
L.I.Anatychuk

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


R.R.Kobylianskyi

INCREASE IN THERMAL GENERATOR EFFICIENCY WITH THE USE OF HUMAN THERMAL ENERGY IN DYNAMIC MODES

This paper studies increase of thermoelectric generator efficiency in transient unsteady conditions due to a thermal contact between the surface area of human body and the thermopile. For such investigations, a computer method for determination of the energy characteristics of thermal generator in unsteady thermal conditions is developed. A physical model for such processes with the respective computer simulation is built. The specific feature of this model is a substitution of a heat sink that extracts heat from a thermopile by a heat accumulator. A mathematical description is performed and a computer model is created on the basis of object-oriented programming.
The case study of a model for a thermopile of Bi-Te based material with a contact area 0×10 mm and a copper heat accumulator is presented. The optimal length of module legs is determined as 2 ÷ 2.5 mm and heat accumulator length – as 5 ÷ 10 mm. In so doing, the thermopile during 20 s generates about 25 mJ of electric energy which is quite sufficient for the operation of electronic medical thermometer.

Key words: thermoelectric microgenerator, dynamic mode, computer simulation.

Introduction

Thermoelectric microgenerators using human heat are promising for power supply to all kinds of low-power electronic equipment [1-11]. In [12] it was established that for power supply to short-life devices one should use thermoelectric microgenerators in dynamic operating modes, since under certain conditions such modes yield higher electric power than in steady-state modes. The use of short-life transient operating modes allows doing away with cumbersome heat sinks that are the major obstacle when creating efficient and compact electric power sources operated by human heat.

Therefore, the purpose of this work is to develop computer methods for simulation of thermal generator operation in transient thermal modes and to use them for the optimization of specific design variants of such generators.

Physical model

According to a physical model (Fig.1), an area of human biological tissue is a structure consisting of three skin layers (epidermis 1, dermis 2, subcutis 3) and internal tissue 4 and 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 and specific heat release q_{meti} due to metabolic processes (Table 1). The respective biological tissue layers 1-4 are regarded as the bulk sources of heat q_i where:

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

The geometric dimensions of each such layer are a_i, b_i and l_i. The temperatures at the boundaries of the respective biological tissue layers are T_1, T_2, T_3 and T_4. The thermophysical properties of human biological tissue are given in [12-17].

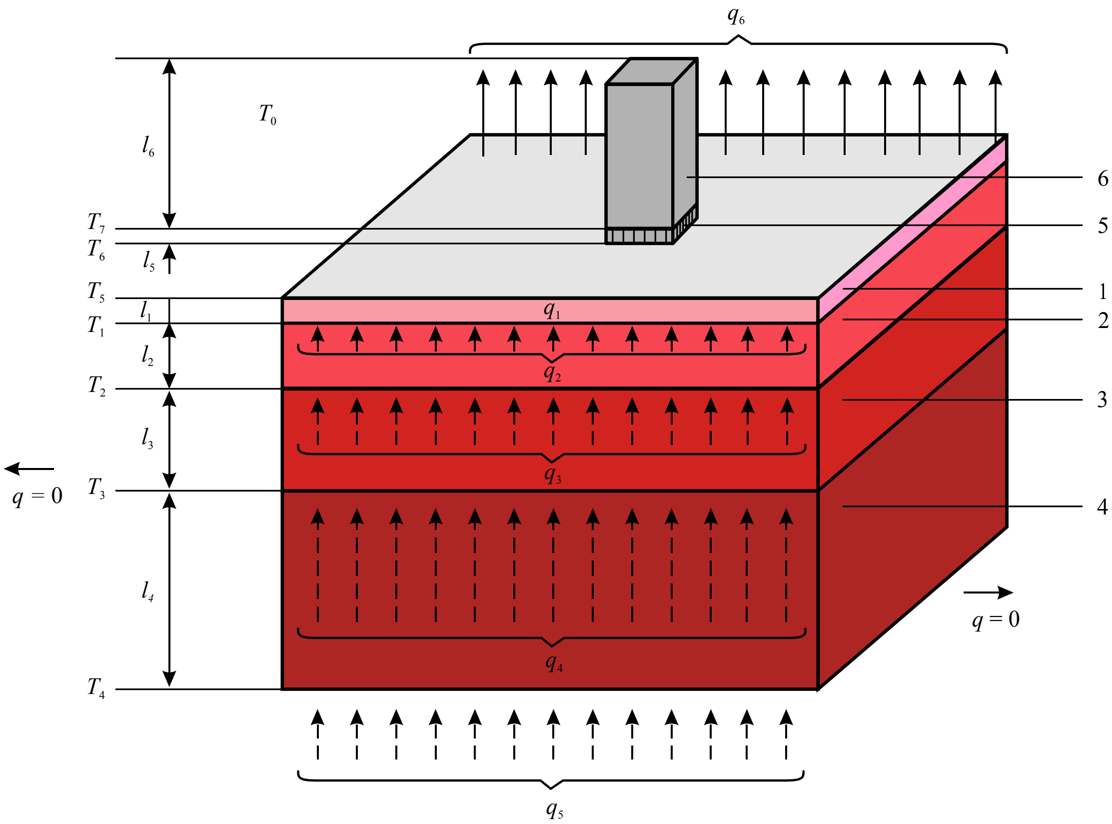


Fig. 1. A physical model of biological tissue with a thermoelectric microgenerator and a heat accumulator: 1 – epidermis, 2 – dermis, 3 – subcutis, 4 – internal tissue, 5 – thermoelectric microgenerator, 6 – heat accumulator.

A thermoelectric microgenerator 5 is an equivalent rectangular bar with dimensions a_5, b_5, l_5, characterized by thermal conductivity corresponding to microgenerator thermal conductivity κ.

The thermoelectric microgenerator 5 with contact surface temperature T_6 is located on the surface of biological tissue (epidermis 1) with temperature T_5. The thermoelectric microgenerator 5 is in a state of heat exchange with a bar-shaped heat accumulator 6 of high thermal conductivity material with geometric dimensions a_6, b_6, l_6. The contact surface temperature is T_7.

Free surface of skin area (epidermis 1) is in a state of heat exchange with the environment with temperature T_0 which is taken into account by heat exchange coefficient α. The rest of free surfaces of thermoelectric microgenerator 5 and bar 6 are adiabatically isolated. The specific heat flux from the free skin surface is q_6, and the specific heat flux from the internal parts of human body is q_5. Skin heat exchange due to radiation and perspiration is disregarded.

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 through the lateral surface of biological tissue ($q = 0$).

Mathematical description of the model

As long as this research aims at studying the dynamics of physical processes in a thermoelectric microgenerator since the moment it is brought into a thermal contact with the skin surface, one must know the steady-state distribution of temperature in biological tissue in the absence of a microgenerator on its surface. Such temperature distribution should be chosen as the initial conditions in biological tissue in the process of thermal interaction between thermoelectric microgenerator and biological tissue. This, in turn, means that the research should be performed in two steps. At the first step it is necessary to find the steady-state temperature distribution in biological tissue in the absence of a microgenerator on its surface. At the second step – the dynamic temperature distribution in biological tissue and the thermoelectric microgenerator and bar 6 located on its top, assuming as the initial conditions for biological tissue the temperature distribution found at the first step.

A general equation of heat exchange in biological tissue is as follows [12-17]:

$$\rho_i \cdot C_i \cdot \frac{\partial T}{\partial t} = \nabla(\kappa_i \cdot \nabla T) + \rho_b \cdot C_b \cdot \omega_{bi} \cdot (T_b - T) + q_{meti}\,, \tag{2}$$

where $i = 1..4$ are corresponding layers of biological tissue,

ρ_i is the density of corresponding biological tissue layer (kg/m^3),

C_i is specific heat of corresponding biological tissue layer (J/kg·K),

ρ_b is blood density (kg/m^3),

C_b is specific heat of blood (J/kg·K),

ω_{bi} is blood perfusion rate of corresponding biological tissue layer (m^3·s^{-1}·m^{-3}),

T_b is human blood temperature (°C), where T_b = 37 °C,

q_{meti} is the amount of metabolic heat of corresponding biological tissue layer (W/m^3),

T is the absolute temperature (K),

κ_i is thermal conductivity coefficient of corresponding biological tissue layer (W/m·K),

t is time (s).

The left-hand side of equation (2) is the rate of change in thermal energy comprised in a 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.

At the first step of research, $\frac{\partial T}{\partial t} = 0$, so Eq.(2) is simplified as:

$$\nabla(\kappa_i \cdot \nabla T) + \rho_b \cdot C_b \cdot \omega_{b_i} \cdot (T_b - T) + q_{met_i} = 0\,. \tag{3}$$

A steady-state equation of heat exchange in biological tissue (3) is solved with the boundary conditions (4), where q is thermal flux density, T_0 is ambient temperature, α is heat exchange coefficient:

$$\begin{cases} q\big|_{x=0} = 0, \\ q\big|_{x=a} = 0, \end{cases} \qquad \begin{cases} q\big|_{y=0} = 0, \\ q\big|_{y=a} = 0, \end{cases} \qquad \begin{cases} T\big|_{z=0} = 37\ °\text{C}, \\ q\big|_{z=b} = \alpha \cdot (T_0 - T), \end{cases} \tag{4}$$

At the second step, temperature distribution in biological tissue is found by solving Eq.(2) with the boundary conditions (4) and the initial temperature distribution T(x, y, z). In so doing, in the thermoelectric microgenerator and heat accumulator we solve a general equation of heat exchange [1, 2]:

$$\rho_i \cdot C_i \cdot \frac{\partial T}{\partial t} = \nabla(\kappa_i \cdot \nabla T), \quad (5)$$

where $i = 5, 6$ is thermal generator and heat accumulator material, ρ_i is substance density, C_i is substance specific heat, κ_i is thermal conductivity coefficient. The boundary conditions for Eq.(5) include adiabatic insulation of thermoelectric microgenerator surfaces and the initial temperature distribution $T = T_{amb} = \text{const}$.

Computer simulation

To study the dynamic operating modes of thermoelectric microgenerators using human heat, a three-dimensional computer model of biological tissue was created having on its top a thermoelectric microgenerator and a heat accumulator. The computer model was constructed with the aid of Comsol Multiphysics applied program package [18] allowing simulation of thermophysical processes in biological tissue with regard to blood circulation and metabolism.

The distribution of temperature and heat flux density in the biological tissue, thermoelectric microgenerator and heat accumulator 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 [18].

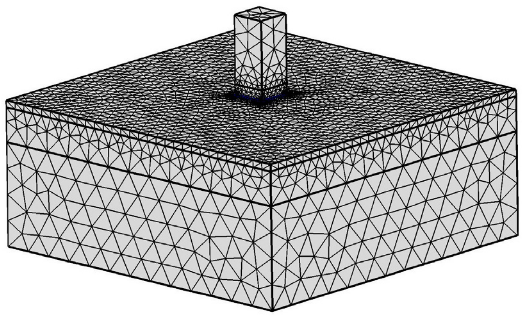


Fig. 2. Finite element method mesh.

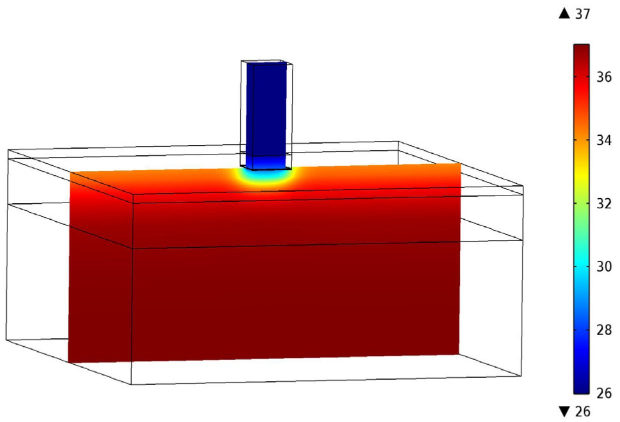


Fig. 3. Temperature distribution in the section of human biological tissue having on its top a thermoelectric microgenerator and a heat accumulator.

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

Example of computer simulation

Figs. 4-5 a,b,c,d,f represent the dynamics of change in EMF and electric power of a thermoelectric microgenerator of dimensions 10 × 10 mm with the number of legs $N = 624$ and their cross section $S_0 = 0.35 \times 0.35$ mm^2 for different leg length $L = 0.5$; 1.0; 1.5; 2; 2.5; 3 mm and bar-shaped heat accumulator length $h = 0$; 2; 5; 10; 20; 30 mm (ambient temperature $T = 24$ °C).

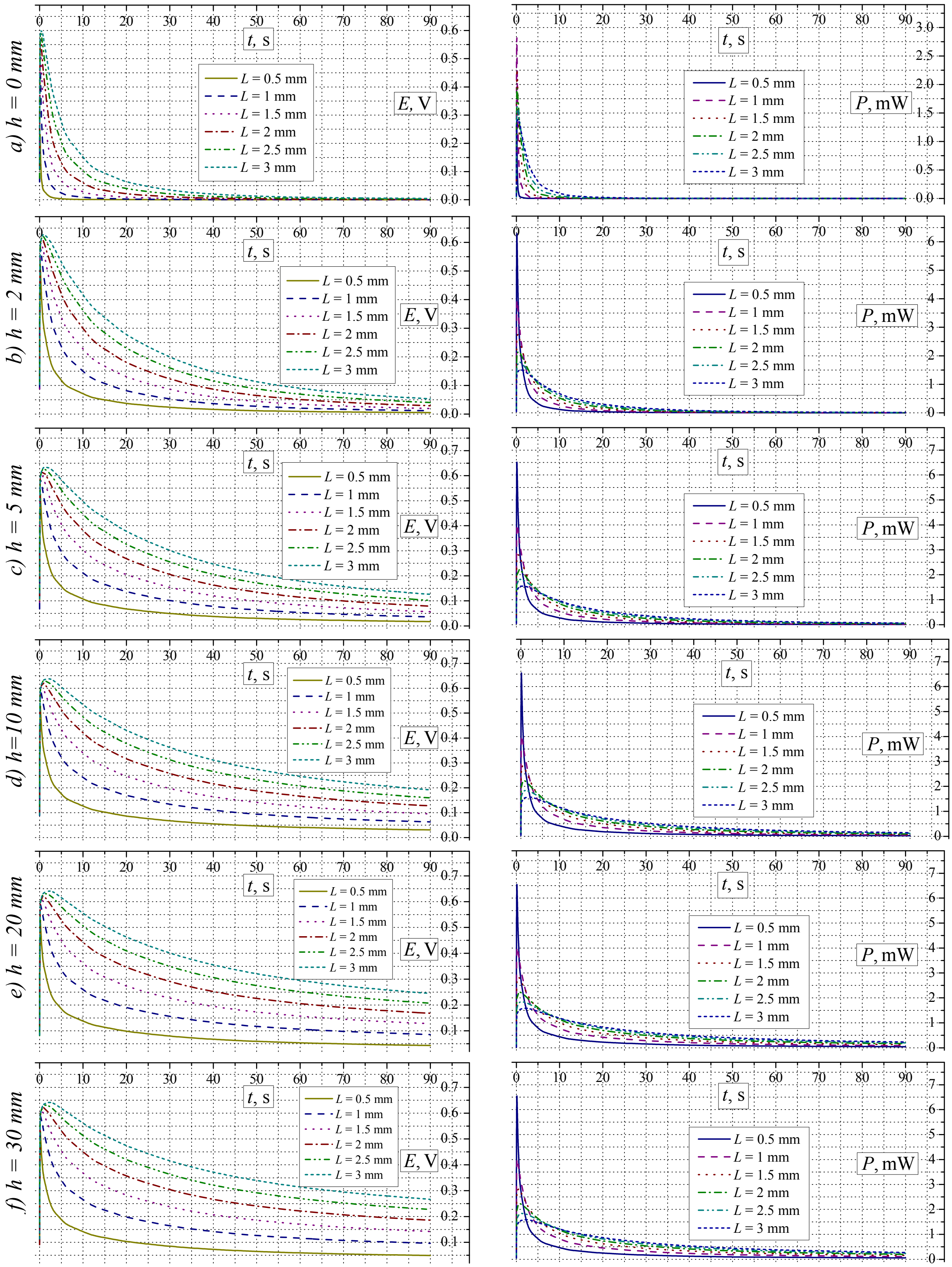


Fig. 4. Dynamics of change in EMF and electric power of thermoelectric microgenerator with different length of legs and heat accumulator (each curve corresponds to certain length of thermogenerator legs, and each figure – to certain length of heat accumulator).

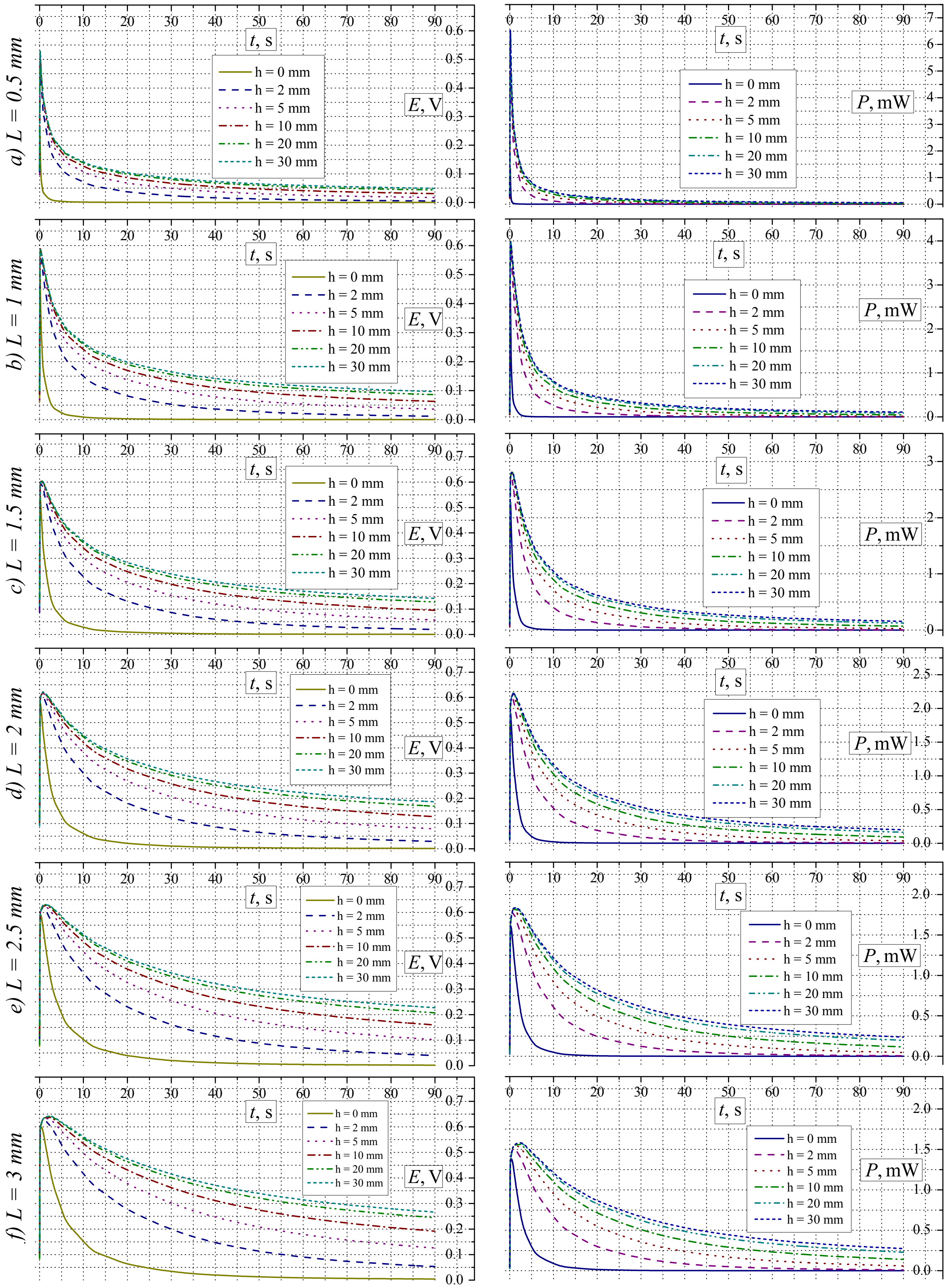
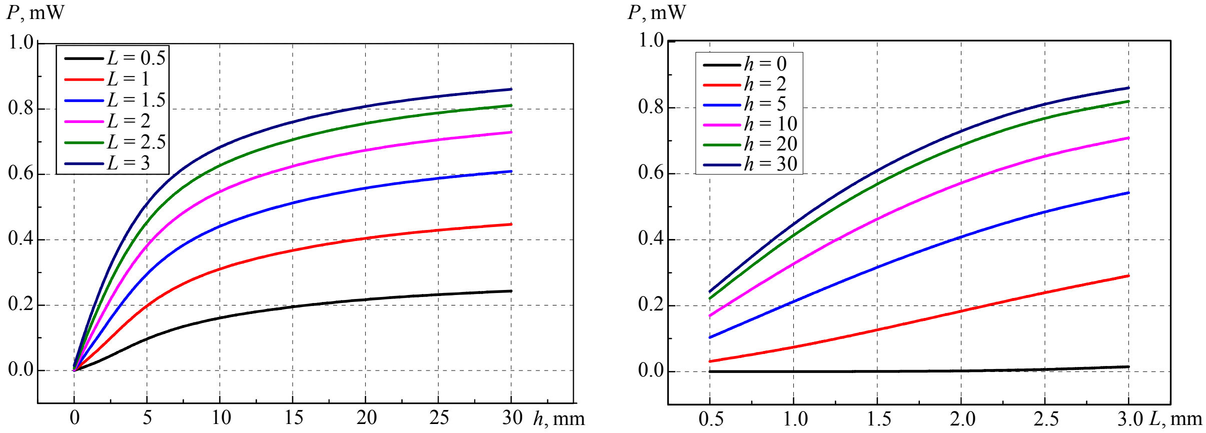


Fig. 5. Dynamics of change in EMF and electric power of thermoelectric microgenerator with different length of legs and heat accumulator (each curve corresponds to certain length of heat accumulator, and each figure – to certain length of thermal generator legs).

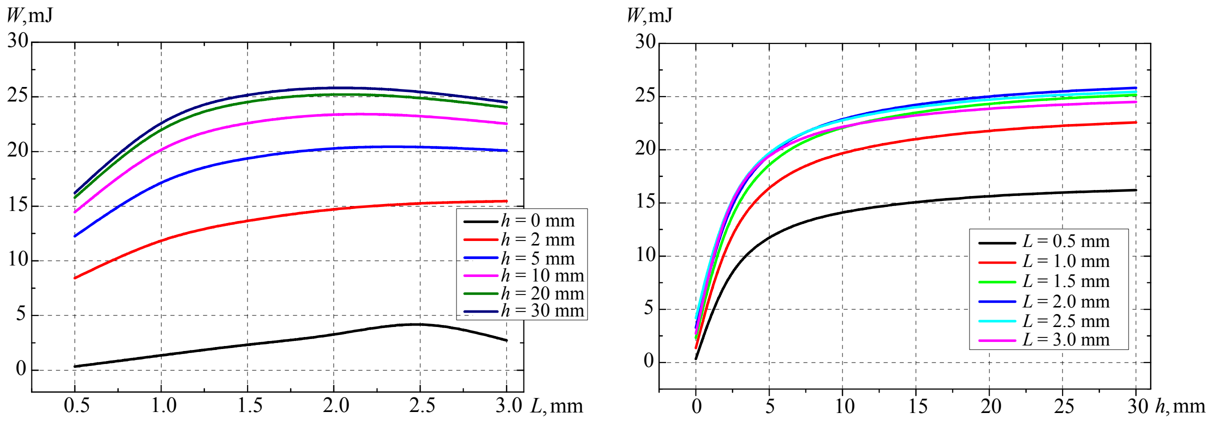
From the analysis of Figs. 4-5 a,b,c,d,f it is evident that increasing the length of heat accumulator and the length of thermoelectric microgenerator legs improves its energy characteristics. However, from this representation it is difficult to estimate the rates of the energy characteristics improvement and to determine the optimal length values of heat accumulator and thermoelectric microgenerator legs. Let us consider a more specific case when microgenerator first works in the mode of electric energy accumulation, and then this energy is used to power the electronic circuit of a short-life medical device, for instance, electronic thermometer. The time of electric energy accumulation in this case corresponds to the heating time of thermometer temperature sensor and is nearly 20 s. The dependence of electric power of such microgenerator at this time moment is given in Fig. 6.



a) *b)*

Fig. 6. Electric power of thermoelectric microgenerator at time moment t = 20 s:
a) versus the length of heat accumulator h for different lengths of legs L;
b) versus the length of legs L for different lengths of heat accumulator h.

From the plots it is evident that it will be most reasonable to use heat accumulator of length about h = 5÷10 mm, since the rates of increasing the electric power of thermoelectric microgenerator are essentially reduced at lengths larger than h = 10 mm.



a) *b)*

Fig. 7. Electric energy produced during time t = 20 s:
a)versus the length of legs L for different lengths of heat accumulator h;
b) versus the length of heat accumulator h for different lengths of legs L.

Fig. 6b shows that in the absence of heat accumulator on a thermoelectric microgenerator located on the surface of human skin, the electric power generation is practically absent. Also from the figure it is seen that with heat accumulator length $h = 2 \div 10$ mm the electric power is directly proportional to the length of microgenerator legs.

However, using thermoelectric microgenerators with the length of legs larger than $L = 3$ mm is unreasonable, which is evident if we estimate not the power at certain time moment, but the electric energy W produced by this moment (Fig. 7).

Fig. 7 shows a dependence of electric energy obtained during time $t = 20$ s since the moment of contact between thermoelectric microgenerator and the skin surface. From Fig. 7 a it is seen that in the absence of heat accumulator the optimal length of microgenertaor lengs is $L = 2.5$ mm, and with increasing the length of heat accumulator, the optimal length of legs is gradually reduced to $L = 2$ mm. Thus, the optimal length of microgenerator legs is $L = 2 \div 2.5$ mm (Fig.7 a,b). In so doing, the energy obtained during the first 20 s of microgenerator work is at the best W = 25.8 mJ.

For comparison to the steady-state mode, let us consider the work of a thermoelectric microgenerator of size 10×10 mm with a mass- and size-alike heat sink in the state of heat exchange with the environment. For correct comparison, we will give the energy obtained during time $t = 20$ s in steady-state operating condition of thermal generator depending on the length of microgenerator legs L and the length of heat sink fins h (Fig.8).

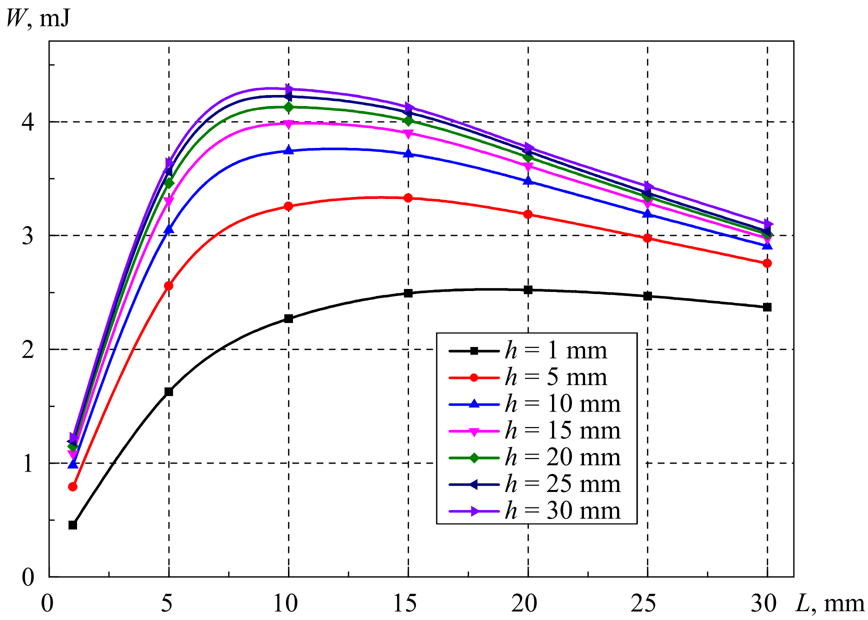


Fig.8. Electric energy produced during time t = 20 s versus the length of microgenerator L for different lengths of heat sink fins h in steady-state mode.

From Fig. 8 it is easily seen that in steady-state operating mode of microgenerator the electric energy is at the best case W = 4.3 mJ. Thus, the energy obtained during the first 20 s of transient mode is 6-fold the energy obtained during a similar time interval in steady-state operating mode of microgenerator. Using a device for electric energy accumulation and output voltage stabilization, one can use the energy generated at the initial step for power supply to short-life equipment, such as electronic thermometers. This confirms the advisability of using dynamic operating modes of thermoelectric microgenerator using human heat for power supply to low-power electronic devices.

Conclusions

A theory of computer simulation of processes of thermal human energy conversion into electric energy is developed enabling one to design thermoelectric microgenerators using the heat of human body and to optimize their design in order to achieve the highest efficiency of thermoelectric energy conversion in dynamic operating modes.

Computer methods of simulation of thermal and electrical processes occurring at the interaction of thermoelectric microgenerators and human body are developed. For the partial case it is established that the energy of the first 20 s of transient mode is 6-fold the energy obtained during the same time interval in steady-state operating mode of microgenerator.

The advisability of using dynamic operating modes of thermoelectric microgenerator for power supply to low-power electronic devices is confirmed.

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Submitted 17.10.14