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Peculiarities of Nanostructured Fabrics for Operation Under Thermal Impact

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The article considers the urgent issue of developing protective clothing for work in adverse conditions during ultra-high heat exposure. As found, the heat-protective military clothing insufficiently provides the necessary preservation and impedes the calculation of the maximum effective time of protective action under severe operating conditions. As shown, the nanotechnology in the creation of modern textile materials tends to grow in accessibility from the economic and technological point of view. Therefore, new capabilities have emerged for modelling technological processes carried out at the nanoscale level. The advancement of this area is fostered by the growing demand for the latest materials with fundamentally new properties. This up-to-date approach is being applied and further developed in the research laboratories of the Kyiv National University of Technologies and Design. As confirmed, in multilayer clothing, the amount of air layers between individual layers of materials is insignificant. In addition, the amount of air layers in the garment package, rather than in the package of materials of the corresponding garment components, is found to be more significant. This is the factor being relied upon in the development of complex types of overalls for critical applications. Design and practical approaches to the creation of effective thermal protective packages applying modern textile materials of the 'advanced textiles' class are proposed in order to reveal the possibilities of creating critical components and elements of clothing as a starting point for the development of types of heat-protective clothing.

Розглянуто актуальну проблему проєктування захисного одягу для робіт у несприятливих умовах під час надвисокого теплового впливу. Виявлено, що теплозахисний спецодяг військового призначення неповною мірою забезпечує необхідне збереження й ускладнює визначення гранично допустного часу захисної дії згідно з важкими умовами експлуатації. Показано, що нанотехнології у створенні сучасних текстильних матеріялів стають нині все більш доступними з економічного та технологічного погляду. Тому з'явилися нові можливості моделювання технологічних процесів, які відбуваються на наномасштабному рівні. Розвиток цього напряму визначається зростаючим попитом на новітні матеріяли з принципово новими властивостями. Такий сучасний підхід застосовується та розробляється у наукових лабораторіях Київського національного університету технологій та дизайну. Доведено, що в багатошаровому одязі величина прошарків повітря між окремими шарами матеріялів є незначною. Виявлено, що в пакеті одягу, та не в пакеті матеріялів відповідних вузлів одягу величина повітряних прошарків більш значуща. Такий ефект використовується для створення складних видів спецодягу відповідального призначення. Запропоновано проєктно-практичні підходи щодо створення ефективних теплозахисних пакетів із застосуванням сучасних текстильних матеріялів класу 'advanced textiles' з метою виявлення можливостей проєктування критичних вузлів і елементів одягу як підґрунтя розробки різновидів теплозахисного одягу.

Key words: clothing design, thermal protection of a human, heat-protective clothing for special purposes, textile barrier materials, multilayer protective clothing, thermal protection characteristics of materials, heat-protective costumes.

Ключові слова: проєктування одягу, тепловий захист людини, теплозахисний одяг спеціяльного призначення, текстильні бар'єрні матеріяли, багатошаровий захисний одяг, теплозахисні характеристики матеріялів, костюми теплозахисні.

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1. INTRODUCTION

As a primary objective of the innovation development in the creation of protective clothing, the implementation of the latest technologies and production facilities is crucial to ensure the entry into modern high-tech markets. The transition of design and production processes is aimed at fundamentally enhancing the protecting properties of human protective equipment for work in adverse environmental conditions. This mechanism requires subsequent advancement of scientific, technical and innovation policy to promote the quality and competitiveness of the final product. With this range of objectives outlined, the relevance of the present study is determined. The selected approach is distinguished by a higher complexity and depth of the functional concept of previous studies by the authors of the scientific school of ergonomics and design of special-purpose clothing. Of importance is the analysis of the nature and context of real production operations in relation to human work in conditions of high temperature exposure and other extreme hazardous factors of an aggressive environment.

The work of a human in conditions of advanced temperatures may only be enabled by the use of heat-protective special clothing (HPSC). In the current scientific environment, the development of effective heat-protective clothing is an urgent matter, the complexity of which is conditioned by the multi-parametric nature of the tasks of designing, manufacturing and operating the clothing. Of particular urgency is the challenge of creating an effective HPSC designed to protect a human from the effects of a combination of thermal factors—thermal radiation, high air temperature, flame, and contact with heated objects. Consequently, human work in a variety of environmental conditions and temperatures necessitates scientifically based approaches to the development of special heat-protective clothing. This requirement holds especial relevance in conditions that dramatically deviate from normal and are approximating extreme levels, which places a major responsibility on the developers of protective clothing in terms of reducing production injuries and fatalities during traditional and emergency rescue operations of varying severity.

It is suggested that the sets of special protective clothing currently in service in Ukraine and abroad for traditional and emergency rescue operations be divided into two groups depending on the type of work. As for conventional work in the oil and gas industry, the following lightweight protective suits are used: jackets and trousers (or semi-coveralls), coveralls of various types, as well as overalls of known global brands AVER (Germany), TWIMAN-TEMPLETON&CO (USA), DU PONT (USA), *etc*. In case of minor outbreaks of fire, insulating lightweight costumes or coveralls, as well as overalls by AVER, EXGALOR (Germany), DU PONT (USA), COMASEC (France), *etc.* are used for carrying out repair work [1].

The variety of types and operating conditions of special protective clothing implies that the clothing developer is aware of physiological and hygienic standards, when selecting the entire set of equipment, as well as takes into account the organism's functional reactivity to external factors. Operational experience with heat-protective clothing illustrates not only does it not fully provide the necessary protection, but in some cases it causes additional thermal dangers. This effect is caused by the thermal failure and flashover of the constituent materials. The reason for this stems from insufficient research on the resistance of HPSC materials to thermal factors caused by the limited laboratory and experimental basis, which inevitably leads to a difficulty in determining the maximum effective time of protective action of heat-protective clothing under specific operating conditions.

Lately, nanotechnology has grown into a more accessible medium from an economic and technical point of view. Now, it appears possible to model processes running at the nanoscale. Such a tendency is stimulated by the ever-growing demand for the latest materials with fundamentally new properties. It is the development of nanomaterials with new thermophysical properties that is an all-purpose solution to many problems in the light industry. The convergence of nano-, info-, bio-, and cognitive technologies may serve in the prospect as a key to prolonging the active stage of human functioning. The identified areas direct the level of future technologies, which are often associated with the creation of hybrid structures capable of combining and connecting organic fragments with inorganic ones or living tissues with synthetic components. The modern technologies mentioned above may impart new properties in the development of materials with primarily unique strength, elasticity, thermal conductivity (thermal protection), and significantly accelerate the search for new ecological systems with advantageous properties [2–5].

The aim of the work is to study the process of heat transfer through a protective package of materials in a passive mode of protection, as well as to determine the temperature of the subjoint space and the time of protective action of the sets to solve the problems of developing varieties of heat-protective clothing.

The specificity of developing heat-protective clothing depends on the modes and parameters of thermal load during operation and is characterized by a passive or active degree of protection. According to the ergothermic load of a human, when working in personal protective equipment (PPE), as well as the thermal resistance of the package, which is determined by the combination of materials to provide barrier multifunctional heat protection, the main characteristic of a human's comfortable state remains the temperature of the subjoint space.

2. MATERIALS AND METHODS OF RESEARCH

At the end of the twentieth and beginning of the twenty-first century, there was a significant expansion of the production of various technical and environmental materials (eco-, agro-, geo-, and construction textiles, *etc.*), along with materials for clothing with special properties: heat-protective, heat-repellent, antistatic, electrically conductive, antibacterial, sorptive, waterproof, *etc.* [5–9]. They have a corresponding application in specific types of clothing (protective, medical, sportswear, *etc.*). Such materials, as a rule, demonstrate several properties and can be used as separate layers of clothing and underwear, as well as, in a layered form in certain clothing packages in accordance with the zonal placement on different parts of the human body, generating barrier multifunctional protection. As intended, diverse properties of such multifunctional materials may be obtained by mixing fibres with a variety of properties; modifying textile materials and their surfaces; creating multilayer materials, *etc*.

Over the years, the Kyiv National University of Technologies and Design (KNUTD) has pursued research into the development of new types of protective clothing and textile materials for their manufacture and industrial production. With the use of KNUTD laboratory equipment, a technology for obtaining materials based on a thermoplastic polymer composition modified with Ag, Cu, and Fe nanoparticles by depositing the molten mass of metal nanodispersion on the low-melting surface of a polypropylene granule was established [1, 10–14]. Such barrier materials enable the creation of clothing with predictable protective properties by combining layers of materials into packages, according to the zoning of the clothing surface and the properties of each material. When designing personal protective equipment, taking into account environmental conditions and human capabilities, the process of selecting the initial parameters results in a compromise optimization of the life support system. The protective role of clothing increases particularly in cases of extreme external exposure (temperature 35–40°C and above) and when the natural thermoregulation system is unable to maintain thermal homeostasis at a given level [1, 10–11, 15].

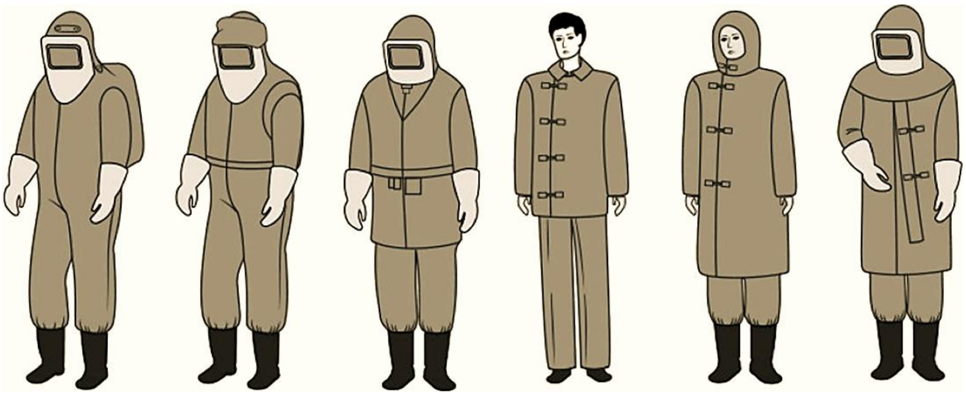
Therefore, today brings about the emergence of new types of lightweight, durable composite materials for a wide range of applications, including materials for insulating clothing for various purposes, sportswear and paraphernalia, as well as medical products. The use of biomimetic nanomaterials and materials for medical purposes, in particular for personal protective equipment, various auxiliary tools, face protection masks, surgical implants, sets the stage for ensuring the high level of human safety in extreme environmental conditions, and for high-quality and effective medical care in case of emergencies [2, 15–19].

Nanotechnology enables the creation of new systems for visualizing the surface of materials with high accuracy. The development and use of the latest materials and nanotechnologies is the main driving force behind the modernization and advancement of production, infrastructure, and the social sphere. Another breakthrough is the spread of self-assembly production technologies; namely, the so-called 'desktop nanofactory' is capable of producing certain products with molecular precision and in a short time [20–22]. Intelligent functional structural materials with high strength, ductility, lightness, transparency, and reflectivity substitute metals and plastic compositions these days, possessing an increased ability to improve the technical properties of products: resistance to radiation and corrosion, high and low temperature effects, material ageing, *etc*. Challenges in this regard include a deficiency of modern scientific and industrial equipment for the development of new materials based on nanotechnology and the production of nanoproducts for various purposes; a shortage of high-quality domestic raw materials; a demand for qualified personnel; competition in the markets; and the need for substantial investments in organizing large-scale production of significant volumes. Promising markets to focus on are textiles and leather goods, medical equipment and medical supplies. The methodology of theoretical research is grounded in the basic provisions of the theory of heat and mass transfer, and in the fundamental principles of the theory of thermoelasticity of shells and plates.

3. DISCUSSION

Heat-resistant nanostructured composite, ceramic, and metal materials prove vastly beneficial in many industries due to their resistance to chemical decomposition at elevated temperatures. It is materials with such properties that should not only be used in various types of PPE, but also to protect humans from ultra-high heat, which are up to now on the list of most demanded in the manufacture of reliable products. It should be noted that the main contribution to thermal protection of a human is made by such groups of PPE as special clothing and insulating costumes, which are types of protective overalls (Fig. 1). Such PPE operates under conditions of various thermal effects and degrees of protection corresponding to the operating conditions [1, 16, 22–25], making it necessary to study the peculiarities of heat transfer in the subjoint space packages for the purpose of their qualitative development and design.

The presented varieties of heat-protective clothing indicate that the generalized classification of costumes is lightweight and insulating, and that they meet the standards and specifications for PPE. Lightweight protective clothing is of high mass and is made of



a *b* *c* *d* *e* *f*

Fig. 1. Varieties of heat-protective costumes, coveralls, insulating sets of special clothing.

thick materials of high surface density. Insulating suits that function as emergency protection against extremely high temperatures are of even more mass, which puts an additional strain on the human and requires careful study of the composition of materials and their thermal protection characteristics for specific clothing design conditions.

Overalls are known to represent an approximate three-dimensional shape of the human body, formed by connecting individual cut parts using various (primarily threaded) joints. Overalls can be single-layer; however, complex, multilayer, multicomponent overalls are more commonly used [1, 16–18, 22].

In multilayer clothing, the amount of air layers between individual layers of materials is insignificant, due to these layers being bonded to each other at the edges and in the middle areas of the clothing. Between individual types of overalls, in the so-called garment package (rather than in the package of materials), the amount of air interlayers is more significant. This factor is the primary driver in the creation of sophisticated overalls for critical applications. Their size depends on the allowances for a loose fit, which for overalls range from 1.5 to 2.0 cm. While this means that the size of air interlayers between the layers of clothing is the same, it is certain that an increase in allowances contributes to an increase in air interlayers in clothing.

The intricate shape of the human body, and the way it performs certain movements, leads to a considerable imbalance of air layers in the package of a set of overalls. The high thermal insulation properties of air in an inert state necessitate considering it when determining the total thermal insulation properties of clothing.

It is known that the thermal insulation of the human body for the account of clothing is expressed by the value of the average total thermal resistance. For a package of overall materials, the equation is as follows [1, 12, 23, 25]:

$$R_{sum} = \sum_{1}^{n} \frac{\overline{\delta}_{air}}{\lambda_{v}} + \sum_{1}^{m} \frac{\overline{\delta}_{f}}{\lambda_{f}} + \frac{1}{\alpha}, \tag{1}$$

where $\sum_{1}^{n} \overline{\delta}_{air}/\lambda_{air}$ is the sum of thermal resistances of n air layers in the clothing; $\sum_{1}^{m} \overline{\delta}_{f}/\lambda_{f}$ is the sum of thermal resistances of m layers of fabric in the clothing; $1/\alpha$ is heat transfer coefficient; λ_{air} is air thermal conductivity coefficient; λ_{f} is thermal conductivity coefficient of the fabric; δ_{air} is the average measured thickness of the air interlayer between the layers of materials, as well as between the linen and human skin; δ_{f} is the average measured thickness of the materials.

All the terms of the sum of Eq. (1) are variable values. The first two of them determine the average equivalent resistance and depend on the constructive structure of the clothing, the last one, namely, surface thermal resistance, is largely determined by the resistance of the environment, each of which is to be considered.

The thermal resistance of air layers in clothing varies with their thickness and thermal conductivity. Maximum thermal insulation is achieved through the inertness of air, *i.e.*, when heat is transferred by conduction. Air stillness is feasible in narrow layers not exceeding 1.27 cm [24]. For this reason, air layers in overalls above this value are impractical. Since 1.27 cm is the maximum value, the largest average air interlayer should strive to a lower value. Given that a set of clothes consists of several items that a human wears in layers, starting with underwear, there is natural pressure from the outer layers on the inner ones. This reduces the size of air layers in a set of clothes in correspondence with certain indicators of the elastic properties of fabrics and construction details.

The air inertness generated by sequentially applying the clothing items depends not only on the size of the air layers: movement patterns, gait, and working postures change the size of the air layers of the clothing. In addition to heat transfer by conduction, a convective component occurs, as a result of which the thermal conductivity of the air increases with the thermal resistance of the air layers decreasing, thereby reducing the thermal resistance of the entire set of overalls. Meanwhile, the circulation of air inside the clothing during human movement is by no means a disadvantage:

rather, it is even advisable, since human movements are accompanied by increased heat generation and automatic reduction of the total thermal resistance of clothing is required to maintain comfortable conditions in the sub-joint space. This is not the case, when, due to the presence of openings in the clothing, as well as the breathability of materials and seams, outside air enters the sub-joint space. In this regard, the convective component of the air in the layers rises with the increase in air velocity quite significantly, resulting in a dramatic decrease in the total thermal resistance of the clothing. Consequently, when developing protective clothing, it is imperative to take into account the variability of the total thermal resistance of its air layers. To maintain comfort conditions when a human moves, natural air circulation should be sustained by increasing air layers in clothing. At the same time, it is necessary to prevent air from entering the clothing, for which purpose blind fasteners, sealed joints of parts, and the application of air-resistant materials or substrates are advisable.

A similar nature is the variability of the total thermal resistance of materials in a clothing package depending on the nature of the fibre. The fibre composition of materials determines the thermal protection properties of fabrics, *i.e.*, the ability to keep air in a stationary state well or poorly. The amount of air contained in a material depends on the thickness, porosity and volumetric content of the material. The requirements for materials, as well as their ergonomics, allow us to determine with sufficient accuracy the total thermal resistance of the combination of materials included in the clothing package. Nonetheless, the diversity of requirements is unlikely to lead to a substantial increase of this value. Therefore, for the purpose of designing overalls with high heat protection performance, a prominent role is played by nonwoven insulating materials (substracts), the insulating properties of which are largely determined by their thickness and significant porosity. The softness and flexibility of these materials enables the designed shape of overalls to be shaped into any constructive structure. However, to maintain high heat protection properties, insulating membranes shall have good elastic properties, since the thermal insulation properties diminish with decreasing thickness.

The most critical component of the packages' thermal insulation properties belongs to the top material, the main purpose of which is to protect the entire set from the main aggressive environmental factor. But, under any combination of aggressive factors, one cannot neglect the changeability of the heat transfer coefficient due to the presence of the so-called 'boundary layer' of air at the interface between the outer surface of the clothing and the environment, further increasing the total thermal resistance. In Eq. (1), this is taken into account by the third term.

Among the numerous parameters that affect the value of the heat transfer coefficient, the most influential for overalls are the constructive shape of the clothing (surface curvature factor) and air velocity. Considering that the human body is a complex spatial shape, clothing is unable to copy it in exact form, *i.e.*, it reflects the curvature factor to a high extent, but in a steadier form, especially in matters of the average heat transfer coefficient over the entire surface of the overalls.

As such, knowing the air velocity and assuming the clothing as a flat parallel plate or cylinder with a diameter of 0.18 m, the convective-conductive component of the heat transfer coefficient may be calculated by the theory of similarity. The radiation component of the heat transfer coefficient is a function of the temperature of the objects surrounding the human and the radiation constant of the outer fabric. The higher the equivalent resistance of the clothing, the more its surface temperature approximates the ambient air temperature, the smaller the temperature difference and the lesser the heat transfer by radiation. Therefore, when designing overalls, consideration should be given to the value of the surface thermal resistance of clothing and its variability, similar to thermal resistance.

The analysis of the components of Eq. (1) in relation to a set of protective clothing on a human indicates the complexity of the heat transfer process in the human-environment system, taking into account the constructive specifics of the clothing structure. The solution of the stated tasks appears to be possible when conducting an array of theoretical studies and their experimental confirmation, calculating the time of the protective effect of the set in order to predict the behaviour of types of heat-protective clothing, as well as keeping in view its constructive and technological level for specific situations and searching for unified models of design solutions.

Summarizing, the paper outlines the directions of basic research addressing the problem of developing heat-protective clothing to determine heat loss of the body and human comfort zones in heat-protective clothing, heat-protective properties of materials and thermal insulation membranes, thermal protective properties of material packages and clothing in general. The first group of issues is within the competence of hygienists, without whom no research on protective clothing and further advancement of this area is practicable. Long-term cooperation between the authors and physiologists and hygienists led to the successful completion of the tasks [1, 12–14, 16–19]. Other areas require separate studies of the heat protection properties of fabrics and membranes, which is the key objective in accordance with the aim of the present work. It is associated with the disclosure of the mechanisms of the immobilizing properties of textile materials, which should allow establishing rational values of their thickness, porosity, volumetric content, and elasticity. The results obtained allow us to proceed to a reasonable selection of materials and membranes to address the issues of designing overalls with specific heat-protective properties and calculating the time spent by humans working in adverse environmental conditions.

In calculating the effectiveness of human protection against thermal effects using a composition of layers of clothing materials, a stationary thermal regime is assumed. However, under the influence of powerful radiation fluxes and high atmospheric temperatures, in the course of clothing operation, it is necessary to take into account a significantly non-stationary thermal regime. The conventional methods of estimating heat-protective clothing in stationary training with a relatively short time of its stable operation may lead to major errors [12–14, 25]. For this reason, approaches have been developed to establish a mathematical model of nonstationary heat transfer through a multilayer set of clothing to the human body and an instrumentation base has been set up [17–19, 26–28].

The heat-protective clothing package is represented as a system of flat plates that may be separated by gas-air layers (Fig. 2).

For the sake of simplicity, suppose we neglect the effect of the steam flow formed by the evaporation of sweat and air from the surface of the human body on heat transfer through a set of clothes, since the influence of these flows is negligible.

The heat transfer in the i-th layer of clothing, $i = 1, 2, \ldots, j$, is described by the acclaimed Fourier–Kirchhoff heat-transfer equation:

$$c_i \rho_i \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda_i \frac{\partial T}{\partial x}\right), \tag{2}$$

where c_i, ρ_i, λ_i are the heat capacity, density and thermal conductivity of the i-th layer of clothing, which can be functions of the coordinate x, time τ and temperature T.

Should there be no gas-air space between the layers i and $i+1$, the thermal interaction between these layers is characterized by heat transfer conditions of the fourth grade at the boundary of their contact $x = x_{i+1}$:

$$\begin{cases} \lambda_i \dfrac{dT(x_{i+1} - 0, \tau)}{dx} = \lambda_{i+1} \dfrac{dT(x_{i+1} + 0, \tau)}{dx}, \\ T(x_{i+1} - 0, \tau) = T(x_{i+1} + 0, t), \end{cases} \tag{3}$$

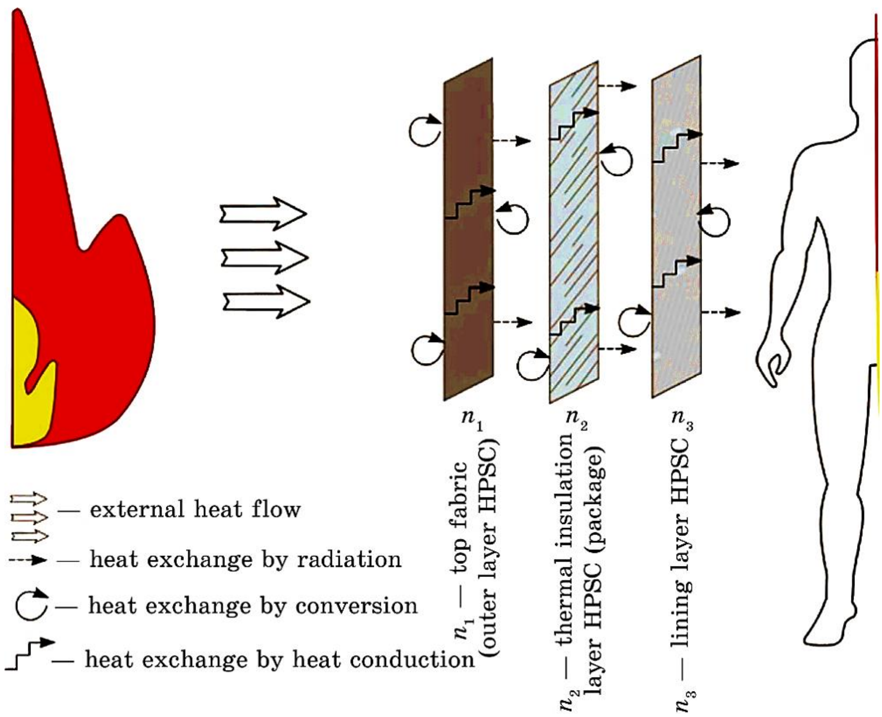


Fig. 2. Physical model of heat transfer through a package of materials of protective clothing.

where $T(x_{i+1}-0,\tau)$ and $T(x_{i+1}+0,\tau)$ are the limits of the temperature function T, when, at a constant time τ, point x proceeds to the point $x = x_{i+1}$, remaining in the clothing layer, respectively, i and $i+1$.

The heat transfer through a unit surface of the gas-air layer i, which has a thickness δ_i, is defined as

$$q_i = \frac{\lambda_f}{\delta_i}\left[T(x_{1+1},\tau) - T(x_i,\tau)\right] + \bar{\varepsilon}_i\sigma_0\left[\left(\frac{T(x_{i+1},\tau)}{100}\right)^4 - \left(\frac{T(x_i,\tau)}{100}\right)^4\right], \quad (4)$$

where σ_0 is the radiation coefficient of an absolutely black body; $\bar{\varepsilon}$ is the given degree of blackness of the gas-air layer, which is determined by the values of the degrees ε_i and ε_{i+1} layers of the clothing i and $i+1$, by the ratio:

$$\bar{\varepsilon}_i = 1/\left(\varepsilon_i^{-1} + \varepsilon_{i+1}^{-1} - 1\right),$$

λ_v is thermal conductivity of air, referred to the medium temperature of the layer:

$$T_i = \frac{\left[T\left(x_{i+1}, \tau\right) + T\left(x_i, \tau\right)\right]}{2}.$$

Pursuant to Eq. (5), for the conditions of complex heat transfer and clarity of the process description, it is convenient to introduce the effective thermal conductivity coefficient λ_{eff}, which is determined in accordance with the expression $q_i = \lambda_{eff_i}\delta_i^{-1}\left[T\left(x_{i+1}, \tau\right) - T\left(x_i, \tau\right)\right]$, and is obtained by the relationship

$$\lambda_{eff,i+1} = \lambda_f + \frac{\bar{\varepsilon}\sigma_0\delta}{T\left(x_{i+1}, \tau\right) - T\left(x_i, \tau\right)}\left[\left(\frac{T\left(x_{i+1}\right) + 0, \tau}{100}\right)^{-4} - \left(\frac{T\left(x_{i+1} - 0, \tau\right)}{100}\right)^{-4}\right]. \tag{5}$$

Air layers have a significant impact on the heat protection properties of clothing. It is common for the total thermal resistance of air layers to surpass that of the clothing layer composition. Depending on the composition of the clothing set, the total thermal resistance of the air layers may be several times greater (or less) than the thermal resistance of the clothing materials. With that said, the thickness of air layers for a set of household clothing is practically within 4–7 mm. Therefore, to determine the temperature $T_2(\tau)$ on the inner surface of the clothing separated from the body by an air layer ($i = 1$), an equation akin to Eq. (5) may be implemented:

$$q_T = \frac{\lambda_f}{\delta_1}\left(T_2 - T_1\right) + \bar{\varepsilon}_1\sigma_0\left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4\right]. \tag{6}$$

To meet the many and often contradictory requirements of consumers, it is essential that multifunctional textile materials be developed. Such consumer requirements are an impetus for researchers and textile manufacturers. The analysis of scientific and patent literature has revealed a consistent interest in the development of multifunctional textile materials [29–31].

With a large number of modern textile materials, referred to as advanced textiles, which are classified as high-tech and possess various physical, mechanical and thermal protection properties, it may be assumed that the method of layering (or joining) individual textile products into one structure enables the technical properties of textile composite materials to be adjusted within a wide range to ensure thermophysiological comfort. The mentioned works have been identified as promising for many years and have been successfully implemented in the research of the Kyiv National University of Technologies and Design [1, 22, 32–33]. The most basic methods of obtaining multifunctional textiles (mixing fibres, modifying yarns, modifying the structure and surface of textile fabrics) are of limited potential. The transition to complex layered composite textile structures opens up wide opportunities for product manufacturing. Such structures should consist of different functional layers arranged in the right order. In recent years, global developments in this area have received a high priority: they are directly related to the creation of Intelligent Textiles and Smart Textiles—advanced and innovative textile materials.

4. CONCLUSIONS

It has been shown that the study of the heat-protective properties of clothing packages implies the issue of rational arrangement and alternation of materials with proven physical properties to obtain the optimal thermal insulation effect. It has been established that environmental factors and air layers of clothing material packages exert a significant influence. The composition of the material packages was calculated and determined, and the selection of physical models for the design of heat-protective clothing sets was substantiated. For the first time, a mathematical model of unsteady heat transfer through a multilayer set of heat-protective clothing was presented as a system of flat plates distributed by gas layers. Due to the air mobility, the model is considered for the case of flow around a circular cylinder under the influence of incoming air with a natural degree of flow tubulisation. The analytical equations for determining the temperatures on the inner surface of clothing, which is separated from the body by a clothing package and air layers, are obtained.

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