L. I .Anatychuk

L. I. Anatychuk, *acad. National Academy of Sciences of Ukraine*[1,2]
V. V. Lysko, *cand. phys. - math. Sciences*[2]

Institute of Thermoelectricity of the NAS
and MES of Ukraine,
1, Nauky str., Chernivtsi, 58029, Ukraine,
e-mail: anatych@gmail.com
[2]Yu.FedkovychChernivtsiNationalUniversity,
2, Kotsiubynskyistr., Chernivtsi, 58012, Ukraine

V. V. Lysko

ON THE DESIGN OF A TRENCH THERMOELECTRIC SOURCE OF HEAT AND ELECTRICITY

The article presents physical and mathematical models of a trench thermoelectric source of heat and electricity intended for heating the military and powering low-power military equipment, mobile and special communications systems, charging batteries and lighting, providing heat and minimal electrical energy to the civilian population in places where the energy infrastructure has been destroyed, as well as in non-electrified areas outside the combat zone.A computer model has been created for designing the structure of such a heat and electricity source, as well as optimizing the thermoelectric material it is made of for various operating modes.Bibl. 15, Fig.1.
Keywords: thermoelectric source of heat and electricity, physical model, efficiency, cyclic mode.

Introduction

At present, the use of chemical current sources as autonomous low-power sources of electricity remains traditional for powering military equipment. However, their significant disadvantages are self-discharge and low reliability, especially at low ambient temperatures and under conditions of increased mechanical loads. Mobile mini-power plants are practically unsuitable for use in combat areas due to unacceptable mass and dimensional characteristics, the need for fuel, which may not always be available in combat conditions, and most importantly - due to the noise accompanying their operation, they become a significant unmasking factor. In this regard, it is important to search for and create fundamentally new designs of autonomous heat and electricity sources that are as close as possible to military equipment and at the same time suitable for use in combat areas.

In this regard, autonomous thermoelectric power sources operating from the heat of combustion of any fuel are especially promising. They can offer a long service life, have increased reliability and resistance to climatic and shock loads, are universal, silent in operation and easy to use.Scientists and engineers from many countries are actively working on the creation of such sources. Thermoelectric generators with an electric power of 2 - 20 W, intended for charging mobile phones, MP3 players, navigators during travel and hiking trips, have been developed by a number of foreign companies (TES, Power Pot, Biolite) [1 – 5]. Thermoelectric generators have also been developed, the operation of which is based on the use of heat from solid fuel furnaces [6 – 9]. They are mass-produced by a number of foreign enterprises [8 – 10]. However, all of these thermoelectric generators are expensive, have an exclusively domestic purpose and are not suitable for military needs.

At the same time, the main obstacle for their widespread practical use is a relatively high cost, primarily due to the high cost of the thermoelectric material from which they are made. Therefore, it is important to carry out research aimed at significantly reducing the cost of materials for autonomous thermoelectric sources of electricity and heat, as well as finding optimal designs of such sources, specialized according to the conditions of their use.

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

Physical model

The physical model of the thermoelectric generator (Fig. 1) comprises: heat sources 1 (heated surface), heat exchangers for supply 3 and discharge 8 of the heat flow to/from the thermopile 6, thermal insulation 5, water tank 10, electronic device for stabilizing the output voltage with electric energy accumulator 11. The model also takes into account thermal contact resistances 2, 4, 7 and 9: between the heat source (heated surface) and the hot heat exchanger – K_1; between the hot heat exchanger and the thermopile - K_2; between the thermopile and the cold heat exchanger - K_3; between the cold heat exchanger and the water container - K_4.

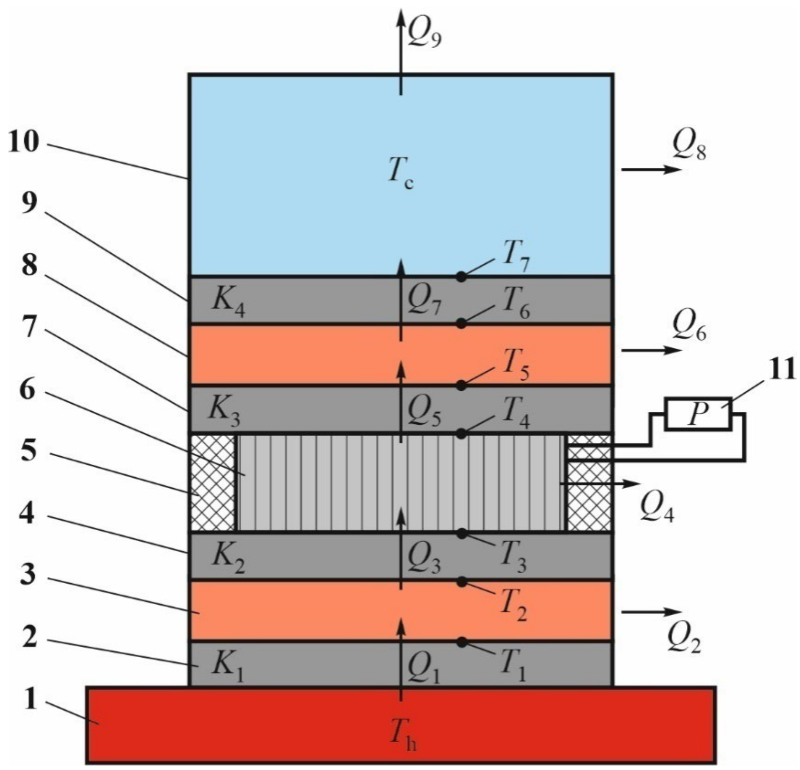

Fig. 1 Physical model of a trench thermoelectric generator:
1 – heat source (heated surface); 2, 4, 7, 9 – thermal contact resistances; 3 – hot heat exchanger;
5 – thermal insulation; 6 – thermopile;8 – cold heat exchanger; 10 –container with water:
11 – electronic device for stabilizing output voltage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

In Fig. 1: Q_1 – is heat entering the hot heat exchanger from the heat source; Q_2 – is heat loss from the lateral surface of the hot heat exchanger to the environment due to radiation and convection; Q_3 – is heat entering the hot side of the thermopile from the hot heat exchanger; Q_4 – is heat loss from the lateral surface of the thermopile; Q_5 – is heat coming from the cold side of the thermopile to the cold heat exchanger; Q_6 – is heat transferred from the lateral surface of the cold heat exchanger to the environment due to radiation and convection; Q_7 – is heat transferred from the cold heat exchanger to the container with water; Q_8 – is heat transferred from the lateral surface of the container with water to the environment due to radiation and convection; Q_9 – is heat transferred from the container with water to the environment due to evaporation; P is electric power of the thermopile.

The thermoelectric generator can have two modes of operation:

1) heating water in the container to boiling temperature and gradually reducing the amount of water due to evaporation;
2) heating water in the container to boiling temperature and replacing it with water at room temperature.

Since it is assumed that the generator is mounted on a heated surface with a constant temperature T_h, heat exchange processes between the real source of fuel combustion and this surface are not considered.

Mathematical and computer descriptions of the model

To calculate the thermoelectric generator according to its physical model (Fig. 1), a system of heat balance equations was used:

$$\begin{cases} Q_1 = Q_2 + Q_3, \\ Q_3 = P + Q_4 + Q_6 + Q_8 + Q_9. \end{cases} \tag{1}$$

The supply of heat from the heated surface to the hot side of the thermopile and the removal of heat from its cold junctions to the cold heat exchanger is carried out due to thermal conductivity and is described by the equations:

$$Q_3 = \frac{\kappa_h S_h}{l_h}\left(T_2 - T_3\right), \tag{2}$$

$$Q_7 = \frac{\kappa_c S_c}{l_c}\left(T_6 - T_7\right), \tag{3}$$

where: κ_h, κ_c – is the thermal conductivity of the material of the hot and cold heat exchangers; l_h, l_c, S_h, S_c – are the thickness and area of the hot and cold heat exchanger.

The thermal power of Q_5 is removed from the cold side of the thermopile by a cold heat exchanger, which is a container with water.

In doing so, different approximate formulae can be used to calculate the heat transfer coefficient during boiling, which are in good agreement with the experimental data [11]. In particular, the following approach to calculating the heat transfer coefficient during boiling is presented in [12]

$$h_{boil} = \frac{q}{\Delta T}, \tag{4}$$

where q is the heat flow density at the solid-liquid interface; ΔT is the temperature head between the surface and the liquid,

$$\Delta T = T_{cm} - T_{нас}\,. \tag{5}$$

It is considered that the heat flow density on the wall:

$$q_c = q_{conv} + q_{vapor}, \tag{6}$$

where q_{conv} takes into account the transfer of heat by convection of a single-phase liquid; q_{vapor} takes into account the transfer of heat by vapour bubbles breaking away from the wall.

The heat flow density corresponding to heat transfer by vapour bubbles is equal to:

$$q_{vapor} = V\rho_n r \frac{N_z}{\Delta F} f, \tag{7}$$

where: V is the average volume of the bubble at the moment of separation from the heating surface; ρ_n is vapour density on the saturation line; N_Z is the number of active vaporization centres on the area ΔF; f is the average frequency of separation of vapour bubbles; r is the heat of vaporization.

Assuming that the main amount of heat is transferred due to boiling, and the effect of convection is taken into account by introducing a correction, we can write:

$$q_c = q_{conv} + q_{vapor} = q_{vapor}\varepsilon = V\rho_n r \frac{N_z}{\Delta F} f\varepsilon, \tag{8}$$

where ε is the correction for q_{conv}, which takes into account the proportion of heat transferred by convection.

Substituting the value $V = \frac{\pi}{6} d_0^3$ and making some permutations we get:

$$\frac{q_c}{r\rho_n f d_0} = \frac{\pi}{6} \frac{N_z}{\Delta F} d_0^2 \varepsilon \tag{9}$$

Here, the left side of the equation is the ratio of the average rate of vaporization $\frac{q_c}{r\rho_n}$ (this value has the dimension *m/s*) to the average rate of growth of vapour bubbles $d_0 f = w''$.

In general, the dependence for calculating the heat exchange coefficient will have the form [12]:

$$\frac{h_{boil}\delta}{\lambda_p} = 75\left(\frac{q_c}{r\rho_n f d_0}\right)^{0.7} \left(\frac{\nu_p}{a_p}\right)^{-0.2}, \tag{10}$$

where δ is the characteristic size, in this case the Laplace capillary constant

$$\delta=\sqrt{\frac{\sigma}{g\left(\rho'-\rho''\right)}}\,. \tag{11}$$

The average growth rate of vapour bubbles is determined by the relationship:

$$w'' = w_n = d_0 f = 0.36\cdot 10^{-3}\Pi^{1.4}, \tag{12}$$

Where $\Pi = \frac{P_{cr}}{P}$; defining temperature $t_{def} = t_p = t_{sat}$.

The electric power generated by the thermopile is proportional to Q_3 and the thermopile efficiency η.

The main heat loss:

- from the lateral surface of the hot heat exchanger due to convection and radiation

$$Q_2 = h_h A_h\left(\frac{T_2+T_3}{2}-T_0\right)+\varepsilon_h\sigma_{C.-Б.}A_h\left(\left(\frac{T_2+T_3}{2}\right)^4-T_0{}^4\right), \tag{13}$$

where: h_h is the coefficient of convection heat exchange between the lateral surface of the hot heat exchanger and the environment; A_h is the area of the lateral surface of the hot heat exchanger; ε_h is the radiation coefficient of the lateral surface of the hot heat exchanger; $\sigma_{S.-B.}$ is the Stefan-Boltzmann constant.

- from the lateral surface of the thermopile due to thermal insulation

$$Q_4 = \frac{\kappa_{iз}S_{iз}}{l_{iз}}\left(T_4-T_5\right), \tag{14}$$

where: $\kappa_{iз}$ is the thermal conductivity of the insulating material; $S_{iз}$ is the surface area of the hot heat exchanger not occupied by the thermopile; $l_{iз}$ is the thickness of the thermal insulation layer.

The electric power P generated by a thermopile is proportional to Q_3 and the efficiency of the thermopile η and is determined primarily by the operating temperatures of the thermopile T_4 and T_5, as well as the properties of the thermoelectric material it is made of.

The solution of the system of equations (1) with regard to formulae (2) - (15) allows one to determine the main energy and design parameters of a thermoelectric generator for various properties of the thermoelectric material, generator designs and its operating modes.

In this case, the Comsol Multiphysics software package [13] was used for the computer representation of the mathematical model of the thermopile. To do this, it is necessary to present the equation in the following form.

To describe the flows of heat and electricity, we will use the laws of conservation of energy

$$div\vec{E} = 0 \tag{15}$$

and electric charge

$$div\vec{j} = 0, \tag{16}$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \tag{17}$$

$$\vec{q} = \kappa\nabla T + \alpha T\vec{j}, \tag{18}$$

$$\vec{j} = -\sigma\nabla U - \sigma\alpha\nabla T. \tag{19}$$

Here $\vec{E}$ – is energy flow density, $\vec{q}$ – is heat flow density, $\vec{j}$ – is electric current density, U – is electric potential, T – is temperature, α, σ, κ – are the Seebeck coefficient, electric conductivity and thermal conductivity.

From equations (17) – (19), one can obtain

$$\vec{E} = -(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T - (\alpha\sigma T + U\sigma)\nabla U. \tag{20}$$

Then the laws of conservation (15), (16) will acquire the form:

$$-\nabla\left[(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T\right] - \nabla\left[(\alpha\sigma T + U\sigma)\nabla U\right] = 0, \tag{21}$$

$$-\nabla(\sigma\alpha\nabla T) - \nabla(\sigma\nabla U) = 0. \tag{22}$$

By solving equations (21) - (22), it is possible to obtain the distribution of physical fields, as well as the value of the efficiency and power of a thermopile, depending on the thermoelectric properties of the thermopile material and the temperature conditions of its operation, obtained by solving the thermal part of the model.

This information is the basis for the creation of specialized thermoelectric modules based on thermoelectric materials optimized for different modes of their operation. The significant change in the cost of thermoelectric generators can be achieved, especially due to the development and use of optimized functional thermoelectric materials, use of flat extruded thermoelectric materials, etc. Indoingso, material optimization is usually done experimentally. For this purpose, samples of different chemical composition and with different impurity concentrations in the expected range of its values are prepared using different methods. The set of thermoelectric materials obtained in this way is subjected to measurements of σ, α, κ in the required temperature ranges.The measurement results provide information used to adjust the initial chemical composition and concentration of impurities and, accordingly, to find their optimal values. The decisive role in this will be played by the accuracy of the measurements and their speed [14, 15].

Conclusions

1. A physical model of a trench thermoelectric generator designed to power low-power military and civilian equipment is presented, as well as a mathematical and computer description of this model.
2. The created computer model allows determining the dynamic and average power of a thermoelectric generator, and designing a generator with specialized thermoelectric modules based on thermoelectric materials optimized for various operating modes.

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Анатичук Л. І., *акад. НАН України* [1,2]
Лисько В. В., *канд. фіз.-мат. наук* [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, *e-mail: anatych@gmail.com*

ПРО ПРОЄКТУВАННЯ ОКОПНОГО ТЕРМОЕЛЕКТРИЧНОГО ДЖЕРЕЛА ТЕПЛА ТА ЕЛЕКТРИКИ

Наведено фізичну та математичну моделі окопного термоелектричного джерела тепла та електрики, призначеного для обігріву військових та живлення малопотужної військової апаратури, систем мобільного та спеціального зв'язку, зарядки акумуляторів та освітлення, забезпечення теплом та мінімальною електричною енергією цивільного населення в місцях, де зруйнована енергетична інфраструктура, а також у неелектрифікованих районах поза зоною бойових дій. Створено комп'ютерну модель для проєктування конструкції такого джерела тепла та електрики, а також оптимізації термоелектричного матеріалу, з якого його виготовлено, для різних режимів експлуатації. Бібл. 15, рис. 1.

Ключові слова: термоелектричне джерело тепла та електрики, фізична модель, ефективність, циклічний режим.

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