Substantiation of parameters of the heat-shielding product for disabled people by using the system analysis and alternative synthesis

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Abstract. The article deals with topical issues of the development theory of heat-protective clothing for people with limited moving capabilities. In particular, the results of the study based on of the interaction of elements in the dynamic system «man – environment – heat protection product» are presented. The aim of the work was the scientific substantiation of heat-protective clothing parameters by means of using the author's model of the thermal state of the human lower limbs. The relevance of research work is due to the increased need for special heat-shielding products and insufficient knowledge of thermal processes in space and time. At the same time, the main difference of the proposed methodology is the solution of the problem within the framework of the analysis of the interaction of the human lower limbs and the product. In the process of solving the problem, the analysis of scientific publications and experimental results of the research conducted by the authors was carried out. At the same time to obtain complete and objective information, modern methods of mathematics and prognostics, including system analysis, alternatives synthesis, modeling and mathematical statistics are used. As part of the research work, an algorithm for evaluating the interaction of the elements of the «human – environment – heat-resistant product» system was substantiated and a model for predicting the thermal state of the human lower limbs was developed. As a result, temperature criteria were determined for the package of materials of an adaptation bag for people with limited moving capabilities. Scientific development has got experimental verification, which showed the effectiveness of the idea underlying the design. The obtained results represent a scientifically based and technically feasible method of selecting parameters and materials of a heat-shielding product. The implementation of the outlined development will contribute to improving the life quality of people with disabilities.

1. Introduction

The global integration of citizens with disabilities in all spheres of life of the modern Russian society is one of the strategic objectives of the federal and municipal authorities of the Russian Federation. In order to implement the strategy of socialization of people with disabilities, several important documents have been taken that regulate practical steps to improve the quality of life of this part of the population [1-3]. In particular, a special program was developed, according to which people with limited moving capabilities should be provided with modern rehabilitation products with relevant characteristics such as functionality, safety, operating reliability and high quality [3].

According to the Federal State Information System «Federal Register of Disabled Persons», more than 350 thousand Russian citizens have disabilities due to limited moving capabilities [4]. The
specified group of the population moves with the help of technical means and it can be characterized with the concept «people with limited moving capabilities» (PLMC). It is important to note that PLMC represent a group of citizens with an increased risk of being in high and low ambient temperatures. This negative situation is associated with reduced thermoregulation and the lack of natural reaction of the dynamic system of lower limbs among people with limited moving capabilities. The described risk factors must be taken into account when designing heat-shielding products for PLMC.

Issues of designing special clothes for people with disabilities are pointed out in the scientific publications of Agafonova L. P., Bekmurzaev L. A., Brink I. Yu., Karabanova N. Yu., Savelieva N. Yu., Chashchina O. V., Cherunova I. V. and other scientists who specialize in this branch of science. A significant part of the works is devoted to the design of special clothes for people with limited moving capabilities, as well as to study the properties of materials used in the design of rehabilitation products [5-11].

At the same time, as the detailed consideration of the issue shows, the problem of designing special thermal protective clothing for PLMC with a thermal management device, remains insufficiently studied. So, one of the main reasons, according to the authors’ opinion, is the incomplete account of the factors shaping the microclimate in the so-called «under clothing space». In particular, it can be stated that the incorrect assessment of the thermo-physical situation is associated with the problem of «scientific uncertainty» known to modern scientists. Thus, the established multi-factorial nature and specificity of risks caused by the influence of temperature and other physical fields from clothing and the external environment require specialists to develop scientifically based design solutions.

Summarizing the results of the analysis of the development of high-quality and functional products for people with diseases of lower limbs, it can be noted that there are no publications that consider scientific and methodological approaches to the design of thermal protective clothing at the current system level, taking into account the full range of negative factors and their interdependent influence on human organism. In connection with the current situation, the authors consider it possible to present in this article the results of their experimental and theoretical studies for achieving the goal aimed at the scientific substantiation of the parameters of heat-protective clothing, taking into account the thermal state of the human lower limbs.

2. Technique, methods and research materials of the interaction of human organs, clothes and environment

In the process of carrying out scientific research on the problem of assessing the impact of heat-protective clothing and external factors on people with moving disabilities, a detailed analysis of scientific works, regulatory and methodological documents published in Russian editions was carried out. The subject of close examination was articles on the assessment of thermal effects and their sources listed in the introduction.

A detailed analysis of publications convinced the authors that the implementation of research work (RW) should be based on the following assumptions: a) all measurement and analytical procedures are carried out on the basis of a systematic approach; b) the object of research is a complex dynamic system «man – environment – heat-shielding product»; c) the subject of research is the impact of factors on the human body and their sources.

In the context of the presentation of the question under consideration, it is advisable to give some explanations. As the main method of research, the authors of the article selected integrated system analysis (ISA). This is done because, according to the fundamental principles of mathematics and prognostics, the level of the method must correspond to the complexity of the object (process) under study. Due to the fact that the object of study is a complex system, ISA is reasonably used [12-13].

Integrated system analysis, which currently represents, according to experts, the highest level of confidence, allows doing the most accurate and objective assessment of all physical and geometric parameters of the system, as well as the relationship between its elements. At the same time, using
ISA, it is possible to study the properties of the complex object under consideration in detail, due to its emergence and openness.

Based on the analysis of available materials, the authors came to the fundamental conclusion that the human body and specifically the lower limbs of people with disabilities, the environment and the heat-shielding article (clothing, bag) form a complex dynamic system (CDS). Within the framework of the CDS, it is possible, in our opinion, to consider all logical connections and processes, including those of a thermal nature. This concept is graphically shown in Figure.1

![Diagram](image)

**Figure 1.** The block diagram of the relationship between the elements of the system «man – environment – heat protection product».

It can be reasonably stated that the proposed concept is in satisfactory agreement with the laws of physics and the theory of heat transfer.

Synthesis of alternatives when used together with ISA and the methods of prognostic theory allows you to choose the optimal solution to the problem, bearing in mind the following basic elements:
- the most probable forecast of the development of thermo-physical processes;
- material of heat-protective clothing;
- design of an adaptable heat-shielding product

The optimal solution chosen on the basis of consideration of a number of alternative proposals, as shown by many years of practice, ensures the quality of information by about 10-15% higher than using other methods [14].

In the process of carrying out the research work, methods of mathematical statistics and modeling were also used. Statistical methods were used by the authors to process the results of the experiment, the purpose of which was to determine the degree of influence of materials on the skin temperature of the hypo-dynamic system of the human lower limbs.

Large-scale experimental studies were conducted by the authors in real microclimatic conditions (at a temperature of 0°C, minus 15°C) with the involvement of people with disabilities as testers. During the tests, local and average temperatures of the skin surface of the lower limbs were determined using heat-proofing product layouts with various combinations of insulation materials. At the same time, besides quantitative parameters, the qualitative indicator of the comfortable well-being of PLMC, the so-called «heat sensation», was also assessed. The experiments were carried out in the amount of thirty-three tests, which, according to the theory of mathematical statistics, is quite enough for the sound formulation of conclusions based on the results of the analysis [15].

### 3. The results of the evaluation of thermophysical parameters

As mentioned above, the main purpose of the research was the scientific substantiation of the parameters of thermal protective clothing. In order to achieve this goal, an algorithm was developed for selecting the parameters of a heat-shielding product based on the analysis of theoretical materials and experimental results in Figure.2.
Figure 2. The algorithm for selecting the parameters of the heat-shielding product.

In the process of forming a set of clothing parameters, a comparative analysis of impact indicators was made, in particular temperature values, on the underclothes space with the corresponding criteria defined by regulatory documents. As a result of a comprehensive assessment, a package of materials was selected that showed the best heat-shielding properties. When carrying out the experiments, this package was constructed from a membrane insulation of the «Tinsuleyt» brand and fleece lining.

For a more substantiated confirmation of the decisions made, the authors carried out mathematical modeling of the thermal state of the lower limbs of people with disabilities in the developed structure. The corresponding mathematical model for predicting the state of the system of the lower limbs of PLMC in a heat-shielding article is described by the formula:

$$ T_i(t) = \Theta_i(t) + T_C = \sum_{k=1}^{n} \left( \int_{0}^{\infty} Q_k(t) e^{\mu_i t} dt + L_k \right) e^{-\lambda k t} M_{ik} \left( J_0 \left( \frac{\mu_i}{\sqrt{a_i}} \right) + A_0 Y_0 \left( \frac{\mu_i}{\sqrt{a_i}} \right) \right) + T_C. \quad (1) $$

where $t$ – is time (minutes); $T_i$ – is $i$-th layer temperature, °С; $T_C$ – is ambient temperature, °С; $a_i$ – is thermal diffusivity of the $i$-th layer, m2 / h; $J_0, Y_0$ – are Bessel functions of zero order of the first and second kind. The above formula was used to determine the dependence of the surface temperature of the skin of the lower limbs in heat-protective clothing and the ambient temperature for a specific period of time (2 minutes). In the described way, the so-called thermal comfort of a person with limited moving capabilities is reasonably and objectively predicted as temperature criteria. The conditions, procedure, and results of this work are described in details in the previously published article by the authors [16]. In the framework of the presentation of the question we give Figure 3a, 3b and 3c, which show the predicted curves of dependence of the skin temperature of the tested people on the time of using the product at an ambient temperature of minus 15°C.

Figure 3. Graphs of the temperature of the skin of PLMC on the time of use of the product: a – in the area of the knees; b – in the area of the legs; c – in foot areas.

The predicted curves made it possible to reliably find the freezing point of the lower limbs of PLMC in the coordinate system «temperature – time». The prediction results are confirmed by practical data with satisfactory convergence.
4. Conclusion
The use of a systematic approach and other modern methods of mathematics and prognostics to the study of processes taking place in the dynamic system «man – environment – heat protection product» allowed:

– to determine the nature of the impact of heat-protective clothing and the environment on people with limited moving capabilities;
– to develop an algorithm for selecting parameters of a heat-shielding product for people with disabilities;
– to establish the dependence of the temperature of the surface of the skin of the lower limbs in thermal protective clothing and the ambient using mathematical modeling,
– to justify the prediction of thermal comfort for people with limited moving capabilities (predictive assessment of temperature criteria).

It is important to point out that the socio-economic efficiency of this development is confirmed by the practice of using heat-shielding products in real conditions [16].

In the framework of the further research development of the problem considered in this article, it is planned to improve the methodological apparatus of the analysis of thermal processes and the selection of the structural elements of thermal protective clothing.

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