УДК 622.867:623.455.1

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PROCESSES OF HEAT AND MASS TRANSFER IN GAS AND HEAT PROTECTIVE SUIT WITH ICE-WATER COLD-STORAGE ACCUMULATORS

The article dwells on the mathematical model of heat and mass transfer processes in „environment-protective clothing-human" system which takes into account simultaneous penetration of ambient heat and toxic chemicals in the multi-layer membrane of garments with air gap. On the basis of this model, the parameters of a gas and heat protective suit are reasonably defined.

This is due to the fact that during emergency and rescue operations units of the fire and rescue service and mining and rescue services at the enterprises of the coal, chemical, oil refining and metallurgical industries of the national economy there are unfavorable microclimatic conditions (high temperature, humidity of air, smoothness, gas pollution of the environment). So, in the case of firefighting or mine-rescue operations, there were situations when poisonous chemicals entered into fires or mines: chlorobenzene, acetone, benzene, sulfuric acid, and others. As a result, many firefighters or rescuers received poisoning and thermal damage (air temperature reached 40 °C), with the use of rescuers of the best in the world of gas-protective suits proved to be ineffective.

In this regard, there was the necessity in developing a gas and heat protective suit with the multi-layered membrane and with the use of ice-water cold-storage elements (CE) which are used by mine rescuers in heat protective clothing. In addition, according to the requirements of the State Militarized Mine Rescuing Service of Ukraine, the duration of works, conducted by a rescuer in a suit with the minimal mass and under 40 ºC temperature, has to constitute not less than 120 minutes. When a rescuer is under the influence of the most toxic substance (chlorobenzene when its concentration in outputs is 15 g/m^3), the duration of operations has to be 180 min.

Objective of the research is to develop the mathematical model of nonstationary processes of heat and mass transfer in "environment – protective clothing – human" system, and on the basis of it to define parameters of a gas and heat protective suit which would ensure safe work under the above-mentioned conditions.

To develop a mathematical model of heat transfer in the system "the environment – protective clothing – a person" we accept the design scheme of the shell of a suit, which is subject to thermal and chemical effects from the environment and the thermal – the human body.

Key words: mathematical model, temperature, toxic substances, gas and heat protective suit, heat and mass transfer, cooling elements, space under the suit, intensity of heat exchange, number of elements.

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ПРОЦЕСИ ТЕПЛОМАСОПЕРЕНЕСЕННЯ У ГАЗОТЕПЛОЗАХИСНОМУ КОСТЮМІ З ВОДОЛЬОДЯНИМИ АКУМУЛЯТОРАМИ ХОЛОДУ

Наведено математичну модель процесів тепломасоперенесення в системі „навколишнє середовище–захисний одяг–людина”, що враховує одночасне проникнення з навколишнього середовища теплоти і отруйних хімічних речовин до багатошарової оболонки одягу з повітряними прошарками, на підставі результатів якої обґрунтовано параметри газотеплозахисного костюму.

Це зумовлено тим, що під час ведення аварійно-рятувальних робіт підрозділами пожежо-рятувальної і гірничорятувальної служб на підприємствах вугільної, хімічної, нафтопереробної та металургійної промисловостей народного господарства виникають несприятливі мікрокліматичні умови (висока температура, вологість повітря, задимленість, загазованість довкілля). Так, під час пожежогасіння або ведення гірничорятувальних робіт виникали ситуації, коли до шахт проникали отруйні хімічні речовини: хлорбензол, ацетон, бензол, сірчана кислота тощо. У результаті багато пожежників-рятувальників або гірничорятувальників отримували отруєння і теплові ураження (температура повітря сягала понад 40 °С), причому використання рятувальниками кращих у світовій практиці газозахисних костюмів виявилося неефективним.

Ключові слова: математична модель, температура, отруйні речовини, газотеплозахисний костюм, тепломасоперенесення, охолоджувальні елементи, підодяговий простір, інтенсивність теплообміну, кількість елементів.

Formulation of the problem. During accident rescue operations, conducted by departments of mine and fire rescue service at the enterprises of metallurgy, coal, chemical and oil refining industries of the national economy, adverse microclimatic conditions emerge (increased or high temperature, air humidity, smokiness, fumes contamination of the environment). Thus, there were situations when, in the process of conducting mine rescue works, the following toxic chemical substances were pierced with outputs mines from the surface: chlorobenzene, acetone, benzene, sulfuric acid etc. [1, 6]. As a result, many miners and mine rescuers were intoxicated and affected with heat (air temperature reached 40 °C). What is more, rescuers were using some of the best in the world practice gas protective suits like „Trellchem” with „Spiromatic-324” breathing valves produced by „Inerspiro”, and it was inefficient considering the presence of one-layer membrane with insufficient protective capacity and absence of cooling means.

In this regard, there was the necessity in developing a gas and heat protective suit with the multi-layered membrane and with the use of ice-water cold-storage elements (CE) which are used by mine rescuers in heat protective clothing. In addition, according to the requirements of the State Militarized Mine Rescuing Service of Ukraine, the duration of works, conducted by a rescuer in a suit with the minimal mass and under 40 ºC temperature, has to constitute not less than 120 minutes. When a rescuer is under the influence of the most toxic substance (chlorobenzene when its concentration in outputs is 15 g/m^3), the duration of operations has to be 180 min.

Analysis of recent findings and publications. Gas protective suits with one-layered membrane produced with different materials, without cooling means are developed by the National Scientific and Research Institute of Safety Rules in Chemical Industry (Severodonetsk, Luhansk district). On the basis of experimental research, it is determined that mathematical models of heat and mass transfer in heat protective suits [2, 3] do not take into account intensity of heat exchange between a membrane, CE, and the space under the suit (US), the area (the number of CE and US). This leads to increase in the suit mass and decrease in the duration of suit's working capability (the time of its protective effect).

Objective. Objective of the research is to develop the mathematical model of nonstationary processes of heat and mass transfer in "environment – protective clothing – human" system, and on the basis of it to define parameters of a gas and heat protective suit which would ensure safe work under the above-mentioned conditions.

Main findings of the research. A gas and heat protective suit, which consists of an outer insulation membrane (EIM), cooling suit (CS) and respirator, has been designed (fig. 1).

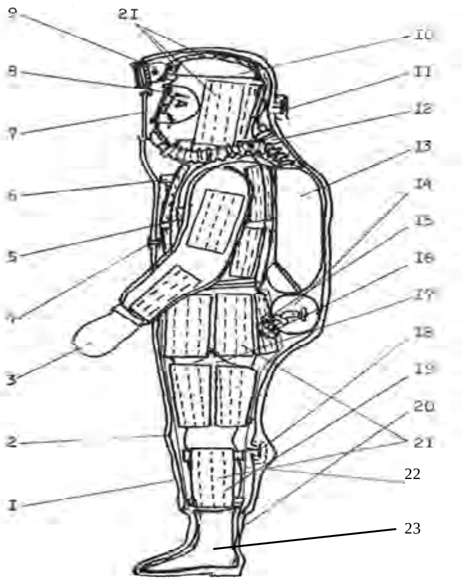

Fig. 1. The design of a gas and heat protective suit:
1 – outer membrane; 2 – inner membrane; 3 – handgear;
4 – coupling of air supply into under-suit space;
5 – jacket; 6 – manometer of the respirator; 7 – glass wall of the suit; 8 – panoramic mask; 9 – light lamp of an illuminator; 10 – cooling hook with helmet; 11 – valve of sweeping out the outer membrane; 12 – accumulator;
13 – respirator; 14 – air compressed tank;
15 – manometer; 16 – reducer with flow-control valve;
17 – cooling belt; 18 – valve of sweeping out the inner membrane; 19 – calf cold-storages; 20 – boots;
21 – ice-water cold-storage elements OE-2;
22 – trousers; 23 – felt boots

EIM is designed to protect a person from the effect of toxic substances. It is represented by a hermetic two-layered coverall, which is made with a helmet and boots. CS absorbs heat released by a person when performing physical activity and penetrated from the environment into US. A tank with compressed air, surplus of which is regulated by valve, is used to fill in interlayer space of the coverall and to sweep out layers. It is possible to use air respirators with chemical absorber I and chemically bound oxygen, and the period of it is not less than 120 min. A person is dressed in the following garments and accessories: CS which includes a jacket, trousers and a hood with internal plastic lattice pockets containing cooling elements (CE); a respirator with a mask, a manometer and a tube to remove oxygen from a relief valve; an accumulator of an illuminator with a light lamp; interphone set with a controlled button and radio aerial (not depicted in the figure), felt boots.

To design the mathematical model of heat and mass transfer in „environment – protective clothing – man" system, the design pattern of suit's membrane (fig. 2), which is inclinable to thermal and chemical influence of the environment and to thermal one of a human body, is considered.

Dynamics of allocation of the chemical substance or its temperature through the thickness of suit's membrane is defined by the following equation:

$$\frac{\partial \Phi}{\partial t} = j^{2} \frac{\partial^{2} \Phi}{\partial h^{2}}, \qquad (1)$$

where $\Phi = \Phi(h, t)$ is a physical variable, which characterizes the temperature, T, K, caused by thermal flow Q_C, W, or concentration C, kg/m^3, of chemical substances caused by the flow of their mass, kg/s; $\varphi = \varphi(h)$ is a coefficient of diffusion conductivity of the membrane material: thermal conductivity a^2 or diffusion D^2, m^2/s; h is a coordinate, measured from the outer surface of a suit along the normal depthward the membrane.

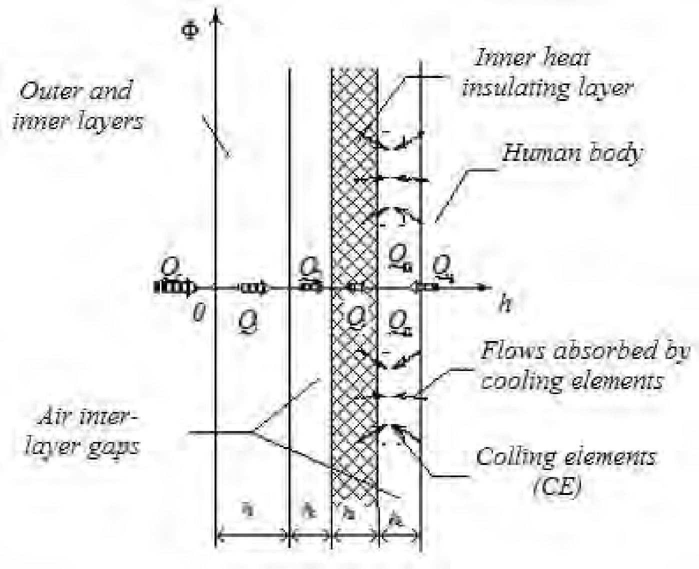

Fig. 2. Design pattern of suit's membrane

It is assumed that the concentration Φ_c in the environment is constant:

$$\Phi|_{h<0} = \Phi_c = \text{const}, \tag{2}$$

and in the initial moment, concentration in the membrane Φ_0 is minimal and the same in all layers:

$$\Phi|_{t=0} = \Phi_0 = \text{const}, \tag{3}$$

Penetration of a substance from the environment into the membrane and from the membrane into US is modelled according to Newton's law by the boundary conditions of the third kind:

$$s_c(\Phi_c - \Phi_1|_{h=0}) = -j_1^2 \frac{\partial \Phi_1}{\partial h}\bigg|_{h=0}; \quad -j_3^2 \frac{\partial \Phi_3}{\partial h}\bigg|_{h=\Delta} = s_{\text{П}}(\Phi_3|_{h=\Delta} - \Phi_{\text{П}}), \tag{4}$$

where an inferior index $i = 1.3$ indicates the value of a variable in the boundaries of i-layer; $\Delta = \sum_{i=1}^{3} h_i$ - total thickness of the membrane layers, m; h_i – thickness of i-layer or an interlayer, m; s_C i $s_П$ - coefficients of substance exchange between the environment and the membrane, the membrane and US, m/s, and the exchange between the substance on the border line of an air interlayer happens according to the Fourier's law which corresponds to the boundary conditions of the fourth kind

$$\Phi_i|_{h=d_i} = \Phi_{i+1}|_{h=d_i}; \quad j_i^2 \frac{\partial \Phi_i}{\partial h}\bigg|_{h=d_i} = j_{i+1}^2 \frac{\partial \Phi_{i+1}}{\partial h}\bigg|_{h=d_i}, \tag{5}$$

where an inferior index $i = 1.2$ indicates the value of a variable within the boundaries of i-layer of an interlayer; $d_1 = h_1$; $d_2 = h_1 + h_2$.

The transfer of heat is represented with the following formula:

$$r c_p V_\text{П} \frac{dT_\text{П}}{dt} = a_\text{П} S_\text{П} (T_\Delta - T_\text{П}) + Q_\text{ч} - a_\text{э} S_\text{э} (T_\text{П} - T_\text{э}) \,, \tag{6}$$

where r is density of US medium, kg/m^3; c_p – specific heat of US medium, J/(kg·K); $V_\text{п}$ – volume of US, m^3; $T_\text{п}$ – temperature in US, K; $a_\text{п}$ – total coefficient of convective and radiant heat transfer between the inner surface of the membrane and US, $\text{W/(m}^2 \cdot \text{K)}$; $S_\text{П}$ – area of inner surface of the membrane, m^2; $T_\Delta = T_3 \big|_{h=\Delta}$ – temperature of inner surface of the membrane, K; $a_\text{э}$ – total coefficient of convective and radiant heat transfer between the membrane surface of cooling elements and US, $\text{W/(m}^2 \cdot \text{K)}$; $S_\text{э}$ – total area of cooling elements surface, m^2; $T_\text{э}$ – temperature of cooling elements, K, and the mass balance of a toxic substance is defined with the following equation:

$$V_\text{П} \frac{\partial C_\text{П}}{\partial t} = s_\text{П} S_\text{П} (C_\Delta - C_\text{П}) \,, \tag{7}$$

where – concentration of a toxic substance on the inner surface of the membrane.

If two parts of the equation (6) are divided by $(r \cdot c_p \cdot V_\text{П})$, and the equation (7) – by $V_\text{П}$, they will be written in agreed notations in one equation

$$\frac{\partial \Phi_\text{П}}{\partial t} = \frac{s_\text{П}}{d_\text{П}} (\Phi_\Delta - \Phi_\text{П}) + q_\text{ч} + \frac{s_\text{э}}{d_\text{э}} (\Phi_\text{П} - \Phi_\text{э}) \,, \tag{8}$$

where for the process of heat transfer: $s_\text{П} = (a_\text{П} S_\text{П})/(r c_p)$ и $s_\text{э} = (a_\text{э} S_\text{э})/(r c_p)$ – relative values of heat transfer coefficients, m/s; $q_\text{ч} = Q_\text{ч} /(r c_p V_\text{П})$ – relative value of the background capacity of thermal flow, K/s; $d_\text{П} = V_\text{П} / S_\text{П}$ и $d_\text{э} = V_\text{э} / S_\text{э}$ – conventional thickness of US and cooling elements, m; $\Phi_\Delta = \Phi \big|_{h=\Delta}$ – substance concentration on the inner surface of the membrane.

Therefore, due to dynamics of substance concentration on the inner surface of the membrane by the equation (8), there is a possibility to predict its content in US, and thus, membrane's throughput capacity. The value C_Δ (or T_Δ) is determined by the equation (1) with boundary conditions (2-5).

The solution of the equation (8) shows that at each temporary step, the concentration in US, depending on its value on inner surface of the membrane, can be determined in the following way:

$$\Phi_\text{П} = \frac{1}{s_\text{пэ}} \Phi_\text{и} - \left(\frac{1}{s_\text{пэ}} \Phi_\text{и} - \Phi_0 \right) \cdot e^{-s_\text{пэ} \cdot t} \,, \tag{9}$$

where

$$s_\text{пэ} = \frac{s_\text{П}}{d_\text{П}} - \frac{s_\text{э}}{d_\text{э}} \,; \quad \Phi_и = \frac{s_\text{П}}{d_\text{П}} \Phi_\Delta - \frac{s_\text{э}}{d_\text{э}} \Phi_э + q_ч \,. \tag{10}$$

In order to use this analytical dependence of $\Phi_\text{П}$ on Φ_Δ, it is necessary to have data about the concentration of absorption (emission) source, which can be obtained through real-time measurements. The dependence enables predicting through h put capacity of the membrane on its inner surface. As an example of such prediction, here is one result (fig. 3) of dynamics calculation of toxic substance concentration in the membrane obtained if: $\varphi_1^2 = 3.5 \cdot 10^{-7}\ \text{m}^2\text{/s}$; $\varphi_2^2 = 4.0 \cdot 10^{-7}\ \text{m}^2\text{/s}$; $\varphi_3^2 = 2.5 \cdot 10^{-7}\ \text{m}^2\text{/s}$; $\sigma_c = 5.0 \cdot 10^{-5}$ m/s and layer thickness $h_1 = 5\,\text{mm}$; $h_2 = 10\,\text{mm}$; $h_3 = 3\,\text{mm}$.

In this case, concentration of a toxic substance in US can reach a half of its concentration in the environment in an hour. It is noticeable that the surface of the membrane concentration area tends to the plane surface, i. e. to stationary allocation of the concentration already in 2 hours.

In order to research a concentration area in general case, the problem solution is represented with dimensionless variables

$$q_i = \frac{\Phi - \Phi_0}{\Phi_c - \Phi_0}; \qquad h = \frac{h}{\Delta}; \qquad \mathrm{Fo} = \frac{j_1^2 \cdot t}{\Delta^2}; \qquad \mathrm{Bi} = \frac{s_c \cdot \Delta}{j_1^2}, \tag{11}$$

thus,

$$q_i = -b_i \left[1 - y\left(\frac{h}{2 \cdot x_i \cdot \sqrt{\mathrm{Fo}}}\right)\right], \tag{12}$$

where $b_1 = -\frac{\mathrm{Bi} \cdot \sqrt{p \cdot \mathrm{Fo}}}{1 + \mathrm{Bi} \cdot \sqrt{p \cdot \mathrm{Fo}}}$;

$$\beta_i = \beta_{i-1} \frac{1 - \psi\left(\frac{\eta_{i-1}}{2 \cdot \xi_{i-1} \cdot \sqrt{\mathrm{Fo}}}\right)}{1 - \psi\left(\frac{\eta_{i-1}}{2 \cdot \xi_i \cdot \sqrt{\mathrm{Fo}}}\right)}, \quad i = 2,3; \tag{13}$$

$h_{i-1} = d_{i-1}/\Delta$, $i = 2.3$; $x_1 = 1$; $x_2 = j_2/j_1$; $x_3 = j_3/j_1$.

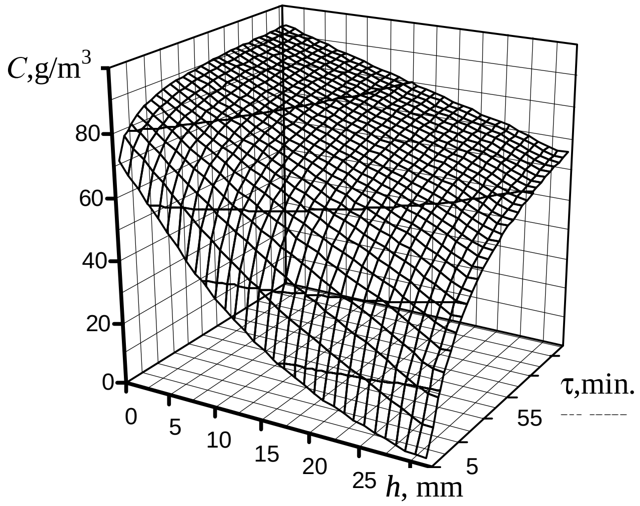

Fig. 3. Concentration area of a chemical substance in a coverall membrane

Due to modelling of a concentration area of various chemical substances in the protective suit membrane according to (12), necessary conduction of its layers was defined at a given concentration in the environment depending on the necessary period of protective effect and acceptable concentration in the under-suit space.

In particular, it was found (fig. 4) that in case of keeping chlorobenzene in the environment $C_c = 17.0\,\mathrm{g/m^3}$ and acceptable concentration $0.05\,\mathrm{g/m^3}$, to ensure protection of a person in a suit during 180 min, at the indicated in the previous example thickness of layers, conduction of the outer surface has to be of the order of $D_1 \approx 10^{-11}\,\mathrm{mm^2/s}$.

$(\mathrm{Bi} = 0.06; \mathrm{Fo} = 0.14)$, where the lower curve corresponds to the moment of time of 20 min, the next one – 100 min, the upper one – 200 min; interim curves are calculated and constructed with the interval of 20 min.

Equation (6) and formula (9) can be used to calculate temperature in US if data about CE temperature at every moment of time is available. In its turn, dynamics of the latter one is determined with the temperature on its surface and thus, with the temperature in US.

Using the system of differential values, similar to (1), for the dynamics of temperature in CE, initial and boundary conditions [5] are obtained in dependence of the temperature in US on the total area of CE: $\bar{S}_Э = S_Э / S_П$ (between the total area of all CE, located in US, and the area of membrane's inner surface), correlation of intensities of heat transfer $\overline{a}_э = a_э / a_п$ (between CE and US, the membrane and US), in the layers of the membrane, CE before and after ice melting and in US (fig. 5). Hence, during 120 min, the temperature in US does not exceeds sanitation norms.

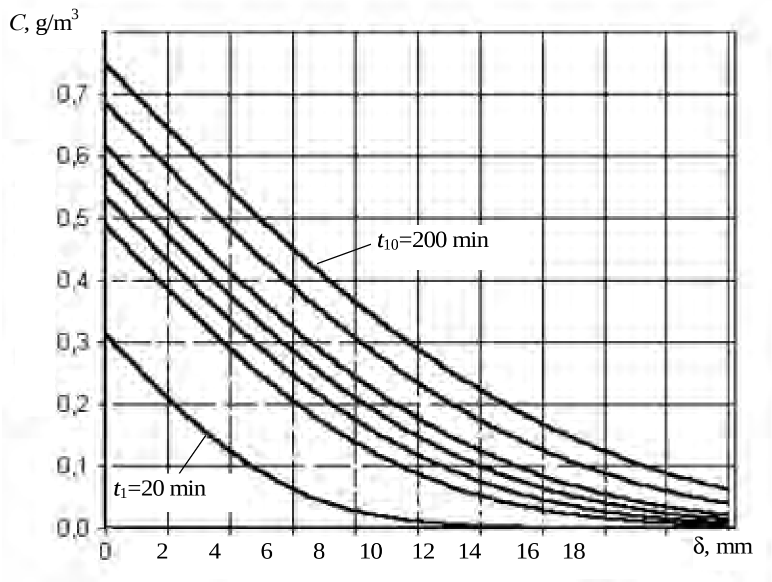

Fig. 4. Dynamics of chlorobenzene concentration in layers of the coverall membrane at intervals of 20 min while its concentration in the environment is C_c= 17,0 g/m^3

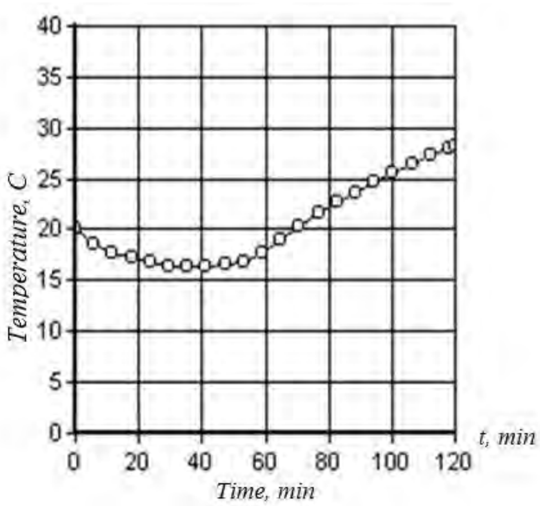

Fig. 5. Temperature dynamics in the under-clothing space

Based on the results of theoretical and experimental research conducted in a specially equipped box of the National Scientific and Research Institute of Safety Rules in Chemical Industry, in heat chamber of the Scientific Institute of Mine Rescuing „Respirator", and in a training mine of the State Militarized Mine Rescuing Service of Ukraine, a gas and heat protective suit has been designed. Technical characteristics of the suit is provided in the following table.

Table 1

Technical characteristics of the gas and heat protective suit

Title of an indicator	Value
Duration of suit's protective operation at 40 °C air temperature of the environment, its relative humidity to 100 % (and the influence of toxic substances), min, not less than	120 (180)
Utilized respirators, type	PC
Total load of ice in the cold-storage system, kg	4.8
The number of cooling elements CE-2, items	28
Mass of the equipped suit with a respirator, kg, not more than	21
Operational endurance, years, not less than	5

Along with that it was determined that the suit mass is lighter by 1.3 times from the mass of an analogous suit, obtained as a result of the research according to existing mathematical models.

Conclusions. The difference between the developed mathematical model of nonstationary processes of heat and mass transfer in a gas and heat protective suit and previous models is that the design pattern of a suit was determined. It includes a multi-layered membrane, which consists of a coverall with an air gap and an insulation layer, ice-water CE. Such a suit takes into account simultaneous influence of toxic substances and temperature of the environment, intensity of heat exchange between CE, a membrane and US, ratio of CE area (mass) in US. This has enabled creating gas and heat protective suits with a minimal mass and necessary duration of protective effect, which are used by the State Militarized Mine Rescuing Service of Ukraine and can be used at the departments of mine and fire rescuing services at the plants of metallurgy, coal, chemical and oil refining industries.

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