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L.I. Anatychuk, *Academician of NAS of Ukraine*
V.V. Lysko *Cand.Sc. (Phys & Math)*

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

L.I. Anatychuk *V.V. Lysko*

METHOD FOR DETERMINING THE THERMOELECTRIC PARAMETERS OF MATERIALS FORMING PART OF THERMOELECTRIC COOLING MODULES

A method for determining the thermoelectric parameters of materials forming part of thermoelectric cooling modules is proposed. A detailed physical model of this method is considered and the results of estimation of possible error values are given. The efficiency of application of various methods of error reduction is investigated. Bibl. 6, Figs. 2, Table 1.
Key words: measurement, electrical conductivity, thermoEMF, thermal conductivity, figure of merit, thermoelectric module.

Introduction

When developing thermoelectric power converters, including thermoelectric cooling modules, and when creating thermoelectric devices on their basis, module metrology plays an important role. At the same time, the accuracy of determining the parameters must be high in order to reliably record the impact of new technologies and designs on the quality of modules.

Among the existing methods for determining the parameters of thermoelectric cooling modules, the most common is the Harman method [1 – 3]. However, in this method, the parameters of the cooling module under study (cooling capacity, coefficient of performance, maximum temperature difference) are not measured, but calculated from the obtained figure of merit of the module. In this case, the temperature dependences of the material parameters are not taken into account. And since the requirement of the method is a small temperature difference on the module, the obtained figure of merit values will differ from those that will actually be in the operating mode, especially in the mode close to ΔT_{max}. The total influence of factors leading to errors in the Harman method for measuring micromodules can reach 60-70 %. Even taking them into account by introducing corrections makes it possible to reduce the errors only to 10-15 %. In so doing, it is necessary to know a lot of additional information about the properties of thermoelectric material, interconnect material, current and potential wires, ceramics, etc.

The absolute method has no such shortcomings [5]. Measurement errors by the absolute method, as well as by the Harman method, can also be high (up to 25 %). However, the peculiarity and advantage of the absolute method is that these errors can be instrumentally minimized and taken into account in the form of corrections [6].

However, such equipment is designed to determine the parameters of finished products - cooling capacity, coefficient of performance and temperature difference on the module. It can be improved to obtain information about the properties of the material in the module - thermoelectric power, electrical conductivity and thermal conductivity of a pair of thermoelectric legs. This information is useful both for optimizing the thermoelectric material for specific applications and for improving the design of the modules.

The purpose of this work is to develop a method for determining the thermoelectric parameters of materials forming part of thermoelectric cooling modules, to evaluate possible errors of this method and to determine the conditions for their minimization.

Description of method for determining the σ, α, κ, *Z* of legs material when measuring the parameters of thermoelectric cooling module

When using the absolute method to determine the parameters of a thermoelectric cooling module, the module under study is placed between a thermostatically controlled base and a heat source - an electric heater (Fig. 1). It is assumed that the side and top surfaces of the heat source, as well as the side surface of the module, are adiabatically insulated.

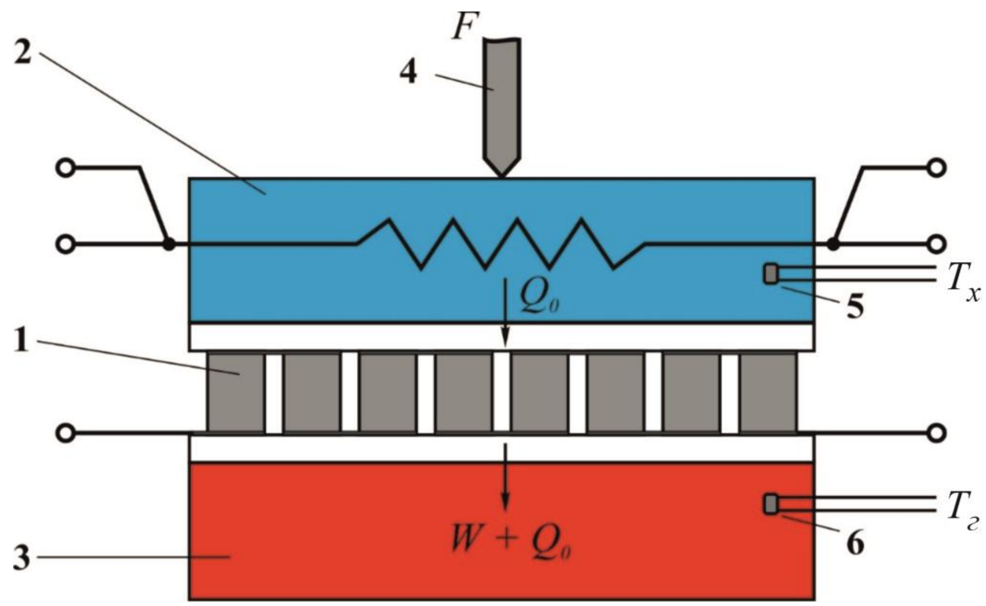

Fig. 1. Absolute method for measuring the parameters of thermoelectric cooling modules:
1 – thermoelectric module, 2 – reference heater, 3 – thermostat,
4 – clamping mechanism, 5, 6 – thermocouples.

The values of cooling capacity Q_0, temperature difference ΔT and coefficient of performance ε are determined by the formulae

$$Q_0 = I_0 \cdot U_0 , \tag{1}$$

$$\Delta T = T_{г} - T_{x} , \tag{2}$$

$$\varepsilon = \frac{Q_0}{W} , \tag{3}$$

where I_0 and U_0 is current through the heater and voltage drop thereupon, T_c is "cold" side temperature of module, T_h is "hot" side temperature of module, W is electric power consumed by the module, F is clamp.

The method for determining the average values σ, α, κ, Z of the material of legs forming part of the module is as follows:

– determination of electrical conductivity σ by the measured value of the AC resistance of the module and the known design of the module;
– creation on the module of temperature difference by means of electrical heater (with the current switched off through the module);
– determination of the Seebeck coefficient α by the measured values of module EMF and temperature difference on the module;
– determination of thermal conductivity κ by the measured values of heat flux through the module (electric heater power) and temperature difference on the module.

The average values of electrical conductivity, thermoEMF, thermal conductivity and figure of merit of the material of thermoelectric module legs are determined by the formulae

$$\sigma = \frac{1}{R_M / 2N} \frac{h_1}{a_1 \cdot b_1} , \tag{4}$$

$$\alpha = \frac{E / 2N}{\Delta T} , \tag{5}$$

$$\kappa = \frac{Q / 2N}{\Delta T} \frac{h_1}{a_1 \cdot b_1} , \tag{6}$$

$$Z = \frac{\alpha^2 \sigma}{\kappa} , \tag{7}$$

where R_M is module resistance measured on alternating current; a_1 x b_1 is the cross-section of legs; h_1 is the height of legs; N is the number of pairs; E is the EMF of module; ΔT is temperature difference between thermocouples arranged on the heat equalizing plates between which a module under study is located; Tc_0

is the temperature on heat meter located on the cold side of module; Q is heat flow through the module which is considered equal to the power of electric heater.

However, the values of σ, α, κ, Z obtained by formulae (4 – 7) will be inaccurate, since these formulae do not take into account temperature differences between the heater (cooler) and the module, temperature differences on ceramic plates and interconnect, contact and interconnect electrical resistances, heat exchange with the environment by convection, radiation through thermocouple wires and module wires.

Estimation of possible errors of the proposed method

To estimate possible values of errors, it is necessary to consider a detailed physical model of measurement, shown in Fig. 2. It contains the thermoelectric module under study, on both sides of which copper heat equalizing plates are located. On the "cold" side of the module, above the heat equalizing plate, there is an electric heater. The module, heater and plates are pressed to the base of the thermostat by means of a clamping mechanism consisting of a screw and a bar, the ends of which are fixed to the wall of the thermostat. The clamping screw has a pointed end to reduce heat leakage. The entire system is placed under the hood of a vacuum unit that provides a vacuum of 10^{-4} Pa.

Current to electrical heater is supplied through the wires, voltage drop on it is measured by additional potential wires. To determine the properties of thermoelectric material of which the module is made, by means of electrical heater a small temperature difference, about 10K, is created on the module.

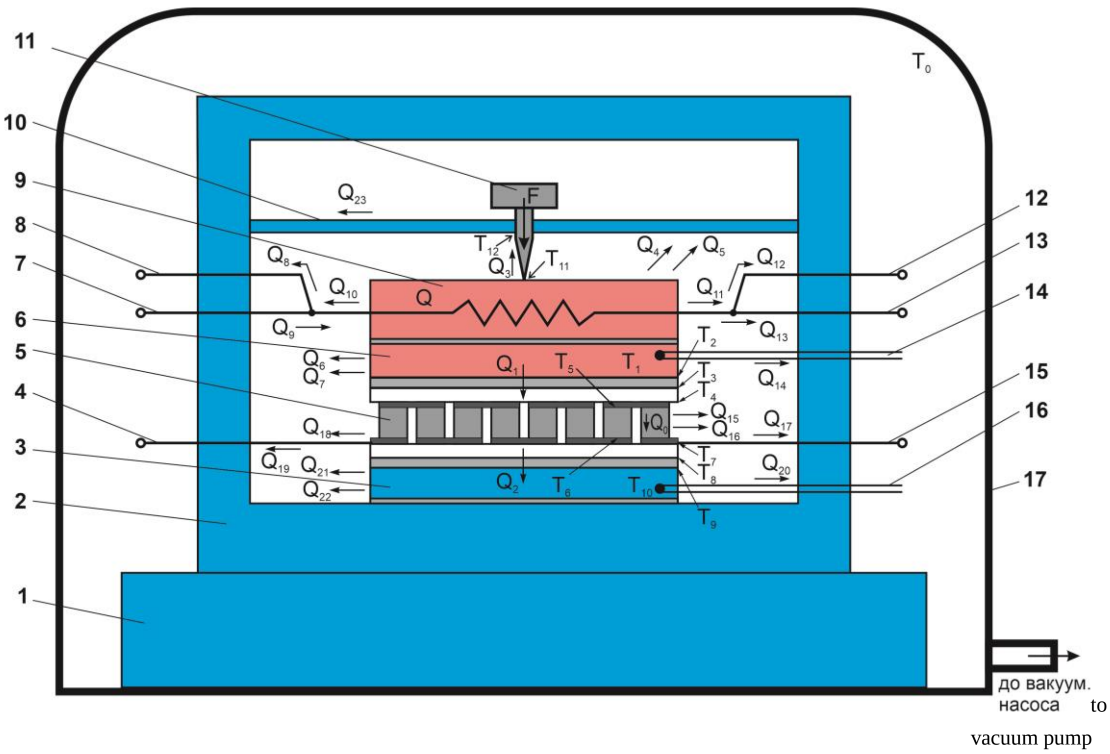

Fig. 2. Schematic of absolute method for measuring the parameters of thermoelectric cooling modules: 1 – thermostat; 2 – isothermal shield; 3, 6 – heat equalizing plates; 4, 15 – wires of module under study; 5 – module under study; 7, 13 – current heater wires; 8, 12 – potential heater wires; 9 – heater; 10 – clamping bar; 11 – clamping screw; 14, 16 – thermocouples; 17 – bell jar.

In Fig. 2: Q_1 is heat transferred from electric heater 9 to module under study 5 through heat equalizing plate 6; Q_2 is heat transferred from module 5 to heat equalizing plate 3; Q_3 is heat transferred from electric heater 9 to clamping bar 10; Q_4 is heat transferred from heater 9 to the inner surface of isothermal shield 2 by radiation; Q_5 is heat transferred from heater 9 to the inner surface of isothermal shield 2 by convection; Q_6 is heat transferred from heat equalizing plate 6 to the inner surface of isothermal shield 2 by radiation; Q_7 is heat transferred from heat equalizing plate 6 to the inner surface of isothermal shield 2 by convection; Q_8 – Q_{13} is heat transferred from heater 9 to isothermal shield 2 through current (7 and13) and potential (8 and 12) heater wires; Q_{14}, Q_{20} is heat transferred from heat equalizing plate 6 to isothermal shield 2 through thermocouple wires (14 and 16); Q_{15} is heat transferred from the lateral surface of module 5 to the inner surface of isothermal shield 2 by radiation; Q_{16} is heat transferred from the lateral surface of module 5 to the inner surface of isothermal shield 2 by convection; Q_{17}, Q_{18}, Q_{19} is heat transferred from module 5 to isothermal shield 2 through module wires (4 i 15); Q_{21} is heat transferred from heat equalizing plate 3 to the inner surface of isothermal shield 2 by radiation; Q_{22} is heat transferred from heat equalizing plate 3 to the inner surface of isothermal shield 2 by convection; Q_{23} is heat transferred from heater 9 to isothermal shield 2 through clamping bar 10, Q_0 is heat flow through module legs.

Errors in determining electrical conductivity

When determining the average value of the electrical conductivity of thermoelectric module legs, determined by formula (1), the total AC resistance of the module R_M is used, which, in addition to the resistance of the legs R_1, also includes the interconnect resistance R_2, the contact resistance R_3 and the resistance of the wires R_4

$$R_M = R_1 + R_2 + R_3 + R_4 . \quad (11)$$

To estimate possible errors, the parameters of the thermoelectric cooling module of the type Altec-CM-1-S-SQ-27-1.8x1.8-2.0 were used as an example:

- number of pairs – N = 127;
- height of legs h_1 = 2 mm;
- cross-section of legs a_1 x b_1 = 1.8 mm x 1.8 mm;
- ceramics thickness h_2 = 0.65 mm;
- ceramics area a_2 x b_2 = 40 mm x 40 mm;
- interconnect thickness h_3 = 0.5 mm;
- electrical conductivity of legs material σ = 1000 $Ohm^{-1}\cdot cm^{-1}$.

For the above values of module geometry and material properties: R_1 = 1.568 Ohm; R_2 ≈ 0.011 Ohm; R_3 = 0.078 Ohm (with the value of specific electrical contact resistance $5\cdot10^{-6}$ $Ohm\cdot cm^2$); R_4 = 0.008 Ohm (for two wires of diameter 1 mm and length15 cm); R_M ≈ 1.665 Ohm.

Therefore, the error in determining the electrical conductivity due to disregard for contact resistance will be ~ 4.7%; interconnect resistance ~ 0.7%; wires resistance ~ 0.5%. The errors associated with the accuracy of information about the geometric dimensions of the legs will be determined by the manufacturing technology of the legs and methods for their geometry control. These errors can be reduced by introducing appropriate corrections calculated for a given module design or determined experimentally.

Errors in determining thermoEMF

The errors in determining the Seebeck coefficient of the material of thermoelectric module legs will arise due to the fact that formula (5) should include not the temperature difference ($T_1 - T_{10}$) on the plates in contact with the module, but the temperature difference ($T_5 - T_6$) directly on the legs

$$\alpha = \frac{E/2N}{(T_5 - T_6)}. \tag{12}$$

Temperature difference on the legs ($T_5 - T_6$) can be found as

$$(T_5 - T_6) = (T_1 - T_{10}) - (T_1 - T_2) - (T_2 - T_3) - (T_3 - T_4) - (T_4 - T_5) - (T_6 - T_7) -$$
$$- (T_7 - T_8) - (T_8 - T_9) - (T_9 - T_{10}). \tag{13}$$

where ($T_1 - T_2$) and ($T_9 - T_{10}$) are temperature differences on the parts of heat equalizing plates between thermocouple and the surfaces of plates in contact with the "hot" and "cold" module sides; ($T_2 - T_3$) and ($T_8 - T_9$) are temperature differences on the thermal contact resistances of the "hot" and "cold" module sides; ($T_3 - T_4$) and ($T_7 - T_8$) are temperature differences on the ceramic plates of the "hot" and "cold" module sides; ($T_4 - T_5$) and ($T_6 - T_7$) are temperature differences on the interconnects of the "hot" and "cold" module sides.

To estimate the values of these differences, the value of the heat flux Q_1 passing through the module was initially estimated. Without taking into account heat losses from the module and when a temperature difference of 10 K is created on the legs, the heat flux through one leg will be 0.00324 W, and through the entire module - 0.823 W (with the thermal conductivity of the legs material κ = 2 W/(m·K). Then the temperature differences on each of the elements can be estimated as:

– $(T_1 - T_2) = \dfrac{Q_1}{\kappa_{Cu} \cdot \dfrac{a_2 \cdot b_2}{h_{Cu}}} = 0.0026K$ (with the distance between the thermocouple and the surface in contact with the module h_{Cu} = 2 mm);

– $(T_2 - T_3) = \dfrac{Q_1}{K_{конт.}} = 0.0412K$ (with the value of contact thermal resistance $K_{\text{cont.}}$ = 20 W/K);

– $(T_3 - T_4) = \dfrac{Q_1}{\kappa_{Al_2O_3} \cdot \dfrac{a_2 \cdot b_2}{h_2}} = 0.0223K$;

– $(T_4 - T_5) = \dfrac{Q_1}{\kappa_{Cu} \cdot \dfrac{2N \cdot a_1 \cdot b_1}{h_3}} = 0.0013K$ (on the assumption that heat flux Q_1 is uniformly distributed between *2N* interconnect areas with the cross-section equal to leg cross-section and the height equal to interconnect thickness);

- $(T_6 - T_7) = (T_4 - T_5) = 0.0013K$;
- $(T_7 - T_8) = (T_3 - T_4) = 0.0223K$;
- $(T_8 - T_9) = (T_2 - T_3) = 0.0412K$;
- $(T_9 - T_{10}) = (T_1 - T_2) = 0.0026K$.

Thus, the temperature difference measured by thermocouples will be ($Th_0 - Tc_0$) = 10.135 K, which is 9.1 % more than the difference on the legs. In this case, the greatest contribution to the error is made by contact thermal resistance (0.82 %) and thermal resistance of ceramic plates (0.45 %). These errors can be significantly reduced by introducing corrections determined experimentally.

Errors in determining thermal conductivity

The error in determining the thermal conductivity of the material according to formula (3) will consist of errors in determining the temperature difference on the legs (without introducing corrections ~ 1.35%, according to the calculations given in clause 2.2), errors in measuring the geometric dimensions of the legs and errors in determining the heat flux passed through the legs.

Heat fluxes from the module and the heat equalizing late ($Q_{17} - Q_{22}$) can be ignored, since they have no impact on determining the thermal conductivity of legs material by formula (6).

To reduce heat losses, all the wires and clamping mechanism must have the so-called thermal switches, which are elements of electrically insulating material, the temperature of which is maintained close to the temperature of the heater.

Transfer of heat in the gap between the legs by radiation (Q_{24})

$$Q_{24} \approx \varepsilon_1 \sigma_B S \left(T_4^4 - T_7^4 \right), \tag{14}$$

where ε_1 is the emissivity of the inner ceramic surface; σ_B = 5.67·10^{-8} W/(m^2·K^4) is Stephan-Boltzmann constant; $S = (a_1 \cdot b_1 - 2N \cdot a_2 \cdot b_2)$ is the total area of gap between the legs.

Loss of heat Q_4 from the heater by convection

$$Q_4 = H_{conv}(h_4)(2a_2 + 2b_2)\left(T_{11} - T_{екр} \right), \tag{13}$$

where H_{conv} is coefficient of convective heat exchange, h_4 is the height of the heater.

Loss of heat Q_5 from the heater by radiation

$$Q_5 = \varepsilon_4 \sigma_B (h_4)(2a_2 + 2b_2)\left(T_{11}^4 - T_{екр}^4 \right), \tag{14}$$

where ε_4 is the emissivity of the lateral surface of the heater.

Loss of heat Q_6 from the heat equalizing plate by convection

$$Q_6 = H_{conv}(h_5)(2a_2 + 2b_2)\left(T_1 - T_{екр}\right), \qquad (13)$$

where h_5 is the height of the heat equalizing plate.

Loss of heat Q_7 from the heat equalizing plate by radiation

$$Q_7 = \varepsilon_5 \sigma_B (h_5)(2a_2 + 2b_2)\left(T_1^4 - T_{екр}^4\right), \qquad (14)$$

where ε_5 is the emissivity of the lateral surface of the heat equalizing plate.

Loss of heat from the module through potential heater wires (Q_8 and Q_{12})

$$Q_8 = Q_{12} = \kappa_8 \frac{S_8}{L_8}\left(T_{11} - T_{ключа}\right), \qquad (11)$$

where: S_8 is cross-section of potential wire; L_8 is the length of potential wire; κ_8 is thermal conductivity of the potential wire material; T_{switch} is thermal switch temperature.

Loss of heat from the module through heater wires (Q_9 and Q_{13})

$$Q_9 = Q_{13} = \kappa_9 \frac{S_9}{L_9}\left(T_{11} - T_{ключа}\right), \qquad (11)$$

where: S_9 is cross-section of potential wire; L_9 is the length of potential wire; κ_9 is thermal conductivity of the potential wire material.

Loss of heat Q_{14} from thermocouple wires

$$Q_{14} = \kappa_{10} \frac{S_{10}}{L_{10}}\left(T_1 - T_0\right) + \kappa_{11} \frac{S_{11}}{L_{11}}\left(T_1 - T_{ключа}\right), \qquad (12)$$

where S_{10} and S_{11} are cross-sections of thermocouple wires; L_{10} and L_{11} are lengths of thermocouple wires; κ_{10} and κ_{11} are thermal conductivities of thermocouple wires.

Loss of heat Q_{15} from the module lateral surface by convection

$$Q_{15} \approx H_{conv}(h_1 + 2h_2 + 2h_3)(2a_2 + 2b_2)\left(\frac{T_3 + T_8}{2} - \bar{T}_{екр.}\right), \qquad (9)$$

where H_{conv} is coefficient of convective heat exchange, $\bar{T}_{екр.}$ is the average temperature of shield surface which opposite to the surface of module.

Loss of heat Q_{16} from the lateral surface of module by radiation

$$Q_{16} \approx \varepsilon_2 \sigma_B (h_1 + 2h_2 + 2h_3)(2a_2 + 2b_2)\left(\left(\frac{T_3 + T_8}{2}\right)^4 - \bar{T}_{екр.}^4\right), \qquad (10)$$

where ε_2 is the emissivity of the lateral surface of module.

The following parameters were used to calculate possible values of these heat losses: emissivity – 0.7; diameter of wires and potential heater wires – 0.2 mm; their length (before contact with the thermal switch) – 10 cm; diameter of thermocouple wires – 0.2 mm; their length (before contact with the thermal switch) – 10 cm; number of pairs – 127; legs height – 2 mm; legs cross section – 1.8 mm×1.8 mm; ceramics thickness – 0.65 mm; ceramics area – 40 mm×40 mm; interconnect thickness – 0.5 mm; heater height – 5 mm; heat equalizing plate height – 5 mm.

The results of estimating possible errors in determining the heat flux through the legs of the material, caused by heat losses through the wires of the heater and thermocouples, clamp, as well as heat losses by radiation from the surface of the heater, heat equalizing plate and module are given in Table 1. The results are obtained for the case when the temperature of the thermal switch is equal to the temperature of the heat equalizing plate T_{10}, and the temperature difference between the hot and cold plates ($T_1 - T_{10}$) is 10 K. The case of using a protective shield with a temperature that differs from the heater temperature by no more than 1K is also considered.

Table 1.

Results of estimating possible errors when determining heat flux through material legs.

№	**Name of losses**	**δ*Q*, % (the ratio of heat losses to heat flux through the legs)**	
		Without a protective shield	With a protective shield
1	Losses by radiation in the gap between the legs	3.85	3.85
2	Losses by radiation from the heater surface	11.9	1.25
3	Losses by radiation from the plate surface	3.96	0.42
4	Losses by radiation from the module surface	1.56	0.16
5	Losses in the clamp	2.77	0.28
6	Losses in heater wires	0.04	<0.01
7	Losses in thermocouple wires	<0.01	<0.01
Total:		24.08	5.96

Thus, the greatest losses are caused by radiation from the surface of the heater, module and heat plate, as well as radiation in the gap between the legs inside the thermoelectric module. In general, radiation losses account for almost 90 % of all heat losses. However, they can be drastically reduced when using a protective shield. For the case when the shield temperature differs from the heater temperature by no more than 1K, the total heat loss, hence the error in determining the heat flux through the legs of the module will not exceed 6 %. Taking into account the errors in determining the temperature difference on the legs (without introducing corrections ~ 1.35 %), the error in determining the thermal conductivity of the thermoelectric material from which the module legs are made will be up to 7.4 %.

The obtained results are the basis for the modernization of equipment for measuring the parameters of thermoelectric cooling modules.

Conclusions

1. A method is proposed for determining the thermoelectric parameters of the legs material of thermoelectric cooling module when measuring its parameters by the absolute method. A detailed physical model of this method is considered and the results of estimating possible values of errors are given by the example of a thermoelectric module of the type Altec-CM-1-S-SQ-127-1.8x1.8-2.0.
2. It is shown that, in determining the electrical conductivity, the decisive factor leading to errors of ~ 4.7 %, is failure to take into account the electrical contact resistance. The impact of the interconnect resistance will be ~ 0.7 %, the resistance of wires ~ 0.5 %. To reduce the value of these errors, appropriate corrections should be made, calculated for a given module design or determined experimentally.
3. In determining the thermoEMF, the largest contribution to the error is made by errors in determining the temperature difference on the legs caused by contact thermal resistance (0.82 %) and thermal resistance of ceramic plates (0.45 %). These errors can be also significantly reduced by making appropriate corrections.
4. When determining the thermal conductivity, apart from the errors in determining the temperature difference on the legs, an additional factor is the presence of heat losses, the total value of which, when using thermal switches and a protective shield, will be up to 7.4 %. The largest component here (up to 4 %) is heat loss by radiation in the gap between the legs. However, these losses for a known module design can be determined and taken into account in the form of corrections.

References

1. Harman T.C. (1958). Special techniques for measurement of thermoelectric properties. *J. Appl. Phys.*, 29, 1373.
2. Buist R.J. (1992). A new method for testing thermoelectric materials and devices. *XI International Conference on Thermoelectrics* (October 7-9, 1992, Arlington, Texas, USA).
3. Gromov G., Kondratiev D., Rogov A., Yershova L. (2001). Z-meter: easy-to-use application and theory. *Proc. of Sixth European Workshop on Thermoelectricity of the European Thermoelectric Society* (September 20-21, 2001, Freiburg im Breisgau, Germany).
4. Anatychuk L.I., Lysko V.V. (2012). Modified Harman’s method (2012). *AIP Conf. Proc.*, 449, 373-376.

5. Kolodner P. (2014). High-precision thermal and electrical characterization of thermoelectric modules. *Review of Scientific Instruments*, 85(5), 054901/1-054901/11.
6. Anatychuk L.I., Lysko V.V. (2014). On improvement of the accuracy and speed in the process of measuring characteristics of thermoelectric materials. *J. Electronic Materials,* 43(10), 3863-3869.

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Анатичук Л.І. *акад. 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,
e-mail: anatych@gmail.com;
[2]Чернівецький національний університет
імені Юрія Федьковича, вул. Коцюбинського 2,
Чернівці, 58012, Україна

МЕТОДИКА ВИЗНАЧЕННЯ ТЕРМОЕЛЕКТРИЧНИХ ПАРАМЕТРІВ МАТЕРІАЛІВ У СКЛАДІ ТЕРМОЕЛЕКТРИЧНИХ МОДУЛІВ ОХОЛОДЖЕННЯ

Запропоновано методику визначення термоелектричних параметрів матеріалів у складі термоелектричних модулів охолодження. Розглянуто детальну фізичну модель цієї методики та наведено результати оцінки можливих величин похибок. Досліджено ефективність застосування різних методів зниження похибок. Бібл. 6, рис. 2, табл. 1.
Ключові слова: вимірювання, електропровідність, термоЕРС, теплопровідність, добротність, термоелектричний модуль.

Анатычук Л.И. *акад. НАН Украины*
Лысько В.В. *канд. физ.-мат. наук*

[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

МЕТОДИКА ОПРЕДЕЛЕНИЯ ТЕРМОЭЛЕКТРИЧЕСКИХ ПАРАМЕТРОВ МАТЕРИАЛОВ В СОСТАВЕ ТЕРМОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ ОХЛАЖДЕНИЯ

Предложена методика определения термоэлектрических параметров материалов в составе термоэлектрических модулей охлаждения. Рассмотрена подробная физическая модель этой методики и приведены результаты оценки возможных величин погрешностей. Исследована эффективность применения различных методов снижения погрешностей. Библ. 6, рис. 2, табл. 1.

Ключевые слова: измерение, электропроводность, термоЭДС, теплопроводность, добротность, термоэлектрический модуль.

References

1. Harman T.C. (1958). Special techniques for measurement of thermoelectric properties. *J. Appl. Phys.*, 29, 1373.
2. Buist R.J. (1992). A new method for testing thermoelectric materials and devices. *XI International Conference on Thermoelectrics* (October 7-9, 1992, Arlington, Texas, USA).
3. Gromov G., Kondratiev D., Rogov A., Yershova L. (2001). Z-meter: easy-to-use application and theory. *Proc. of Sixth European Workshop on Thermoelectricity of the European Thermoelectric Society* (September 20-21, 2001, Freiburg im Breisgau, Germany).
4. Anatychuk L.I., Lysko V.V. (2012). Modified Harman’s method (2012). *AIP Conf. Proc.*, 449, 373-376.
5. Kolodner P. (2014). High-precision thermal and electrical characterization of thermoelectric modules. *Review of Scientific Instruments,* 85(5), 054901/1-054901/11.
6. Anatychuk L.I., Lysko V.V. (2014). On improvement of the accuracy and speed in the process of measuring characteristics of thermoelectric materials. *J. Electronic Materials*, 43(10), 3863-3869.

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