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DESIGN OF AN ANNULAR THERMOPILE FOR A SINGLE ACTING CURRENT SOURCE

The results of studies on the creation of an annular thermopile for a current source with a pyrotechnic heat source are presented. The method of computer simulation confirmed the possibility of creating an annular thermopile with predetermined geometric dimensions, providing an output power of 2W at a voltage of 5V. Bibl. 2, Fig. 4, Tabl. 3.

Key words: thermoelectric battery, current source, rated voltage, output power.

Introduction

In connection with a significant expansion of the scope of autonomous control systems at military facilities, the issue of developing electric power supplies intended for various electronic devices becomes urgent.

Such power supplies have increased requirements for their performance and specific energy characteristics. In addition to their small weight and size parameters, they must meet the requirements for the probability of trouble-free operation after long (at least 10 years) storage in warehouses as well as in the field. In addition, they must maintain their performance under conditions of high climatic and mechanical loads.

The combination of these requirements directs developers to create power supplies that work on the principle of direct conversion of one of the types of energy (chemical, mechanical or thermal) into electrical energy. At the same time, special requirements are imposed on the design of current source, the implementation of which requires new technical and technological solutions. From the information given in [1], thermoelectric (TE) current sources are most in line with the requirements for single acting power supplies.

The main parts of TE current sources which determine their efficiency include a heat source in which capacity mixtures based on zirconium and barium chromate are best suitable [1], and a thermoelectric converter of corresponding design.

However, the nature of using the aforementioned power supplies has determined their specificity, and the assessment of the present state of development of TE current sources on the basis of the analysis of scientific and technical information is a problem.

The purpose of this work is research to create a high performance annular thermopile for a single acting TE current source.

Annular thermopile

Ref. [2] provides descriptions of dozens of thermoelectric generators (TEGs) with different heat sources based on gaseous, liquid or solid fuels. Such TEGs can operate for a long time under conditions of climatic and mechanical influences close to normal. Constructive designs of TEGs, as well as their specific energy characteristics cannot be applied in a single acting TE current source. At the same time, the experience of creating thermopiles for such TEGs is the basis for the creation of optimum, both from the point of view of design and from the point of view of technology of manufacturing high performance thermopile for a TE current source. The closest analogue in this regard is a thermopile consisting of 8 series-connected spiral elementary thermopiles located in a circle on the inner surface of the cylindrical body of a TE current source [1]. The space between the spiral thermopiles is filled with a heat-resistant compound to ensure the mechanical strength of the thermopile in a TE current source.

With a number of obvious advantages over the constructions of the well-known TE current sources, the thermopile design described in [1] has a number of disadvantages. In particular, the manufacturing technology of spiral thermopiles is very complicated, which is financially costly for serial production of TE current sources. Besides, spiral thermopiles are made of extruded thermoelectric material with a low thermoelectric figure of merit (Z ~ 2 * 10-3 K). Therefore, an annular thermopile was created, in which the legs of thermoelements are made of high-performance Bi_2Te_3.

Computer design of an annular thermopile for a current source

Taking into account the requirements of the technical specifications under the contract № 3/2019 от 16.04.2019 the thermoelectric converter for a TE current source should be designed with an inner diameter of 39 mm and an outer diameter of 50 mm in the form of an annular thermopile consisting of the calculated number of elementary single-row thermopiles, providing an output voltage of 5V and an electric power of 2W at a working temperature drop of not more than 300K. In turn, thermopiles should consist of a given number of thermoelements connected in series with an optimal combination of weight and size characteristics and thermoelectric properties.

Therefore, for computer design, we used the model of the thermopile structural unit - a thermoelement consisting of n- and p-type legs, connecting materials, and heat-leveling insulating ceramic plates, Fig. 1.

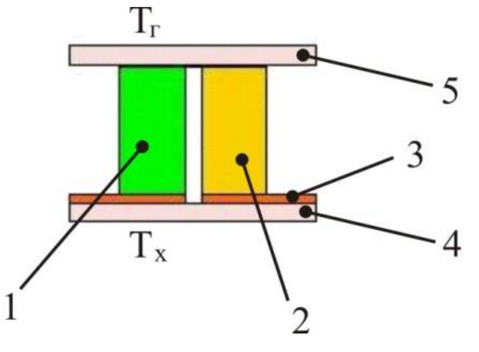


Fig. 1. Physical model of the structural element of thermopile. 1, 2 – thermoelement legs of n- and p-type conductivity; 3 – copper connecting plates; 4 – lower ceramic plate; 5 –upper ceramic plate.

The temperatures on the heat-releasing and heat-absorbing thermoelement surfaces T_h and T_c are fixed, the lateral surface is adiabatically isolated. Parameters of thermoelectric materials are functions of temperature. T_0 determine maximum efficiency and maximum electric power, it is necessary to find the distribution of temperatures and current density in thermoelement legs.

The solution of this problem is realized by the numerical method of successive approximations using the Comsol Multiphysics software environment.

Mathematical description of the model

To describe the flows of heat and electricity in such a thermoelement, we used the laws of conservation of energy:

$$div\vec{W} = 0, \tag{1}$$

and electric charge:

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

where:

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

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

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

($\vec{W}$ is energy 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 of materials).

Taking into account (3) - (5) yields:

$$\vec{W} = -(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T - (\alpha\sigma T + U\sigma)\nabla U\,. \tag{6}$$

Then the laws of conservation (1), (2) will take on the form:

$$-\nabla\left[(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T\right] - \nabla\left[(\alpha\sigma T + U\sigma)\nabla U\right] = 0, \tag{7}$$

$$-\nabla(\sigma\alpha\nabla T) - \nabla(\sigma\nabla U) = 0\,. \tag{8}$$

These second-order nonlinear differential equations in partial derivatives (7) and (8) determine the distributions of temperature T and potential U in the materials of thermoelement legs, contact, connecting and insulating layers of the thermoelement.

The boundary conditions for solving equations (7) and (8) were chosen as follows. The temperatures of the heat-absorbing and heat-releasing surface of the thermoelement T_h and T_c were recorded. The potential value on the connecting plate of the n-type leg was set to zero. On the other connecting plate of the *p*-type leg the value of U was set, which is half the thermoEMF generated by the thermoelement. In turn, the value of the generated thermoEMF was determined by the system of equations (7) and (8) in the absence of current flow through the thermoelement.

At the boundaries of the legs of thermoelements and connecting plates, connecting plates and ceramics, the conditions of equality of temperatures and heat flows were taken into account.

The general equation of the “Comsol Multiphysics” program is as follows:

$$\nabla\left(-C\nabla M + \alpha M + \gamma\right) + \delta M + \beta\nabla M = f\,, \tag{9}$$

where

$$C=\begin{bmatrix}C_{11} & C_{12}\\ C_{21} & C_{22}\end{bmatrix},\ \alpha=\begin{bmatrix}\alpha_{11} & \alpha_{12}\\ \alpha_{21} & \alpha_{22}\end{bmatrix},\ \gamma=\begin{bmatrix}\gamma_{11} & \gamma_{12}\\ \gamma_{21} & \gamma_{22}\end{bmatrix},\ \delta=\begin{bmatrix}\delta_{11} & \delta_{12}\\ \delta_{21} & \delta_{22}\end{bmatrix},$$

$$\beta=\begin{bmatrix}\beta_{11} & \beta_{12}\\ \beta_{21} & \beta_{22}\end{bmatrix},\ f=\begin{bmatrix}f_1\\ f_2\end{bmatrix},\ M=\begin{bmatrix}T\\ U\end{bmatrix}. \tag{10}$$

From the analysis of Eqs.(7) - (10) it follows that Eq.(9) can be simplified as:

$$\nabla\left(-C\nabla M\right)=0. \tag{11}$$

The differential equation for matrix components is given by:

$$\left.\begin{array}{l}\nabla\left(-C_{11}\nabla T\right)+\nabla\left(-C_{12}\nabla U\right)=0\\ \nabla\left(-C_{21}\nabla T\right)+\nabla\left(-C_{22}\nabla U\right)=0\end{array}\right\}. \tag{12}$$

Comparing the laws of conservation in the form of (7), (8) with equations (12), we obtain coefficients for a computer model:

$$C=\begin{pmatrix}\kappa+\alpha^2\sigma T+\alpha U\sigma & \alpha\sigma T+U\sigma\\ \sigma\alpha & \sigma\end{pmatrix}. \tag{13}$$

Computer research results

Using this method, the energy characteristics of elementary thermopiles for TE power supplies were calculated. The temperature dependences of the thermoelectric parameters α, σ, κ of materials based on bismuth telluride of n- and p-types of conductivity ((n-Bi_2Te_3), and (p-Bi_2Te_3) were used as input data, Fig. 2.

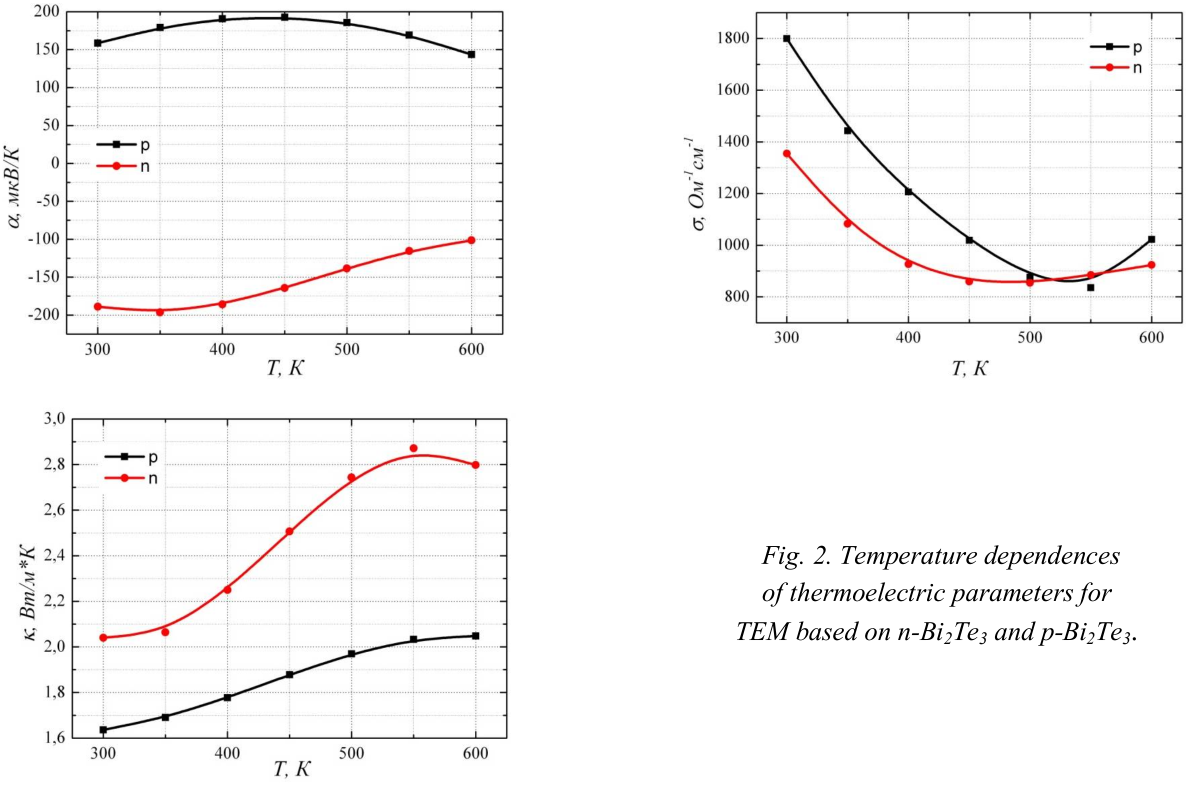
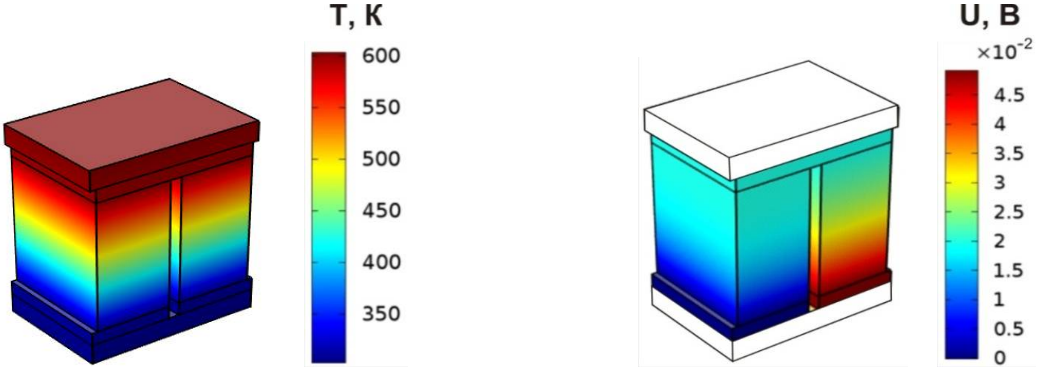


Fig. 2. Temperature dependences of thermoelectric parameters for TEM based on n-Bi_2Te_3 and p-Bi_2Te_3.

The temperature dependences (Fig. 2) were approximated by one-dimensional polynomials in the form of $\alpha^{n,p} = \alpha^{n,p}(T)$, $\sigma^{n,p} = \sigma^{n,p}(T)$, $\kappa^{n,p} = \kappa^{n,p}(T)$, whose coefficients were entered into computer program.

As a result of simulation we obtained the distributions of temperature and electric potential for one of thermoelements which form elementary thermopiles (Fig 3).

The calculated electric parameters of thermoelement (voltage U, power P, efficiency η) at operating temperature gradients ΔT = 473 K, 523 K and 573 K on its surfaces are represented in Table 1.



a) *b)*

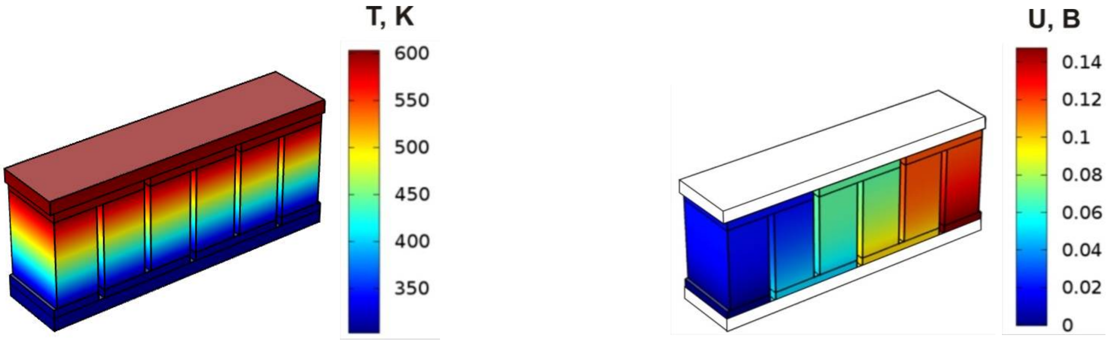
Fig. 3. The distribution of temperatures (a) and electric potential (σ) in thermoelement

Table 1

Parameters of thermoelement

ΔT, K	U, V	P, W	η, %
473	0.035	0.1	5.8
523	0.045	0.16	6.7
573	0.05	0.18	6.9

Taking into account the above data, the temperature and electric potential distributions were found (Fig. 4), as well as the energy characteristics of elementary thermopile for a TE current source (Table 2).



a) *b)*

Fig 4. The distribution of temperatures (a) and electric potential (b) in elementary thermopile.

Table 2

Characteristics of elementary thermopile for a TE current source

ΔT, K	TE current source		
	U, V	P, W	η, %
473	0.105	0.31	6.0
523	0.135	0.48	6.7
573	0.145	0.56	7.0

Based on the data given in Table 2, the electrical characteristics of an annular thermopile were calculated for a TE current source at operating temperature gradients ΔT = 200°C, 250°C and 300°C (Table 3).

Table 3

Calculated electrical characteristics of an annular thermopile

ΔT, K	TE current source	
	U, V	P, W
473	3.78	11.16
523	4.86	17.28
573	5.22	20.16

Thus, taking into account the estimated calculations and the data given in the Tables 2-3 it follows that to achieve the assigned electrical power and voltage of a TE current source, an annular thermopile of each sample must consist of 36 series-connected elementary thermopiles. For a TE current source -1 the optimal number of thermoelements in one elementary thermopile is 3 pcs (6 legs).

It should be noted that computer design of thermoelectric converters was carried out for the maximum power mode, when the resistance of the thermopile is equal to the value of the external load. In fact, the operating mode of a TE current source will be different and a significant power reserve of power supply will ensure the required voltage values.

Moreover, a number of factors that affect the initial characteristics of a TE current source were not considered in computer design. In particular, the influence of contact resistances at the boundaries of thermoelement legs with connecting plates, at the boundaries of connecting plates with ceramics is not taken into account. In addition, heat loss from the side surfaces of the thermopile legs and the layer of heat-conducting glue K - 400 is disregarded.

However, the calculations confirmed the reality of achieving the output characteristics of a TE current source at a given operating temperature difference not exceeding 300K.

Conclusion

Computer simulation and experimental studies confirmed the possibility of creating an annular thermopile with an outer diameter of 50 mm and an inner diameter of 39 mm for a thermoelectric current source, providing an output power of at least 2 W at a voltage of 5V.

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ДО ПИТАННЯ ВИБОРУ МАТЕРІАЛУ ТЕРМОПАРИ ДЛЯ ТЕРМОПЕРЕТВОРЮВАЧІВ МЕТРОЛОГІЧНОГО ПРИЗНАЧЕННЯ

Розглянуто особливості застосування термоелектричного матеріалу (ТЕМ) при конструюванні термоелектричних перетворювачів (ТП) метрологічного призначення. Порівняння математичних виразів для основних параметрів різних термоелектричних пристроїв показало, що існують суттєві відмінності у виборі ТЕ для термопари ТП. Зокрема, максимальна термоелектрична ефективність ТЕМ Z для ТП не завжди є визначальною у забезпеченні найкращих параметрів ТП. Для ТП, крім високих значень Z, *важливими є максимальні значення термоЕРС ТЕМ та раціональне використання тепла, що виділяється нагрівником ТП (так званий "конструктивний фактор"). Бібл. 12, рис. 1.*

Ключові слова*: термоелектричний перетворювач, нагрівник, термопара, чутливість, термоелектричний матеріал.*

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ПРОЕКТИРОВАНИЕ КОЛЬЦЕВОЙ ТЕРМОБАТАРЕИ ДЛЯ ИСТОЧНИКА ТОКА ОДНОРАЗОВОГО ДЕЙСТВИЯ

Приведены результаты исследований по созданию кольцевой термоэлектрической батареи для источника тока с пиротехническим источником тепла.

Методом компьютерного моделирования подтверждена возможность создания кольцевой термобатареи с заданными геометрическими размерами, обеспечивающая выходную мощность 2Вт при напряжении 5В. Библ. 2, рис. 4, табл. 3.

Ключевые слова*:* термоэлектрическая батарея, источник тока, номинальное напряжение, выходная мощность.

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