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COMPUTER DESIGN OF THERMOELECTRIC HEAT METER READINGS UNDER REAL-SERVICE CONDITIONS

This paper presents the results of computer investigations of thermal insulation effect on thermoelectric heat meter readings under real-service conditions. Three-dimensional physical, mathematical and computer models of biological tissue having on its surface thermoelectric heat meter with thermal insulation are constructed. It is established that the presence of medical thermal insulation on thermoelectric heat meter and biological tissue can change heat meter readings up to 35 %.

Key words: computer design, thermoelectric heat meter, medical thermal insulation.

Introduction

General characterization of the problem. It is known [1, 2] that inflammatory processes are attended by a change in heat release that can become a reliable indicator of various diseases. Any changes in human heat release can be readily determined by thermoelectric heat meters [3, 4] that are an efficient tool for local diagnostics of human organism, early detection of inflammatory processes, oncologic diseases, blood circulation anomalies and analysis of human state of health under extreme conditions [5-8]. The effect of such heat meters on the object under research was studied with the help of computer simulation in [9, 10].

In the investigation of human heat release of paramount importance is a manner of heat meter fastening to human body surface, heat meter spatial orientation, the presence of thermal insulation on heat meter (medical bandage, clothes, etc) that can essentially distort the temperature field of investigated human body area and affect thermoelectric heat meter readings.

The purpose of this work is to determine the effect of thermal insulation on thermoelectric heat meter readings under real-service conditions.

A physical model of biological tissue with thermoelectric heat meter and thermal insulation

According to a physical model (Fig. 1), an area of human biological tissue is a three-layered structure (epidermis 1, dermis 2, subcutis 3) and internal tissue 4 characterized by thermal conductivity κ_i, specific heat C_i, density ρ_i, blood perfusion rate ω_{bi}, blood density ρ_b, blood heat capacity C_b, human blood temperature T_b and specific heat release q_{met} due to metabolic processes (Table 1). The respective biological tissue layers 1 – 4 are considered as the bulk sources of heat q_i, where:

$$q_i = q_{met} + \rho_b \cdot C_b \cdot \omega_{bi} \cdot (T_b - T), \quad i = 1...4. \tag{1}$$

The geometric dimensions of each such layer are a_i, b_i and l_i. The temperatures at the boundaries of respective biological tissue layers are T_1, T_2, T_3 and T_4.

Thermoelectric heat meter 6 is a rectangular bar of the geometric dimensions a_6, b_6 and l_6, characterized by thermal conductivity κ. From the theory it is known [3, 4] that thermoelectromotive force (EMF) of thermoelectric gradient heat meter is determined as follows:

$$E = \alpha \cdot N \cdot \Delta T, \qquad (2)$$

where α is the Seebeck coefficient, N is the number of thermoelectric material legs in heat meter, ΔT is temperature difference between the upper and lower surfaces of thermoelectric heat meter. As a rule, the number of thermoelectric material legs in heat meter is $N = 1500 - 2500$ pcs. Simulation of heat meter with such a number of elements is an intricate problem even for modern personal computers. As the same time, from formula (2) it is seen that the heat meter EMF values are mainly influenced by temperature difference ΔT between heat meter surfaces. Therefore, to reach the purpose set in this paper, it is quite sufficient to replace thermoelectric heat meter having a large number of elements by the bulk homogeneous sample of equivalent thermal conductivity κ. Then, on the basis of calculated ΔT, one can easily determine heat meter EMF value according to formula (2).

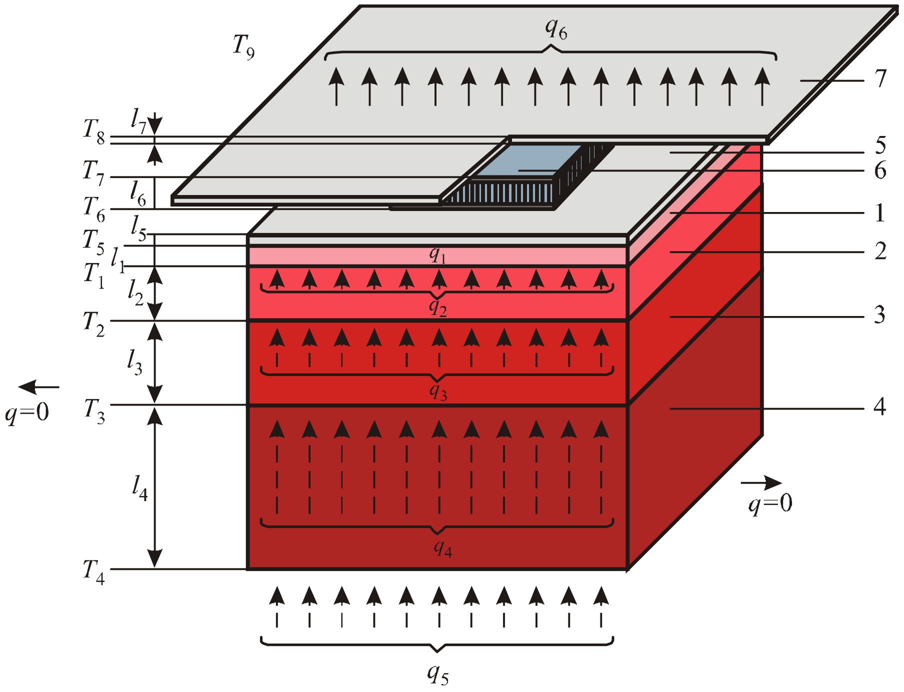

Fig. 1. A physical model of biological tissue with thermoelectric heat meter and thermal insulation 1 – epidermis, 2 – dermis, 3 – subcutis, 4 – internal tissue, 5, 7 – thermal insulation, 6 – thermoelectric heat meter.

As long as a physical model is an area of a four-layered biological tissue, with identical biochemical processes occurring in adjacent layers, it can be assumed that there is no heat overflow along biological tissue ($q = 0$).

The skin surface layer (epidermis 1) of temperature T_5 is in the state of heat exchange with thermal insulation 5 of the geometrical dimensions a_5, b_5 and l_5 and contact surface temperature T_6. Located on the surface of thermal insulation 5 is thermoelectric heat meter 6 of the geometric dimensions a_6, b_6, and l_6 and contact surface temperature T_7. In the absence of thermal insulation 5, the heat exchange between skin surface and the environment of temperature T_9 is taken into account by heat exchange coefficient α_1 and emissivity coefficient ε_1. Skin heat exchange due to perspiration is disregarded.

Additional thermal insulation 7 of the geometric dimensions a_7, b_7 and l_7 is arranged on the surface of thermoelectric heat meter 6. Free surface of thermal insulation 7 of temperature T_8 is in the state of heat exchange with the environment of temperature T_9 which is taken into account by heat exchange coefficient α_2 and emissivity coefficient ε_2. Specific heat flux from the surface of thermal insulation 7 to the environment is q_6, and specific heat flux from human internals – q_5.

Table 1

Thermophyical properties of human biological tissue [11-15]

Biological tissue layers	Epidermis	Dermis	Subcutis	Internal tissue
Thickness, l (mm)	0.08	2	10	30
Specific heat, C ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$)	3590	3300	2500	4000
Thermal conductivity, κ ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)	0.24	0.45	0.19	0.5
Density, ρ ($\mathrm{kg \cdot m^{-3}}$)	1200	1200	1000	1000
Metabolism, q_{met} ($\mathrm{W \cdot m^{-3}}$)	368.1	368.1	368.3	368.3
Tissue blood perfusion rate, ω_b ($\mathrm{m^3 \cdot s^{-1} \cdot m^{-3}}$)	0	0.00125	0.00125	0.00125
Blood density, ρ_b ($\mathrm{kg \cdot m^{-3}}$)	1060	1060	1060	1060
Blood heat capacity, C_b ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$)	3770	3770	3770	3770

Mathematical description and a computer model

A general equation of heat exchange in biological tissue is as follows [11-15]:

$$\rho_i \cdot C_i \cdot \frac{\partial T}{\partial t} = \nabla(k_i \cdot \nabla T) + \rho_b \cdot C_b \cdot \omega_{bi} \cdot (T_b - T) + q_{met}, \tag{3}$$

where ρ_i is the density of corresponding biological tissue layer, C_i is specific heat of biological tissue layer, ρ_b is blood density, C_b is specific heat of blood, ω_{bi} is blood perfusion rate, T_b is human blood temperature, where $T_b = 310.15$ K, q_{met} is specific metabolic heat release.

The sum in the left-hand side of equation (3) is the rate of change in thermal energy comprised in the unit volume of biological tissue. Three summands in the right-hand side of this equation are the rate of change in thermal energy due to thermal conductivity, blood perfusion and metabolic heat, respectively.

To solve the problem formulated in this work, it is sufficient to consider a three-dimensional steady-state model. Then equation (3) will acquire the form of (4):

$$k_i \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \rho_b \cdot C_b \cdot \omega_{bi} \cdot (T_b - T) + q_{met} = 0. \tag{4}$$

Steady-state equation of heat exchange in biological tissue (4) was solved with the respective boundary conditions (5 – 6):

$$\begin{cases} q\big|_{x=0} = 0, \\ q\big|_{x=a} = 0, \end{cases} \quad \begin{cases} q\big|_{y=0} = 0, \\ q\big|_{y=a} = 0, \end{cases} \quad i = 1...4. \tag{5}$$

$$\begin{cases} T_4\Big|_{z=0} = 310.15\,\text{K}, \\ q_6\Big|_{z=b} = \alpha_1 \cdot (T_9 - T_8) + \alpha_2 \cdot (T_9 - T_8). \end{cases} \tag{6}$$

Here, q_i is heat flux density of the respective layer of biological tissue, T_4 is absolute temperature of the lower surface of internal tissue 4, T_8 is absolute temperature of thermal insulation surface 7, T_9 is ambient temperature, α_1 is effective heat exchange coefficient of skin surface, α_2 is effective heat exchange coefficient of heat meter and thermal insulation. Conditions of temperature equality and thermal balance are observed at the boundaries between the biological tissue layers.

To determine the effect of thermal insulation on thermoelectric heat meter readings, a three-dimensional computer model of biological tissue having on its top thermoelectric heat meter with thermal insulation was created. For this purpose, the Comsol Multiphysics software package was employed [16] enabling simulation of thermophysical processes in biological tissue with regard to blood circulation and metabolism.

The distribution of temperature and heat flux density in biological tissue and thermoelectric heat meter was calculated by finite element method (Fig. 2). According to this method, an object under study is split into a large number of finite elements, and in each of them the value of function is sought which satisfies given differential equations of second kind with the respective boundary conditions. The accuracy of solving the formulated problem depends on the level of splitting and is assured by using a large number of finite elements [16].

Computer simulation results

Calculations were performed for two models: in the first case the values of effective heat exchange coefficient α_2 were taken from the experimental measurements of heat exchange between the environment and heat meter surface without thermal insulation, and in the second case medical thermal insulation was taken into account.

Computer simulation was used to obtain the distributions of temperature and heat flux density lines in human biological tissue and thermoelectric heat meter (Figs. 3 to 5), as well as to construct the isothermal surfaces in biological tissue (Figs. 6 and 7) with regard to edge effects in a three-dimensional computer model.

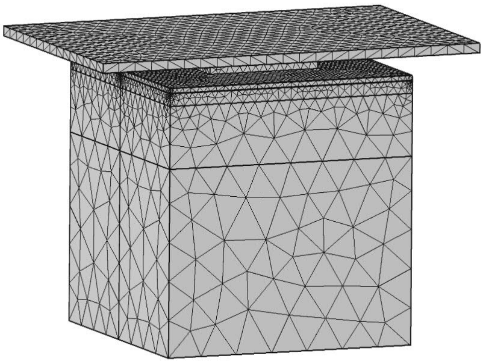

Fig. 2. Finite element method mesh.

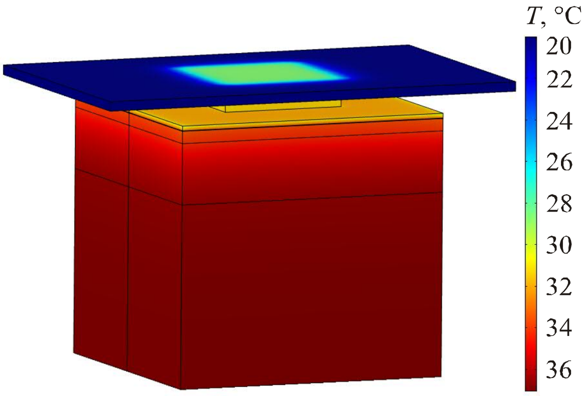

Fig. 3. Temperature distribution in biological tissue having on its top thermoelectric heat meter with thermal insulation.

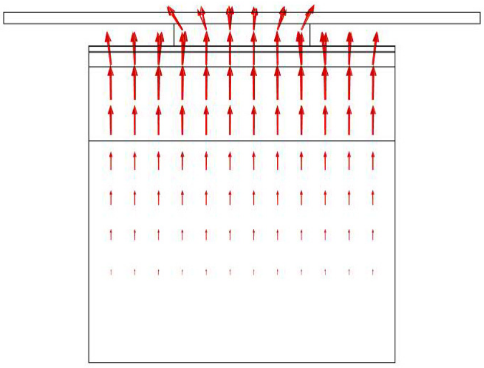

Fig. 4. Heat flux density distribution in biological tissue having on its top thermoelectric heat meter with thermal insulation.

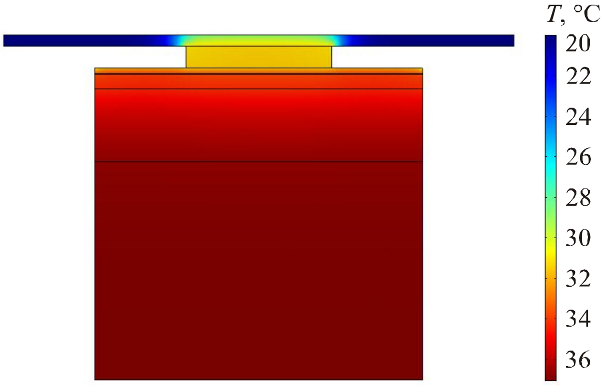

Fig. 5. Temperature distribution in the cut of biological tissue having on its top thermoelectric heat meter with thermal insulation

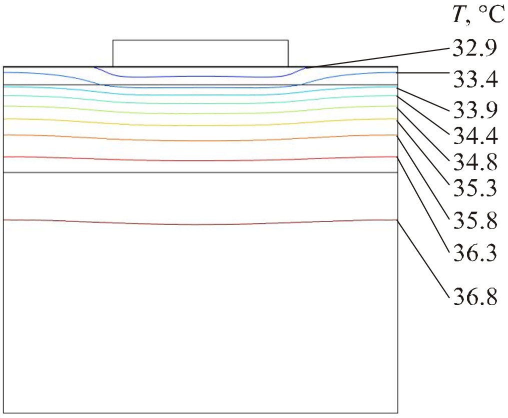

Fig. 6. Isothermal surfaces in biological tissue having on its top thermoelectric heat meter without thermal insulation.

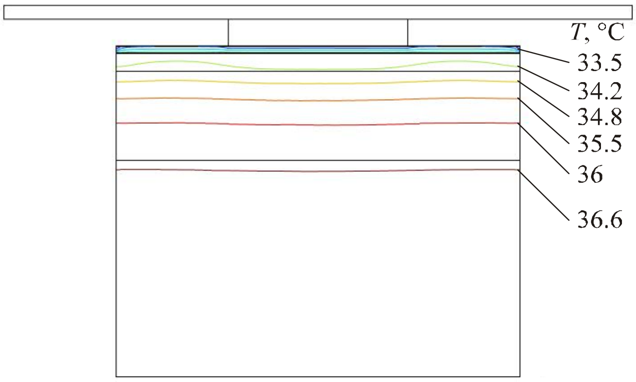

Fig. 7. Isothermal surfaces in biological tissue having on its top thermoelectric heat meter with thermal insulation.

To determine temperature difference between thermoelectric heat meter surfaces, the resulting temperature distributions on the upper and lower heat meter surfaces were averaged, since such distributions are uneven. As an example, temperature distributions along the line in the centre of the lower (Fig. 8) and upper (Fig. 9) surfaces of thermoelectric heat meter are shown.

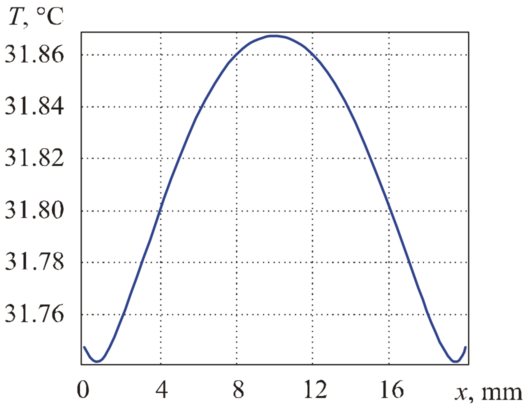

Fig. 8. Temperature distribution on the lower surface of thermoelectric heat meter with thermal insulation extending beyond the heat meter.

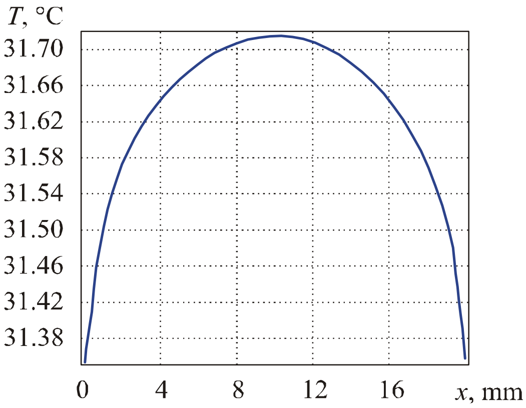

Fig. 9. Temperature distribution on the upper surface of thermoelectric heat meter with thermal insulation extending beyond the heat meter.

Fig. 10 depicts temperature distribution in biological tissue having on its top thermoelectric heat meter with thermal insulation. Fig. 11, accordingly, shows temperature distribution on the surface of external thermal insulation.

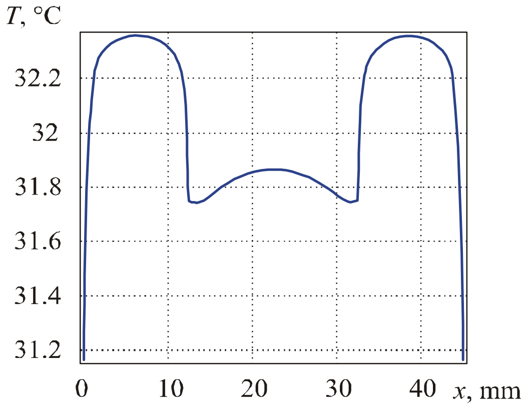

Fig. 10. Temperature distribution on the surface of biological tissue having on its top thermoelectric heat meter with thermal insulation.

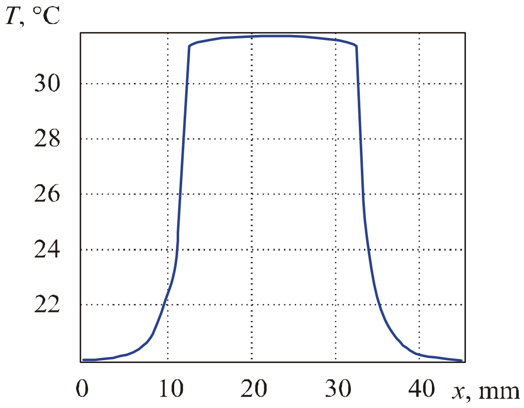

Fig. 11. Temperature distribution on the surface of thermal insulation located on thermoelectric heat meter.

Computer simulation was used to determine the effect of thermal insulation on thermoelectric heat meter readings under real-service conditions. Dependence of temperature difference in thermoelectric heat meter on the thickness of heat meter thermal insulation (the number of external bandage layers N_{extern}) with a different thickness of thermal insulation between biological tissue and heat meter (the number of internal bandage layers N_{in}) was established for the case when thermal insulation does not extend beyond the heat meter (Fig. 12) and does so (Fig. 13).

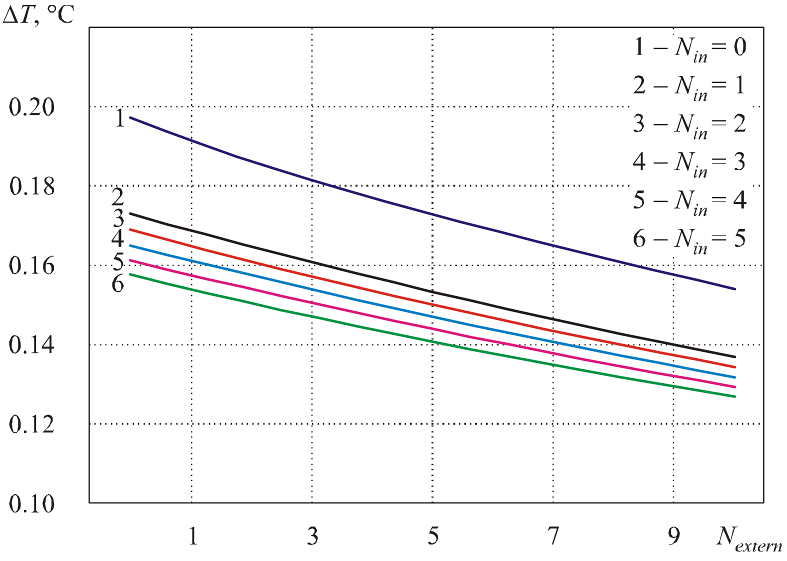

Fig. 12. Dependence of temperature difference in thermoelectric heat meter on the thickness of heat meter thermal insulation (the number of external bandage layers N_{extern}) with a different thickness of thermal insulation between biological tissue and heat meter (the number of internal bandage layers N_{in}) for the case when the external thermal insulation does not exceed beyond the heat meter upper surface.

From Fig. 12 it is seen that increasing the thickness of thermal insulation between biological tissue and thermoelectric heat meter, as well as increasing the thickness of external insulation on heat meter definitely results in decreasing temperature difference between heat meter surfaces. A reduction in thermoelectric heat meter readings can reach 35 % as compared to the case when thermal insulation is absent. The irregularity of curves in Figs. 12 and 13 is due to the difference in heat exchange coefficients between the skin surface and thermoelectric heat meter surface.

For the case when the external thermal insulation extends beyond the heat meter upper surface, its effect on temperature difference changes for the opposite (Fig. 13).

Thus increasing the thickness of thermal insulation on the biological tissue results in the reduction of temperature difference between heat meter surfaces, however, increasing the thickness of heat meter insulation in this case results in the increase of the corresponding temperature difference. It is due to the fact that thermal insulation on thermoelectric heat meter serves as a peculiar heat exchanger. From Fig. 13 it is seen that the presence of external thermal insulation on thermoelectric heat meter can increase heat meter readings up to 30% as compared to the case when such insulation is absent.

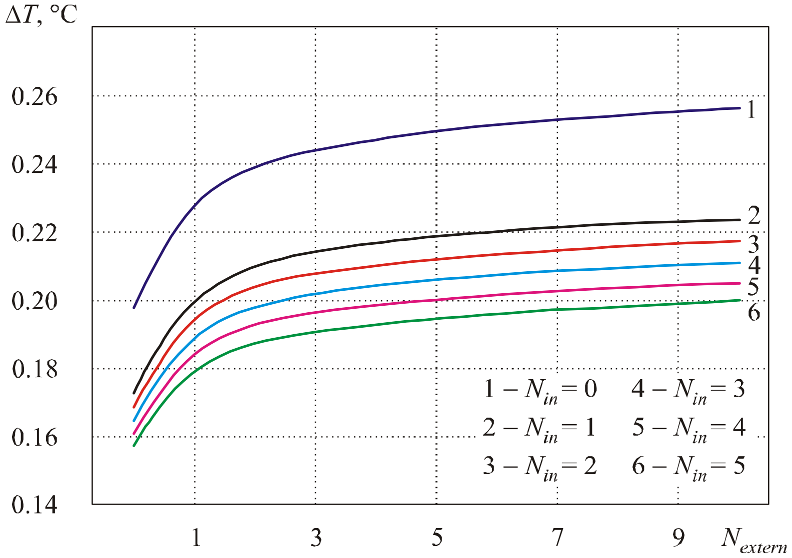

Fig. 13. Dependence of temperature difference in thermoelectric heat meter on the thickness of heat meter thermal insulation (the number of external bandage layers N_{extern}) with a different thickness of thermal insulation between biological tissue and heat meter (the number of internal bandage layers N_{in}) according to a physical model when the external thermal insulation extends beyond the heat meter.

Thus it is established that the presence of thermal insulation on the biological tissue and thermoelectric heat meter really has an effect on heat meter readings. Thermal insulation does not always cause a decrease in heat meter readings. In some cases it leads to their increase, since thermal insulation serves as a peculiar heat exchanger. This, in turn, should be taken into account in the measurement of human heat fluxes by creating identical conditions at repeated measurements.

Conclusions

1. With the aid of computer simulation the effect of thermal insulation on thermoelectric heat flux readings under real-service conditions is investigated. It is established that the presence of thermal insulation on thermoelectric heat meter does not always cause a decrease in its readings, and there are instances where it leads to their increase, since thermal insulation serves as a peculiar heat exchanger.
2. It is established that due to the presence of medical thermal insulation on thermoelectric heat meter and biological tissue, heat meter readings can change up to 35%. This fact should be taken into account in the measurement of human heat fluxes by creating identical conditions at repeated measurements.

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