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RESEARCH INTO THE EFFECT OF THERMOELECTRIC HEAT METER ON HUMAN HEAT RELEASE MEASUREMENT

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• *This paper presents the results of computer research into the effect of thermoelectric heat meter on the accuracy of human heat release measurement. It was established that the effect of thermoelectric heat on human heat release measurement can be minimized on condition of equality of heat exchange coefficients α_1, α_2 and emissivity coefficients ε_1, ε_2 of heat meter and human skin surface, respectively. In case of considerable difference between these thermophysical characteristics, the error in human heat flux measurement can reach over 200%.*

Introduction

General characterization of the problem. A timely and high-quality diagnostics is a guarantee of successful treatment of various human diseases. For this purpose it is essential to have information on human heat release, since it is exactly heat flux density that reflects most adequately the degree of intensity of inflammatory processes in human organism [1, 2]. Therefore, human flux measurement is efficient for the early disease detection. Thermoelectric heat meters that offer high sensitivity, precision, fast response, parameter stability over a wide temperature range and are consistent with up-to-date recording equipment do hold promise for such measurements [3, 4]. The above advantages enable thermoelectric heat meters to be used for the diagnostics of healthy and hurt parts of human organism [5-8].

However, the problem of effect of thermoelectric heat meter on the accuracy of human heat flux measurement is still not completely understood. The effect of heat meters was studied for the cases when heat transfer from heat meters was due to thermal conductivity from heat sources [4].

However, for living objects such problem is considerably complicated, because there is heat transfer by blood in each layer of biological tissue and the metabolic heat is additionally released [9, 10]. It is very difficult to solve this problem analytically, so one should use the methods of object-oriented computer simulation [11]. Besides, it is still unknown what human heat flux measurement error might be in the case when thermophysical characteristics of thermoelectric heat meter are much different from similar characteristics of biological tissue. Therefore, the problem of investigating the effect of thermoelectric heat meter on the determination of heat flux and change in human skin surface temperature during medical and biological research is timely.

Therefore, *the purpose of this work* is to determine the errors of human heat flux measurement related to the effect of thermoelectric heat meter on the object under study.

Physical, mathematical and computer models of a biological tissue with a thermoelectric heat meter

According to a physical model (Fig. 1), an area of human biological tissue is a structure of three skin layers (epidermis 1, dermisc 2, hypodermic layer 3) and internal tissue 4 and is characterized by thermal conductivity κ_i, specific heat C_i, density ρ_i, blood perfusion rate ω_i, blood density ρ_b, blood heat capacity C_b and specific heat release q_{met} due to metabolic processes (Table). The respective layers of biological tissue 1 – 4 are considered as volumetric heat sources q_i, where:

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

The thickness of each such layer is l_i. The interface temperatures of the respective biological tissue layers are T_4, T_5, T_6 and T_7.

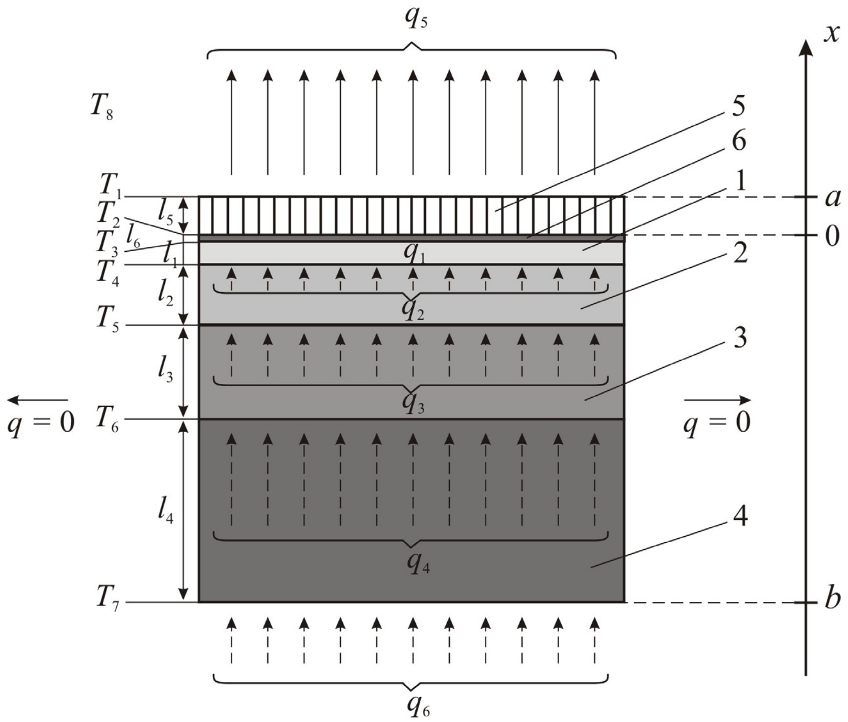

Fig. 1. A physical model of a biological tissue with a thermoelectric heat meter 1 – epidermis, 2 – dermis, 3 – hypodermic layer, 4 – internal tissue, 5 – thermoelectric heat meter, 6 – additional layer characterizing thermal resistance of a contact between thermoelectric heat meter and surface skin layer (epidermis).

Thermoelectric heat meter 5 is a rectangular bar of thickness l_5 characterized by thermal conductivity κ and specific heat C.

The surface layer of skin area (epidermis 1) with temperature T_3 is in the state of heat exchange with thermoelectric heat meter 5 with contact surface temperature T_2. Skin heat exchange due to perspiration is not taken into account. Thermal resistance of a contact between thermoelectric heat meter 5 and epidermis layer 1 is taken into account by additional layer 6 of thickness l_6 with thermal resistance of R_m. The free surface of heat meter 5 with temperature T_1 is in the state of heat exchange with the ambient of temperature T_8 which is taken into account by heat exchange coefficient α_1 and emissivity coefficient ε_1. Specific heat flux from the surface of thermoelectric heat meter to the ambient is q_5, and specific heat flux of internal human organs – q_6.

As long as a physical model is a four-layer area of biological tissue, with identical biochemical processes occurring in the other adjacent layers, we can consider that there is no heat overflow along the skin (q = 0).

Table

Thermophysical properties of human biological tissue [9, 10]

Biological tissue layers	Thickness (mm)	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)	Tissue blood perfusion rate ($m^3 \cdot s^{-1} \cdot m^{-3}$)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^2$)
Epidermis	0.08	3590	0	0.24	1200
Dermis	2	3300	0.00125	0.45	1200
Hypodermic layer	10	2500	0.00125	0.19	1000
Internal tissue	30	4000	0.00125	0.5	1000

Blood density ρ_b = 1060 ($kg \cdot m^{-3}$), blood heat capacity C_b = 3770 ($J \cdot kg^{-1} \cdot K^{-1}$).

If there is no thermoelectric heat meter 5 on the skin, convective heat exchange between the skin and the ambient is taken into account by heat exchange coefficient α_2, and heat exchange by radiation – by ε_2.

In order to determine the effect of thermoelectric heat meter on human heat release, computer simulation was made by using Comsol Multiphysics software package [11], which allows simulation of thermophysical processes in biological tissues with regard to blood circulation and metabolism. Equation of heat exchange in a biological tissue looks as follows [9, 10]:

$$\rho \cdot C \cdot \frac{\partial T}{\partial t} = \nabla (k \cdot \nabla T) + \rho_b \cdot C_b \cdot \omega_b \cdot (T_b - T) + q_{met}, \tag{2}$$

where ρ is the density of biological tissue respective layers (kg/m^3), C_b is specific heat of biological tissue layers ($J/kg \cdot K$), ρ_b is blood density (kg/m^3), C_b is blood specific heat ($J/kg \cdot K$), ω_b is blood circulation rate (l/s), T_b is human blood temperature (K), with T_b = 310.15 K, q_{met} is the amount of heat due to metabolism (W/m^3).

A component in the left-hand side of equation (2) is the rate of change in thermal energy located in unit volume of biological tissue. Three components in the right-hand side of this equation are the rate of change in thermal energy due to thermal conductivity, perfusion and metabolic heat, respectively. For this simplified physical model (Fig. 1) the metabolic heat is taken to be equal to zero as compared to other heat fluxes of this area.

To solve the problem set in this work, it is sufficient to consider a one-dimensional steady-state model. Then equation (2) simplifies to (3):

$$\frac{d}{dx}\left(k \cdot \frac{dT}{dx}\right) + \rho_b \cdot C_b \cdot \omega_b \cdot (T_b - T) = 0. \tag{3}$$

Heat exchange equation in a biological tissue (3) was solved with the respective boundary conditions (4) by finite element method used in Comsol Multiphysics computer program (Fig. 2):

$$\begin{cases} T\big|_{x=b} = 310.15\ \text{K}, \\ q\big|_{x=0,\ x=a} = \alpha \cdot (T_0 - T) + \varepsilon \cdot \sigma \cdot (T_0^4 - T^4), \end{cases} \tag{4}$$

where q is heat flux density, T is absolute temperature, T_0 is ambient temperature, α is heat exchange coefficient, ε is emissivity coefficient, σ is Boltzmann constant.

Computer simulation was used to obtain temperature distributions in the bulk of human biological tissue and thermoelectric heat meter (Fig. 3), as well as to construct isothermal surfaces and heat flux density lines for this area (Fig. 4).

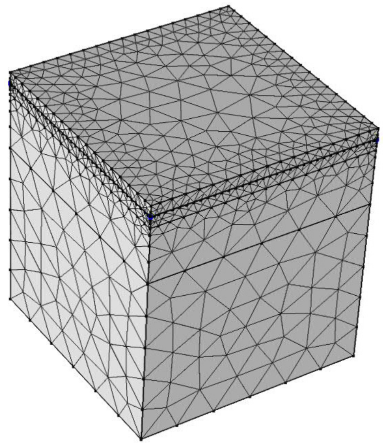

Fig. 2. Finite element method grid.

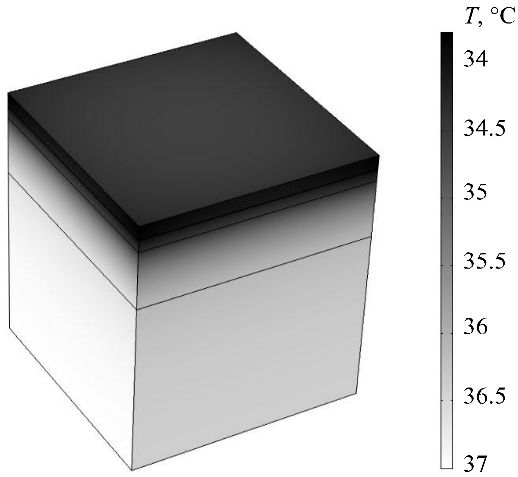

Fig. 3. Temperature distribution in a biological tissue bearing on its surface a thermoelectric heat meter.

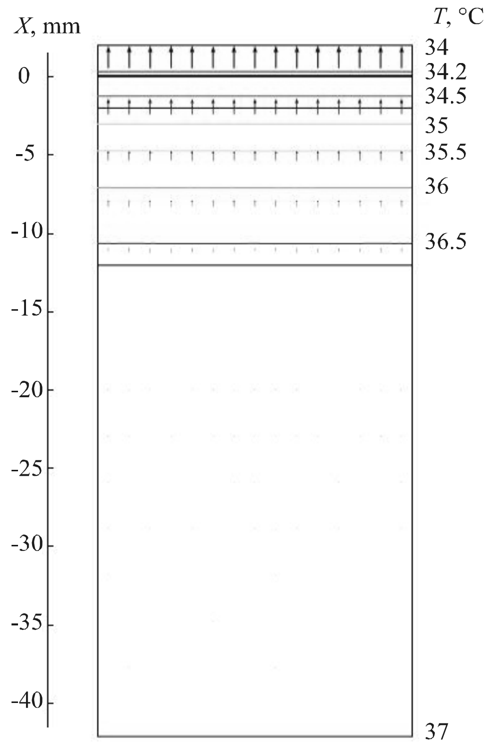

Fig. 4. Isothermal surfaces and heat flux density lines in the biological tissue bearing on its surface a thermoelectric heat meter.

Computer simulation results

Computer simulation was used to establish the dependence of errors in measurement of human heat flux δ_q on the heat exchange coefficient of skin α_2 with different values of emissivity coefficient ε_2 (Fig. 5) and on the emissivity coefficient of skin ε_2 with different values of heat exchange coefficient of skin α_2 (Fig. 6) for the case of thermoelectric heat meter with thermophysical characteristics $\alpha_1 = 5.6$ (W/m^2·K), $\varepsilon_1 = 0.7$.

δq is the difference in heat fluxes of human body portion in the presence and absence of thermoelectric heat meter on the surface of this portion.

It was established that the effect of thermoelectric heat meter on human heat release measurement can be minimized on condition of equality of heat exchange coefficients α_1, α_2 and emissivity coefficients ε_1, ε_2 of heat meter and human skin surface, respectively. In case these thermophysical characteristics differ considerably, the error in human heat flux measurement can reach over 200%, since heat meter creates thermal conditions that are different from those in its absence.

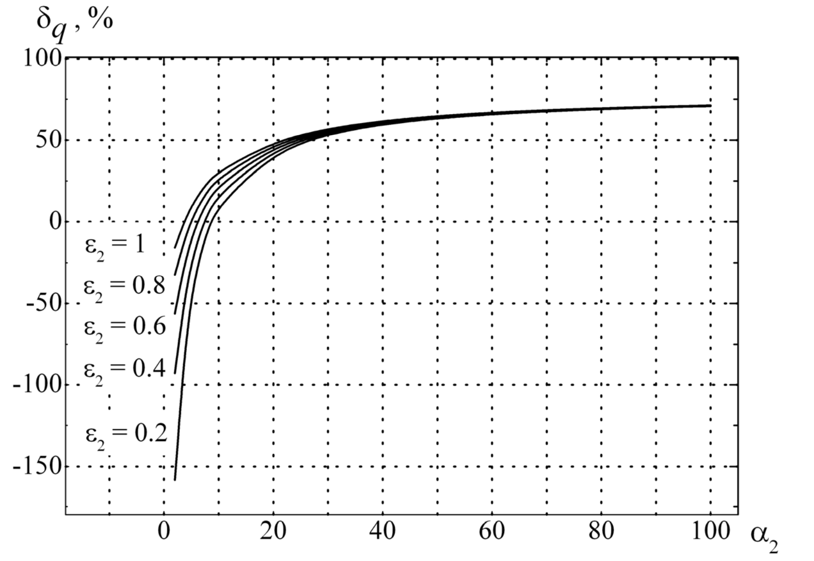

Fig. 5. Dependence of human heat flux measurement error on skin heat exchange coefficient α_2 with different values of skin emissivity coefficient ε_2 for the case of thermoelectric heat meter with parameters α_1 = 5.6 (W/m^2·K), ε_1 = 0.7.

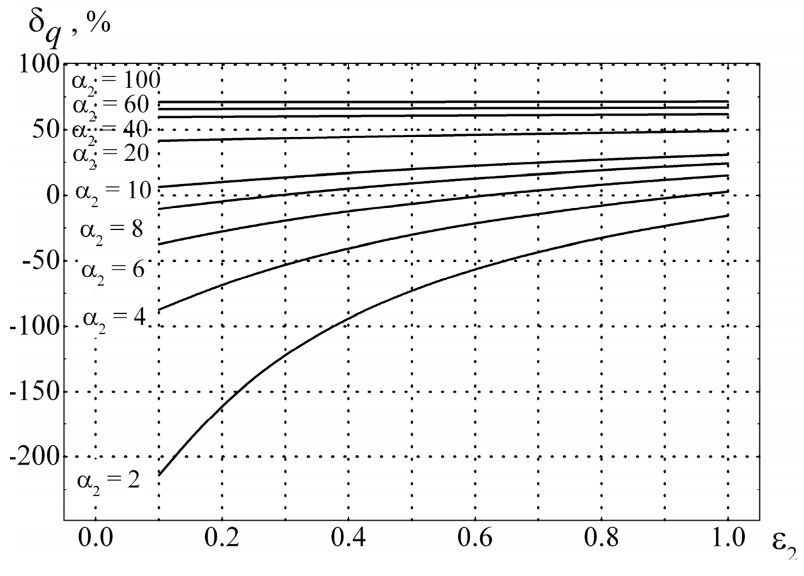

Fig. 6. Dependence of human heat flux measurement error on skin emissivity coefficient ε_2 with different values of skin heat exchange coefficient α_2 for the case of thermoelectric heat meter with parameters α_1 = 5.6 (W/m^2·K), ε_1 = 0.7.

Also studied was a dependence of thermoelectric heat meter temperature difference with different values of heat exchange and emissivity coefficients (Fig. 7). It was established that maximum temperature difference on thermoelectric heat meter of *Bi-Te* based material is as low as ΔT_{max} = 0.2 °C with heat meter thermophysical characteristics ε_1 = 0.5, α_1 = 10 (W/m^2·K) and ambient temperature T_0 = 20 °C.

However, despite the low temperature difference, thermoelectric heat meter affects considerably a change in the temperature of human skin surface and the temperature inside the biological tissue. Temperature distribution inside and on the surface of human skin if there is thermoelectric heat meter with different heat exchange coefficients is represented in Fig. 8.

From Fig.8 it is seen that the temperature of human skin surface if there is thermoelectric heat meter is reduced from the value of T = 35 °C to T = 32.5 °C with a change in heat exchange coefficient $\alpha_1 = 2 \div 10$ (W/m^2·K) and fixed values of emissivity coefficient $\varepsilon_1 = 0.5$ and ambient temperature T_0 = 20 °C. In this case, further growth of heat exchange coefficient leads to reduction of human skin surface temperature which can distort considerably the measurement of human heat release in medico-biological investigations.

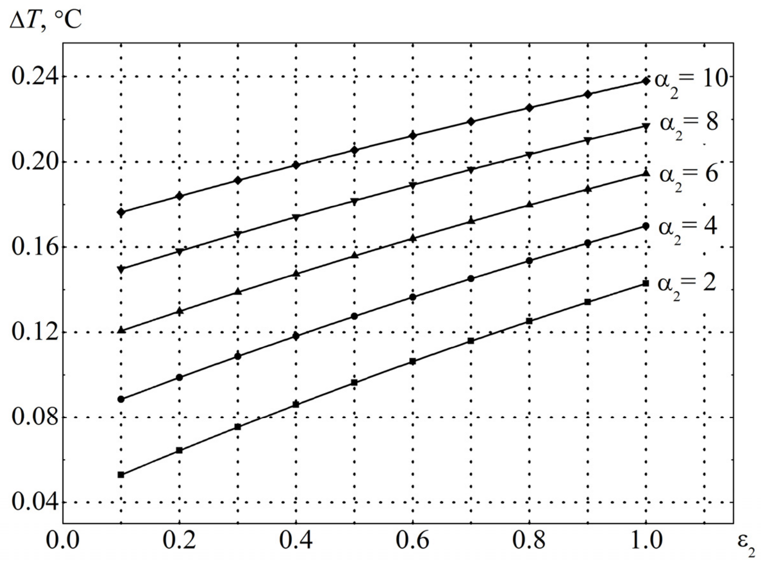

Fig. 7. Temperature difference on thermoelectric heat meter with different values of heat exchange and emissivity coefficients.

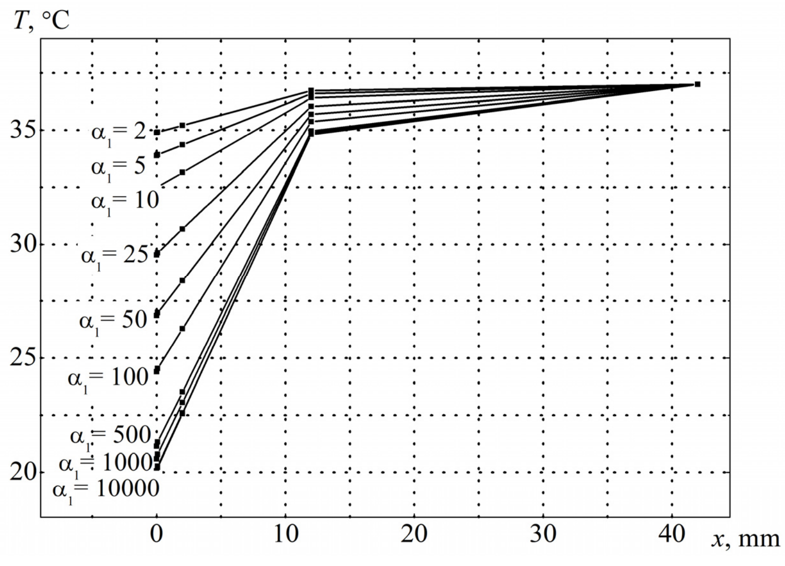

Fig. 8. Temperature distribution inside and on the surface of human skin if there is thermoelectric heat meter with different heat exchange coefficients α_1 *(emissivity coefficient* $\varepsilon_1 = 0.5$, *ambient temperature* T_0 = 20 °C).

Conclusions

1. Computer simulation was used to study the effect of thermoelectric heat meter on the accuracy of human heat release measurement. It was established that the error of human heat flux measurement can reach over 200%.
2. It was established that the effect of thermoelectric heat meter on human heat release measurement can be minimized under the condition that heat exchange coefficients and emissivity coefficients of human skin surface are equal.

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