2 m<sup>2</sup>, taking into account the data in Table 1, the estimated probabilities of burns of varying severity are presented in Table 3.

## 4 Conclusions

It is quite natural that changing the spill to more energy fuel (gasoline, gases), will lead to higher probabilities of human burns of varying severity, but the methodology for assessing the probability of damage will not change.

The analysis of the presented calculations, using the example of a diesel fuel spill, allows to conclude that the method is preferable [15] and that a thorough analysis of the methods for assessing the probability of human injury when igniting a spill of hydrocarbon raw materials on hard underlying surfaces is necessary.

The subject of individual studies is to take into account the influence of weather conditions on the damaging effect of a hydrocarbon spill fire.

The presented results and their analysis indicate the priority of assessing a person's damage by thermal radiation during a fire spill in a dynamic setting.

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