Geometric conditions of mathematical modeling of human heat exchange processes with the environment for CAD systems creating heat-shielding clothing

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Abstract. In the article research results are presented, which aim to provide of automation algorithm mathematical model of designing technology clothing of the cold protection. The method of calculating heat transfer in the &quot;human - environment&quot; system takes into account the variable thermal parameters and the geometric dimensions of the elements, the presence of internal heat sources and convective heat transfer with the heat-carrier flow along the layers and between the calculated elements. Then the problem is reduced to a one-dimensional heat conduction problem with a variable thermal conductivity coefficient. When modeling a human body, we assume that each element of the model is represented as a set of elliptical cylinders forming the inner layers. Four main concepts of the geometric representation of the outer and inner solutions of the human body model have been developed to simulate the problems of human heat exchange with the environment. An algorithm is proposed for determining the type and structure of a mathematical model for use in CAD systems of protective clothing designing. The research was made in Don State Technical University within the framework of State Assignment of the Ministry of education and science of Russia under the project 11.9194.2017/BCh.

1. Introduction
The modern development of mathematical modeling for technical systems of various types has become the basis of modern technology. The purpose of mathematical modeling is to withdraw the need for a significant number of experiments as part of the program for creating new technology objects or processes and their treatment (processing).

Mathematical models for designing clothes that protect a person from dangerous heat flow include the main object - the human. It is a complex system of biological, thermodynamic, and psychological interaction with the environment. It is almost impossible to consider all functioning parameters and features of person as an object of the model. For technical tasks, including the creation of effective protective clothing, thermodynamic processes of human interaction with the environment is of the top priority [1-3]. They have two components: inner and outer.

Human internal thermodynamics refers to a group of very complex tasks, since it includes various physiological reactions, often amenable to the combined laws not only in terms of human physics but...
the human psychology as well. And it is extremely difficult to model them as a set of mathematical dependencies with a high degree of adequacy. Therefore, it is necessary to determine the limitations and tolerances that form the geometry for the boundaries defining the provisions of the thermodynamics laws. The justified concept of determining the geometric conditions for modeling thermal processes in the "man-environment" system is a necessary component to development the mathematical software for CAD systems for designing individual means of thermal protection for a person.

2. Scientific relevancy

The problem of mathematical modeling of heat transfer processes in the human body has been considered in a number of works dedicated to the rationing, prediction and regulation of the thermal state of a person [4-7]. A number of works is based on the principles laid down by such authors as Stolvik, Hardy [8,9]. The basis of these models is the principle of idealization of the human body. These works are based on the concept of the human body as a set of geometric elements, most of which are cylinders. The human body is considered as a system of integral interacting components. Such components are the layers of outlined cylinders: core, muscles, fat, skin. These layers create the elements of the system, i.e. parts of the human body called segments. In the majority of works there are distinguished 6 such segments: head, body, arm, palm, leg, foot. The mathematical model of Stolvik [10] reviews the thermal state of a person as an isolated object, without clothes. This approach allows to represent the of heat exchange process of a person mathematically beyond the external factors affecting him, including thermal stimuli. In terms of the geometric concept, in other papers [11-12] the human body is treated in a similar way, where the body elements are cylinders of various sizes and the head is a sphere. In papers [5], a mathematical model of human thermoregulation considers it similarly to the above model, i.e. as an isolated system, and the components outlined in the system are the brain, scalp, internal organs, body muscles, body skin, limbs muscles, limbs skin, and blood. Human body ability to lose excessive heat and the regulating property of the blood flow is the basis of the thermostatic function. However, the model takes into account the standard amount of heat loss when there is no increased perspiration, and the heat transfer by evaporation is constant and equal to 20% of the total heat transfer [13].

The mathematical model describes the “thermal state of a person in clothing with heating, but does not take into account evaporative heat loss from the skin surface and when breathing, which can reach 27% of the total heat loss of the body. Heating is carried out by convective heat, which does not have a direct contact action on the surface of the human body and is not subject to limiting the ergonomic indicators of clothing design. The mathematical model is a description of human body parts having form of sphere (head) and cylinders (body, arms, legs), which, in its turn marks the areas covered by clothing packages. The model does not take into account the system of organism physiological thermoregulation, since a person is considered to be in a state of heat balance, which is a significant deficiency of this model.

Numerous human bioheat models have been developed with the aim to calculate the human thermal field and estimate the body heat loss in a stable and uniform thermal environment at various levels of activity in order to describe the human thermoregulatory apparatus. The development began with the analytical bio thermal models of Pennes [13] and Weinbaum and Jiji [14], containing two details "core" and "skin". With the work of Gagge [15], development has shifted to single-segment and multi-segment (multisite) models of the human body with thermoregulation solutions, which were originally developed by Stolwijk [10] and Wissler. Multisegmentalbioheat models are based on physiology theories, thermodynamics and transfer processes for modeling thermal distributions of the entire human body or its part. A more sophisticated 3D finite-element bio-thermal model of the element was also developed by Smith (known as the KSU model) [16], but this model computationally prevents the integration of thermal distribution and the calculation of the human thermal comfort state. Few of the developed multi-segmented bioheat models have dealt with a spatially inhomogeneous and unsteady
environment. There is a need to develop effective bio-thermal models for a dressed person to formalize a number of design solutions for the creation of thermal protective means of life support.

The mathematical model UTCI-FIALA [17] of human temperature control is a multi-detail dynamic model of human physiology and thermal comfort. It is based on a new universal thermal climate index (UTC). After numerous verification, adaptation and expansion tests, such as the inclusion of an adaptive clothing model, this model was used to predict a person's temperature in open climatic conditions. The system inserted in this model (passive version) is a multi-segmental multilayered representation of the human body with a spatial division, which includes a detailed designation of the anatomical, thermal, and thermophysiological properties of the human body. It presents conditionally average person weighing 73.5 kg with a fat content of 14% and body surface area of 1.82m² [17]. The body is idealized as a set of spherical and cylindrical elements constructed of annular concentric layers of tissue with corresponding thermophysical properties and physiological functions. However, modern means of individual protection of a person against dangerous heat include not only common methods of heat transfer by convection and radiation, but also a significant role in a number of structures, which is achieved by conduction using special parts of different shapes. This requires expanding the possibilities of mathematical modeling for heat transfer processes in the "person-protective clothing against heat flux-environment" system and the creation of an improved concept to automate the adoption of a number of important decisions in CAD systems.

3. Theoretical part

The person comfort and the internal climate are designed in sub-models, for example such as: Outdoor Standard Effective Temperature [15]; the Munich energy model of human balance MEMI (1984), the ecological thermal model MENEX (1994, 2004), the perspiration rating approach (ISO 7933), AUB is a human multi-segmented bio-thermal model for transient and asymmetric process. “Multi-segmented human bioheat model for transient and asymmetricis” is an improved multi-segmented bio thermal model of the human body and its integration with clothing to calculate the peripheral temperature change of the skin of undressed and dressed segments of a conditional person. In such models, the system is subjected to a complex transient process in a spatially inhomogeneous environment. The passive bioheat model implies the division of the human body into 15 cylindrical segments. Each body segment is divided into one primary detail, six corner details of the skin, one artery as a blood detail, and one detail of venous blood. The Avolio submodel is used to calculate blood circulation parameters. In such submodels, the unsteady heat conduction equations are simultaneously solved for the details of each body segment in order to predict the main indicators of skin temperature, rates for perspiration, absolute and latent heat loss. There is a conjugation principle of border conditions: the thermal model of the undressed body is combined with the clothing model, which takes into account the absorption of moisture by the fibers to make calculations at high temperature and with heat transfer through the clothing layers. The local temperature of the skin can be evaluated as a reaction to the influence of a heterogeneous environment.

The multi-segmented bioheat model is extended to two dimensions in each segment, relative to the standard AUB model, to represent heat transfer in an angular distribution in addition to the radial distribution [17]. The clothing layer is divided into six parts parallel to the skin details. The heat generated by the human body is dispersed into the environment through radiation, convection and evaporation to maintain the main temperature.

The method of calculating heat transfer in the "human - environment" system takes into account the variable thermal parameters and the geometric dimensions of the elements, the presence of internal heat sources and convective heat transfer with the heat-carrier flow along the layers and between the calculated elements [17]. However, in case of asymmetric structures formation with addressable elements of thermal impact, a more detailed concept of modeling is required.

The process of human heat exchange with the environment can be divided into a number of stages:
1. Heat exchange between limbs and the environment.
2. Heat exchange between the head and the environment.
3. Heat exchange between the human body and the environment.

The first two sections are sufficiently detailed in [10], where the classical approach to the geometric concept of human body elements is used.

In the case considered in this paper, we assume that there is no heat transfer in the cross section between sectors. In addition, we replace each sector of an ellipse with a sector of a circle whose radius passes through the middle of the arc of the corresponding elliptical sector (A…P), which is shown in figure 1.

Then the problem is reduced to a one-dimensional heat conduction problem with a variable thermal conductivity coefficient [5]. In this case, the variability of the heat conductivity coefficient is determined by two factors:

1. Body tissue, through which the heat flows (core, muscle, etc.);
2. Expansion with distance from the center of the cross section of the area through which the heat flows.

\[ \frac{dT}{dt} = \lambda(x, t) \frac{d^2T}{dx^2} + c(x, t) \frac{dT}{dx} + f(x, t) \]  

Where \( x \) - distance from the centre of human body, m;
\( t \) - time, sec;
\( T(x, t) \) - temperature,°C, depending on \( x \) and \( t \);
\( f(x, t) \) - the function of heat production process characteristics for human body;
\( \lambda(x, t) \) and \( c(x, t) \) - coefficients, characterizing heat transfer processes.

4. Practical relevance

When modeling a human body, we assume that each element of the model is represented as a set of elliptical cylinders forming the inner designated layers 1,2,3,4,5 (Fig.1). For the further development of mathematical models applicable in CAD systems for designing heat-protective clothing [18], 2 concepts of representing the inner structure of the body were proposed:

The inner layers of the body are distributed in accordance with the proportion of each of them to the total radius of curvature;
The inner layers of the body are distributed in accordance with the specified thickness of layers, and size of the core is formed depending on the radius of curvature in the cross-section area.

Thus, it is possible to form a set of basic concepts for the mathematical description of the outer and inner structure of the human body, shown in Figure 2.

Figure 2. The structure of the concepts of the structure of human body.

On the basis of the proposed definition scheme, a concept variant can be chosen to describe the heat exchange processes for a particular scheme of geometric distribution of layers in the system [19].

All the studied approaches in mathematical modeling allow to form a specific algorithm for identifying the type and content of a mathematical model based on the criteria that are meaningful for the task, which is shown in Figure 3.

Based on the research and development of principles and limitations in mathematical models of "human-heat-protective clothing-environment", the geometric features typical for creating human models are systematized. Four main concepts of the geometric representation of the outer and inner solutions of the human body model have been developed to simulate the problems of human heat exchange with the environment.
An algorithm is proposed for determining the type and structure of a mathematical model for use in CAD systems of protective clothing designing.

The results obtained allow to expand the possibilities of using mathematical modeling resources for CAD systems in order to create heat-protective clothing.

5. Conclusion
An algorithm is proposed for determining the type and structure of a mathematical model for use in CAD systems of protective clothing designing.
The results obtained allow to expand the possibilities of using mathematical modeling resources for CAD systems in order to create heat-protective clothing.

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