L.I. Anatychuk[1,2], R.R. Kobylianskyi[1,2], I.A. Konstantinovich[1,2]

[1]Institute of Thermoelectricity of the NAS and MES Ukraine,
1, Nauky Str., Chernivtsi, 58029, Ukraine;
[2]Yu. Fedkovych Chernivtsi National University, 2, Kotsyubinsky Str.,
Chernivtsi, 58000, Ukraine

THE IMPACT OF A THERMOELECTRIC SUPPLY ON THE ACCURACY OF TEMPERATURE AND HEAT FLUX MEASUREMENT

In this paper, the accuracy of human body temperature and heat flux measurement with a thermoelectric supply on its surface has been studied. For this purpose, physical, mathematical and computer models of biological tissue with a thermoelectric sensor and a thermoelectric supply have been constructed. Object-oriented computer simulation was used to obtain the distributions of temperature and heat fluxes with regard to blood circulation and metabolism of biological tissue. Dependences describing the impact of a thermoelectric supply power and its distance from a thermoelectric sensor on the accuracy of temperature and heat flux measurement have been defined.

Key words: computer simulation, thermoelectric supply, temperature and heat flux sensor.

Introduction

Low-power thermoelectric supplies (10^{-1} W – 10^{-4} W) offer a number of attractive properties, so the possibilities of their application are studied more and more intensively [1-13]. Among them of particular interest are thermoelectric supplies using human heat for their operation. For instance, they are beneficial for the diagnostics of human health status by long-term measurement of temperature and heat fluxes [14-24]. However, if such a supply is arranged sufficiently close to temperature and heat flux sensors, it can affect their readings.

So, *the purpose of this paper* is to study the impact of thermoelectric supplies on the results of measuring temperature and heat fluxes on human skin surface.

A physical model of biological tissue with a thermoelectric sensor and a thermoelectric supply

Such a model is given in Fig. 1. Here, an area of human skin is a structure consisting of three layers (epidermis 1, dermis 2, subcutis 3) and internal tissue 4. This structure 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 1). The respective biological tissue layers 1 – 4 are regarded as the bulk sources of heat q_i, where:

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

T_b is blood temperature, T_i is temperature of the i-th layer of biological tissue. The geometric dimensions of each layer are designated as a_i, b_i and l_i, and the temperatures at the boundaries of the respective biological tissue layers - as T_1, T_2, T_3 and T_4.

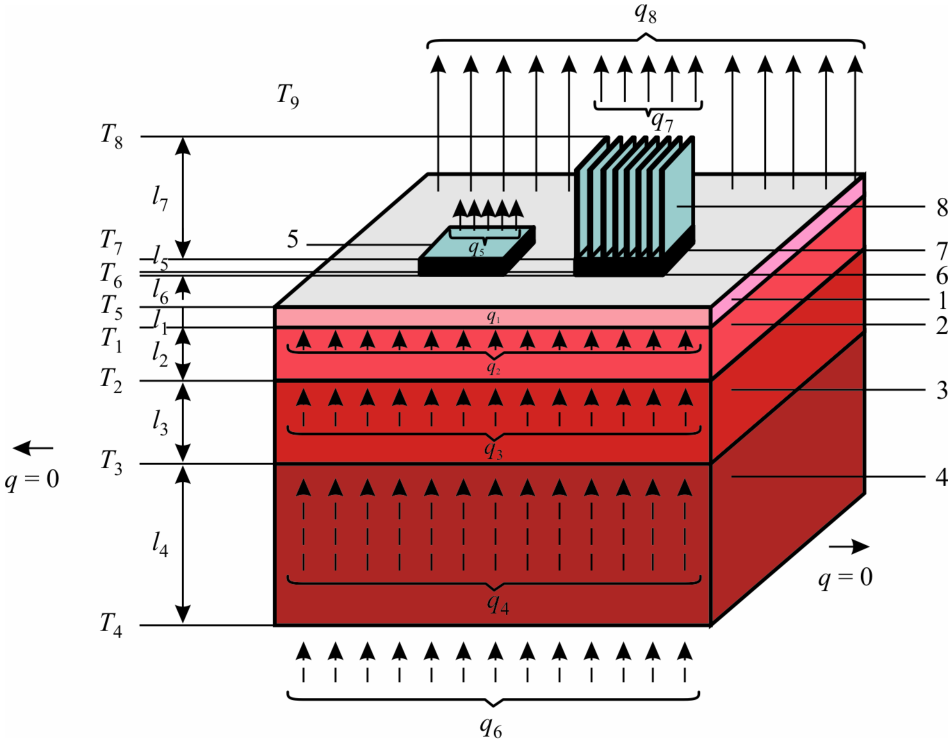

Fig. 1. A physical model of biological tissue with a thermoelectric sensor and a thermoelectric supply: 1 – epidermis, 2 – dermis, 3 – subcutis, 4 – internal tissue, 5 – thermoelectric temperature and heat flux sensor, 6 – heat-leveling plate, 7 – thermoelectric supply, 8 – heat sink.

A thermoelectric temperature and heat flux sensor 5 is a rectangular bar of dimensions a_5, b_5, l_5, consisting of semiconductor thermocouple elements connected into a series circuit and a dielectric package with embedded temperature sensor (thermistor) [25]. The thermoEMF [1, 2] developed by the thermoelectric sensor is given below:

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

where α is the Seebeck coefficient, N is the number of thermoelectric material legs, ΔT is temperature difference between the sensor's upper and lower surfaces. The number of thermoelectric material legs in the temperature and heat flux sensor is $N = 1500 – 3000$ pcs. Simulation of a thermoelectric sensor with such a number of elements is an intricate problem even for modern personal computers. At the same time, from formula (2) it is evident that the sensor's EMF value is mainly influenced by temperature difference ΔT between its surfaces. Therefore, to reach the purpose set in this paper, it is quite sufficient to replace a thermoelectric sensor having a large number of elements by the bulk homogeneous medium of equivalent thermal conductivity κ. Then, on the basis of calculated ΔT, one can easily determine the sensor's EMF and then determine heat flux density according to calibration plots of EMF and heat flux.

The skin surface layer (epidermis 1) of temperature T_5 is in the state of heat exchange with heat-leveling plates 6 of high thermal conductivity material whose geometric dimensions are a_6, b_6, l_6. Let us denote contact surface temperature T_6. Located on the surface of biological tissue (epidermis 1) is a thermoelectric sensor 5 with the geometric dimensions a_5, b_5, l_5 and contact surface temperature

T_7, as well as a thermoelectric supply 7 with the geometric dimensions a_7, b_7, l_7 and contact surface temperature T_8.

Table 1

Thermophysical properties of human biological tissue [26-30]

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

Free surfaces of the thermoelectric sensor 5 of temperature T_7 and the thermoelectric supply 7 of temperature T_8 are in the state of heat exchange with the environment of temperature T_9 which is taken into account by heat exchange coefficient α_1 and emissivity coefficient ε_1. Specific heat flux from the surface of the thermoelectric sensor 5 to the environment is q_5, from the surface of heat sink 8 to the environment is q_7, from free skin surface – q_8, and specific heat flux of human internal bodies – q_6.

Heat exchange between the skin surface and the environment of temperature T_9 is taken into account by heat exchange coefficient α_2 and emissivity coefficient ε_2. Skin heat exchange due to perspiration is disregarded.

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

Mathematical description and a computer model

A general equation of heat exchange in biological tissue is as follows [26-30]:

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

where ρ is the density of corresponding biological tissue layer (kg/m^3), C is specific heat of biological tissue layer ($J \cdot kg^{-1} \cdot K^{-1}$), ρ_b is blood density (kg/m^3), C_b is specific heat of blood ($J \cdot kg^{-1} \cdot K^{-1}$), ω_b is blood perfusion rate ($m^3 \cdot s^{-1} \cdot m^{-3}$), T_b is human blood temperature (°C), where T_b = 310.15 K, q_{met} is the specific amount of metabolic heat (W/m^3).

The summand in the right-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 left-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 (4):

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

A steady-state equation of heat exchange in biological tissue (4) is solved with the corresponding boundary conditions (5 – 6):

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

$$\begin{cases} T\big|_{z=0} = 37\ °\text{C}, \\ q\big|_{z=b,\,c,\,d} = \alpha \cdot (T_0 - T) + \varepsilon \cdot \sigma \cdot (T_0^4 - T^4), \end{cases} \quad \begin{cases} q\big|_{x=e,f} = 0, \\ q\big|_{y=e,f} = 0, \end{cases} \tag{6}$$

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 the Boltzmann constant.

To determine the impact of a thermoelectric supply on the accuracy of temperature and heat flux measurement by a thermoelectric sensor, a three-dimensional computer model of biological tissue having on its top a thermoelectric supply and a sensor was created. For construction of a computer model, the Comsol Multiphysics software package was employed [31], enabling simulation of thermophysical processes in biological tissue with regard to blood circulation and metabolism.

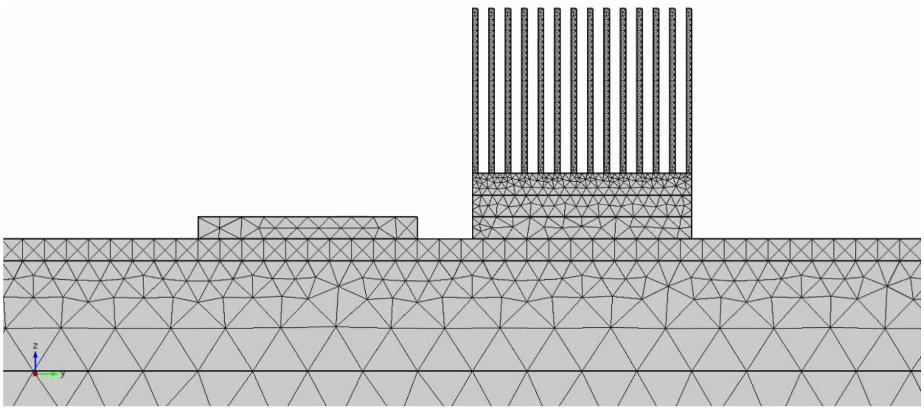

Fig. 2. Finite element method mesh.

The distribution of temperature and heat flux density in human biological tissue, the thermoelectric temperature and heat flux sensor and the thermoelectric supply was calculated by finite element method the essence of which is that an object under study is split into a large number of finite elements (Fig.2), for each of which the value of function is found which satisfies given differential equations of second kind with the respective boundary conditions. The accuracy of solving the formulated problem depends on the method of splitting and is assured by using a large number of finite elements [31].

Computer simulation results

Object-oriented computer simulation was used to obtain the distributions of temperature (Fig. 3, 4) and heat flux density lines in human biological tissue, the thermoelectric temperature and heat flux density sensor and the thermoelectric supply.

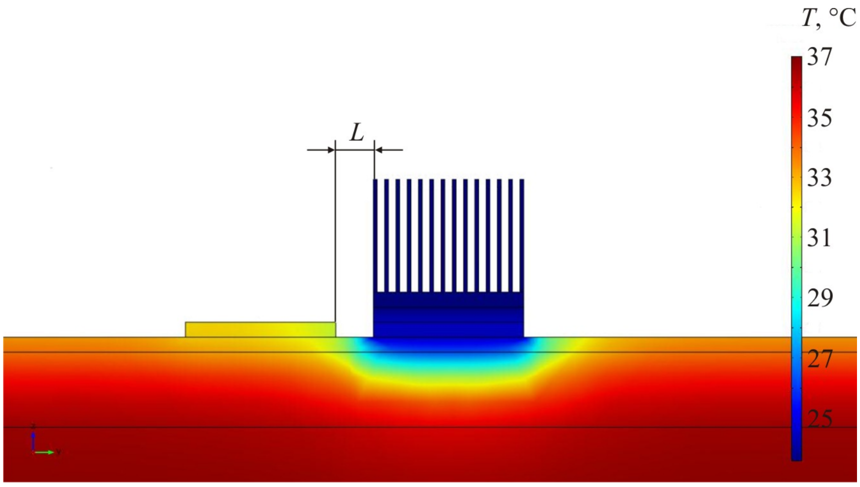

Fig. 3. Temperature distribution in human biological tissue having on its top a thermoelectric temperature and heat flux sensor and a thermoelectric supply for the case of a distance between them L = 0.5 cm and supply power P = 0.6 mW, corresponding to cross-sectional area S = 4 cm².

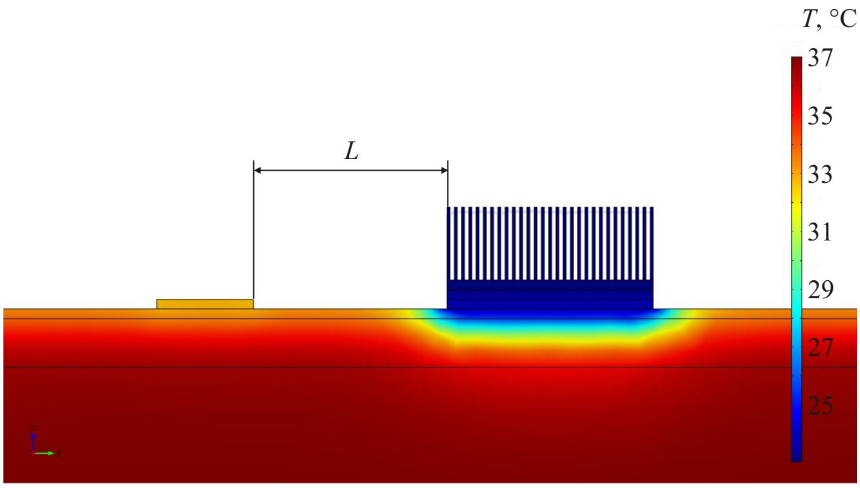

Fig. 4. Temperature distribution in human biological tissue having on its top a thermoelectric temperature and heat flux density sensor and a thermoelectric supply for the case of a distance between them L = 4 cm and the thermoelectric supply power P = 2.23 mW, corresponding to cross-sectional area S = 16 cm².

Computer simulation was used to define dependences describing the impact of the thermoelectric supply power and its distance from the thermoelectric sensor on the accuracy of temperature and heat flux measurement (Figs. 5 – 8).

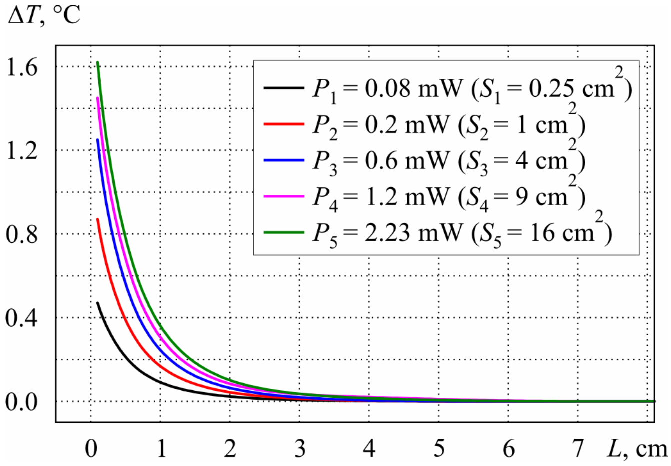

Fig. 5. The error of measuring temperature ΔT versus the distance between the sensor and the thermoelectric supply.

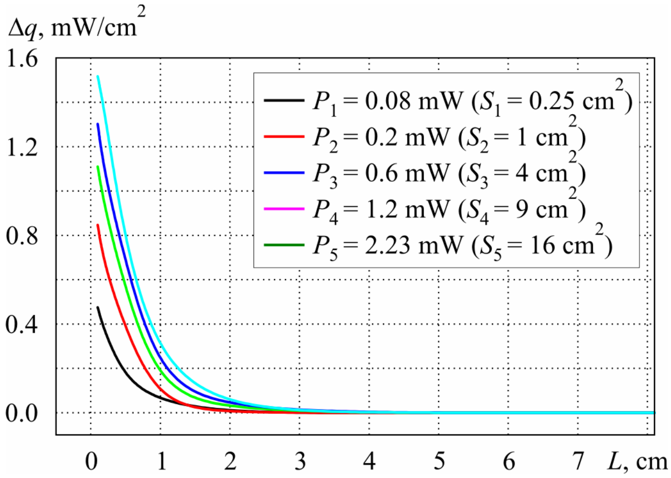

Fig. 6. The error of measuring heat flux density Δq versus the distance between the sensor and the thermoelectric supply.

Calculations have been made for the ambient temperature $T = 20$ °C, the geometric dimensions of the thermoelectric temperature and heat flux sensor (20 × 20) mm^2 and heat exchange coefficients of the biological tissue, sensor and thermoelectric supply with the environment $\alpha = 10$ W/m^2·K.

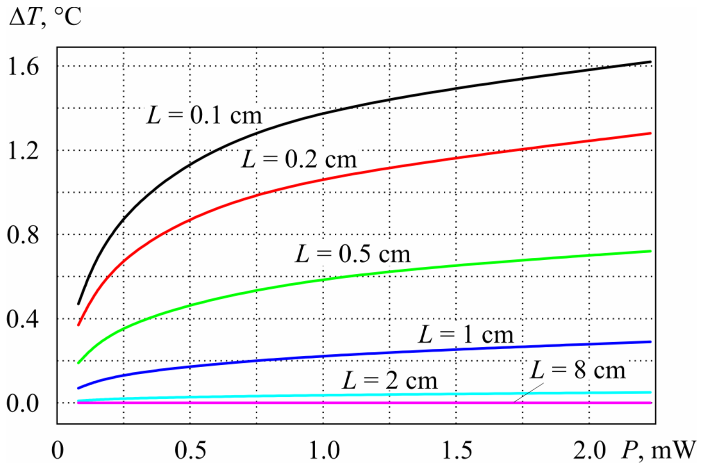

Fig. 7. The error of measuring temperature ΔT versus the thermoelectric supply power.

Figs. 5 – 6 represent dependences showing the impact of the thermoelectric supply distance from the thermoelectric sensor on the errors of measuring temperature ΔT and heat flux density Δq by the thermoelectric sensor.

Figs. 7 – 8 represent dependences showing the impact of the thermoelectric supply power on the errors of measuring temperature ΔT and heat flux density Δq by the thermoelectric sensor.

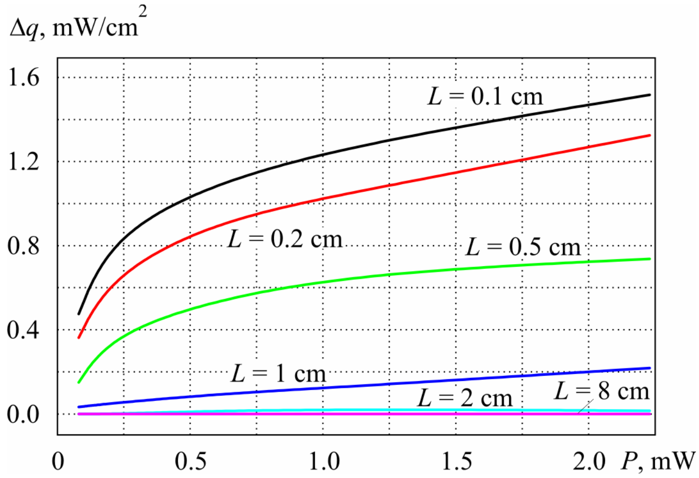

Fig. 8. The error of measuring heat flux density Δq versus the thermoelectric supply power.

From Figs. 5 to 8 it is evident that arrangement of the thermoelectric supply at a distance not less than $L = 5$ cm from the temperature and heat flux sensor leads to measurement errors that do not exceed $\Delta T = 0.01$ °C and $\Delta q = 0.001$ mW/cm^2, respectively. With the arrangement of the sensor and the thermoelectric supply at a distance of $L = 2$ cm, maximum error of temperature measurement is $\Delta T = 0.1$ °C. The above errors of temperature measurement are valid for thermoelectric supplies of power $P = 0.08 \div 2.23$ mW (Fig. 5). Similarly, with the arrangement of the sensor and the thermoelectric supply at a distance of $L = 1$ cm, maximum error of heat flux density measurement is $\Delta q = 0.25$ mW/cm^2, and at the distance of $L = 2$ cm maximum error of heat flux density measurement is $\Delta q = 0.05$ mW/cm^2 (Fig. 6).

Conclusions

1. Object-oriented computer simulation was used to obtain temperature and heat flux distributions in human biological tissue, which afforded an opportunity to determine the impact of the thermoelectric supply on the accuracy of temperature and heat flux measurement by the thermoelectric sensor.
2. Dependences describing the impact of the thermoelectric supply power and its distance from the thermoelectric sensor on the accuracy of temperature and heat flux measurement have been defined. In particular, it has been found that with the arrangement of the thermoelectric supply at a distance not less than $L = 5$ cm from the temperature and heat flux sensor, the errors of temperature and heat flux measurement do not exceed $\Delta T = 0.01$ °C and $\Delta q = 0.001$ mW/cm^2, respectively.

References

1. L.I. Anatychuk, *Thermoelements and Thermoelectric Devices: Handbook* (Kyiv: Naukova Dumka, 1979), 768 p.

2. L.I. Anatychuk, *Thermoelectricity, Vol. 2, Thermoelectric Power Converters* (Kyiv, Chernivtsi: Institute Thermoelectricity, 2003), 376 p.
3. L.T. Strutynska, Thermoelectric Microgenerators. State of the Art and Application Potential, *Tekhnologiya i Konstruirovaniye v Elektronnoi Apparature* **4**, 5 – 13 (2008).
4. Patent US 6222114, Portable Wrist Device, *Mitamura Gen (JP)* (2001).
5. G.J. Snyder, Small Thermoelectric Generators, *The Electrochemical Society Interface. – Fall 2008.*
6. L.I. Anatychuk, R.R. Kobylianskyi, and S.B. Romanyuk, Electronic Medical Thermometer with Thermoelectric Power Source, *XV International Forum on Thermoelectricity (May 21-24, 2013, Tallinn, Estonia).*
7. L.I. Anatychuk, R.R. Kobylianskyi, and S.B. Romanyuk, *Application № u201308794 of 15.07.13*, Electronic Medical Thermometer with a Thermoelectric Power Source.
8. L.I. Anatychuk, R.R. Kobylianskyi, and S.B. Romanyuk, *Application № u201308793 of 15.07.13*, Electronic Medical Thermometer with a Combined Power Source.
9. L.I. Anatychuk, *Application № u201312570 of 28.10.2013*, Electronic Medical Thermometer with a Thermoelectric Power Source.
10. L.I. Anatychuk, R.R. Kobylianskyi, On the Accuracy of Temperature Measurement by Electronic Medical Thermometer with a Thermoelectric Power Supply, *J. Thermoelectricity* **5**, 68 – 72 (2013).
11. L.I. Anatychuk, R.R. Kobylianskyi, *Patent of Ukraine № 71619*, Thermoelectric Medical Heat Meter, Application № u 2011 14007; filed 28.11.11; publ. 25.07.12, Bul. № 14.
12. P.D. Mykytyuk, R.R. Kobylianskyi, and T.V. Slepenyuk, *Patent of Ukraine № 73037*, Thermoelectric Medical Device, Application № u 2012 01922; filed 20.02.12; publ. 10.09.12, Bul. № 17.
13. Vladimir Leonov, Human Machine and Thermoelectric Energy Scavenging for Wearable Devices, *ISRN Renewable Energy*, Vol. 2011, Article ID 785380, 11 pages (doi:10.5402/2011/785380).
14. R.B. Ladyka, D.N. Moskal and V.D. Didukh, Semiconductor Heat Meters in Arthropathy Diagnostics and Treatment, *Meditsinskaya Tekhnika* **6**, 34 – 35 (1992).
15. R.B. Ladyka, O.N. Dakalyuk, L.P. Bulat and A.P. Myagkota, Use of Semiconductor Heat Meters in the Diagnostics and Treatment, *Meditsinskaya Tekhnika* **6**, 36 – 37 (1996).
16. L.I. Anatychuk, N.G. Lozinsky, P.D. Mykytyuk Yu.Yu. Rozver, Thermoelectric Semiconductor Heat Meter, *Instruments and Experimental Techniques* **5**, 236 (1983).
17. L.I. Anatychuk, L.P. Bulat, D.D. Gutsal and A.P. Myagkota, Thermoelectric Heat Meter, *Instruments and Experimental Techniques* **4**, 248 (1989).
18. B.M. Demchuk, L.Ya. Kushneryk, and I.M. Rublenyk, Thermoelectric Sensors for use in Orthopedics, *J. Thermoelectricity* **4**, 78 – 82 (2002).
19. A.A. Ascheulov, L.Ya. Kushneryk, Thermoelectric Device for Medico-Biological Express-Diagnostics, *Tekhnologiya i Konstruirovaniye v Elektronnoi Apparature* **4**, 38 – 39 (2004).
20. R.R. Kobylianskyi, R.G.Garabazhiv, and T.V.Slepenyuk, On Applications of Thermoelectricity in Medicine, *VII School on Thermoelectricity* (July 16-19, 2012, Yaremche, Ukraine, 2012).
21. L.I. Anatychuk, R.R. Kobylianskyi, Research into the Effect of Thermoelectric Heat Meter on Human Heat Release Measurement, *J. Thermoelectricity* **4**, 59 – 65 (2012).
22. L.I. Anatychuk, R.R. Kobylianskyi, Computer Design of Thermoelectric Heat Meter Readings Under Real-Service Conditions, *J. Thermoelectricity* **1**, 47 – 54 (2013).
23. L.I. Anatychuk, R.G. Giba, and R.R. Kobylianskyi, Some Peculiarities of Using Medical Heat Meters in the Investigation of Local Human Heat Release, *J. Thermoelectricity* **2**, 82 – 88 (2013).
24. L.I. Anatychuk, R.R. Kobylianskyi, Peculiarities of Using Thermoelectric Medical Heat Meters

when Measuring Local Human Heat Release, *XV International Forum on Thermoelectricity* (May 21-24, 2013, Tallinn, Estonia).
25. V.S. Gischuk, Modernized Device for Human Heat Flux Measurement, *J. Thermoelectricity* **2**, 92 – 96 (2013).
26. S.C. Jiang, N. Ma, H.J. Li and X.X. Zhang, Effects of Thermal Properties and Geometrical Dimensions on Skin Burn Injuries, *Burns* 28, 713 – 717 (2002).
27. M.P. Cetingul, C. Herman, Identification of Skin Lesions from the Transient Thermal Response Using Infrared Imaging Technique, *IEEE*, 1219 – 1222 (2008).
28. M. Ciesielski, B. Mochnacki and R. Szopa, Numerical Modeling of Biological Tissue Heating. Admissible Thermal Dose, *Scientific Research of the Institute of Mathematics and Computer Science* 1 (10), 11 – 20 (2011).
29. Florin Filipoiu, Andrei Ioan Bogdan and Iulia Maria Carstea, Computer-Aided Analysis of the Heat Transfer in Skin Tissue, *Proceedings of the 3rd WSEAS Int. Conference on Finite Differences - Finite Elements - Finite Volumes - Boundary Elements*, 2010, p. 53 – 59.
30. Daniela Carstea, Ion Carstea and Iulia Maria Carstea, Interdisciplinarity in Computer-Aided Analysis of Thermal Therapies, *WSEAS Transactions on Systems and Control* 6 (4), 115 – 124 (2011).
31. COMSOL Multiphysics User's Guide, COMSOLAB, 2010, 804 p.

Submitted 09.12.2013.