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ENERGY CHARACTERISTICS OF THERMOELECTRIC CONVERTERS POWERED BY HUMAN BODY HEAT

The paper presents a three-dimensional physical model, analytical description and results of computer simulation of thermoelectric converters placed on the surface of the human body. Optimal properties of thermoelectric converters are determined, whereby maximum values of electric power W_{max} and efficiency are achieved in a state of rest and during physical exertion on the human body.
Key words: thermoelectric microgenerator, human body, energy characteristics, state of rest, physical exertion, computer simulation.

Introduction

In [1 – 10], simple one-dimensional physical models of a thermoelectric microgenerator and the process of temperature distribution and heat flows in the "human body – thermoelectric microgenerator" system are used. Such models do not take into consideration thermophysical processes in human biological tissue, namely blood circulation and metabolic processes

Therefore, *the purpose of the work* is to develop a three-dimensional physical model of thermal and electrical processes in the "human body – thermoelectric microgenerator" system, its mathematical description and determination by computer methods of the optimal properties of thermoelectric converters, which achieve the maximum values of electrical power and efficiency in a state of rest and during physical exertion on the human body.

1. Physical model

Consider a three-dimensional physical model of human skin (Fig. 1), on the surface of which a thermoelectric converter 1 is placed. Human skin consists of four layers (epidermis 2, dermis 3, subcutaneous layer 4, internal biological tissue 5) and is characterized by the following parameters: thermal conductivity κ_i, specific heat capacity C_i, density ρ_i, blood perfusion rate ω_{bi}, blood density ρ_b, blood heat capacity C_b and specific heat release q_{meti} due to metabolic processes (Table 1). The geometric dimensions of each skin layer are a_i, b_i, L_i. The temperatures at the boundaries of the corresponding skin layers are $T(z_i)$.

A thermoelectric converter 1 is a monolithic homogeneous bar of thickness L_1 with equivalent thermal conductivity κ_1. The temperature on the contact surface of the human skin and the thermoelectric converter is $T(z_1)$, and the temperature on the surface of the thermoelectric converter is $T(0)$. The temperature difference across the thermoelectric converter is ΔT.

The surface of the skin and the thermoelectric converter are in a state of heat exchange with the environment with heat exchange coefficients α_1 and α_2. The ambient temperature is T_{amb}. The density of the heat flow passing through the thermoelectric converter is Q. The lateral surfaces of the human skin and the thermoelectric converter are adiabatically insulated.

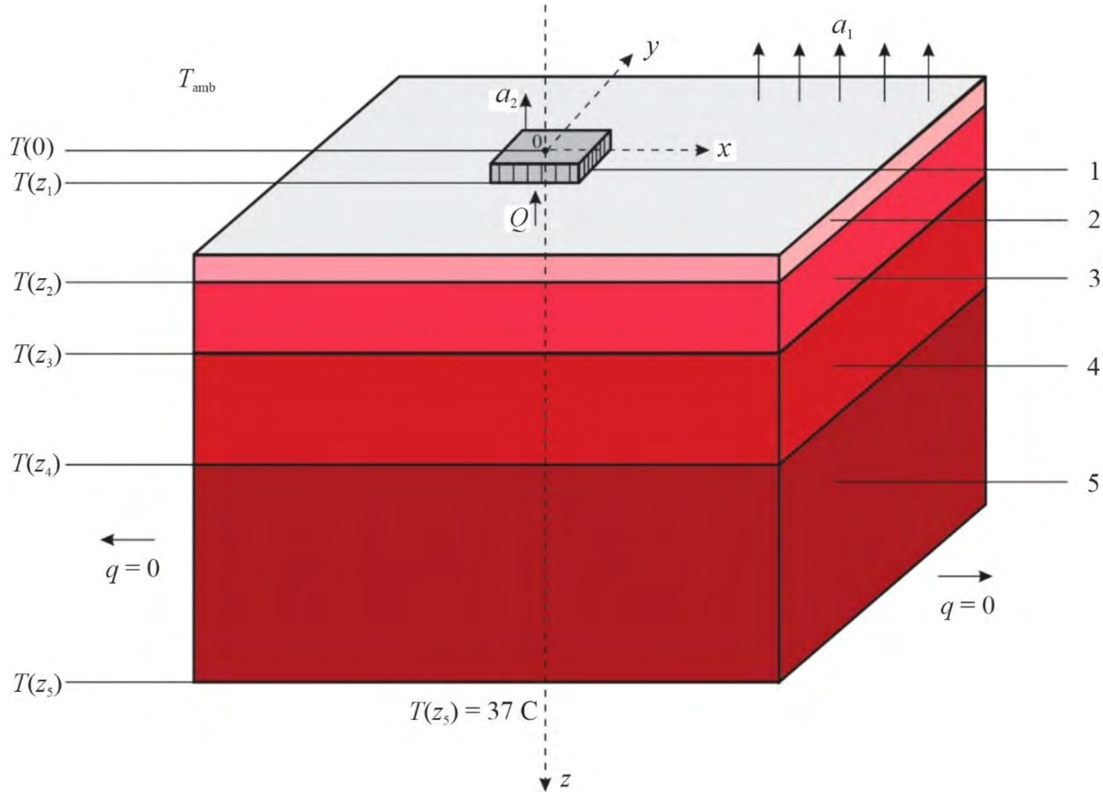

Fig. 1. Physical model of human skin, on the surface of which a thermoelectric converter is located: 1 – thermoelectric converter, 2 – epidermis, 3 – dermis, 4 – subcutaneous layer, 5 – internal tissue.

Table 1

Thermophysical properties of human skin layers [12 – 16]

Layers of biological tissue	*Epidermis*	*Dermis*	*Subcutaneous layer*	*Internal tissue*
Thickness, L (mm)	0.08	2	10	30
Specific heat, C ($W{\cdot}c{\cdot}kg^{-1}{\cdot}K^{-1}$)	3590	3300	2500	4000
Thermal conductivity, κ ($W{\cdot}m^{-1}{\cdot}K^{-1}$)	0.24	0.45	0.19	0.5
Density, ρ ($kg{\cdot}m^{-3}$)	1200	1200	1000	1000
Metabolic heat density, q_{met} ($W{\cdot}m^{-3}$)	368.1	368.1	368.3	368.3
Blood tissue perfusion rate, ω_b ($m^3{\cdot}s^{-1}{\cdot}m^{-3}$)	0	0.00125	0.00125	0.00125
Blood temperature, T_b, *(K)*	310	310	310	310
Blood density, ρ_b ($kg{\cdot}m^{-3}$)	1060	1060	1060	1060
Blood heat capacity, C_b ($W{\cdot}c{\cdot}kg^{-1}{\cdot}K^{-1}$)	3770	3770	3770	3770

2. Analytical description

In general, the equation of heat exchange in biological tissue has the following form [12-16]:

$$\rho c \frac{\partial T}{\partial t} = \nabla\left(\kappa \nabla T\right) + \rho_b c_b w_b \left(T_b - T\right) + q_{met}\,, \tag{1}$$

where ρ is the density of biological tissue, c is the specific heat of biological tissue, κ is the thermal conductivity of biological tissue, ρ_b is the density of blood, c_b is the specific heat of blood, ω_b is blood perfusion rate, T_b is blood temperature, q_{met} is the density of heat release due to metabolism.

The term on the left side of equation (1) represents the rate of change of thermal energy contained in a unit volume of biological tissue. The three terms on the right side of this equation represent, respectively, the rate of change of thermal energy due to thermal conductivity, blood perfusion, and metabolic heat.

To solve the problem posed in this paper, we will consider a three-dimensional stationary case. Then equation (1) will take on the form (2):

$$\kappa \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right) + \rho_b c_b w_b \left(T_b - T\right) + q_{met} = 0\,. \tag{2}$$

The stationary heat exchange equation for a thermoelectric converter, provided that the influence of thermoelectric phenomena is neglected, which is valid for small temperature differences, will have the following form:

$$\kappa\left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right) = 0\,. \tag{3}$$

Therefore, to find the stationary temperature distribution in the "thermoelectric converter – human body surface" system, it is necessary to solve the boundary value problem for a three-dimensional system of equations (4), each equation of which corresponds to the corresponding layer of skin according to the physical model (Fig. 1):

$$\begin{cases}
\kappa_1 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_1\\ y=0\div y_1\\ z=0\div z_1}} = 0 \\
\kappa_2 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_1\div z_2}} + q_{met_1} = 0 \\
\kappa_3 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_1\div z_2}} + \rho_b c_b w_b \left(T_b - T(x,y,z)\right) + q_{met_2} = 0 \\
\kappa_4 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_1\div z_2}} + \rho_b c_b w_b \left(T_b - T(x,y,z)\right) + q_{met_3} = 0 \\
\kappa_5 \cdot \left(\frac{\partial^2 T(x,y,z)}{\partial x^2} + \frac{\partial^2 T(x,y,z)}{\partial y^2} + \frac{\partial^2 T(x,y,z)}{\partial z^2}\right)\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_1\div z_2}} + \rho_b c_b w_b \left(T_b - T(x,y,z)\right) + q_{met_4} = 0
\end{cases} \tag{4}$$

with the following boundary conditions (5 – 9) in the form:

$$\alpha_1 \cdot (T(x,y,z) - T_{пов})\Big|_{\substack{x=0\div x_1\\ y=0\div y_1\\ z=0}} = \kappa_1 \cdot \frac{\partial T(x,y,z)}{\partial z}\Big|_{\substack{x=0\div x_1\\ y=0\div y_1\\ z=0}}$$

$$\kappa_1 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^{-}\Bigg|_{\substack{x=0\div x_1\\ y=0\div y_1\\ z=z_1}} = \kappa_2 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^{+}\Bigg|_{\substack{x=0\div x_1\\ y=0\div y_1\\ z=z_1}} \tag{5}$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=0\\ y=0\div y_1\\ z=0\div z_1}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_1\\ y=0\\ z=0\div z_1}} = 0$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=x_1\\ y=0\div y_1\\ z=0\div z_1}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_1\\ y=y_1\\ z=0\div z_1}} = 0$$

$$T^{-}(x,y,z)\Big|_{\substack{x=0\div x_1\\ y=0\div y_1\\ z=z_1}} = T^{+}(x,y,z)\Big|_{\substack{x=0\div x_1\\ y=0\div y_1\\ z=z_1}};$$

$$\kappa_2 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^{+}\Bigg|_{\substack{x=x_1\div x_2\\ y=y_1\div y_2\\ z=z_1}} = \alpha_2 \cdot \left(T^{+}(x,y,z) - T_{пов}\right)\Big|_{\substack{x=x_1\div x_2\\ y=y_1\div y_2\\ z=z_1}}$$

$$\kappa_2 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^{-}\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_2}} = \kappa_3 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^{+}\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_2}} \tag{6}$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=0\\ y=0\div y_2\\ z=z_1\div z_2}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_2\\ y=0\\ z=z_1\div z_2}} = 0$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=x_2\\ y=0\div y_2\\ z=z_1\div z_2}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_2\\ y=y_2\\ z=z_1\div z_2}} = 0$$

$$T^{-}(x,y,z)\Big|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_2}} = T^{+}(x,y,z)\Big|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_2}}$$

$$\kappa_3 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^{-}\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_3}} = \kappa_4 \cdot \left(\frac{\partial T(x,y,z)}{\partial z}\right)^{+}\Bigg|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_3}} \tag{7}$$

$$\frac{\partial T}{\partial x}\Big|_{\substack{x=0\\ y=0\div y_2\\ z=z_2\div z_3}} = 0 \qquad \frac{\partial T}{\partial y}\Big|_{\substack{x=0\div x_2\\ y=0\\ z=z_2\div z_3}} = 0$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=x_2\\ y=0\div y_2\\ z=z_2\div z_3}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=y_2\\ z=z_2\div z_3}}=0$$

$$\left.T^{-}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_3}}=\left.T^{+}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_3}}$$

$$\left.\kappa_4\cdot\left(\frac{\partial T(x,y,z)}{\partial z}\right)^{-}\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_4}}=\left.\kappa_5\cdot\left(\frac{\partial T(x,y,z)}{\partial z}\right)^{+}\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_4}} \tag{8}$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=0\\ y=0\div y_2\\ z=z_3\div z_4}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=0\\ z=z_3\div z_4}}=0$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=x_2\\ y=0\div y_2\\ z=z_3\div z_4}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=y_2\\ z=z_3\div z_4}}=0$$

$$\left.T^{-}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_4}}=\left.T^{+}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_4}}$$

$$\left.T^{-}(x,y,z)\right|_{\substack{x=0\div x_2\\ y=0\div y_2\\ z=z_5}}=37+273 \tag{9}$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=0\\ y=0\div y_2\\ z=z_4\div z_5}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=0\\ z=z_4\div z_5}}=0$$

$$\left.\frac{\partial T}{\partial x}\right|_{\substack{x=x_2\\ y=0\div y_2\\ z=z_4\div z_5}}=0 \quad \left.\frac{\partial T}{\partial y}\right|_{\substack{x=0\div x_2\\ y=y_2\\ z=z_4\div z_5}}=0$$

where α_1 is the heat exchange coefficient of the skin surface with the environment, α_2 is the heat exchange coefficient of the thermoelectric converter with the environment, $T(x,y,z)$ is the absolute temperature, T_{amb} is the ambient temperature (air).

The solution to this boundary value problem gives the distribution of temperature and heat flow in the “thermoelectric converter – human body surface” system.

To determine the maximum value of the generated electric power W_{max} of the thermoelectric converter, we determine the EMF according to formula (10):

$$E=\lambda\cdot N\cdot\Delta T\,, \tag{10}$$

where

$$\Delta T=T(0,0,z_1)-T(0,0,0)\,. \tag{11}$$

Then the maximum generated electric power W_{max} of the thermoelectric converter is determined by the formula (12):

$$W_{\max} = \frac{E^2}{4 \cdot R_L}, \tag{12}$$

where the load resistance R_L in the W_{max} mode is equal to the resistance of the thermoelectric converter, i.e

$$R_L = R = \frac{1}{\sigma} \cdot \frac{l}{S} \cdot N. \tag{13}$$

The efficiency of the thermoelectric converter is determined by formula (14):

$$\eta = \frac{W}{Q} \cdot 100\%, \tag{14}$$

where the amount of heat passing through the thermoelectric converter is determined as follows:

$$Q = \kappa_1 \cdot S_1 \cdot \int_0^{x_1} \int_0^{y_1} \frac{\partial T(x, y, z)}{\partial z} \Big|_{z=z_1} dxdy. \tag{15}$$

3. Computer model

In order to determine the optimal properties of thermoelectric converters, whereby the maximum values of electric power and efficiency are achieved, a three-dimensional computer model of human skin, on the surface of which a thermoelectric converter is placed, was created. For this, the Comsol Multiphysics package of application programs was used [17], which makes it possible to simulate thermophysical processes in biological tissue, taking into account blood circulation and metabolism [18 – 39].

The calculation of temperature distributions and heat flux density in human skin and a thermoelectric converter was carried out using the finite element method (Fig. 2), the essence of which is that the object under study is divided into a large number of finite elements and in each of them the value of the function is sought that satisfies the specified second-order differential equations with the corresponding boundary conditions. The accuracy of the solution to the problem depends on the level of division and is ensured by using a large number of finite elements [17].

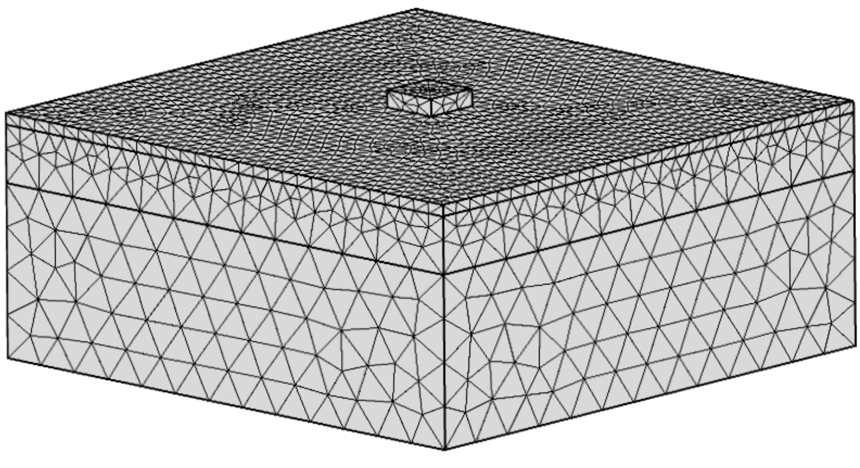

Fig. 2. Finite element method mesh.

Using object-oriented computer simulation, temperature distributions (Fig. 3) and heat flux density lines in the skin and thermoelectric converter were obtained.

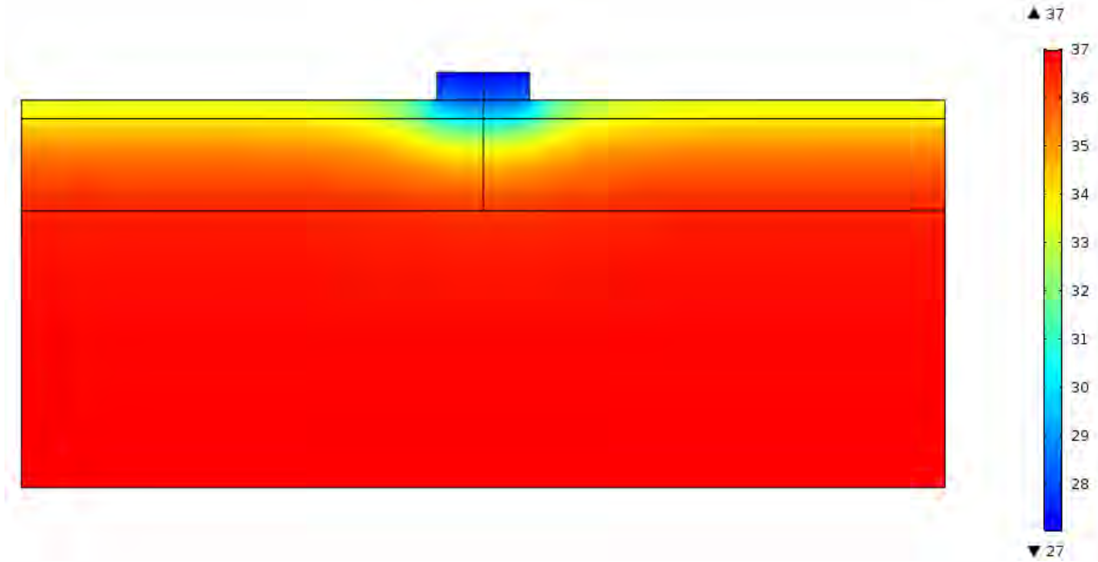

Fig. 3. Temperature distribution in a cross-section of human skin, on the surface of which a thermoelectric converter is located (at an ambient temperature of T = 20 °C).

4. Results of computer simulation

Using computer simulation, the optimal parameters of thermoelectric converters were determined, whereby maximum values of electrical power and efficiency are achieved in a state of rest and during physical exertion on the human body (Fig. 4 – 9).

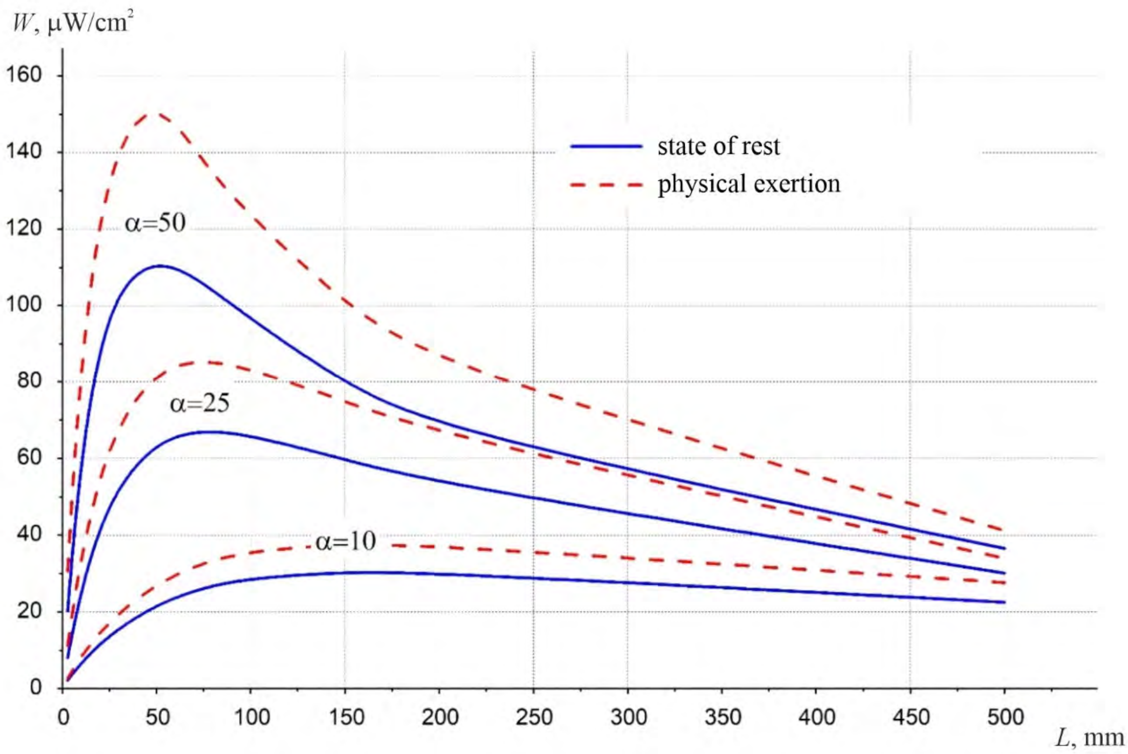

Fig. 4. Dependence of the generated electric power on the height of the thermoelectric converter at an ambient temperature of T = 20 °C and a coefficient of heat exchange with the environment of α = 10, 25, 50 W/m² K.

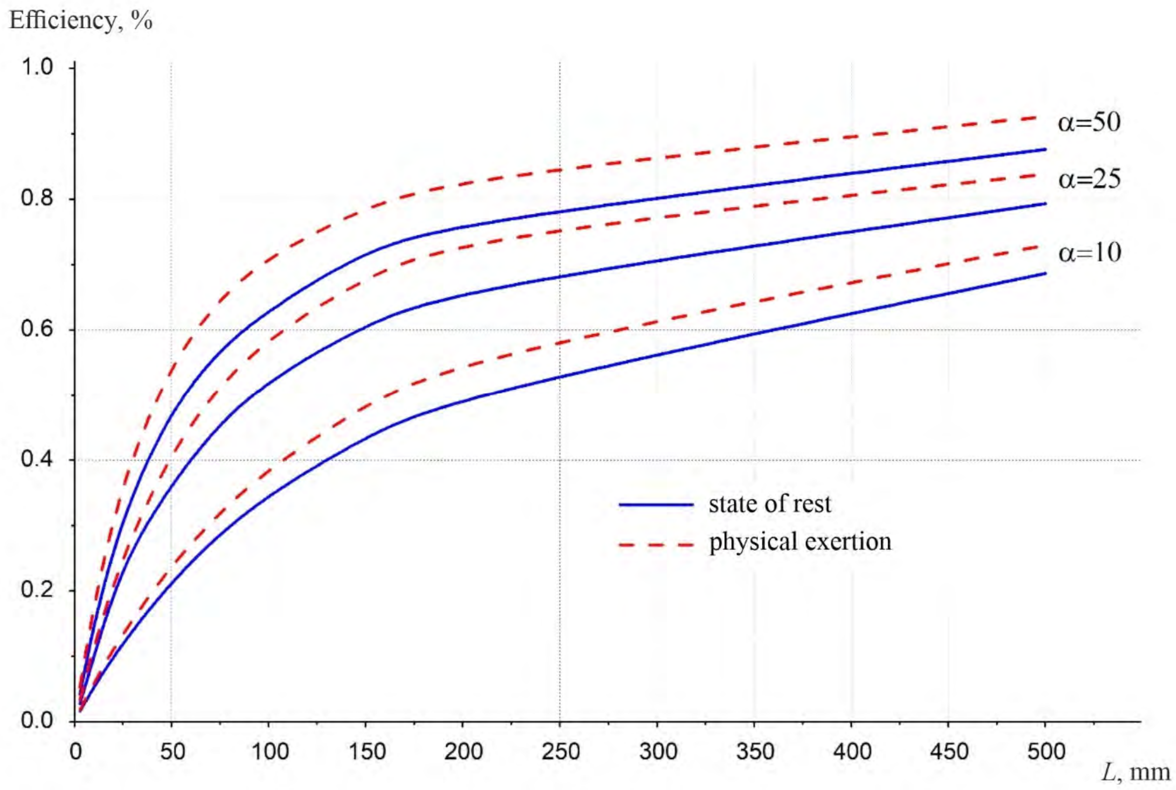

Fig. 5. Dependence of the efficiency on the height of the thermoelectric converter at an ambient temperature of T = 20 °C and a coefficient of heat exchange with the environment α=10, 25, 50 W/m²·K.

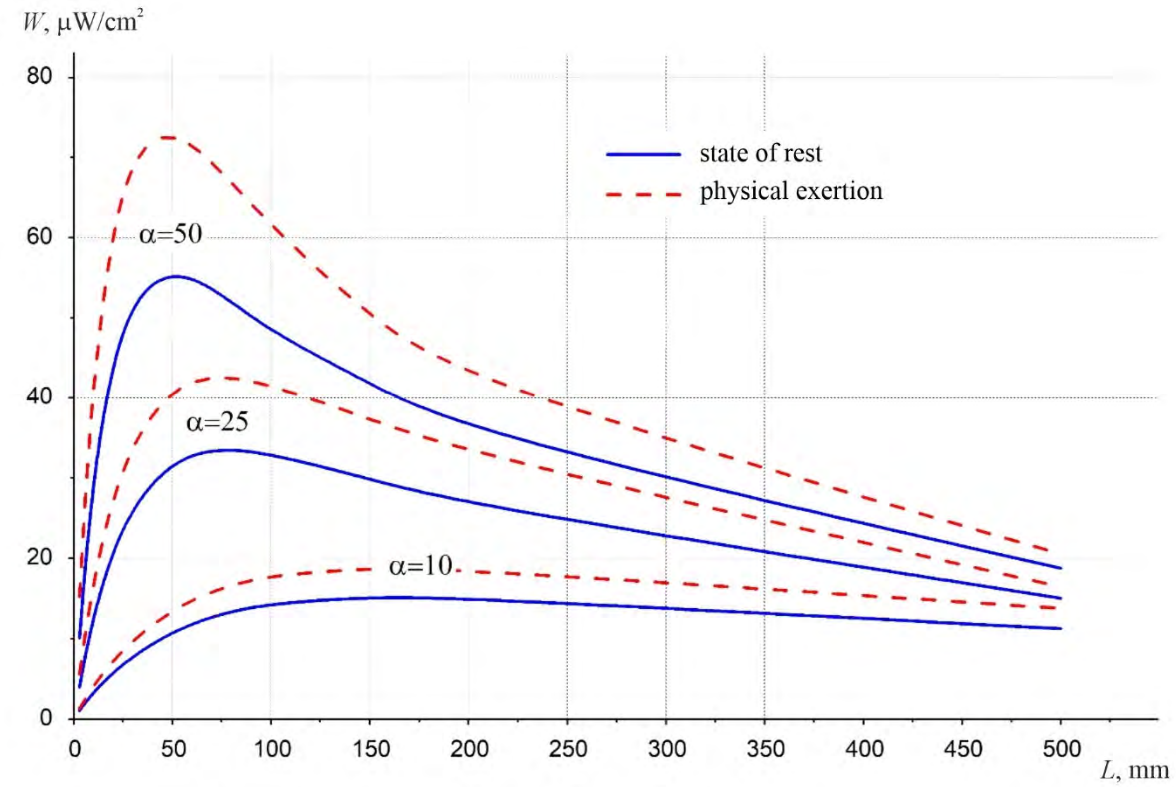

Fig. 6. Dependence of the generated electric power on the height of the thermoelectric converter at an ambient temperature of T = 25 °C and a coefficient of heat exchange with the environment α = 10, 25, 50 W/m² K.

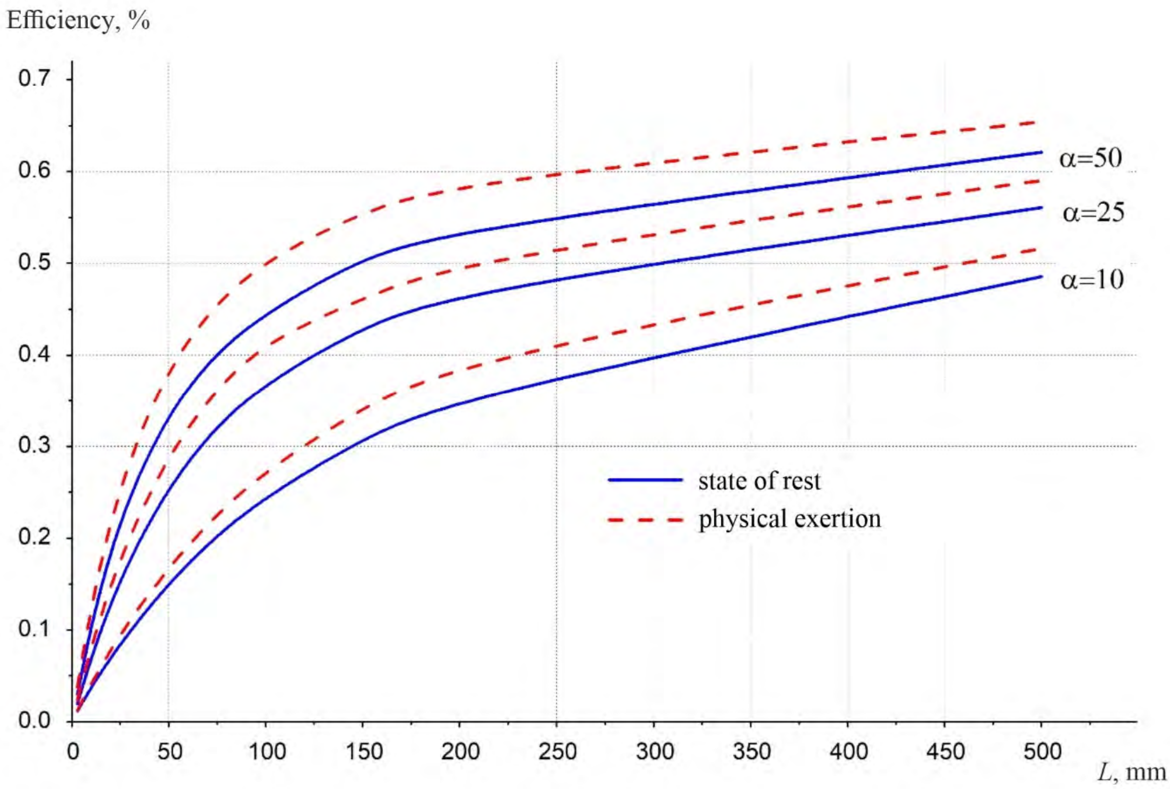

Fig. 7. Dependence of the efficiency on the height of the thermoelectric converter at an ambient temperature of T = 25 °C and a coefficient of heat exchange with the environment α = 10, 25, 50 W/m^2 K.

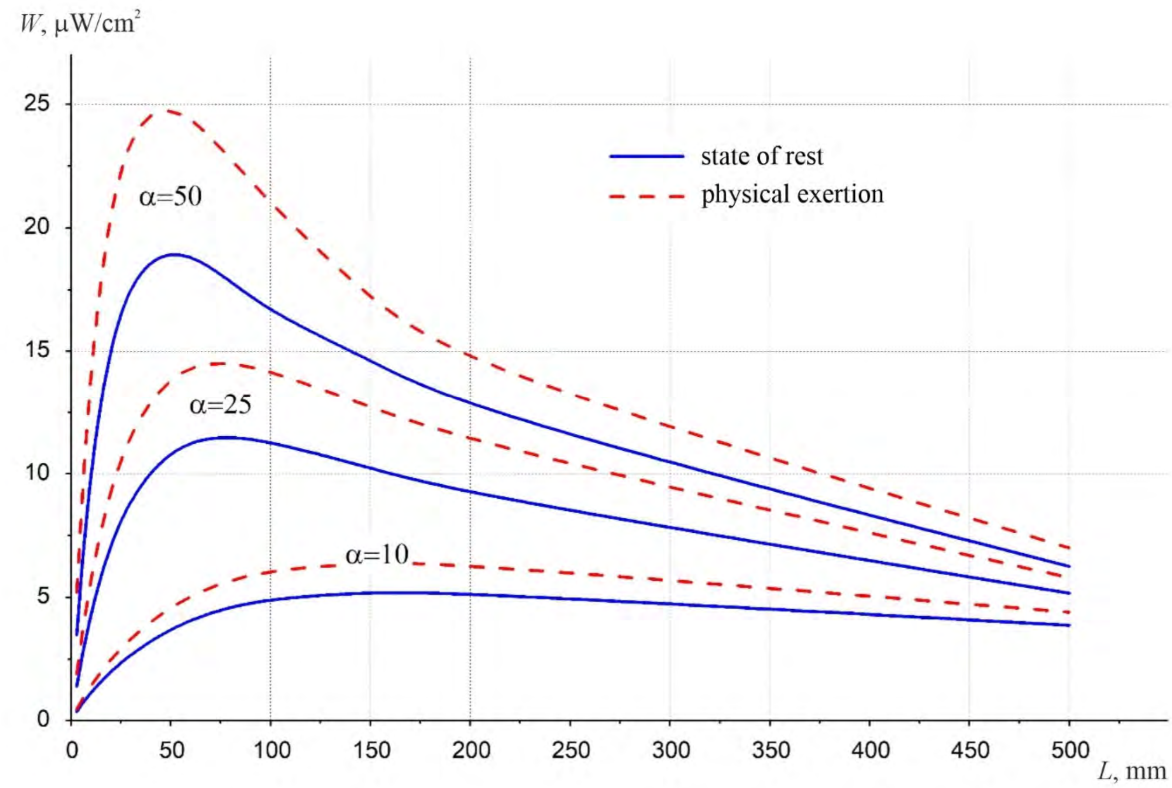

Fig. 8. Dependence of the generated electric power on the height of the thermoelectric converter at an ambient temperature of T = 30 °C and a coefficient of heat exchange with the environment α = 10, 25, 50 W/m2 K.

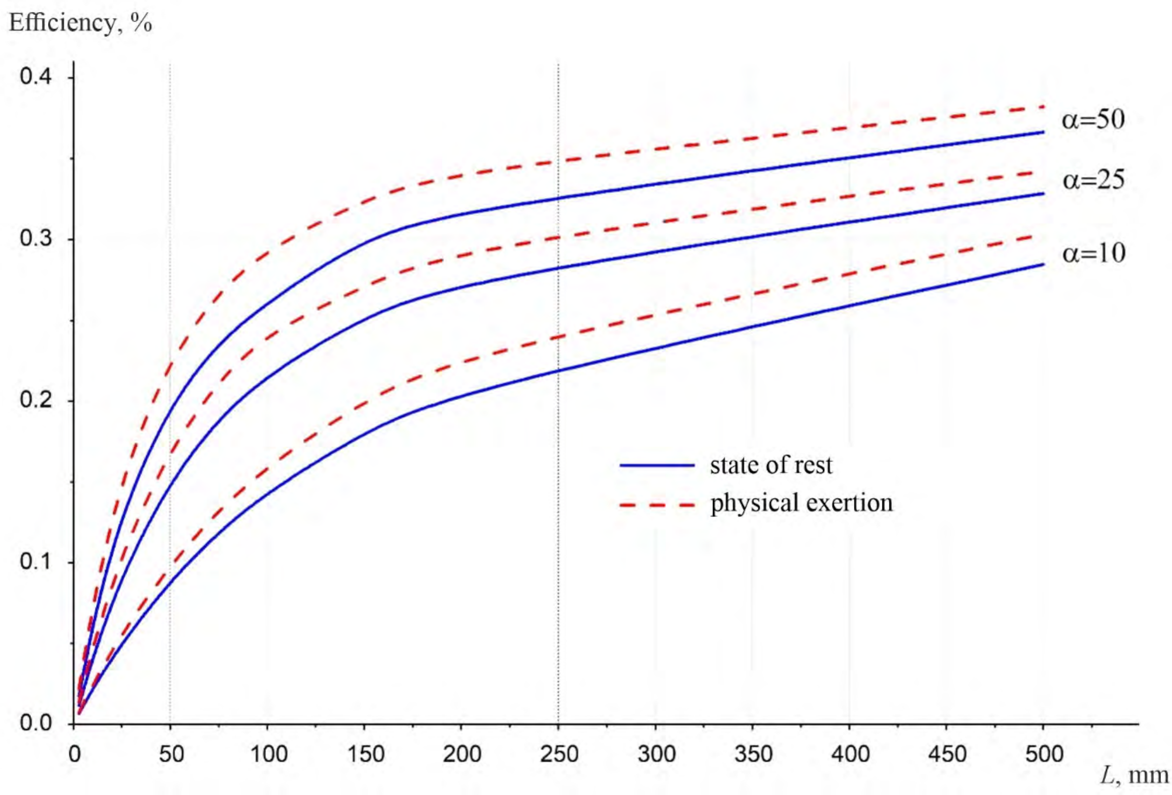

Fig. 9. Dependence of efficiency on the height of the thermoelectric converter at an ambient temperature of T = 30 °C and a coefficient of heat exchange with the environment α = 10, 25, 50 W/m² K.

The obtained results show that the optimal height of the thermoelectric microgenerator is L = 30 ÷ 50 mm, regardless of the heat exchange coefficient of the thermoelectric microgenerator surface with the environment. Improving the heat exchange conditions from α = 10 W/m^{2}K to α = 50 W/m^{2}K leads to an increase in the generated electric power by 4 – 5 times. In this case, the efficiency of the thermoelectric microgenerator increases significantly in the range of L = 0 ÷ 100 mm, and a further increase in the height of the thermoelectric microgenerator does not lead to a sharp increase in efficiency due to a sharp decrease in the generated electric power. Improvement of heat exchange conditions on the surface of the thermoelectric microgenerator provides efficiency increase by approximately 3 times.

As the calculation results showed (Fig. 4 – 9), the generated electric power and efficiency depend significantly on the ambient temperature. It is obvious that at elevated ambient temperatures the value of the working temperature difference on the thermoelectric microgenerator decreases, which leads to a decrease in the value of the generated power and efficiency. Thus, for instance, when the ambient temperature changes from 20 to 30 °C, the optimal value of the generated electric power of the thermoelectric microgenerator decreases several times from 25 μW/cm^2 to 5 μW/cm^2 for a coefficient of heat exchange α = 10 W/m^{2}K and, accordingly, from 110 μW/cm^2 to 18 μW/cm^2 for a coefficient of heat exchange α = 50 W/m^{2}K. Therefore, in order to preserve the energy performance of the thermoelectric microgenerator under elevated ambient temperatures, it is necessary to improve the heat exchange conditions. In practice, this can be ensured by an electronic heat exchange control system on the surface of the thermoelectric microgenerator. For example, for low-power electronic medical equipment, for the power supply of which 20 μW/cm^2 generated by a thermoelectric microgenerator under normal ambient conditions (T = 20 °C, α = 10 W/m^2 K) is sufficient, when the temperature increases to T = 30 °C, it is necessary to improve the heat exchange of the surface of the thermoelectric microgenerator under conditions in which the coefficient of heat exchange will be α = 50 W/m^2 K. In practice, this can be achieved by switching to forced convection from the surface of the thermoelectric microgenerator by controlling the electronic power supply system of the fans that cool the surface of the thermoelectric microgenerator.

Thus, according to estimates and calculations carried out in the work, it was established that in a state of rest, from 1 cm^2 of the surface of the human body can be obtained from 25 μW to 100 μW of electrical energy, and during physical exertion – from 40 μW to 150 μW of electrical energy, depending on the conditions of heat exchange of the surface of the thermoelectric microgenerator with the environment. If we take into account that the average human body surface is 2 m^2, then due to heat emission from the entire surface of the human body, it is possible to obtain from 0.5 W to 2 W of electrical energy in a state of rest, and from 0.8 W to 3 W of electrical energy during physical exertion. Such indicators are sufficient to power many low-power electronic medical devices.

Conclusions

1. A three-dimensional physical model of thermal and electrical processes in the “human body – thermoelectric microgenerator” system has been developed, taking into account thermophysical processes in biological tissue, namely blood circulation and metabolism, and its mathematical description has been performed.
2. Using computer simulation methods, the optimal properties of thermoelectric converters were determined, whereby maximum values of electrical power and efficiency are achieved in a state of rest and during physical exertion on the human body.
3. It has been established that from 1 cm^2 of the human body surface in a state of rest it is possible to obtain a maximum of about 100 μW of electrical energy and during physical exertion – about 150 μW, and, accordingly, from the entire surface of the human body in a state of rest and during physical exertion it is possible to obtain about 2 W and 3 W of electrical energy, which is quite sufficient to power a variety of low-power electronic medical equipment. At the same time, the efficiency of thermoelectric microgenerators powered by the heat of the human body reaches 0.5 – 0.6 %.

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ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ ТЕРМОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ, ЩО ЖИВЛЯТЬСЯ ВІД ТЕПЛА ТІЛА ЛЮДИНИ

У роботі наведено трьохвимірну фізичну модель, аналітичний опис та результати комп'ютерного моделювання термоелектричних перетворювачів, розміщених на поверхні тіла людини. Визначено оптимальні властивості термоелектричних перетворювачів, при яких досягаються максимальні значення електричної потужності W_{max} та ККД у стані спокою та при фізичному навантаженні організму людини.

Ключові слова: термоелектричний мікрогенератор, тіло людини, енергетичні характеристики, стан спокою, фізичне навантаження, комп'ютерне моделювання.

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