Advanced Technique and the Results of a Research of a Heat-Mass-Exchange Processes in Clothes Packages in the Subnormal Climate

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Abstract. Quality of clothes in the conditions of subnormal temperatures can be provided by using a scientifically based approach for completing of a set of materials. In the article, the method of a research of heat-mass-exchange in the conditions of a non-stationary heat-mass-exchange is stated; the results of a research of influence of materials on the efficiency of heat-protective clothes are considered.

1. Introduction
In the temperate climate zone, cold and transient periods of year last from four to nine months a year. The protection problem of the person in these conditions still remains urgent. All ranges of the lowered temperatures are divided on subnormal temperatures (+10°C ÷ -5°C), moderated (-10°C ÷ -25°C) and severe (lower than -25°C) cold. Theoretical bases of protection of the person in the conditions of moderate and severe cold are studied rather widely. Physiological features of heat exchange of the person are investigated by Burton A.C., Edholm O.G., Fanger P.O. et al [3, 5]. Properties of materials for clothing in cold are evaluated by Buzov B.A., Nikitin A.V., Zhikharev A.P. et al [4, 10]. Approaches to completing the sets of clothes are created by Afanasiieva R.F., Koshcheev W.S. et al [2, 6].

Subnormal temperatures are observed during transient periods of the year and are followed by the abrupt change of weather therefore the heat-mass-exchange in a set of materials proceeds in the non-stationary mode. However, approaches of stationary heat exchange are used when completing clothes in these conditions that leads to increasing the number of cold injuries. About 18% of cases of people's death of cooling occur in this range of temperatures while intense cold leads to a lethal outcome only in 4% of cases [6].

The multiple research of a non-stationary heat-mass-exchange in a set of materials will allow to increase the quality of heat-protective garment due to scientifically based approach to completing of clothes. Nowadays the research on processes of moisture transfer in the structure of a package of materials in the conditions close to subnormal is conducted by Gibson P., Rivin D., Weder M. [8, 9]. It should be noted that they neglect the impact of heat on moisture flows that demands carrying out the additional calculations at design of clothes. M. Rock, P. Yeo, and other researchers use these results.
for completing the sets of materials of heat-protective clothes in the conditions close to subnormal temperatures [7].

2. Method of a research of a non-stationary heat-mass-exchange in the garment

The authors developed an experimental method, which allows to investigate processes of a heat-mass-exchange in the set of materials at subnormal temperatures [1]. The hypothesis that the person thermal status in these conditions is provided by the quasistationary mode of heat exchange is the basis for a method. The constant body temperature at change of weather is maintained due to regulation of the heat production level in an organism. The cylindrical device filled with water and equipped with an internal source of heat is used for modeling of heat exchange of the person in the quasistationary mode. On the surface of device the set of materials (pos. 1, fig. 1, a) in the form of the system of the enclosed concentric elements is located. The automated system maintains the target temperature of the cylinder due to adjustable, giving off heat and measures heat flux density on its surface.

Modern sets of garment exclude the possibility of penetration of moisture and a cold air under clothes. Therefore, the processes of a heat-mass-exchange at output of sweat from under the clothes to the environment are considered in the researches. For this purpose the moistening node is provided in the device (pos. 2, figure 1, a), giving moisture between thermal model of the person's body and a set of materials.

The temperature sensors are fixed on the each layer of a set (fig. 1, b), elementary samples are prepared for assessment of moisture increment (fig. 1, c). Before the start the experiment, the samples are fixed by the thread in order to provide a required contact of a set on site of cuts. The airflow hub is placed over an upper face end of thermal model (pos. 3, fig. 1, a); primary transformers of temperature, speed motion (pos. 4, fig. 1, a) and humidity of air (pos. 5, fig. 1, a) are placed in the neck of the hub.

All types of the works, which are carried out in the open air, can be divided into several categories of severity. Work of II "a" category means that the mass of a transferable load does not exceed several kilograms. Sweating of the person is insignificant. Works of II "b" category is for cargo transfer weighing up to 10 kg. Sweat is absorbed by the clothes and has an impact on the intensity of a heat-mass-exchange in a set of materials. At accomplishment of hard physical work (III category) in clothes with low vapor permeability, the essential increment of moisture weight is fixed.

For modeling of these features of heat exchange, the experiment is conducted during five different phases. On the first phase the performed works belong to the II "a" category, heat exchange proceeds in the stationary mode, moistening is not made. Second phase: intensity of work increases, the beginning of sweating is modelled by the inclusion of the moistening node. Supply of moisture is carried out until saturation of a set of materials for a research of the heat-mass-exchange proceeding in case of limit moistening. The fourth phase: abrupt decrease in weight of works that leads to the sweating termination. In the fifth phase, the set completely dries, and thermal properties of materials recover to the initial level.
3. Structure and properties of heat-protective garment materials in the conditions of subnormal temperatures

The processes of a heat-mass-exchange in the set of material for heat-protective garment in the conditions of subnormal temperatures are investigated by means of this method. In accordance with the regulatory requirements, the set of clothes consists of three parts - underwear, warming and upper layers. The characteristics of the most frequently used textile materials are presented in table 1.

Five options of set varying in option of one layer (table 2) were made by combination of the materials.

| No | Set layer | Material type | Fibre composition | Surface density, \( \text{g/m}^2 \) | Thickness, \( \text{mm} \) | Interweaving       |
|----|-----------|---------------|-------------------|-------------------------------|----------------|-------------------|
| 1  | Underwear | Knitted fabric | cotton, 100%      | 240                           | 0.6             | Jersey structure  |
| 2  | Underwear | Knitted fabric | cotton, 100%      | 220                           | 0.5             | Jersey structure  |
| 3  | Heating   | Knitted fabric | 20% PA, 80% Wool  | 360                           | 2.4             | Jersey patterning |
| 4  | Heating   | Knitted fabric | 20% PA, 80% Wool  | 310                           | 1.4             | Jersey double patterning |
| 5  | Heating   | Knitted fabric | 20% PA, 80% Wool  | 280                           | 1.2             | Jersey double patterning |
| 6  | Upper     | Fabric        | 60% cotton, 40% PES | 430                          | 0.45            | Twill, \( \frac{1}{2} \) |
| 7  | Upper     | Fabric        | 60% cotton, 40% PES | 462                          | 0.35            | Twill, \( \frac{1}{3} \) |
Table 2 – Options of completing of the set of materials

| Option of set completing | Layers options (in accordance with table 1) |
|-------------------------|---------------------------------------------|
|                         | Underwear                                   | Heating                         | Upper                          |
| Trad No 1               | Underwear knitted fabric (sample No1)       | Warming knitted fabric (sample No3) | Cotton fabric (sample No6)     |
| Trad No 2               | Underwear knitted fabric (sample No2)       | Warming knitted fabric (sample No3) | Cotton fabric (sample No6)     |
| Trad No 3               | Underwear knitted fabric (sample No1)       | Warming knitted fabric (sample No4) | Cotton fabric (sample No6)     |
| Trad No 4               | Underwear knitted fabric (sample No1)       | Warming knitted fabric (sample No5) | Cotton fabric (sample No6)     |
| Trad No 5               | Underwear knitted fabric (sample No1)       | Warming knitted fabric (sample No3) | Cotton fabric (sample No7)     |

4. Results and discussion

Results of researches are presented in figures 2-4 in the form of curves of dynamics of a heat flow, dynamics and kinetics of moisture. It allows to compare the nature of heat-mass-exchange processes in sets of materials of different completing and to evaluate its influence on a person thermal status.

Figure 2 illustrates the results received for sets with a different underwear layer. Thickness and area density are a little less in Trad No.2. Apparently, during the work of II "a" category of severity (the 1st phase of an experiment) distinction in values of heat flux density do not exceed 10% (fig. 2, a). At intensive sweating (increasing category of severity to III) in a set Trad No.1 accumulated moisture increases by 0.5 g by the end of the 2nd phase of an experiment (fig. 2, b); heat flux density increases on 80 W/m² in comparison with Trad No. 2.

At the beginning of the fourth phase of an experiment, when level of physical activity decreases, Trad No. 2 dries quicker than a set Trad No. 1; however, by the end of a phase these distinctions become almost unnoticeable.

The choice of material of an underwear layer does not influence a person thermal status of the person during accomplishment the work with the low category of severity. Textile fabric of smaller thickness is more preferable when physical activity changes, for the additional weight of moisture of a set of materials and heat loss by the person in wet clothes will be less.
Results of a research of a heat-mass-exchange in set of materials with the reduction of area density and thickness of the warming layer are presented in the figure 3. Values of heat flow density in dry Trad No. 3 and Trad No. 4 are 178 W/m$^2$ and 192 W/m$^2$ respectively (figure 3, a). Thus, reduction of the thickness of the warming layer by 40 and 50% in the conditions of subnormal temperatures leads to increase of heat flow density on 20 and 30%.

In the conditions of intensive sweating, the value of incremented moisture weight in the sets with thinner heat-insulation decreases (by 15 and 17% for Trad No. 3 and Trad No. 4 by the end of the 2nd phase). At the same time, heat flux density in the third phase of an experiment in these sets is higher by 7 and 10% respectively. These distinctions are explained by the high percentage of woolen fibers in a Trad No. 1. It is known that wool better keeps warm in a wet state.

When the level of physical activity decreases, sets Trad No. 3 and Trad No. 4 dry for 9% and 24% faster than the set Trad No. 1. Thus, the duration of a drying-out period is proportional to the change of moisture capacity of the warming layer.
Thus, at constant performance of work of low and high category of severity, it is more preferable to use materials with the bigger thickness of the warming layer if needed to preserve the heat.

When working with constantly changing category of severity where rapid recovery of initial heat-protective properties of clothes is necessary, sets with warming layer of smaller thickness are more preferable. Intensity of removal of moisture from a set with such cloths is higher by 20-25%, and distinction in the value of heat losses in comparison with a set of big thickness does not exceed 30% and 10% in a dry and wet status respectively.

The results of researches received for the sets Trad No. 1 and Trad No. 5 differing with an area density of upper layer fabric are presented in the figure 4. Apparently, change of mentioned parameter in the studied range of values does not affect the intensity of a heat-mass-exchange process in a set of materials.

Developed method will allow to receive rather detailed characteristic of a heat-mass-exchange processes in the set of materials. Obtained results will allow to increase the quality and efficiency of a heat-shielding of completing clothes in the conditions of subnormal temperatures.
5. Conclusions

As a result of a system research of heat exchanging processes in the set of materials at the accomplishment of the work of different category of severity it was established that:

1. Using the more dense and thick cloths of the underwear and warming layers allows to reduce person heat losses in the conditions of subnormal temperatures by 10 - 30% during performing the work of IIa category.

2. At short-term increase of severity of the performed works, a set of materials with thin underwear and warming layers is more preferable. Intensity of moisture removal in these sets is higher by 10-25% in comparison with thicker layers, and the $q_{set}$ value is 15 - 30% lower; that allows to quickly recovering the initial level of heat-protective properties of clothes, promoting the improvement of a person thermal status. At the same time, at accomplishment of hard physical work for the long time, it is preferable to use sets with thicker and dense warming layer. Such set of clothes intensively absorbs moisture from the surface of a person’s body and preserves the high level of heat-protective properties.

3. In the conditions of subnormal temperatures, it is also more preferable to produce a high layer of clothes of more dense and thick cotton fabrics. Influence of thickness and density of high layer fabric in the considered range of values does not influence the intensity of heat-mass-exchange processes in a set, at the same time, increment of these values increases a wind tightness of clothes.

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