Development of Methods for Assessing the Operational Effectiveness of Sets of Personal Protective Equipment for Fighters and Rescue Units

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Abstract. The article discusses modern approaches to the design of special clothing for the technical support of rescue operations. Some problems of using modern thermoregulating textile materials have been analyzed. The author's method of estimating heat and mass transfer in packages of textile materials is considered, some research results are presented.

1. Introduction. The composition of the technical support of rescue operations includes sets of personal protective equipment for fighters, the formation of which must take into account the requirements for the level of ergonomic properties. Among them is the ability to protect the human body during changing cooling effect. Introducing products with “active” heat-shielding properties into a clothing set can meet this requirement [15]. Clothing with “active” heat-shielding properties is developed based on smart thermoregulating textiles. Such materials change their hygroscopicity and total thermal resistance during changes of intensity of the cooling effect of the environment due to the introduction nano-fillers or electronic components into fibers structure [13].

Nano-fillers of modern textile canvases are introduced into the structure of fibers. With a decrease in the cooling effect, these fillers melt, absorbing the heat corresponding to the phase transition, and when cooled, they polymerize, releasing the previously accumulated heat. Figure 1 shows the cut of the fiber “Outlast” with heat-accumulating fillers thermocules [1].

![Figure 1 - Fiber with nano-filler for thermostatic material](image-url)
When using textile materials with electronic components, in the structure of a set of clothes, the transmission of signals and thermal energy is carried out. Integrated microcircuits into the structure of the canvas measure the parameters of microclimate under clothes and, if necessary, transmit control signals to the electronic heating components, thereby adjusting the parameters of the microclimate under clothes [2].

For the introduction of conductive elements into the structure of the textile package were proposed (Figure 2):
- methods of applying conductors to the surface of the fibers (figure 2 a) [5, 8, 16];
- methods for integrating conductors into the structure of yarns (Figure 2b, 2c) [11];
- methods of integrating conductors into the structure of textiles (figure 2 g) [2, 4, 6, 10-12].

![Figure 2](image)

Figure 2 – Modern methods of creating textiles with portable electronics

On the basis of numerous “temperature-controlled” materials, clothing systems are created, which consisted of a limited number of products that can be worn by a person in different sequences. Replacing one product in a set with another allows you to significantly change the properties of the entire set of personal protective equipment. Thus, a limited set of products allows you to create a set of special clothes for the effective protection of a fighter in various climatic conditions.

This approach became widespread in the development of numerous systems of materials, in particular, the Extended Cold Weather Clothing System III (ECWS) for the US Army, which is based on a large amount of physiological research. By summarizing their results, specialists have developed fairly simple and intuitive graphic diagrams illustrating the principles of the formation of clothing sets depending on the degree of physical activity and operational features. An example of such a scheme is shown on Figure 3.

The development of such schemes for the creating personal protective equipment for fighters of rescue units is an urgent task. However, taking into account the specifics of the rescuers’ tasks, the mechanical transfer of recommendations developed for the ECWS material system can lead to serious design errors. The use of sufficiently laborious and costly methods of physiological research in this case is also not difficult. The selection of a system of materials, as well as the development of recommendations for their acquisition are based on the results of experimental studies. In this regard, the urgent task is to develop adequate and affordable methods for studying the operational effectiveness
of textile package, including “thermostatically controlled”, for personal protective equipment for emergency rescue equipment.

Experience shows, the tasks of forming sets of clothing for rescuers are often solved using television and calorimetric methods of research [9, 10]. The result of such studies are: the distribution of the temperature field on the surface of a set of clothes or indirect parameters, such as the TRF-indicator of the quality of materials. For example, the distribution of the temperature field on the surface of a set of traditional and modern materials is presented on Figure 4 [9].

Figure 3 – An example of a graphic scheme with recommendations for the formation a set of clothes based on the ECWS material system

Figure 4 – Some results of television studies of the surface of sleeves made of traditional and thermoregulatory textile

The main disadvantage of these and similar methods is the impossibility of a quantitative assessment of the dynamics of the temperature field and heat flows in the structure and on the surface of clothing packages.

2. Formulation of the problem. An urgent task during designing of personal protective equipment for fighters of special units is the development of methods for the experimental evaluation of the operational effectiveness of sets of clothes with inner thermal regulatory control, which should:

- ensure the possibility of accurate quantitative assessment of indicators of the properties of innovative materials;
allow to investigate the influence of the original properties of "thermostatic" materials on the operational efficiency of clothing;
- to ensure the replication of the test bench.

To date, a sufficient theoretical apparatus has been developed that makes it possible to develop methods for researching the thermal properties of innovative materials that meet these requirements.

3. Theoretical part. It is known that the human body can be approximated by a system of embedded cylinders. On the basis of this presentation, numerous models of thermal processes in the "man-clothing-environment" system have been proposed. For example in Figure 5, a shows the representation of the human body. To maintain the constancy of temperature the mechanisms for changing the level of heat production and sweating should be implemented in the body element.

The package of clothes in this case can be replaced by a set of nested cylindrical elements (Figure 5, b) [12]. Depending on the degree of freedom of the clothes, air gaps can form between the layers or the contact between the layers of clothing can be quite dense.

To study the processes of heat and mass transfer in a textile package, it is necessary to simulate the operating conditions under which heat and moisture flows are dispersed through the structure of a package of clothes into the environment. For this, the authors propose an experimental setup, presented in Figure 6.

The installation contains:
1. The physical model of the body element (Figure 6, a) in the form of a cylinder filled with water (pos. 1, Figure 6, b). Thermal control functions are implemented by an automated system (pos. 4, 5), which controls the temperature of the cylinder by means of a meter (pos. 2) and, if necessary, controls the operation of the electric heater (pos. 3);
2. Moisturizing device (Figure 6, c), which allows you to supply model moisture on the surface of the element of the human body.

During the experiment, the package of materials is located on the surface of the thermal model of segment of a human body (pos. 1, figure 6, d). A distributor (pos. 2) was installed at the upper end of the model, and an air intake (pos. 3) with temperature, velocity (pos. 4) and humidity (pos. 5) transducers were placed above it.

In the process of research, various conditions of heat and mass transfer are reproduced, which are observed in the “man-clothing-environment” system during rescue operations. The study is conducted during five phases, in each phase evaluates the dynamics of the heat flow density (Figure 7, a) and moisture flows (Figure 7, b) in the structure and on the surface of the textile package (Figure 7) [12].

In the first phase, the conditions of heat exchange of the body element with the environment are modeled with a moderate level of physical exertion, when the effect of sweat on the intensity of heat and mass transfer can be neglected. In the second phase, a sharp increase in physical exertion is reproduced, at which the device that moistens the package of materials due to sweat is activated. For this, moisture is supplied to the surface of the element of the human body. During this phase, the heat
flux density \( (q_{\text{pack}, \ W/m^2}) \) in the package and the value of its moisture content \( (u_{\text{pack}, \ g/g}) \) increase. Quantitative values of these parameters characterize the ability of a textile package to absorb moisture, while maintaining heat-shielding properties.

By the beginning of the third phase of the experiment, stabilization of heat and moisture fluxes in the structure of the package of materials is observed, which indicates their saturation.

In the fourth phase (drying phase) the moisturizing device is turned off, which simulates the conditions for reducing the physical load of the fighter. Under these conditions, an important indicator is the intensity of moisture removal from the structures of the textile package, which results in a decrease in the duration of the fourth phase of the experiment. By the beginning of the fifth phase of the experiment, the conditions of stationary heat exchange are restored. The dynamics of heat and moisture flows during the five phases of the experiment illustrates the intensity of heat and mass transfer processes in a textile package for heat-shielding clothing.

Figure 6 – The scheme of the experimental setup
The results obtained are compared with the parameters of human heat production when performing different work \( (q_{cell}, \text{W/m}^2) \). Discrepancies between the density of the heat flow in the textile package and heat production allows us to estimate the thermal state of a person under the conditions of operation.

Comparing the results obtained for textile packages, as well as these results with the data of physiological studies, you can make graphical diagrams illustrating recommendations for the formation of a set of clothes based on the chosen system of materials.

4. Some research results. Let us consider an example of results obtained for a textile package with “active” protective properties, including samples of “thermostatic” materials (Table 1). Now clothing based on this and similar variants of textile packages is used in the manufacture of clothing for outdoor activities at ambient temperatures of about \( t = +10 \degree \text{C} \).

The results of the research will be compared with similar results obtained for traditional textile packages used in the manufacture of special clothing for rescuers.

| Textile package’s layer | Type of fabric | Fiber composition | Density, g/m\(^2\) | Thickness, mm | Weave structure |
|------------------------|----------------|-------------------|-------------------|---------------|----------------|
| Underwear              | Woven fabric «Outlast» | 90% cotton         | 240               | 0.6           | Plain          |
| Interim layer          | Woven fabric «Polartech Power Dry» | 100% polyamide     | 360               | 2.4           | Purl-Stretched |
| Inner layer            | Fabric laminated to reactive polymer membrane | 100% polyester  | 430               | 0.45          | Rip-Stop       |

During conducting experimental studies, the conditions of human heat transfer were simulated with the following levels of physical activity:
- medium level: the value of human heat production \( q_{people} = 180 \text{ W/m}^2 \), sweating is absent;
- increased physical activity: human heat production \( q_{people} = 350 \div 500 \text{ W/m}^2 \), active sweating;
- decrease in physical activity: decrease in heat production to \( q_{cell} = 180 \text{ W/m}^2 \), cessation of sweating.

The results of the study are presented in Figure 8.
The heat flow curve in the material package structure according to Table 1

In the first phase of the experiment, the heat flux density in the textile package is $q_{1f} = 150 \, \text{W/m}^2$, which allows maintaining a person’s heat balance with an average level of physical activity. According to the results of preliminary studies, in the packages of traditional materials of similar configuration, the thickness and weight of which is higher, this indicator is $q_{1f} = 160 \div 190 \, \text{W/m}^2$. This testifies to the positive effect of “thermostatic” materials on the heat-shielding properties of clothing.

When moisture is absorbed in the second phase of the experiment to values $u = 2.3 \, \text{g/g}$, the heat flux density in the package of textile with “active” heat-shielding properties is $q_{2f} = 340 \, \text{W/m}^2$. In packages of traditional textiles of similar configuration, the value is $q_{2f} = 420 \div 450 \, \text{W/m}^2$. Thus, part of the heat expended in the evaporation of moisture in the structure of the textile package is compensated by nanofillers of the Outlast material. During the fourth phase of the experiment, in textile packages with active heat-shielding, a more intensive drying process is observed in comparison with packages of traditional textiles. In spite of this, the density of the heat flux in the structure of such packages is $15 \div 25 \%$ lower than in packages of traditional materials. The presented experimental data are consistent with known calculated results [3].

5. Conclusion. As can be seen, the author’s research method allows one to obtain comparative results characterized the influence of the original properties of new textile on the intensity of heat and mass transfer processes in the “man-clothing-environment” system. In the future, these results will allow to develop a system of materials, as well as recommendations on the formation of a set of clothes within the selected system.

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