Reducing the natural risk of the people working in the open area by clothing based on textile operating systems

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Abstract. The risk of a person’s hypothermia in the open area can be reduced by using heat-protective clothing based on textile operating systems. A method for studying unsteady heat and mass transfer in such clothes is proposed. Studies of heat and mass transfer processes in a package of traditional fabric materials and a textile operating system at an air temperature +5 °C were carried out. When doing light physical work, the efficiency of the packages is similar but the weight of the textile operating system is lower. When a human body is moistened by sweat, the textile operating system absorbs moisture better and removes it from the body, which improves the general condition of the person. With reduced physical activity the textile operating system restores the original heat-transfer properties quicker.

1. Introduction
Natural risks in most of the territory of the Russian Federation are formed, inter alia, under the influence of lowered air temperatures. Under these conditions the main means of ensuring human safety is special clothing. Thermal properties of traditional outfits do not always provide the necessary level of safety, especially when weather changes. The current level of human protection against hypothermia is associated with the use of clothing based on textile operating systems. Such a system is represented by a set of modern materials with original thermophysical effects.

2. Relevance of the problem
Clothing based on a textile operating system provides an optimal microclimate of the underclothing area when environmental conditions change [1]. For example, the Extended Cold Weather Clothing System of the US Army has shown high efficiency in Iraq, Afghanistan, the Arctic zone. The combination of thermophysical effects in the formation of textile operating systems is achieved by the targeted selection of its layers in the process of studying heat and mass transfer in the “man – clothing – environment” system [2]. Taking into account the complexity of heat and mass transfer in textile operating systems, the research is carried out in three stages.

At the first stage, the thermophysical properties of material samples are estimated using stationary heat flux devices [3-7]. Based on these data, making up a set of a textile operating system is carried out. At the second stage, the behavior of the textile operating system is studied under operating conditions; it allows us to assess the degree of formation of the original effects [8-11]. In most cases, the sensing element of the experimental setups has a flat shape. At the same time, the human body is
represented by a set of balls and cylinders. In some cases, it reduces the accuracy of the research results. Therefore, for the selection of a set of textile operating systems, mathematical models of human heat transfer can be used [12-14]. At the last stage, the effectiveness of the ready-made heat-protective clothing is examined by assessing the thermal state of the thermo mannequin, which is a thermal model of the human body [15-17].

3. Objective of the study

As follows from the analysis, the methods of the second group are the least developed. An urgent task is to study the behavior of textile operating systems in setups with a cylindrical or spherical shape of the sensing element, which conforms to the shape of the human body more than a flat element.

4. Theoretical part

4.1. Principle of Operation

We have developed an experimental setup for studying non-stationary heat and mass transfer in textile operating systems with a cylindrical sensing element. The principle of its operation is based on the concept of the heat exchange nature between a person and the environment, according to which the human body maintains a constant body temperature \( t_b \) different from the ambient temperature by \( \Delta t \). The value \( \Delta t \) can change over a short time when the heat transfer conditions in the system “man – clothing – environment” change, for example, due to fluctuations in weather conditions. The body element in the experimental setup is made in the form of a hollow cylinder (pos. 1, figure 1) with distilled water and equipped both with a temperature meter (pos. 5) and an electric heater (pos. 6). The temperature of the body element is set via PC (pos. 4) and is maintained by an automated system (pos. 3) by means of the electric heater control. The heat supplied is evenly distributed over the volume and surface of the cylinder, after which it is dissipated through the material package (pos. 2) into the environment. An automated system measures the density of the heat flux on the cylinder surface \( q_b \) spent on maintaining a constant body temperature. To study the processes of heat and mass transfer in a package of materials, an automated system examines temperature transducers (pos. 7) located between the layers. To study the heat transfer of a material package, the setup is equipped with an air flow concentrator (pos. 8), equipped with temperature and humidity sensors (pos. 9, 10). The setup is equipped with a simulation unit for sweating, which makes it possible to simulate the sweating of the material package by supplying model moisture between the element of the human body and the material package.

The basis of the setup is a thermal model of the human body element (figure 2). The shape and size of the model are selected by mathematical modeling. Figure 3 shows the distribution of the temperature field in the working volume of the setup during heating. The ambient temperature is \( t_{\text{inf}} = 5^\circ \text{C} \).

When doing hard physical work in cold weather, the intensity of sweat secretion is 140 g/h. Accumulating in clothing, moisture reduces heat-protective properties of the clothing set. When forming textile operating systems capable of removing moisture from under clothing, it is necessary to study the processes of heat and mass transfer. For this purpose the setup includes a humidification unit (figure 4) represented by: storage tank (pos. 7) on the bases (pos. 9, 14) fastened with screeds (pos. 15); liquid level meter (pos. 13). Appearance of a humidification unit for modeling sweating parameters is shown in the figure 5.

At low temperatures, heat and moisture given off by the human body form an upward convective flow (figure 6) [18]. A similar flow is formed on the surface of the model of the body element (figure 7). Knowing the parameters of the air in the flow, it is possible to calculate the intensity of the convective heat (1) and moisture loss (2) of a person. To analyze the total heat balance, the heat transfer rate of a person due to heat radiation can be calculated (3)
Figure 1. The scheme of the experimental complex for studying the processes of heat and mass transfer in the system "man - clothes - environment"

Figure 2. The body element in the experimental setup

Figure 3. Temperature field in the working volume of the setup during heating

Figure 4. Scheme of a humidification unit for modeling sweating parameters.

Figure 5. Appearance of a humidification unit for modeling sweating parameters.

\[ \alpha_{\text{conv}} = \frac{cR(T_{\text{con}} - T_{\text{inf}})}{2\pi(0.12 + h_s)(T_s - T_{\text{inf}})} \] (1)
\[ \alpha_{pm} = \frac{Rr(d_{con} - d_{inf})}{(T_s - T_{inf})} \]  

(2)

\[ \alpha_{em} = \frac{\varepsilon C_0 \left[ \left( \frac{T_s}{100} \right)^4 - \left( \frac{T_{inf}}{100} \right)^4 \right]}{2\pi(0,12 + h_s)(T_s - T_{inf})} \]  

(3)

where: c - specific heat of air; R - mass air flow; \( T_{con}, T_s, T_{inf} \) - temperature of air flow in the neck of the air intake, the sample surface and environment; r – specific heat of vaporization; \( h_s \) – the thickness of the test sample of materials; \( d_{con}, d_{inf} \) – moisture content of air in the neck of the air intake and environment; \( \varepsilon \) is the degree of blackness of the surface of the package; \( C_0 \) is the emissivity of a completely black body.

To do this, a concentrator is provided in the experimental setup (figure 8), in the throat of which (pos. 2) the sensors of temperature, speed and air humidity are placed (pos. 3).

Considering the size and shape of the human body element, the test samples are presented as a set of cylindrical shells 1 m high. The diameter of each layer is calculated based on the total thickness of the underlying layers. Samples are put on an element of the human body, after which the heat and moisture fluxes through their structure are measured, and the parameters of external heat transfer are studied.

**Figure 6.** Convective flow from the human body.  
**Figure 7.** Convective flow from the body element.  
**Figure 8.** Air flow concentrator.

### 4.2. Testing Method

When studying the effect of textile operating systems in the open air, in the course of the experiment, a set of environmental conditions and the load on the employee are modeled. In the first stage of the experiment, the operating mode of the setup is set, in which heat and mass transfer is reproduced under the considered state of the outdoor environment and light physical load of the worker. In the second phase of the experiment, the conditions for a sharp increase in the severity of the work are modeled. In the third phase of the experiment, the process of continuous heavy physical work is reproduced. In the fourth phase of the experiment, a sharp decrease in the intensity of the work performed and the cessation of sweating are reproduced. The fifth phase of the experiment characterizes a return to light physical work.
5. Results and Discussion

Let’s consider the results of studies of heat and mass transfer in the system “man – textile operating systems – environment” through some examples (table 1). Textile operating system 1 is composed of traditional materials, system 2 is based on modern materials with original thermophysical effects.

During the experiment, heat and mass transfer conditions were simulated at temperatures close to +5 °C. Figure 9 shows the heat flow dynamics curves illustrating the change in this indicator throughout the entire experiment. Figure 10 shows the dynamics of the heat transfer balance under different modes of heat and mass transfer in the system "man – clothing – environment".

| Layer      | Fabric Material Type | Fiber composition | Surface density, g/m² | Thickness, mm | Type of weaving                  |
|------------|----------------------|-------------------|-----------------------|---------------|----------------------------------|
| Linen      | Knitted fabric       | 100% cotton       | 240                   | 0.6           | Single jersey fabric             |
| Warming    | Knitted fabric       | 20% polyamide 80% wool fibers | 360                   | 2.4           | Single jersey patterned fabric   |
| Upper      | Fabric               | 60% cotton 40% polyester | 430                   | 0.45          | Twill fabric, ½                  |

| Layer      | Fabric Material Type | Fiber composition | Surface density, g/m² | Thickness, mm | Type of weaving                  |
|------------|----------------------|-------------------|-----------------------|---------------|----------------------------------|
| Linen      | Knitted fabric «Outlast» | 100% cotton  | 240                   | 0.6           | Single jersey patterned fabric   |
| Warming    | Knitted fabric «Polartech Power Dry» | 20% polyamide 80% wool fibers | 360                   | 2.4           | Single jersey fabric             |
| Upper      | Fabric «Pertex Endurance» | 60% cotton 40% polyester | 430                   | 0.45          | Twill fabric, ½                  |

Figures 11, 12 show the character of moisture distribution in the structure of a material package during its wetting (70th, 80th and 300th minutes of the experiment). Region 1 illustrates a layer on the surface of an body element, regions 2 - 4 illustrates layers of a package of materials (2 – Linen; 3 – Warming; 3 - Upper). Figure 13 shows the dynamics of the moisture content of the material package throughout the entire experiment.

In the first phase of the experiment, both packages demonstrate similar operational efficiency, which is expressed in close values of the heat flux density on the surface of the body element.
In the second phase of the experiment, material package No. 2 absorbs moisture better, which is expressed in the nature of the moisture distribution between the layers. Material package No. 1 exerts high resistance to the moisture removal process, which is reflected in a gradual decrease in its concentration over the package layers (figure 11). Package No. 2 promotes the removal of moisture from human skin. The maximum moisture concentration is observed in the linen layer (figure 12). In the third phase of the experiment, with the same average moisture content of the packages, the heat flux density in material package No. 2 is lower due to heat generation in the textile operating system, which partially compensates for the excessive heat transfer.

![Figure 11. Moisture kinetics curves in material Package No. 1.](image1)

![Figure 12. Moisture kinetics curves in material Package No. 2.](image2)

![Figure 13. Moisture dynamics curve in material packages.](image3)

With a decrease in physical activity, a more pronounced decrease in the average moisture concentration is observed in material package No. 2 (phase 4 – figure 13). Nevertheless, the heat flux density in material package No. 2 is lower than in material package No. 1, which is also associated with the influence of accumulation and heat generation effect.

According to the obtained data, thermal smart clothing system, due to the original thermophysical effects, contribute to the normalization of the processes of human heat transfer with the environment when changing heat transfer conditions.

The proposed experimental complex allows for fairly detailed studies of heat and mass transfer processes occurring in material packages, which will contribute to solving the problem of purposeful selection of the structure of thermal smart clothing system for the manufacture of effective heat-protective clothing.
6. Conclusions
1. The analysis of existing methods for studying both the thermophysical properties of materials and processes of heat and mass transfer in material packages is conducted; their classification is proposed.
2. The necessity of developing a method for studying non-stationary heat and mass transfer in material packages is shown.
3. A method for the experimental study of heat and mass transfer in the material package during the removal of sweat into the environment has been developed.
4. The construction of the experimental complex has been developed.
5. Comparative studies of heat and mass transfer processes on the example of material packages based on traditional materials and textile operational systems were carried out.
6. It was found that when the surface of the body element is moistened by sweat, material packages from textile operating systems allow more efficient moisture removal from under clothing into the environment. Due to the original effects of accumulation and heat generation, such material systems retain their heat-protective properties better.

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