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Address of editorial office:
Ukraine, 58002, Chernivtsi, General Post Office, P.O. Box 86.
Phone: +(380-372) 90 31 65.
Fax: +(380-3722) 4 19 17.
E-mail: jt@inst.cv.ua
http://www.jt.inst.cv.ua

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CONTENT

L.I. Anatychuk, *acad. NAN Ukraine*[1,2],
V.V. Lysko, *cand. phys.-math. sciences*[1,2]

L.I. Anatychuk

Institute of Thermoelectricity of the NAS and MES
of Ukraine,1, Nauky str, Chernivtsi, 58029, Ukraine;
e-mail: anatych@gmail.com,
[2]Yu.Fedkovych Chernivtsi National University,
2, Kotsiubynskyi str., Chernivtsi, 58000, Ukraine,
e-mail: anatych@gmail.com

V.V. Lysko

MEASUREMENT OF THE TEMPERATURE DEPENDENCES OF THERMOELECTRIC PARAMETERS OF MATERIALS UNDER CONDITIONS OF CONTINUOUS TEMPERATURE CHANGE

The results of computer studies aimed at improving performance when defining the thermoelectric parameters of materials by the absolute method are presented. The possibility of performance increase by measurement under conditions of continuous monotonous heating of the measuring thermostat is considered. The analysis of errors in the measurement of thermal conductivity for this case is carried out, and the conditions for their minimization are established. It was determined that measurements under conditions of continuous temperature change with regard to heat capacities of the test sample and the reference heater allow reducing by a factor of 3-5 the time required to measure the temperature dependences of thermoelectric parameters of the sample, with a slight increase to 0.5 – 1 % of measurement errors. Bibl. 8, Fig. 4.

Key words: measurement, electrical conductivity, thermoEMF, thermal conductivity, figure of merit, errors, performance.

Introduction

General characterization of the problem.

Creation of thermoelectric materials effective in various temperature ranges is one of the important tasks of thermoelectricity [1 – 3]. To solve it, high-precision methods and equipment are needed for measuring the temperature dependences of thermoelectric parameters of materials.

In [4 – 7], it was shown that the absolute method is most effective for ensuring high accuracy of measurements. However, in its application, the measurement performance is problematic. The need to achieve steady-state conditions causes an increase in the duration of measurements. So, to measure the temperature dependence of one sample in the temperature range 30 - 550 °C, up to 20 hours are necessary.

In [8], the possibility of increasing performance of the absolute method by applying alternating current pulses to accelerate the achievement of steady-state conditions in the test samples, as well as programmed forced heating of the sample and the thermostat, was considered. Such methods make it possible to reduce the time required for measuring the temperature dependence of thermoelectric parameters of a sample by a factor of 3-5. However, their implementation requires complex measurement algorithms.

The purpose of this work was to investigate the possibility of increasing performance of the absolute method by measurement under conditions of continuous monotonous heating of the measuring thermostat.

Physical model and its mathematical description. Computer model

The test sample is attached on one side to the measuring thermostat, as shown in Fig. 1. The temperature of the thermostat T_0 monotonically increases, starting from room temperature. For this, an electric power W_0 is supplied to the background heater of the thermostat, the value of which is a function of time. Heat is supplied to the second side of the sample with constant power Q from the reference heater.

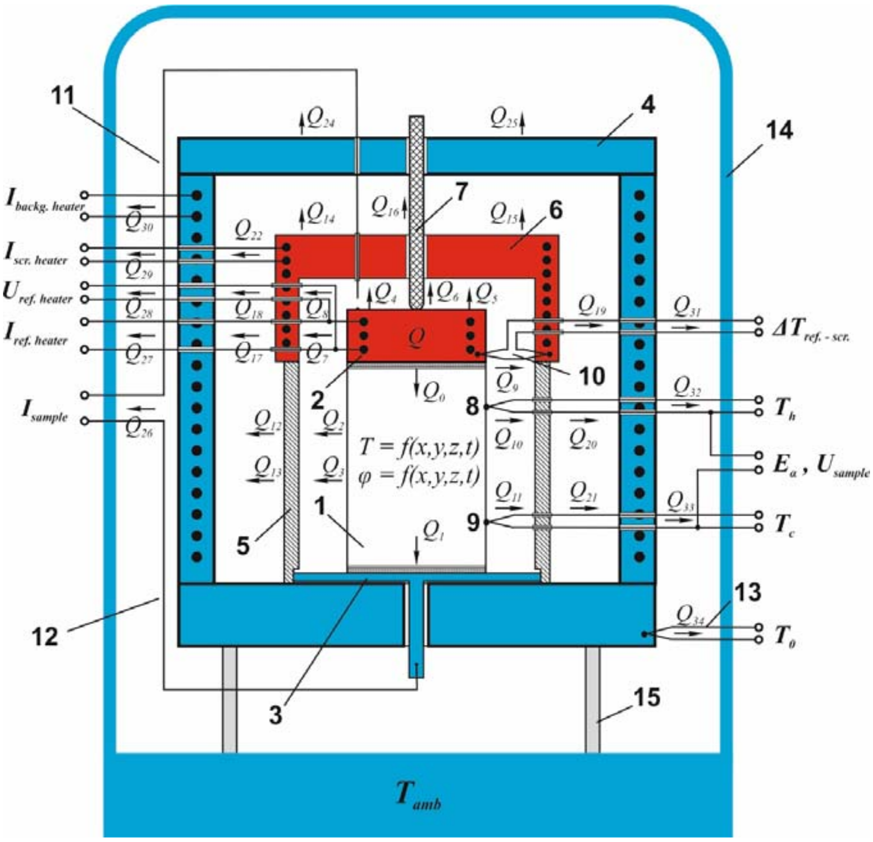

Fig. 3.27. Physical model of a comprehensive absolute method for the study of factors affecting the rate of transition from one temperature point to another: 1 – test sample; 2 – reference heater; 3 – mounting pad; 4 – thermostat; 5 – screen; 6 – screen heater; 7 – clamp; 8, 9 – measuring thermocouple probes; 10 – null-thermocouple; 11, 12 – sample current conductors; 13 – thermostat thermocouple; 14 – external thermostat (vacuum hood); 15 – racks on which measuring thermostat is mounted in the external passive thermostat.

In the physical model shown in Fig.1: Q is heat generated by the reference electric heater when current is passed through it; Q_0 is heat supplied from the reference heater to the sample; Q_1 is heat transmitted from the sample to the thermostat; Q_2 is heat flux between the surfaces of the sample and gradient thermal screen due to radiation; Q_3 is heat flux between the surfaces of the sample and gradient thermal screen due to convection; Q_4 is heat flux between the surfaces of the reference heater and the screen heater due to radiation; Q_5 is heat flux between the surfaces of the reference heater and the screen heater due to convection; Q_6 is heat flux between the surfaces of the reference heater and the screen heater through the clamp; Q_7 and Q_8 is heat flux between the surfaces of the reference heater and the screen heater through current and potential conductors of the reference heater; Q_9 is heat flux between the surfaces of the reference heater and the screen heater through conductors of null- thermocouple; Q_{10} and Q_{11} is heat flux between the surfaces of the sample and gradient thermal screen through conductors of thermocouple probes; Q_{12} is heat flux between the surfaces of gradient thermal screen and the thermostat due to radiation; Q_{13} is heat flux between the surfaces of gradient thermal screen and the thermostat due to convection; Q_{14} is heat flux between the surfaces of the screen heater and the thermostat due to radiation; Q_{15} is heat flux between the surfaces of the screen heater and the thermostat due to convection; Q_{16} is heat flux between the surfaces of the screen heater and the thermostat through the clamp; Q_{17} та Q_{18} is heat flux between the surfaces of the screen heater and the thermostat through current and potential conductors of the reference heater; Q_{19} is heat flux between the surfaces of the screen heater and the thermostat through conductors of null-thermocouple; Q_{20} and Q_{21} is heat flux between the surfaces of gradient heat screen and the thermostat through conductors of thermocouple probes; Q_{22} is heat flux between the surfaces of the screen heaters and the thermostat through current conductors of the screen heater; Q_{23} is heat flux between the surfaces of the screen heater and the thermostat through current conductor, Q_{24} is heat flux between the surfaces of the measuring thermostat and the external passive thermostat due to radiation, Q_{25} is heat flux between the surfaces of the measuring thermostat and the external passive thermostat due to convection, Q_{26} is heat flux between the surfaces of the measuring thermostat and the external passive thermostat through conductors (thermocouple probes, null-thermocouples, potential and current electrodes of the reference heater and the screen heater, etc).

A measuring thermostat is placed under the hood of the vacuum unit to eliminate heat transfer through the air by convection and heat conduction.

For the case of steady-state absolute method, the values of electrical conductivity σ, the Seebeck coefficient α, thermal conductivity κ and figure of merit Z of the test sample are found from the formulae

$$\sigma = \frac{I}{U}\frac{l}{S}, \quad (1)$$

$$\alpha = \frac{E_\alpha}{T_h - T_c}, \quad (2)$$

$$\kappa = \frac{W}{T_h - T_c}\frac{l}{S}, \quad (3)$$

$$Z = \frac{\alpha^2\sigma}{\kappa}, \quad (4)$$

where S is cross-sectional area of the sample; I, U is current through the sample and voltage drop on it when measuring electrical conductivity; E_α is thermoEMF; T_h and T_c are the "hot" and "cold" temperatures at the ends of the sample.

The absence of steady-state conditions during measurements will cause errors, primarily in determining thermal conductivity. To study the values of these errors, it is necessary to find the time dependence of temperature distribution in the test sample. For this, it is necessary for each element of the physical model shown in Fig. 1, to solve the system of differential equations with the corresponding boundary conditions, written in the form

$$\begin{cases} \rho C\dfrac{\partial T}{\partial t} - \nabla\left(\left(\kappa + \alpha^2\sigma T + \alpha\varphi\sigma\right)\nabla T\right) - \nabla\left(\left(\alpha\sigma T + \varphi\sigma\right)\nabla\varphi\right) = 0, \\ \nabla\left(\varepsilon\nabla\dfrac{\partial\varphi}{\partial t}\right) - \nabla\left(\sigma\nabla\varphi\right) - \nabla\left(\sigma\alpha\nabla T\right) = 0. \end{cases}, \quad (5)$$

where α is the Seebeck coefficient, σ is electrical conductivity, κ is thermal conductivity, ρ is density, C is heat capacity, ε is dielectric permittivity.

The boundary conditions for the case of measuring at certain given thermostat temperature T_0 can be written as follows:

– lateral surface of the sample

$$r = \frac{d}{2}, \quad z \in [0;\ l] : q = \varepsilon_1\left(G_1 - \sigma T^4\right); \quad (6)$$

– lateral surface of the reference heater

Ошибка! Объект не может быть создан из кодов полей редактирования., **Ошибка! Объект не может быть создан из кодов полей редактирования.**: **Ошибка! Объект не может быть создан из кодов полей редактирования.**; (7)

– upper surface of the reference heater

$$r = \left[0;\ \frac{d}{2}\right], \quad z \in l + l_2 :\ q = \varepsilon_2\left(G_3 - \sigma T^4\right); \quad (8)$$

– internal surface of the screen

$$r = \frac{d}{2} + \Delta R, \quad z \in [0; l] :\ q = \varepsilon_3\left(G_4 - \sigma T^4\right); \quad (9)$$

– internal surface of the screen heater

$$r = \frac{d}{2} + \Delta R, \quad z \in [l; l + l_4] :\ q = \varepsilon_4\left(G_5 - \sigma T^4\right); \quad (10)$$

$$r = \left[0; \frac{d}{2} + \Delta R\right], \quad z = l + l_2 + \Delta R :\ q = \varepsilon_4\left(G_6 - \sigma T^4\right); \quad (11)$$

– external surface of the screen heater

$$r=\frac{d_4}{2},\quad z\in\left[l;\, l=l_4\right]:\ q=\varepsilon_4\left(G_7-\sigma T^4\right); \tag{12}$$

$$r\in\left[0;\ \frac{d}{2}+\Delta R\right],\ z=l+l_4:\ q=\varepsilon_4\left(G_8-\sigma T^4\right),\ T=T_0+\Delta T; \tag{13}$$

– external surface of the screen

$$r=\frac{d_3}{2},\ z\in\left[0;\ l\right]:\ q=\varepsilon_3\left(G_9-\sigma T^4\right); \tag{14}$$

– thermostat surface between the sample and the screen

$$r\in\left[\frac{d}{2};\frac{d}{2}+\Delta R\right],\ z=0:\ q=\varepsilon_5\left(G_{10}-\sigma T^4\right); \tag{15}$$

– thermostat surface on the external side of the screen

$$r\in\left[\frac{d_3}{2};\frac{d_5}{2}\right],\ z=0:\ q=\varepsilon_5\left(G_{11}-\sigma T^4\right); \tag{16}$$

$$r\in\left[0;\frac{d_5}{2}\right],\ z=l_5:\ q=\varepsilon_5\left(G_{12}-\sigma T^4\right); \tag{17}$$

$$r=\frac{d_5}{2},\ z\in\left[0;\ l_5\right]:\ q=\varepsilon_5\left(G_{13}-\sigma T^4\right); \tag{18}$$

– external surface of the thermostat

$$r\in\left[0;\frac{d_5}{2}+h_5\right],\ z=-h_5:T=T_0; \tag{19}$$

$$r\in\left[0;\frac{d_5}{2}+h_5\right],\ z=l_5+h_5:T=T_0; \tag{20}$$

$$r=\frac{d_5}{2}+h_5,\ z\in\left[-h_5;\ l_5+h_5\right]:T=T_0. \tag{21}$$

where T_0 is the thermostat temperature, T_1 is the temperature of sample heaters and the screen, κ_1 is thermal conductivity of the sample, κ_2 is thermal conductivity of the reference heater; κ_3 is thermal conductivity of the screen, κ_4 is thermal conductivity of the screen heater, ε_1 is absorption ratio of sample surface, ε_2 is absorption ratio of the reference heater surface, ε_3 is absorption ratio of the screen surface, ε_4 is absorption ratio of the screen heater surface, ε_5 is absorption ratio of the thermostat surface, d_1, l_1 are diameter and length of the sample; d_2, l_2 are diameter and length of the reference heater; d_3, l_3 are outer diameter and length of the screen; d_4, l_4 are diameter and length of the screen heater; d_5, l_5, h_5 are inner diameter, length and thickness of the thermostat; ΔR is distance between the sample and the screen;

σ is Stephan-Boltzmann constant; G is input heat flux generated by radiation for each separate boundary:

$$G = G_m + F_{amb}\sigma T_{amb}^4, \tag{22}$$

where G_m is the amount of radiation from other elements of the measuring installation and the sample; F_{amb} is the factor of the field of view, equal to that part of it that does not fall under the influence of other surfaces; T_{amb} are temperatures at far points in the directions included in F_{amb}.

Such problems of finding the distribution of electrical potential and temperature, as well as thermal and electrical fluxes in the test samples are difficult to be solved analytically due to complex geometry, the temperature dependences of the properties of the sample and structural elements of the measuring equipment, etc. To calculate the temperature and electric fields, as well as the effects of various factors on them, computer methods of object-oriented simulation of real physical models can be used. In particular, the COMSOL Multiphysics application package is well suited for solving such problems.

The coefficient G_m, which depends on the relative location of the surfaces, is calculated by introducing into the computer model an additional variable J, given by the equation

$$J = (1-\varepsilon)\left\{G_m(J) + F_{amb}\sigma T_{amb}^4\right\} + \varepsilon\sigma T^4, \tag{23}$$

which is solved in conjunction with other equations of the mathematical model.

Computer research results

When using steady-state absolute method for measuring thermoelectric parameters of the test sample at each fixed temperature of the measuring thermostat, it is necessary to spend 30-60 minutes. In this case, about 3/4 of the time is spent on the transition from one temperature to another, and the rest ¼ - on the measurement of electrical conductivity, the creation of a steady-state temperature gradient on the sample and the measurement of thermal conductivity and the Seebeck coefficient.

Thus, to study the temperature dependence of thermoelectric parameters of one sample in the temperature range from room temperature to 550 °C with increments of 25 °C takes up to 20 hours. This is equivalent to a monotonous heating of the measuring thermostat at a rate of about 0.4 K/min. Using a computer model, you can obtain the appropriate time dependence of the background heater power required for such a monotonous heating (Fig. 2). Similar dependences can be obtained for another rate of monotonous heating of the measuring thermostat.

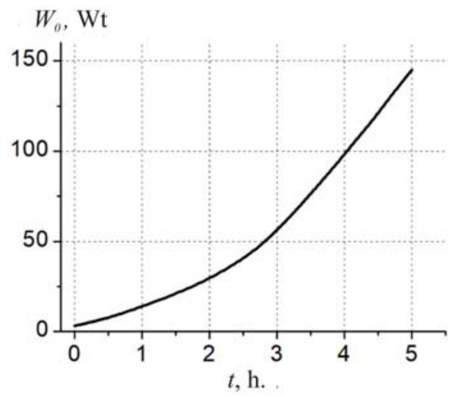

Fig. 2. Temporal dependence of background heater power necessary for monotonous heating of the thermostat from room temperature to 500 °C

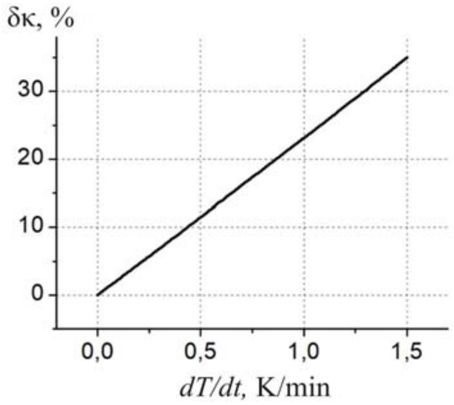

Fig. 3. Dependence of the error in measuring thermal conductivity by the absolute method under conditions of monotonous heating on the rate of thermostat temperature growth

Fig. 3 shows the dependence of the errors in determining the thermal conductivity arising due to heat consumption of the reference heater for heating the sample and the elements of the measuring unit. As can be seen from the figure, even at a heating rate of 0.4 K/min, which corresponds to a steady-state case of 1 hour for measurement at the same temperature, the error in measuring thermal conductivity will be unacceptably large - up to 10%. δκ, %

In order to reduce the errors and achieve the possibility of accelerating the measurement process, it is necessary to take into account the heat capacities of the sample and the elements of the measuring installation, in particular the reference heater. To do this, the following formula shall be used

$$\kappa = \frac{Q - \left[C_2 m_2 + \frac{1}{2} C_1 m_1 \right] \cdot \frac{dT_h}{dt}}{T_h - T_c} \frac{l}{S}, \qquad (24)$$

where C_1 is the heat capacity of the sample; C_2 is the heat capacity of the reference heater; T_h is the temperature of the hot end of the sample (the reference heater); T_c is the temperature of the cold end of the sample (the thermostat); l is the length of the sample; S is the cross-sectional area of the sample.

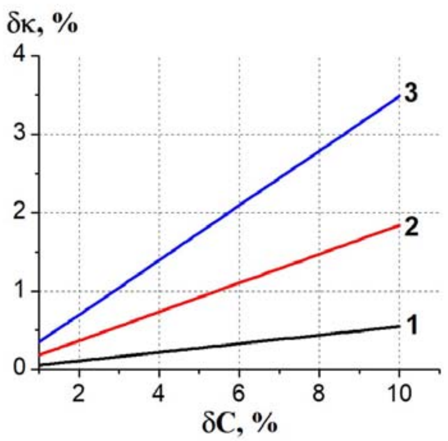

Fig. 4. Dependence of the error in measuring thermal conductivity by the absolute method under conditions of monotonous heating on the accuracy of information on the heat capacities of the test sample and the reference

heater (for different speeds of thermostat temperature rise: 1 – 25 K/h; 2 – 75 K/h; 3 – 125 K/h)

In so doing, accurate information on the capacities C_1 and C_2 will be required to achieve high accuracy of measurements while increasing their performance. Fig.4 shows the dependence of the error in measuring thermal conductivity by the absolute method under conditions of monotonous heating on the accuracy of information on the heat capacities of the test sample and the reference heater for different speeds of thermostat temperature rise. Dependence 1 in Fig. 4 for steady-state measurements by the absolute method corresponds to measurement at the same temperature within one hour. To accelerate measurements by a factor of 3-5 (as is possible in the case of using algorithms for programmed heating of the measuring thermostat with PID controllers and simultaneous heating of the sample with alternating current and the heat of the reference heater) with an additional error not exceeding 0.5%, information is needed on the heat capacities of the sample and the reference heater with an accuracy at least 1 - 3%.

Conclusions

1. A computer model was created allowing to calculate the time dependence of the background heater power required for monotonous heating of the measuring thermostat at a predetermined rate.
2. The errors in the measurement of thermal conductivity by the absolute method are investigated under conditions of continuous temperature rise. It was established that in order to reduce the errors and to achieve the possibility of accelerating the measurement process, it is necessary to take into account the heat capacities of the sample and the elements of the measuring installation, in particular the reference heater.
3. It was established that in order to accelerate measurements by a factor of 3-5 with the introduction of additional error not higher than 0.5%, information on the heat capacity of the sample and the reference heater with an accuracy at least 1 - 3% is required.

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Анатичук Л.І., *ак. НАН України,*[1,2]
Лисько В.В., *канд. фіз. – мат. наук,*[1,2]

[1]Інститут термоелектрики НАН і МОН України,
вул. Науки, 1, Чернівці, 58029, Україна;
[2]Чернівецький національний університет
ім. Юрія Федьковича, вул. Коцюбинського 2,
Чернівці, 58000, Україна, *e-mail: anatych@gmail.com*

ВИМІРЮВАННЯ ТЕМПЕРАТУРНИХ ЗАЛЕЖНОСТЕЙ ТЕРМОЕЛЕКТРИЧНИХ ПАРАМЕТРІВ МАТЕРІАЛІВ В УМОВАХ НЕПЕРЕРВНОЇ ЗМІНИ ТЕМПЕРАТУРИ

Наведено результати комп'ютерних досліджень, направлених на підвищення швидкодії при визначенні термоелектричних параметрів матеріалів абсолютним методом. Розглянуто можливість підвищення швидкодії шляхом проведенням вимірювань в умовах неперервного монотонного розігріву вимірювального термостату. Проведено аналіз похибок при вимірюваннях теплопровідності для такого випадку та встановлено умови їх мінімізації. Визначено, що вимірювання в умовах неперервної зміни температури при врахуванні теплоємностей досліджуваного зразка та еталонного нагрівника дозволяють у 3-5 разів зменшити час, необхідний на вимірювання температурних залежностей термоелектричних параметрів зразка, при незначному, до 0.5 – 1%, збільшенні похибок вимірювань. Бібл. 8, рис. 4.

Ключові слова: вимірювання, електропровідність, термоЕРС, теплопровідність, добротність, похибки, швидкодія.

Анатычук Л.И., *ак. НАН Украины,*[1,2] **Гаврилюк М.В.,**[1,2]
Лысько В.В., *канд. физ – мат. наук,*[1,2] **Тюменцев В.А.**[1]

[1]Институт термоэлектричества НАН и МОН Украины,
вул. Науки, 1, Черновцы, 58029, Украина;
[2]Черновецький национальный университет
им. Юрия Федьковича, ул. Коцюбинского 2,
Черновцы, 58000, Украина, *e-mail: anatych@gmail.com*

ИЗМЕРЕНИЕ ТЕМПЕРАТУРНЫХ ЗАВИСИМОСТЕЙ ТЕРМОЭЛЕКТРИЧЕСКИХ ПАРАМЕТРОВ МАТЕРИАЛОВ В УСЛОВИЯХ НЕПРЕРЫВНОГО ИЗМЕНЕНИЯ ТЕМПЕРАТУРЫ

Приведены результаты компьютерных исследований, направленных на повышение быстродействия при определении термоэлектрических параметров материалов абсолютным методом. Рассмотрена возможность повышения быстродействия путем проведением измерений в условиях непрерывного монотонного разогрева измерительного термостату. Проведен анализ погрешностей при измерениях теплопроводности для такого случая и установлено условия их минимизации. Определено, что измерение в условиях непрерывного изменения температуры при учете теплоемкостей исследуемого образца и эталонного нагревателя позволяют в 3-5 раз уменьшить время, необходимое на измерение температурных зависимостей термоэлектрических параметров образца, при незначительному, к 0.5 – 1 %, увеличении погрешностей измерений.

Ключевые слова: измерение, электропроводность, термоЭДС, теплопроводность, добротность, погрешности, быстродействие.

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


L.I. Anatychuk

[1]Institute of Thermoelectricity
of the NAS and MES of Ukraine,
1, Nauky str., Chernivtsi, 58029, Ukraine;
[2]Yu.Fedkovych Chernivtsi National University,
2, Kotsiubynskyi str., Chernivtsi, 58000, Ukraine
e-mail: anatych@gmail.com


A.V. Prybyla

THERMOELECTRIC GENERATORS WITH VARIABLE POWER FLAME HEAT SOURCES, SINGLE-STAGE THERMOPILES AND ELECTRIC ENERGY BATTERIES

In this paper, calculations of the dynamic power of a thermoelectric generator with variable power flame heat sources are made. The results of calculations of such a generator made of thermoelectric material based on PbTe – TAGS are presented. Bibl. 5, Fig. 3.
Key words: thermoelectric generator, computer design, physical model.

Introduction

General characterization of the problem. Variable power flame sources, including firewood and pressed briquettes, are widely used for space heating and cooking, especially in remote areas. In addition, the relevance of their use is constantly increasing in the face of growing cost of gas and liquid organic fuels.

The use of such solid fuel furnaces, in particular for cooking, is associated with significant heat losses to the environment. The use of thermoelectric generators (TEGs) for partial conversion of said heat into electrical energy is promising [1 – 3]. In addition to economic advantages, the use of heated surfaces of solid fuel furnaces in the TEG design makes it possible to create universal thermoelectric combined heat and power systems, which, compared to similar thermoelectric systems operating on diesel, gasoline or gas fuels, have a simpler and yet reliable design, are safer and more comfortable in operation [1 – 3].

One of the factors limiting the widespread practical use of thermoelectric generators is low efficiency of thermal into electrical energy conversion, due to the use in the TEG design of single-stage modules with low figure of merit values of thermoelectric materials for the operating temperatures of solid fuel furnaces, as well as the use of temperature stabilizers of the hot generator surface which, on the one hand, ensure the reliability of TEG functioning, but lead to a decrease in overall energy conversion efficiency [3].

One of the ways to increase the efficiency of thermoelectric conversion is to extend the operating temperature range of the module by using generator modules optimized for operating temperatures of 30-600 ° C.

For the above TEG operating temperatures, specialized thermoelectric modules were developed from a material based on *n*-type *PbTe* and *p*-type *GeTe-AgSbTe* (TAGS) [4].

The purpose of this work is to calculate the dynamic operating characteristics of a thermoelectric generator with variable power heat sources in the temperature range of 30-600 °C.

Physical model

The calculations used a physical model of a thermoelectric generator unit (Fig. 1), which contains a heated surface of a variable power heat source *1*, heat exchangers for the supply *2* and removal 5 of heat flux to/from a thermoelectric module *3*, thermal insulation *4*, electric voltage stabilizer *6* and electric energy battery *7*.

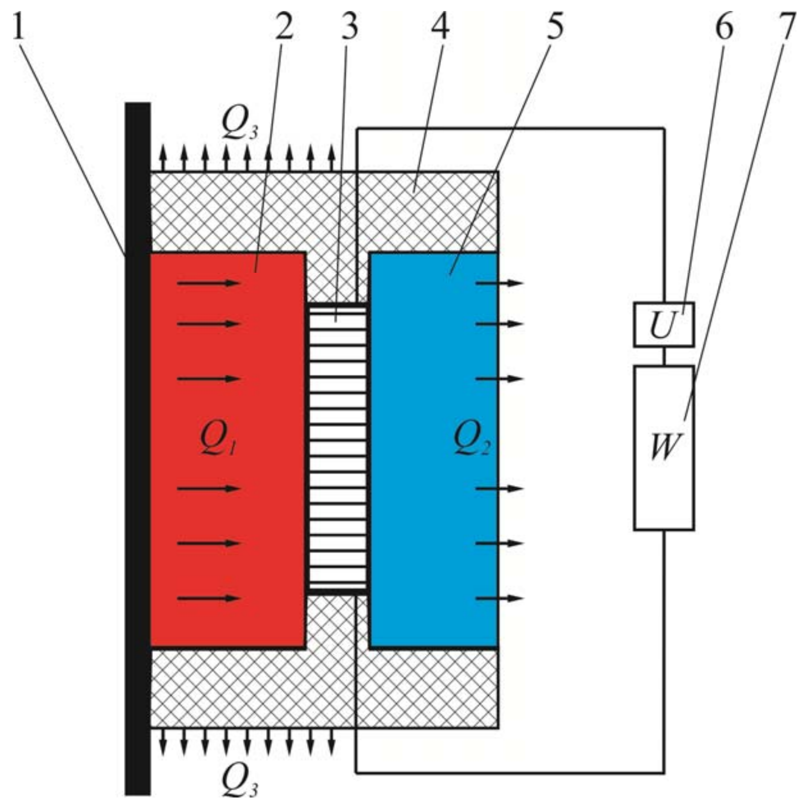


Fig.1. Physical model of thermoelectric generator unit:
1 – heated surface; 2 –hot heat exchanger; 3 – thermoelectric module;
4 – thermal insulation; 5 – cold heat exchanger;
6 – voltage stabilizer; 7 – electric energy battery.

Since the generator is installed on the heated surface, the model does not consider the processes of heat transfer from the actual source of fuel combustion to this surface. Instead, to determine the temperature of the heated surface *1*, the experimental temporal dependences of its temperature in the real cycle of using the solid fuel heat source are used [3].

Mathematical and computer descriptions of the model

Thus, the equation of heat balance is used to calculate the thermoelectric generator in accordance with the physical model (Fig. 1).

On the hot side there is a variable power heat source $Q_1[T_1(t)]$.Its thermal power depends on the temperature of this surface T_1 which, in turn, changes with time t (Fig. 3), and is given in the form of some function $f[T_1(t)]$.

$$Q_1 = f\left[\mathrm{T}_1(\mathrm{t})\right], \tag{1}$$

Heat supply from the heated surface to the hot side of the thermoelectric module and heat removal to the cold heat exchanger is described by the equations:

$$Q_1 = \chi_1[T_1(\mathrm{t}) - T_\Gamma], \tag{2}$$

$$Q_2 = \chi_2[\mathrm{T_X} - T_2], \tag{3}$$

where χ_1, χ_2 are thermal resistances of the hot and cold heat exchangers; T_h, T_c are the hot and cold side temperatures of thermoelectric module, respectively; T_2 is the temperature of the external surface of the cold heat exchanger.

Thermal power Q_2 is removed from the cold heat exchanger by forced convection of air to the environment:

$$Q_2 = \alpha(T_2 - T_0)S_m, \tag{4}$$

where α is coefficient of convective heat exchange between the surface of the heat exchanger and the environment; S_m is the area of heat exchange surface; T_0 is ambient temperature.

The electric power generated by thermoelectric module is proportional to $Q_1[T_1(t)]$ and its efficiency η:

$$W = Q_1\,[T_1(t)]\cdot\eta, \tag{5}$$

The main losses of heat Q_3 occur through thermal insulation:

$$Q_3 = \chi_4 (T_M - T_0), \tag{6}$$

where χ_4 is thermal resistance of insulation, T_M is temperature of the internal surface of thermal insulation.

Thus, the equation of heat balance for the chosen model of thermoelectric generator can be written as:

$$Q_1 = W + Q_2 + Q_3 . \tag{7}$$

For the computer representation of the TEG mathematical model, the Comsol Multiphysics software package [5] was used. For this it is necessary to present our equations in the following form.

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

$$div\vec{E} = 0 \tag{8}$$

and electric charge

$$div\vec{j} = 0, \tag{9}$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \tag{10}$$

$$\vec{q} = \kappa \nabla T + \alpha T \vec{j}, \tag{11}$$

$$\vec{j} = -\sigma \nabla U - \sigma\alpha \nabla T. \tag{12}$$

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

With regard to (10) – (12), one can obtain

$$\vec{E} = -(\kappa + \alpha^2 \sigma T + \alpha U \sigma) \nabla T - (\alpha\sigma T + U\sigma) \nabla U. \tag{13}$$

Then the laws of conservation (8), (9) will take on the form:

$$-\nabla\left[(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T\right] - \nabla\left[(\alpha\sigma T + U\sigma)\nabla U\right] = 0, \tag{14}$$

$$-\nabla(\sigma\alpha\nabla T) - \nabla(\sigma \nabla U) = 0. \tag{15}$$

From the solution of equation (14) - (15) we obtain the distributions of physical fields, as well as the integral values of the efficiency and power of TEG.

Description of the dynamic powers of TEG

To determine the actual temperature conditions on the heated surfaces of furnaces with flame heat sources on solid fuel (firewood), experimental studies were carried out. The dependences of the temperature of the heated furnace surfaces on the time during which the equal amount of firewood was added at identical intervals were determined [3].

The obtained data were processed in the form of functional temporal dependences of the temperatures of heated furnace surfaces and used in the calculations of characteristics of a thermoelectric generator with variable power flame heat sources on solid fuel.

Thus, using computer methods, the dynamic powers of a TEG installed on the furnace surface were calculated

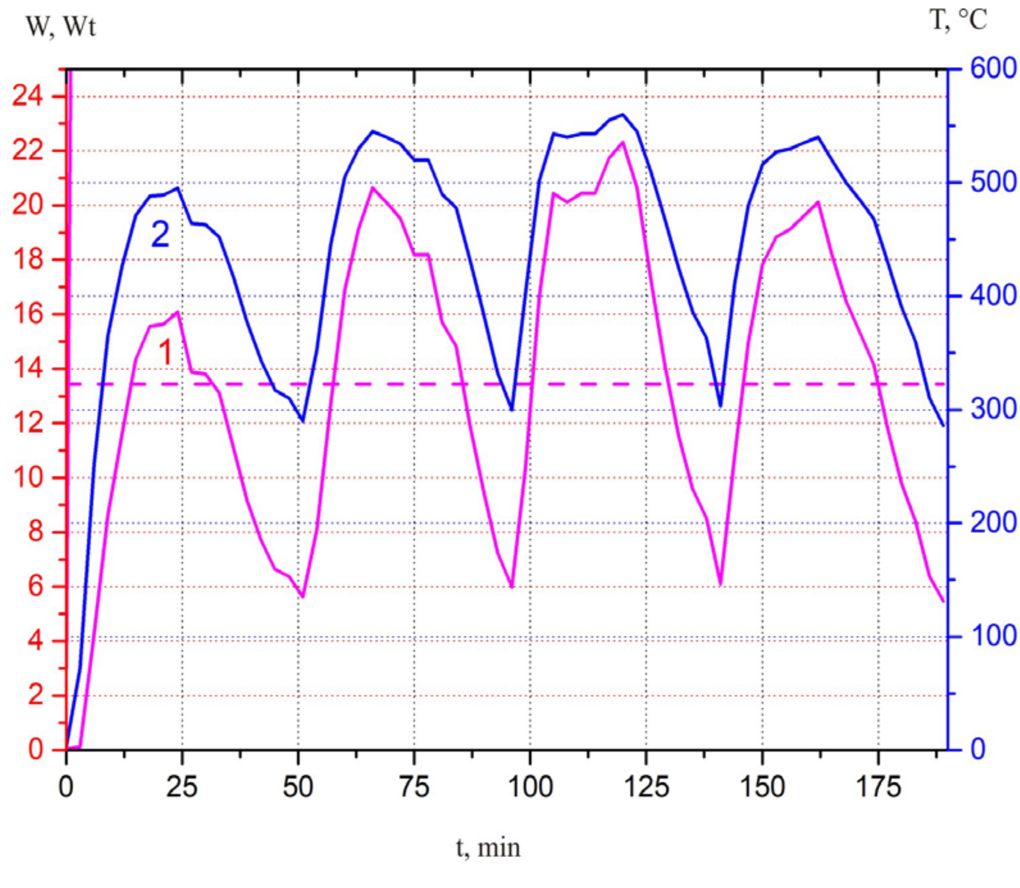
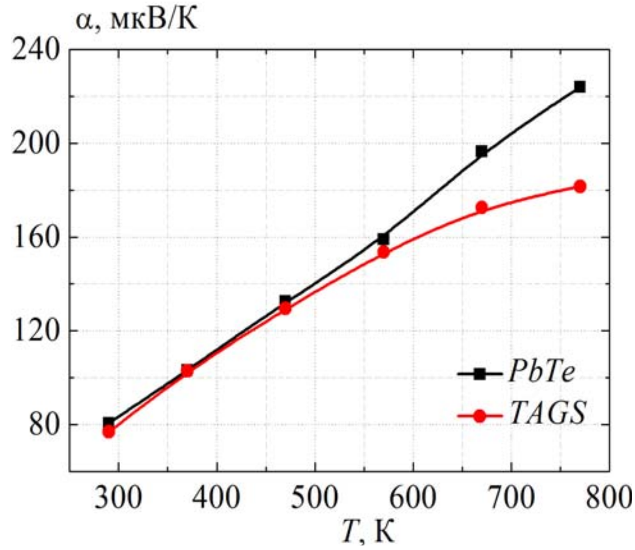


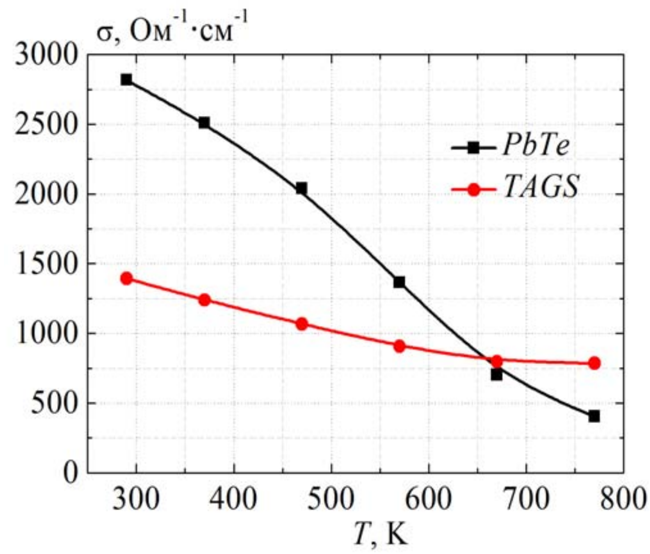
Fig. 2. Temporal dependence of the power of TEG located on the rear surface of the furnace: 1 – TEG power at $T_X = 30$, 2 – the furnace surface temperature.

As thermoelectric converters for TEG, 1 thermoelectric module made of a material based on *n*-

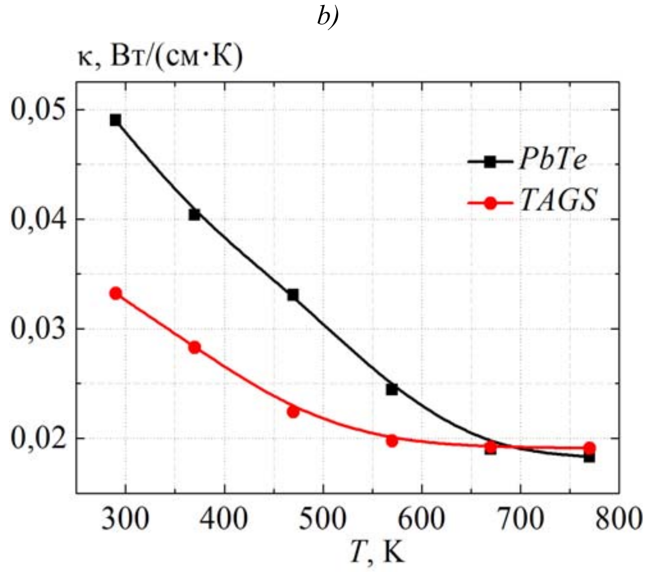
type *PbTe* and *p*-type *GeTe-AgSbTe* (TAGS) was used. The characteristics of such a material made at the Institute of Thermoelectricity of the NAS and MES of Ukraine are presented in Fig.3.



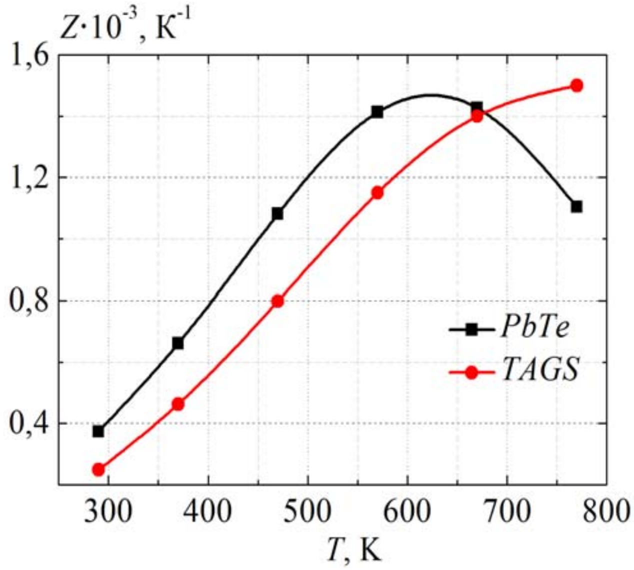
a)



b)



c)



d)

Fig. 3. Temperature dependences of thermoelectric materials based on n- PbTe and p-TAGS: a) Seebeck coefficient; b) electrical conductivity; c) thermal conductivity; d) figure of merit.

Fig. 2 shows a temporal dependence of the power of TEG located on the rear surface of the furnace for the cold side temperature of TEG T_c = 30°C (1 in Fig. 2). The hot side temperature of TEG is shown by a solid curve 2 in Fig. 2.

As can be seen from Fig.2, the type of the temporal dependence of the dynamic power in general reproduces the dependences of the furnace surface temperature. For the cold side temperature T_c=30°C, the average power of a TEG consisting of one thermoelectric module, is 13.44 W for a selected period of time. In so doing, the energy generated by the TEG per 1 hour is ~51 kJ.

Thus, the above variant of TEG made of specialized materials based on *PbTe* – TAGS allows increasing its overall power by ~ 33 % as compared to a generator using temperature stabilizers of the hot furnace surface [3].

If we analyze curve 1 in Fig. 2, it becomes clear that the output power of TEG is strongly dependent on the temperature of furnace surface. Under actual operating conditions of TEG, when the average temperatures of furnace surface are very much different from its maximum values (curve 2 in Fig. 2), this leads to considerable losses of TEG power that make up to ~ 35 %.

Therefore, in order to further improve the quality of thermoelectric generators using variable power flame heat sources on solid fuel, it is important to pursue studies aimed at seeking opportunities for a more complete use of thermal power of furnaces, in particular, development of new designs of thermoelectric converters composed of several stages matched for certain temperatures. Due to this approach, the output characteristics of TEG will be improved, which will make them more competitive and expand the possibilities of their practical use.

Conclusions

1. Based on the experimental data, the dynamic power of TEG with flame heat sources on solid fuel using specialized thermoelectric modules based on n-type *PbTe* and p-type *GeTe-AgSbTe*(TAGS) material was calculated.
2. The average power value of TEG which consists of one thermoelectric module mounted on the rear surface of the furnace, in the given time interval is 9.5 W (at its cold side temperature T_c = 30°C), which is 33 % more compared to the generator using hot temperature stabilizers of the furnace surface.
3. It was established that in the dynamic operating mode the output power of TEG is lower than its maximum values by ~ 35 %.
4. Possibilities were analyzed for quality enhancement of thermoelectric generators using variable power flame heat sources on solid fuel, in particular, due to development of new designs of thermoelectric converters consisting of several stages matched for certain temperatures.

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Анатичук Л.І., *акад. НАН Украини*[1,2]
Прибила А.В., *канд. физ.-мат. наук*[1,2]

[1]Інститут термоелектрики НАН і МОН України,
вул. Науки, 1, Чернівці, 58029, Україна;
[2]Чернівецький національний університет
ім. Юрія Федьковича, вул. Коцюбинського 2,
Чернівці, 58012, Україна, *e-mail: anatych@gmail.com*

ТЕРМОЕЛЕКТРИЧНІ ГЕНЕРАТОРИ З ПОЛУМ'ЯНИМИ ДЖЕРЕЛАМИ ТЕПЛА ЗМІННОЇ ПОТУЖНОСТІ, ОДНОКАСКАДНИМИ ТЕРМОБАТАРЕЯМИ ТА АКУМУЛЯТОРАМИ ЕЛЕКТРИЧНОЇ ЕНЕРГІЇ

У роботі виконано розрахунки динамічної потужності термоелектричного генератора з полум'яними джерелами тепла змінної потужності. Наводяться результати розрахунків такого генератора виготовленого із термоелектричного матеріалу на основі PbTe – TAGS.
Ключові слова: термоелектричний генератор, комп'ютерне проектування, фізична модель.

Анатычук Л.И., *акад. НАН Украини*[1,2]
Прибыла А.В., *канд. физ.-мат. наук*[1,2]

[1]Институт термоэлектричества НАН и МОН Украины,
ул. Науки, 1, Черновцы, 58029, Украина,
e–mail: anatych@gmail.com;
[2]Черновицкий национальный университет
им. Юрия Федьковича, ул. Коцюбинского, 2,
Черновцы, 58012, Украина

ТЕРМОЭЛЕКТРИЧЕСКИЕ ГЕНЕРАТОРЫ С ПЛАМЕННЫМИ ИСТОЧНИКАМИ ТЕПЛА ПЕРЕМЕННОЙ МОЩНОСТИ, ОДНОКАСКАДНЫМИ ТЕРМОБАТАРЕЯМИ И АККУМУЛЯТОРАМИ ЭЛЕКТРИЧЕСКОЙ ЭНЕРГИИ

В *работе выполнены расчеты динамической мощности термоэлектрического генератора с пламенными источниками тепла переменной мощности. Приведены результаты расчетов такого генератора изготовленного из термоэлектрического материала на основе PbTe – TAGS.*
Ключевые слова: термоэлектрический генератор, компьютерное проектирование, физическая модель.

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Ashcheulov A.A.

Ashcheulov A.A. *doctor of techn. scien., professor*[1],
Romaniuk I.S. *cand of techn scien.*[2]

Romaniuk I.S.

[1]Institute of Thermoelectricity of the NAS and MES of Ukraine, 1, Nauky str., Chernivtsi, 58029, Ukraine,
e–mail: anatych@gmail.com
[2]Plant Quartz, ALC, 246, Holovna str., Chernivtsi, 58000, Ukraine

DEVICE FOR NON-CONTACT EXPRESS CONTROL OF THE EFFICIENCY OF ANISITROPIC THERMOELECTRIC MATERIALS

The method is based on the determination of electric power losses during the flow of Foucault eddy currents of a thermoelectric sample placed in the field of action of the core of the inductor, through which electric currents, symmetric and asymmetric in nature, flow sequentially. The expressions for the electrical conductivity σ, the Seebeck coefficient α, the thermal conductivity κ and the figure of merit Z are determined. The proposed method allows automating the processes of monitoring and sorting of thermoelectric ingots, billets and parts. Bibl. 11, Fig. 3.

Key words: Foucault eddy current, anisotropic thermoelectric materials, thermoelectric figure of merit, symmetric and asymmetric components of electric conductivity tensor

Introduction

The main parameters of a thermoelectric material are the Seebeck coefficient α, the electrical conductivity σ and the thermal conductivity χ, as well as its figure of merit *Z* [1, 2]. At present, a sufficient number of methods for their determination are known [3, 4], including by successive measurements of the electrical conductivity of a thermoelectric sample under isothermal and adiabatic conditions [5]. However, the presence of the electrical pin contacts necessary for such measurements on the controlled samples leads to known inconveniences and additional errors.

In [6], the prospects of the eddy-current method for the case of non-contact determination of the electrical conductivity of thermoelectric materials with a relatively small error are shown, and later a real device was developed for its implementation [7].

In the present work, a description of the eddy-current method device is presented, which makes it possible to determine the main parameters of anisotropic thermoelectric materials, such as the figure of merit Z_{ii},, and the electrical conductivity σ_{ii},, as well as the design of the device for its implementation.

Brief description of the method

The physical effects of the interaction between the electromagnetic field and the test substance, which underlie the implementation of the eddy-current method for measuring the parameters of materials, are considered in [6–9]. They show that in the case of placing a controlled sample in the field of action of the core of the coil through which a current feeds an alternating asymmetric current, a magnetic field arises with induction B consisting of a variable sinusoidal (B_1) and constant (B_0) components. The variable component induces a Foucault current in the sample, each half-period of which is characterized by the presence of intrinsic induction. The interaction of these components leads to the appearance of both radial and axial components of the Ampere forces. Axial components shift the negative and positive half-periods of the Foucault currents to the upper and lower end faces of the sample, and the radial components cause a change in the effective radius of the magnetic field R_{ef}. This zonal-volume bundle of half-periods of induced current leads to a significant volume redistribution of heat fluxes caused by both the Joule ($q_{av./J}$) and Peltier ($q_{av/P}$) effects.. The implementation of the proposed method is carried out by determining the loss of electrical power in the event of eddy Foucault currents in the sample.

The integral error of this method was minimized by computer simulation of the physical processes occurring during measurements using the ComsolFenlab 3.3 software package. As a result of these studies, it was found that for thermoelectric materials based on *Cd-Sb* compounds [8], the operating frequency of the measuring sensor is in the range of 36 - 250 kHz, and the current flowing through it is subject to the inequality $q_{av./P}/q_{av./J}>10q$. The ratio of the values of the magnetic field induction and its components is selected from the condition $B_0/B > 8.6$, which also meets the conditions for the minimum effect on the parameters of the sample from the side of galvanothermomagnetic phenomena [10].

In [8], it was shown that in the presence of values of the electrical figure of merit of the measuring circuit without the sample Q_1 and in the case of symmetric and asymmetric currents (Q_2 and Q_3, respectively) with the sample it is possible to determine the average values of the symmetric and asymmetric conductivity of the material σ^c and σ: [a]

$$\sigma^{sa} = c\frac{Q_1 - Q_{2,3}}{Q_1 Q_{2,3} d\left(1 + 4\ln\frac{R_0}{R_{ef}}\right)} \tag{1}$$

According to [3], the thermoelectric figure of merit Z_{ef} is given by:

$$Z_m = \frac{\sigma_c}{\sigma^a}\frac{1}{T} \qquad (2)$$

where c is coefficient, $c = \dfrac{\pi\omega\mu_0(\mu_n^{'})^2 R_{ef} l_m}{8\mu_n^{'} S}$

d is gap width;

R_0 is radius of annular sensor;

T is temperature;

ω is circular frequency of measuring oscillating circuit

μ_0, $\mu_n^{'}$ are dynamic magnetic permeability of the sample and the ferrite core of the circuit, respectively;

l_m is average length of magnetic field line;

I_f is ferrite sensor of bias current.

In the case of anisotropic thermoelectric material whose electric conductivity tensor $\hat{\sigma}$ in the crystallographic axes [1′, 2′, 3′] coinciding with the axes of the laboratory system of coordinates [1, 2, 3], is given by:

$$\hat{\sigma} = \begin{vmatrix} \sigma_{11} & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{vmatrix} \qquad (3)$$

$$\hat{\sigma} = \begin{vmatrix} \sigma_{11} & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{vmatrix} \qquad (3)$$

If, however, the crystallographic axes 1′, 2′ are rotated about axis 3′relative to the laboratory axes 1 and 2 by certain angle φ, the electric conductivity tensor $\hat{\sigma}$ is represented as follows:

$$\hat{\sigma} = \begin{vmatrix} \sigma_{11}\cos^2\varphi + \sigma_{22}\sin^2\varphi & (\sigma_{11} - \sigma_{22})\sin\varphi\cos\varphi & 0 \\ (\sigma_{11} - \sigma_{22})\sin\varphi\cos\varphi & \sigma_{11}\sin^2\varphi + \sigma_{22}\cos^2\varphi & 0 \\ 0 & 0 & \sigma_{33} \end{vmatrix} \qquad (4)$$

and is characterized by the presence of both longitudinal $\sigma_{\parallel}$ transverse $\sigma_{\perp}$ components, where

$$\sigma_{\parallel} = \sigma_{11}\cos^2\varphi + \sigma_{22}\sin^2\varphi \qquad (5)$$

$$\sigma_{\perp} = (\sigma_{11} - \sigma_{22})\sin\varphi\cos\varphi \qquad (6)$$

Optimization of these presented values by the angle φ $\left(\frac{\partial\sigma}{\partial\varphi} = 0, \frac{\partial^2\sigma}{\partial^2\varphi} < 0\right)$ shows that their maximum is observed for σ_{11} at φ_1=45° and φ_2=135°, in which case

$$\sigma_{\parallel} = 0.5(\sigma_{11} + \sigma_{22}); \qquad (7)$$

$$\sigma_{\perp} = 0.5(\sigma_{11} - \sigma_{22}). \quad (8)$$

Therefore, non-contact measurement of the values $\sigma_{\parallel}$ and $\sigma_{\perp}$ with the symmetric and asymmetric electrical currents of measuring sensor located at the angles of φ_1=45°, φ_2=135°, respectively, makes it possible to get the following equations:

$$\sigma_{11}^{c} = 0.5(\sigma_{\parallel}^{c} + \sigma_{\perp}^{c}); \quad (9)$$

$$\sigma_{22}^{c} = 0.5(\sigma_{\parallel}^{c} - \sigma_{\perp}^{c}); \quad (10)$$

$$\sigma_{11}^{a} = 0.5(\sigma_{\parallel}^{a} + \sigma_{\perp}^{a}); \quad (11)$$

$$\sigma_{22}^{a} = 0.5(\sigma_{\parallel}^{a} - \sigma_{\perp}^{a}), \quad (12)$$

substituting (11-12) into the Harman formula [2] yields the expressions for thermoelectric figures of merit Z_{11} and Z_{22} of anisotropic thermoelectric material

$$Z_{11} = \left(\frac{\sigma_{11}^{c} + \sigma_{22}^{c}}{\sigma_{11}^{a} + \sigma_{22}^{a}} \right) \cdot T^{-1} \quad (13)$$

$$Z_{22} = \left(\frac{\sigma_{11}^{c} - \sigma_{22}^{c}}{\sigma_{11}^{a} - \sigma_{22}^{a}} \right) \cdot T^{-1} \quad (14)$$

Thus, the presented method allows for non-contact determination of the thermoelectric figures of merit Z_{11} and Z_{22} in the crystallographic axes 1′, 2′ of anisotropic thermoelectric materials.

It should be noted that the measured sample should be appropriately crystallographically oriented with respect to the given direction of the magnetic induction vector arising in the gap of the eddy-current sensor [10, 11]. It must be positioned so that the selected crystallographic axes overlap in the plane of the end face. Thermoelectric inhomogeneous materials are measured on a plane with maximum heterogeneity. The parameters of thermoelectric homogeneous materials are measured on the samples made in the form of two geometrically identical samples, one of which is a reference with known parameters, and the second is from a controlled material.

Design features of a device for non-contact determination of the efficiency Z_{ii} of anisotropic thermoelectric materials

In order to implement the proposed eddy-current non-contact method, the device presented in [1b, 7] was modernized. This device allows non-contact measurement of the average value of not only symmetric conductivity σ_c, but also asymmetric σ_a, which is necessary for further determination of the parameters of anisotropic thermoelectric materials. To do this, an additional inductance is introduced into its measuring sensor of attachable type. The direct current flowing through it creates a constant magnetic bias field in the working gap of the sensor, which forms the necessary physical processes in the bulk of the controlled sample. However, at the same time, this field also affects the characteristics of the material of the ferromagnetic core of the measuring sensor, changing its inductance and the magnitude of inductive coupling with the controlled sample. Accordingly, the resonant (working) frequency of the sensor changes, as well as its sensitivity in comparison with the same parameters at zero bias current. These changes cause a significant distortion of the measurement results of the main parameters of thermoelectric materials.

The use of measuring sensor which is schematically shown in Fig.1, allowed eliminating the dependence of its inductance on the bias current.

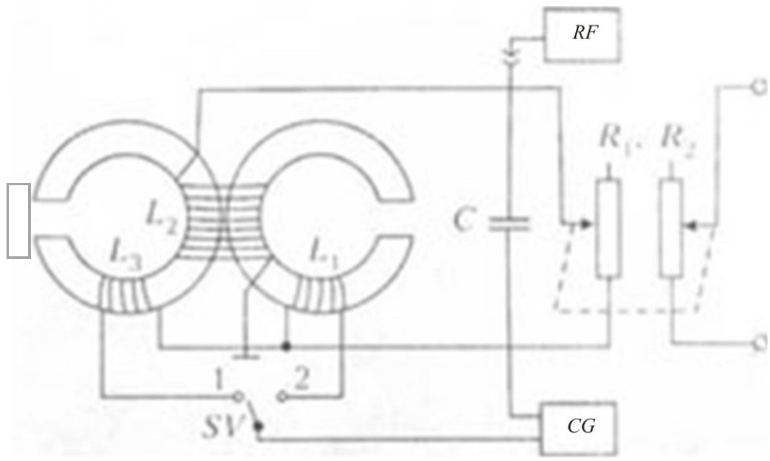

Fig. 1. Schematic of activation of the measuring sensor with magnetization

Structurally, this sensor consists of two identical ferrite rings with bias coils L_3 and L_4, electrically connected in series and back-to-back, as well as working coil L_1, wound simultaneously on the two ferrite rings. Inductances L_3 and L_4 are connected via switch *SV* to direct current generator CG, and inductance L_1, together with capacitor *C* forms a parallel oscillatory circuit connected to a high-frequency current generator *RF*, the operating frequency f_p of which is equal to the resonance frequency f_0 of the *LC*-circuit. The paired variable resistors R_1 and R_2 provide control of the heat loss introduced into the *LC*-circuit when placing the controlled sample in the operating gap of the sensor.

If the switch *SV* is in position 1, then the asymmetric conductivity σ_a is measured, and the bias field affects the parameters of both the sample and the ferrite ring with inductance L_3. When the switch *SV* is in position 2, the symmetric conductivity σ_c is measured (there is no bias field in the working gap, in which case the parameters of the ferrite ring with inductance L_4, through which the corresponding bias current flows are changed). As long as ferrite rings with inductances L_3 and L_4 are identical, and the currents through them are the same in both cases, changing the parameters of the ferrite rings at any position of the switch *SV* does not affect the inductance L_1, and, accordingly, the resonance frequency of the *LC*-circuit.

Full block-diagram of the modernized device is given in Fig. 2**.**

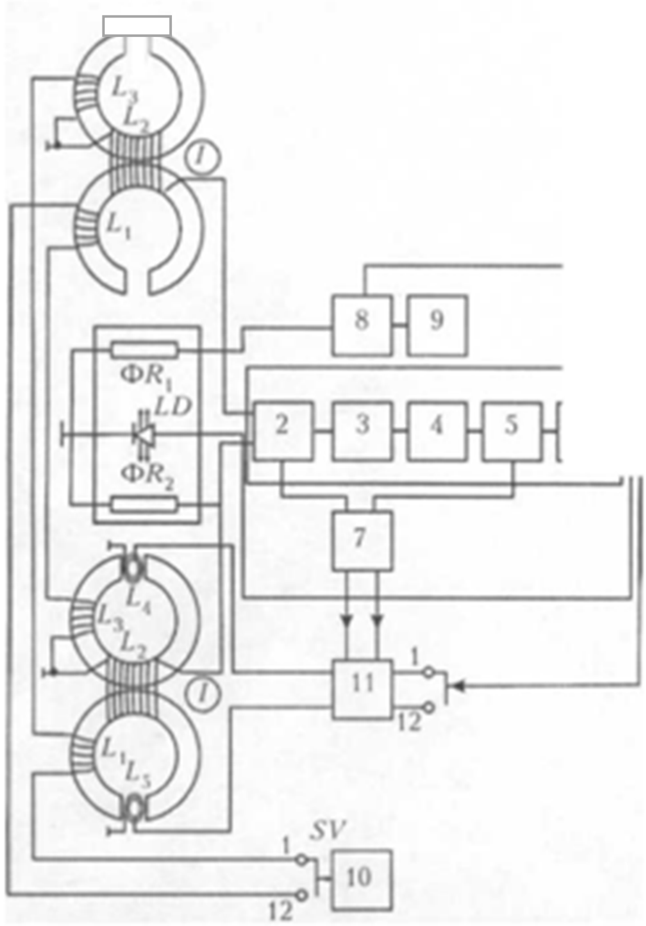

Fig. 2. Structural diagram of a device for non-contact measurement of symmetric σ_c and asymmetric σ_a conductivity of thermoelectric materials: 1, 12 – position of the switch SV; 2 – electronic switch; 3 – auto generator; 4 –AC amplifier; 5 –synchronous detector; 6 – DC amplifier; 7 – pulse generator; 8 – signal processing unit; 9 – display device; 10 – DC indicator; 11 –correction unit; ΦR_1, ΦR_2 – photoresistors

In the gap of the second sensor with inductance L_2 there are microsensors of an alternating magnetic field (in the form of special microinductances $L_5^{'}$ and $L_5^{''}$). The device contains a switch *SV* and a DC generator 10*,* similar to the device shown in Fig. 1, as well as comparing unit 11, similar to that used in [6, 7]. The output signal of this unit is proportional to a change in the sensitivity of the inductive sensor under the influence of the bias current, which is then used with the help of unit 8 to automatically correct the readings of the output device. Unit 2 is assembled according to the scheme of amplitude detectors, and unit 3 – according to the scheme of the adder.

The real work of the created device is illustrated in Fig.3 by the time diagrams of voltage on the inductances B of the sensors, as well as of magnetic field induction in the operating gap of the sensor with induction B, with and without the bias, which corresponds to positions 1 and 12 of switch SV, i.e. to the modes of measuring the asymmetric (σ_a) and symmetric (σ_c) electric conductivity.

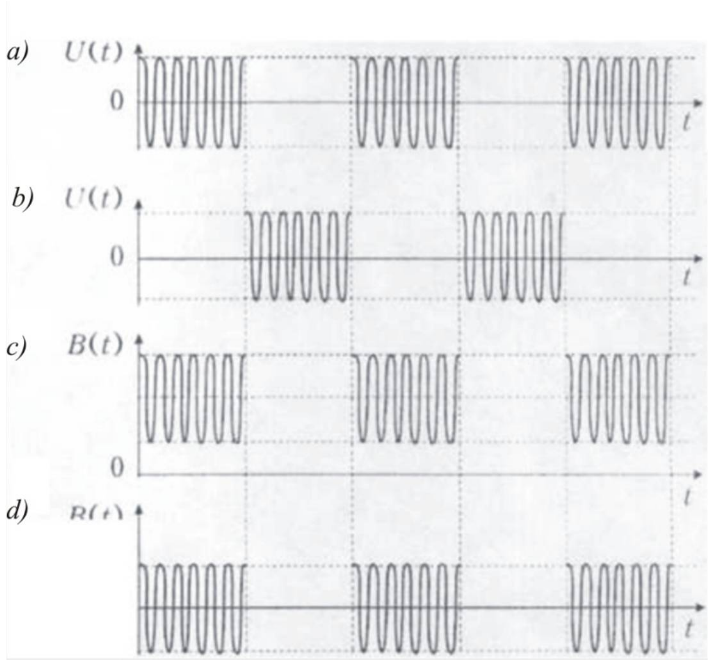

Fig. 3. Time diagrams of voltages (a, b), as well as magnetic field induction in the operating gap of sensor (a, d) without bias (a, c) and with it (b, d)

When measuring σ_c, the output signal of unit 11 through the switch *SV* comes to unit 8, which measures the resistance of photoresistor ΦR_1 and adjusts its value in conformity with the change in the sensitivity of the measuring sensor. Its use will automate the control processes for the sorting of anisotropic ingots, billets and parts.

Conclusions

Measurements of the parameters of *CdSb* samples showed that the real measurement error is 2%. The proposed eddy-current method can be successfully used for non-contact measurement of the figure of merit Z of the anisotropy of thermoelectric materials. Its use will automate the control processes for the sorting of anisotropic ingots, billets and parts.

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Ащеулов А.А. *докт. техн. наук, професор*[1],
Романюк І.С. *канд. техн. наук*[2]

[1]Інститут термоелектрики НАН і МОН України,
вул. Науки, 1, Чернівці, 58029, Україна,
e-mail:anatych@gmail.com
[2]Завод «Кварц» ТДВ, вул. Головна,
246, Чернівці, 58000, Україна

ПРИСТРІЙ ДЛЯ БЕЗКОНТАКТНОГО ЕКСПРЕС-КОНТРОЛЮ ЕФЕКТИВНОСТІ АНІЗОТРОПНИХ ТЕРМОЕЛЕКТРИЧНИХ МАТЕРІАЛІВ

Метод ґрунтується на визначенні втрат електричної потужності при протікання вихрових струмів Фуко у термоелектричному зразку, розміщеному в полі дії осердя котушки індуктивності, через яку послідовно протікають симетричний і асиметричний за характером електричні струми. Визначено вирази для коефіцієнтів електропровідності σ, термоЕРС α, теплопровідності κ та добротності Z. Запропонований метод дозволяє автоматизувати процеси контролю і розбракування термоелектричних злитків, заготовок і деталей.

Ключові слова: вихровий струм Фуко, анізотропні термоелектричні матеріали, термоелектрична добротність, симетрична і асиметрична складові тензора електропровідності

Ащеулов А.А. *докт. техн. наук, професор*[1],
Романюк И.С. *канд. техн. наук*[2]

[1]Институт термоэлектричества НАН и МОН Украины,
ул. Науки, 1, Черновцы, 58029, Украина,
e–mail: anatych@gmail.com
[2]Завод «Кварц» ТДВ, ул. Главная, 246,
Черновцы, 58000, Украина

УСТРОЙСТВО ДЛЯ БЕСКОНТАКТНОГО ЭКСПРЕСС-КОНТРОЛЯ ЭФФЕКТИВНОСТИ АНИЗОТРОПНЫХ ТЕРМОЭЛЕКТРИЧЕСКИХ МАТЕРИАЛОВ

Метод основан на определение потерь электрической мощности при протекание вихревых токов Фуко термоэлектрического образца, размещенного в поле действия сердечника катушки индуктивности, через которой последовательно протекают симметричный и асимметричный по характеру электрические токи. Определены выражения для коэффициентов электропроводности σ, термо-ЭДС α, теплопроводности κ и эффективности Z. Предложенный метод позволяет автоматизировать процессы контроля и разбраковки термоэлектрических слитков, заготовок и деталей.

Ключевые слова: вихревой ток Фуко, анизотропные термоэлектрические материалы термоэлектрическая эффективность, симметричная и асимметричная составляющие тензора электропроводности

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R.R. Kobylianskyi, *cand. phys. - math. sciences*[1,2]
Manyk O.M., *cand. phys. - math. sciences*[1,2], **V.Yu.Vyhonnyi**[2]

[1]Institute of Thermoelectricity of the NAS and MES of Ukraine,
1 Nauky str., Chernivtsi, 58029, Ukraine;
e-mail: anatych@gmail.com,
[2]Yu.Fedkovych Chernivtsi National University,
2, Kotsiubynskyi str., Chernivtsi, 58000, Ukraine

ON THE USE OF THERMOELECTRIC COOLING FOR CRYODESTRUCTION IN DERMATOLOGY

The paper provides an analysis of the current state of application of cryodestruction in dermatology, the mechanism and temperature modes of cryodestruction. The disadvantages of devices based on liquid nitrogen and the prospects for the use of thermoelectric cooling for cryodestruction in dermatology are determined. Bibl. 37.

Key words: cryodestruction, dermatology, thermoelectric cooling**.**

Introduction

It is a well-known fact in medical practice that thermal effect is an important factor in the treatment of many diseases inherent to human body [1, 2]. In recent years, a tendency has been observed to use non-drug methods of treating skin diseases. One of the trends of non-drug treatment is cryotherapy, whose mechanism of action is to stimulate the nerve endings of the skin, which improves metabolic and reparative processes and accelerates the regression of inflammatory processes in cases of chronic dermatoses. Cold activates the metabolism, helps to slow down the aging process of the skin, cleanses and facilitates its respiration, accelerates blood circulation, helps remove vital products of the body from the surface layers of the skin, and also supports muscle tone. The therapeutic effect of cold reduces skin temperature, and has anti-inflammatory, anti-allergic and analgesic effects.

One of the promising areas is cryodestruction, i.e., a method of removing various skin formations by deep freezing of biological tissues. To implement cryodestruction, it is necessary to cool a certain part of the human body down to a temperature of - 50 °C. At the present moment, such cooling is implemented with the help of special cryo-tools using nitrogen [1, 3 – 7]. However, the use of nitrogen has several disadvantages, namely, nitrogen does not ensure cooling with the required accuracy of maintaining the temperature, and there also exist risks of overcooling with negative consequences. Furthermore, liquid nitrogen is a rather dangerous substance and requires proper care when used, and the delivery of liquid nitrogen is not always available, which limits the possibility of using this method. Here the prospects for the use of thermoelectric cooling for cryodestruction step forward, since it can provide cooling down to a temperature of (0 ÷ -80) °C. Thermoelectric medical devices enable precise setting the required temperature of the working tool, the time of the thermal effect on the corresponding part of the human body and provide a cyclic change between cooling and heating modes [2].

Therefore, *the objective of the work* is to analyze the current state of the use of cryodestruction and determine the prospects for the use of thermoelectric cooling in dermatology.

Use of cryodestruction in dermatology

Cryodestruction is considered to be the most natural and physiological way to obtain necrosis [19]. In the process of cryodestruction, the pathogenic tissue is not removed during the operation, however, the tissue is destroyed by the cryothermic influence and remains in its place for a considerably long time. Cryonecrosis is gradually formed in the destroyed pathological tissue, it is partially dissolved and renewed by healthy tissues, and it can be sloughed on the surface of the human body.

As medical practice has shown, liquid nitrogen is most often used as a refrigerant for cryodestruction; it is a colorless, odorless liquid whose boiling point under atmospheric pressure is – 195 °C [5, 6].

Cryodestruction in dermatology is successfully applied in such areas as: removal of warts, skin lesions, fibromas, keratosis, hemangiomas, condylomas, colloids, basal cell carcinomas, sarcomas, solar and senile lentigo, birthmarks; destruction of unwanted formations, including viral warts, dermatofibroma, contagious molluscum, actinic and seborrheic keratosis; treatment of seborrhea and acne, eczema, dermatitis, atopic neurodermatitis, acne, as well as the treatment of other skin defects.

Cryodestruction mechanim

The problem of the effect of cold on biological tissue should be scrutinized in two different temperature ranges: above the freezing temperature of tissue fluid and below this temperature [8 - 13]. In the first case, the physiological reaction of biological tissue to a decrease in ambient temperature is considered, whereas in the second it is damage to cellular structures due to expansion of tissue fluid through its freezing (the formation of ice crystals). In various types of cells, with a decrease in temperature, the synthesis of the so-called cold shock proteins is accelerated (some tenfold), which ensures the adaptation of cells to new temperature conditions. During this adaptation, many cellular processes that practically stop due to cold shock are resumed, and the cell begins to function normally under the new conditions.

Below the freezing point, the process of freezing of the intercellular fluid begins, then intracellular icing occurs, resulting in the formation of ice crystals that move around the crystallization centers. Cryonecrosis (destruction of biological tissue) occurs gradually, while ice crystals damage (submicroscopically “cut”) cells and intracellular membranes. Blood circulation, oxygen, nutrients, tissue respiration, and all biochemical processes cease completely when frozen. As a result, the cell, in which all life processes were paralyzed for a long time, perishes. During formation of ice crystals in the tissues, a sharp increase in the osmotic pressure in the cells occurs, since the extracellular fluid freezes faster and salt cations are directed inside the cells through the membranes. Biological cells are absolutely unable to survive such osmotic shock.

Cryodestruction is widely used for the destruction of pathogenic tissues, namely tumors. In the first hours after cryosurgical operation, a spontaneous edema of the tumor and surrounding tissue occurs. The edema plays an important role in providing hemostatic characteristics of cryodestruction. In this case, the surrounding tissue is compressed by the edema, which causes the restriction in the blood circulation of the destroyed tissue area. Thus, the tumor isisolated, the metabolism stops and the intracellular pressure increases. Therefore, cryodestruction is considered to be a dissemenating method for the destruction of malignant tumors [13 – 18].

Cryodestruction temperature modes

Reducing the temperature at the border of pathological and healthy tissue must be carried out within the minimal limits required for cryogenic destruction of the entire pathological formation [5, 19]. The temperature value of cryogenic destruction of various types of tissues ranges within the limits: 0 °C - brain; -20 ÷ -30 °C - skin; -50 °C - biological tissue.

A decrease in the temperature of the biological tissue to (-5 ÷ -10) °C causes the beginning of the process of crystal formation in the extracellular space, and with a decrease in temperature to (- 15 ÷ -20) °C and below, the formation of ice crystals inside the cells begins, thus resulting in biological tissue death. It is essential to note that the mass of the ice formed occupies a volume 10% larger than that of the liquid ice crystals are formed from. [18, 19, 21]. The most damaging effect is achieved by cooling the biological tissue to -50 °C, whereas further lowering of the temperature will not increase cells lethality [5, 6, 18-28].

A slower freezing (3-5 °C/min) is not reasonable, since intracellular ice formation does not occur here. It is also irrational to use ultrafast freezing (more than 100 °C/min), since amorphous ice is formed in this case, which does not damage the structure of biological tissue [18].

The reliability of cryodestruction depends significantly not only on the cooling rate, but also on the rate of further warming, since the harmful effects of low temperatures arise both in the process of transformation of cells into ice crystals and during their thawing to normal temperature. The destruction of cells during thawing occurs with no less intensity than that during freezing, since ice thawing occurs in the process of thawing and enhances the destructive effect on living cells. By slow warming, intracellular ice crystals continue to grow and damage intracellular formations for some time. The most reliable cell destruction happens at thawing at a rate of (10-12) °C/min [18 – 22].

Repeated freezing-thawing enabled reducing the temperature lethal for pathological tissue, finding a kind of compromise between the desire to freeze the tumor focus as much as possible and the necessity to maintain surrounding tissues healthy [18 – 28].

Prospects of thermoelectric cooling application

Studies [5 – 7, 18 – 28] have confirmed that, to achieve the necessary therapeutic effect due to the effects of low temperatures, very low temperatures, i.e., those to the level of (-190) °C, inherent in liquid nitrogen, are not necessary to be applied. Significantly more moderate temperatures can be used, e.g., (0 ÷ -50) °C, and this opens up prospects for the use of thermoelectric cooling, which can ensure cooling down to a temperature of (0 ÷ -80) °C.

It should be noted that the destruction occurs not only at cooling, but also at heating the chilled tissue, where thermoelectric cooling devices can be implemented by way of reversing current through them. This creates the potential advantage of thermoelectric devices over nitrogen-based ones. The efficiency of destruction increases significantly during the performance of cyclic cooling-heating; it is also easily implemented with the use of thermoelectric devices.

Thermoelectric cooling is an effective tool for creating various thermoelectric medical devices, for dermatology in particular [29 – 35]. Structural flexibility, reliability, ease of control and the ability to accurately adjust the temperature create favourable conditions for the wide practical application of such devices in medical practice. The prospects for the use of thermoelectric cooling in dermatology are stipulated by a number of advantages [29 – 35]:

- the ability to create miniature cooling devices with an almost unlimited service life;
- the ability to control the temperature by changing the supply current through the Peltier thermoelectric module;
- the ability to visualize, maintain at a given level and control the temperature of the working tool during therapeutic treatment;
- the possibility of cyclical changes in the temperature of the working tool (-80 ÷ +50) °C according to a predetermined law in order to avoid freezing it to the skin, which increases the effectiveness of the treatment process;
- the possibility of use in pollen disease (an allergic reaction to cold), because the thermoelectric method can smoothly change the temperature of the therapeutic effect.

Thus, the use of thermoelectric cooling in dermatology is quite promising for the treatment of purulent-inflammatory processes and various skin diseases, as well as for the removal of malignant and benign skin tumors.

Conclusions

1. Thermoelectric cooling has several advantages over traditional methods of cryotherapy, namely: the ability to create controlled temperature conditions of thermal effects on human skin; the ability to control and cyclically change the temperature of the working tool by changing the supply current through the Peltier thermoelectric module; the ability to visualize, maintain at a given level and control the temperature of the working tool during therapeutic treatment.
2. From the practice of applying cryodestruction, it was found that the temperature of -50 °C is optimal for the destruction of biological tissue. Moreover, the cooling rate should be in the range of -(40-50) °C/min. Destruction efficiency improves after cyclic cooling and heating. To implement the optimal conditions for cryodestruction, thermoelectric cooling has several advantages over nitrogen. Thermoelectric devices available nowadays for cryodestruction confirm their effective use in medicine.
3. It has been established that thermoelectric cooling is promising in dermatology for the treatment of many different skin disease, such as rosacea, acne, psoriasis, neurodermatitis, prurigo, varicose forms

of lichen planus, etc.; cryomassage, stimulation of metabolism, smoothing of wrinkles and elimination of cosmetic defects of skin by cryodestruction [36, 37].

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Кобилянський Р.Р. *канд. фіз.-мат. наук*[1,2]
Маник О.М. *канд. фіз.-мат. наук*[1,2] **Вигонний В.Ю.**[2]

[1]Інститут термоелектрики НАН і МОН України,
вул. Науки, 1, Чернівці, 58029, Україна,
e-mail: anatych@gmail.com;
Чернівецький національний університет ім. Ю.
Федьковича, Чернівці, Україна

ПРО ВИКОРИСТАННЯ ТЕРМОЕЛЕКТРИЧНОГО ОХОЛОДЖЕННЯ ДЛЯ КРІОДЕСТРУКЦІЇ У ДЕРМАТОЛОГІЇ

У роботі наведено аналіз сучасного стану використання кріодеструкції у дерматології, механізм та температурні режими кріодеструкції. Визначено недоліки приладів на основі рідкого азоту та перспективи застосування термоелектричного охолодження для кріодеструкції у дерматології. Бібл. 37.

Ключові слова: кріодеструкція, дерматологія, термоелектричне охолодження.

Кобылянский Р.Р. *канд. физ.-мат. наук*[1,2]
Манык О.М. *канд. физ.-мат. наук*[1,2], **Выгонный В.Ю.**[2]

[1]Институт термоэлектричества НАН и МОН Украины
ул. Науки, 1, Черновцы, 58029, Украина, *e-mail: anatych@gmail.com;*
Черновицкий национальный университет им.
Ю. Федьковича, Черновцы, Украина

ОБ ИСПОЛЬЗОВАНИИ ТЕРМОЭЛЕКТРИЧЕСКОГО ОХЛАЖДЕНИЯ ДЛЯ КРИОДЕСТРУКЦИИ В ДЕРМАТОЛОГИИ

В работе приведен анализ современного состояния использования криодеструкции в дерматологии, механизм и температурные режимы криодеструкции. Определены недостатки приборов на основе жидкого азота и перспективы применения термоэлектрического охлаждения для криодеструкции в дерматологии. Библ. 37
Ключевые слова: криодеструкция, дерматология, термоэлектрическое охлаждение.

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L.I. Anatychuk *acad. National Academy of Sciences of Ukraine*[1,2]
A.V. Prybyla *cand. phys. - math. sciences*[1,2]
Maksymuk M.V.[1], **Rozver Yu.Yu., Romaniuk I. F.**

[1]Institute of Thermoelectricity
of the NAS and MES of Ukraine,
e-mail: anatych@gmail.com
1, Nauky str., Chernivtsi, 58029, Ukraine;
[2]Yu.Fedkovych Chernivtsi National University,
2, Kotsiubynskyi str., Chernivtsi, 58000, Ukraine

THERMOELECTRIC GENERATORS WITH VARIABLE POWER HEAT SOURCES AND THERMOSIPHONS

In this work, the dynamic power of a thermoelectric generator with variable power flame heat sources and a thermosiphon as a temperature stabilizer is calculated. The results of calculations of such a generator made of BiTe based materials are presented. Bibl. 4, Fig. 4, Tabl. 1.

Key words: thermoelectric generator, computer design, physical model, thermosiphon.

Introduction

General characterization of the problem. Solid-fuel flame heat sources, including firewood and pressed briquettes, are widely used for space heating and cooking, especially in rural and remote areas. This creates good opportunities for the use of thermoelectric converters as stand-alone sources of electricity in conjunction with such furnaces [1 – 3].

Serial production of thermoelectric generators with solid-fuel flame heat sources is carried out by many manufacturers [4, 5]. They use thermoelectric modules made of materials based on bismuth telluride with the boundary "hot" temperature of 300 ° C. However, the surface temperature of solid-fuel heat sources on which the TEG is installed also reaches 600 ° C and changes continuously over time. This leads to a decrease in the TEG life and, as a consequence, to the rapid failure of the generator. To eliminate this, the design of thermogenerator assumes the presence of a temperature stabilizer on the hot surface of the furnace, which cuts off temperatures in excess of 300 ° C. It is clear that this leads to a decrease in the electric power of the TEG, since it does not use all thermal power of the furnace.

In this paper, it is proposed to use thermosiphons as a temperature stabilizer on the working surface of a thermoelectric generator [6], which ensures optimal conditions for TEG operation.

So, the purpose of this work is to calculate the dynamic characteristics of a thermoelectric generator with variable power heat sources using a thermosiphon as a temperature stabilizer.

Physical model

A physical model of TEG [3] was used for the calculation of the main energy characteristics of solid- fuel thermogenerator with thermal stabilization of thermopile temperature.

The schematic design of the developed TEG with a heat pipe is shown in Fig. 1.

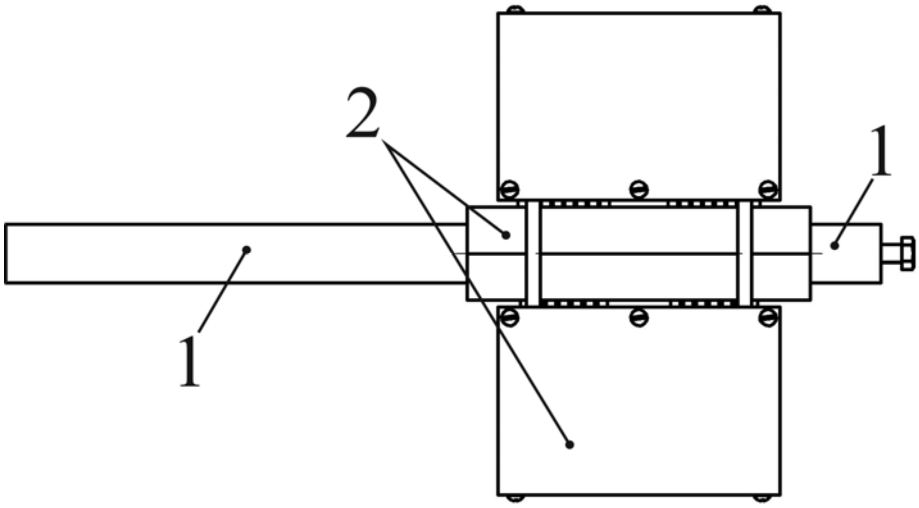

Fig.1. Schematic design of solid-fuel TEG with a heat pipe:
1 –thermosiphon; 2 – thermoelectric converter.

The main structural elements of the thermogenerator are thermosiphon 1 and thermoelectric converter 2 that are in thermal contact.

The thermoelectric converter consists of two symmetrical parts, which are heat exchangers and thermoelectric generator modules "Altec-1061" made of bismuth telluride material.

The thermogenerator operates as follows. Thermal energy from the surface of the solid-fuel furnace heats the thermosiphon evaporator, which causes the working fluid to evaporate and its vapor to move to the condensation zone, where heat transfer between the liquid vapor and the thermoelectric converter takes place. Due to heat removal, the liquid vapor condenses and returns to the evaporator zone under the influence of gravitational forces, where the heating process is repeated.

The thermal energy taken from the liquid vapor passes through the hot heat exchangers of the TEG thermal converter, heats the thermoelectric modules and is discharged into the surrounding space by air radiators. To intensify the removal of heat, fans are arranged on the air radiators.

Mathematical and computer descriptions of the model

To calculate the thermoelectric generator, the equation of heat balance is used.

On the hot side there is a heat source of variable power $Q_1[T_1(t)]$.Its thermal power depends on the temperature of this surface T_1 which, in turn, changes with time t (Fig. 3), and is given in the form of some function $f[T_1(t)]$.

$$Q_1 = f\left[\mathrm{T}_1(\mathrm{t})\right], \tag{1}$$

Heat supply from the heated surface to the hot side of the thermoelectric module and heat removal to the cold heat exchanger is described by the equations:

$$Q_1 = \chi_1[T_1(\text{t}) - T_\Gamma], \tag{2}$$

$$Q_2 = \chi_2[\text{T}_\text{X} - T_2], \tag{3}$$

where χ_1, χ_2 are thermal resistances of the hot and cold heat exchangers; T_h, T_c are the hot and cold side temperatures of thermoelectric module, respectively; T_2 is the temperature of the external surface of the cold heat exchanger.

Thermal power Q_2 is removed from the cold heat exchanger by forced convection of air to the environment:

$$Q_2 = \alpha(T_2 - T_0)S_m, \tag{4}$$

where α is coefficient of convective heat exchange between the surface of the heat exchanger and the environment; S_m is the area of heat exchange surface; T_0 is ambient temperature.

The electric power generated by thermoelectric module is proportional to Q_1 [$T_1(t)$] and its efficiency

$$W = Q_1[T_1(t)] \cdot \eta, \tag{5}$$

The main losses of heat Q_3 occur through thermal insulation:

$$Q_3 = \chi_4(T_M - T_0), \tag{6}$$

where χ_4 is thermal resistance of insulation, T_M is temperature of the internal surface of thermal insulation.

Thus, the equation of heat balance for the chosen model of thermoelectric generator can be written as:

$$Q_1 = W + Q_2 + Q_3. \tag{7}$$

For the computer representation of the TEG mathematical model, the Comsol Multiphysics software package [5] was used. For this it is necessary to present our equations in the following form.

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

$$div\vec{E} = 0 \tag{8}$$

and electric charge

$$div\vec{j} = 0, \tag{9}$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \tag{10}$$

$$\vec{q} = \kappa\nabla T + \alpha T\vec{j}, \tag{11}$$

$$\vec{j} = -\sigma\nabla U - \sigma\alpha\nabla T. \tag{12}$$

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

With regard to (10) – (12), one can obtain

$$\vec{E} = -(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T - (\alpha\sigma T + U\sigma)\nabla U. \tag{13}$$

Then the laws of conservation (8), (9) will take on the form:

$$-\nabla\left[(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T\right] - \nabla\left[(\alpha\sigma T + U\sigma)\nabla U\right] = 0, \tag{14}$$

$$-\nabla(\sigma\alpha\nabla T) - \nabla(\sigma\nabla U) = 0. \tag{15}$$

From the solution of equation (14) - (15) we obtain the distributions of physical fields, as well as the integral values of the efficiency and power of TEG.

Description of the dynamic powers of TEG

Thus, using computer methods, the dynamic powers of a TEG installed on the furnace surface were calculated (Fig. 2).

Fig. 2 shows a temporal dependence of the power of TEG located on the rear surface of the furnace for the cold side temperature of TEG T_c = 30°C (1 in Fig. 2). The hot side temperature of TEG is shown by a solid curve 2 in Fig. 2.

As can be seen from Fig. 2, the electric power of TEG with a thermosiphon is practically time-independent and equal to ~ 26 W on condition of using 4 thermoelectric modules ALTEC-22.

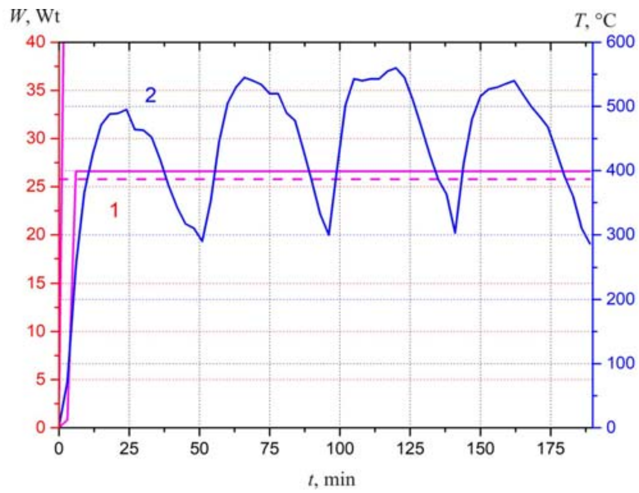

Fig. 2. Temporal dependence of the power of TEG located on the rear surface of the furnace: 1 – TEG power at T_c=30°, 2 – the furnace surface temperature.

Experimental studies of TEG

The appearance of the developed solid-fuel TEG is shown in Fig. 3.

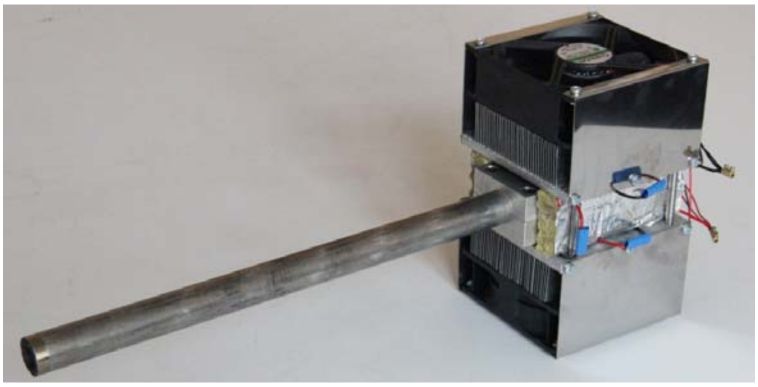

Fig. 3. Appearance of TEG with a thermosiphon

To study the thermal characteristics of heat pipe, an experimental test bench was developed which is shown in Fig. 4.

In the course of bench tests, the temperature gradient between the heating and condensation zones at heat fluxes of 560-200 W was determined. Heat was removed from the thermosiphon by heat exchange with the environment and the angle of inclination to the horizontal was regulated from 4 to 10 degrees.

To measure and control the supplied heat flux, a D5088 wattmeter with an accuracy class of 0.2 and a LATR laboratory autotransformer were used. As a heat source for a heat pipe, a resistive heater was used. To reduce the contact resistance between the surfaces of the heat pipe and the heater, a graphite film was used, and to reduce heat loss from the surface of the heating zone, basalt thermal insulation was used.

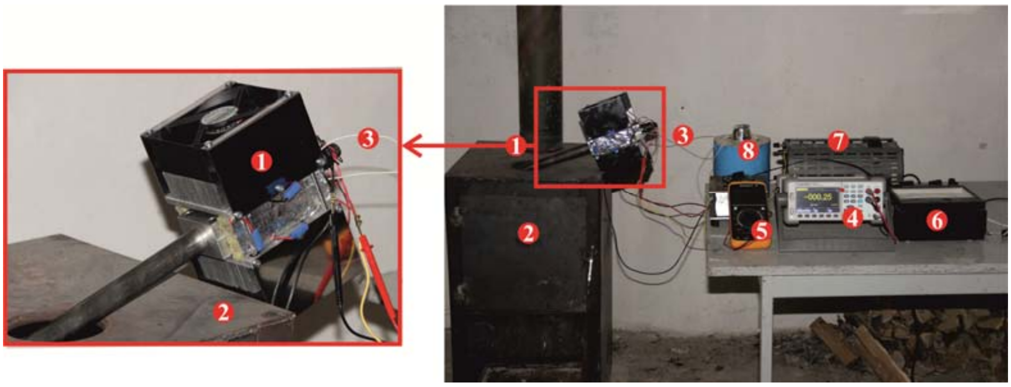

Fig.4. Experimental test bench for studying the energy characteristics of TEG with a thermosiphon: 1 – solid-fuel furnace; 2 – TEG; 3 – thermocouples; 4 – multimeter; 5 –digital voltmeter; 6 – ammeter; 7 –rheostat; 8 – dewar with ice.

The temperature distribution along the pipe was controlled by chromel-alumel (TCA) type thermocouples. The temperature measurement system is calibrated in the temperature range from -10 ° C to 700 ° C with an absolute error of ± 1.5 ° C.

Table 1

Energy characteristics of solid-fuel TEG with a thermosiphon

№	Name, measurement units	Value
1	Maximum electric power, W	21
2	Electric voltage output (without electron stabilization unit), V	6
3	Current strength, A	3.5
4	External resistance of matched load, Ohm	1.75
5	Hot side temperature of thermopile, °C	250
6	Cold side temperature of thermopile, °C	50

Thus, experimental studies of TEG with a heat pipe confirmed the main design results and create good prerequisites for the further practical use of such generators.

Conclusions

1. Based on the experimental data, the dynamic power of TEG with solid-fuel flame heat sources and a thermosiphon as a temperature stabilizer was calculated
2. The electric power for the investigated TEG version was calculated, which is ~ 26 W when using 4 thermoelectric modules ALTEC-22.

3. As a result of experimental studies, it was confirmed that the use of a thermosiphon in the design of solid-fuel thermogenerators is an effective method of stabilizing the hot side temperature of thermoelectric modules.
4. It was established that the nominal electric power of a TEG with a thermosiphon is ~ 21 W. Moreover, the use of a thermosiphon in the design of the developed TEG allows one to obtain stable temperature values on the hot side of the thermopile at a level of 250 ° C.

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Анатичук Л.І., *акад. НАН України*[1,2]
Прибила А.В., *канд. фіз.-мат. наук*[1,2]
Максимук М.В.[1], Розвер Ю.Ю.[1], Романюк І.Ф.

[1]Інститут термоелектрики НАН і МОН України,
вул. Науки, 1, Чернівці, 58029, Україна;
[2]Чернівецький національний університет
ім. Юрія Федьковича, вул. Коцюбинського 2,
Чернівці, 58012, Україна, *e-mail: anatych@gmail.com*

ТЕРМОЕЛЕКТРИЧНІ ГЕНЕРАТОРИ З ПОЛУМ'ЯНИМИ ДЖЕРЕЛАМИ ТЕПЛА ЗМІННОЇ ПОТУЖНОСТІ, ТА ТЕРМОСИФОНАМИ

У роботі виконано розрахунки динамічної потужності термоелектричного генератора з полум'яними джерелами тепла змінної потужності та термосифоном у якості

стабілізатора температури. Наводяться результати розрахунків такого генератора, виготовленого із матеріалів на основі BiTe. Бібл. 4, рис. 4, табл. 1.
Ключові слова: термоелектричний генератор, комп'ютерне проектування, фізична модель, термосифон.

Анатычук Л.И. *акад. НАН Украини*[1,2]
Прибыла А.В. *канд. физ.-мат. наук*[1,2]
Максимук Н.В.[1], **Розвер Ю.Ю.**[1], **Романюк И.Ф.**

[1]Институт термоэлектричества НАН и МОН Украины,
ул. Науки, 1, Черновцы, 58029, Украина;
[2]Черновицкий национальный университет
им. Юрия Федьковича, ул. Коцюбинського 2,
Черновцы, 58000, Украина, *e-mail: anatych@gmail.com*

ТЕРМОЭЛЕКТРИЧЕСКИЕ ГЕНЕРАТОРЫ С ПЛАМЕННЫМИ ИСТОЧНИКАМИ ТЕПЛА ПЕРЕМЕННОЙ МОЩНОСТИ, И ТЕРМОСИФОНАМИ

В работе выполнен расчет динамической мощности термоэлектрического генератора с пламенными источниками тепла сменной мощности и термосифоном в качестве стабилизатора температуры. Приводятся результаты расчета такого генератора, изготовленного из материалов на основе Bi-Te.
Ключевые слова: термоэлектрический генератор, компьютерное проектирование, физическая модель, термосифон.

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Kuz R.V. *cand. phys. - math. sciences*

Kuz R. V.

Institute of Thermoelectricity of the NAS and MES of Ukraine,
1 Nauky str., Chernivtsi, 58029, Ukraine,
e-mail: anatych@gmail.com

THERMOELECTRIC GENERATORS FOR VEHICLES. ANALYSIS OF PRACTICAL ACHIEVEMENTS

The paper presents the results of the analysis of experimental work related to the use of thermoelectric generators in conjunction with internal combustion engines in vehicles in order to obtain additional electrical energy and, accordingly, to save fuel. The progress and current state of the development of such generators are considered. Conclusions are made about the possibility and necessary conditions for the use of thermoelectric generators with internal combustion engines. Bibl. 76, Tabl. 1.

Key words: thermoelectric generator, internal combustion engine, heat recovery.

Introduction

General characterization of the problem. The use of thermoelectric generators to utilize the heat of automobile engines to generate electricity over the past three decades has remained a matter of increasing interest to the automotive industry and thermoelectricians. This is evidenced by the large number of publications, patents and conference papers [1]. This interest is understandable, as more than 2/3 of the thermal energy obtained from fuel combustion is released into the environment.

As you can see, only with exhaust gases 30-35% of thermal energy is lost. According to OPEC (Organization of Petroleum Exporting Countries), about 1.2 billion vehicles are currently registered worldwide. Its share in world oil consumption reaches 65%, or ~ 65 million barrels per day [2]. That is, ~ 1017 J of thermal energy is lost daily with the exhaust gases of vehicles. Conversion of this energy into electrical energy with an efficiency of 10% will give a value that coincides in order with the amount of electricity that is now produced by all nuclear power plants in the world [3]. This situation determines the development of thermoelectric generators for vehicles. The utilization of exhaust gas heat has two main goals. This is fuel savings and, accordingly, a decrease in carbon dioxide emissions into the atmosphere.

The beginning of the era of thermoelectric generators for vehicles can be considered to be 1961, when the **Naval Institute**, USA filed a patent for a thermoelectric generator that can operate from the heat of exhaust gases [4]. The first thermoelectric generator to use exhaust heat was introduced by the institute at the Detroit Congress of Automotive Engineering in 1963 [5].

In 1988, at the 7th International Conference on Thermoelectricity, the **University of Karlsruhe**, Germany, presented a thermoelectric generator based on $FeSi_2$ materials [6]. The generator was tested on a

160 kW Porsche 944 engine. The generator was cooled by the car's water circulation system. The following results were obtained at maximum engine power. Exhaust gas thermal power - 120 kW, gas temperature - 800 K, temperature difference - 490 K, generator electrical output power - 58 W. The decrease in gas temperature at the generator was 30 K, from which it was concluded that it is possible to use more thermoelements, which was not allowed by the dimensions of the exhaust system.

In the early 90s, on the basis of its own modules in the company **Hi-Z**, (USA) [7-26], a thermogenerator was created and tested, in which the heat of exhaust gases of a 300 hp NTC-350 diesel engine was used. It developed an electrical power of 1 kW. The exhaust gas temperature was 200-400°C.

Later, in 2004, Hi-Z, in conjunction with Delphi Systems, developed and tested a generator on a Sierra pickup with a 270 hp petrol engine. 228 watts of electricity were actually generated [27].

In 1993, Shiroki (Japan) [28] developed a thermoelectric generator for a car using Global Thermoelectric module blocks (Canada). Material of modules was Pb-Te. The generator had the shape of a cylinder with a diameter of 190 mm and a height of 180 mm. Generator weight was 5.8 kg. The generator was installed on a 2000 cm^3 petrol engine. At idle, it developed an electric power of 1 W, at a speed of 40-60 km/h on a level road 10-20 W, at a speed of 60-65 km/h at a rise of up to 130 W.

Company **Nissan Motor** (Japan) [29] in 1998 developed and tested a generator with Ge-Si thermoelectric converters. The generator is made in the form of a flat rectangular chamber with an inner shell for the passage of gases and ribbed radiators for heat dissipation from the gases. Heat removal is carried out by water passing through the outer shell. The generator was tested on a 3-liter petrol engine. At an exhaust gas temperature of 592 °C and a coolant temperature of 35 °C, the generator developed a power of 35.6 watts. The thermal power through the generator was 4 kW. In 2001, the company patented a car power supply system that contains a thermoelectric generator [30].

In the 2000s, the Komatsu company (Japan) [31] created a prototype of a TEG for a thermosyphon-type diesel engine. It contained an evaporator with a condenser that formed a thermosyphon. This achieved an intensive heat transfer from the exhaust gas to the modules. The heat was removed from the modules by water. The generator was tested on a bench that simulated the thermal conditions in the generator. Achieved 3.35 kW of electrical energy with the efficiency of modules 4.3%.

Using such modules, a generator was created, installed on a car with a petrol engine with a volume of 2000 cm^3. At a speed of 60 km / h, the generator developed 266 watts.

The study was performed within the framework of the "National Project for the Development of Advanced Thermoelectric Energy Conversion Systems".

In 2001, **Monash University** (Australia) [32-33] presented a mock-up of a thermoelectric generator made of Hi-Z modules. The source of heat was the exhaust gases from a diesel engine with a capacity of 140 kW. The total electric power of the generator was 42.3 watts. Considerations were given on the prospects of using thermoelectricity for heat recovery from internal combustion engines

At **Clarkson University**, (USA) [34-39] in 2004, a 300 W thermoelectric car generator was developed. For the generator, modules from *Hi-Z* were used. The generator was tested on a General Motors Sierra pickup truck containing a 200 kW V8 engine. The maximum value of the initial electrical power of the generator of 225.1 W was achieved at a vehicle speed of 112.65 km/h. The temperature of the hot gas was 530 ° C, the temperature of the coolant was 86.7 °C.

Company **Gentherm**, (USA) [40-56] from 2004 to 2011 at the initiative of the US Department of Energy under the program "Utilization of the type of exhaust gases" implemented a program to create a thermoelectric generator for a car. Generators have been created and installed on BMW and Ford Lincoln MKT cars. In the BMW X6, with a petrol engine capacity of 225 kW, the generator develops a maximum power of 450 watts. When driving in the city, the generator develops an average power of 200 watts. The generator for the Ford Lincoln MKT car with the petrol engine with a power of 260 kW at the maximum temperature of exhaust gases develops power about 600 W.

In 2007, the **National Institute of Advanced Industrial Technology and Science**, (Japan) [57] together with Atsumitec developed a thermoelectric material and modules based on Fe-V-Ti-Al. The modules were used in a generator mounted on a motorcycle, which developed an electric power of up to 12 watts at a speed of 60 km/h, which was quite enough to recharge the batteries.

In 2008, the **Aristotle University** (Greece) [58-59] presented the results of research on a generator for a car consisting of standard Melcor modules 2.5x2.5 cm^2. The design of the generator contains the heat-exchange equipment for heat removal from a cylindrical exhaust pipe, thermoelectric modules and an air radiator. The generator is installed on a Toyota Starlet with a 1.3-liter engine volume. The generator was installed in different parts of the exhaust pipe. The operation of the generator at different speeds of the car was studied.

The values of electrical power from 0.5 to 1.5 W are obtained. It is concluded that the installation of a series of such generators along the exhaust pipe will provide an electrical power of about 30 W. The simplest calculations of the generator are carried out, assumptions are made that the cost of the generator can be returned in the form of fuel savings within 2-3 years when the car is operated 10,000 km per year.

Research and development of a car generator was carried out at the **University of Cracow** together with the **University of Poznan** (Poland) [60-62]. In 2007, the possibilities of heat removal from exhaust gases were studied. Heat exchange systems have been developed for the 1.3-liter engine, through which up to 25 kW of thermal power was removed. It was assumed that when creating a generator with an efficiency of 5%, you can get up to 750 watts of electricity. In 2010, a thermoelectric generator for a 1.3-liter diesel engine was created. The generator has developed a maximum power of 200 watts. The thermal power of the exhaust gases was 35 kW. The hot temperature at the inlet of the generator is 290 °C.

In 2008, company **Volkswagen** (Germany) [63] presented a Volkswagen Golf Plus with a thermoelectric generator at the Thermoelektrik-Eine Chance Fur Die Atomobillindustrie conference in Berlin. Volkswagen said it received 600 watts of electricity while driving on the highway. This power is about 30% of the power required to power the car's electrical appliances.

BMW company (Germany) [64, 65] in October 2008 presented a thermoelectric generator for using heat from vehicle exhaust gases, developed in cooperation with **DLR** (German Aerospace Center). An average electrical output of 200 watts was achieved with a petrol engine of 225 kW. The maximum power of 800 W was achieved at a vehicle speed of 135 km/h.

The generator has successfully operated on motorway mileage of more than 12,000 km. Heat removal from the generator was provided by an additional cooling system. The temperature in the cold loop was 60 °C, heat was dissipated by two additional radiators located in the wheel arches. The testing of the generator was preceded by thorough theoretical calculations, measurements of temperatures and exhaust gas flow in various places of the exhaust system and in different operating modes. Further studies of the TEG were focused on achieving a specific power of 50 W/kg. (Now 25 W/kg). In 2012, the generator was demonstrated at the International Conference on Thermoelectricity ICT / ECT-2012.

Chungbuk and **Yonsei Universities** (Korea) [66-67] have carried out a number of joint works to create thermoelectric generators for hybrid cars. In 2011, a thermoelectric generator for a hybrid car with a 2-liter petrol engine was introduced. The generator developed a power of 75 watts at a car speed of 80 km/h. It is proposed to use such a generator instead of a standard car generator.

In 2012, the **FIAT Research Center** (Italy) [68] presented a prototype of a thermoelectric generator for a light truck with a 2.3 liter diesel engine. The generator developed a maximum electrical power of 1 kW at a truck speed of 130 km/h. At the same time, the temperature of the exhaust gas at the generator inlet was 450 °C. The coolant temperature was 110-130 ° C. The generator used 504 *Bi-Te*-based modules with dimensions of 16x16x6, 8 mm.

In 2014, the **Wuhan Technological University** (China) [69 – 70] presented a thermoelectric generator for a 3.9 liter petrol engine. The generator used Bi-Te modules. The dimensions of the generator were 1420x670x185 mm. With an engine power of 35 kW, the generator developed an electrical power of 390 W. Conclusions were drawn about the need to optimize the hot heat exchanger.

In the developments carried out at the **University of Hong Kong** (China) [71], special attention is paid to current and voltage converters for thermoelectric generators used in various operating modes. Various schemes and algorithms of operation of such converters are developed, in which MPPT technology - tracking of the point of maximum power – is used in transient operating mode. Conclusions are made about the possibility of increasing the efficiency of the generator by 20% using MPPT technology. Similar work is being done at the **University of Glasgow** (UK) [72].

In 2015, the **Boise University** USA [73] presented a thermoelectric generator with a maximum power of 1 kW, powered by the heat of the exhaust gases of a petrol engine. Thermoelectric generator modules are made of nanostructured semi-Heusler elements. The hot temperature at the generator inlet was 600 °C. The cold temperature was maintained at 100 °C. The gas flow was 480 g/s.

At the initiative of company **Scania** (Sweden), a study was conducted at the **University of Linköping** (Sweden) [74] to find the most suitable materials for use in a Scania truck thermoelectric generator. Together with the German company **Eberspächer Exhaust Technology**, TEG was designed and integrated into the Scania truck. The TEG truck was presented in 2015 at the International Conference on Thermoelectrics ICT / ECT-2015 in Dresden [75]. According to the test results, the TEG develops a maximum power of about 300 watts. The exhaust gas flow was 1000 kg/h at a temperature of 300 °C. The used thermal power was 18 kW. The flow of coolant was 30 l/min at a temperature of 30 °C.

In 2015, company **Friedrich Boysen GmbH** (Germany) [76] introduced a thermoelectric generator for a diesel car engine. The main emphasis in the work is given to the design of a hot heat exchanger in order to intensify heat transfer, reduce heat loss and reduce back pressure in the exhaust system. 2 types of generators were tested - with modules based on PbTe and with modules based on Bi-Te. The generator develops a maximum power of 80 W with modules based on PbTe at an inlet temperature of hot gas of 700 °C and a flow of 50 kg/h. A similar power is developed by a generator with modules based on Bi-Te at a hot gas temperature of 600 °C and a flow of 43.2 kg/h. The temperature of the cold heat exchanger was maintained at 47 °C and provided by an external cooling system.

Advances in the design and construction of thermoelectric generators for vehicles are shown in Table.

Table

Advances in the creation of thermoelectric generators for vehicles

Company	Power (engine volume	Engine type	TEG power, W	TEG efficiency, %*	TEG unit cost, $/W**	References
Karlsruhe University, Germany	160 kW	petrol	58	0.1%	-	3
Hi-Z, USA	220 kW	diesel	1000	1.1%	32	18-19
Hi-Z, USA	198 kW	petrol	228	0.3%	-	18-19
Shiroki, Japan	(2000 cm^3)	petrol	130	0.3%	-	24
Nissan Motor, Japan	(3000 cm^3)	petrol	35,6	0.1%	-	25-26
Komatsu, Japan	(2000 cm^3)	petrol	266	0.4%	-	28
Monash University, Australia	140 kW	diesel	42,3	0.1%	-	29-30
Clarkson University, USA	200 kW	petrol	225	0.3%	70	27
Gentherm, USA	225 kW	petrol	450	0.5%	-	51
Gentherm, USA	260 kW	petrol	600	0.6%	-	52
Atsumitec, Japan	-	petrol	12	-	25	72
Aristotle University, Greece	(1300 cm^3)	petrol	30	0.1%	65	73-74
Cracow University,	(1300 cm^3)	diesel	200	0.8%	-	77-79

Poland						
Volkswagen, Germany	90 kW	petrol	600	1.7%	24	75
BMW, Germany	225 kW	petrol	800	1%	29	109
Chungbuk University, Korea	(2000 cm^3)	petrol	75	0.2%	-	94-95
FIAT, Italy	(2300 cm^3)	diesel	1000	1.7%	25	87
Wuhan University, China	(3900 cm^3)	petrol	390	1.3%	30	96-97
Boise University, USA	220 kW	petrol	1000	1.4%	26	93
Scania, Sweden	220 kW	diesel	300	0.4%	-	55-56
Friedrich Boysen GmbH, Germany	90 kW	petrol	80	1.6%	23	112

* Estimates of TEG efficiency are made on the basis of the information provided in the links on the power and type of the engine on which the generator was installed, or on the basis of the specified parameters of exhaust gas.

** Estimates of the unit cost of TEG are made on the basis of the information provided in the links on the thermoelectric modules used, assuming that they constitute ~ 40% of the TEG cost.

In the "Multiannual Program for the Development of Automotive Technology" of the Department of Energy Efficiency and Renewable Energy of the US Department of Energy [121], the argumentation of the generator price (1 $/W) is formulated as follows:

"Thermoelectric devices / systems must be competitive with existing in-car power generation technologies and be available for mass production." As you can see, the unit cost of thermoelectric generators to date is much higher. This explains the lack of widespread use of TEG in cars.

The analysis gave the following results. Among the surveyed works, 15% are patents related to the use of thermoelectricity for heat recovery of internal combustion engines. The remaining 75% of papers are reports at conferences and in scientific journals. Among them:

– reviews and reports on achievements in the use of TEG for internal combustion engines;
– experimental works on the development of TEG, which are based on the use of computer simulation or simplified analytical models;
– experimental works of empirical nature, which use only the basics of design of conventional thermoelectric generators.

Conclusions

1. The created samples of generators confirm the possibility of obtaining electricity from the heat of the exhaust gases. At present, the electric power of ~ 1 kW and efficiency of ~ 1.7% have been achieved.
2. Among the developed generators there are not yet those that could be used for their industrial production. Currently, the specific cost of generators (10-60 $/W) significantly exceeds the recommended 1 $/W, which is necessary for the competitiveness of the TEG over other sources of electricity.
3. There are no studies in which the system "motor-thermogenerator" would be considered as a whole. There is no data on the influence of the thermogenerator on the engine operation, especially when heat is removed from the generator by the engine cooling system.
4. The design of automotive thermoelectric generators in all cases is empirical. The design is based on a search of different components of the model in order to find the best. However, such approaches do not reveal the general patterns that describe TEG, which reduces the possibility of finding optimal designs.

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Кузь Р. В. *канд. фіз.-мат. наук*

Інститут термоелектрики НАН і МОН України,
вул. Науки, 1, Чернівці, 58029, Україна,
e-mail: anatych@gmail.com

ТЕРМОЕЛЕКТРИЧНІ ГЕНЕРАТОРИ ДЛЯ ТРАНСПОРТНИХ ЗАСОБІВ. АНАЛІЗ ПРАКТИЧНИХ ДОСЯГНЕНЬ

У роботі наводяться результати аналізу експериментальних робіт, що стосуються використання термоелектричних генераторів у сукупності з двигунами внутрішнього згорання на автотранспорті з метою отримання додаткової електричної енергії і, відповідно, економії палива. Розглянуто розвиток і сучасний стан розробок таких генераторів. Зроблено висновки про можливості і необхідні умови для використання термоелектричних генераторів з двигунами внутрішнього згорання. Бібл. 76, табл. 1.

Ключові слова: термоелектричний генератор, двигун внутрішнього згорання, утилізація тепла.

Кузь Р.В. *канд. физ.-мат. наук*

Институт термоэлектричества НАН и МОН Украины,
ул. Науки, 1, Черновцы, 58029, Украина,
e-mail: anatych@gmail.com

ТЕОРИЯ И ПРОЕКТИРОВАНИЕ ТЕРМОЭЛЕКТРИЧЕСКИХ ГЕНЕРАТОРОВ, ИСПОЛЬЗУЮЩИХ ОТХОДЫ ТЕПЛА НА ТРАНСПОРТНЫХ СРЕДСТВАХ

В работе приводятся результаты анализа теоретических работ, касающихся использования термоэлектрических генераторов для транспортных средств с целью получения дополнительной электрической энергии и, соответственно, экономии топлива. Рассмотрены тенденции развития и современное состояние разработки таких генераторов. Библ. 76, табл. 1.

Ключевые слова: термоэлектрический генератор, двигатель внутреннего сгорания, утилизация тепла.

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Anatychuk L.I., Mykhailovsky V.Ya., Maksymuk M.V., Andrusiak I.S. Experimental research on thermoelectric automobile starting pre-heater operated with diesel fuel. *J.Thermoelectricity*. 2016. №4. P.84–94.

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