R.R. Kobylianskyi

R.R. Kobylianskyi[1,2]

[1]Institute of Thermoelectricity, 1, Nauky str.,
Chernivtsi, 58029, Ukraine;
[2]Yu.Fedkovych Chernivtsi National University,
2, Kotsyubinsky str., Chernivtsi, 58012 Ukraine

COMPUTER SIMULATION OF MEDICAL-PURPOSE THERMOELECTRIC SENSOR READINGS

This paper presents the results of computer research on the impact of thermal medical insulation on the readings of thermoelectric heat flux sensor. A three-dimensional (3D) physical, mathematical and computer model of biological tissue having on its top a thermoelectric sensor with thermal insulation was constructed. It was established that the presence of medical thermal insulation on thermoelectric sensor and biological tissue can change sensor readings up to 75 %.

Key words: Thermoelectric sensor, heat flow and thermal insulation medical, computer modeling.

Introduction

General characterization of the problem. It is known that timely and quality diagnosis is critical to successful treatment of various human diseases [1 – 5]. For its performance it is important to have information on human heat release, as long as exactly heat flux density reflects most adequately the severity level of inflammatory processes in human organism [6, 7]. So, for early diagnosis of diseases it is efficient to measure human body heat flux. Promising for such measurements are thermoelectric sensors [8 – 11] which offer high sensitivity, precision, speed of response, parameter stability in a wide range of operating temperatures and are consistent with up-to-date recording equipment. A combination of miniature size and high sensitivity of semiconductor heat metering sensors yields high locality and precision of heat metering measurements during medico-biological investigations. The above advantages make it possible to use thermoelectric sensors for local diagnosis of human body, early detection of inflammatory processes, oncologic diseases, blood circulation anomalies and analysis of human body state under extreme conditions.

It is also important to control heat release on human body areas after operational intervention. With normal wound healing, heat release, though increased, is within corresponding limits. However, if healing is accompanied by essential inflammatory processes (for instance, due to breach of wound sterility), it is thermoelectric sensor in the first place that can inform of such processes by recording local thermal anomalies. Thus, monitoring of human body heat release is of exceptional importance, since it can yield information both on the disease recurrence and, on the contrary, on rehabilitation processes.

When investigating human heat release in the post-surgical period an important role is played by thermal insulation (for instance, medical bandage) on thermoelectric sensor which can essentially distort the temperature field of human body area under study and affect the readings of such sensor. The impact of such sensors on the object of investigation was analytically studied in [12] and for the case of living objects with the aid of computer simulation for simplified physical models in [13 – 16].

Therefore, *the purpose of this work* is to create improved computer model and to determine the impact of medical thermal insulation on the readings of thermoelectric heat flux sensor.

A physical model of biological tissue with thermoelectric sensor and thermal medical insulation

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

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

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.

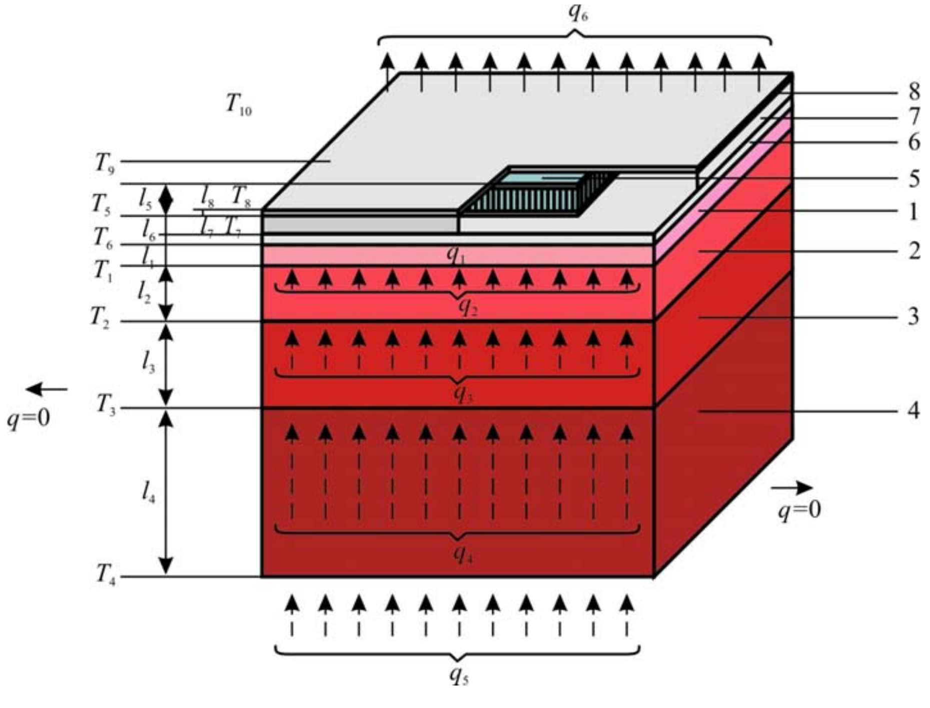


Fig. 1. A physical model of biological tissue with thermoelectric heat meter and thermal medical insulation: 1 – epidermis, 2 – dermis, 3 – subcutis, 4 – internal tissue, 5 – thermoelectric heat flux sensor, 6, 7, 8 – thermal medical insulation.

Thermoelectric heat flux sensor 5 is a rectangular bar of the geometric dimensions a_5, b_5 and l_5, which consists of a large number of *n*- and *p*-type crystals based on *Bi-Te* thermoelectric material. From the theory it is known [8, 12] that thermoelectromotive force (EMF) of thermoelectric gradient sensor is determined as follows:

$$E = \alpha N \Delta T\,, \tag{2}$$

where α is the Seebeck coefficient, N is the number of thermoelectric material legs, ΔT is temperature difference between the upper and lower surfaces of thermoelectric heat flux sensor.

Table

Thermophysical properties of human biological tissue [17 – 21]

Biological tissue layers	Epidermis	Dermis	Subcutis	Internal tissue
Thickness, l (mm)	0.08	2	10	30
Specific heat, C ($J \cdot kg^{-1} \cdot K^{-1}$)	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
Tissue blood 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 ($J \cdot kg^{-1} \cdot K^{-1}$)	3770	3770	3770	3770

The skin surface layer (epidermis 1) of temperature T_6 is in the state of heat exchange with thermal medical insulation 6 of the geometric dimensions a_6, b_6, l_6 and contact surface temperature T_5. Located on the surface of thermal insulation 6 is thermoelectric heat flux sensor 5 of the geometric dimensions a_5, b_5, l_5 and contact surface temperature T_8. In the absence of thermal insulation 6, 7, 8 the heat exchange between skin surface and the environment of temperature T_{10} 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 medical insulation 7, 8 of the geometric dimensions a_7, b_7, l_7 and a_8, b_8, l_8 is arranged on the surface and on the sides of thermoelectric sensor 5. Free surface of thermal insulation 8 of temperature T_9 is in the state of heat exchange with the environment of temperature T_{10} 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 8 to the environment is q_6, and specific heat flux from human internals – q_5.

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 no heat overflow occurs along biological tissue ($q = 0$).

Mathematical description and a computer model

A general equation of heat exchange in biological tissue is as follows [17 – 21]:

$$\rho C \frac{\partial T}{\partial t} = \nabla(\kappa \nabla T) + \rho_b C_b \omega_b (T_b - T) + q_{met}, \tag{3}$$

where ρ is the density of corresponding biological tissue layer, C is specific heat of biological tissue layer, κ is thermal conductivity of biological tissue, ρ_b is blood density, C_b is specific heat of blood, ω_b is blood perfusion rate, T_b is human blood temperature, q_{met} is metabolic heat density.

The summand on 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 on 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 paper, it is enough to consider a 3D steady-state model. Then Eq. (3) will acquire the form (4):

$$\kappa(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2})+\rho_b C_b \omega_b (T_b - T)+q_{met}=0\,. \tag{4}$$

A steady-state equation of heat exchange for thermoelectric heat flux sensor with regard to the impact of thermoelectric phenomena and the temperature dependence of material is given by:

$$\kappa(T)(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2})=-\alpha^2(T)\sigma(T)\left((\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2})\right)^2 . \tag{5}$$

The corresponding steady-state equation of heat exchange for thermal medical insulation will be of the form (6):

$$\kappa(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2})=0\,. \tag{6}$$

A steady-state system of equations (4) – (6) for the corresponding layers of physical model (Fig. 1) must be solved with the respective boundary conditions (7) – (8):

$$\begin{cases} q\big|_{x=0}=0, \\ q\big|_{x=a}=0, \end{cases} \qquad \begin{cases} q\big|_{y=0}=0, \\ q\big|_{y=a}=0, \end{cases} \tag{7}$$

$$\begin{cases} T\big|_{z=0}=310.15\text{ K}, \\ q\big|_{z=b,c,d}=\alpha(T_0-T)+\varepsilon\sigma(T_0^4-T^4), \end{cases} \qquad \begin{cases} q\big|_{x=e,f}=0, \\ q\big|_{y=e,f}=0, \end{cases} \tag{8}$$

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

In order to determine the impact of thermal medical insulation on the readings of thermoelectric heat flux sensor, a 3D computer model of biological tissue was created having on its surface a thermoelectric sensor with thermal insulation. For this purpose Comsol Multiphysics applied program package was used [22] allowing simulation of thermophysical processes in biological tissue with account of blood circulation and metabolism.

The distribution of temperature and heat flux density in biological tissue and thermoelectric sensor was calculated by the 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 [22].

Computer simulation results

With the aid of computer simulation the distributions of temperature and heat flux density lines in human biological tissue and thermoelectric heat flux sensor were obtained (Fig. 3 – 5), as well as isothermal surfaces in biological tissue were constructed (Fig. 6, 7) with regard to boundary effects in a 3D computer model.

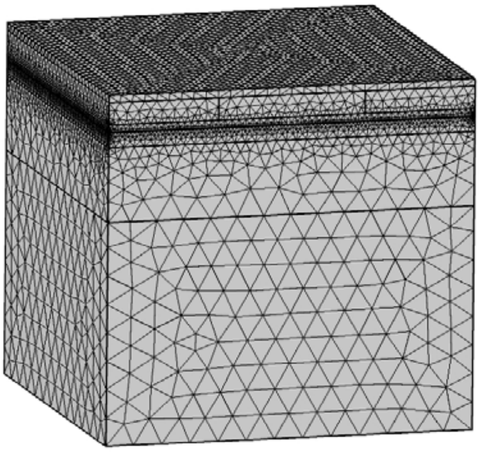


Fig. 2. Finite element method mesh.

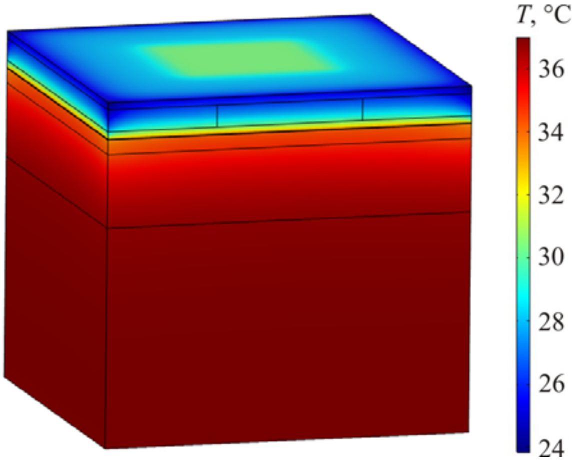


Fig. 3. Temperature distribution in biological tissue having on its top a thermoelectric sensor with thermal medical insulation.

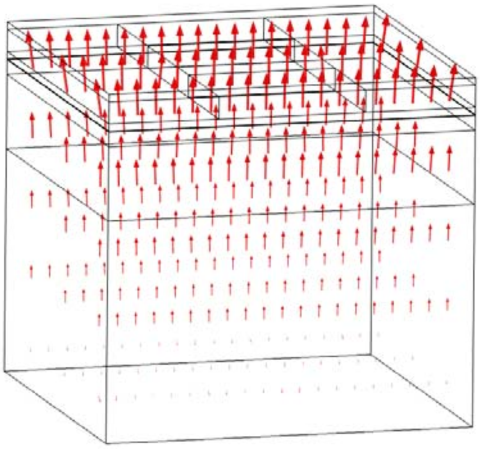


Fig. 4. Distribution of heat flux density lines in biological tissue having on its top a thermo-electric sensor with thermal medical insulation.

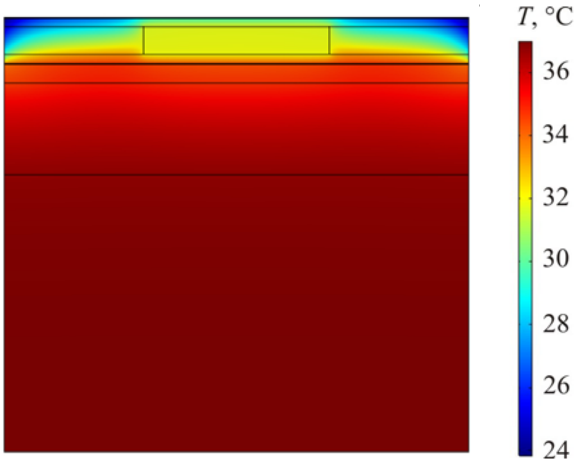


Fig. 5. Temperature distribution in the section of biological tissue having on its top a thermoelectric sensor with thermal medical insulation.

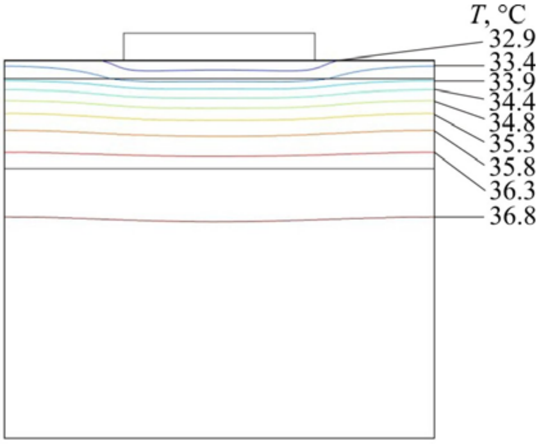


Fig. 6. Isothermal surfaces in biological tissue having on its top a thermoelectric sensor without thermal medical insulation.

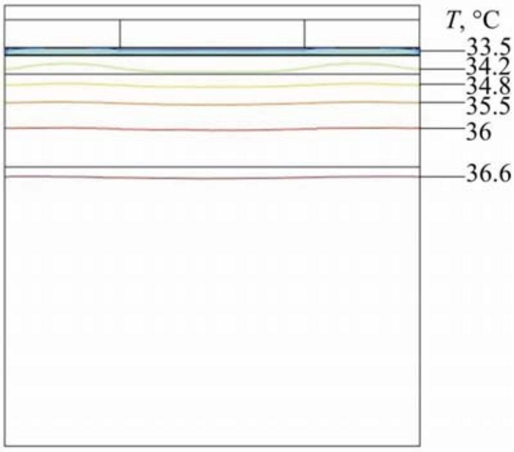
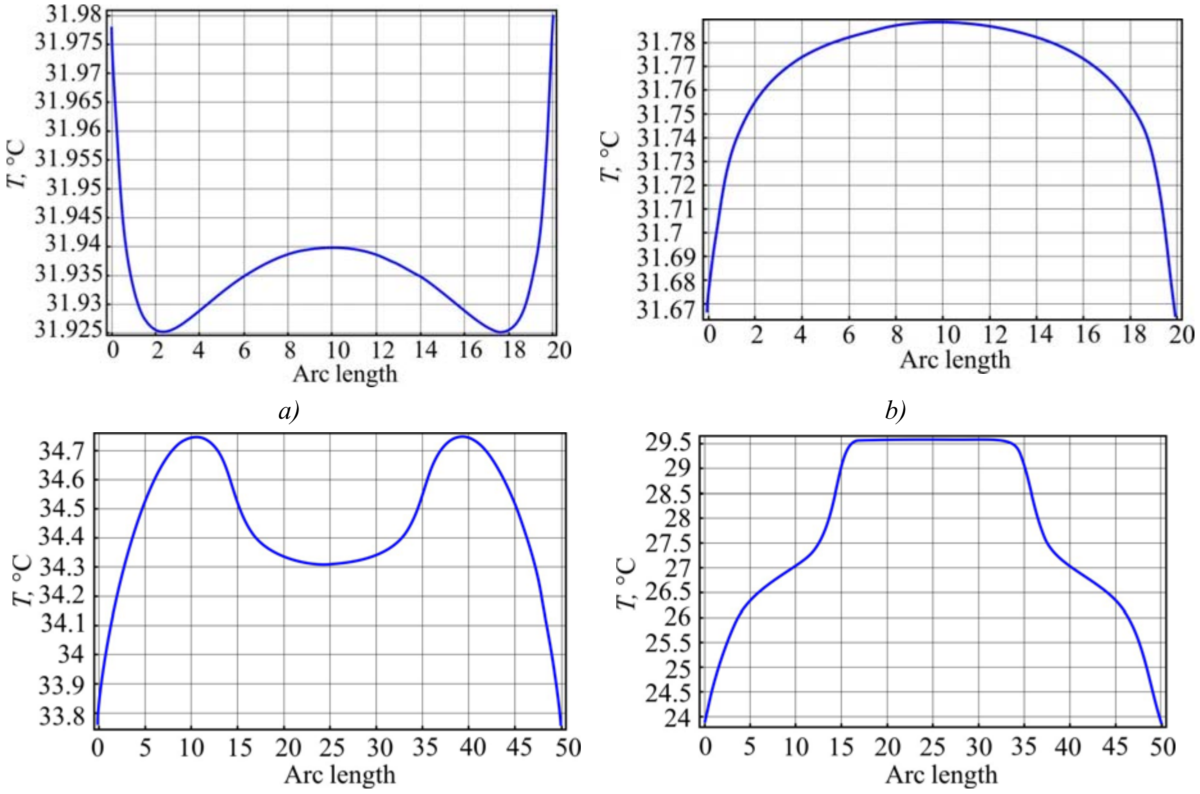


Fig. 7. Isothermal surfaces in biological tissue having on its top a thermoelectric sensor with thermal medical insulation.

To determine temperature difference between the surfaces of thermoelectric sensor, averaging of the obtained temperature distributions on the upper and lower sensor surfaces was obtained, as long as such distributions are irregular. As an example, the distributions of temperature along the line in the centre of the lower (Fig. 8*a*) and upper (Fig. 8*b*) surfaces of thermoelectric sensor are shown.

Fig. 8*c* shows temperature distribution on the surface of biological tissue having on its top a thermoelectric sensor with thermal medical insulation. Temperature distribution on the surface of external thermal insulation is shown in Fig. 8*d*.



a) *b)*

c) *d)*

Fig. 8. Temperature distribution of thermoelectric sensor with thermal insulation exceeding the limits of sensor. a) on the lower surface, b) on the upper surface, c) on the surface of biological tissue, d) on the surface of thermal insulation.

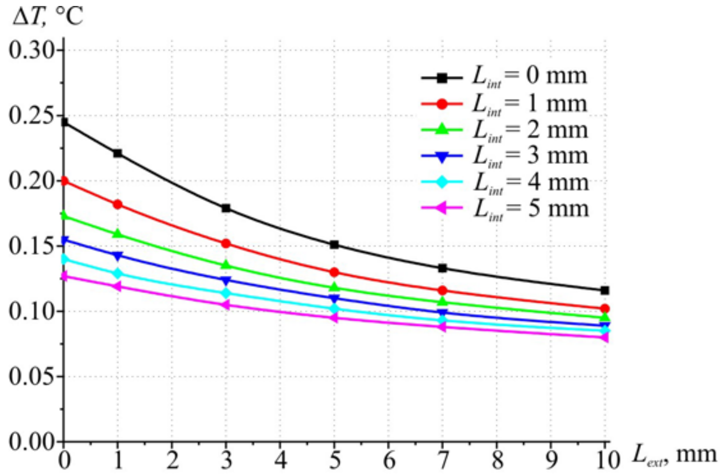


Fig. 9. Dependence of temperature difference on thermoelectric heat flux sensor on the thickness if thermal medical insulation on the sensor (external bandage layer L_{ext}) with different thickness of thermal insulation between biological tissue and the sensor (internal bandage layer L_{int}).

Computer simulation was used to determine the impact of thermal medical insulation on the readings of thermoelectric heat flux sensor. A dependence of temperature difference on thermoelectric sensor on the thickness of thermal medical insulation on the sensor (external bandage layer L_{ext}) was determined with different thickness of thermal insulation between biological tissue and the sensor (internal bandage layer L_{int}) for the case when external thermal insulation does not exceed the sensor limits (Fig. 9).

From Fig. 9 it is seen that increasing the thickness of thermal insulation between biological tissue and thermoelectric heat flux sensor, as well as increasing the thickness of external insulation on the sensor definitely results in decreasing temperature difference between the sides of such sensor. Reduction of heat flux thermoelectric sensor readings can reach 75 % as compared to the case without thermal medical insulation. This, in turn, must be taken into account for the diagnosis of post-surgical inflammatory processes in human organism by creating identical conditions with repeated measurements of heat release.

Conclusions

1. Computer methods were developed for simulation of thermal and temperature processes in “thermoelectric sensor- human body surface” system with regard to thermophysical properties of biological tissue, blood circulation and metabolism. It was established that proposed methods are much more efficient as compared to known analytical methods that are based on solving approximate boundary problems.
2. Computer simulation was used to study the impact of thermal medical insulation on the readings of medical-purpose thermoelectric sensor. It was established that the presence of thermal insulation on thermoelectric heat flux sensor and biological tissue can change sensor readings up to 75 %. This factor must be taken into account when measuring human body heat fluxes by creating identical conditions during repeated measurements.

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