N.A. Godovanets[1],
I.A. Konstantynovych *cand. phys.– math. sciences, dochent*[1,2],
A.V. Konstantynovych *doc. phys.– math. sciences, dochent*[2],
S.D. Shugani[1]

[1]Chernivtsi National University, 2 Kotsiubynskyi Str.,
Chernivtsi, Ukraine, 58012, *e-mail: anatych@gmail.com*
[2]Institute of Thermoelectricity of the NAS and MES of Ukraine,
1, Nauky str., Chernivtsi, 58029, Ukraine; *e-mail: dj_kneo@ukr.net aconst@ukr.net*
i.konstantynovych@chnu.edu.ua

GYROTROPIC THERMOELEMENT IN UNIFORM AND NON-UNIFORM MAGNETIC FIELDS

Using computer simulation, the temperature distributions in the working medium of gyrotropic thermoelements in uniform and non-uniform magnetic fields have been determined. Temperature dependences of the efficiency of gyrotropic thermoelements in uniform and non-uniform magnetic fields are determined. It has been established that the efficiency of generator gyrotropic thermoelements is higher in a non-uniform magnetic field than that in a uniform field. Bibl. 19, Fig. 3.
Key words: Nernst-Ettingshausen coefficient, gyrotropic thermoelement, non-uniform magnetic field, thermoelectric material, thermomagnetic figure of merit, efficiency.

Introduction

Nowadays, one of the promising areas of thermoelectric progress is the development of new types of thermoelements, including gyrotropic, and a more detailed study of those already known. In recent years, a number of works on gyrotropic thermoelements in constant magnetic fields have been published [1 – 18], and some parameters of these thermoelements in non-uniform magnetic fields have also been considered [7]. The gyrotropic thermoelements whose efficiency increases due to the excitation of eddy thermoelectric currents in a gyrotropic thermoelectric medium, make it possible to obtain elevated thermoelectric voltages and differ from the known multifunctionality; they are promising for use in special thermal generators , as well as in measuring equipment. However, these opportunities are used but little, so their development will increase the element base of thermoelectricity, improve the competitiveness of both thermoelectric converters and gyrotropic thermoelements, and allow developing more advanced thermoelectric products based on them, and improving their quality and reliability.

Therefore, the topicality of the work lies in the need for further study of gyrotropic thermoelements in uniform and non-uniform magnetic fields, to increase their efficiency and reliability and to create thermoelectric energy converters with improved characteristics.

The objective of this work is to evaluate the efficiency of gyrotropic thermoelements in uniform and non-uniform magnetic fields in the mode of electric energy generation.

Mathematical Model

To study the parameters of gyrotropic thermoelements, it is necessary to solve the following equation of thermal conductivity with the corresponding boundary conditions:

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

where T is the temperature; κ is the thermal conductivity of gyrotropic medium; ρ_0 is the electrical resistivity; x, y are the coordinates; j, j_x, j_y are the modulus and projections of the electric current density vector; $\alpha_\perp = Q_\perp B$ is the asymmetric part of the thermoEMF tensor; $Q_\perp$ is transverse Nernst-Ettingshausen coefficient; B is magnetic field induction.

$$\alpha = \begin{pmatrix} \alpha_0 & \alpha_a & 0 \\ -\alpha_a & \alpha_0 & 0 \\ 0 & 0 & \alpha_\perp \end{pmatrix}, \qquad (2)$$

Where $\alpha_0, \alpha_\perp$ are the diagonal components of the thermoEMF tensor.

To obtain eddy currents, it is advisable to consider spiral thermocouples. Considering the axial symmetry, (1) we have

$$\Delta T + \frac{j_\varphi{}^2}{\kappa\sigma} + \frac{1}{\kappa} j_\varphi 2\alpha_a(r)\frac{\partial T}{\partial r} = 0, \qquad (3)$$

where σ is the electrical conductivity, φ is the angle, r is the radius, j_φ is the - angular component of current density, which is determined by the expression

$$j_\varphi = \sigma Q_\perp(r) B(r) \frac{dT}{dr}. \qquad (4)$$

Whereas thermoEMF is set by the expression

$$E = 2\pi r Q_\perp(r) B(r) \frac{dT}{dr}. \qquad (5)$$

The thermomagnetic figure of merit of the gyrotropic material

$$Z_Q(r) = \frac{Q_\perp^2(r) B^2(r)}{\kappa\rho}. \qquad (6)$$

Non-uniformity can be obtained by changing the magnetic field B in a homogeneous gyrotropic medium, or by creating an anisotropy of the Nernst-Ettingshausen coefficient $Q^\perp$ in the ring at a constant magnetic field B. Let us consider the case when the magnetic field B in the ring changes along the radius of the ring, at a constant Nernst-Ettingshausen coefficient $Q^\perp$.

To solve (3) taking into account (4) and (5) and considering the boundary conditions, we obtain the expression for the efficiency of a spiral gyrotropic thermoelement in a non-uniform magnetic field

$$\eta = \frac{1}{6}\frac{\left(1 \pm \sqrt{1+6Z_Q\left(T_1 - T_2\right)}\right)^2}{6Z_Q\left(T_1 - T_2\right) - \left(1 \pm \sqrt{1+6Z_Q\left(T_1 - T_2\right)}\right)^2 - 2Z_Q T_1\left(1 \pm \sqrt{1+6Z_Q\left(T_1 - T_2\right)}\right)} \tag{7}$$

were

$$Z_Q = \frac{Q_\perp^2 B^2(r)}{\kappa\rho}. \tag{8}$$

Using (6), (7) one can calculate the efficiency of the gyrotropic spiral thermoelement in a non-uniform magnetic field.

Computer simulation results

Comsol Multiphysics software package was used to build a computer model of a spiral-shaped gyrotropic thermocouple [19]. The calculation of temperature distributions in the gyrotropic thermocouple was carried out by the finite element method. Using computer simulations, the temperature distributions for the *InSb* material in the temperature range 300 - 700 K and the magnetic field with induction B = 1 T were determined.

Fig.1 shows the temperature dependences of the figure of merit for thermoelectric materials *InSb, InAs* and *Bi2Te3*. It is seen that the best material for the manufacture of generator gyrotropic thermocouples is *InSb*, which is consistent with the experimental results presented in [1].

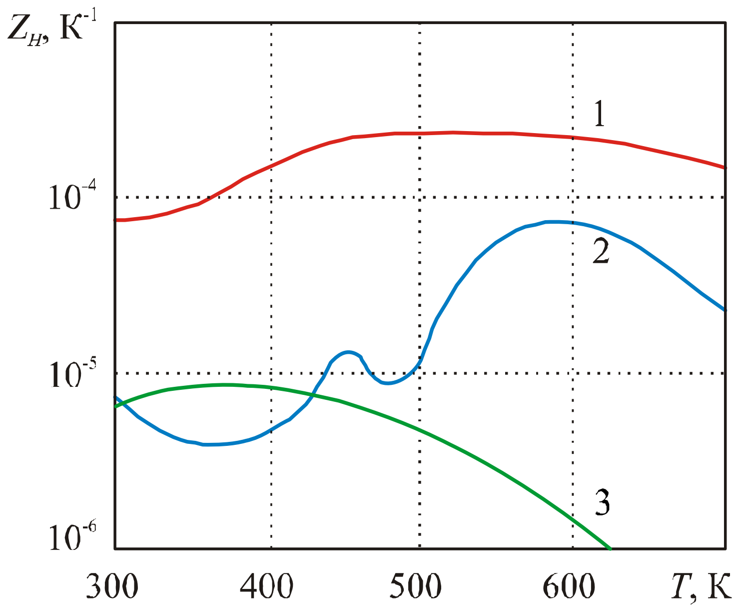
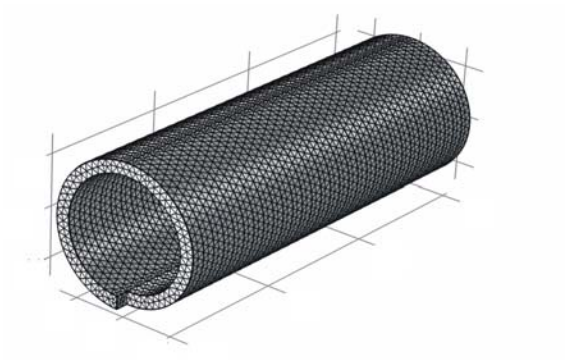
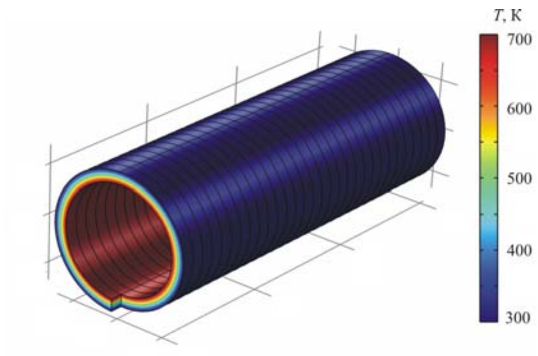


Fig. 1. Temperature dependences of the figure of merit of thermoelectric materials for gyrotropic thermoelements (1 – InSb, 2 – InAs, 3 – Bi_2Te_3).

Fig. 2 shows 3D mesh models of the finite element method *(a)* and temperature distribution *(b)* in a spiral gyrotropic thermoelement.



a)



b)

Fig. 2. 3D mesh models of the finite element method (a) and temperature distribution (b) in a gyrotropic spiral thermoelement.

According to the calculations, the dependences of efficiency on the hot side temperature temperature of thermoelement T_2 at the constant cold side T_1 = 300 K for *InSb* are constructed (Fig. 3).

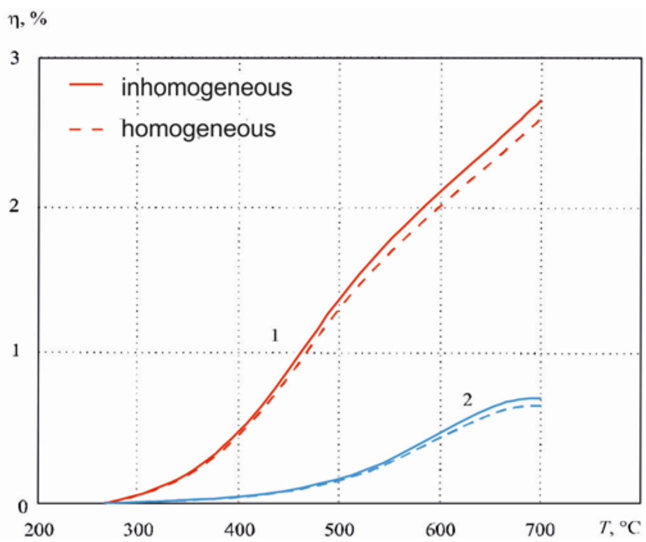


Fig. 3. Temperature dependence of the efficiency for cylinder-shaped gyrotropic thermoelement (1 – InSb, 2 – InAs).

The figure shows that the use of non-uniform magnetic fields in spiral thermoelements is more efficient. And spiral thermoelements, whose work is based on the excitation of eddy thermoelectric currents in a homogeneous gyrotropic thermoelectric medium, allow obtaining high thermoelectric voltages and differ from the known ones by multifunctionality, being promising for use both in special thermal generators and in measuring equipment. Studies of gyrotropic thermoelements of rectangular and optimal shapes have also shown efficiency increase in the case of using a non-uniform magnetic field.

Conclusions

1. The parameters of thermoelectric materials (*InSb, InAs* and Bi_2Te_3) for gyrotropic thermoelements are compared. It is established that the best material for the manufacture of generator gyrotropic thermoelements is *InSb,* the average value of the figure of merit of which in the temperature range 400 - 700 K is approximately $4\cdot10^{-4}$ K^{-1}.
2. Using computer simulations, the temperature distributions in the working fluid of a spiral-shaped gyrotropic thermoelement for *InSb* and *InAs* thermoelectric material were determined.
3. Temperature dependences of the efficiency are determined. It is established that the maximum efficiency value of spiral-shaped gyrotropic thermoelement for material *InSb* in the range of temperatures 300 - 700 K and magnetic induction of 1 T makes 2.75%.

References

1. Anatychuk L.I. (1979). *Termoelementy i termoelektricheskiie ustroistva [Thermoelements and thermoelectric devices].* Kyiv: Naukova dumka [in Russian].
2. Samoilovich A.G. (2006). *Termoelektricheskiie i termomagnitnyie metody preobrazovaniia energii [Thermoelectric and thermomagnetic methods of energy conversion].* Chernivtsi: Ruta [in Russian].
3. Anatychuk. L.I. (2003). *Termoelektrichestvo. T.2. Termoelektricheskiie preobrazovatelu energii [Thermoelectricity. Vol.2. Thermoelectric energy converters].* Kyiv, Chernivtsi: Naukova Dumka [in Russian].
4. Samoilovich A.G., Korenblit L.L. (1953). The current state of the theory of thermoelectric and thermomagnetic phenomena in semiconductors. *Uspekhi Fizicheskikh Nauk*, 49(2), 243 - 272.
5. Nakamura H., Ikeda K., Yamaguchi S. (1997). Transport coefficients of *InSb* in a strong magnetic field. *Proc. of XVI International Conference on Thermoelectrics*. (Dresden, Germany, 1997, 142 – 146).
6. Anatychuk L.I., Luste O.J., Fedoruk Ya.G., Shinkaruk S.M. (2004). Eddy thermoelectric currents in a gyrotropic medium with radial temperature distribution. *J. Thermoelectricity*, 1, 19 - 24.
7. Luste O.Ya., Fedoruk Ya.G. Gyrotropic thermocouple in an non-uniform magnetic field // Thermoelectricity. - 2006. - №1. - P. 16 - 22.
8. Luste O.J., Fedoruk Ya.G. (2008). Optimization of materials for gyrotropic thermoelements. *J. Thermoelectricity*, 4, 21 - 26.
9. Agayev Z.F., Arasly D.G., Aliyev S.A. (2003). Thermomagnetic converter of IR radiation. *Energy Problems*, 3, 12 - 21.
10. Nemov S.A., Proshin V.I., Tarantasov G.L., Parfenyev R.V., Shamshur D.V., Chernyaev A.V. (2009). Nernst-Ettingshausen transverse effect, resonant scattering and superconductivity in SnTe: In. *Solid State Physics*, 51(1), 461 - 464.

11. Harman T.G., Honig J.M. (1967). *Thermoelectric and thermomagnetic effects and applications*. New York, Mc. Graw - Hill.
12. Nakamura H., Ikeda K. and Yamaguchi S. (1998). Transport coefficients of InSb in a strong magnetic field. Research report. *NIFS series (Nagoya, Japan).*
13. Hiroaki Nakamura, Kazuaki Ikeda, Satarou Yamaguchi. Transport coefficients of InSb in a strong magnetic field. (1997). *Proc. of XVI International conference on Thermoelectrics*. (Dresden, Germany, August 26-29, 1997).
14. Baransky P.I., Gaidar G.P. (2014). Anisotropy of thermoelectric properties of multi-valley semiconductors of cubic symmetry under the influence of external directional effects. *J.Thermoelectricity*, 1, 13.
15. Goldsmid H.J., Volckmann E.H. (1997). Galvanomagnetic and thermoelectric measurements on polycrystalline. *Proc. of 16 International Conference on Thermoelectrics* (Dresden, Germany, August 26 - 29, 1997).
16. Anatychuk L.I., Vikhor L.N. (1997). Low-temperature thermoelectric cooling under optimal legs inhomogeneity in the optimal nonuniform magnetic field. In: *Proc.of the 16 International Conference on Thermoelectrics* (Dresden, August 26-29, 1997).
17. Konstantinovich I.A., Rendigevich O.V. (2016). On the efficiency of gyrotropic thermoelements in generation mode. *J.Thermoelectricity*, 1, 69-74.
18. Zakharchuk T.V, Konstantinovich I.A., Konstantinovich A.V, Forbatyuk A.V. (2019). On the efficiency of spiral gyrotropic thermoelements in cooling mode. *J. Thermoelectricity*, 1, 63-68.
19. *COMSOL Multiphysics User's Guide* (2010).

Submitted 14.04.020

Годованець Н.А.[1],
Константинович І.А. *канд. фіз-мат. наук, доцент*[1,2]**,**
А.В. Константинович *док. фіз.-мат. наук, доцент*[2]**,**
Шугані С.Д.[1]

[1]Чернівецький національний університет ім. Ю. Федьковича,
вул. Коцюбинського 2, Чернівці, 58012, Україна,
[2]Інститут термоелектрики Національної академії наук і Міністерства освіти
і науки України, вул. Науки 1, Чернівці, 58029, Україна
dj_kneo@ukr.net; aconst@ukr.net; i.konstantynovych@chnu.edu.ua

ГІРОТРОПНІ ТЕРМОЕЛЕМЕНТИ В ОДНОРІДНОМУ ТА НЕОДНОРІДНОМУ МАГНІТНИХ ПОЛЯХ

За допомогою комп'ютерного моделювання визначено розподіли температур у робочому тілі гіротропних термоелементів в однорідному та неоднорідному магнітних полях. Визначено температурні залежності ККД гіротропних *термоелементів в однорідному та неоднорідному магнітних полях. Встановлено, що ККД генераторних гіротропних термоелементів більше в неоднорідному магнітному полі ніж в однорідному полі. Бібл. 19, рис. 3.*

Ключові слова: коефіцієнт Нернста-Еттінгсгаузена, гіротропний термоелемент, неоднорідне магнітне поле, термоелектричний матеріал, термомагнітна добротність, ККД.

Годованец Н.А. [1],
Константинович И.А.. *канд. физ-мат. наук, доцент*[1,2]**,**
Константинович а.В. *док. физ.-мат. наук, доцент*[2]**,**
Шугани С.Д.[1]

[1]Черновицкий национальный университет им. Ю. Федьковича,
ул. Коцюбинского 2, [2]Черновцы, 58012, Украина,
[2]Институт термоэлектричества НАН и Мон Украины,
ул. Науки 1, Черновцы, 58029, Украина
e-mail: dj_kneo@ukr.net; aconst@ukr.net;
i.konstantynovych@chnu.edu.ua

ГИРОТРОПНОГО ТЕРМОЭЛЕМЕНТ В ОДНОРИДНОМУ ТА НЕОДНОРОДНОМ МАГНИТНОМ ПОЛЯХ

С помощью компьютерного моделирования определены распределения температур в рабочем теле гиротропных термоэлементов в однородном и неоднородном магнитном поле. Определены температурные зависимости КПД гиротропных термоэлементов в однородном и неоднородном магнитном поле. Установлено, что КПД генераторных гиротропных термоэлементов больше в неоднородном магнитном поле чем в однородном поле. Библ. 19, рис. 3.

Ключевые слова: коэффициент Нернста-Эттингсгаузена, гиротропный термоэлемент, неоднородное магнитное поле, термоэлектрический материал, термомагнитная добротность, КПД..

References

1. Anatychuk L.I. (1979). *Termoelementy i termoelektricheskiie ustroistva [Thermoelements and thermoelectric devices].* Kyiv: Naukova dumka [in Russian].
2. Samoilovich A.G. (2006). *Termoelektricheskiie i termomagnitnyie metody preobrazovaniia energii [Thermoelectric and thermomagnetic methods of energy conversion].* Chernivtsi: Ruta [in Russian].
3. Anatychuk. L.I. (2003). *Termoelektrichestvo. T.2. Termoelektricheskiie preobrazovatelu energii [Thermoelectricity. Vol.2. Thermoelectric energy converters].* Kyiv, Chernivtsi: Naukova Dumka [in Russian].

4. Samoilovich A.G., Korenblit L.L. (1953). The current state of the theory of thermoelectric and thermomagnetic phenomena in semiconductors. *Uspekhi Fizicheskikh Nauk*, 49(2), 243 - 272.
5. Nakamura H., Ikeda K., Yamaguchi S. (1997). Transport coefficients of *InSb* in a strong magnetic field. *Proc. of XVI International Conference on Thermoelectrics*. (Dresden, Germany, 1997, 142 – 146).
6. Anatychuk L.I., Luste O.J., Fedoruk Ya.G., Shinkaruk S.M. (2004). Eddy thermoelectric currents in a gyrotropic medium with radial temperature distribution. *J. Thermoelectricity*, 1, 19 - 24.
7. Luste O.Ya., Fedoruk Ya.G. Gyrotropic thermocouple in an non-uniform magnetic field // Thermoelectricity. - 2006. - №1. - P. 16 - 22.
8. Luste O.J., Fedoruk Ya.G. (2008). Optimization of materials for gyrotropic thermoelements. *J. Thermoelectricity*, 4, 21 - 26.
9. Agayev Z.F., Arasly D.G., Aliyev S.A. (2003). Thermomagnetic converter of IR radiation. *Energy Problems*, 3, 12 - 21.
10. Nemov S.A., Proshin V.I., Tarantasov G.L., Parfenyev R.V., Shamshur D.V., Chernyaev A.V. (2009). Nernst-Ettingshausen transverse effect, resonant scattering and superconductivity in SnTe: In. *Solid State Physics*, 51(1), 461 - 464.
11. Harman T.G., Honig J.M. (1967). *Thermoelectric and thermomagnetic effects and applications*. New York, Mc. Graw - Hill.
12. Nakamura H., Ikeda K. and Yamaguchi S. (1998). Transport coefficients of InSb in a strong magnetic field. Research report. *NIFS series (Nagoya, Japan).*
13. Hiroaki Nakamura, Kazuaki Ikeda, Satarou Yamaguchi. Transport coefficients of InSb in a strong magnetic field. (1997). *Proc. of XVI International conference on Thermoelectrics*. (Dresden, Germany, August 26-29, 1997).
14. Baransky P.I., Gaidar G.P. (2014). Anisotropy of thermoelectric properties of multi-valley semiconductors of cubic symmetry under the influence of external directional effects. *J.Thermoelectricity*, 1, 13.
15. Goldsmid H.J., Volckmann E.H. (1997). Galvanomagnetic and thermoelectric measurements on polycrystalline. *Proc. of 16 International Conference on Thermoelectrics* (Dresden, Germany, August 26 - 29, 1997).
16. Anatychuk L.I., Vikhor L.N. (1997). Low-temperature thermoelectric cooling under optimal legs inhomogeneity in the optimal nonuniform magnetic field. In: *Proc.of the 16 International Conference on Thermoelectrics* (Dresden, August 26-29, 1997).
17. Konstantinovich I.A., Rendigevich O.V. (2016). On the efficiency of gyrotropic thermoelements in generation mode. *J.Thermoelectricity*, 1, 69-74.
18. Zakharchuk T.V, Konstantinovich I.A., Konstantinovich A.V, Forbatyuk A.V. (2019). On the efficiency of spiral gyrotropic thermoelements in cooling mode. *J. Thermoelectricity*, 1, 63-68.
19. *COMSOL Multiphysics User's Guide* (2010).

Submitted 14.04.2020