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DESIGNING THERMAL PROTECTIVE WORKWEAR WITH AUTONOMOUS LIFE SUPPORT SYSTEM

Purpose. *The purpose of this study is to provide scientific and experimental substantiation of the principles for designing effective thermal protective special clothing (TPSC) equipped with an autonomous life support system, based on the integrated implementation of passive and active thermal protection methods under conditions of extreme and ultra-high temperature exposure. The research is aimed at establishing thermophysical regularities of heat transfer within multilayer material assemblies and developing a predictive model for temperature distribution and protective performance time under convective heat removal conditions.*

Methods. *The research methodology is based on a combination of theoretical modeling, experimental determination of thermophysical characteristics, and engineering design approaches. The theoretical framework relies on the theory of non-stationary heat transfer and the method of regular thermal regime, employing analytical solutions of differential equations describing heat conduction and convective heat exchange processes in porous multilayer systems. The thermophysical parameters of materials and material assemblies were determined using a flat bicalorimeter and a regular regime microcalorimeter. The study encompassed material packages composed of metallized heat-reflective outer layers, heat-resistant fabrics, membrane materials, thermal insulation interlayers, and lining materials. In addition, a nanostructured textile material modified with silver nanoparticles synthesized via a green technology approach was* *developed and implemented as a hygienic underwear layer. A comparative analysis of various package configurations was conducted in order to identify optimal combinations according to thermal resistance, density, and ergonomic performance criteria.*

Results. *It was established that the exclusive use of passive thermal protection under ultra-high temperature conditions is ergonomically inefficient due to the necessity of significantly increasing garment thickness and mass. The integration of an active convective cooling system ensures a substantial increase in the effective thermal resistance of the multilayer structure. A mathematical model describing temperature distribution within a porous thermal insulation layer under forced air filtration conditions was developed. An efficiency coefficient of active thermal protection was introduced and analytically determined, enabling quantitative evaluation of cooling system performance. Experimental results confirmed that optimized material packages incorporating metallized outer layers and advanced thermal insulation materials provide enhanced thermal resistance while maintaining acceptable weight and dimensional characteristics. The application of the nanomodified textile material in the inner layer ensures compliance with hygienic requirements, ultraviolet radiation protection, and improved environmental sustainability of the production process.*

Scientific novelty. *For the first time, a comprehensive physical model of heat transfer in thermal protective clothing combining passive multilayer thermal insulation with active convective cooling has been theoretically substantiated. An analytical solution to the problem of temperature distribution within a porous thermal insulation layer under convective filtration conditions was obtained, enabling determination of the heat flux penetrating toward the human body as well as calculation of the efficiency coefficient of active thermal protection. The approach to the classification of heat-resistant materials according to their thermophysical characteristics and functional role within multilayer assemblies has been further developed. The use of a nanostructured textile material containing silver nanoparticles synthesized through an environmentally safe method is proposed as an integral component of combined thermal protection systems.*

Practical significance. *The obtained theoretical relationships and experimental results provide the possibility of predicting the protective performance time and ergonomic characteristics of thermal protective special clothing at the pre-design stage. The developed design principles contribute to the creation of competitive, high-technology products intended for fire-rescue units and professionals operating under extreme temperature conditions. The implementation of nanomodified textile materials enhances the hygienic properties of garments, ensures ultraviolet protection, reduces energy consumption in the manufacturing process, and improves the environmental safety of the technology. The proposed approach establishes a methodological foundation for the further development of adaptive and autonomous life support systems in the design of modern protective clothing.*

Keywords: *clothing design; special-purpose thermal protective clothing; textile barrier materials; convective heat transfer; thermal-protective properties of materials.*

ПРОЄКТУВАННЯ ТЕПЛОЗАХИСНОГО СПЕЦОДЯГУ З АВТОНОМНОЮ СИСТЕМОЮ ЖИТТЄЗАБЕЗПЕЧЕННЯ

КОЛОСНІЧЕНКО ОЛЕНА, ОСТАПЕНКО НАТАЛІЯ, СТРУМІНСЬКА ТЕТЯНА,
ЛУЦКЕР ТЕТЯНА, МАМЧЕНКО ЯНА, ЯЛОВИЙ ВІТАЛІЙ, КОЛОСНІЧЕНКО МАРИНА
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Мета. *Метою дослідження є наукове та експериментальне обґрунтування принципів проєктування ефективного теплозахисного спеціального одягу (ТЗСО) з автономною системою життєзабезпечення на основі інтегрованої реалізації пасивних і активних способів теплозахисту в умовах впливу екстремальних та надвисоких температур. Дослідження спрямоване на встановлення теплофізичних закономірностей теплопереносу в багатошарових пакетах матеріалів і розроблення прогностичної моделі розподілу температур та часу захисної дії за умов конвективного теплознімання.*

Методологія дослідження *ґрунтується на поєднанні теоретичного моделювання, експериментального визначення теплофізичних характеристик і інженерно-конструкторських підходів. Теоретичне обґрунтування базується на положеннях теорії нестаціонарного теплопереносу та методу регулярного теплового режиму, з використанням аналітичного розв'язання диференціальних рівнянь, що описують процеси теплопровідності та конвективного теплообміну в пористих багатошарових системах. Теплофізичні показники матеріалів і пакетів* *визначалися із застосуванням плоского бікалориметра та мікрокалориметра регулярного режиму. Дослідження охоплювали пакети, сформовані з металізованих тепловідбивних шарів, термостійких тканин, мембранних матеріалів, теплоізоляційних прошарків і підкладкових матеріалів. Окрім того, розроблено та впроваджено наноструктурований текстильний матеріал, модифікований наночастинками срібла, синтезованими за «зеленою» технологією, що застосовано як гігієнічний білизняний шар. Проведено порівняльний аналіз різних конфігурацій пакетів з метою визначення оптимальних комбінацій за показниками термічного опору, щільності та ергономічності.*

Головні результати. *становлено, що використання виключно пасивного теплозахисту в умовах надвисоких температур є ергономічно неефективним через необхідність значного збільшення товщини та маси виробів. Інтеграція активної конвективної системи охолодження забезпечує суттєве зростання ефективного термічного опору багатошарової системи. Отримано математичну модель розподілу температур у пористому теплоізоляційному шарі за умов примусової фільтрації повітря. Запроваджено та аналітично визначено коефіцієнт ефективності активного теплозахисту, що дозволяє кількісно оцінювати результативність систем охолодження. Експериментально підтверджено, що оптимізовані пакети з металізованими зовнішніми шарами та сучасними теплоізоляційними матеріалами забезпечують підвищений термічний опір за збереження прийнятних масо-габаритних показників. Використання наномодифікованого текстильного матеріалу у внутрішньому шарі забезпечує відповідність санітарно-гігієнічним вимогам, захист від ультрафіолетового випромінювання та підвищення екологічності виробництва.*

Наукова новизна. *Уперше теоретично обґрунтовано комплексну фізичну модель теплопереносу в теплозахисному одязі, що поєднує пасивну багатошарову теплоізоляцію з активним конвективним охолодженням. Отримано аналітичний розв'язок задачі розподілу температур у пористому теплоізоляційному шарі за умов конвективної фільтрації, що дозволяє визначати тепловий потік, який проникає до тіла людини, а також розраховувати коефіцієнт ефективності активного теплозахисту. Подальшого розвитку набув підхід до класифікації термостійких матеріалів за їх теплофізичними характеристиками та функціональним призначенням у структурі пакетів. Запропоновано використання наноструктурованого текстильного матеріалу з наночастинками срібла, отриманими екологічно безпечним способом, як складової комбінованих систем теплозахисту.*

Практична значимість. *Отримані теоретичні залежності та експериментальні результати забезпечують можливість прогнозування часу захисної дії та ергономічних показників теплозахисного спеціального одягу на передпроєктному етапі. Розроблені принципи проєктування сприяють створенню конкурентоспроможних високотехнологічних виробів для пожежно-рятувальних підрозділів та фахівців, що працюють в умовах екстремальних температур. Упровадження наномодифікованих текстильних матеріалів підвищує гігієнічні характеристики виробів, забезпечує ультрафіолетовий захист, зменшує енерговитрати у виробничому процесі та підвищує екологічну безпечність технології. Запропонований підхід формує методологічну основу для подальшого розвитку адаптивних і автономних систем життєзабезпечення у конструкції сучасного захисного одягу.*

Ключові слова: *проєктування одягу; теплозахисний одяг спеціального призначення; текстильні бар'єрні матеріали; конвективна теплопередача; теплозахисні характеристики матеріалів.*

Introduction. The experience of working in hazardous areas exposed to high temperatures, performing emergency rescue operations, and protection of workers that need to move long distances shows that the principle of passive thermal protection does not completely provide high-quality performance of work. This is due to the fact that the efficacy of passive protection methods is determined solely by the ability to withstand external thermal loads thanks to the well-founded selection of materials in composites, which is an integral complex task [1]. Based on the above, the development of modern personal protective equipment (PPE) against extreme heat makes it impossible to apply the passive principle for reasons of product ergonomics. This principle implies multilayered, multifunctional, and interdependent of individual materials used for thermal protection of the human body, which, under conditions of extreme heat impact, requires the development of very thick (more than 30 mm) composite clothing. Therefore, it is important to combine passive and active protection methods when developing effective PPEs against the impact of ultra-high and extreme temperatures. It should be noted that "heat-resistant nanostructured composite, ceramic, and metal materials have great potential for use in many industries due to their resistance to chemical decomposition at elevated temperatures" [1]. Among these innovative products, carbon structural materials with a maximum operating temperature of up to 1650 °C can be distinguished. While the outer layers of PPE materials are designed to provide direct protection against the impact of environmental heat, the inner layers that come into contact with the human body should have physiological compatibility. Such materials can improve the sanitary, hygienic, and protective properties of clothing.

Analysis of previous studies and problem statement. In recent years, nanotechnology has become increasingly available from an economic standpoint, while from a technical standpoint, it has become possible to model, implement, and control processes at the nanoscale. This progress has been stimulated by the growing demand for new materials, caused, on the one hand, by the depletion of raw material resources and, on the other hand, by the active implementation of nanotechnologies into the production of products with fundamentally new properties [2, 3]. Due to the use of nanomaterials, effective solutions to a number of tasks related to the development of modern types of protective workwear may appear in the near future [4]. The large number of new materials requires studying their properties and developing a classification of heat-resistant materials, which makes it possible to easily determine their entire range and predict their behavior in high-temperature aggressive environments [5].

The first noticeable effects in the application of nanomaterials and nanobiotechnology for human protection, as well as nanoelectromechanical systems, are expected in the next five years. The most significant breakthroughs of the next decade may be the molecular production of macroscopic objects, so-called "desktop nanofactories". The convergence of nano-, info-, bio-, and cognitive technologies may eventually provide extending the active stage of human life [6–8]. Perhaps these fields will determine the modern technologies in the future. High expectations are primarily associated with the development of hybrid structures that combine organic segments with inorganic ones, or living tissues with synthetic components which provide new properties through the development of nanocomposites in the design of modern protective materials.

The aim of the study was to determine the features of designing effective thermal-protective special clothing (TPSC) combining passive and active methods of protection against the impact of extremely high temperatures. Heat transfer processes were theoretically analyzed for determining temperature distribution in clothing layered materials during convective heat removal. This research is aimed at predicting the protective effect of the clothing in order to reduce injuries and deaths among workers, and conduct emergency rescue operations at the proper level, that can be a basis for the development of new types of TPSC.

Materials and Experimental Techniques. Modern concepts for the development of functional thermal-protective clothing involve searching for universal solutions in combining materials into composite packages that are potentially capable of providing thermal protection for people in finished products. The implementation of the above tasks makes it possible to develop innovative, competitive, high-tech textile products with targeted properties for various applications. Clothing made from modified materials should reduce risks under harmful environmental conditions and, together with special design and technological solutions, favor the adjustment of clothing for various conditions. The following useful methodological and technical procedures should be highlighted:

- methodological approach to the peculiarities of designing special-purpose clothing;
- methodology for the informed choice of textile materials and their protective properties, as well as threads and accessories through comparative analysis of targeted properties;

– methodology for experimental research to determine the heat-resistant properties of materials under the impact of high-temperature environments;

– methodology for an ergonomic design of a reasonable product range, etc.

A scientifically based approach is important to develop TPSCs with targeted operational, ergonomic, protective, and, accordingly, technical and economic properties. Ukrainian and mainly foreign samples of fire-resistant materials for external covering, thermal insulation liner, and pad were selected for research due to a significant reduction in the market segment for these materials in Ukraine.

The implementation of the principle of combining passive and active protection requires the use of textile nanostructured materials. We proposed the use of innovative textile materials developed under a Kyiv National University of Technologies and Design (KNUTD) patent, with silver nanoparticles incorporated in the lining layer of protective clothing [9]. The use of newly developed materials fully meets hygiene requirements and provides protection against ultraviolet radiation. At the same time, the proposed technology is cost-effective in industrial implementation compared to existing techniques of producing materials; besides, it enhances the environmental friendliness of the production due to the use of "green" technology for manufacturing silver nanoparticles [10]. The goal was achieved by using a colloidal solution of protective substances extracted from fungal mycelium cell filtrate, which stabilizes silver nanoparticles.

Thus, in the proposed method, the production of modified material is simplified by permeating the textile material with a colloidal solution containing silver nanoparticles. The colloidal solution is absorbed and uniformly distributed throughout the textile material. Silver nanoparticles are located between the fibers of the fabric and on its surface, that results in a protective effect against ultraviolet radiation. The production of modified material is comparatively cost-effective due to the absence of heat treatment such as heating or high-temperature drying, i.e., energy costs are reduced by carrying out material modification under normal conditions. It should also be noted that the use of “green” technology for producing silver nanoparticles enhances the environmental friendliness of the technology.

The advantages of the proposed technique are as follows: (1) simplification of the process of producing modified material by permeating the textile material with a colloidal solution containing silver nanoparticles; (2) the possibility of modifying textile material using existing finishing production equipment; (3) energy efficiency, as the modification is carried out under normal conditions; (4) environmental friendliness due to the use of "green" technologies.

The textile material is permeated with a colloidal solution containing silver nanoparticles, which is stabilized for five minutes with protective substances produced from the cell filtrate of fungal mycelium. The permeated modified material is dried under normal conditions. We tested the new material in a clothing with passive thermal protection, as well as in a clothing with active thermal protection under extreme thermal conditions.

Unlike passive clothing, TPSCs with active thermal protection require the presence of a cooling layer in the composite material, which depends on the type of protection. In this study, we examined heat transfer processes in clothing with active thermal protection to provide effective human performance in superheated environments.

There are several approaches to actively maintaining thermal homeostasis in the human body under extreme thermal conditions [11]. The main requirements for active thermal protection systems are:

the system should have sufficient heat transfer, which corresponds to the intensity of heat production by the body and the microclimatic parameters of the environment;

the system should provide the heat exchange structure and body temperature topography necessary to maintain thermal comfort.

As known, regular thermal regime is based on the phenomenon of free cooling of a heated body (system) in a gaseous or liquid environment. Therefore, a non-stationary thermal process is always associated with a change in the heat content of a body and is determined by it. Since the rate of change in heat capacity is directly proportional to the material's ability to conduct heat (thermal conductivity coefficient λ) and inversely proportional to its heat storage capacity (i.e., specific heat capacity per volume c), the overall rate of heating or cooling of a body under non-equilibrium conditions is determined by the value of the temperature conductivity coefficient:

$$\alpha = \frac{\lambda}{c \cdot \rho},\ m^2/h \tag{1}$$

where ρ is the density (specific weight) of the composite material, m^3/kg.

In the fundamental theorem of steady-state theory, the logarithm of the temperature difference θ at any point of the body and the surrounding environment changes according to a linear law, with the same rate at each point and decreases over time τ according to an exponential law:

$$\theta = \mathrm{A} \cdot e^{-m\tau}, \tag{2}$$

where A is the proportionality factor that does not depend on time;

m is a positive value corresponding to limited time, which is the same for any point of the body.

The parameter m is a central concept in the steady-state theory, which describes the relative cooling rate of a body, and is called the cooling rate. The materials and packets made of heat-resistant fibers were studied, which were tested in certified laboratories of KNUTD [12]. Depending on the type of materials, TPSC packets included: outer material, insulating layer, and lining (non-woven material). A modified textile material with silver nanoparticles was used as the undergarment layer of protective clothing.

If the clothing contained heat-reflective material with a metallized coating, the packets were formed with it as the outer layer. As widely known, the effectiveness of thermal protection depends on the thermophysical properties of materials, especially those used as a thermal insulation layer (insulation). In order to increase the thermal resistance of thermal-insulative clothing, the number of insulative layers may vary, but the total thickness of the layered composite materials should not exceed 20 mm in accordance with the ergonomic requirements of the product.

Results and Discussion. Specific heat capacity was measured in a regular mode at a "Kaplya" microcalorimeter. As noted above, determination of heat capacity does not allow for a complete understanding and prediction of the thermal insulation properties of composite packets and finished products. The thermal conductivity of a layered composite packet is determined by the thermal conductivity coefficient λ, while for materials used in clothing, the thermal resistance R of materials and layers of protective clothing packets is considered more useful and illustrative.

The thermal insulation properties of materials were determined using a device with an improved regular mode – a flat-plate calorimeter, which allowed determining the thermal conductivity coefficient of both technical materials (0.1< y <1000 kg/m^3) and the thermal resistance of fabrics, layered composite packets, fur, corrugated board, etc. [13, 14].

The thermal conductivity coefficient, thermal resistance, and temperature conductivity coefficient were calculated based on the results obtained at a flat-plate calorimeter. The following formula was used for calculating thermal resistance R (m^2K)/W:

$$R = \frac{1}{\varPhi \cdot f \cdot \left(\frac{m}{Б} - A \right)}, \tag{3}$$

where Φ is the device factor, which depends on the dimensions and material of the device, device constant Φ=14.1 103 J/(m2K);

f is the heat flux dissipation factor, that is a function of sample thickness, $f = 0.90$;

m is the cooling rate (c-1);

A is the instrument constant that determines heat loss through the side surface: A = 1.15 10-4, c-1

The thermal conductivity coefficient (W/(m K)) is determined as

$$\lambda = \frac{\delta}{R}, \tag{4}$$

where δ is the thickness of material (packet of layers of different materials), m.

The thermal and physical properties of the materials and composite packets studied are listed in Tables 1 and 2.

Table 1

Properties of materials used in TPSCs

Material, manufacturer	Code	Surface density, g/m^2	Thickness, δ, x 10^{-3}, m	Specific heat capacity, C, J/ (kg·K)	Air permeability coefficient, dm^3/(m^{2}c)	Flammability	Coefficient λ, W/(m·K)
1	2	3	4	5	6	7	8
Function of material layer in packet **1 Heat reflective**							
Vacuum metallized Nomex, AV 1/Z (Tempex GmbH, Germany)	A$_1$	370	0.410	1489	0	non-flammable	0.044
Terlon, metallized with PET film, RF1/Y (Tempex GmbH, Germany)	A$_2$	540	0.532	1518	0	non-flammable	0.046
Linen canvas with heat-resistant filling by 88 glue, metallized by transfer (TU 17-21-193-77, Ukraine)	A$_3$	480	0.523	1314	8.0	flammable, hardly combustible	0.054
Function of material layer in packet **2 Heat resistant**							
Linen canvas with heat-resistant filler, item 11116 (GOST 115530, Ukraine)	B$_1$	470	0.511	1636	15	flammable, medium flammability	0.052
Nomex III fabric, (Dupont, Switzerland)	B$_2$	265	0.326	1938	52	non-flammable	0.042
Nomex Delta T fabric (Dupont, Switzerland)	B$_3$	195	0.302	1964	58	non-flammable	0.043
Nomex fabric, GORE-TEX laminate (Gore GmbH, Germany)	B$_4$	310	0.338	1768	0	non-flammable	0.048
Special heat-resistant fabric (HRF) (TU U17242-41-96, Ukraine)	B$_5$	248	0.322	1924	54	non-flammable	0.045
Function of material layer in packet **3 Waterproof**							
GORE-TEX membrane material, (Gore GmbH, Germany)	C$_1$	160	0.120	-	0	-	-
Rubberized fabric, item 356 (Ukraine)	C$_2$	380	0.351	1830	0	hardly flammable	-
Function of material layer in packet **4 Heat-insulating**							
Polyamide synthetic wadding (synthetic winterizer), (Ukraine)	T$_1$	338	5.61	2950	98	non-flammable, melting	0.038
Wool-phenyl knitted quilt batting (Ukraine)	T$_2$	416	6.36	2135	86	non-flammable, smoldering	0.042
Needle-punched nonwoven fabric made of Nomex fibers (DuPont, Switzerland)	T$_3$	190	4.56	1998	92	non-flammable	0.036
Needle-punched nonwoven fabric, 70% polyamide fibers, 15% wool, and 15% Nomex (Ukraine)	T$_4$	348	6.05	2315	96	non-flammable, melting	0.041
Wool batting (GOST 18273-80, Ukraine)	T$_5$	448	6.48	1382	103	non-flammable, smoldering	0.040
Function of material layer in packet **5 Lining**							
Lining twill fabric (item 3224, Ukraine)	E$_1$	126	0.13	-	160	-	-
Cotton-polyester fabric (item SP322, Ukraine)	E$_2$	130	0.14	-	110	-	-
Plain dyed calico (item 524, GOST 11680-76, Ukraine)	E$_3$	124	0.13	-	180	-	-
Nomex fiber lining fabric (DuPont, Switzerland)	E$_4$	115	0.13	-	115	-	-

Table 2

Thermal properties of special protective clothing packets

Code number of packet	Packet number (Table 2.1)	Packet thickness, $\delta, \times 10^{-3}$, m	Density, γ, kg/m^3	Thermal resistance, R, (m^{2}K)/W	Specific heat capacity, c, J/(kg K)	Thermal conductivity coefficient, λ, W/(m K)	Temperature conductivity coefficient α, 10^{-7}m^2/c
1.	$A_1B_4T_3E_4$	5.45	59.8	0,121	1430	0,045	1.67
2.	$A_3T_1T_4E_1$	12.18	37.2	0,283	1440	0,043	4.36
3.	$A_1B_5C_1T_4T_4E_2$	13.15	39.3	0,313	1370	0,042	3.88
4.	$A_2B_2C_1T_2T_4E_2$	13.69	41.7	0,334	1540	0,041	3.48
5.	$B_1C_1T_2E_3$	6.98	42.4	0,148	2130	0,047	2.26
6.	$B_3C_1T_4E_3$	6.77	40.1	0,138	2060	0,049	2.33
7.	$B_5C_2T_4E_3$	6.97	44.8	0,134	1940	0,052	2.42
8.	$B_4T_3E_3$	5.04	47.5	0,105	2350	0,048	1.37
9.	$B_1C_2T_5E_1$	7.53	55.3	0,134	1240	0,056	3.42
10.	$B_4T_3E_4$	4.96	29.1	0,127	2165	0,039	2.46

According to the data shown in the tables above, packets 2–4 had the best properties. Nevertheless, the properties of the packets with an outer metallized layer should be emphasized. This layer enhances thermal resistance and provides fire protection, but significantly increases the weight of the clothing due to the metal layer, as well as the necessary double-layer thermal insulation required due to more severe conditions of use.

Among the packets used to make clothing with passive thermal protection, packets 5 and 6 are particularly noteworthy, although others are also suitable for use in a wide range of temperatures due to well-grounded combination of materials. All packets are water-proof, contain surface-active substances, and also have the ability to remove moisture from interior volume. Packet 9, whose composition is currently used in modern types of TPSCs in various professions, raises serious doubts. Linen canvas saturated with heat-resistant substance has unsatisfactory flammability, while the rubberized fabric in packets 9 and 7 impedes removing excess moisture from the interior volume, which is unacceptable. Packet 10 is remarkable, which includes the materials produced by DuPont company (USA). Beside high thermal insulation, this fabric has a low density, which is an important advantage of this clothing. Due to these properties, these materials can be applied in TPSCs both with passive and active protection, which are used in a wide range of temperatures. However, its widespread use is hampered by excessively high prices. Thus, the searching experiment allowed narrowing down the search and further research on materials and composite packets that are most versatile in terms of their properties for most types of TPSCs used at high temperatures.

The problem of using clothing at extremely high temperatures was solved based on well-known designs of ventilation in clothing. Active heat protection was used, which involved supplying cool air into the interior volume of the clothing, cooling the human body with it, and removing a uniform flow of used air into the atmosphere through the porous heat-insulating clothing. The study of this method of thermal protection leads to the following conclusions. Let us consider a heat-insulating layer of clothing in the form of an infinite flat plate with a thickness of δ, made of a material with through porosity, which has a constant thermal conductivity coefficient λ. On one surface, the plate has a temperature close to human body temperature T0, and on the other surface, it has elevated temperature T1 (boundary conditions of the first type). In this case, the heat conduction problem is one-dimensional, and the heat flow through the plate is:

$$q = \frac{\lambda}{\delta}\left(T_1 - T_0\right) = \frac{\Delta T}{R_T}, \tag{5}$$

where $R_T = \dfrac{\delta}{\lambda}$ is the thermal resistance of the system.

Let us consider a flow of a gas with heat capacity cp. Let its initial temperature be T_0, and the flow rate per second through a unit surface area be j kg/(m^{2}c). Obviously, in this case, heat transfer inside the plate is determined by two components: thermal conductivity, and convective heat exchange between the plate and the filtered gas. The first component in the cross sections *x* and (*x*+*dx*) is

$$q_x = -\lambda \frac{dT_c}{dx}, \qquad (6)$$

$$q_{(x+dx)} = -\lambda \frac{d}{dx}\left(T_c + \frac{dT_c}{dx} dx\right). \qquad (7)$$

The difference between these values, based on the energy balance condition, is equal to the second component, which is determined by the change in gas enthalpy between these cross-sections:

$$dq = q_x - q_{(x+dx)} = dh = h_x - h_{(x+dx)}. \qquad (8)$$

If we assume that, due to slow continuous gas permeation through the porous material of the plate, a local temperature equilibrium forms between the layers, then

$$\lambda \frac{d^2T}{dx^2} dx = jc_p \cdot dT. \qquad (9)$$

Therefore, the temperature distribution in the plate is described by the following differential equation:

$$\frac{d^2T}{dx^2} - \chi \frac{dT}{dx} = 0, \qquad (10)$$

where $\chi = \frac{jc_p}{\lambda}$.

Equation (10) has the following solution:

$$T = c_1 e^{\chi_{\text{ч}}} + c_2. \qquad (11)$$

Taking into account boundary conditions:

$T = T_0$ at $x=0$

$T = T_1$ at $x=\delta$

equation (11) gives

$$c_1 = \frac{T_1 - T_0}{e^{\chi_\delta} - 1}; \quad c_2 = T_0 - \frac{T_1 - T_0}{e^{\chi\delta} - 1}. \qquad (12)$$

Then equation (11) takes the form

$$T = T_0 + \frac{T_1 - T_0}{e^{\chi\delta} - 1}\left(e^{\chi x} - 1\right). \qquad (13)$$

The temperature distribution profile inside the plate, according to equation (13), is plotted in Fig. 1. The amount of heat transferred through the plate with air reaching the human body can be calculated using the equation

$$q' = -\lambda \left.\frac{dT}{dx}\right|_{x=0} = -\frac{\lambda}{\delta}\left(T_1 - T_0\right)\frac{\chi\delta}{e^{\chi\delta} - 1} = \frac{\Delta T}{R_T^*}, \qquad (14)$$

where $R_T^* = \frac{\delta}{\lambda}\frac{e^{\chi\delta} - 1}{\chi_\delta}$ is thermal resistance of a plate with active thermal protection.

Comparison of this expression with the equation (5) that describes the normal thermal conductivity of the plate allows evaluating the effectiveness of proposed approach to thermal protection [14]. In the latter case, the thermal resistance of the plate increases by a factor of n:

$$n = \frac{R_T^*}{R_T} = \frac{e^{\chi\delta} - 1}{\chi_\delta}, \qquad (15)$$

Parameter n can be called the coefficient of active thermal protection efficiency (Fig. 2).

However, despite the obvious advantages of ventilation systems (relative plainness of design and the possibility of using air from industrial enterprises' systems; providing oxygen supply to humans; sufficient psychophysiological suitability for humans; the possibility of high perspiration efficiency; the ability to remove toxins (anthropotoxins) from the interior volume), convective protection systems have a number of certain drawbacks. These include: insufficient overall protection against extremely high heat; the possibility of pain at extreme air temperatures and increased air velocity; significant contribution to overall water loss. This necessitates the development of heat-protective clothing with other means of active heat protection under various environmental conditions.

Thus, the study showed the need to develop and implement a physical model for the design of protective workwear with active thermal protection, as well as to suggest approaches to the design of clothing with active thermal protection not only by convective, but also by conductive and combined ways of heat removal, and removal of metabolic products from the interior volume. We will consider these issues in further research.

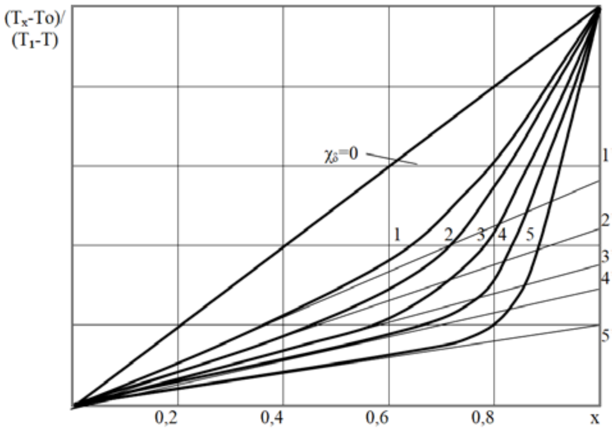

Fig. 1. **Dependence of plate temperature T on parameter χ_δ (0' – 5' – tangents to temperature curves 0 – 5)**

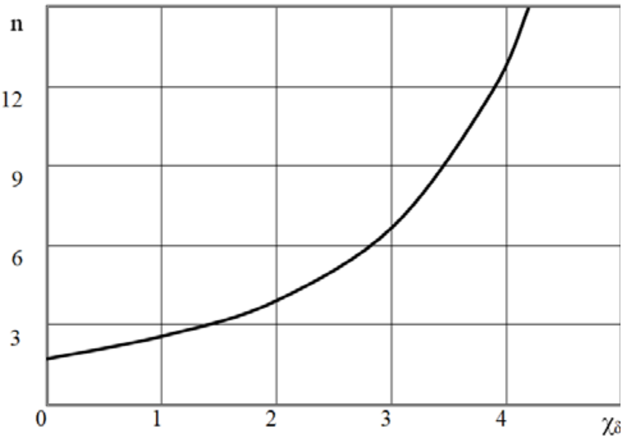

Fig. 2. **Dependence of active thermal protection efficiency coefficient on parameter χ_δ**

Conclusions. The presented study scientifically proved the concept regarding the implementation of the principle of combining passive and active protection in the development of effective means of individual protection against extreme temperatures. It is shown that the use of passive thermal protection at extremely high temperatures does not provide the ergonomic performance of new types of clothing, so the use of active thermal protection systems is required. It is proven that the development of passive protection needs the implementation of the concepts of multilayeredness, multifunctionality, and interdependence of individual layers of the composite material packet. A classification of materials is developed based on the production and composition of raw materials used for the manufacture of special thermal-protective clothing. The author's nanostructured innovative textile material is proposed for the design of thermal-protective clothing, which contains a lining layer with silver nanoparticles and combines the concepts of passive and active thermal protection.

The main directions of research in the development of modern structural and functional materials for the design of thermal-protective workwear are identified. The international research is expected to lead to the following results: the development of the gradient coatings based on nanocomposites with effective protection of seams and products from external factors; the development of thermal-resistant and thermally stable carbon materials, including those modified with nanoparticles, ultra-lightweight foamed materials, fibrous thermal insulation, shielding and thermal insulation materials, etc., as well as disposable thermal-protective coatings with a low thermal conductivity ceramic layer and composite barrier layers.

Based on heat and mass transfer theory, assuming accepted hypotheses, boundary conditions, and assumptions, the problem of temperature distribution inside a layered composite packet during convective heat removal is solved for the first time. The equations obtained make it possible to determine the amount of heat reaching the human body, as well as to determine the coefficient of thermal protection efficiency during convective heat transfer. The relationships between parameters and dependencies of the thermal protection system in a clothing with an autonomous convective life support under conditions of various material packets are obtained. This allows predicting the time of protective action of a thermal-protective workwear at the pre-design stage and improving the ergonomic performance of the clothing.

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