

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

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**Abstract**—This paper 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 method introduces a complex heat transfer calculation method and a 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. In this paper the simultaneous work scheme of the human blood system and the thermoregulation system is described. It allows counting volume flow of the heat carrier (blood) in calculated elements. Influence of the heat transfer with the heat carrier current between calculated elements and layers on thermal processes in the “Human body –Environment” system is investigated. Analysis of the obtained results allows adding the computer research data to experiments and optimizing individual life-support system elements, which are intended to protect a human body from exposure to external factors.

**Keywords**—life support systems, heat exchange processes, heat carrier, thermal resistance, thermal losses, low temperatures

## I. INTRODUCTION

Today the meaningful problem is development of physical and mathematical alive systems models. Studies in this area matter for development and improvement of life support systems elements, which provide thermal comfort for the human [1-4]. 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 should not cause overheating during the physical activity

The most difficult question in the solution of this problem is the description of the heat carrier transfer processes between elements of the thermoregulation system (TRS) [5,6]. Often in thermoregulation system models, it is not considered or reflected by means of empirical coefficients. For the solution of this question in this work, the developed heathydraulic scheme is submitted. It allows one to calculate the amount of the heat carrier and its temperature depending on different conditions

## II. A HUMAN BODY THERMOREGULATION MODEL

### A. Heat Exchange Processes Modeling

For the simulation of a human body, a thermoregulation system, the object was approximately split into two parts: “shell” (external body tissues) and “core” (internal organs and muscles). The circulatory system works in conjunction with the thermoregulation system and transfers heat from the internal organs to the body surface. 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).

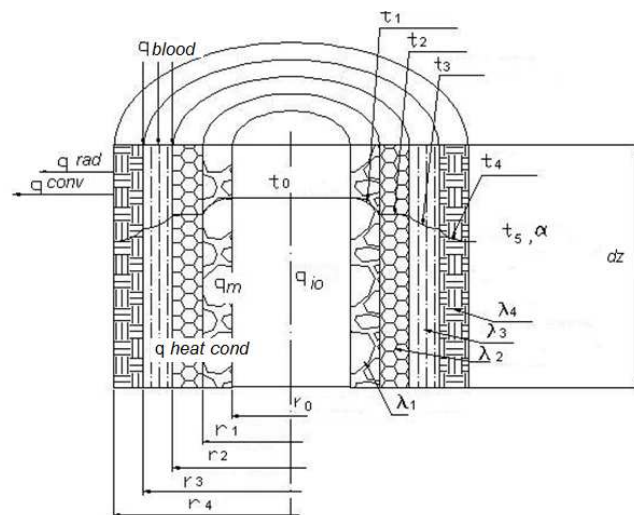


Fig. 1. The calculated element scheme (index number: 0 - internal organs, 1 - muscles, 2 - adipose tissue, 3 - external body tissues, 4 - protective clothing, 5 - environment).

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 (1):

$$c_j \rho_j \frac{\partial T_j}{\partial \tau} = \lambda_j \left( \frac{\partial^2 T_j}{\partial r^2} + \frac{1}{r} \frac{\partial T_j}{\partial r} \right) + \lambda_j \frac{\partial^2 T_j}{\partial z^2} + q_v. \quad (1)$$

Internal heat sources  $q_v$  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 ( $q_{blood}$ ) 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 (2). There is 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:

$$q_v = q_{ih} + q_{blood}. \quad (2)$$

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 is allowed for any selected elementary volume that the heat transfer process is stationary in every current moment of time ( $\partial \tau$ ). The heat transfer process is determined by the values of the effective thermal conductivity coefficient ( $\lambda$ ), specific heat capacity ( $c$ ) and density ( $\rho$ ). Specific heat capacity and density vary insignificantly within the element; so they are considered to be constant. The 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 specify environmental parameters. As the result of the calculation, the heat flows, temperatures at the layers boundaries and bulk temperatures are determined.

Heat fluxes in the calculated element layers are divided into four categories: heat conductivity, thermal losses from the surface layers (convection and radiation), internal sources of heat (heat production) and heat transfer from the heat carrier, which depends on the heat carrier amount and its properties.

For calculation of the heat flux from heat carrier ( $q_{blood}$ ) it is necessary to know its quantity in element, intake and outlet temperatures (3):

$$q_{blood\ j} = \frac{\rho_{ij}}{m_{ij}} G_{blood\ ij} C_{P\ blood} (t_{in\ ij} - t_{out\ ij}), \quad (3)$$

where  $G_{blood}$  – the heat carrier volume flow through a calculated element ( $i$ ) and a layer ( $j$ ),  $C_{P\ blood}$  – heat carrier thermal capacity,  $t_{in}$ ,  $t_{out}$  – heat carrier intake and outlet temperatures in calculated element and a layer.

Average layers temperatures are determined by the following algorithm. For each layer (e.g.  $i = 2$  and  $j = 1, 2$ ), average temperature variation  $\Delta T_{2j}$  in time period  $\Delta \tau$  is calculated (4):

$$\Delta T_{21}^L = \frac{Q_{conv21}^L + Q_{rad21}^L + Q_{blood21}^L}{c_{21} m_{21} / \Delta \tau + G_{blood21} C_{blood}}, \quad (4)$$

$$\Delta T_{22}^L = \frac{Q_{conv22}^L + Q_{rad22}^L + Q_{blood22}^L + Q_{cond22}^L}{c_{22} m_{22} / \Delta \tau + G_{blood22} C_{blood}},$$

where  $L$  – the time period number, *conv* – convection, *rad* – radiation, *cond* – heat conductivity.

Then average layers temperatures are defined by expressions (5):

$$T_{21}^L = T_{21}^{L-1} + \Delta T_{21}^L; \quad T_{22}^L = T_{22}^{L-1} + \Delta T_{22}^L. \quad (5)$$

As the capillary sizes are very small, average outlet heat carrier temperature in calculated layer is (6):

$$T_{ij}^L = T_{out\ ij}^L. \quad (6)$$

Average outlet heat carrier temperature in calculated element depends on temperature in the layer (6) and blood volume flow (7):

$$T_{out2}^L = \frac{(T_{out21}^L G_{blood21} + T_{out22}^L G_{blood22})}{G_{blood21} + G_{blood22}}. \quad (7)$$

Outlet temperatures on a  $L$  step are accepted as intake for the following  $L+1$  step (the following time period). Initially, intake temperature for all elements and layers is equal to 36,7 °C (the normal temperature of the body). The heat carrier volume flow  $G$  is calculated by the following algorithm.

## B. Calculation of Hydraulic Characteristics

On the basis of biological and medical data [7] for the presented model, the thermal and hydraulic scheme of the human thermoregulation system is created (fig. 2).

In calculated elements, the heating or cooling of the heat carrier depending on environment parameters is considered. Also there is a heat carriers mix with a different temperature. Thus, an important TRS feature is existence of several calculated elements types which are connected among themselves by the composite serial-parallel hydraulic system having variable thermal and hydraulic properties.

As in each element there are many capillaries and their sizes are very small, the dependence of a temperature profile on a velocity distribution can be neglected. Hydraulic characteristics are defined by the equations (8) set for each element:

$$P_{aorta} = \xi(\text{var})_i \frac{\rho V_i^2}{2} + \zeta(\text{var})_i \frac{\rho W_i^2}{2} + k(\text{var})_{ij} G_{ij} + P_{veins\ i} + \rho g h_i + \Delta P_{accel\ i} + \Delta P_{press\ i} \quad (8)$$

$$k_{ij}G_{ij} + \xi_i \rho \frac{V_i^2}{2} + \zeta_i \frac{\rho W_i^2}{2} + \Delta P_i = 0,$$

where  $P$  – pressure (*aorta*, *veins*, *accel* – linear acceleration, *press* – compression pressure),  $k(var)$ ,  $\zeta(var)$  and  $\xi(var)$  – resistance coefficients (capillaries, arterioles and arteries),  $V$ ,  $W$  – blood-groove speed in arteries and arterioles.

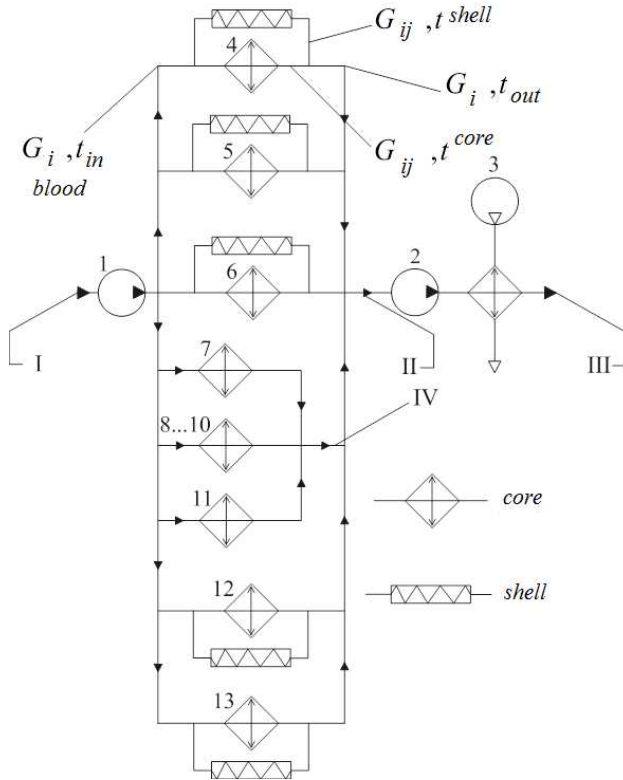


Fig. 2. The conditional thermal and hydraulic scheme of the human thermoregulation system: *I* – heat carrier entrance to the first contour; *II* – heat carrier exit from the first contour; *III* – exit from the second contour; *IV* – heat carrier exit from the core; *1*, *2* – pump (heart); calculated elements: *3* – lungs; *4* – head; *5* – hands; *6* – thorax muscles; *7* – cardiac muscle; *8 ... 10* – digestive organs; *11* – buds; *12* – the lower half muscles of a trunk; *13* – legs.

Techniques for calculation of resistance coefficients are developed for each vascular section (are described explicitly in [8]). They consider the geometrical sizes and hydraulic characteristics of the contour (a volume flow of the heat carrier, intake pressure in the system, classification, diameters, lengths and the number of vessels and flow rate of blood). The calculated scheme considers the attitude, the divisions and branches scheme and also length of vascular section. As a result pressure drops  $\Delta P_i$  and a volume flow  $G_{ij}$  for seven calculated elements depending on external conditions are calculated.

Separately the heat carrier volume flow coming to “shell” are calculated. It allows considering the amount of heat which transfers the heat carrier from “shell” to “core” in thermal calculation, and considering the variable thermal resistance of a hypodermic capillaries layer.

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%.

### III. THE RESULTS

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).

The presented technique allows considering temperature and speed of a surrounding medium, gender, age, somatotype, and internal heating of an organism, the bound to physical activity.

The heat carrier inflow from “core” to “shell” considerably increases (in 4 ... 8 times) when a human experiences an exercise stress. It happens due to rush of blood to muscles and expansions of hypodermic capillaries network to the purpose to dump excess heat in a surrounding medium (fig. 3). The physical activity was simulated to determine the redistribution of the heat carrier between elements and layers (fig. 4). The amount of internal heating were 500 and 1000 Watt. 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 was found out that at very low temperatures, intensive physical activity is ineffective [9].

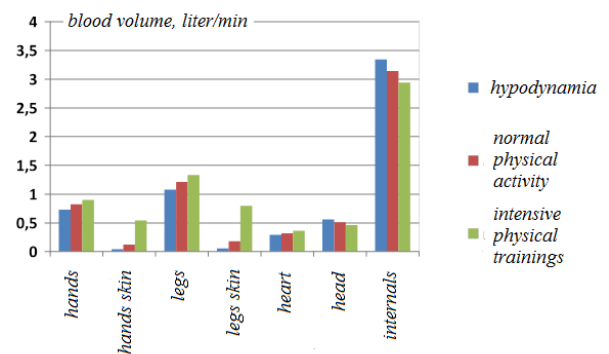


Fig. 3. Influence of external work during heat carrier redistribution between elements and layers.

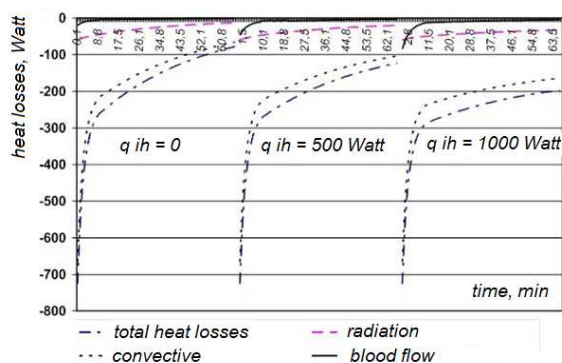


Fig. 4. The hand heat losses.

The presented method allows calculating the heat carrier volume flow in elements (fig. 5). Maximum heat carrier volume flow for the men (40 years) is in torso and internals (the blood volume per minute - 54%). Minimum - in the heart and the head (5% and 8%). In the muscle group - 14% and 19% for hands and legs, respectively. At the same time, the largest heat losses (environment temperature is 20 °C) are in the muscle group (fig. 6).

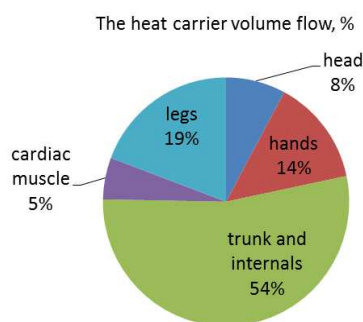


Figure 5. The heat carrier volume flow in elements.

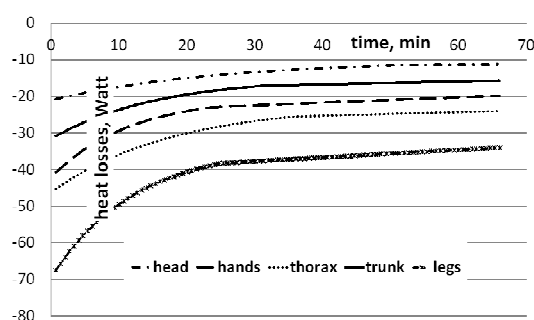


Fig. 6. The heat losses of calculated elements.

The heat carrier is redistributed not only between elements, but also between layers. The thermal insulation layer (hypodermic capillaries) has variable thermal resistance. At low temperatures the "shell" resistance increases because blood is outflows from this layer. It allows to reduce heat losses of "core" and to keep its temperature of a constant as long as possible. The outflow speed and heat carrier amount

depends on environment temperature and specific features of an organism.

When creating the personal protective equipment, it is necessary to ensure proper thermal resistance at minimum costs and weight. For this purpose, it is important to investigate the effectiveness of protective clothing that made of materials with different thermal resistance values, under various environmental conditions. As a result of the research on the model, it was revealed that the use of materials with high thermal resistance under conditions of very low ambient temperatures was impractical; these materials under such conditions are not much more effective than materials with a small thermal resistance (fig. 7). At moderately low ambient temperatures, an increase in the thermal resistance of protective clothing up to 3 clo (1 clo = 0.155 m<sup>2</sup> °C/W) significantly increases the allowable time spent in the cold.

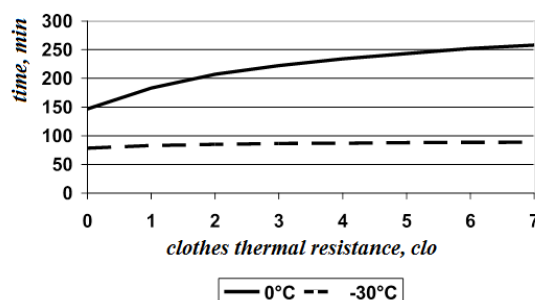


Fig. 7. The safe stay time in cold (environment temperature -30 °C and 0 °C, clothes thermal resistance - 1 ... 7 clo).

The important parameter for heat losses analysis in the zero gravity conditions is the heat carrier redistribution between calculated elements [10]. The presented method allows calculating blood volume deviations in a minute in the zero gravity conditions (in a percentage ratio) from norm on Earth (fig. 8). An astronaut has the cooperative blood volume that is 16% less than the norm, which leads to a decrease of heat convection with blood flow. In the absence of exercise stresses, such redistribution of blood between calculated elements is observed: the blood consumption in the head increases by 70 %, for hands and legs - decreases by 11 % and 37 %, respectively.

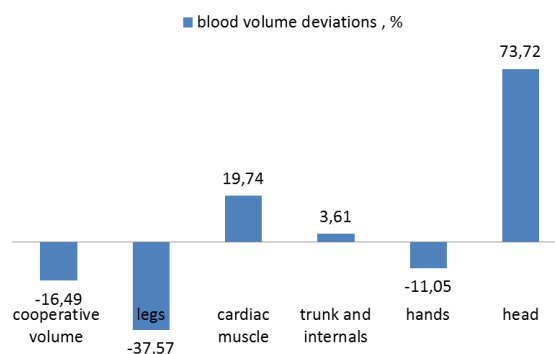


Fig. 8. The blood volume deviations per minute in the zero gravity conditions (in a percentage ratio) from norm on Earth.



Thus, considering padding heat wastes during respiration is expedient to introduce the warming elements in places where blood supply is worsened: legs, back, thorax (fig. 9, a). The similar solution is proposed for the windproof suit intended for the emergency landing in adverse weather conditions (fig. 9, b).

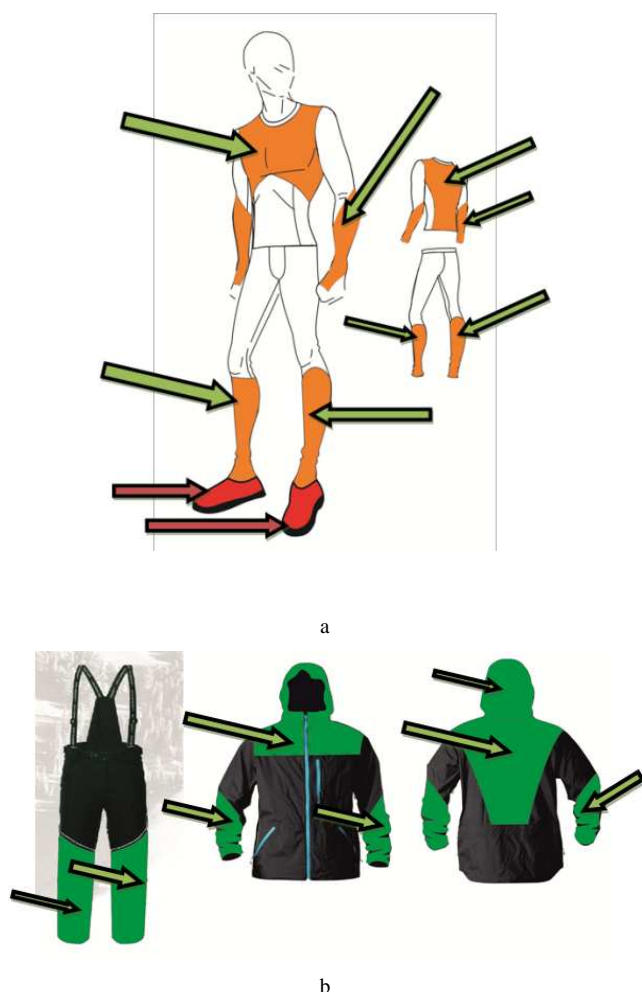


Fig. 9. The thermal insulation elements in the design of underwear for astronauts (a) and windproof thermal insulation suits for emergency landing (b)

#### IV. CONCLUSION

The received results analysis allows one to estimate qualitatively and quantitatively influence of the heat carrier redistribution between calculated elements on the “Human body – Thermal protection – Environment” system functioning and to receive local thermal parameters in the wide range of surrounding medium properties. It gives opportunity to define experiments borders and to create models for training in extreme situations, which are bound to overcooling and overheating. Also it can help to improve individual protection means from influence of adverse heating environments by means of the thermal insulation elements in a clothes design. The research results can be useful for specialists when designing 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.

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