Integrated Approach To An Efficiency Assessment Of Self-Organizing Textile Materials Packages In The Subnormal Climate

M Rodicheva, A Abramova, P Kanatnikova, N Kanatnikov, G Kharlamov

Orel State University named after I.S.Turgenev,
Naugorskoe shosse 29, Orel, Russian Federation, 302020

E-mail: aAnt-lin88@mail.ru, bNVKanatnikov1989@gmail.com

Abstract. Design of heat-shielding clothes for subnormal climate still remains one of the unsolved problems of complex security. The solution is connected with the use of the self-organizing textile materials. Reasoning of textile package optimal selection requires the development of a comprehensive approach combining theoretical and experimental researches.

1. Introduction

One of aspects of complex security is creating of the demanded working conditions for workers including using the uniform. Its quality is estimated using the compliance of materials properties indicators and structure with regulatory requirements and is confirmed in the certification course for the majority of the exploited sets of overall. However, the statistic data shows that there is no essential decreasing of the level of professional-caused catarrhal diseases. In our opinion, it is connected with the shortcomings of standard requirements to the level of heat-shielding properties. For example, the size of the heat conductivity coefficient is established as a constant which is defined by the configuration of a set of materials; the uniform is effective only in the narrow range of environmental factors fluctuation. Compliance of uniform quality index with requirements under essential changes of values of external factors does not guarantee its efficiency. That is why regulatory requirements for the heat-shielding properties are established not for all climatic conditions. For example, they are not established for subnormal climate - in this case the temperature varies between -5 and +10 centigrade, fitful wind and possible precipitation are noted.

In these conditions uniform efficiency increase is connected with the development of new research techniques of a non-stationary heat mass exchange in textile materials packages. Special attention in scientific literature is paid to the solution of this problem. Methods of mathematical model construction of the heat mass exchange and its solving are developed within the theoretical researches. The essential contribution to this work was made by D. Ambesi, A. K. Haggi, M. Sobera et al [2, 6, 9].

On the basis of these methods a number of mathematical models of a heat mass exchange is offered [7, 10, 12]. R. Barauskas's model allows to optimize the structure of a textile materials package by parameters of water vapor and air permeability [7]. Model of C. Voelker et al allows to estimate the change of thermal comfort parameters of the person in clothes within non-stationary influences of environment [10]. Model of Y. Zhang et al allows to calculate the intensity of a complex heat mass exchange in "the person - clothes - environment" system [12].

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During the course of experimental works the assessment of particular coefficients of quality of materials and an assessment of the influence of these indicators on a thermal condition of a person are carried out. Water vapour permeability as an important parameter is studied by W. Gibson, P. Yip et al on the example of modern membrane fabrics [4, 5]. M. Richards investigated the influence of humidity on the heat exchange between the person and environment at a temperature of +10ºC [8].

For an assessment of efficiency of uniform under operating conditions a number of researchers develop accurate thermal models of the person - thermal manikin. I. Holmer, H. Nillson et al have made an important contribution to the development of methodology of such researches [7, 11].

Results of experimental and theoretical studies did not become widespread in Russia in a design of special uniform for conditions of subnormal climate. It is connected to complexity of coordination of theoretical and experimental results as well. This problem can be solved by using a single methodology of development of mathematical models of a heat mass exchange in the packages of materials and elements of an experimental complex on a single methodological foundation.

A similar approach is realized by authors on the example of research of complex processes of a heat mass exchange in the system "the person - clothes - environment" in the conditions of subnormal climate.

For this purpose, it is offered to use the experimental complex (fig. 1), allowing to investigate dynamics of thermal properties of textile fabrics at change of heat exchange conditions and intensity of a non-stationary heat mass exchange in packages of materials as well. At the same time on a thermal model of an element of a human body (position 1, figure 1) with an internal source of heat (position 2) the studied sample (position 3) is placed. Specialized devices (position 4-6) allow to model the influence of wind, precipitations and sweat on the intensity of processes of a heat mass exchange in the studied sample. Also the complex is equipped with devices for an assessment of a temperature field in a sample and environment for measuring the intensity of heat generation in a model of a human body element.

The methodical basis of an experimental complex allows to investigate dynamics of heat-shielding properties of packages of materials within the change of conditions of a heat mass exchange process. Therefore, with the help of this technique the efficiency of packages of the self-organizing textile materials can be investigated; this will allow to solve the problem of protection of the person from overheating in subnormal climate.

Figure 1 – Design of an experimental complex
2. Results of research of thermal properties of some samples of the self-organizing textile materials

Options of packages of the self-organizing textile materials in which optimum adaptive properties to change of conditions of a heat mass exchange of the person with the environment in the range of temperatures of 0°C ÷ +20°C are reached are presented in the Table 1. These temperatures correspond to the lower bound of a comfort zone and subnormal climate.

Table 1. Options of a selection of the structure of the materials package for conditions of subnormal temperatures

| Recommended temperature range | Package configuration number | Package layers |
|-------------------------------|-----------------------------|----------------|
|                               |                             | Lower (underwear) | Medium | Upper |
| 0 °C ÷ +10 °C | 1 | Knitted fabric of the Outlast brand | Knitted fabric of the Polartech Thermal Pro brand | Fabric of the Softshell brand |
| +5 °C ÷ +20 °C | 2 | Knitted fabric of the Outlast brand | - | Fabric of the Softshell brand |

It is necessary to confirm the efficiency of packages by objective data for the use of these recommendations in the course of heat-shielding clothes production. The authors collected data on mechanical and thermal properties of the considered samples of the self-organizing textile materials (table 2).

Adaptive properties of the samples are formed owing to the original physical and chemical processes which are proceeding at the mesolevel of material structure. We have already analyzed the influence of these structural features on the character of a heat mass exchange in packages of materials earlier [1]. We offer to conduct the assessment of self-organization processes in the samples of materials within the change of heat exchange conditions by researching the dynamics of coefficients of heat conductivity and heat emission within the change of heat mass exchange conditions. Figure 2, a demonstrates the dynamics of heat conductivity coefficient of all considered samples of the self-organized materials; figure 2, b shows the results of research of a heat emission coefficient of Softshell fabric as a material of top.

Researches were conducted on the basis of the theory of similarity of thermal processes whereby the intensity of heat exchange on a border "a solid body - gas" is defined by a difference of temperatures between a surface and gas. In the considered range of temperatures (0 ÷ 20°C) the size of a temperature gradient is varied in the range of 10 ÷ 40°C. During the experiment these conditions were modelled using the heating of thermal model by this value concerning the environment. Therefore the temperature of thermal model is 32 - 72°C, temperature of samples 30 - 70°C.

Table 2. Samples of the self-organizing materials for clothes of subnormal climate conditions

| № | Material trademark | Type of material | Fibrous structure | Weave | Area density, g/m² | Thickness, mm | Specific heat, J/(kg·K) |
|---|-------------------|-----------------|------------------|-------|-------------------|--------------|-------------------------|
| 1 | Outlast knitted fabric 100% PL | Stockinette structure | 190 | 0.5 | 1900 |
| 2 | Polartech Thermal Pro knitted fabric 100% PL | Lined | 237 | 1.9 | 2000 |
| 3 | Softshell fabric 100% Ny | Linen | 128 | 0.3 | 1100 |

* - polyester fibers; ** - nylon fibers.
Figure 2 – Results of research of thermal properties of the self-organizing textile materials

As follows from the obtained data, processes of self-organization are displayed in violation of linear change of thermal properties of a sample; that is especially remarkable on the example of heat conductivity coefficient of knitted fabric of the "Outlast" brand and heat emission coefficient of the "Softshell" brand fabric.

3. Finite element model of heat exchange in multilayer textile package

The package of materials is presented in the cover form (position 2, figure 3, a), which is evenly fitting the cylindrical element of a human body (position 1, figure 3, a) during the designing of mathematical model of a heat mass exchange. An impact of a wind, rainfall and sweating was not considered during the modelling. Therefore the heat transfer from a surface of a package is carried out by convection and thermal radiation.

Thermal energy is produced in a body element in an amount of $Q_\text{met}$, W and is transferred to a package of materials with a density of a heat flux $q_\text{net}$, W/m$^2$. Due to this, temperature $t_\text{in}$, °C is maintained on its internal surface. The vertical cut of a package of materials, which is perpendicular to a vector of a heat flux, is accepted as the design geometry of the model (position 3, figure 3, a; figure 3, b).

Textile materials are porous materials, that is why the heat in their structure is transferred by all mechanisms of transfer, but heat conductivity is dominating. Therefore, the equation (1) was chosen to describe the thermal processes in the structure of a package.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T + \rho C_p Tu) = Q$$

(1)

where $T$ – is the temperature; $\rho$ is the density; $C_p$ – is the heat capacity at a constant pressure; $k$ is the thermal conductivity; $Q$ – is and heat source or heat sink; $u$ is the velocity field.

The equation is written down in the form containing an environment speed vector that allows to connect the process of heat transfer in a package of materials with a heat emission. Value $q$ (2) was expressed through the equation (1) for calculation of a field of heat flux density.

$$q = -k \nabla T + \rho C_p Tu$$

(2)

In the solution of the problem of heat conductivity basic data are: value of temperature on an internal surface of a package of materials, values of coefficient of heat conductivity of layers and the law of heat exchange of a package with the environment in the form of heat transfer coefficient.
Therefore the combined boundary conditions are used for its solving:

$$- n \cdot q = q_0 + h(T_{\text{inf}} - T)$$

(3)

where $n$ – is the normal vector of the boundary; $q_0$ – is inward heat flux, normal to the boundary; $h$ – is a heat transfer coefficient.

This form allows to connect an obvious heat flux with a heat transfer coefficient as functions of ambient temperature.

Author's method of experimental studies of a heat mass exchange in the system "the person - clothes - environment" allows to determine the value of heat transfer coefficient of the self-organizing materials. Therefore, in mathematical model the following form (3) of the equation was used for calculation of heat transfer intensity:

$$- n \cdot (- k \nabla T + \rho C_p u T) = q_0 + h(T_{\text{inf}} - T) + \varepsilon \sigma (T_{\text{amb}}^4 - T^4)$$

(4)

where $\varepsilon$ – is the emissivity; $T_{\text{amb}}$ – is the ambient temperature.

The temperature of a surface of the package of materials is defined by solving the thermal conductivity equation. Therefore, boundary conditions for the heat transfer equation can be written in the following form (5):

$$q \cdot n = \left( \rho C_p u T \right) \cdot n$$

(5)

On the next step one solution (figure 3 c, d) was obtained for each configuration of sets of a materials package. For experimental verification of these solutions the package of materials was placed on the thermal model of an element of the human body. Primary converters of temperature were fixed on the each of layers. The thermal model of an element of a body was heated up to the working temperature determined by the size of the modelled gradient of temperatures. Thus, during the test of the first package the size of the temperature of a working surface was 45.8°C and 37.8°C for the second package.

For the next 90 minutes of experiment temperature of layers, thermodynamic parameters of air before and after heat exchange with a surface of a package of materials, and heat generation parameters in the thermal model of an element of a human body were measured. According the obtained results the comparison of experimentally determined distributions of a temperature field and

![Figure 3](image)

**Figure 3** - Stages of mathematical modeling of heat exchange in the packages of the self-organizing textile materials.
field of heat flux density in a package with the results of the numerical decision was carried out (figure 4).

![Figure 4 – Comparison of results of experimental and model researches](image)

The maximum divergence between theoretical and experimental results made: on temperature no more than 4.3%; on the density of a heat flux is not higher than 3.5%. Therefore the mathematical model a heat mass exchange in the packages of the self-organizing materials can be used for the theoretical research of processes of a heat mass exchange in "person - clothes - environment" system.

4. An assessment of efficiency of packages of the self-organizing materials in the conditions of comfortable temperatures and subnormal climate

At the following stage of researches the complex of numerical decisions in the form of distribution of a field of temperature and density of a heat flux in a package of materials (figure 5) was found. Decisions are received under changing of ambient temperature with 5°C interval.

![Figure 5 – Results of numerical solutions](image)
According to the obtained data the ratio between the heat source from human metabolism during performing a physical activity of work difficulty categories IIa, IIb and III, and a heat emission in the environment through the packages of self-organizing materials for each configuration option from table 3 is calculated.

According to the SanPiN 2.2.2.540-96 requirements, continuous being in the conditions of the lowered temperatures should not exceed one and a half hours, after that time it is necessary to do the regulated break lasting 5-20 min in the warmed place. Therefore the estimated time made 60 and 90 min.

The received results need to be compared with requirements MR 2.2.7.2129-06; according to this document, maximum permissible change of heat content of an organism on cold is 5.2 kJ/kg during the work within 60 min and about 5 kJ/kg during the work within 90 minutes.

Table 3. The rate of gaining heat accumulated by an organism under exploited the clothes of the offered materials packages, kJ/kg

| Work difficulty category | Ambient temperature, °C | 0 | 5 | 10 | 15 | 20 |
|--------------------------|-------------------------|---|---|----|----|----|
|                          |                         | Package 1 | Package 1 | Package 2 | Package 1 | Package 2 | Package 2 | Package 2 |
| After 60 minutes of continuous work |
| IIa                      |                         | 0.9 | 1.0 | 0.1 | 1.2 | 0.6 | 1.0 | 1.6 |
| IIb                      |                         | 1.4 | 1.5 | 0.6 | 1.6 | 0.5 | 1.5 | 2.0 |
| III                      |                         | 2.4 | 2.5 | 1.6 | 2.6 | 2.5 | 2.5 | 3.0 |
| After 90 minutes of continuous work |
| IIa                      |                         | 1.4 | 1.5 | 0.4 | 1.8 | 1.7 | 3.1 | 4.9 |
| IIb                      |                         | 2.0 | 2.2 | 1.7 | 2.5 | 3.0 | 4.4 | 6.1 |
| III                      |                         | 3.5 | 3.7 | 4.7 | 4.0 | 6.0 | 7.4 | 9.1 |

5. Conclusion

The obtained results were assessed by the SanPiN 2.2.2.540-96 and MR 2.2.7.2129-06 requirements, therefore it is possible to make the following conclusions:

1. During operation of clothes on the basis of the recommended packages of the self-organizing materials, heat source from the metabolism of person prevails over a heat emission during working categories of IIa, IIb and III difficulty. Therefore the rate of gaining heat in an organism of the worker will accumulate.

2. The heat excess value meets the requirement to the maximum thermal condition of the person at the duration of a work of 60 minutes. The maximum thermal condition at the duration of a work of 90 minutes for configuration set №2 of clothes is upset in the case of:
   - performance of the work of IIb difficulty category at ambient temperature +20°C;
   - performance of the work of III difficulty category as the ambient temperature varies between 10°C and +20°C.

3. The recommended service conditions of packages of the self-organizing materials are crossed in the range of temperatures of +5 °C of ÷ +10 °C. During the work within 60 minutes the package No. 2 is preferable under all considered conditions since the rate of gaining heat accumulated in an organism in this case is less. During the work within 90 minutes efficiency of packages of materials may be different because of the effects of self-organization. The package No. 2 remains more preferable for carrying out the working category of IIa and IIb at the temperature of the air of -5 °C. The package No1 is more preferable in need of performance of work of category of weight of III, and also works of category of weight of IIb at the air temperature of +10 °C.
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