ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ТЕРМОЭЛЕКТРИЧЕСКОГО МОДУЛЯ ОХЛАЖДЕНИЯ ДЕТЕКТОРА РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ

В работе приведены результаты экспериментальных исследований термоэлектрического многокаскадного термоэлектрического модуля охлаждения рентгеновских детекторов. Разработан специализированный стенд, изготовлен термоэлектрический модуль охлаждения и проведена серия его исследований в условиях, которые имитируют его роботу в составе детектора рентгеновского излучения. Библ. 6, рис. 3.

Ключевые слова: экспериментальное исследование, термоэлектрическое охлаждение, рентгеновский детектор.

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Submitted 20.06.2019

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INFLUENCE OF THE NUMBER OF CHANNELS ON THE EFFICIENCY OF PERMEABLE THERMOELEMENTS OF *Bi-Te-Se-Sb* BASED MATERIALS

The basic properties of thermoelectric materials are analyzed. For a permeable thermoelement of Bi-Te-Se-Sb based materials a physical model is presented and a mathematical description is given. Computer calculation of parameters for Bi-Te-Se-Sb based permeable thermoelements is made. The dependence of permeable thermoelement efficiency and its generated power W on the number of channels N_k is presented graphically. Bibl. 5, Fig. 2.

Key words: Thermoelectric materials, generator efficiency, design of permeable segmented thermoelement, thermoEMF

Introduction

Permeable thermoelectric elements are characterized by the presence in their structure of channels for pumping liquid or gaseous heat carrier through them. The presence of heat exchange in the bulk of the leg increases the intensity of heat transfer, leads to the redistribution of temperature fields, potentials and heat fluxes, thus affecting the energy characteristics of the thermoelement. By controlling the thermophysical parameters (heat carrier pumping rate, heat transfer rate, electric current density), it is possible to realize such working conditions whereby the energy efficiency of power conversion will be improved [1].

The first theoretical studies of permeable thermoelements for gas fluxes showed the prospect of their creation, predicting a 30-40% increase in the coefficient of performance while cooling the air and an increase in the efficiency of the generators by 20-30 % with the use of low-potential thermal energy of gases. The use of permeable structures in *Bi-Te* thermoelectric elements can improve energy conversion efficiency by 30 % [2]. However, such studies were conducted for the simplest model of permeable thermoelement in one-dimensional approximation without taking into account the temperature dependences of the material parameters, connecting heat spreaders.

Over the past decade, promising *Bi-Te-Se-Sb* based thermoelectric materials have been attracting increasing attention of researchers. They are environmentally safe and are characterized by high values of the Seebeck coefficient and electrical conductivity with maximum values of dimensionless thermoelectric figure of merit parameter ZT at the level of 1 - 1.1 in the temperature range 300-600 K.

Physical model and its mathematical description

A physical model of permeable thermoelement of materials based on *Bi-Te-Se-Sb* in electric energy generation mode is represented in Fig. 1.

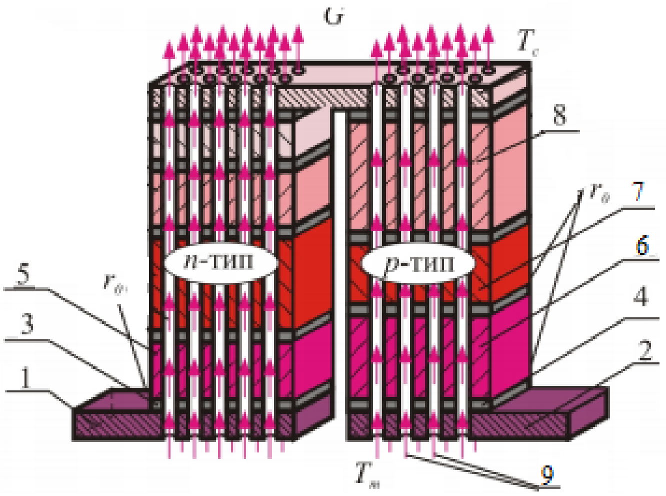

Fig. 1. Physical model of permeable segmented thermoelement
1, 2 – connecting plates; 3, 4 – connecting layers; 5 – segments (sections) of n-type leg; 6, 7, 8 – segments (sections) of p-type leg; 9 – heat carrier.

The thermoelement consists of *n*- and *p*-type legs whose physical properties are temperature-dependent. Heat input is realized by passing heat carrier along the legs through the channels (pores). Each leg comprises N_n and N_p segments, and the contact resistance of compound is r_0. The lateral surfaces of the legs are adiabatically isolated; heat carrier temperature at thermoelement inlet T_m is assigned. The temperature of cold junctions T_c is thermostated.

A system of differential equations describing the distribution of temperatures and heat fluxes in a steady-state one-dimensional case, in the infinitely small part *dx* of each *k*-th segment of *n*- and *p*-type legs, in the dimensionless coordinates is given by relations [2]:

$$\left.\begin{aligned} \frac{dT}{dx} &= -\frac{\alpha_k j}{\kappa_k} T - \frac{j}{\kappa_k} q, \\ \frac{dq}{dx} &= \frac{\alpha_k^2 j}{\kappa_k} T + \frac{\alpha_k j}{\kappa_k} q + j\rho_k + \frac{\alpha_T \Pi_K^1 N_K l_K^2}{(S - S_K) j}(t - T), \\ \frac{dt}{dx} &= \frac{\alpha_T \Pi_K^1 N_K l_k}{G c_p}(t - T), \end{aligned}\right\}_{n,p} \quad \begin{aligned} & k = 1, \ldots, N_{n,p} \\ & x_{k-1} \le x \le x_k \end{aligned}$$

where $\Pi^1{}_K$ is channel perimeter; N_K is the number of channels; S_K is cross-sectional area of all the channels; S is a section of leg together with the channels; *G* is heat carrier consumption in the channels; C_p is specific heat of heat carrier; t is heat carrier temperature at point x; *T* is leg temperature at point *x*; α*T* is heat-transfer coefficient; α and κ are the Seebeck coefficient and thermal conductivity, and ρ is the resistivity of leg material.

Specific heat fluxes *q* and the reduced density of electric current *j* are determined through the expression:

$$q = \frac{Q}{I}, \qquad j = \frac{Il}{S},$$

where *Q* is power of heat flux passing through thermoelement leg, *I* is electric current, *S* is cross-sectional area of thermoelement legs.

The boundary conditions necessary for solving the equation with regard to the Joule-Lenz heat release due to contact resistance r_0 at points of connection of leg segments are formulated as:

$$T_{n,p}(0)=T_C,\qquad t_{n,p}(1)=T_m,\qquad q_{n,p}(1)=0,$$
$$T_{n,p}(x_k^+)=T_{n,p}(x_k^-),\qquad q_{n,p}(x_k^+)=q_{n,p}(x_k^-)+\frac{r_0}{S_{n,p}}I,$$

where indices "-" and "+" denote the values of functions immediately to the left and right of the interface of segments x_k; $k = 1, \dots, N$ is the index which determines leg segment number.

For seeking optimal concentrations of doping impurities which determine carrier concentrations in leg segments it is necessary to assign the dependences of material parameters α, κ, ρ on temperature and concentration of carriers (or impurities).

The main task in the design of permeable segmented generator thermoelement is to determine such matched parameters (reduced current density j in the legs, heat carrier consumption in channels G, concentration of doping impurities in materials of each segment) whereby the efficiency of the thermoelement reaches a maximum [3].

The efficiency will be determined through the relation of electric power P generated by the thermoelement to a change in heat carrier enthalpy:

$$\eta=\frac{P}{\sum_{n,p}Gc_p(T_m-T_C)},$$

and its maximum will be reduced to achievement of functional minimum:

$$J=\ln\left[\sum_{n,p}\left\{Gc_P(T_m-T_C)\right\}\right]-\ln\left[\sum_{n,p}\left\{Gc_P(T_m-t(0))+q(0)\frac{j(S-S_K)}{l}-I\left(\frac{r_0}{S_n}+\frac{r_0}{S_p}\right)\right\}\right].$$

This problem was solved through use of the Pontryagin maximum principle, on which basis the relations yielding the necessary optimality conditions were obtained. Such a method as applied to thermoelectric power conversion is described in many works, for instance [4]. The same method was also used for creation of computer program and research on permeable thermoelement of *Bi-Te-Se-Sb* based thermoelectric materials [5].

Results of solving the problem

Calculations of permeable thermoelectric generator were performed with regard to losses of heat with exhaust gas and such input data as optimization of current density and heat carrier consumption, and optimization by equal concentration in leg sections with introduction of complex – $G.\ b_r := G \cdot C_p \cdot S_k \cdot N_k$.

The following input data was used. The inlet heat carrier temperature is 600 K, the temperature of thermoelement cold junctions is 300 K; the channel diameter is 0.01 cm; the channel perimeter (circle) is 0.031416 cm; the cross-sectional area of all N_k – channels is 0.0024 cm^2; the number of sections in one leg is 1 pcs; the height of legs is 20 cm; the cross-sectional area of leg material is 0.9976 cm^2.

The temperature dependences of α, σ, κ parameters of *Bi-Ti-Se-Sb* based materials were used for calculations [5]

It is seen that the efficiency of *Bi-Te-Se-Sb* based permeable thermoelement increases with increasing the number of channels. Maximum efficiency lies in the area from 25 to 80 channels per 1cm^2, and power – from 25 to 60. The specific electric power has a maximum in this case with 40 channels per 1 cm^2 and is P = 1.57 W. So, the rational number of channels per unit area will be within 25 – 60 pcs.

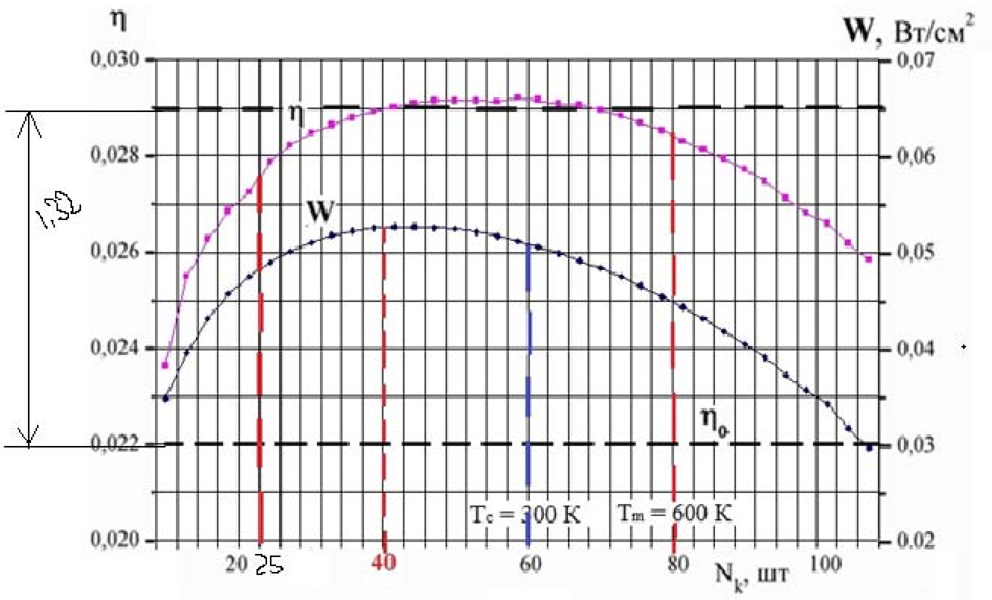

Fig. 2. Dependences of the efficiency and the generated power W of Bi-Te-Se-Sb based permeable thermoelement on the number of channels N_k.

The data obtained testify that the efficiency increases with increasing the number of channels and reaches the highest value, just as in the two previous cases, at heat carrier temperature T_m = 600 K and is η = 6.8%. The increase in efficiency can reach 1.32 times as compared to conventional thermoelement.

Conclusions

Thus, for different operating conditions of a permeable generator thermoelement of *Bi-Te-Se-Sb* based materials it is necessary to determine its optimal design parameters (leg height, channel diameter and their number), whereby the maximum energy conversion efficiency and electric power will be obtained. The efficiency under optimal working conditions is higher than that of conventional thermoelement by a factor of 1.32. Comparison with η_0, the efficiency of conventional thermoelement operating under similar conditions, also indicates the possibility of about 32% increase in the efficiency of *Bi-Te-Se-Sb* based permeable thermoelement when converting energy.

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Submitted 03.07.2019

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ВПЛИВ ЧИСЛА КАНАЛІВ НА ЕФЕКТИВНІСТЬ ПРОНИКНИХ ТЕРМОЕЛЕМЕНТІВ З МАТЕРІАЛІВ НА ОСНОВІ *Bi-Te-Se-Sb*

Проведено аналіз основних властивостей термоелектричних матеріалів. Для проникного термоелементу з матеріалів на основі Bi-Te-Se-Sb приведено фізичну модель та дано математичний опис. Зроблено комп'ютерний розрахунок параметрів для проникних термоелементів, що виготовлені на основі Bi-Te-Se-Sb. Представлено графічний вигляд залежності ККД і потужності проникного, яка генерується W від числа каналів N_k.

Ключові слова: Термоелектричні матеріали, ККД генератору, проектування проникного сегментного термоелемента, термо-ЕРС.

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ВЛИЯНИЕ ЧИСЛА КАНАЛОВ НА ЭФФЕКТИВНОСТЬ ПРОНИЦАЕМЫХ ТЕРМОЭЛЕМЕНТОВ ИЗ МАТЕРИАЛОВ НА ОСНОВЕ *Bi-Te-Se-Sb*

Проведен анализ основных свойств термоэлектрических материалов. для проницаемого термоэлемента из материалов на основе Bi-Te-Se-Sb, приведена физическая модель и дано ее математическое описание. Сделан компьютерный расчет параметров проницаемых термоэлементов, изготовленных на основе Bi-Te-Se-Sb. Представлены графически зависимости КПД и мощности, проницаемого генерируемого W вид числа каналов N_k.

Ключевые слова: термоэлектрические материалы, КПД генератора, проектирование проницаемого сегментного термоэлемента, термоЭДС.