Structural optimization of heat-protective fabric military outfit

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Abstract. Here we have studied and estimated the indices of the military personnel thermal state and pieces of military clothes both common and according to body areas (head, arm (shoulder and forearm) hands, hips, lower legs, feet) per unit of clothes area for selection and estimation of materials and structure of the outfit which shall provide the given thermal resistance. The cooling physiological limits and their endpoints were determined, taking into account the discomfort limitation based on warmth sense modalities. Functional indices of the military personnel are determined by the hypothermia criteria. The cold sense modalities of the body were determined based on the calculation of the heat deficit index.

1. Introduction
The implementation of any activity under the low-temperature conditions is related to the necessity of solving the problem of total body supercooling and freezing of certain body parts. A significant part of the territory of the Russian Federation is located in the north polar region and the most time of year falls on winter and spring-autumn periods being characterised by low ambient temperatures [1].

Cold exposure causes significant changes in the activity of a range of human organs and systems. The evidence of these changes depends on the specific values of climatic variables, the duration of stay under the low-temperature conditions and the structure of means used for protection against cold [2].

Experimental methods currently used for estimation of the clothes heat retention [3, 4, 5] are extremely bulky and labour-intensive, require the precise and complex apparatus, numerous field studies and often cannot provide sufficient assurance of obtained results. So, the clothes researchers try to create analytical (computational) methods of clothing thermal design including the empirically obtained temperature index of the wet bulb to the reasonable thermal index based on the human body thermal balance [6, 7]; based on calculation of textile thermal characteristics and temperature variations at different heat strains [8]; based on calculation of the heat deformation index and the material perceptual deformation index [9]; based on calculation of thermal conductivity in the air layer and heat convection on the clothes external surface [10]; with the use of the intellectual hybrid membrane based on synthesis of heat-sensitive thermoplastic polymer [11] and others.

The assay of existing methods [5, 12, 13] of approximate thermal design of military clothes has shown that all of them are carried out based on the heat-balance analysis of a soldier's body, as the final result, they estimate what total thermal resistance the military clothes shall have to create comfort to the person under the different environmental conditions and physical activity. In this case, as usual, the weighted average values of physiological parameters are widely used. However, in terms of the design and production of reasonable heat-protective military clothes, these data can be important only as purely approximate, while in fact, it is clear that they are insufficient.

If the index of total thermal resistance of military clothes is known, it is possible to determine what thermal resistance shall have the pieces (headwear, hand gears, footwear, jacket, etc), from what materials and with what thermal and physical properties they shall be made, what the most reasonable structure shall be in terms of cold feel. This is responsible for the goal of this paper.

2. Methods
The winter field outfit was considered as the study object. Estimation of the physiologic and hygienic state of the military personnel was carried out under the thermal chamber conditions at the air temperature not lower than $-30 \, ^{\circ}\text{C}$ and the wind speed up to 1.5 m/s. During studies, test persons perform the medium-hard work being dosed by walk-in prescribed pace or rest. The duration of stay of the military personnel in the gear under the specified conditions was 120 minutes.

To determine deficit (accumulation) of heat in the body during the use of the outfit, the total thermal resistance of the heat-protective clothes $R$ was calculated according to Fourier's law by formula (1):

$$R = \frac{t_m - t_c}{Q}$$

where $t_m$ – average weighted temperature of the body, $^\circ\text{C}$; $t_c$ – ambient temperature, $^\circ\text{C}$; $Q$ – heat flow from body areas covered by the clothes, W.

It should be pointed out that the thermal resistance calculation of pieces of clothing should be carried out according to human body areas: head, body, arm (shoulder and forearm), hands, upper leg, lower leg, feet.

For heat calculations of clothing pieces and determination of heat-flow rate, it is necessary to know the body surface of the area $S$ thermally insulated with the designed clothes which was defined according to widely known in hygienic practices Du Bois formula (2):

$$S = \frac{P^{0.425} \cdot H^{0.725} \cdot 71.84}{10000}$$

where $P$ – body weight, kg, $H$ – body height, cm.

While analyzing the heat output by the organism into the environment through the clothes from 1 m$^2$ of its surface, the heat flow $Q$ was determined in accordance with the law (3):

$$Q = K \cdot (t_o - t_c) + B \cdot V \cdot (t_o - t_c) + W \cdot I,$$

where $K$ – heat transfer coefficient of the clothes, W/m$^2$$^\circ\text{C}$; $t_o$ – temperature of air under the clothes, $^\circ\text{C}$; $t_c$ – environment temperature (external temperature), $^\circ\text{C}$; $B$ – coefficient taking into account the clothes air permeability when wind blowing and the air heat capacity; $V$ – wind speed, m/s; $W$ – the quantity of evaporated moisture taken relative to 1 m$^2$ of the clothes surface; $I$ – vapor heat content.

To estimate the thermal insulating properties of materials and outfits, we used the coefficient of heat resistance (Rct) $\lambda$ which, providing firm fitting, is independent of the material structure and the finish and equals to 0.049 W/(m$^2$s).

3. Results and Discussion

To determine the values of thermal resistance indices of the military clothes, the average weighted indices of temperature distribution and surface areas of the body closed with the clothes were calculated (Table 1).

| The areas of the body | Skin temperature, $^\circ\text{C}$ | Plot area to total body surface, % | Area of area to the surface of the body covered by clothing, % |
|-----------------------|----------------------------------|-----------------------------------|----------------------------------------------------------|
| The head and the adjacent half of the neck | 32.0                             | 7.36                               | 4.50                                                      |
Prior to this study, the body surface areas of the military personnel for the certain body parts were approximately determined according to so-called «rule of nines» (surface of head and neck is 9 %, body is 36 %, arms is 18 %, legs is 36 %). Undertaken studies have allowed determining more precisely the areas of certain body parts to the whole body surface including surfaces closed with the clothes. In terms of these data and with the knowledge of the outfit structure, it is possible to easily define the value of the body surface closed with it. For example, the winter outfit covering the body (34 %), shoulder and forearm (13.4 %), upper leg (20.3 %) and lower leg (12.5 %) will protect 81.2 % of the whole body surface.

While analyzing the data of the Table 1 relating to values of the body temperature in some areas, it should be noted that the difference first of all results from the features of the physiologic structure of muscular, bony, cartilage tissues and the liquid content in different organs and systems of the body of the military personnel.

In addition, there exist cooling physiological end points. Their limits are much more narrow. In this case, cold exposure has no significant negative influence on the body of a military man. In case of moderate cooling, he/she feels discomfort at different degrees which are closely associated with warmth sense modalities.

In terms of generalizations of investigation results, Table 2 presents the values of functional indices depending on hypothermia evidence.

### Table 2. Characteristics of the body thermal status of a military person

| Heat sensing          | The weighted average skin temperature of the body, °C | The weighted average skin temperature of the foot, °C |
|-----------------------|------------------------------------------------------|-----------------------------------------------------|
| Feeling «comfortable» | 32.0–34.5                                            | 29.0–31.0                                           |
| The feeling of «cool» | 29.0–31.0                                            | 25.0–29.0                                           |
| The feeling of «cold» | 28.0–29.0                                            | 22.0–25.0                                           |
| Feeling «very cold»   | below 28.0                                           | 17.0–21.0                                           |

Analysis of Table 2 shows that for a comfortable sensation, the skin temperature should not be below 34.5 °C for the body, and for the foot – below 31.0 °C.

Moreover, it should be noted that clothing cannot provide thermal comfort under all conditions of the life activity of a military man. In case of long-term occupancy in cold (especially in harsh climates), any clothing becomes insufficient in its heat-protective properties [14]. In this case, when designing the heat-protective military clothing, it is necessary to have a clear knowledge of the limits of possibly permissible discomfort of the clothes, so-called feeling of cold.

It makes sense for cold conditions to introduce the concept of three degrees of cold feel:

- the cold feel of 1st degree – is the state when a person feels cool but it is not dangerous to health (heat deficit up to 0.75 kcal∙kg⁻¹);
- the cold feel of 2nd degree – is the body state in which the long term being is dangerous to health (heat deficit up to 1.25 kcal∙kg⁻¹);
- the cold feel of 3rd degree – is the state when a person feels intensive cold, the clothes and the body thermal regulation mechanism cannot prevent him/her against excessive cooling (heat deficit more than 1.25 kcal∙kg⁻¹).
However, it should be noted that the cold feel states will be different for different body areas. It is known that the main component of heat losses under the studied conditions are the heat flows coming to the environment through respiratory organs and from the body surface. The intensity of heat losses associated with breathing is in direct dependence on the heaviness of the performed physical activity due to the increase of lung ventilation during the growth of energy expenditure [15].

Determinations of the heat consumption for heating the inhaled air by the military personnel under the different temperature conditions are given in Table 3.

| State in the process of experiment | Heat consumption, W, at ambient temperature, °C |
|-----------------------------------|-----------------------------------------------|
| State of rest                     | 6.12                                          |
| Moderate walking                  | 12.2                                          |
| Performance of work of average weight | 17.1                                          |

Table 3. Heat consumption for heating the inhaled air by the military personnel under the different temperature conditions

The data of the Table 3 shows that under the conditions of full outfit at the temperature from 0 °C to –30 °C the heat consumption for heating the inhaled air by the military personnel decreases relatively proportionally while the environmental temperature decreases and increases with the growth of the military personnel physical activity from the state of rest to performance of the medium heaviness work.

Table 4 presents the data on the thermal resistance of the military outfit after a two-hour stay of the military personnel under the different temperature conditions.

| State in the process of experiment | Thermal resistance of clothing, m²°C/W, at ambient temperature, °C |
|-----------------------------------|---------------------------------------------------------------|
| State of rest                     | 0.56 0.63 0.72 0.82 0.92 1.02 1.11                             |
| Moderate walking                  | 0.20 0.24 0.28 0.33 0.37 0.41 0.46                             |
| Performance of work of average weight | 0.14 0.16 0.20 0.22 0.23 0.28 0.32                             |

Data of Table 4 gives regularities of the empiric nature for designing and manufacturing the military outfit taking into account climatic features of certain districts of the country in accordance with specified operating conditions.

Irregularity in the distribution of thermal insulation in different elements of the winter outfit is due to the thermal dissipation from surfaces of different curvature that is functionally reasonable but additionally increases the development of hypothermia. In this context, it is quite difficult to solve the problem of the limbs heating because this is the place where the thickness of the heat-protective layer is smaller than necessary.

Indices of performance and functional state of the body when using the military clothes in winter conditions are presented in Table 5.

| Name of the indicator | Values of indicators at ambient temperature –10 °C |
|-----------------------|---------------------------------------------------|
| performance of work of average weight | moderate walking | state of rest |

Table 5. Indices of performance and functional state of the body when using the military clothes in winter conditions
Heart rate, beats per minute

| Source | After 120 minutes | Source | After 120 minutes | Source | After 120 minutes |
|--------|-------------------|--------|-------------------|--------|-------------------|
| 80±6   | 101±5             | 76±8   | 99±7              | 79±5   | 93±4              |

Blood pressure, mm Hg.

| Art. | Bodies under the tongue | The back of the hand | The finger | The back of the foot | The toe | The cheeks' |
|------|-------------------------|----------------------|-----------|----------------------|--------|------------|
| 122±2 | 36.3±0.2                | 35.4±0.2             | 36.5±0.2 | 35.5±0.4             | 36.6±0.2 | 35.3±0.3   |
| 138±5 | 31.7±0.4                | 21.8±0.4             | 30.3±1.6 | 23.8±0.7             | 30.6±0.9 | 20.6±0.3   |
| 125±6 | 30.2±1.8                | 18.9±1.4             | 30.6±1.3 | 19.6±1.6             | 29.8±0.8 | 17.2±0.8   |
| 130±7 | 31.5±1.8                | 22.4±0.7             | 32.3±0.8 | 22.7±1.3             | 31.6±1.3 | 21.6±0.5   |
| 120±5 | 25.8±2.9                | 15.2±0.2             | 25.2±1.4 | 15.0±0.1             | 25.1±0.6 | 15.3±0.2   |
| 128±3 | 31.3±2.4                | 13.3±1.7             | 30.5±2.1 | 12.3±0.7             | 31.4±1.1 | 15.5±0.6   |

Temperature, °C

| Source | Weighted average skin temperature, °C | Heat deficit, kcal∙kg⁻¹ |
|--------|---------------------------------------|------------------------|
|        | 32.8±0.4                              | – 0.83±0.05            |
|        | 31.2±0.5                              | – 0.92±0.04            |
|        | 32.8±0.3                              | – 1.15±0.08            |

In this regard, it should be noted that in all cases under consideration the reason for the study termination was the achievement of criteria temperature values of the phalangites skin. Over the range from 60 to 85 minutes from the start of the experiment, the research personnel began present problems of fingers freezing.

The hands cooling stayed within the limit values. However, by the time when the investigations were completed, most of their participants estimated their warmth sense modalities from the surface of hands at the «cold» level.

Decreasing the temperature of the limb is important for body heat control [16]. On cooling, the key place in the heat transfer from inside to outside takes the heat convection by blood-stream. On the one hand, owing to their configuration, hands and feet are distinctive radiators that quickly give off heat to the environment. On the other hand, decreasing the temperature of the limb is the buffer for the body as a whole that to known limits keeps the temperature consistency of visceral organs and their normal functions [17].

In the cases under consideration, the heat deficit was – 0.83 kcal∙kg⁻¹ during the performance of moderate work, in moderate walking – 0.95 kcal∙kg⁻¹ and in the state of rest – 1.15 kcal∙kg⁻¹. Moreover, the rate of heat losses in the state of rest was 2 times more than the same index in the first two states. This gives evidence of the importance of satisfactory thermal insulation because the fact that some body areas quickly give off heat to the environment can lead to more significant hypothermia.

In general, the cold exposure invoked active protective and adaptive reactions on the part of the test person body directed to saving the heat balance. The increase of the vascular tone of the body «shell» resulted in decreasing the skin surface temperature that led to the reduction of heat losses into the environment [18].

As for the cardio-vascular system, the tendency to cold hyperthermia had been observed. Average values of the heart rate to the end of the experiment at all three cases were within 100 beats per minute⁻¹. It shows the significant resources of the cardio-vascular system and the capacity of further physical performance.

In conclusion, it should be noted that the use of the winter set of uniform is provided for the wide temperature range (from low positive to minus 30 °C) and possibilities of variation of its heat-protective properties relevant to climatic conditions and heaviness of the work being performed are severely limited. In winter conditions, hypothermia most often is in progress due to the low physical activity of a person [19]. On the other hand, the rise of temperature caused by intensive physical work
4. Conclusions
For the purpose of optimizing the structure of heat-protective fabric military outfits based on the results of undertaken studies, the following conclusions have been made:

1. The areas of certain parts to the whole body surface including surfaces covered with the clothes have been determined. In terms of these data and with the knowledge of the outfit structure, it is possible to easily define the value of the body surface closed with it. For example, the winter suit will protect 81.2 % of the whole body surface.

2. Physiological cooling limits and their endpoints have been determined taking into account the discomfort degree based on warmth sense modalities of the military personnel. For comfortable sensation, the skin temperature shall not be lower than 34.5 °C, for foot – lower than 31.0 °C.

3. The heat consumption for heating inspired air under the different temperature conditions has been determined. Under the conditions of full outfit at a temperature from 0 °C to –30 °C, the heat consumption for heating inspired air by the military personnel decreases relatively proportionally as the environmental temperature decreases and increases with the increase in their physical activity from the state of rest to performance of moderate works.

4. Thermal resistance of the military outfit after a two-hour stay under the different temperature conditions in the state of rest, moderate walk and performance of moderate works has been determined. The results give conformities of the empirical nature for designing and manufacturing the military clothes taken into account climatic features of certain districts of the country in accordance with specified operational conditions.

5. Indices of performance and functional state of the body using the military clothes in winter have been determined. It was noted that the cold exposure caused active protective and adaptive reactions on the part of the body of a test person directed to keeping the thermal balance. Heat deficit after two-hour stay at a temperature of –10 °C amounted to 0.83 kcal·kg⁻¹ during moderate work, in moderate walking – 0.95 kcal·kg⁻¹, and in the state of rest – 1.15 kcal·kg⁻¹, and the rate of heat losses in the state of rest was almost 2 times higher than the same index in other conditions. The body state of the military personnel in all conditions was evaluated as the cold feel of the II degree with a heat deficit of up to 1.25 kcal·kg⁻¹.

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