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V.V. Lysko, *Cand.Sc. (Phys-Math)* [1,2]
I.A. Konstantynovych, *Cand.Sc. (Phys-Math)* [1,2]
R.V. Kuz, *Cand.Sc. (Phys.& Math)* [1]
T.V. Derevianko [1,2]

[1] Institute of Thermoelectricity of the National Academy of Sciences
and the Ministry of Education and Science of Ukraine,
1 Nauky St., Chernivtsi, 58029, Ukraine;
[2] Yuriy Fedkovych Chernivtsi National University,
2 Kotsiubynsky St., Chernivtsi, 58012, Ukraine

POSSIBILITIES OF REDUCING THE SPECIFIC COST OF THERMOELECTRIC GENERATOR ENERGY CONVERTERS

The paper presents the results of computer simulation of a thermoelectric generator module for waste heat recovery. The influence of the module leg height on its energy and economic indicators is analyzed. Bibl. 11, Fig. 15.
Key words: thermoelectric generator module, computer simulation, power, efficiency, specific cost

Introduction

Thermoelectric products have great potential. In particular, one of the options for its implementation is the generation of electrical energy through the recovery of waste heat. After all, one of the current problems of our time is the large amount of low-grade waste heat, which accounts for more than 70% of the energy used in the world. These are wastes from power plants, heavy industry, cars, airplanes, ships (which use internal combustion engines), cooling systems (in industry, powerful computer technology), household appliances, etc. [1–5]. The temperatures of such wastes are in a range convenient for thermoelectric conversion of their heat into electrical energy.

The main component of a thermoelectric generator (TEG) is thermoelectric converters (modules). At the same time, thermoelectric material accounts for a significant part of the cost of a thermoelectric module - about 50%. Nowadays, the cost of mass-produced thermoelectric generator modules, for example, such as Hi-Z or Komatsu [6–7], is quite high – about \$10–20/W, which is the main obstacle to the mass use of such generator modules. Therefore, it is relevant to optimize the use of materials in thermoelectric modules in order to reduce the cost of the module while maintaining its maximum efficiency [8]. This will lead to an increase in the competitiveness of manufactured thermoelectric products.

The purpose of this work is computer simulation of a thermoelectric generator module and analysis of the possibility of reducing the specific cost of module by optimizing its design.

1. Physical model

To analyze the energy characteristics of a thermoelectric generator module, we will consider the physical model shown in Fig. 1.

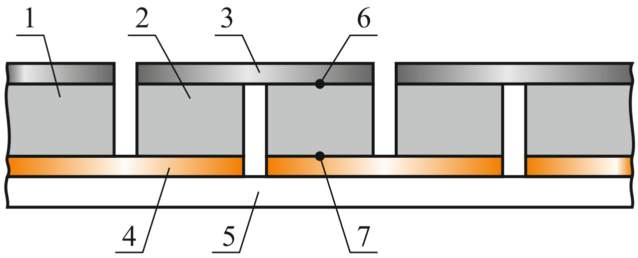

Fig. 1. Physical model of a thermoelectric generator module:
1 – n-type leg; 2 – p-type leg; 3, 4 –electrical interconnects;5 – ceramic plates;
6, 7 – electrical contacts between the legs and interconnect plates

The thermoelectric module consists of legs of n-type (1) and p-type (2) conductivity, which are connected in a series electric circuit using interconnect plates: the hot (3) and cold (4) sides of the module. Electrical contacts (6) and (7) have contact resistances, the values of which differ for the hot and cold sides. The base of the module is formed by a ceramic plate (5) on the cold side of the module, which ensures the mechanical stability of the module structure.

The basic equations for finding the distributions of temperature, potential, and current in a thermally and electrically conductive medium, with regard to thermoelectric effects, can be obtained based on the general laws of conservation of energy and electric charge.

$$\operatorname{div}\vec{w} = 0\,, \tag{1}$$

$$\operatorname{div}\vec{j} = 0\,, \tag{2}$$

where $\vec{w}$ is the energy flux density, $\vec{j}$ is the electric current density.

$$\vec{w} = \vec{q} + U\vec{j}\,, \tag{3}$$

where $\vec{q}$ is the heat flux density, U is the electrochemical potential.

The heat flux density is found from the generalized law of heat conduction

$$\vec{q} = -\kappa\nabla T + \alpha T\vec{j}\,, \tag{4}$$

where κ is thermal conductivity, T is temperature, α is thermoelectric coefficient.

The electric current density is found from the generalized law of electric conductivity

$$\vec{j} = -\sigma\nabla U - \sigma\alpha\nabla T\,, \tag{5}$$

where σ is electric conductivity.

Substituting (3)–(5) into (1), we obtain the equation for finding the temperature distribution

$$-\nabla\left(\kappa\nabla T\right) = \sigma\nabla\left(\alpha T + U\right)\left(\nabla U + \alpha\nabla T\right). \tag{6}$$

From the law of conservation of electric charge (2) using (5) we obtain the equation for determining the distribution of electric potential

$$-\nabla\left(\sigma\alpha\nabla T\right) - \nabla\left(\sigma\nabla U\right) = 0\,. \tag{7}$$

Equations (6), (7) form a system of second-order partial differential equations with variable coefficients, describing the distributions of interconnected fields of temperature T and electric potential U in an inhomogeneous thermoelectric medium.

The peculiarity of the system of equations (6), (7) is that the kinetic coefficients α, σ and κ are functions of the spatial coordinates x, y, z. In addition, they all depend on the temperature T, which in turn also depends on the spatial coordinates. Such a statement of the problem leads to the use of numerical methods to find its solution.

In this work, computer simulation was performed on the COMSOL Multiphysics platform [9].

2. Computer simulation results

The paper considers the design of the Altec-1061 thermoelectric module manufactured by the Institute of Thermoelectricity (Ukraine) [10]. Based on it, an analysis of the electrical and energy characteristics of the module was carried out depending on the height of the module leg for different temperature differences.

The design of the thermoelectric module and its computer model are presented in Fig. 2.

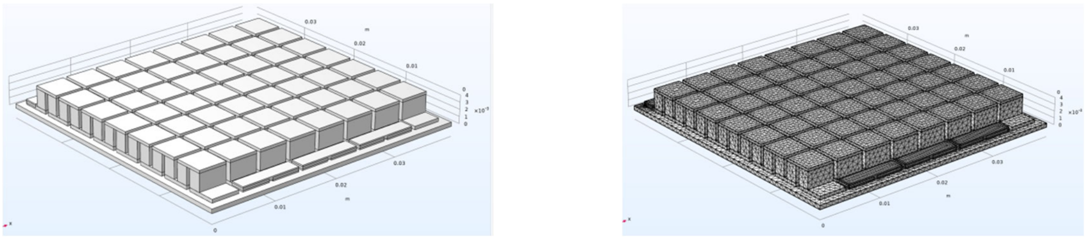

Fig. 2. Design and finite element mesh of a thermoelectric module

Parameters of the thermoelectric materials of module – $\alpha_n(T)$, $\alpha_p(T)$, $\sigma_n(T)$, $\sigma_p(T)$, $\kappa_n(T)$, $\kappa_p(T)$ – the Seebeck coefficients, electrical conductivity and thermal conductivity of thermoelectric material of *n*-and *p*-type accordingly, were obtained on the equipment developed at the Institute of Thermoelectricity [11].

The parameters of other structural elements were obtained from the manufacturers' passports.

The boundary conditions of the computer model used correspond to the physical model shown in Fig. 1 and the design solutions, as shown in Fig. 2.

Temperature and electric potential distribution

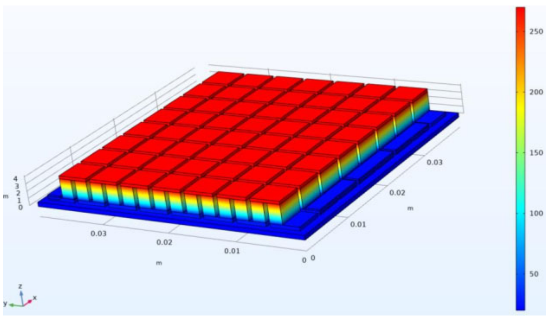

Fig. 3. Temperature distribution in a thermoelectric module

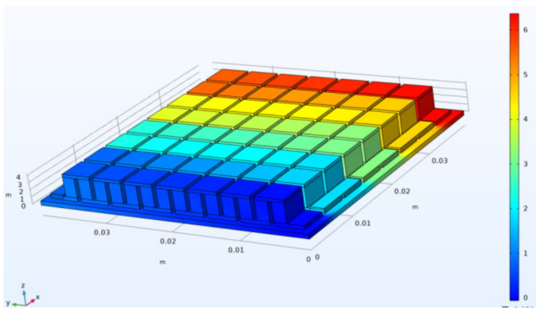

Fig. 4. Electric potential distribution in a thermoelectric module

Figs. 3–4 show examples of computer-simulated temperature and electric potential fields in a thermoelectric module. These data allow us to calculate the heat flux through the module Q_h,, the module’s EMF in the unloaded state ε, and the electric current through the module I in the loaded state. We obtain the module’s electric power W and its efficiency η:

$$W = I\frac{\varepsilon}{2}, \tag{8}$$

$$\eta = \frac{W}{Q_h}. \tag{9}$$

Influence of the height of thermoelectric module legs

One of the important geometric parameters of a thermoelectric module is the height of the legs. As the height of the legs decreases, the thermal resistance of the module decreases, and the heat flux through the module and its electrical power increase accordingly. In addition, the consumption of thermoelectric material, the most expensive component of a thermoelectric module, decreases in proportion to the height of the legs.

Figs. 5–12 show the dependences of power and efficiency on the leg height h calculated using computer simulation. The calculations were made for the hot-side temperatures in the range of 200–300 °C for different cold-side temperatures.

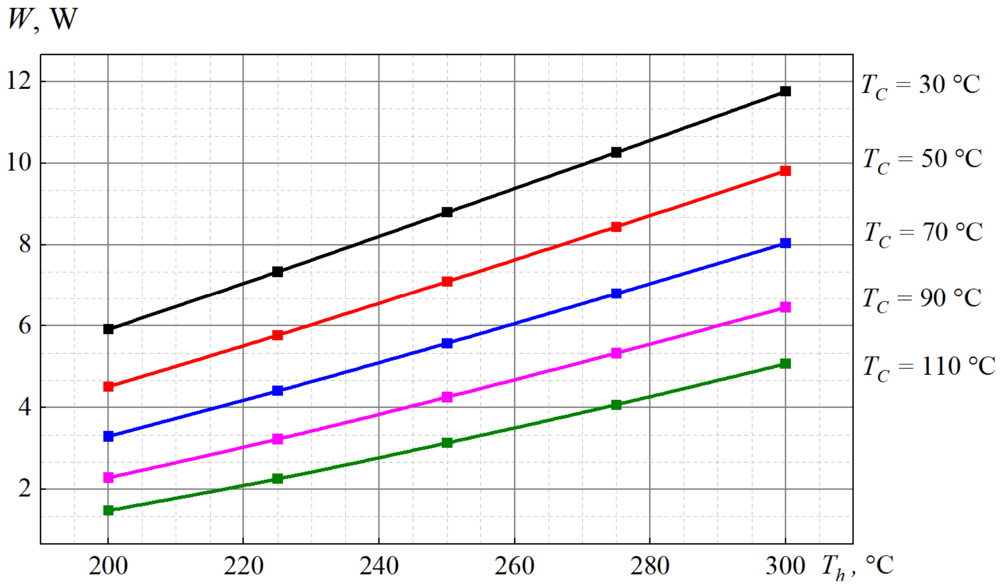

Fig.5.Dependence of module power on the hot side temperature for leg height h = 3.2mm.

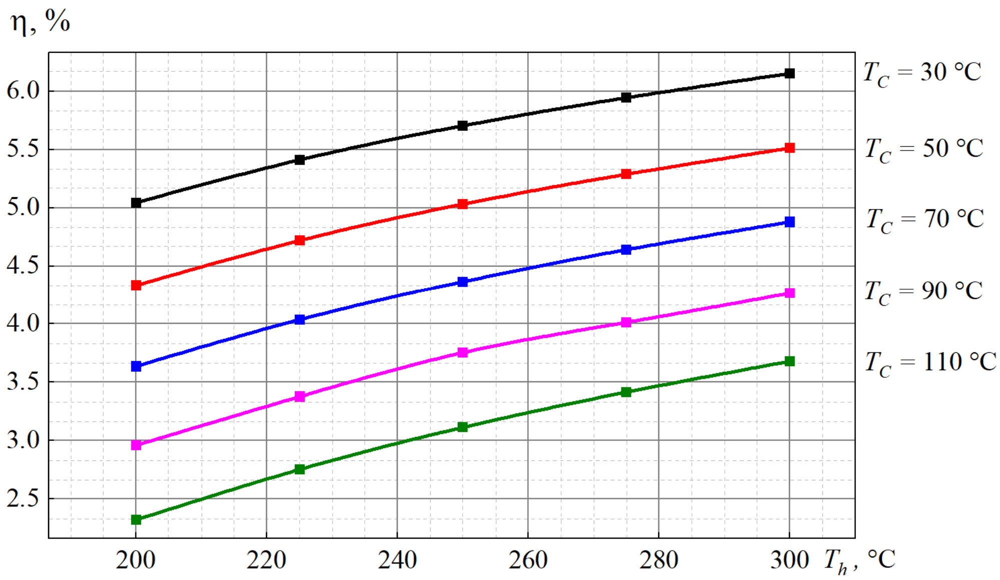

Fig. 6 Dependence of module efficiency on the hot side temperature for leg height h = 3.2mm

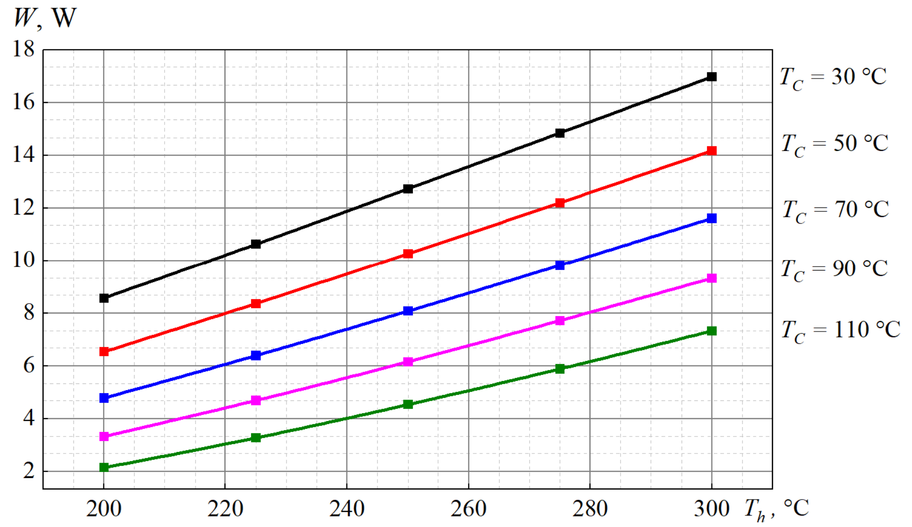

Fig.7. Dependence of module power on the hot side temperature for leg height h = 2.1mm.

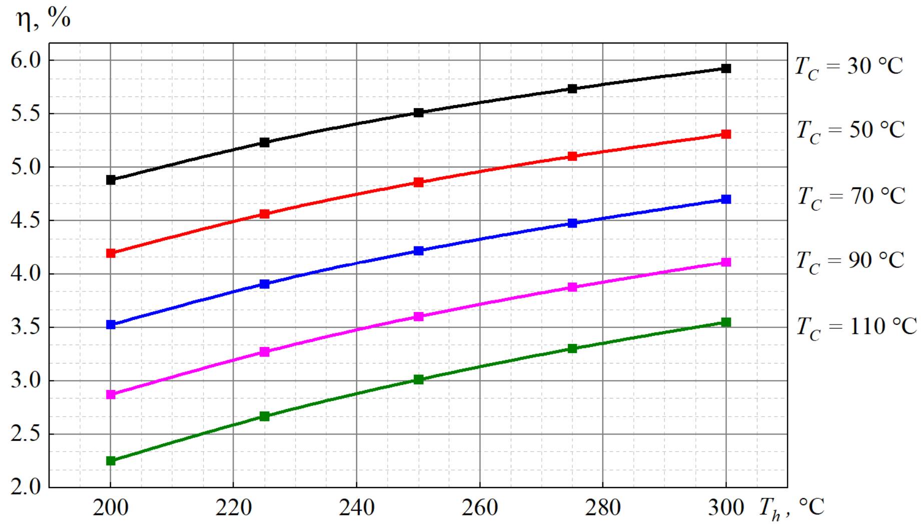

Fig. 8. Dependence of module efficiency on the hot side temperature for leg height h = 2.1mm

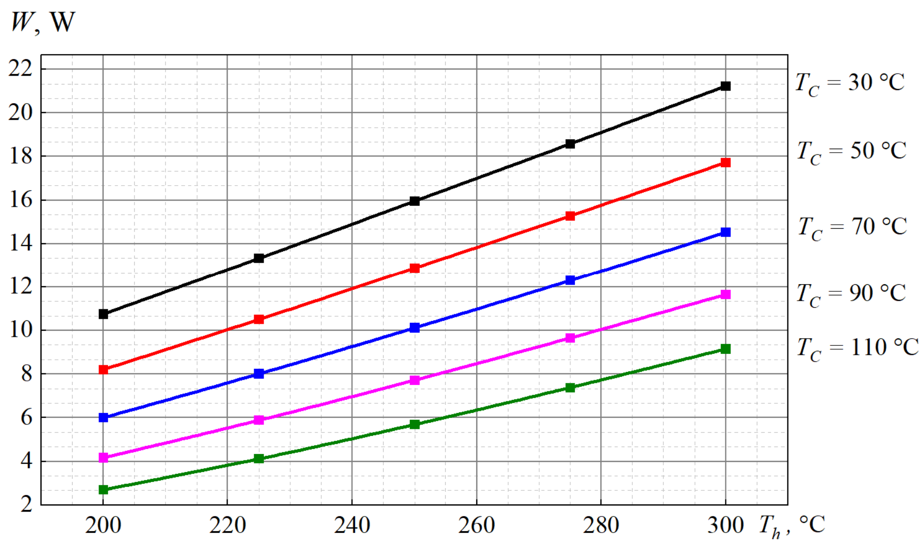

Fig.9. Dependence of module power on the hot side temperature for leg height h = 1.6 mm.

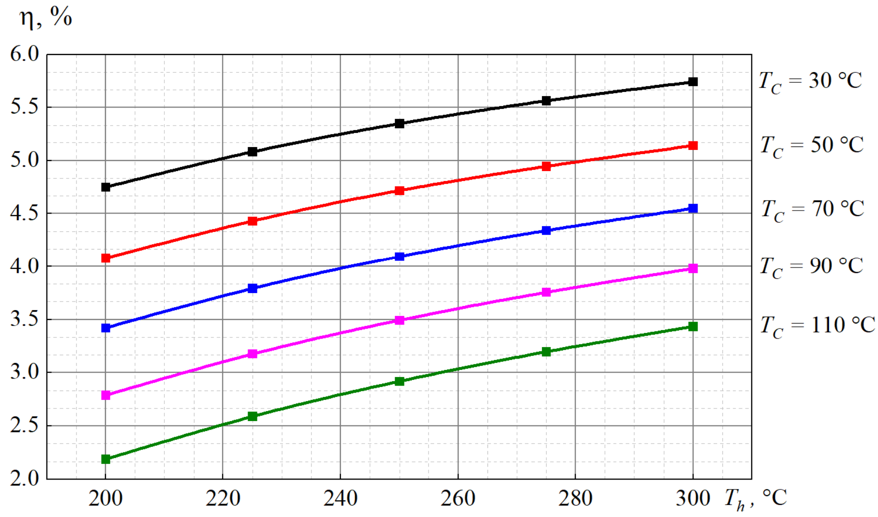

Fig.10. Dependence of module efficiency on the hot side temperature for leg height h = 1.6 mm

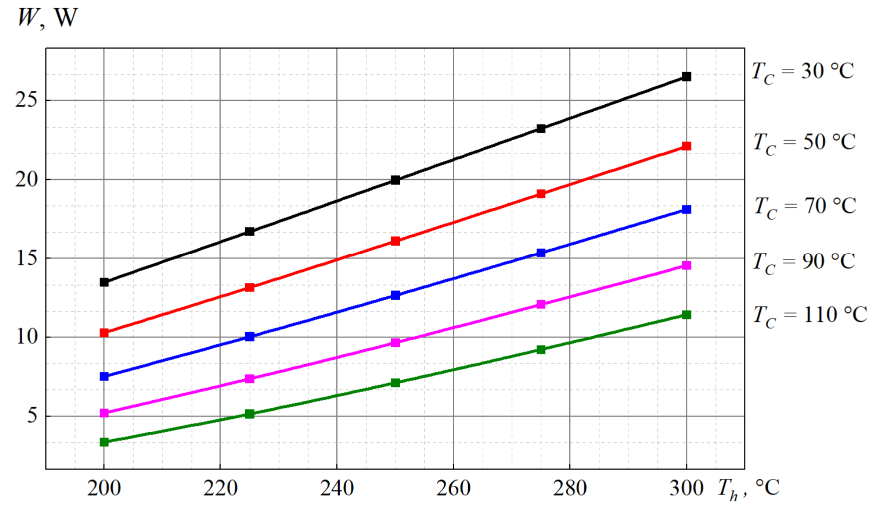

Fig. 11. Dependence of module power on the hot side temperature for leg height h = 1.2 mm.

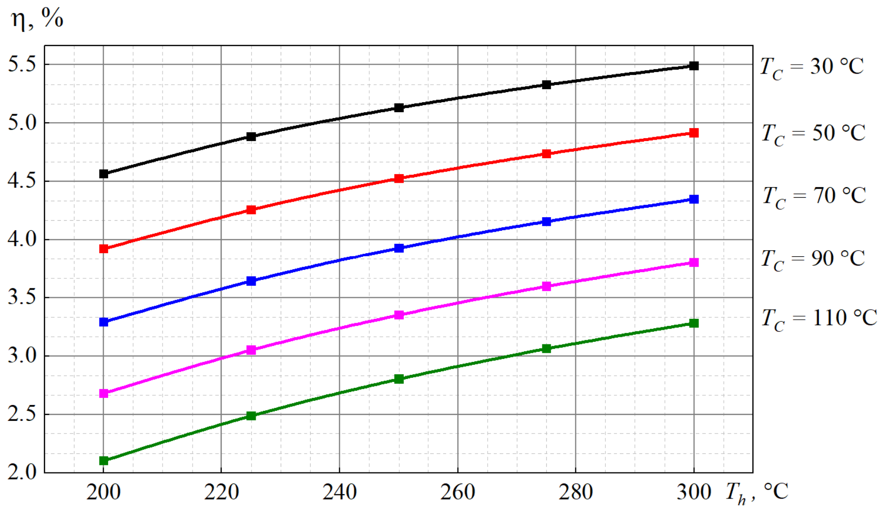

Fig.12.Dependence of module efficiency on the hot side temperature for leg height h = 1.2 mm

Figs. 12, 13 show the dependences of the efficiency and electric power on the height of the module leg for the hot side temperature of 300 °C.

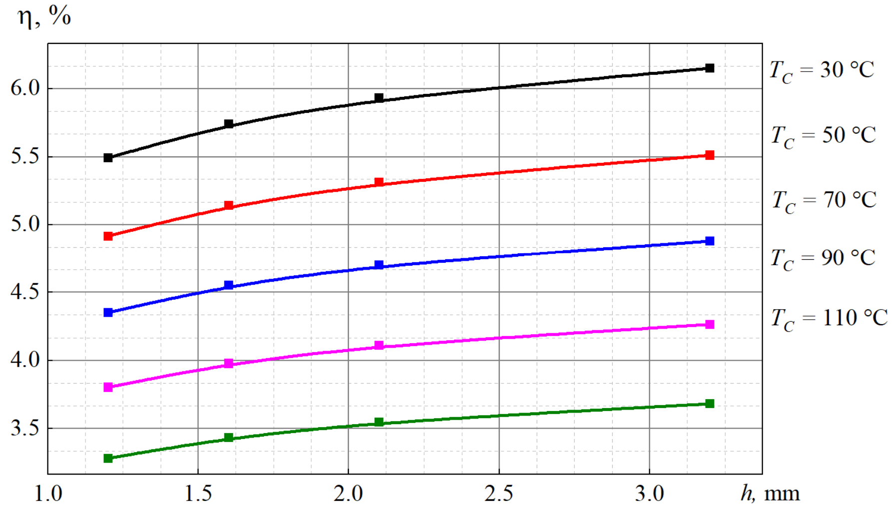

Fig 13. Dependence of module efficiency on the leg height at T_h = 300 °C.

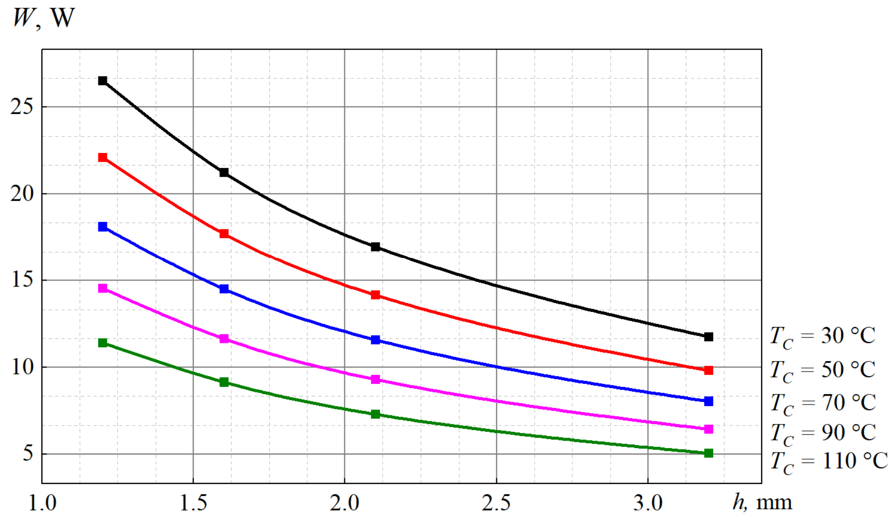

Fig 14. Dependence of module power on the leg height at T_h = 300 °C.

As can be seen from Fig. 13, when the leg height decreases, the efficiency of the module decreases slightly, but the electric power of the module increases (Fig. 14). For example, when the leg height is reduced two times, the electric power of the module increases by a factor of ~1.8. This should affect the specific cost of the thermoelectric module (USD /W).

Let P_0 be the cost of the module at the standard leg height h_0 = 3.2 mm, P is the cost of the module for an arbitrary leg height. P_R is the relative specific cost of the module. Then

$$P_R = \frac{P/W}{P_0/W_0} = \left[1 - k_0\left(1 + \frac{h}{h_0}\right)\right]\frac{W_0}{W}, \tag{10}$$

where $k_0 = \frac{P_0^m}{P_0}$, P_0^m – the cost of the thermoelectric material at the leg height h_0. That is, the coefficient k_0 indicates the contribution of the cost of the thermoelectric material to the total cost of the module.

Fig. 15 shows the dependence of the specific cost of the module on the leg height relative to the initial specific cost.

From Fig. 15 it can be seen that reducing the height of the thermoelectric module leg by a factor of 2 significantly reduces its specific cost approximately 2.4–3 times, depending on what proportion of the module cost is the cost of the thermoelectric material.

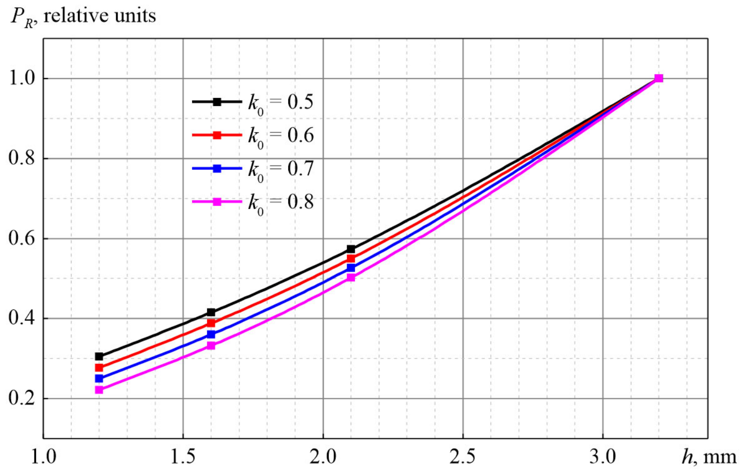

Fig.15. Dependence of relative specific cost of thermoelectric module on the height of its leg (T_h = 300 °C, T_c = 30 °C, k_0 – the cost of thermoelectric material relative to the cost of the module)

Conclusions

1. Using computer simulation, the energy characteristics of the Altec-1061 thermoelectric module were obtained for its modifications with different leg heights.
2. When maintaining the module area constant, the most significant parameter of the module is the height of its leg, which has a significant impact on the energy and economic characteristics. By reducing the height of the module leg by half, its electrical power can be increased by a factor of ~1.8. At the same time, its specific cost (USD/W) can fall 2.4–3 times.

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Лисько В.В., *канд. фіз.-мат. наук* [1,2]
Константинович І.А., *канд. фіз.-мат. наук* [1,2]
Кузь Р.В., *канд. фіз.-мат. наук* [1]
Деревянко Т.В. [1,2]

[1] Інститут термоелектрики НАН і МОН України, вул. Науки, 1, Чернівці, 58029, Україна;
[2] Чернівецький національний університет,
ім. Юрія Федьковича, вул. Коцюбинського, 2, Чернівці, 58012, Україна.

МОЖЛИВОСТІ ЗНИЖЕННЯ ПИТОМОЇ ВАРТОСТІ ТЕРМОЕЛЕКТРИЧНИХ ГЕНЕРАТОРНИХ ПЕРЕТВОРЮВАЧІВ ЕНЕРГІЇ

У роботі наведено результати комп'ютерного моделювання термоелектричного генераторного модуля для рекуперації відходів тепла. Проаналізовано вплив висоти гілки модуля на його енергетичні й економічні показники. Бібл. 11, рис. 15.

Ключові слова: термоелектричний генераторний модуль, комп’ютерне моделювання, потужність, коефіцієнт корисної дії, питома вартість

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