DOI: 10.63527/1607-8829-2024-1-2-78-89

M.M. Ivanochko, *Cand. Sc (Phys-Math)* [2]
I.A. Konstantynovych, *Cand. Sc (Phys-Math)* [1,2]
K.O. Kadelnyk [1,2]

[1] Institute of Thermoelectricity of the NAS and MES of Ukraine,
1 Nauky str., Chernivtsi, 58029, Ukraine;
[2] Yuriy Fedkovych Chernivtsi National University,
2 Kotsiubynskyi str., Chernivtsi, 58012, Ukraine

ON THE DESIGN OF A PORTABLE UNIVERSAL THERMOELECTRIC GENERATOR

A physical and mathematical model of a portable universal thermoelectric generator designed to power low-power equipment, mobile and special communication systems, charge accumulators and lighting, and provide the civilian population in places where the energy infrastructure is destroyed, as well as in non-electrified areas, with minimal electrical energy is presented. The solution to simplified heat transfer problems in single-layer and multilayer structures in stationary and non-stationary conditions is considered. A computer model has been elaborated for developing the design of a portable universal thermoelectric generator, together with optimizing the thermoelectric material from which it is made, for various operating modes. Bibliography 17, Fig. 7.

Key words: heat and electricity source, thermoelectric generator, physical model, efficiency, heat source.

Introduction

To date, chemical current sources are usually used to power equipment, including military equipment, in the field. However, among main disadvantages are their tendency to self-discharge and low reliability, especially at low ambient temperatures and under significant mechanical loads. Portable mini-power plants are of little use in the field due to their large size and weight, the need for fuel, which is often unavailable, and the noise they create. Therefore, it is particularly relevant to search for new and develop existing designs of autonomous heat and electricity sources that would meet these requirements, be compact, convenient to use, and suitable for use in the field.

Autonomous thermoelectric power sources that operate on heat from burning any fuel seem to be a promising solution in this context. Such sources are characterized by a long service life, high reliability, stability to climatic conditions and mechanical influences, and are also universal, silent and easy to operate. Scientists and engineers worldwide are involved in the development of such systems. In particular, thermoelectric generators with a power of 2 – 20 W for charging mobile phones, navigators and other devices during hiking trips have been developed by foreign companies such as TES, Power Pot and Biolite [1 – 5]. Thermoelectric generators utilizing the heat of solid fuel stoves have also been developed and are mass-produced by foreign enterprises [6 – 11]. However, these generators are expensive, intended mainly for domestic needs and have a number of disadvantages.

The high cost of thermoelectric materials remains the crucial factor that hinders the widespread implementation of such devices Thus, conducting research aimed at reducing the cost of materials, developing affordable autonomous thermoelectric energy sources and creating optimal designs adapted to specific operating conditions are topical tasks for this purpose.

Therefore, *the aim of the work* is to create tools (physical and mathematical models, computer programmes) necessary for the design of autonomous thermoelectric generators and optimization of the thermoelectric material from which they are made, to ensure that their operating conditions are brought as close to reality as possible.

Physical model of a portable universal thermoelectric generator

In general, the design of a portable universal thermoelectric generator is presented in Fig. 1. It consists of the following parts: heat source (1) (heated surface); "hot" heat exchanger (2); thermoelectric generator modules (3); "cold" heat exchanger (4); water tank (5); water (6); high thermal conductivity paste (7, 13); ceramic plates (8, 12); connecting plates (9, 11); legs of thermoelectric material of *n*- and *p*-types (10); current leads of thermoelectric modules (14).

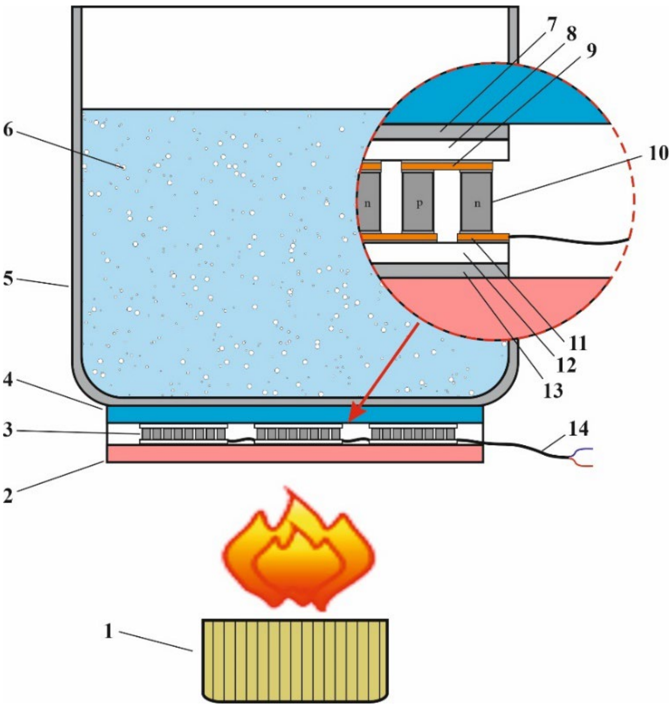

Fig. 1. Design of a portable universal thermoelectric generator: 1 – heat source (heated surface); 2 – "hot" heat exchanger; 3 – thermoelectric generator modules; 4 – "cold" heat exchanger; 5 – water tank; 6 – water; 7, 13 – highly thermally conductive paste; 8, 12 – ceramic plates; 9, 11 – connecting plates; 10 –legs of thermoelectric material of n- and p-types; 14 – current leads of thermoelectric modules.

The physical model of a portable universal thermoelectric generator is presented in Fig. 2, where Q_1 is the heat supplied to the hot heat exchanger from the heat source; Q_2 is the heat loss from the side surface of the hot heat exchanger to the environment by radiation and convection; Q_3 is the heat supplied to the hot side of the thermopile from the hot heat exchanger; Q_4 is the heat loss from the side surface of the thermoelectric battery; Q_5 is the heat supplied from the cold side of the thermopile to the cold heat exchanger; Q_6 is the heat transferred from the side surface of the cold heat exchanger to the environment by radiation and convection; Q_7 is the heat transferred from the cold heat exchanger to the water tank; P is the electric power of the thermopile.

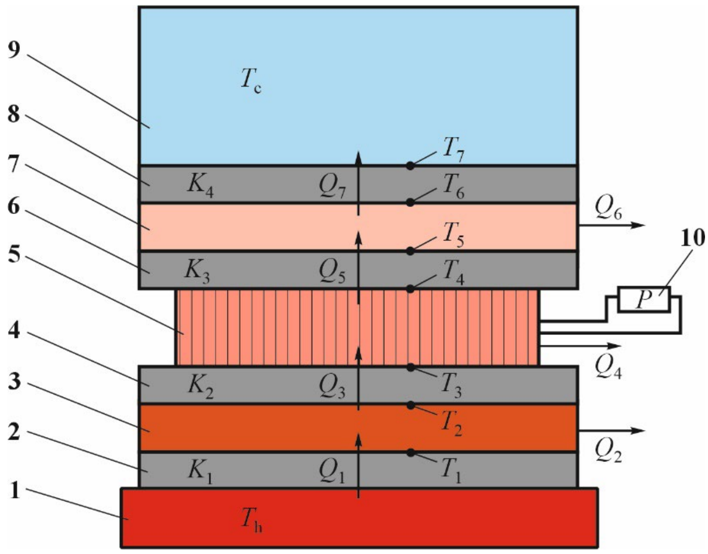

Fig. 2. Physical model of a portable universal thermoelectric generator: 1 – heat source (heated surface); 2, 4, 6, 8 – thermal contact resistances; 3 – hot heat exchanger; 5 – thermopile; 7 – cold heat exchanger; 9 – water tank; 10 – electronic output voltage stabilization device with electric energy accumulator.

A thermoelectric generator can have two operating modes:

• heating the water in the tank to the boiling point and gradually reducing the amount of water through evaporation;

• heating the water in the tank to the boiling point and replacing it with water at room temperature.

Heat transfer in the problem under consideration is the typical heat exchange between two media through a solid wall (often multilayer) that separates them. This heat transfer process includes heat transfer (mostly by radiation) from the first medium to the surface of the wall, includes thermal conductivity through the wall and further heat transfer (also more often by radiation) from the opposite surface to another medium.

Heat transfer phenomena are considered on the basis of the phenomenological method, which considers the relationships between the parameters that generally characterize the phenomenon under consideration, without taking into account the microstructure of the medium in which the process takes place.

The optimization problem for this design of a portable universal thermoelectric generator is multiparametric and extremely difficult to solve in the general case, therefore, further in the work, simplified models and the transition from simple problems to more complex ones are considered.

Thermal conductivity in steady state mode

1. Heat transfer through a flat wall in the absence of internal heat sources $(q_v = 0)$

Let us consider the process of heat transfer through a flat homogeneous isotropic wall of thickness δ with a constant coefficient of thermal conductivity λ. The temperatures on the wall surfaces are constant $T_{Cm1} > T_{Cm2}$. The heat flow is directed along the axis Ox, directed perpendicular to the plane of the wall, and therefore the temperature will change only along Ox, remaining constant in the directions Oy and Oz.

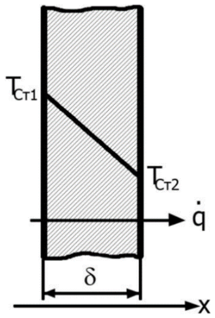

Fig. 3. Temperature distribution in a flat wall.

The stationary equation of heat conduction for this case is the Laplace equation

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0\,. \tag{1}$$

Temperature changes only along the axis Ox , therefore $\frac{\partial^2 T}{\partial y^2}=0$, $\frac{\partial^2 T}{\partial z^2}=0$, hence

$$\frac{\partial^2 T}{\partial x^2}=0\,. \tag{2}$$

Having integrated this differential equation, we obtain

$$T=C_1x+C_2\,. \tag{3}$$

Equation (2) is the equation of a straight line, therefore, the temperature in a flat wall varies linearly.

Let us set the boundary conditions of the first kind for this problem:

$$\left.\begin{matrix} x=0 & T=T_{Cm1} \\ x=\delta & T=T_{Cm2} \end{matrix}\right\}. \tag{4}$$

Then the equation of the line that describes the temperature distribution in a flat wall will be:

$$T=-\frac{T_{Cm1}-T_{Cm2}}{\delta}x+T_{Cm1}\,. \tag{5}$$

Equation (5) enables calculating the temperature at any point on the wall. Let us write Fourier's law for calculating the thermal conductivity through a flat wall:

$$q=\lambda\frac{\partial T}{\partial \overline{n}}, \tag{6}$$

For this case:

$$\frac{\partial T}{\partial \overline{n}}=\frac{\partial T}{\partial x}=C_1=-\frac{T_{Cm1}-T_{Cm2}}{\delta}, \tag{7}$$

then

$$q=\lambda\frac{T_{cm1}-T_{Cm2}}{\delta}\,. \tag{8}$$

It should be noted that the heat flow is determined not by the absolute value of temperatures, but by their difference $T_{Cm1}-T_{Cm2}=\Delta T$, which is usually called the temperature difference.

Or for the total amount of heat transferred:

$$\dot{Q} = \frac{\lambda}{\delta} F (T_{Cm1} - T_{Cm2}) . \tag{9}$$

The total amount of heat Q_τ that is transferred through the surface F of the wall in an hour τ:

$$Q_\tau = qF\tau = \frac{\lambda}{\delta} F (T_{Cm1} - T_{Cm2})\tau . \tag{10}$$

Equation (9) describes the process of heat transfer by thermal conductivity in a single-layer flat wall in a stationary mode. The ratio λ/δ, $\mathrm{W}/(\mathrm{m}^2 \times \mathrm{K})$ is called the thermal conductivity of the wall, and the inverse value is the heat or thermal resistance of the wall.

2. Thermal conductivity of a multilayer flat wall

Let us consider the process of steady-state heat conduction through a three-layer flat wall. Layers of different thicknesses $(\delta_1, \delta_2, \delta_3)$, which are closely adjacent to each other and have different values of thermal conductivity $(\lambda_{T1}, \lambda_{T2}, \lambda_{T3})$. Since the process is a steady-state one, $q = const$ is directed along the axis Ox.

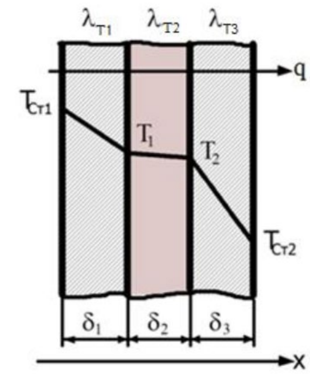

Fig. 4. Temperature distribution in a multilayer flat wall.

Let us assume that on the surfaces of the external planes the temperatures T_{Cm1} and T_{Cm2}, whereas $T_{Cm1} > T_{Cm2}$ and between the layers the temperatures T_1 and T_2.

By analogy with (8), the equation of heat transfer through each layer of the structure can be written as:

$$q = \frac{\lambda_1}{\delta_1} (T_{Cm1} - T_1) , \tag{11}$$

$$q = \frac{\lambda_2}{\delta_2} (T_1 - T_2) , \tag{12}$$

$$q = \frac{\lambda_3}{\delta_3} (T_2 - T_{Cm2}) . \tag{13}$$

From the last system of equations, we determine the heat flux q through a layered flat wall:

$$q = \frac{T_{Cm1} - T_{Cm2}}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{\delta_3}{\lambda_3}} = \frac{T_{Cm1} - T_{Cm2}}{\sum_i \frac{\delta_i}{\lambda_i}} . \tag{14}$$

The values $\frac{\delta_i}{\lambda_i}$ are the thermal resistances of the individual layers that form the multilayer wall.

The heat conductivity equation for the established heat transfer process will have the form of:

$$\dot{Q} = F\frac{T_{Cm1} - T_{Cm2}}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{\delta_3}{\lambda_3}} = F\frac{T_{Cm1} - T_{Cm2}}{\sum_i \frac{\delta_i}{\lambda_i}}. \quad (15)$$

In each layer, the temperature changes linearly along the thickness; in general, the temperature profile has the form of a broken line, and in Fig. 4 $\lambda_{T_2} > \lambda_{T_1} > \lambda_{T_3}$.

The problem of modeling non-stationary heat propagation processes in a cylindrical layered structure

Problem statement: It is necessary to write the heat conduction equation and formulate the boundary conditions for the time instant $\tau > 0$ to solve the non-stationary thermal problem in a region that is a three-layer continuous homogeneous region of a circular cylinder with radius R, different thicknesses δ_i (i = 1, 2, 3) of layers with different thermal conductivities λ_i (i = 1, 2, 3) and densities of media ρ_i (i = 1, 2, 3) each.

The problem is considered cylindrically symmetric, and therefore the solution of the problem will not depend on the azimuthal angle ϕ.

At the initial moment of time $\tau = 0$, a heat flow $\vec{q}$ is supplied to the lower base of the first (i = 1) layer of the cylindrical region at $z = 0$ (in cylindrical coordinates r, ϕ, z), the power of which is such that this base, according to Newton's law, is heated to a temperature of $T \sim 300 - 400$°C.

Heat spreads over time $\tau > 0$ inside the cylindrical structure along the axis Oz directed along the axis of the cylindrical layered structure, through the boundaries of the layers $z = \delta_1$ and $z = \delta_1 + \delta_2$, and on the surface of the last third upper layer, when it reaches the temperature $T_k = 100$°C, heat is removed from this surface, so that its temperature T_k remains constant over time.

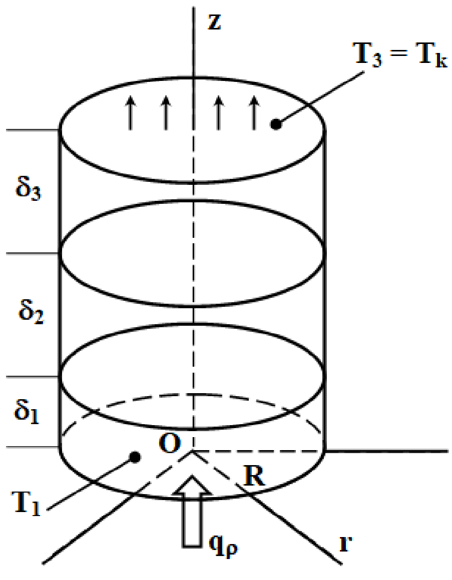

Fig. 5. Model of a cylindrical three-layer structure.

Heat exchange of the side surfaces of the structure with the surrounding environment by convection is neglected due to the small area of the side surfaces compared to the areas of the surface of the layers.

1) Heat conduction equation

For each layer i = 1, 2, 3 the problem is described by the heat conduction equation in non-stationary form

$$\rho_i c_i \frac{\partial T_i}{\partial \tau} = \lambda_i \left(\frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r}\frac{\partial T_i}{\partial r} + \frac{\partial^2 T_i}{\partial z^2} \right), \quad (16)$$

where $T_i(r,z,\tau)$ is the temperature in the i_{th} layer; λ_i, ρ_i, c_i are thermal conductivity, density, heat capacity for the i_{th} layer, respectively; τ is the time.

2) Boundary conditions:

Bottom base $(z = 0,\, i = 1)$.

Heating of the bottom base occurs according to Newton's law due to a given heat flow q_ρ:

$$-\lambda_1 \frac{\partial T_1}{\partial z} = q_\rho \,,\; T_1\big|_{z=0} \approx 300°\text{C} \div 400°\text{C} \tag{17}$$

Boundaries between layers $(z = \delta_1, z = \delta_1 + \delta_2)$.

The condition of continuity of temperature and heat flux at the boundaries between adjacent layers:

$$T_i = T_{i+1} \,,\; \lambda_i \frac{\partial T_i}{\partial z} = \lambda_{i+1} \frac{\partial T_{i+1}}{\partial z} \,. \tag{18}$$

Upper surface $(z = \delta_1 + \delta_2 + \delta_3)$.

The temperature on this surface is maintained constant $T_k = 100°\text{C}$.

$$T_3\big|_{z=\delta_1+\delta_2+\delta_3} = T_k \,. \tag{19}$$

Lateral surface $(r = R)$.

Heat exchange through the lateral surfaces of the layers is neglected, since the areas of these surfaces are small as compared to the surface areas of the layers of the structure. Therefore, the condition is accepted:

$$\frac{\partial T}{\partial r} = 0 \,. \tag{20}$$

3) Initial condition

Initially, the temperature $(\tau = 0)$ is uniform throughout the region:

$$T_i(r,z,0) = T_{поч} \,, \tag{21}$$

where $T_{поч}$ is the initial temperature, corresponding to room or other given temperature.

The temperature $T(r,z,\tau)$ is a function r, z, τ only due to the cylindrical symmetry of the problem, and therefore the solution of the problem does not depend on the azimuthal angle ϕ.

The conditions at the layer boundaries describe physical continuity; the change in thermal conductivity between the materials is also considered.

Our task is to determine the temperature field $T(r,z,\tau)$ for all three layers with given properties (λ_i, ρ_i, c_i), geometric parameters $(R, \delta_1, \delta_2, \delta_3)$ and heat fluxes.

Analytical solution of the non-stationary problem of heat propagation in a cylindrical layered structure

The heat conduction equation (16) should be solved using the separation of variables method. The solution is found in the form:

$$T_i(r,z,\tau) = T_{r,i}(r) T_{z,i}(z) T_{\tau,i}(\tau) \,, \tag{22}$$

where $T_{r,i}(r)$, $T_{z,i}(z)$, $T_{\tau,i}(\tau)$ are separate functions from r, z and τ. This allows solving the problem by the method of separation of variables.

For the radial component in a cylindrical coordinate system, we obtain the equation:

$$\frac{\partial^2 T_{r,i}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{r,i}}{\partial r} = -\lambda_{r,i} T_{r,i} . \tag{23}$$

The solutions for such an equation are modified Bessel functions I_O and K_O.

For the component along the axis Oz, the equation has the form:

$$\frac{\partial^2 T_{z,i}}{\partial z^2} = -\lambda_{z,i} T_{z,i} , \tag{24}$$

whose solutions are exponential functions:

$$T_{z,i}(z) = C_1 e^{kz} + C_2 e^{-kz} . \tag{25}$$

For the time component $T_{\tau,i}(\tau)$, the equation will take the form

$$\frac{\partial T_{\tau,i}}{\partial \tau} = -\lambda_{\tau,i} T_{\tau,i} , \tag{26}$$

whose solutions are exponential functions as well:

$$T_{\tau,i}(\tau) = A e^{-\alpha\tau} . \tag{27}$$

Boundary conditions

Solutions must satisfy boundary conditions at the boundaries of the media:

• Lower base $(z = 0)$:

$$-\lambda_1 \frac{\partial T_1}{\partial z} = q_\rho . \tag{28}$$

This imposes a condition on the coefficients C_1 and C_2 for the solution of $T_{z,1}(z)$ з (25).

• Boundaries between layers $(z = \delta_1, \delta_1 + \delta_2)$:

$$T_i = T_{i+1} , \qquad \lambda_i \frac{\partial T_i}{\partial z} = \lambda_{i+1} \frac{\partial T_{i+1}}{\partial z} . \tag{29}$$

From these conditions, the temperature and heat flux matching coefficients at the boundaries are determined.

• Upper surface $(z = \delta_1 + \delta_2 + \delta_3)$:

$$T_3 = T_k = 100°\text{C} \ \textit{(special case).} \tag{30}$$

From the heat balance equation, $P \cdot t = m \cdot c(T(t) - T_O)$, dependence $T(t)$ for the general case is found:

$$T(t) = \begin{cases} T_O + \dfrac{P \cdot t}{m \cdot c}, \ if \ \ T(t) < T_{boil} \\ T_{boil}, \ if \ \ T(t) \geq T_{boil} \end{cases} \tag{31}$$

Complete solution

The general solution to a problem is the sum of partial solutions, and therefore the final analytical solution to the problem has the form of an infinite convergent series:

$$T_i(r,z,\tau) = \sum_{i=1}^{\infty} \left[A_{n,i} I_O(k_{r,n} r) + B_{n,i} K_O(k_{r,n} r) \right] \cdot (C_{n,i} e^{k_{z,n} z} + D_{n,i} e^{-k_{z,n} z}) e^{-\alpha_n \tau} . \tag{32}$$

The coefficients of the series $A_{n,i}$, $B_{n,i}$, $C_{n,i}$, $D_{n,i}$ are determined from the initial $T_i(r,z,0)=T_{init.}$ and boundary conditions.

The problem of non-stationary thermal conductivity of a bounded layered cylinder placed in a medium with a time-varying temperature is solved by numerical methods. Solving a nonlinear non-stationary problem by the finite element method is a complex task that involves the use of numerical methods to solve differential equations of thermal conductivity. The development of rational methods and algorithms for numerical solution of non-stationary problems of thermal physics with a significant temperature dependence of thermal properties is of overwhelmingy importance and topicality.

Computer simulation of a portable universal thermoelectric generator

For more complex cases, taking into account heat exchange with the environment, temperature dependences of model parameters, and other factors, it is advisable to use computer modeling. Further, the temperature distribution in the generator was considered using the COMSOL Multiphysics application package [12], the heat conduction equation for each element of the physical model is written in the form

$$\rho\, C_p \frac{\partial T}{\partial t} + \rho\, C_p u\, \nabla T + \nabla q = Q, \tag{33}$$

where ρ is density, C_p is heat capacity of the material, κ is thermal conductivity, u is he velocity of the medium, which in the problem under study is equal to zero, T is temperature, Q is external heat flux.

Fig. 6 shows the dependence of temperatures on the “hot” (blue curve) and “cold” (green curve) sides of the thermoelectric converter on time. The results were obtained using the parameters of thermoelectric energy converters obtained experimentally [13 – 17].

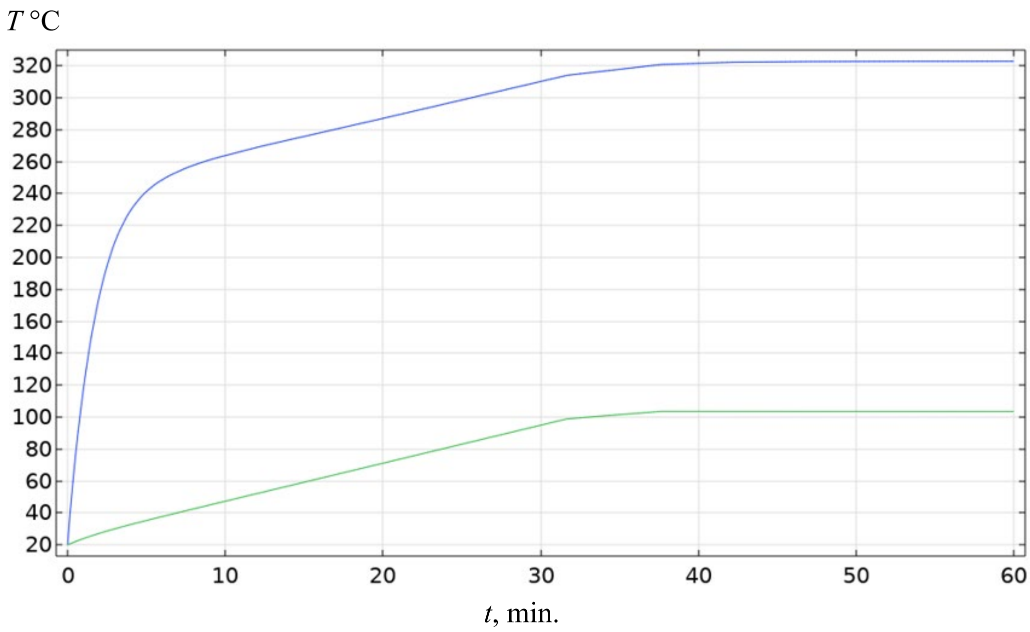

Fig. 6. Temperature dependence on the “hot” (blue curve) and “cold” (green curve) sides of the thermoelectric converter on time.

Fig. 7 here shows the temperature distribution in a portable universal thermoelectric generator at time t = 3600 s, obtained using the COMSOL Multiphysics application package.

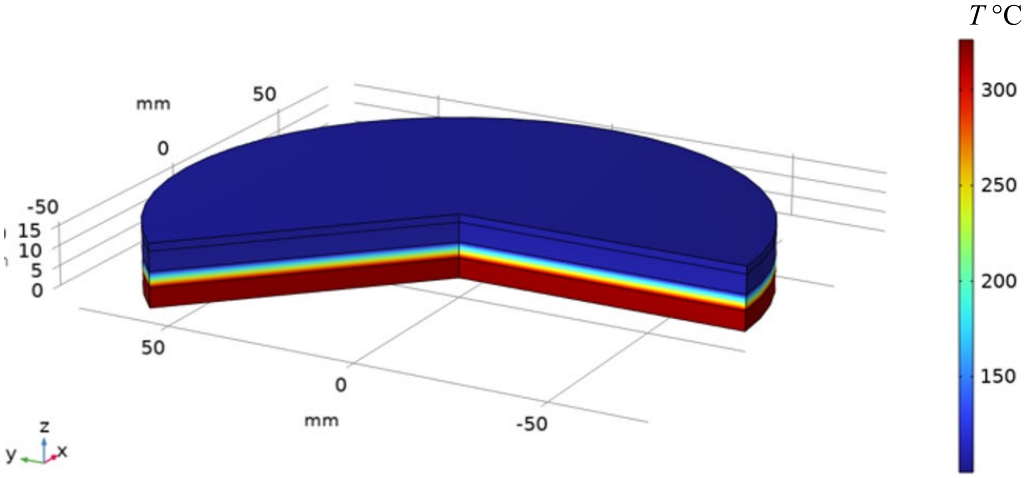

Fig. 7. Temperature distribution in a portable universal thermoelectric generator at time t = 3600 s.

The results of this article will be taken into account when manufacturing a real design of a portable universal thermoelectric generator.

The authors express their gratitude to Lysko V.V. for useful advice and valid comments during the preparation of this work.

Conclusions

1. A physical model of a portable universal thermoelectric generator designed to power low-power equipment is presented, as well as a mathematical and computer description of this model. Solutions to simplified heat transfer problems in single-layer and multilayer structures in stationary and non-stationary conditions are considered.
2. The developed computer model enables determining the dynamic and average power of a portable universal thermoelectric generator and designing a generator structure with specialized thermoelectric modules optimized for different modes of their operation.

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Submitted: 24.01.2024.

Іваночко М.М., *канд. фіз.-мат. наук* [1,2]
Константинович І.А., *канд. фіз.-мат. наук* [1,2]
Кадельник К.О. [1,2]

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

ПРО ПРОЄКТУВАННЯ ПОРТАТИВНОГО УНІВЕРСАЛЬНОГО ТЕРМОЕЛЕКТРИЧНОГО ГЕНЕРАТОРА

Наведено фізичну та математичну моделі портативного універсального термоелектричного генератора, призначеного для живлення малопотужної апаратури, систем мобільного та спеціального зв'язку, зарядки акумуляторів та освітлення, забезпечення мінімальною електричною енергією цивільного населення в місцях, де зруйнована енергетична інфраструктура, а також у неелектрифікованих районах. Розглянуто рішення спрощених задач теплообміну в одношарових та багатошарових структурах в стаціонарних та нестаціонарних умовах. Створено комп'ютерну модель для проєктування конструкції портативного універсального термоелектричного генератора, а також оптимізації термоелектричного матеріалу, з якого його виготовлено, для різних режимів експлуатації. Бібл. 17, рис. 7.

Ключові слова: джерело тепла та електрики, термоелектричний генератор, фізична модель, ефективність, джерело тепла.

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Надійшла до редакції: 24.01.2024.