Heat Exchange in “Human body - Thermal protection - Environment” System

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Abstract. This article is devoted to the issues of simulation and calculation of thermal processes in the system called “Human body – Thermal protection - Environment” under low temperature conditions. It considers internal heat sources and convective heat transfer between calculated elements. Overall this is important for the Heat Transfer Theory. The article introduces complex heat transfer calculation method and local thermophysical parameters calculation method in the system called «Human body – Thermal protection – Environment», considering passive and active thermal protections, thermophysical and geometric properties of calculated elements in a wide range of environmental parameters (water, air). It also includes research on the influence that thermal resistance of modern materials, used in special protective clothes development, has on heat transfer in the system “Human body – Thermal protection – Environment”. Analysis of the obtained results allows adding of the computer research data to experiments and optimizing of individual life-support system elements, which are intended to protect human body from exposure to external factors.

1. Introduction
One of the most important tasks in the life-support systems development is research on the cooling effect on a human body and ongoing improvement of protective equipment. Requirements to be met by protective clothing are: low weight, elasticity, strength and high thermal resistance. It also should protect human body from cooling in resting state and shouldn’t cause overheating during the physical activity. This research is a refinement of the previously developed heat transfer calculation method in the system called «Human body – Environment» [1]. The modernization is focused on the inclusion of thermal protection as an additional element for the calculations in the system.

2. A human body thermoregulation model
For the simulation of a human body thermoregulation system the object was approximately split into two parts: "shell" (external body tissues) and "core" (internal organs and muscles). This is a multi-layered and multi-element model, where every part of the body is represented as a calculated element with the corresponding amount and type of layers (fig. 1). The circulatory system works in conjunction with the thermoregulation system (TRS) and transfers heat from the internal organs to the body surface [1]. The system of non-stationary one-dimensional differential heat conductivity equations is used for each calculated element (multilayer cylindrical wall) to calculate the cooling process. It considers thermal processes in each of its layers. In general
the heat conductivity equation, including internal heat sources in cylindrical coordinates, has the following form:

\[
c_{p} \rho \frac{\partial T}{\partial t} = \lambda \left( \frac{\partial ^{2} T}{\partial r^{2}} + \frac{1}{r} \frac{\partial T}{\partial r} \right) + \lambda \frac{\partial ^{2} T}{\partial z^{2}} + q_{i}.
\]

Internal heat sources \(q_{i}\) are divided into two types. The first one \((q_{ih})\) is muscular heat production \((q_{m})\) and internal organs heat production \((q_{io})\). The second one \((q_{b})\) is heat transfer along the length of a layer, performed by the heat carrier (blood), and it depends on the properties and the amount of the heat carrier that entered into the layer under specified conditions. There's an assumption that due to the small size of capillaries, the heat transfer between the heat carrier and the tissues proceeds with energy conversion efficiency of 1 until complete thermal equilibrium: \(q_{c} = q_{ih} + q_{b}\).

![Figure 1. The calculated element scheme (index number: 0 – internal organs, 1 – muscles, 2 – adipose tissue, 3 – external body tissues, 4 – protective clothing, 5 – environment)](image)

The changing of the heat flow along the length of the layer \((\partial z)\) due to the heat conduction process is assumed to be zero. The calculated element is divided into a number of elementary geometrical volumes, and within each of them temperature varies linearly. The calculated points are chosen on the plane intersections, obtained after division. It's allowed for any selected elementary volume that the heat transfer process is stationary in every current moment of time \((\partial t)\). The heat transfer process is determined by the values of effective thermal conductivity coefficient \((\lambda)\), specific heat capacity \((c)\) and density \((\rho)\). Specific heat capacity and density vary insignificantly within the element; so they're considered to be constant. Effective thermal conductivity coefficient is taken as a linear function of temperature \((\lambda = f(t))\).

Boundary conditions describe temperatures and heat flows at the layers' juncture, and also specified environmental parameters. The normal temperature of the core (36,7 °C) is considered to be initial condition.

As the result of the calculation the heat flows, temperatures at the layers boundaries and bulk temperatures are determined. The reliability validation performed by comparing the obtained results with known experimental and calculated data. The qualitative and quantitative correspondence is determined, the divergence is not more than 10% [1, 2].

3. Thermal processes in the system called "Human body - Thermal protection - Environment". Implementation of research complex

The cooling process depends on many parameters: environmental conditions (water or air environment with its temperature and speed), a human body physiological characteristic (gender, age, body fat
percentage, the amount of internal heating), protective clothing properties (thermal resistance, breathability). When creating the personal protective equipment, it's necessary to ensure proper thermal resistance at minimum costs and weight. For this purpose, it's important to investigate the effectiveness of protective clothing that made of materials with different thermal resistance values, under various environmental conditions.

3.1. Research on the influence of environmental parameters
Developed method allows investigation into the influence of temperature and velocity of the medium on the cooling process in water and air [2]. As the speed increases from 0 to 2 m/s, allowable cooling time decreases by half and further it decreases insignificantly. The use of protective clothing reduces negative effect of the environment motion.

3.2. Research on the thermal resistance of protective clothing
As a result of the research on the model it's revealed that the use of materials with high thermal resistance under conditions of very low ambient temperatures is impractical; these materials under such conditions are not much more effective than materials with a small thermal resistance [3, 4]. At moderately low ambient temperatures, an increase in the thermal resistance of protective clothing up to 3 clo (1 clo = 0.155 m² °C / W) significantly increases the allowable time spent in the cold.

3.3. Internal heat sources (physical activity)
The heat production increasing process under condition of ambient temperature decreasing it is an increase in the metabolic rate processes in various kinds of tissue. The most of the heat is generated in organs with high metabolic activity: liver and kidneys, endocrine and digestive glands, skeletal muscles. The least amount of heat is generated in bones, cartilage and connective tissue. The amount of the heat generated in various organs of the body is unequal. The main regulator of the internal heating amount is muscles. During intensive physical activity they provide about 90 % of heat. The physical activity was simulated to determine the redistribution of the heat carrier between elements and layers (fig. 2). The amount of internal heating were 500 W and 1000 W. The more amount of internal heating increases, the more total heat losses increase, but it is detected that participation of various components is redistributed. The heat loss into environment increases because the convective component part of the total heat flow increases. In particular, the part of the heat that blood (warmed-over heat carrier) transfers from "core" to "shell" (and after that to environment) increases by 80% at the initial stage of cooling. The increase of muscle activity promotes the heat production increase by 25 ... 30 %. At very low ambient temperatures the increase in the amount of internal heating affects the cooling time insignificantly. It found out that at very low temperatures intensive physical activity is ineffective [5].

![Figure 2. The hand heat losses](image-url)
3.4. Individual parameters and condition of a human body

In addition, the model allows comparison of different ages, genders, body types and the condition of a human body [1, 2, 4]. In particular, there's a separate research devoted to design of specialized clothes, including high-elastic membranes used for constructing the altitude-compensating pilots suits, the constant wear astronauts garments and sportswear, including clothing for Paraolympic skiers. It revealed that significant redistribution of blood between human body parts depends on factors such as weightlessness and hypodynamia. To determine the human body heat losses under weightlessness condition (an astronaut) and hypodynamia the mass flow rate of blood (heat carrier) should be precalculated for each separate body part. The astronaut's body has the total blood volume 30% less than normal. For this reason, convective heat transfer between "core" and "shell" (the calculated layers) decreases. Also there is a significant redistribution of blood between body parts (the calculated elements). Basing on the analysis of distribution of temperature and heat flows in different parts of the human body, depending on the environmental conditions, presence of high-altitude factors and the human body condition, it is possible to determine location and thermal resistance of the thermal insulation elements in the design of underwear for astronauts (fig. 3, a), and also windproof thermal insulation suits for emergency landing (fig. 3, b).

![Figure 3](image1.png)

Figure 3. The thermal insulation elements in the design of underwear for astronauts (a) and windproof thermal insulation suits for emergency landing (b)

4. Conclusion

The presented research provides an opportunity to determine experiments’ boundaries and create model simulators for examination of extremal overcooling and overheating situations. Also, this research allows optimizing of the personal protective equipment elements from exposure to adverse temperature conditions by adding new elements into the clothes design. The research results can be useful to specialists in the design of thermal underwear for people with disabilities, specialized fire proximity suits, altitude-compensating suits for pilots, constant wear garments for astronauts, and also for improving elements of the space suits thermoregulation systems.

5. References

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