I.A. Konstantynovych

I.A. Konstantynovych[1,2], O.V. Rendigevich[2]

[1]Institute of Thermoelectricity, 1, Nauky str.,
Chernivtsi, 58029, Ukraine;
[2]Yu.Fedkovych Chernivtsi National University
2, Kotsyubinsky str., Chernivtsi,
58012 Ukraine

O.V. Rendigevich

ON THE EFFICIENCY OF GYROTROPIC THERMOELEMENTS IN GENERATION MODE

In this paper, analytical and numerical methods were used to study the basic relations for the calculation of optimal characteristics of gyrotropic thermoelements in electric energy generation mode. The InSb, InAs and Bi_2Te_3 thermoelectric materials for gyrotropic thermoelements were examined. Computer simulation was performed for InSb material and temperature distributions in various-shaped gyrotropic thermoelements were found. The temperature dependences of efficiency for gyroptropic thermoelements of optimal, rectangular and annular shapes were obtained.

Key words: gyrotropic thermoelement, magnetic field, thermoelectric material, figure of merit, efficiency.

Introduction

It is known that thermoelectric devices and systems developed on their basis are widely used in power engineering, refrigeration and measurement technology [1 – 3]. The main achievements of thermoelectricity in the field of instrument engineering were exactly based on the physics of thermocouple thermoelements. However, the upcoming trend of thermoelectricity development is devising of new types of thermoelements, for instance, based on gyrotropic media, and improving the efficiency of the existing ones. The properties of gyrotropic thermoelements are investigated in a series of papers [1 – 16].

Gyrotropic thermoelements offer a number of attractive features:

- absence of internal junctions, assuring their reliability and ease of manufacture;
- possibility of junction-free connection of rings into a spatial spiral structure for buildup of the necessary voltages;
- possibility of efficiency increase due to the effect of temperature and magnetic fields, particularly with their use in measurement technology.

Therefore, the relevance of the paper lies in the necessity to increase the efficiency and reliability of thermoelectric power converters based on gyrotropic thermoelements for their further use in instrument engineering.

The purpose of the paper is to estimate the efficiency of gyrotropic thermoelements in electric energy generation mode.

Mathematical model

Thermal conductivity equation for the homogeneous gyrotropic medium is given below [1]:

$$\kappa\Delta T + \rho_0 j^2 + 2\alpha_B \left(j_y \frac{\partial T}{\partial x} - j_x \frac{\partial T}{\partial y} \right) = 0, \qquad (1)$$

where κ is thermal conductivity of gyrotropic medium; ρ_0 is electric resistivity; j is modulus of electric current density vector; j_x, j_y are projections of vector $\mathbf{j}$ in Cartesian coordinate system; $\alpha_B = Q_\perp B$ is the asymmetric part of thermoEMF tensor which in the gyrotropic medium is of the form

$$\alpha = \begin{pmatrix} \alpha_0 & \alpha_B & 0 \\ -\alpha_B & \alpha_0 & 0 \\ 0 & 0 & \alpha_\perp \end{pmatrix}, \tag{2}$$

where $Q_\perp$ is the Nernst-Ettingshausen coefficient.

With regard to the system axial symmetry, Eq. (1) will be written in a polar coordinate system

$$\kappa \Delta T + \rho_0 j^2 + 2Q_\perp B\left(j_\varphi \frac{\partial T}{\partial r} - \frac{j_r}{r}\frac{\partial T}{\partial \varphi}\right) = 0, \tag{3}$$

where j_φ is azimuth and radial components of current density vector $\mathbf{j}$, $r_1 \le r \le r_2$ is thermoelement radius.

Computer simulation results

For the construction of computer model of gyrotropic thermoelements of rectangular, spiral and optimal shapes the Comsol Multiphysics application software package was used [17].

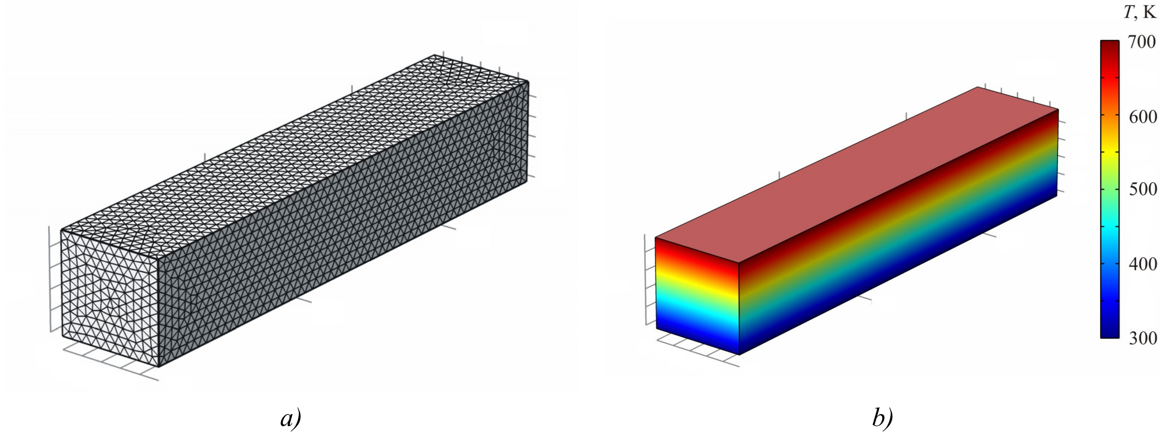


Fig. 1. Three-dimensional models of finite element method mesh (a) and temperature distribution (b) in gyrotropic rectangular-shaped thermoelement.

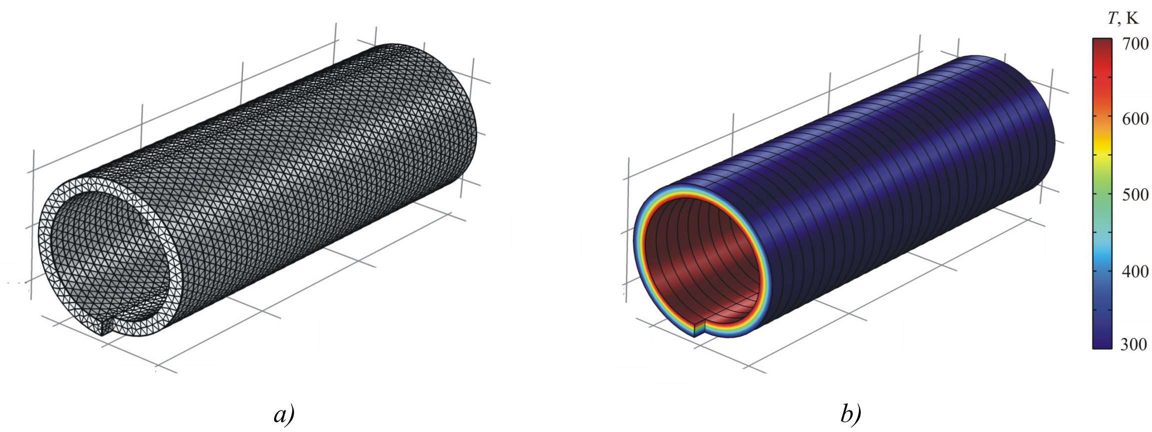
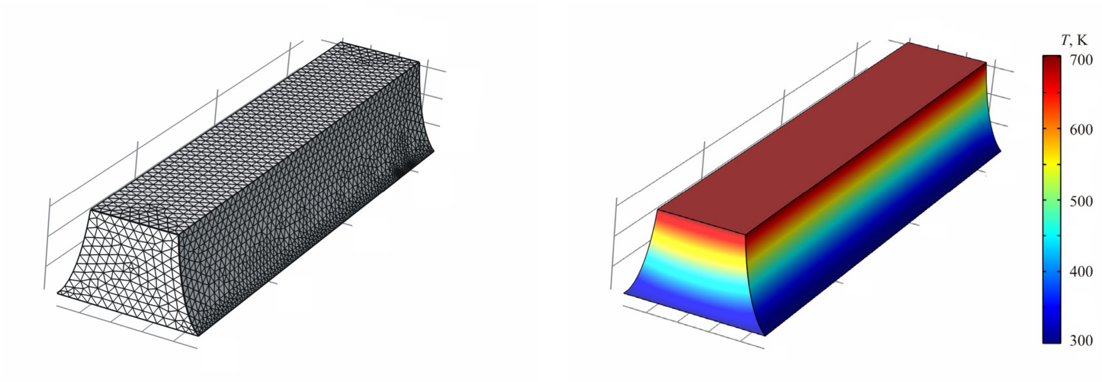


Fig. 2. Three-dimensional models of finite element method mesh (a) and temperature distribution (b) in a gyrotropic spiral thermoelement.

Calculation of temperature distributions in gyrotropic thermoelements was done by finite element method [18]. By means of computer simulation the temperature distributions in various-shaped gyrotropic thermoelements were determined for *InSb* material in the temperature range of 300 – 700 K and magnetic field with induction $B = 1$ T. Fig. 1 shows three-dimensional models of finite element method mesh (*a*) and temperature distribution (*b*) in rectangular-shaped gyrotropic thermoelement (the Nernst-Ettingshausen thermoelement).

Fig. 2 shows three-dimensional models of finite element method mesh (*a*) and temperature distribution (*b*) in spiral gyrotropic thermoelement.

Fig. 3 shows three-dimensional models of finite element method mesh (*a*) and temperature distribution (*b*) in optimal-shaped gyrotropic thermoelement.



a) *b)*

Fig. 3. Three-dimensional models of finite element method mesh (a) and temperature distribution (b) in optimal-shaped gyrotropic thermoelement.

Efficiency calculation

It is known that the efficiency of optimal-shaped gyrotropic thermoelement [2] is determined as follows:

$$\eta_1 = \eta_k \frac{1}{1 + \dfrac{2M_H(1+M_H)}{T_2 Z_H}}, \tag{4}$$

where $M_H = \sqrt{1 - Z_H \bar{T}}$, Z_H is thermomagnetic figure of merit, T_2 is the hot side temperature, η_k is the Carnot cycle efficiency, $\bar{T}$ is the average temperature.

The efficiency of rectangular-shaped gyrotropic thermoelement is given below [1]:

$$\eta_2 = \frac{\eta_k}{\dfrac{4}{Z_H T_2} - \dfrac{2T_1}{T_2} - \dfrac{1}{2}\eta_k}, \tag{5}$$

where T_1 is the cold side temperature.

For the annular gyrotropic thermoelement the efficiency is as follows [3]:

$$\eta_3 = Z_H \frac{\Delta T}{4}. \tag{6}$$

Fig. 4 shows the temperature dependences of figure of merit for *InSb*, *InAs* and Bi_2Te_3 thermoelectric materials. It is seen that the best material for the manufacture of generator gyrotropic thermoelements is *InSb*, which is in agreement with experimental results presented in [1].

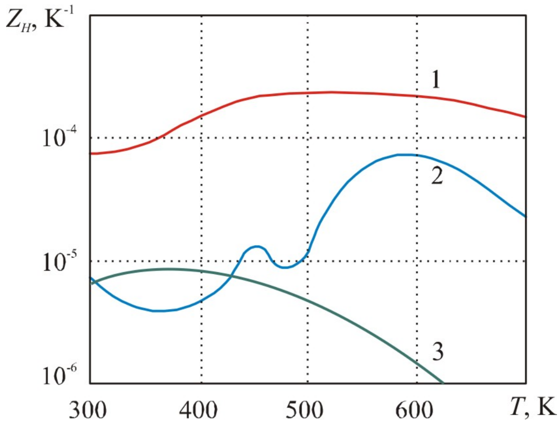


Fig. 4. Temperature dependences of figure of merit of thermoelectric materials for gyrotropic thermoelements (1 – InSb, 2 – InAs, 3 – Bi_2Te_3).

For the calculations *InSb* material was selected in the temperature range of 300 – 700 K. Various-shaped gyrotropic thermoelements were exposed to magnetic field with induction 1 T. According to calculated results, the dependences of efficiency on the hot side temperature of thermoelement T_2 were constructed at the constant cold side T_1 = 300 K for *InSb* (Fig. 5).

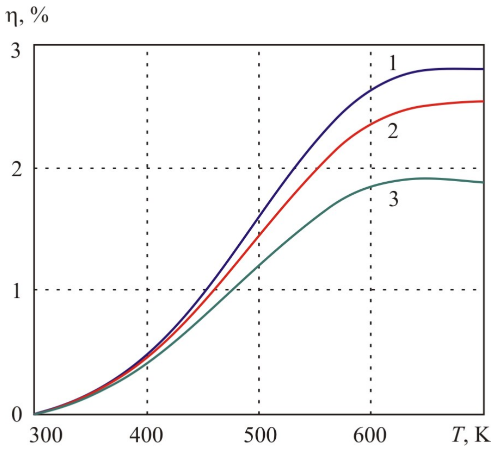


Fig. 5. Temperature dependence of efficiency for various-shaped gyrotropic thermoelements (1 – optimal-shaped, 2 – rectangular-shaped, 3 – annular-shaped).

From Fig. 5 it is seen that at temperature difference between the hold and cold side 400 K and magnetic field induction 1 T for an optimal-shaped gyrotropic thermoelement maximum efficiency value is about 2.8 %, which is less than in thermocouple elements based on Bi_2Te_3 and *PbTe*. However, gyrotropic thermoelements are characterize ed by increased reliability and possibility of high voltages build-up due to junction-free connection into a spatial spiral structure which makes such thermoelements promising for use in measurement and defense technology. Also, such thermoelements can be used for the manufacture of high-sensitive temperature and heat flux sensors.

Conclusions

1. Parameters of thermoelectric materials (*InSb*, *InAs* and Bi_2Te_3) for gyrotropic thermoelements

were compared. It was established that the best material for the manufacture of generator gyrotropic thermoelements is *InSb* whose average figure of merit value in the temperature range of 400 – 600 K is $4 \cdot 10^4$ K^{-1}.

2. With the aid of computer simulation the distributions of temperature in the working medium of gyrotropic thermoelements of rectangular, spiral and optimal shapes for thermoelectric material *InSb* were determined.
3. The temperature dependences of efficiency for various-shaped gyrotropic thermoelements were determined. It was established that maximum efficiency value of optimal-shaped gyrotropic thermoelement for *InSb* material in the temperature range of 300 – 700 K and magnetic induction 1 T is 2.8 %.

References

1. L.I.Anatychuk, *Thermoelements and Thermoelectric Devices* (Kyiv: Naukova Dumka, 1979), 766 p.
2. A.G.Samoiloivich, *Thermoelectric and Thermomagnetic Energy Conversion Methods* (Chernivtsi: Ruta, 2006), 226 p.
3. L.I.Anatychuk, *Thermoelectricity, Vol.2, Thermoelectric Power Converters* (Kyiv, Chernivtsi: Naukova Dumka, 2003), 386 p.
4. A.G.Samoilovich, L.L.Korenblit, Current Status of Theory of Thermoelectric and Thermomagnetic Effects in Semiconductors, *Advances in Physical Sciences* **49**(2), 243 –272 (1953).
5. H.Nakamura, K.Ikeda, and S.Yamaguchi, Transport Coefficients of *InSb* in a Strong Magnetic Field, *Proc. of XVI-th International Conference on Thermoelectrics* (Dresden, Germany, 1997), P. 142 – 146.
6. L.I.Anatychuk, O.J.Luste, Ya.G.Fedoruk, and S.M.Shinkaruk, Eddy Thermoelectric Currents in a Gyrotropic Medium with a Radial Temperature Distribution, *J.Thermoelectricity* 1, 19 – 24 (2004).
7. O.J.Luste, Ya.G.Fedoruk, Gyrotropic Thermoelement in the Inhomogeneous Magnetic Field, *J.Thermoelectricity* 1, 16 – 22 (2006).
8. O.J.Luste, Ya.G.Fedoruk, Optimization of Materials for Gyrotropic Thermoelements, *J.Thermoelectricity* 4, 21 – 26 (2008).
9. Z.F.Agayev, D.G.Arasli, and S.A.Aliyev, Thermomagnetic Converter of IR Radiation, *Problemy Energetiki* 3, 12 – 21 (2003).
10. S.A.Nemov, V.I.Proshin, G.L.Tarantasov, R.V.Parfenyev, D.V.Shamshur, and A.V.Chernyayev, Transverse Nernst-Ettingshausen Effect, Resonance Scattering and Supercoductivity in *SnTe*: In, *Physics of the Solid State* **51**(1), 461 – 464 (2009).
11. T.G.Harman, J.M.Honig, *Thermoelectric and Thermomagnetic Effects and Applications* (New York, Mc. Graw – Hill, 1967), 377 p.
12. H.Nakamura, K.Ikeda, and S.Yamaguchi, Transport Coefficients of InSb in a Strong Magnetic Field, *Research Report. NIFS Series*, Nagoya, Japan (1998), 23 p.
13. Hiroaki Nakamura, Kazuaki Ikeda, and Satarou Yamaguchi, Transport Coefficients of *InSb* in a Strong Magnetic Field, *Proc.of XVI International Conference on Thermoelectrics* (Dresden, Germany, August 26 – 29, 1997), P. 142 – 146.
14. P.I.Baranskii, G.P.Haidar, Anisotropy of Thermoelectric Properties of Multi-Valley Semiconductors of Cubic Symmetry under the Influence of External Directional Effects, *J.Thermoelectricity* 1, 13 (2014).

15. H.J.Goldsmid, E.H.Volckmann, Galvanomagnetic and Thermoelectric Measurements on Polycrystalline $Bi_{88}Sb_{12}$, *Proceedings of XVI Internatial Conference on Thermoelectrics* (Dresden, Germany, August 26 – 29, 1997), P. 142 – 146.
16. L.I.Anatychuk, L.N.Vikhor, Low-Temperature Thermoelectric Cooling under Optimal Legs Inhomogeneity in the Optimal Nonuniform Magnetic Field, *Proc.of XVI International Conference on Thermoelectrics* (Dresden, Germany, 1997), P. 397 – 400.

Submitted 10.02.2016.