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MATHEMATICAL MODEL OF HEAT EXCHANGE PROCESSES FOR HEAT PTOTECTIVE COOLING SUIT OF A RESCUER

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Fires are followed by the range of factors hazardous for human health; a radiant thermal stream accompanied by the high temperature of the environment is one of these factors. For protection of firemen special protective clothing from heat impact and the insulation type clothing are used. The paper demonstrates that the concept of action of such clothing is based on the passive heat protection owing to the use of materials with low conducting capacity or high specific heat. The time of effective protection of a suit is not considerable which reduces the duration of work under the unfavorable climatic conditions drastically, increases the work labor input, leads to the hyperthermia.

One of the ways focused on the improvement of the heat protective clothing is a design of suits with cooling, which is stated in the paper. The paper shows that the developed heat protective suits on the basis of water-ice cooling elements are not widely used due to considerable costs. A more reasonable idea refers to the design of heat protective suits with cooling by using running water as the most available coolant circulating along polyvinylchloride pipes arranged between the layers of a suit.

The objective stated in the paper is to derive the patterns of non-stationary heat exchange processes in the system «heat flow of the fire source – heat protective suit – rescuer's body» with cooling the rescuer's organism by running water circulating along polyvinylchloride pipes in the inner lining space as well as a development of a method to determine time of effective protection of the heat protective suit which was realized by solving the equation of non-stationary heat conductivity by the finite elements method. A mathematical model differs in the way of taking into consideration the external radiant thermal stream from a fire, internal thermal stream of a rescuer's body, heat insulation properties of the suit materials, their geometrical parameters, temperature of coolant.

The paper stated that the time of effective protection of a protective suit with water cooling is well above in comparison with the suits of a similar purposes for firemen and rescuers of the Ministry of emergency situations.

Key words: fire, non-stationary heat transfer, heat flow, temperature, heat protective suit, rescuer, protective action, thermal and physical parameters, running water

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Introduction. Ensuring fire safety at the enterprises and organizations is rather complicated task, oriented to fire prevention during human activities and fire suppression in case of fire breaking-out having minimal economical, ecological and social impact. Fires are followed by the range of hazardous factors posing a serious threat to life and health of people caught by fire and rescuers participating in the emergency response. A radiant thermal stream plays a role of one of such factors; when coupled with the high temperature of the gas-vapour environment it does not allow to approach to the fire source and makes an effective fire fighting impossible. For protection from the unfavorable influence, special protective clothing from heat impact and a special protective insulated clothing of a fireman are used. A function principle of such a protective clothing is based on passive thermal protection, i.e. a protection, which is achieved owing to the use of materials of low conductivity or high heat-absorbing capacity and density without heat removal by coolant with force-feed circulation [4].

In case of not using a heat protective suit with cooling, it impairs the safety of emergency-rescue operations, reduces dramatically duration of stay in the fire operation area, especially in summer time. This often leads to the hyperthermia and, consequently, to loss of health, considerable treatment expenses and compensation for occupational injuries and diseases. For disease prevention, the duration of work under the unfavorable climate conditions are reduced [5]. So, for example, the permissible duration of work for medium hard labor conditions (fire reconnaissance, nozzle operations, etc.) in a heat protective suit (HPS) regarding heat flows of 10.5; 7.0 and 4.2 kW/m^2 should not exceed the values of 10; 15 and 20 min respectively. For heavy labor conditions (moving with nozzle, carrying of loads, dismantling of constructions, etc.) and regarding the same heat flows, the permissible duration of works is equal to 8; 12 and 16 min respectively. Considering use of a fire proximity suit (FPS) in the zones where the temperatures of environment reach 450-650 °C and heat flow is equal to 35-59 kW/m^2 - not more than 13 min, the duration of heavy work in such conditions is limited by 9 min [4]. Such small duration of stay in the zone of fire suppression works increases the work labor input and reduces their efficiency. Similar circumstances require a constant improvement of the personal heat protective equipment for firemen, rescuers of the Ministry of emergency situations and mine rescuers of mine rescue brigades (MRB).

Currently for the emergency-rescue works under the conditions of heating environment, mine rescuers use a type of heat protective clothing (coats, suits) with cooling by means of locally distributed in the inner lining space water-ice cooling elements; the heat removal is possible owing to convection and radiation [6, 7, 10]. For the purpose of freezing, storage and delivery of the elements to the working area it is necessary to use freezing installations including mobile nitrogen ones, portable and moveable insulation heat containers [1], which make the organization of emergency-rescue operations more complicated and significantly increase the costs.

Regarding foreign experience at the end of XXth century, heat protective clothing with water-ice cooling was also used. A cooling vest produced by the Dräger company (Germany) and used now in some CIS countries is well known [13, 14]. A vest's cooling action is derived from cooling elements which are incorporated into the vest. A basic material of the cooling elements is a Glauber's salt which stays as a solid body under the temperature below 22 °C. If the temperature of the surface is equal to 28 °C the contents of the cooling elements terns into a liquid state absorbing the heat energy released by the worker's body. Depending on the intensity of physical work and the temperature environment, a vest ensures cooling of a body during not less than 3 hrs. After being used the cooling elements of the vest should be removed. If the temperature of the environment is less than 22 °C the contents of the cooling elements turns into the solid state during 2 hrs and a vest may be used again.

The Dräger cooling vest has the following advantages: there is no need to freeze cooling elemets; it is ready for instant use; a long time of protective action, light load, fire-resistance qualities. One of the disadvantages of a vest with salt mixture refers to the necessity of ensuring a tight contact with a human body as the cooling effect may be possible owing to the process of heat conductivity and in case of a long-term use it may result in what is known as „glasshouse effect" and, consequently, be a cause of various deseases. Provided that the vest is used under the conditions of high temperature values, it will be impossible to recover its functional state.

The developed heat protecting suits for cooling firemen and mine rescuers by means of absorption of heat released by human body when there is a phase transfer of a refrigerating agent of cooling elements in the process of fire suppression with high radiant thermal stream [2] have not occurred to be widely used due to high costs. The development of a heat protective suit with the conductive heat remover with the help of running water – a coolant circulating through polyvinylchloride pipes and to be widely used by firemen for fire suppression, seems to be reasonable under the circumstances.

Paper [8] provides the results of mathematical simulation of non-stationary heat exchange processes in heat protective suits with water cooling; the solution is derived on the basis of a method of finite differences. The following allowance was made: polyvinylchloride pipes are fixed in the cross-section over the width of an air space, which does not coincide with the design of a suit as the pipes are arranged in two directions and an air space is between the external and the internal layers of a suit but not between the pipes. Besides, various values of layers emissivity were not taken into account. As the result, the obtained data concerning the calculation of duration of protective action of heat protective suits was overestimated by 44 % in contrast to the results of the experimental studies [5].

Problem statement. The objective of the study is to derive the patterns of non-stationary heat exchange processes in the system "heat flow of a fire source – heat protective suit – rescuer's body" with cooling the organism of a rescuer by running water, circulating along the polyvinylchloride

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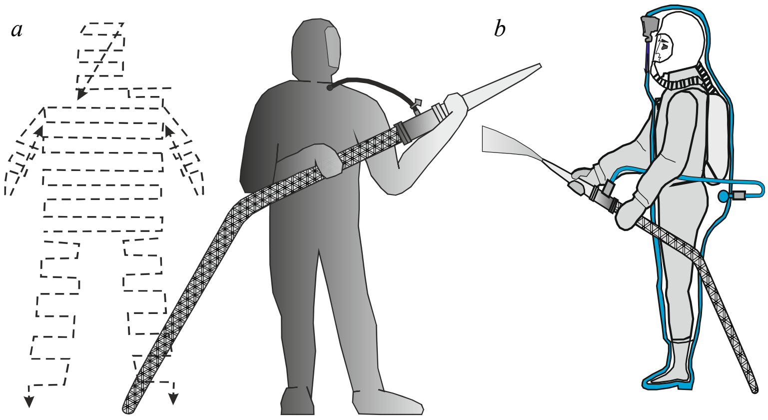

Fig.1. Scheme of water cooling of heat protective suit of a rescuer:
a – water withdrawal from a nozzle and its move along polyvinylchloride pipes;
b – device for water supply to the suit

pipes in the inner lining space, as well as the development of a method to determine a duration of protective action of a heat protective suit. This allows to justify the parameters of heat protective clothing with heat removal providing an increase of the efficiency and safety of rescuers when suppressing fires.

Methodology. Theoretical studies of non-stationary heat exchange processes in the heat protecting suit with running water cooling by polyvinylchloride pipes are conducted on the basis of a method of finite elements – one of the main methods consisting in solution of thermal conductivity equation; as the result, the duration of protective action of heat protective suit with cooling is possible to determine.

Discussion. For the purpose of development of a mathematical model of non-stationary heat exchange processes in the system «environment – heat protective suit – coolant – rescuer's body» a scheme of a rescuer work in a suit when water inflows into the hydraulic device from a booster hose was taken (Fig.1).

A heat protective suit consists of an external layer with the metalized reflecting coating, heat shield, internal layer – a water-cooling coverall and an air space between the layers. A role of a cooling element in the heat protective suit belongs to the polyvinylchloride pipes filled with water, joined together and combined with the nozzle. After circulating along the pipes, used water flows out of peripheral areas of the suit at the level of lower extremities. A design scheme of a heat protective suit is represented in Fig.2.

A non-stationary thermal conductivity equation takes the form

$$\frac{\partial\theta}{\partial t} = \frac{\lambda}{C_p\rho}\left(\frac{\partial^2\theta}{\partial x^2}\right), \tag{1}$$

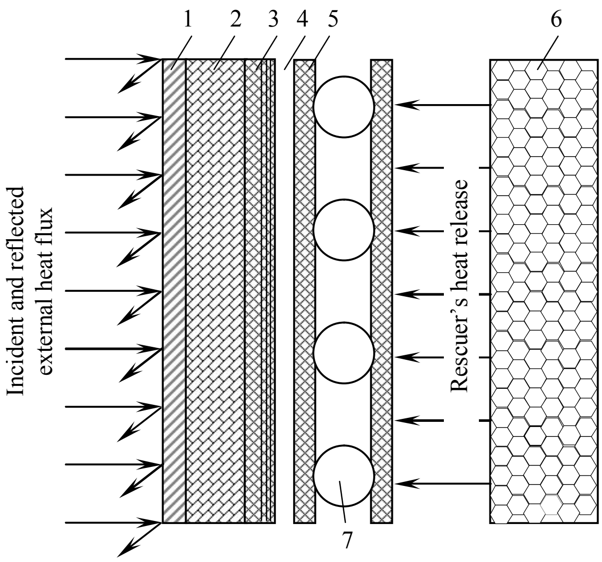

Fig.2. Design scheme of a heat protective suit
1 – External layer with metalized reflecting coating;
2 –heat shield; 3 – internal layer; 4 – air space;
5 –water cooling layer; 6 – rescuer's body; 7 – water pipes

where θ – temperature, °C; t – time, s; λ – heat conductivity factor, W/(m·°C); C_p – variable specific heat, J/(kg·°C); ρ – density, kg/m^3.

For solution of the equation (1) a method of finite elements was used [9]. Boundary conditions of the first and the second kind have respectively a view

$$\theta|_{x,z} = \theta_w \quad и \quad q|_{x,z} = q_w,$$

where θ_w и q_w – temperature, °C, and respectively a heat flow, W/m^2 at the boundary of design area.

Radiative heat exchange between the layers of the heat protective suit and the pipes is taken into account by solving an integral equation of radiative heat exchange between the surface areas. A boundary condition of the third kind

$$\sum_{j=1}^{N}(\delta_{ij} - \varphi_{ij})\sigma T_j^4 = \sum_{j=1}^{N}\frac{1}{A_j}\left(\frac{\delta_{ij}}{\varepsilon_j} - \varphi_{ij}\frac{1-\varepsilon_i}{\varepsilon_j}\right)q_j,$$

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where δ_{ij} – a parameter equal to zero, if $i \neq j$, and is equal to one, if $i = j$; φ_{ij} – radiative form-factor depending on mutual arrangement of i and j surface areas, which exchange the radiation and are defined by the integral equation of radiative heat exchange between surface areas radiating heat; σ – Stefan-Boltzmann constant equal to $5.67 \cdot 10^{-11}$ kW/(m^2·K^4); T – temperature, K; ε_i, ε_j – emissivity factor; q_j – a surface heat flow through i surface area which exchanges heat with j surface.

Boundary conditions for heat exchange between the layers of a suit and points in which we determine the temperature in the layers are shown in Fig.3; a composition and thermal-and-physical characteristics of a suit material are represented in the Table.

To solve the equation (1) we apply a method of effective heat flow of radiation. For this case a generalized law of Stefan-Boltzmann is used [9]

$$\sum_{j=1}^{N}[\delta_{ij} - (1-\varepsilon_i)\varphi_{ij}]q_j^0 = \varepsilon_i \sigma \theta_i^4,$$

where q_j^0 – heat flow from surface radiation of j finite element (FE).

An equation for the approximation of thermal conductivity equation in case of using FE may be represented as follows:

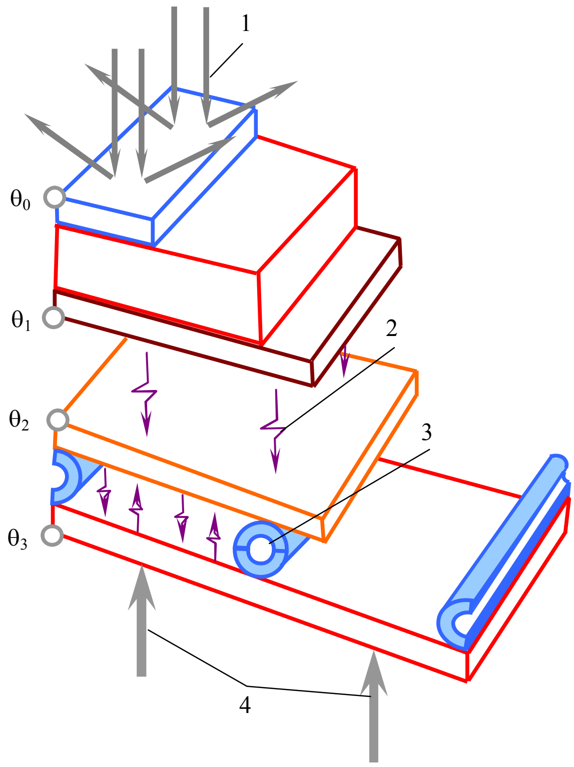

Fig.3. Scheme of boundary conditions (BC) on the surfaces of design area of a suit and check points to determine temperature in the layers

1 – heat flow from the fire source (BC of II kind); 2 – radiative heat exchange in the layers (BC of III kind); 3 – heat removal by water cooling (BC of I kind); 4 – heat flow of a rescuer (BC of II kind); θ_0- θ_3 – temperature in the layers

$$[C_e]\{\theta_e\} + [K_e]\{\theta_e\} = \{Q_e\},$$

where $[C_e] = \rho C_p \int_V \{N\} dV$ – matrix of FE specific heat; $[K_e] = \int_V [B]^T [D] [B]\, dV$ – heat conduction matrix of FE; $\{Q_e\} = q_W \int_S \{N\} dS$ – matrix of boundary heat flow of FE; $[B] = \{L\}\{N\}\theta$ – matrix of temperatures distribution in the area limited by FE; $\theta = \{N\}^T\{\theta_e\}$ – temperature inside the area limited by FE; $[D] = \begin{pmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{pmatrix}$ – heat conduction matrix; $\{L\} = \left\{ \frac{\partial}{\partial x} \; \frac{\partial}{\partial y} \; \frac{\partial}{\partial z} \right\}^T$ – vector of differential operator; $\{N\}$ – vector of FE mode which is defined by the interpolation function in the area limited by FE.

For non-stationary problem of heat conductivity we may write down the resolving system of non-linear equations as a matrice:

$$[K]\{\theta\} = \{Q_e\}, \quad (2)$$

where [K] – an equivalent matrix of heat conductivity depending on the volume specific heat and heat conductivity factor of a material.

The equation (2) may be written down in the aggregate view as the following:

$$\{P(\theta)\} = \{Q_e\}, \quad (3)$$

where $\{P(\theta)\}$ – vector of the internal node heat flows determined by the densities of heat flows of an element.

Thermal and physical characteristics of suit materials

Suit layer	Material	Heat conductivity factor λ, W·m^{-1}·°C^{-1}	Specific heat C_p, kJ·kg^{-1}·°C^{-1}	Density ρ, kg/m^3
External layer with metalized reflecting coating	Ceramic fiber LYTX – 208A2	0.164	0.6	500
Heat protective layer	STBF (Super-thin basalt fiber)	0.034	0.8	14
Internal layer	Nomex	0.047	1.3	316.8
Air space	Air	1.005	0.2375	1.225
Thermal underwear (double-layer)	Nomex	0.047	1.3	316.8
Cooling pipes	Polyvinylchloride	0.15	1.2	1300

This system of equations may be solved by the iteration method known as a Newton-Rafson method [12]. When using this method a disparity is minimal:

$$\{\Phi\} \equiv \{Q_e\} - \{P(\theta)\} \to \{0\}.$$

A Newton-Rafson method is based on the application of truncated Taylor series for residual vector of disparity. The system of equations (3) is linearized and may be written down as the following

$$\left[K_T^{(i-1)}\right]\left\{\Delta\theta_e^{(i)}\right\} = \left\{Q^{(i)}\right\} - \left\{P^{(i)}\right\}. \tag{4}$$

The iterations are balanced (i = 1, 2, 3 ...) and, as the result, we determine new values of temperatures for each iteration, derived from the equation

$$\left\{\theta^{(i)}\right\} = \left\{\theta^{(i-1)}\right\} + \left\{\Delta\theta^{(i)}\right\}.$$

The process of iterating should continue until the acceptable convergence is not reached.

Considering the equation (4) the coefficients of a tangential matrix $[K_T]$ are determined by the equation

$$\left[K_T^{(i-1)}\right] \equiv \left(\frac{d\{\Phi\}}{d\{\theta\}}\right)_{i-1}.$$

The resolution of vector $\{\Phi\}$ to the truncated Taylor series may be presented as follows

$$\left\{\Phi^{(i)}\right\} \cong \left\{\Phi^{(i-1)}\right\} + \left[K_T^{(i-1)}\right]\left\{\Delta\theta^{(i)}\right\},$$

where $\left\{\Delta\theta^{(i)}\right\} = \left\{\theta^{(i)}\right\} - \left\{\theta^{(i-1)}\right\}$ – required incremental vector of temperature for next iteration.

Referring to equation (4) $\{Q^{(i)}\}$ – a vector of node heat flows, calculated for overdetermination of a given external heat flow $\{Q_{0n}\}$ and the equivalent matrix of heat conductivity [K]; $\{\overline{P}\}$ – an equivalent vector of node internal heat flows calculated for overdetermination of an equivalent matrix of heat conductivity which is determined by numerical integration of vector $\left\{\Delta\theta^{(i)}\right\}$ over time by Euler method [12] on the basis of the equation

$$\{\theta_{n+1}\} - \{\theta_n\} = \Delta t_n (1-\varsigma)\{\theta_n\} + \Delta t_n \varsigma \{\theta_{n+1}\}, \tag{5}$$

where Δt_n – integration step over time; ζ – Euler parameter equal to 0.5 which means that the Crank-Nicolson implicit computational scheme was realized [9, 12].

Taking into account the entirety of FE surface areas which exchange the radiation, we may write down the system of nonlinear equations as a matrice:

$$[G]\{q^0\} = \{S\}. \tag{6}$$

The matrix elements [G] are determined by the formula

$$G_{ij} = \delta_{ij} - (1-\varepsilon_i)\varphi_{ij}, \tag{7}$$

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And the matrix elements {S} are determined by the equation

$$S_{ij} = \varepsilon_i \sigma \theta^4 . \qquad (8)$$

The system of equations (15) may be solved for each radiating surface area by the method of iterations by scheme which is expressed by the formula

$$q_i^n = \psi q_i^{k+1} + (1 - \psi)\, q_i^k, \qquad (9)$$

where ψ – relaxation coefficient of radiative heat flow; k – number of iteration.

A hexahedral FE of a Lagrangian type was chosen to solve the problem of heat conductivity on the basis of finite elements method.

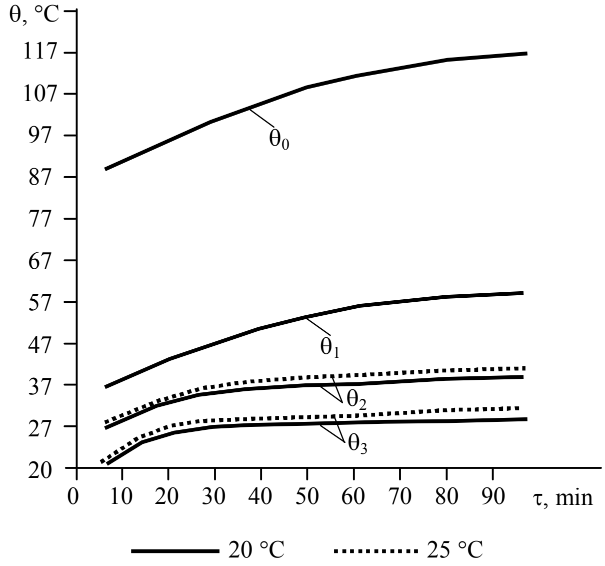

Fig.4. Temperature pattern n the suit layers for various values of temperature of the inflow water θ_3
θ_0 – external layer with metalized reflecting coating; θ_1 – heat protective layer; θ_2 – air space layer

Using the pattern (5) and in compliance with the equations (6)-(9) and abovementioned matrices we obtain the temperature pattern in the layers of a suit over the time for various influencing radiant heat flows (temperatures) of the environment and temperatures of the cooling water for medium hard labor conditions. Particularly, these patterns are shown in Fig.4 provided by the temperature of external surface area of a suit is equal to 200 °C, temperature of cooling water is 20 and 25 °C, the flow rate of 0.23 m^3/h and rational distance between polyvinylchloride pipes equal to 20 mm.

According to medical indications, the permissible temperature in the inner lining space (in the air space) of a heat protective suit for medium hard labor conditions and 100 % relative humidity of the air should not exceed 40 °C [3, 11, 15]. Referring to Fig.4 we see that this requirement is fulfilled during 76 min (curve θ_2). This time period is equal to a time of effective protection of a suit. A measure of inaccuracy by comparing with the data of experimental studies does not exceed 16 % (90 min).

The results of studies show that in case of an influence on a heat protective suit with running water cooling of an air of 100 and 300 °C temperatures, the duration of its protective action is equal to 114 and 51 min respectively. The parameters of the designed suit in comparison with the suits of the similar purpose for firemen (HPS and FPS) as well as the heat protective suit for mining rescuers PTK-300 show that for the temperature of the environment equal to 200 °C the effective protection time of a suit increases by five and two times

Conclusions

1. A mathematical model of non-stationary heat exchange processes in the system "environment – heat protective suit – rescuer's body" was developed; the external radiant heat flow from a fire and the internal flow represented by metabolic heat of a rescuer's body removed by running water circulating along polyvinylchloride pipes of heat protective suit with high insulating characteristics were taken into account when developing the model.

2. Basic technical characteristic of a developed suit which consists in an effective protection time for average load of a rescuer for equal conditions of use is well above in contrast to the suits of the similar purpose used by the firemen (rescuers) of the Ministry of emergency situations and mine rescuers of mine rescue brigades. The implementation of the suit will allow to increase the performance and safety of the emergency-rescue operations under the conditions of high temperatures of the environment.

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