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DESIGN OF A FIRE FIGHTER'S PROTECTIVE MASK WITH A THIN LAYER OF WATER

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A firefighter's protective mask with a viewing porthole, in which a thin layer of water is used as an optical filter, has been considered in this study. Such mask's structure is designed to solve the task of protecting the firefighter's face from intense thermal radiation in a fire zone.

The porthole of the mask is two parallel transparent plates with a gap between them, through which water continuously flows. The porthole exploits the unique optical properties of water, which is transparent in the visible region of the spectrum and opaque in the infrared region, characteristic of fire radiation. In addition to the function of weakening the radiant heat flux, water also performs the function of cooling the protective mask.

This paper reports a theoretical analysis of physical processes, the calculation formulae, as well as the estimated calculations of the design and operational parameters for a protective mask under typical operating conditions in a fire zone. In particular, a methodology was devised for calculating water consumption, changes in its temperature, and attenuation of radiant heat flux under given conditions in a fire zone. For example, for a heat flux intensity of 25 kW/m^2, a temperature at the fire site of 1200 K, and a water layer thickness in the porthole of 1 mm, a 15-fold attenuation of the heat flux was established. Under these conditions, the maximum operating time in a fire zone reaches 12 minutes, which is three times higher than the similar parameter for existing samples of heat-resistant suits. These parameters indicate the possibility of significant improvement of protective masks for firefighters.

Subject to experimental confirmation, the results of this work could be practically applied at design institutions engaged in the development of protective fire-fighting equipment

Keywords: firefighter protective clothing; thermal radiation shielding; viewing porthole; layer of water

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1. Introduction

One of the key factors that determine the dangerous impact of fire on the environment is thermal radiation. Its share in the energy balance of a fire can reach 30–50%, depending on the combustible substance and combustion conditions [1]. In this regard, the task to protect firefighters from the effects of thermal radiation is important. For this purpose, in particular, protective suits of the heat-reflecting type are used.

For example, according to specifications, protective properties of the heat-reflecting suit "Index-800" (Fig. 1) are as follows:

– resistance to the action of a heat flux of 40 kW/m^2: 120 sec;
– resistance to the action of a heat flux of 25 kW/m^2: 240 sec;
– resistance to the action of a heat flux of 18 kW/m^2: 960 sec;
– time of protective action at an ambient temperature of 800°C: 20 sec.

Heat-reflective suits of other types such as "Index-1", "Index-3" (Ukraine), X-40 (USA), 4HK (China), and others have worse protective properties.

The surface of the heat-reflective suit is capable of reflecting electromagnetic radiation falling on it in a wide spectrum, including the infrared range, in which the main share of thermal radiation is concentrated. Thus, the goal of protecting almost the entire body of the firefighter is achieved, with the exception of the face, since the protective face mask must remain transparent in the optical range to enable the function of vision. Existing samples of suits of this type are equipped with protective masks that have significant drawbacks. As a material for the manufacture of a porthole in such masks, a polycarbonate plate with a transparent film applied to it that protects the face from ultraviolet radiation is used. However, it is known that the spectrum of fire radiation does not contain an ultraviolet component since 90–95% of it (in terms of power) are in the infrared, and the rest in the visible part of the spectrum. Therefore, polycarbonate cannot provide effective face protection for the following reasons:

1) it is transparent to the infrared part of the spectrum;

2) it has a temperature range of preservation of mechanical properties, limited from above by a too low temperature of +120°C.

Fig. 1. Heat-reflective suit "INDEX-800"

Thus, masks in the existing samples of heat-reflective suits need significant improvement. This mask should protect the face and eyes of the firefighter from the effects of infrared radiation, while remaining transparent to visible radiation. Therefore, research on the design of a protective mask with better effective protective properties is relevant.

2. Literature review and problem statement

The intensity of fire radiation depends on a number of factors: the composition and mass of the combustible substance, the composition of the gas medium, gas exchange conditions, the size and geometry of the fire site, the distance to it, etc. This is evidenced by the results from experimental studies of fires under various conditions taking into account the above factors. In studies of large-area forest fires, various results were obtained, since the intensity of thermal radiation significantly depends on the height and type of trees, their location, burning area, and wind speed. For example, in a forest fire dominated by oak and pine, at a wind speed of up to 8.9 m/s, the radiation intensity on the fire line was within 4.2–57.7 kW/m^2 [2]. However, these experiments do not take into account the influence of obstacles and surrounding buildings on the local increase or decrease in the heat flux. Mathematical modeling of forest fires makes it possible to take these factors into account, as well as to determine the radiation heat flux as a function of the distance to the fire [3]. However, the authors did not study the dynamics of flow changes during human (firefighter) movement in the radiation exposure zone.

Experimental studies on the combustion processes of tanks with flammable liquids (FLs) and their spills made it possible to establish their characteristic parameters. In particular, in paper [4], fires in tanks with a large height of unfilled space were studied. Based on the analysis of numerical results, a function was proposed for predicting the flame height. In paper [5], the burning rate, flame length, and flame inclination angle were experimentally studied in fires in heptane pools behind a partition at different crosswind speeds (from 0 to 5 m/s). In paper [6], computer simulation of a fire in a pool in a large insufficiently ventilated room was performed. With proper adjustment of the boundary conditions of heat transfer on the walls, good agreement was found between the experimental and numerical data on the rate of heat release and combustion efficiency. However, the relative contribution of radiant heat flux to the overall heat balance of fires was not investigated in [4–6]. This issue is explored in detail in paper [7], which investigates three different models for predicting radiant heat flux. Through the research and analysis performed in [4–7], we can understand the combustion characteristics during fires in FL pools and tanks and the mode of thermal radiation propagation. They provide reference materials for plant planning, fire risk assessment, safety design, and fire protection in the petroleum and chemical industries. However, the authors did not consider the impact of personal protective equipment on firefighter safety.

In addition, based on experimental and computational studies, regularities in the formation of the thermal field of fires in tanks and spills of FLs were determined. The levels of thermal radiation intensity were established depending on the heat release, flame geometry, visibility coefficients, and distance to the combustion source. That has made it possible to devise engineering methods for assessing the radiation thermal impact on people, building structures, and infrastructure elements.

Paper [8] gives a review of the literature and reported full-scale measurements in order to assess the current state of modeling thermal radiation from fires in hydrocarbon basins. Based on the review, a semi-empirical model was built, in which a comparison was performed with a wide range of field test data. The review also allowed the construction of a database of properties containing data on burning rate and surface emissivity for a wide range of liquid hydrocarbon fuels.

Work [9] describes the experimental conditions and results of a cylindrical container exposed to a large (>20 m^2) and powerful (>40 MW) fire in a pool. The experiment was conducted to test the Fire Dynamics Simulator code to assess its predictive capabilities for modeling large-scale fires in enclosed pools. The numerical results showed good agreement with experimental data.

In paper [10], the radiative heat flux of fires in annular pools under the influence of cross-flow air (0–5 m/s) was investigated. The results show that the radiative heat flux decreases with increasing distance from the fire source but increases with higher air flow velocities and larger diameters of the annular pool. The results of this comprehensive study show a good agreement between the newly built model and empirical data. However, the influence of local turbulent flows on the non-uniformity of the thermal field around the flame remains unaccounted for.

According to the summary table of experimental data, at the flame boundary, the power density of the radiant heat flux of FL is from 25 kW/m^2 (oil) to 80 kW/m^2 (propane-butane) and decreases with distance from the source. The combustion of liquefied methane is capable of forming extremely high heat flux densities – up to 220 kW/m^2 on the flame surface. This is explained by the high energy density of the fuel, intensive heat release, and the propagation of a turbulent diffusion flame with a large surface emissivity. Experimental and computational studies of large spills and fires in tanks, performed in paper [11], show that such values of thermal radiation exceed the levels characteristic of most liquid hydrocarbons. They induce a significant fire and thermal hazard to people, equipment, and building structures in the zone of influence. However, the analysis performed in the paper does not solve the problem of protecting rescuers from these threats and effectively reducing the risk of burns. Personal protective equipment that can reduce local heat energy flows reaching the rescuer to a safe level has not been considered.

The spectral range of thermal radiation significantly depends on the temperature of its source. For typical fires with temperatures of their sites within 1000–1500 K, the main part of the thermal radiation spectra is in the infrared range in the wavelength range of 1–10 μm. Falling on the surface of a substance, thermal radiation is absorbed and converted into thermal energy, as a result of which the temperature of the substance increases according to the mechanisms defined in papers [12, 13]. Similar processes occur during the influence of thermal radiation on living organisms. If a person stays in the zone of radiant heat flow for a long time, local disruption of the body's thermal balance is possible, which leads to overheating.

The degree of influence of thermal radiation on the human body depends on the intensity and time of irradiation, as well as the size of the irradiated surface. During a fire in a production room, the radiant heat flow, in addition to directly affecting the workers, heats the walls and equipment, as a result of which the air temperature inside the room increases. This also worsens working conditions and creates additional risks.

To calculate the thermal radiation protection systems, it is necessary to take into account the characteristic limits of its intensity levels, which are determined experimentally. In paper [14], an experimental study was conducted to examine the influence of air gaps on heat transfer through the fabric-air gap system. The study aimed to evaluate the heat-shielding characteristics of protective clothing under the influence of radiation with an intensity of up to 60 kW/m^2 and its ability to prevent skin burns. This study was further advanced in [15], in which a mathematical model was built that investigates the influence of air gaps in the fabric material on the protective properties of multilayer fire-resistant clothing. Heat transfer through a three-layer protective fabric (outer shell, moisture barrier, thermal lining), the air gap, and the skin (epidermis, dermis, and subcutaneous layer) was considered in detail. The numerical model constructed was verified on the basis of experimental results, which showed excellent consistency. However, in [14, 15] there is no study of the problem of protecting the human face zone.

A study in paper [16] on the thermal characteristics of firefighter protective clothing under extreme environmental conditions revealed the problem of internal heat and moisture accumulation. The multilayer structure of this clothing leads to the retention of moisture and body heat between the layers, which under conditions of extreme radiation flux causes body burns. When the source temperature increases from 800 K to 1135 K, the time to a second-degree burn (44°C) at a 1-meter distance is reduced from 210 to 48 seconds. The results of the study also show that the use of aluminized coatings increases the safe stay time by 2.2 times, and the safe zone at 1135 K begins at 4.5–5 meters. Therefore, when designing thermal protection systems, it is necessary to take into account not only the limit levels of radiation intensity but also a number of other parameters. These are, for example, the duration of radiation exposure, thermal characteristics of protective materials. and conditions of heat exchange with the environment.

If the intensity of thermal radiation exceeds the safe limit, it is necessary to use appropriate protective equipment to reduce its impact on the human body to a safe level. One of the methods used for this purpose is thermal shielding using water. In paper [17], the use of sprayed water jets for this purpose was considered. A theoretical analysis of the interaction with a spherical drop of water of thermal radiation, the spectrum of which corresponds to the spectrum of radiation of a completely black body (ABB), was performed.

For quantitative calculations in paper [17], a table of values of the real and imaginary parts of the complex refractive index of water depending on the wavelength, reported in paper [18], was used. A more detailed table with the corresponding graphical dependences and in a wider spectral range, which can be found in paper [19], was also used.

Based on quantitative calculations of the droplet transmission coefficient in paper [17], an approximation function was found for the dependence of this value on the droplet diameter and the ABB temperature. Further in the work, a formula was derived for calculating the transmission coefficient of a jet of sprayed water (water curtain) for ABB radiation. This approach to the analysis of the process of shielding thermal radiation by sprayed water was further developed in [20–22]. In paper [20], a mathematical model of hydrodynamic processes during the formation of jets of sprayed water was considered. In paper [21], a formula was derived for calculating the average value of the diameter of droplets of a sprayed jet and its dependence on technological parameters. In paper [22], a summary of research in this area and recommendations for their practical application were provided. The case of shielding thermal radiation by a continuous layer of water was not considered in [17, 20–22]. However, the approaches, analysis methods, and individual mathematical relations used in those works can be used to solve this problem.

Water has a high thermal shielding efficiency due to a unique combination of physicochemical and other properties (high heat capacity, environmental safety, availability, and prevalence in nature). When using water to protect against thermal radiation, the optical properties of water are of particular importance [23].

Water is one of the most important natural environments that can effectively influence the passage of electromagnetic radiation. Its optical properties are determined by the complex refractive index and strongly depend on the wavelength, which allows water to act as a natural optical filter for certain spectral ranges. The uniqueness of the optical properties of water lies in the fact that it is transparent only in a narrow spectral range, which coincides with the spectral range of visible light, to which the human eye is sensitive. For other parts of the electromagnetic radiation spectrum from radio waves to ultraviolet radiation, even a thin layer of water is practically opaque [23].

Thus, a thin layer of water is a natural optical filter, transparent to visible light and almost opaque to the thermal radiation of fires. The use of water as an optical filter is a simple and effective solution for increasing safety when working under conditions of intense thermal radiation.

These properties allow it to be used for the manufacture of a protective porthole in a heat-reflecting suit, which provides both a viewing function and effective blocking of the radiant heat flux of fires. The water in the porthole is in a liquid state, which allows it to enable its continuous cyclic movement in a closed circuit and the removal of excess heat.

So, based on our review of the scientific literature, the following conclusions can be drawn:

1. For firefighters involved in extinguishing a fire, one of the most dangerous factors is thermal radiation, the source of which is the fire site. The spectral distribution of this radiation is concentrated mainly in the infrared range with a wavelength interval of 1–10 microns.

2. Effective means for protecting firefighters from thermal radiation are heat-reflecting suits, which, however, have a significant drawback. Protective masks included in these suits are not able to sufficiently protect the faces of firefighters and, in particular, the organs of vision. Polycarbonate, which is traditionally used to manufacture portholes in these masks, is transparent to both visible light and infrared light. Thus, the issue is that the protective mask provides a viewing function for the firefighter but does not protect his/her face from the radiant heat flux of the fire.

3. To resolve this issue, the porthole of a protective mask as part of a heat-reflecting suit must provide simultaneous performance of 2 functions:

1) protect the face and eyes of a firefighter from the effects of infrared radiation from fires, while remaining transparent to visible radiation;

2) absorb and remove excess heat coming from external heat flows.

4. A natural optical filter capable of providing such properties of the porthole is a thin layer of water. It is transparent to visible light and almost opaque to thermal radiation from fires.

5. To use water as an optical filter in the design of the porthole of a protective fire-fighting mask, it is necessary to provide a thin layer of water between two transparent plates. To maintain a stable temperature regime of the mask under extreme fire conditions, this structure must enable continuous movement of water to remove thermal energy.

6. Since there are no reports in literary sources about the existence of a protective mask of this type, it is necessary to perform theoretical and experimental studies to analyze the fundamental possibility and practical feasibility of its design.

3. The aim and objectives of the study

The purpose of our study is to determine the optimal structure and basic properties of a protective mask with a porthole containing an optical filter from a thin layer of water. This will provide the firefighter using this mask with a viewing function and protect his/her face and eyes from radiant heat flux in the fire zone.

To achieve the goal, the following tasks were set:

– to find a conceptual solution for the design of a protective mask with a porthole containing a thin layer of water;

– to perform a hydrodynamic analysis of the water flow in the porthole (velocity, pressure) provided that the laminar flow regime is observed;

– to analyze conditions for observing the thermal regime of the porthole, taking into account the influence of external thermal radiation;

– to devise a methodology for calculating the porthole transmittance for thermal radiation;

– to perform estimated numerical calculations of parameters for the protective mask under typical operating conditions in the fire zone.

4. Materials and methods

The object of our study is a firefighter's protective mask with a viewing porthole, in which an optical filter is used to protect against intense thermal radiation, transparent in the visible and opaque in the infrared range of the spectrum. The design of the mask should ensure that it maintains a stable temperature regime under extreme conditions near the fire site.

The principal hypothesis assumes the possibility of using a thin moving layer of water as an optical filter to provide 3 main functions over a sufficient time interval for practical needs:

1) protect the face and eyes of the firefighter from the effects of infrared radiation,

2) maintain the transparency of the porthole in the visible range of the spectrum;

3) absorb and remove excess heat coming from external heat flows to ensure a stable temperature regime.

In the process of the study, it is necessary to propose a conceptual basis for the design of a protective mask with a porthole containing a thin layer of water flowing between two transparent plates. For this structure, it is necessary to perform a detailed theoretical analysis of the above physical processes and derive calculation formulae to define the basic parameters of this design. Then, based on quantitative calculations, it is necessary to confirm or refute the hypothesis regarding the effectiveness of a protective mask of this type under realistic operating conditions. The results should be the key argument when making a decision to design prototypes and conduct experimental studies with the prospect of its implementation in fire protection practice.

To build an adequate mathematical model and perform practical calculations, it is logical to adopt the following assumptions:

– water is sufficiently clean and does not contain impurities that can significantly affect its optical properties;

– a laminar flow regime of water is maintained in the gap between the transparent plates of the porthole;

– the temperature of water in the circuit during operation cannot exceed a certain limit, which is determined based on physiological limitations for humans.

Simplifications accepted in the process of conducting the study, which did not significantly affect the results, are as follows:

– to model the spectrum of thermal radiation from the fire site, the spectrum of an absolutely black body described by the Planck function was adopted;

– to determine the coefficient of transmission of thermal radiation through a thin layer of water, a simplified calculation approximation function established in [22] was used;

– when calculating the thermal radiation transmittance, the light absorption in the transparent plates used in the porthole was neglected;

– when calculating the thermal regime of the porthole and the thermal radiation transmittance, the radiation reflection coefficient from the porthole surface was neglected. In the case of applying a special reflective coating to the porthole surface, this coefficient can be taken into account separately.

Hydrodynamic analysis of water flow in a porthole to determine the maximum permissible water velocity under laminar flow conditions is performed using the Navier-Stokes equation. Next, the heat balance equation determines the minimum permissible water velocity under the condition of limiting the heating of water by thermal radiation during its passage along the porthole. After selecting a certain value of the water velocity in the calculated interval of permissible velocities, the pressure difference at the upper and lower edges of the porthole is calculated.

Calculation of the thermal regime of the porthole is intended to determine the maximum operating time in the fire zone, based on the criterion of reaching a certain maximum value by the water temperature. It is performed based on the analysis of the heat balance equation to determine the dependence of the increase in water temperature in the circuit on time, the design parameters of the porthole and the intensity of thermal radiation.

To determine the transmittance of the porthole for thermal radiation, the calculation method proposed in [17, 20–22] was used. These studies report the results of mathematical modeling of the process of shielding thermal radiation from fires by jets of sprayed water. Based on the data set obtained as a result of numerical integration of the transmittance spectra of electromagnetic radiation by sprayed water, their authors defined a simplified calculation approximation function. In our work, this function is modified for the case of a continuous flat jet of water. With its help, a calculation was performed that makes it possible to determine the transmittance of the radiant heat flux through the porthole and its dependence on the design parameters of the porthole. This calculation should answer the question of enabling a reduction in the intensity of thermal radiation that has passed through the porthole to a safe level.

5. Results of research on a firefighter's protective mask with a thin layer of water

5. 1. Conceptual basis for the design of a protective mask with a porthole containing a thin layer of water

Based on the analysis of literature sources performed in chapter 2, a simplified diagram of the viewing porthole and water supply to it can be proposed, shown in Fig. 2.

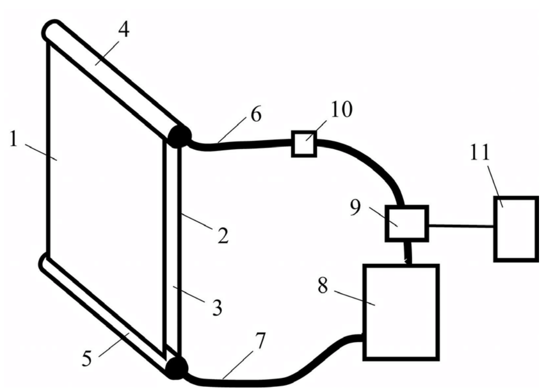

Fig. 2. Schematic of the viewing porthole: 1, 2 – transparent plates; 3 – gap between the plates; 4, 5 – means for supplying and removing water from the gap; 6, 7 – water pipelines; 8 – water tank; 9 – pump; 10 – regulating valve; 11 – power source

The basic elements of the porthole design are two parallel plates 1, 2 made of transparent material (glass, polycarbonate, etc.), with gap 3 between them about 1 mm thick, intended for filling with water. The water gap is sealed along its vertical ends with strips of waterproof material, and along the horizontal ones with means 4, 5 for supplying and removing water from the gap. These means are metal pipes hermetically connected to the transparent plates. Each pipe has a system of holes or slots that connect them to the gap between the transparent plates and ensure continuous flow of water through the gap. Forced circulation of water is carried out using compact pump 9 with battery power source 11, built into the structure of the firefighter's heat-reflecting suit. This design also includes small water tank 8 built into the suit, from which water is supplied to the porthole through flexible pipes 6, 7. Tap 10 makes it possible to adjust the water flow rate depending on external conditions. The water supply system is autonomous, forming a closed circuit in which water circulates cyclically, enabling continuous heat exchange and temperature equalization throughout its volume.

Water gradually heats up during the firefighter's stay in the fire zone, receiving heat from the absorption of radiant heat flux, as well as from the heat exchange of transparent plates with the surrounding air. The rate of water heating depends on the intensity of the heat flux, the area of the porthole and the capacity of the water tank. Due to the high specific heat capacity of water, the process of its heating is quite slow, and its temperature does not reach critical values for a long period of time. To extend the maximum permissible time of work in the fire zone, it is necessary to fill the tank with as cold water as possible before starting work in order to have a sufficient time reserve.

5. 2. Hydrodynamic analysis of water flow in a porthole

Hydrodynamic analysis of water flow in a flat channel between two plates was performed under the condition that the water movement inside the porthole is laminar and uniform, neglecting edge effects. To calculate the water flow velocity profile, it is assumed that the x axis is in the direction of water movement in the middle between the plates (Fig. 3). The y axis is directed along the perpendicular to the plates, so that the plates are located at coordinates $y = \pm d/2$. The following designations of quantities are adopted in the calculation:

– l – width of the porthole;
– h – height of the porthole;
– d – distance between the plates;
– T_0 – initial water temperature in the porthole water supply system;
– T – current water temperature in the porthole water supply system;
– v_{ave} – average speed of water movement in the porthole;
– q – power density of the radiant heat flux;
– V – volume of water in the cooling circuit;
– S – area of the porthole.

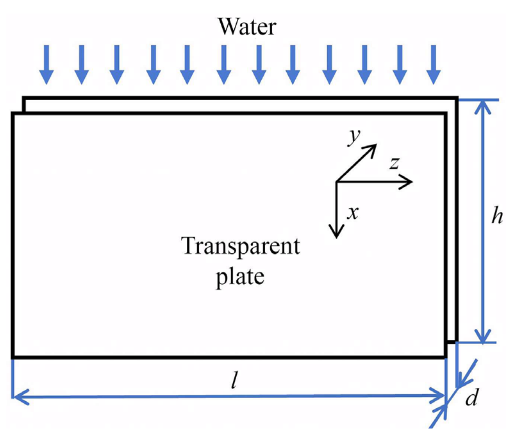

Fig. 3. Diagram of the movement of water inside the porthole

The Navier-Stokes equation for the stationary flow of an incompressible Newtonian fluid in this case takes the form

$$\mu \cdot \frac{d^2 v}{dy^2} = \frac{dp}{dx}, \tag{1}$$

where μ is the dynamic viscosity of water, v is the current velocity of water, p is the pressure of water.

For an incompressible fluid at a constant distance between the plates, the dp/dx value is constant along the x axis and equal to $\Delta p/h$, where Δp is the pressure difference along the water flow in the porthole at distance h. The integration of equation (1) is performed under the condition of flow symmetry relative to the plane $y = 0$, taking into account the immobility of the water layer tangential to the plates. Hence, the boundary conditions:

– $dv/dy = 0$ at $y = 0$;

– $v = 0$ at $y = \pm d/2$.

The integration of equation (1) under these boundary conditions makes it possible to obtain the profile of the water velocity in the gap between the plates in the form

$$v = v_m \left[1 - \left(\frac{2y}{d} \right)^2 \right], \tag{2}$$

where the maximum velocity is in the middle between the plates (at $y = 0$)

$$v_m = \frac{\Delta p \cdot d^2}{8\mu h}. \tag{3}$$

Average speed of water movement in the gap between plates

$$v_{ave} = \frac{2}{d} \int_0^{d/2} v\,\mathrm{d}y = \frac{2v_m}{d} \int_0^{d/2} \left[1 - \left(\frac{2y}{d} \right)^2 \right] \mathrm{d}y = = \frac{2}{3} v_m = \frac{\Delta p \cdot d^2}{12\mu h}. \tag{4}$$

Since in this case it is essential for the normal operation of the porthole to ensure a laminar mode of water flow in the interval, the condition for such a mode is the following ratio

$\mathrm{Re} < 2000,$

where Reynolds number

$$\mathrm{Re} = \frac{\rho v_{ave} d}{\mu},$$

hence, the condition

$$v_{ave} < v_{\max} = \frac{2000\mu}{\rho d}. \tag{5}$$

In addition to the requirement to enable laminar flow, the speed of water movement is limited by the rate of heating of water by thermal radiation during its stay in the porthole. The speed of water must be sufficient so that during its passage through the porthole its temperature due to the absorption of radiant heat flux does not increase by more than a certain limit value ΔT_1. The heat balance equation for an elementary particle of water that travels along the porthole with speed v_{ave}, while being heated by external thermal radiation

$$\frac{q \cdot h}{v_{ave}} = c \cdot \rho \cdot d \cdot \Delta T_1,$$

hence the condition for the minimum speed of water movement in the porthole is

$$v_{ave} > v_{\min} = \frac{q \cdot h}{c \cdot \rho \cdot d \cdot \Delta T_1}. \tag{6}$$

The limiting value of water heating in the porthole ΔT_1 is chosen based on the requirement that it, passing through the pipeline in the water supply system, should not significantly affect the internal microclimate of the protective suit. From these considerations, it is possible to choose the value of $\Delta T_1 = 10$ K.

Thus, according to the analysis performed, the average speed of water movement in the porthole should be within $v_{\min} < v_{ave} < v_{\max}$.

If a certain v_{ave} value is set from this interval, then, according to relation (4), the difference in water pressures at the upper and lower edges of the porthole can be obtained from the following formula

$$\Delta p = \frac{12\mu h v_{ave}}{d^2}. \tag{7}$$

Taking into account formula (7) allows one to carry out the correct hydrodynamic calculation of the water supply system to the inspection porthole.

5. 3. Analyzing the thermal regime of a porthole during external thermal irradiation

The water in the porthole, acting as an optical filter that absorbs the infrared part of the radiant heat flux, heats up while in the fire zone. Under certain given irradiation conditions, it is possible to determine the maximum operating time, which is limited by the maximum permissible temperature of the water in the circuit.

Radiant heat flux falling on the porthole (with normal incidence of rays on the surface of the porthole)

$$W = q \cdot S = q \cdot l \cdot h. \tag{8}$$

Neglecting the reflection of radiation by the surface of the porthole, it can be assumed that the entire heat flux is absorbed by the water inside the porthole.

During time Δt, a volume of water flows through the porthole

$$\Delta V = l \cdot d \cdot v_{ave} \cdot \Delta t.$$

During this time, the water absorbs the amount of heat $W \cdot \Delta t$, and its average temperature in the cooling circuit increases by $\Delta T = T - T_0$, according to the equation

$$Wt = c \cdot \rho \cdot V \cdot \Delta T, \tag{9}$$

where c is the specific heat capacity of water, ρ is its density.

Taking into account (8), the maximum operating time of the porthole in the fire zone is obtained, during which the water temperature increases by a certain limit value ΔT_{lim}

$$t_{lim} = \frac{c \cdot \rho \cdot V \cdot \Delta T_{lim}}{q \cdot l \cdot h}. \tag{10}$$

The actual water heating time exceeds the specified calculation result, since while in the fire zone the rescuer changes his/her spatial location relative to the source of thermal radiation (fire site). As a result, the angle of incidence of the rays on the surface of the porthole also changes and, therefore, the time-averaged radiant heat flux will take a smaller value compared to that determined from equation (8).

5. 4. Devising a methodology for calculatl ing the transmittance of a porthole for thermal radiation

The optical properties of water are determined by its complex refractive index [23]

$$m = n - i \cdot k, \tag{11}$$

where n is the refractive index, k is the absorption index. Both parameters have strong dependences on the wavelength of radiation, represented in the plots of Fig. 4.

For accurate calculations of the optical properties of water, detailed tables of the values of the real and imaginary parts of the complex refractive index depending on the wavelength are used [18, 19].

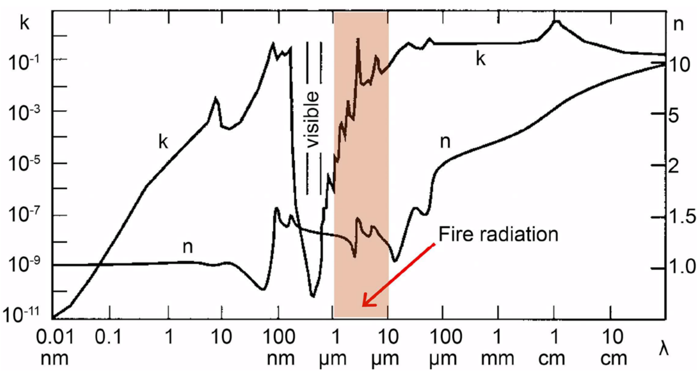

Fig. 4. Spectral dependence of optical characteristics of water [23]

When electromagnetic radiation passes through a homogeneous medium (water), its spectral intensity, corresponding to wavelength λ, is attenuated depending on the path s traveled according to the Bouguer-Lambert-Beer law [23]

$$I_\lambda = I_{\lambda 0} e^{-\alpha \cdot s}, \tag{12}$$

where $I_{\lambda 0}$ is the initial intensity; α is the water absorption coefficient related to its absorption index k by the following ratio

$$\alpha = \frac{4\pi \cdot k}{\lambda}. \tag{13}$$

The water absorption index has an intense minimum in the visible light range at $\lambda \approx 0.5$ µm (Fig. 4). In this narrow wavelength range, water is transparent, absorption of electromagnetic radiation is almost absent, and, for example, a water thickness of about 60 m is required to attenuate it by e times. In the infrared range, water has a much higher absorption coefficient with several intense resonance bands that have extremely high absorption coefficient values. Fig. 5 shows a plot of the dependence $\alpha(\lambda)$, calculated from relation (13) based on tabular data [18] for the spectral region corresponding to wavelengths of 0.5–10 µm [17]. A significant part of this wavelength interval is characteristic of thermal radiation from fires. When radiation passes through water, the greatest influence on the efficiency of thermal shielding is exerted by intense absorption bands at wavelengths of 3 µm and 6.1 µm.

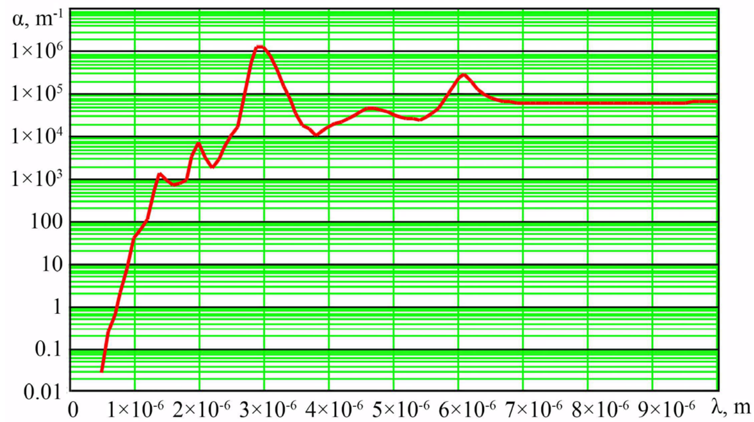

Fig. 5. Dependence of the absorption coefficient of electromagnetic radiation in water on wavelength [17]

The main part of the spectrum of thermal radiation from fires is close to the theoretical spectrum of absolutely black body (ABB) radiation. The wavelength corresponding to the maximum intensity of ABB radiation is determined from the formula of Wien's displacement law

$$\lambda_m = \frac{b}{T}, \tag{14}$$

where $b = 2.9\ 10^{-3}$ m K is the Wien constant. For example, for a typical fire site temperature $T = 1200$ K (about 930°C), we obtain $\lambda_m = 2.4\ 10^{-6}$ m $= 2.4$ µm, which corresponds to the infrared region of the spectrum.

Compared to the value at $\lambda = 0.5$ µm (in the visible range), the water absorption coefficient k (and with it the absorption coefficient α) at wavelengths of 2–10 µm is 5–7 orders of magnitude higher (Fig. 4, 5). Calculation using ratio (12) makes it possible to determine that a water layer of about 1 mm thick is sufficient to attenuate the typical thermal radiation of fires with wavelengths of 2–10 µm by 10 times.

The transmittance of a flat layer of water is the ratio of the intensity I_2 of radiation that has passed through this layer to the intensity I_1 of radiation that falls on its surface

$$\eta = \frac{I_2}{I_1}.$$

Hence, using relation (12), we can find the spectral transmittance for radiation with wavelength λ

$$\eta_\lambda = e^{-\alpha d}. \tag{15}$$

Under real conditions, the thermal radiation of fires is not monochromatic but distributed in a wide spectrum, mainly in the infrared range. Therefore, to determine the transmittance of the entire radiant heat flux, it is necessary to perform integration over the spectral range, taking into account the dependence of water absorption coefficient α on the wavelength.

To perform this task, one can use the results from mathematical modeling of the process of shielding thermal radiation of fires by jets of sprayed water, reported in [17, 20–22]. Based on the data array built as a result of numerical integration of the transmittance spectra of electromagnetic radiation by sprayed water, a simplified calculation approximation function was derived in those papers. Using this function, for the transmittance of a flat layer of water with thickness d, we obtain the following calculation formula

$$\eta = A \cdot (1{,}2 \cdot d)^{B} + C, \tag{16}$$

where coefficients A, B, and C are calculated from the following ratios [22]:

$$A = 1.25 \cdot 10^{-35} \cdot (T_f - 207.6)^{11.02}, \tag{17}$$

$$B = -2.329 + 1.6362 \cdot 10^{-3} \cdot T_f + 1.0519 \cdot 10^{-6} \cdot T_f^2 - \\ -1.386 \cdot 10^{-9} \cdot T_f^3 + 5 \cdot 10^{-13} \cdot T_f^4 - 0.651 \cdot 10^{-16} \cdot T_f^5, \tag{18}$$

$$C = -9.59 \cdot 10^{-5} \cdot 10^{0.002495 \cdot T_f}, \tag{19}$$

where T_f is the effective temperature of the fire site (on the Kelvin scale). This temperature is called the temperature of an absolutely black body, for the radiation of which the transmittance of a thin layer of water coincides with the transmittance for fire radiation.

5. 5. Estimated calculations of parameters for a protective mask under typical working conditions in a fire zone

To substantiate the feasibility of introducing a protective mask of this type into fire protection practice, it is necessary to perform estimated calculations of its basic parameters and compare them with existing samples. For this purpose, the formulae derived above can be used.

The speed of water flow in the porthole should be within the limits determined from formulae (5) and (6). Formula (5) defines the condition for enabling a laminar flow regime of water in the gap between transparent plates. Formula (6) is due to the limitation associated with the speed of heating water by thermal radiation during its stay in the porthole.

Assuming d = 1 mm, $\rho = 10^3$ kg/m^3, $\mu = 6.5\ 10^{-4}$ Pa s (at 40°C), the maximum permissible water velocity in the porthole calculated using formula (5) resulted in $v_{\max} = 1.3$ m/s.

To calculate the minimum permissible water velocity, typical or logically determined numerical values of the parameters were adopted. The following values were accepted: water heating in the porthole $\Delta T_1 = 10$ K; heat flux intensity q = 25 kW/m^2; specific heat capacity of water 4.19 kJ/(kg K); design parameters d = 1 mm, h = 6 cm. As a result, $v_{\min} = 0.036$ m/s was obtained.

Thus, according to our analysis, the average speed of water movement in the porthole should be within 0.036 m/s $< v_{ave} <$ 1.3 m/s.

The operating time of the porthole in the fire zone is limited by the maximum permissible temperature to which water can heat up due to the absorption of thermal radiation energy. To calculate the limiting operating time t_{lim}, the following numerical values of the parameters were adopted: q = 25 kW/m^2; l = 12 cm; h = 6 cm; V = 1 l. For the limiting value of water heating, the value $\Delta T_{lim} = 30$ K was accepted (for example, at the initial and final water temperatures, respectively, 10 °C and 40 °C). As a result of calculations using formula (10), the value t_{lim} = 698 s = 11 min. 38 s was obtained.

Therefore, the limiting operating time in the fire zone of the porthole of this design is approximately three times higher than the above indicator (240 s) for the heat-reflecting suit "Index-800". But more importantly, such a porthole protects the face from thermal radiation, while existing samples of heat-reflecting suits do not provide such protection.

The calculation of the graphical dependence of the porthole transmittance for thermal radiation $\eta(d)$ is shown in Fig. 6. It is performed using the Mathcad software package using relations (16) to (19) for 3 values of the fire site temperature. For it, in particular, it was determined that for a typical temperature value T_f = 1200 K at d = 1 mm, the transmittance η = 0.065. Thus, for the specified parameters, the radiant heat flux when passing through the water layer is weakened by approximately 15 times. For example, after the passage of an external radiant heat flux with a power density of q = 25 kW/m^2 through a protective porthole with the specified parameters, this value decreases to 1.6 kW/m^2, which for short periods of time of 10–15 min is safe for the eyes and facial skin.

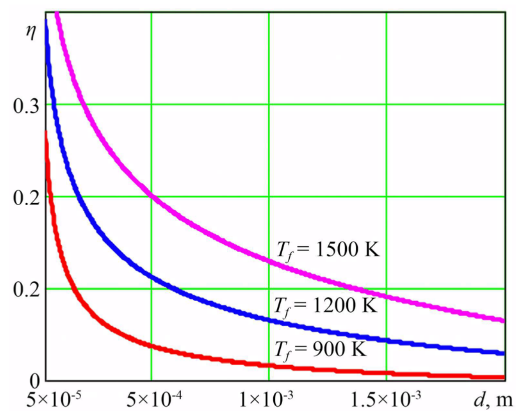

Fig. 6. Dependence of the transmittance of a flat layer of water on its thickness for different values of the fire site temperature

According to formulae (16) to (19), the transmittance η, which determines the protective properties of the mask, depends on 2 parameters: the thickness of the water layer d and the effective temperature of the fire site T_f. An additional quantitative characteristic of these dependences, in addition to the plot in Fig. 6, is given in Tables 1, 2. They show the results of calculations using formulae (16) to (19) of the value η for certain fixed values of values d and T_f.

Table 1

Thermal radiation transmittance η at T_f = 1200 K for different values of water layer thickness d, mm

d, mm	0.6	0.8	1.0	1.2	1.5	2.0
η	0.1	0.08	0.065	0.055	0.043	0.03

Table 2

Thermal radiation transmittance η at d = 1 mm for different values of the effective temperature of the fire site T_f

T_f, K	800	1000	1200	1500	1800
η	0.006	0.029	0.065	0.129	0.198

They indicate, in particular, that in this interval of values, the $\eta(d)$ dependence is close to an inversely proportional dependence. The $\eta(T_f)$ dependence is such that the water layer is a good screen for thermal radiation from a low-temperature flame at $T_f < 1200$ K. At the same time, it screens thermal radiation from higher-temperature sources much worse. Therefore, if it is known that a protective suit will have to be used under conditions of a high-temperature fire flame, it is advisable to equip it with a protective mask with a layer of water of greater thickness.

Using formulae (16) to (19), it is possible to determine the optimal value of the thickness of the water layer d in the porthole to ensure safe conditions for the rescuer to stay in the fire zone. For this purpose, it is necessary to perform calculations using the predicted characteristics of the radiant heat flux.

6. Discussion of results based on investigating a firefighter's protective mask with a thin layer of water

To protect the face and eyes of rescuers in a fire zone with a high level of thermal radiation intensity, it is proposed to use a protective mask of the innovative design, in the porthole of which it was possible to combine the following properties:

1) transparency in the spectral range of visible light;

2) opacity in the main part of the spectral range of fire radiation (infrared radiation);

3) continuous updating of the working part of the optical filter in order to avoid its excessive heating due to the absorption of radiant heat flux.

Such a combination of mutually contradictory properties was achieved owing to the use of a thin moving layer of water between two transparent plates as an optical filter. Unlike existing samples of heat-reflective protective suits, this mask provides full protection of the rescuer's face from thermal radiation of the fire.

Despite the relevance of this task, it has not been reflected in published scientific works. The issue of protecting the face and head of firefighters from dangerous fire factors is considered, for example, in [24, 25]. But, unlike our work, they do not offer methods with a combination of the above properties that could solve the task of protecting the face from the infrared component of thermal radiation of fires. In [24], the improvement of the ventilation and thermoregulation system inside the helmet is considered. In [25], the influence of the condition of the surface of the fire helmet on the level of protection against thermal radiation is analyzed. At the same time, the improvement of the viewing porthole is not discussed in those works.

A typical solution used in modern heat-reflective suits "Index-800" (Ukraine), X-40 (USA), 4HK (China), and others is the use of a heat-resistant polycarbonate plate as a viewing porthole. However, polycarbonate, unlike water, has approximately the same transmittance for visible and near-infrared radiation. Therefore, it does not provide effective protection against the radiant heat flux of a fire, the main part of the spectrum of which (λ = 1–10 μm) lies precisely in the infrared range.

Of all known substances, only water makes it possible to design a porthole with the above-mentioned combination of physical properties and, in particular, with a unique spectral dependence of the absorption coefficient (Fig. 4, 5). A thin, 1–2 mm layer of water is transparent in the optical range (λ = 0.4–0.8 μm) and practically opaque in the infrared range ($\lambda > 1$ μm). The structure of the protective mask proposed in our work makes it possible to solve the problem of the weakest point of heat-reflecting protective suits, in which the entire body of the rescuer, except for the face, is protected by heat-reflecting material. The innovative structure of the mask is built on the principle of not reflecting but absorbing the radiant heat flux by a thin moving layer of water, while simultaneously transmitting visible light in a narrow spectral range, which makes it possible to enable the rescuer's vision function.

The theoretical analysis performed above allowed us to derive calculation formulae, with the help of which it is possible to carry out a design calculation of a protective mask of this type with predetermined properties. Such properties are the attenuation of the radiant heat flux, the water flow regime in the porthole, and the maximum time of the rescuer's stay in the fire zone with given characteristics (temperature of the fire, radiation intensity).

To calculate parameters for a water supply system in the protective mask, ratios (5), (6) are used to determine, respectively, the maximum and minimum permissible water speeds in the porthole. And after selecting the average water speed in this range of speeds according to formula (7), the difference in water pressure at the upper and lower edges of the porthole is calculated. Subsequently, these parameters could be used for the hydrodynamic calculation of the water supply system as a whole.

The permissible operating time using a protective mask of this type is limited by the time of heating the water in the water supply circuit to the limit temperature and is determined from calculation formula (10). If it is necessary to increase the permissible operating time, there are two options:

1) reduce the initial water temperature T_0 in the porthole water supply system;

2) increase the water volume V in the water supply circuit (the volume of the water tank).

Thus, the above calculation formulae (5) to (7), (10), (16) to (19) can lay the foundation of the methodology for designing a protective mask for a fire-fighting heat-reflective suit.

Limitations in the use of protective masks of this type include operating conditions in the temperature range in which the water inside the protective suit is in a liquid state (0–100°C).

The disadvantage of this work is the lack of experimental confirmation of its conclusions, drawn purely theoretically.

The study reported here is of a preliminary, purely theoretical nature. It covers the main aspects of the stated purpose of the research but is not comprehensive. In particular, it requires additional analysis of the issue of the influence of the convective heat exchange of the porthole with the surrounding air on the temperature regime of water in the porthole circuit. An important issue, not covered in our work, is the possible use of a light-reflecting coating on the outer transparent plate in the porthole, which could improve its protective properties. In addition, the next mandatory stage of the research before its practical application is the manufacture of prototypes and conducting versatile experimental studies. They should clarify and confirm some of the calculation formulae derived in our work.

7. Conclusions

1. To improve the firefighter's protective mask, designed for operation under conditions of intense thermal radiation,

a conceptual solution has been found for its structure. It involves the use of a viewing porthole containing a thin moving layer of water. This layer of water must provide attenuation to a safe level of the infrared component of thermal radiation in the fire zone, as well as a stable temperature regime of the protective mask.

2. Based on the assumptions about the laminar flow regime of water in the porthole and its temperature regime, formulae have been derived for its maximum and minimum speeds, respectively. For a certain average value of the water speed, a formula has been obtained for the pressure difference at the edges of the porthole. Taking this formula into account allows for a correct hydrodynamic calculation of the water supply system to the viewing porthole.

3. Based on the condition of maintaining the water temperature in the porthole within the specified limits when it is heated by thermal radiation, a formula was derived for calculating the maximum operating time of the porthole in the fire zone. This is the time of heating the water in the porthole water supply system to a certain limit value. It depends on the intensity of thermal radiation, the initial temperature of the water, its volume, as well as the size of the porthole.

4. A methodology for calculating the porthole transmittance for thermal radiation has been devised. For this purpose, the results from mathematical modeling of the process of shielding thermal radiation from fires were used. Based on them, a calculated approximation function was derived, which depends on the effective temperature of the fire site and the thickness of the water layer in the porthole.

5. For typical operating conditions in the fire zone, estimated calculations of the design and operational parameters of the protective mask were performed. In particular, for the intensity of the heat flux $q = 25\ \text{kW/m}^2$, the effective temperature of the fire site $T_f = 1200$ K, and the thickness of the water layer in the porthole $d = 1$ mm, the porthole transmittance for thermal radiation $\eta = 0.065$ and the maximum operating time in the fire zone $T_{lim} \approx 12$ minutes were established. These parameters are sufficient to protect the firefighter when working in currently existing heat-reflective suits with the prospect of their significant improvement.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Anatolii Vynogradov: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration; **Denis Kolesnikov:** Validation, Investigation, Resources, Writing – review & editing, Supervision; **Serhiy Stas:** Software, Formal analysis, Resources, Data Curation, Writing – review & editing; **Myhalenko Kostiantyn:** Investigation, Resources, Visualization.

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