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INFLUENCE OF ELECTRICAL AND THERMAL RESISTANCES OF CONTACTS AND INTERCONNECTS ON THE COEFFICIENT OF PERFORMANCE OF THERMOELECTRIC MODULE

The paper describes a method for calculating the maximum coefficient of performance for a real model of a thermoelectric module, which takes into account the influence of the electrical resistance of contacts and interconnects and the thermal resistance of interconnect and insulating plates. The dependences of the maximum coefficient of performance of the module on the height of its legs and temperature difference are calculated. A comparative analysis of the coefficient of performance of a real module model with its "ideal" value, which does not take into account the influence of electrical and thermal resistances of contacts, interconnects and insulating plates, is carried out. Bibl. 7, Fig. 4, Tabl. 2.

Key words: thermoelectric cooling module, coefficient of performance, electrical contact resistance, thermal resistance of interconnect and insulating plates

Introduction

Thermoelectric cooling technology has been widely used in various spheres of human life for over 50 years due to its main advantages, such as the absence of harmful refrigerants, quiet operation, the ability to operate in any orientation in space, the ability to accurately maintain temperatures, long service life, etc. Thermoelectric devices are used for cooling, controlling thermal conditions and stabilizing the temperature of elements and systems of electronics and optoelectronics, such as photodetectors, IR radiation sensors [1], CCD matrices, laser diodes, integrated chips, microprocessors [2 – 10], LEDs [11, 12]. The thermoelectric cooling method is used in biological and medical equipment: in cryodestructors, cold-heat stimulators, mini thermostats for medicines, in biocalorimeters, spectrometers and bioanalyzers [13-18]. Household appliances with thermoelectric cooling modules are diverse, these are household air conditioners [19 – 21], portable household refrigerators, minibars for drinks, cooler bags for picnics [22 – 25]. Thermoelectric coolers (TECs) are used in the automotive and transport industries for cooling-heating seats [26, 27] and in air conditioners for vehicles [28].

It is well known that the main disadvantage of thermoelectric coolers is the low coefficient of performance compared to mechanical cooling methods. Increasing the coefficient of performance is an urgent task [29, 30]. The coefficient of performance of a thermoelectric module as the main element of the cooler depends on the figure of merit of the materials of the thermoelement legs and the electrical and thermal resistance of the contacts, inetrconnect and insulating plates of the module. These resistances lead to electrical and thermal losses in the efficiency of thermoelectric energy conversion [31, 32]. An increase in the figure of merit of materials contributes to an increase in the coefficient of performance. However, since the 1950s, cooling modules have been manufactured from materials based on Bi_2Te_3, the dimensionless figure of merit of which remains at the level of 1 – 1.2 [30]. The search for new materials with increased figure of merit has not yet yielded tangible positive results. Electrical and thermal losses in modules reduce the coefficient of performance and are one of the main reasons why thermoelectric coolers do not fully realize the properties of materials.

The works [31, 32] describe approximate analytical methods for calculating the coefficient of performance, taking into account the electrical and thermal resistances of contacts, interconnect and insulating plates in the module. It is shown that the coefficient of performance decreases if the height of the thermoelement legs is reduced.

The purpose of this work is to theoretically establish the influence of the combined action of the contact resistance, the electrical resistance of interconnects, the thermal resistance of interconnect and insulating plates on the value of the maximum coefficient of performance of the module and to determine which of the resistances more significantly affects the coefficient of performance with a decrease in the height of thermoelement legs.

Method for calculating the maximum coefficient of performance

A model of thermoelectric module is shown in Fig. 1.

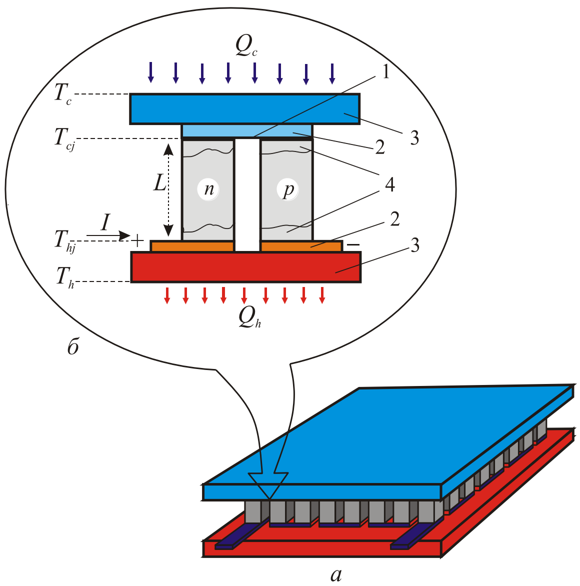


Fig. 1. A model of cooling module (a) and thermoelement (b). 1 – heat-absorbing thermoelement junction, 2 – interconnect plate, 3 – insulating plate, 4 – contact zone.

The module contains a number of thermoelements from semiconductor legs of n- and p-types of conductivity. Typically, the legs are connected in a series electrical circuit by metal plates and are mounted between two insulating plates in parallel with respect to the heat flow. If we pass an electrical current I, of indicated in Fig. 1*b* polarity, then heat is absorbed at the junctions of thermoelements 1, and is released at the opposite junctions. If the heat-releasing surface of the module is maintained at a temperature T_h close to the ambient temperature, the heat-absorbing surface will be cooled down to a certain temperature T_c.

The energy efficiency of the module is determined by the coefficient of performance

$$\varepsilon = \frac{Q_c}{W}, \tag{1}$$

where $W = Q_h - Q_c$ is power consumption, Q_c is cooling capacity, Q_h is heat productivity of each thermoelement in the module.

The following approximations were used to calculate and optimize the coefficient of performance:

1. In the stationary state, the temperature distribution in the legs of thermoelements is one-dimensional, i.e. $T = T(x)$, where x is the coordinate directed along the height of the leg.
2. The Seebeck coefficient $\alpha_{n,p}$, resistivity $\rho_{n,p}$ and thermal conductivity $\kappa_{n,p}$ of the materials of n- and p-type legs are temperature independent.
3. The influence of electrical contact resistance r_c, electrical resistance r_{com} of interconnects and thermal resistance R_t of interconnect and insulating plates is taken into account.

With such approximations, the cooling capacity Q_c and the heat productivity Q_h are determined from the system of heat balance equations for a thermoelement, which is given by

$$Q_c = \frac{1}{R_t}(T_c - T_{cj}), \tag{2}$$

$$Q_c = \alpha I T_{cj} - \left(\frac{1}{2}\rho\frac{L}{s} + \frac{2r_c}{s} + r_{com}\right)I^2 - \kappa\frac{s}{L}\left(T_{hj} - T_{cj}\right), \tag{3}$$

$$Q_h = \alpha I T_{hj} + \left(\frac{1}{2}\rho\frac{L}{s} + \frac{2r_c}{s} + r_{com}\right)I^2 - \kappa\frac{s}{L}\left(T_{hj} - T_{cj}\right), \tag{4}$$

$$Q_h = \frac{1}{R_t}(T_{hj} - T_h), \tag{5}$$

where $\alpha = |\alpha_n| + \alpha_p$, $\rho = \rho_n + \rho_p$, $\kappa = \kappa_n + \kappa_p$, L is the height of the leg, s is the cross-section of the leg, T_{cj} and T_{hj} are temperatures of the heat-absorbing and heat-releasing thermoelement junctions. The resistance of the interconnect plate is calculated by the formula $r_{com} = \frac{\rho_{com}}{l_{com}\sqrt{s}}\left(\frac{2}{3}\sqrt{s} + a\right)$ [33], and thermal resistance of the interconnect and insulating plates is determined as follows: $R_t = \frac{l_{com}}{\kappa_{com} s_{com}} + \frac{l_{ins}}{\kappa_{ins} s_{ins}}$, where ρ_{com} is resistivity of interconnect plate, κ_{com}, κ_{ins} is thermal conductivity of interconnect and insulating plates, respectively, l_{com}, l_{ins} is their height, $s_{com} = (2\sqrt{s} + a)\sqrt{s}$ is the area of interconnect plate, $s_{ins} = 2(\sqrt{s} + a)^2$ is the area of insulating plate, a is the distance between thermoelectric legs.

The temperatures T_{cj}, T_{hj} are found from Eqs. (2), (5) and are substituted into Eqs. (3), (4), the solution of which is the following expressions for Q_c, Q_h:

$$Q_c = \frac{Q_{c0} - \kappa \frac{s}{L} R_t Q_{ho}}{F_2}, \tag{6}$$

$$Q_h = \frac{Q_{h0} - Q_c \kappa \frac{s}{L} R_t}{F_1}, \tag{7}$$

where $F_1 = 1 - (\alpha I - \kappa \frac{s}{L}) R_t$, $\quad F_2 = 1 + 2\kappa \frac{s}{L} R_t - (\alpha I R_t)^2$,

$$Q_{c0} = \alpha I T_c - \left(\frac{1}{2} \rho \frac{L}{s} + \frac{2r_c}{s} + r_{com} \right) I^2 - \kappa \frac{s}{L} (T_h - T_c), \tag{8}$$

$$Q_{h0} = \alpha I T_h + \left(\frac{1}{2} \rho \frac{L}{s} + \frac{2r_c}{s} + r_{com} \right) I^2 - \kappa \frac{s}{L} (T_h - T_c). \tag{9}$$

Cooling capacity Q_c and heat productivity Q_h depend on the value of current I in thermoelement legs. Computer methods are used to calculate the optimal value of current I_{opt}, whereby the maximum coefficient of performance is achieved which is found by the formula (1).

Note that for an ideal model of module in which the influence of the electrical and thermal resistances of contacts, interconnect and insulating plates is neglected, that is $r_c \to 0$, $r_{com} \to 0$, $R_t \to 0$, formulae (6), (7) for Q_c, Q_h acquire a classical form [33]

$$Q_c = \alpha I T_c - \frac{1}{2} \rho \frac{L}{s} I^2 - \kappa \frac{s}{L} (T_h - T_c),$$

$$Q_h = \alpha I T_h + \frac{1}{2} \rho \frac{L}{s} I^2 - \kappa \frac{s}{L} (T_h - T_c),$$

which makes it possible to calculate maximum coefficient of performance by the classical formula [33]

$$\varepsilon_{\max} = \frac{MT_c - T_h}{\Delta T(M+1)}, \tag{10}$$

where $\Delta T = T_h - T_c$, $M = \sqrt{1 + 0.5Z(T_h + T_c)}$, $Z = \frac{\alpha^2}{\rho\kappa}$.

Results of calculating maximum coefficient of performance and their analysis

For the theoretical study of the influence of electrical and thermal resistance of contacts, interconnect and insulating plates on the energy efficiency of thermoelectric coolers, the maximum coefficient of performance was calculated for modules made of Bi_2Te_3 based materials. The thermoelectric parameters of the materials of n- and p-type legs were considered to be the same. Calculations are made for modules with copper interconnects of legs and with insulating plates made of aluminum oxide Al_2O_3 and aluminum nitride AlN, the thermal conductivity of which is 5 times better than that of Al_2O_3.

To analyze the impact of electrical contact resistance r_c on the maximum coefficient of performance, calculations were made for two values of r_c, namely, for the value $r_c = 5\cdot10^{-6}$ Ohm·cm^2, which is considered typical for mass production modules [34], and for the minimum value $r_c = 10^{-7}$ Ohm·cm^2 of contact resistance due to the potential barrier at the boundary between the thermoelectric material and the nickel anti-diffusion layer [35].

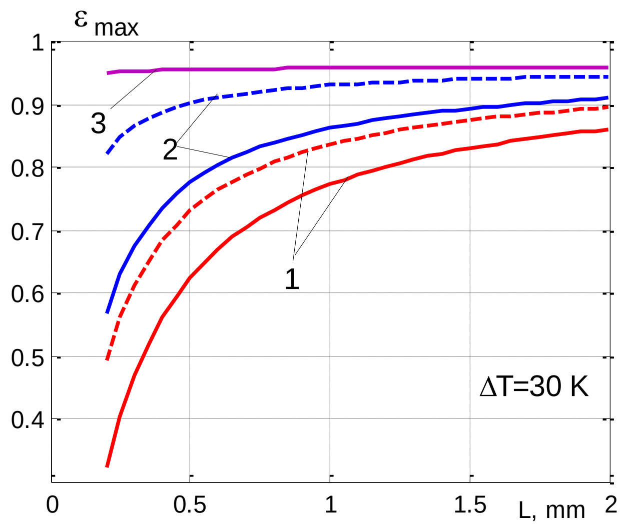
The initial data for the calculation of $\varepsilon_{\max}$ are given in Table 1.

Table 1

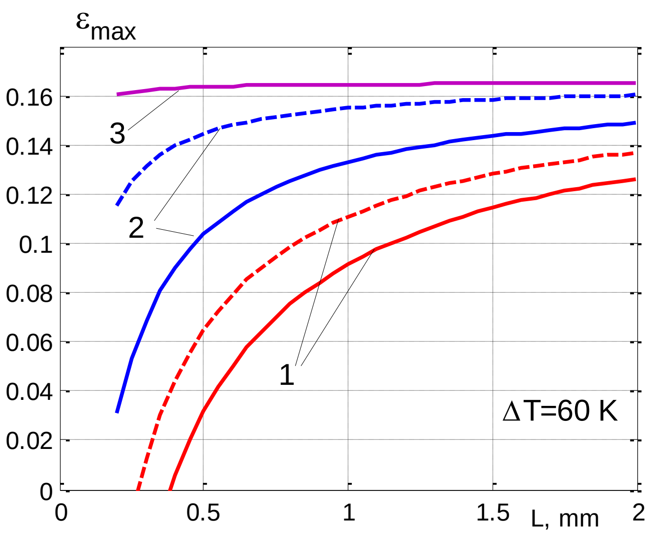
The values used for calculating maximum coefficient of performance

Quantity	Value
Seebeck coefficient α, μV/K	210
Resistivity ρ, Ohm·cm	10^{-3}
Thermal conductivity κ, W/cm·K	0.015
Height of legs L, cm	0.02 – 0.2
Cross-section of legs s, cm^2	0.1×0.1
Distance between legs a, cm	0.05
Height of interconnect plate l_{com}, cm	0.025
Height of insulating plate l_{ins}, cm	0.063

The dependences of $\varepsilon_{\max}$ on the height of thermoelement legs, calculated for the temperature differences on the module 30 K and 60 K, are shown in Fig. 2.



a)



b)

Fig. 2. Dependences of maximum coefficient of performance ε_{max} on the height L of thermoelement legs. 1 and 2 – with account of electrical resistance of contacts and interconnect plates and thermal resistance of interconnect and insulating plates of Al_2O_3 (solid lines), of AlN (dashed lines). 1 – contact resistance $r_c=5\cdot10^{-6}$ Ohm·cm^2; 2 – $r_c=10^{-7}$ Ohm·cm^2; 3 – thermal resistance is not taken into account, $r_c=10^{-7}$ Ohm·cm^2. Temperature difference $\Delta T=30$ K (a), $\Delta T=60$ K (b), $T_h=30$ °C.

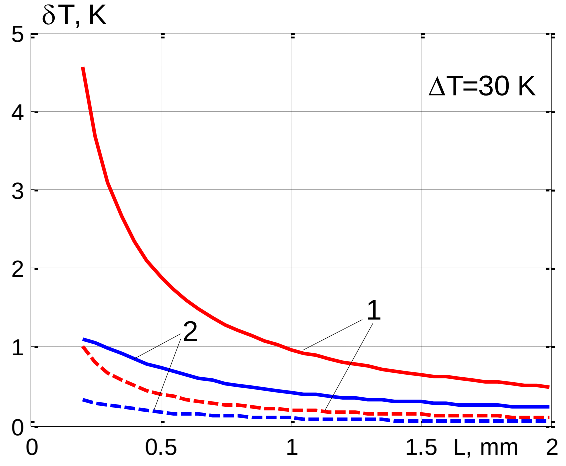
If the contact resistance is low, and the heat losses due to the thermal resistance of interconnect and insulating plates are not taken into account, then the coefficient of performance does not depend on the height of the thermoelement legs (dependence 3 in Fig. 2). These conditions correspond to the ideal model of the cooling module, and the maximum coefficient of performance can be calculated using the classical formula (10).

Note that the results of calculations of ε_{max} have shown that the electrical resistance of interconnect plates practically does not affect ε_{max}.

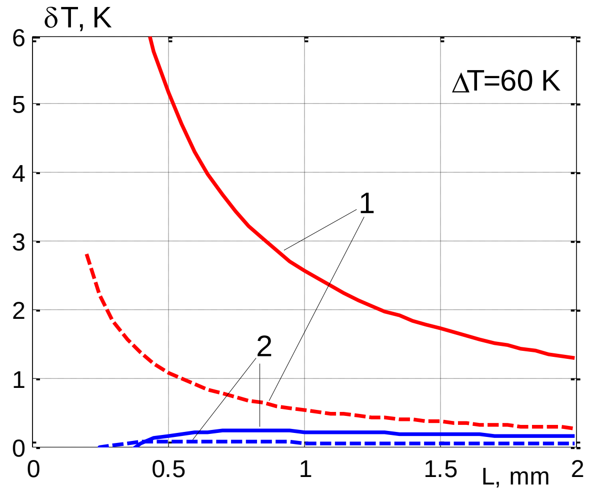
The influence of the thermal resistance of interconnect and insulating plates under the condition of both minimal (dependences 2 in Fig. 2) and real (dependences 1 in Fig. 2) contact resistance determines the dependence of ε_{max} on the height of the thermoelement legs.

A decrease in the height of the legs leads to a decrease in the coefficient of performance, which is especially noticeable during the miniaturization of thermoelements, when the height of the legs is less than 0.1 cm.

Thermal resistance is the reason for the temperature difference ΔT on interconnect and insulating plates (Fig. 3), which for miniature legs is the greater, the smaller their height. It is obvious that $\delta T_h = T_{hj} - T_h$ on the heat-releasing insulating plate will be significantly greater than $\delta T_c = T_c - T_{cj}$ on the heat-absorbing one. For modules with leg height L = 0.05 cm and Al_2O_3 insulating plates, δT_h reaches 5 degrees (Fig. 3*b*) and, accordingly, the temperature of the heat-generating junctions of thermoelements increases, which leads to a decrease in the coefficient of performance.



a)



b)

Fig.3. Dependences of temperature difference δT on interconnect and insulating plates of Al_2O_3 (solid lines), of AlN (dashed lines) on the height of thermoelement legs L. 1 – δT_h on the heat-releasing surface of thermoelements in the module, 2 – δT_c on the heat-absorbing surface. Temperature difference on the module ΔT = 30 K (a), ΔT = 60 K (b), T_h = 30 °C.

The loss of cooling efficiency can be reduced by reducing the thermal resistance of the insulating plates by using thinner plates made of materials with higher thermal conductivity, such as AlN. For insulation with AlN at L=0.05 cm, δT_h instead of 5 K will reach a value of less than 1 K (Fig. 3).

The dependence of ε_{max} on the temperature difference on the module is shown in Fig. 4. Here are the results of calculations for the modules with the height of legs L=0.2 cm and for the miniature legs with L=0.02 cm. If the legs are high, then ε_{max} of a real model of module (dependence 3, Fig. 4), which takes into account the electrical and thermal resistances of contacts, interconnect and insulating plates, is nor essentially different from ε_{max} of an ideal model (dependence 4, Fig. 4). For miniature legs this difference will be insignificant only on condition of minimum contact resistance and the use of insulating plates with high thermal conductivity (dependence 2 for AlN plates, Fig. 4). Otherwise, ε_{max} of a real micromodule will be 2–5 times less as compared to ε_0, calculated with the use of ideal model approximation. This conclusion follows from the results of calculation of the ratio $\varepsilon_0/\varepsilon_{max}$ of the coefficients of performance of the ideal and real models presented in Table 2.

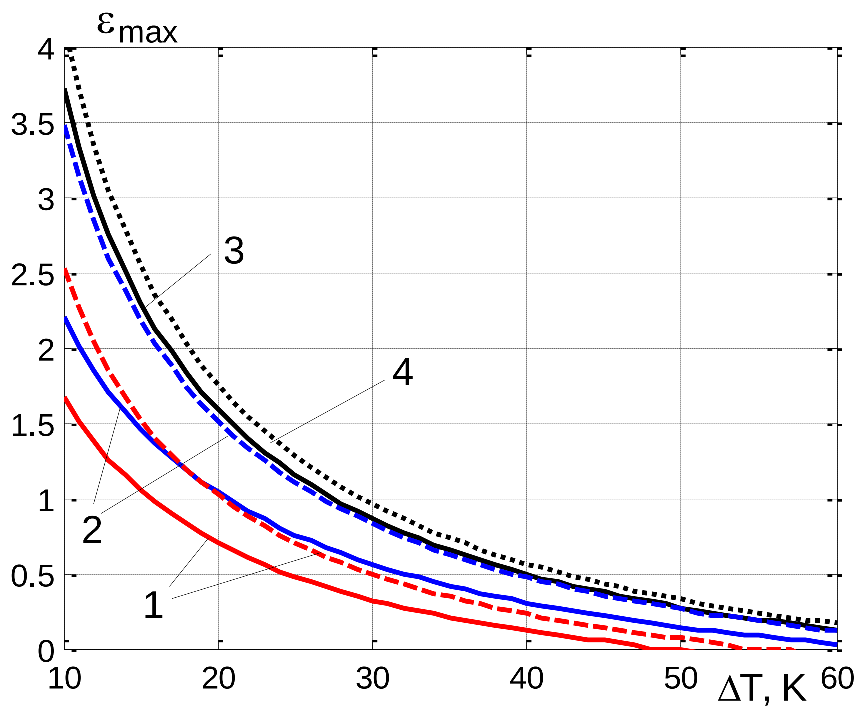


Fig.4. Dependences of maximum coefficient of performance ε_{max} on temperature difference ΔT, T_h=30 °C. 1, 2, 3 – with account of thermal losses in interconnect and insulating plates of Al_2O_3 (solid lines), of AlN (dashed lines). 1 – height of legs L=0.02 cm, contact resistance $r_c=5\cdot10^{-6}$ Ohm·cm^2; 2 – L=0.02 cm, $r_c=10^{-7}$ Ohm·cm^2; 3 – L=0.2 cm, $r_c=5\cdot10^{-6}$ Ohm·cm^2; 4 – thermal losses are not taken into account, L=0.2 cm, $r_c=10^{-7}$ Ohm·cm^2.

Table 2

Dependence of the ratio $\varepsilon_0/\varepsilon_{max}$ on the height of thermoelement legs.
ε_{max} – the value of coefficient of performance with account of electrical and thermal losses in the contacts with resistance r_c and in copper interconnect and insulating plates of Al_2O_3, ε_0 – the value of coefficient of performance for an ideal model of module with no account of the losses.

Height of legs L, cm	$\varepsilon_0/\varepsilon_{max}$ With account of only electrical losses in the contacts $r_c=10^{-7}$ Ohm·cm^2	$\varepsilon_0/\varepsilon_{max}$ With account of electrical and thermal losses $r_c=10^{-7}$ Ohm·cm^2	$\varepsilon_0/\varepsilon_{max}$ With account of only electrical losses in the contacts $r_c=5\cdot10^{-6}$ Ohm·cm^2	$\varepsilon_0/\varepsilon_{max}$ With account of electrical and thermal losses $r_c=5\cdot10^{-6}$ Ohm·cm^2
Temperature difference on the module ΔT=10 K, ε_0=4.15				
0.2	1.0	1.08	1.04	1.12
0.15	1.0	1.10	1.06	1.16
0.1	1.002	1.16	1.08	1.24
0.05	1.003	1.32	1.17	1.51
0.02	1.008	1.89	1.43	2.48
Temperature difference on the module ΔT=30 K, ε_0=0.96				
0.2	1.00	1.06	1.06	1.12
0.15	1.001	1.08	1.08	1.16
0.1	1.002	1.12	1.12	1.24
0.05	1.004	1.24	1.24	1.54
0.02	1.01	1.71	1.69	2.99
Temperature difference on the module ΔT=60 K, ε_0=0.17				
0.2	1.00	1.11	1.17	1.31
0.15	1.004	1.15	1.24	1.45
0.1	1.006	1.25	1.39	1.81
0.05	1.01	1.60	2.08	5.24
0.02	1.03	5.37	-	-

Here are the calculation data of the ratio $\varepsilon_0/\varepsilon_{max}$, the analysis of which also shows that the module efficiency losses with a decrease in the height of the thermoelement legs, which are caused by the thermal resistance of interconnect and insulating plates, are commensurate with the losses caused by the electrical contact resistance.

Thus, for the design of cooling modules with legs less than 1 mm high, it is important to take into account both the electrical contact resistance and the thermal resistance of interconnect and insulating plates. For modules with legs larger than 0.15 cm, an ideal model can be used that does not take into account the influence of electrical and thermal losses in energy efficiency.

Conclusions

1. The calculation and analysis of the maximum coefficient of performance, carried out on the basis of a real model of the cooling module, taking into account the influence of the electrical contact resistance and the electrical and thermal resistances of interconnect and insulating plates, allow us to draw the following conclusions:
2. The coefficient of performance depends on the height of thermoelement legs. The lower the height of the legs, the lower is coefficient of performance. For temperature differences less than 40 K, the coefficient of performance of modules with insulating plates made of Al_2O_3 and legs made of Bi_2Te_3 based materials with the height of 0.05 cm reaches only 65 % of its "ideal" values, which does not take into account the influence of electrical and thermal resistances, and for ΔT = 60 K this will be only 19 %. At the same time, for modules with a leg height 0.2 cm this figure is 90 %.
3. The greater the electrical contact resistance and thermal resistance of interconnect and insulating plates, the more significantly the coefficient of performance decreases with a decrease in the height of the legs. In so doing, the decrease in the coefficient of performance due to thermal resistance is commensurate with its decrease as a result of the impact of electrical contact resistance.
4. The energy efficiency of the modules can be improved by applying manufacturing technologies that minimize contact resistance [35] and by using insulating plates made of highly thermally conductive materials, such as AlN instead of Al_2O_3. The coefficient of performance of such modules will not significantly depend on the height of the legs and will approach its "ideal" value.

References

1. Anatychuk L.I., Vikhor L.M. (2013). The boundaries of thermoelectric cooling for photodetectors. *J.Thermoelectricity*, 5, 58–63.
2. Vainer A.L., Moiseev V.F. (2000). *Sovmeshchennyie pribory kriotermoelektricheskoi elektroniki [Combined devices of cryothermoelectric electronics]*. Odessa: Negotsiant studio [in Russian].
3. Mansour K., Qiu Y., Hill C.J., Soibel A., Yang R.Q. (2006). Mid-infrared interband cascade lasers at thermoelectric cooler temperatures. *Electron. Lett*. 42 (18), 1034-1036.
4. Chein Reiyu, Huang Guanming (2004). Thermoelectric cooler application in electronic cooling, *Appl. Therm. Eng*., 24, 2207-2217.
5. Zhou Yuanyuan, Yu Jianlin (2012). Design optimization of thermoelectric cooling systems for applications in electronic devices. *Int. J. Refrig*. 35,1139-1144.

6. Zhang H.Y., Mui Y.C., Tarin M. (2010). Analysis of thermoelectric cooler performance for high power electronic packages. *Appl. Therm. Eng*. 30, 561-568.
7. Phelan Patrick E., Chiriac Victor A., Tom Lee Tien-Yu (2002). Current and future miniature refrigeration cooling technologies for high power microelectronics. *IEEE Trans. Compon. Packag. Technol.* 25 (3).

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ВПЛИВ ЕЛЕКТРИЧНИХ ТА ТЕПЛОВИХ ОПОРІВ КОНТАКТІВ І КОМУТАЦІЙ НА ХОЛОДИЛЬНИЙ КОЕФІЦІЄНТ ТЕРМОЕЛЕКТРИЧНОГО МОДУЛЯ

В роботі описаний метод розрахунку максимального холодильного коефіцієнта для реальної моделі термоелектричного модуля, яка враховує вплив електричного опору контактів та комутацій і теплового опору комутаційних та ізоляційних пластин. Розраховані залежності максимального холодильного коефіцієнта модуля від висоти його віток і перепаду температур. Проведено порівняльний аналіз холодильного коефіцієнта реальної моделі модуля з його “ідеальним” значенням, яке не враховує вплив електричних і теплових опорів контактів, комутаційних та ізоляційних пластин. Бібл. 7, рис. 4, табл. 2.

Ключові слова: термоелектричний охолодний модуль, холодильний коефіцієнт, електричний контактний опір, тепловий опір комутаційної та ізоляційної пластин

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ВОЗДЕЙСТВИЕ ЭЛЕКТРИЧЕСКИХ И ТЕПЛОВЫХ СОПРОТИВЛЕНИЙ КОНТАКТОВ И КОММУТАЦИЙ НА ХОЛОДИЛЬНЫЙ КОЭФФИЦИЕНТ ТЕРМОЭЛЕКТРИЧЕСКОГО МОДУЛЯ

В работе описан метод расчета максимального холодильного коэффициента для реальной модели термоэлектрического модуля, учитывающей влияние электрического сопротивления контактов и коммутаций и теплового сопротивления коммутационных и изоляционных пластин. Рассчитаны зависимости максимального холодильного коэффициента модуля от высоты его ветвей и перепада температур. Проведен сравнительный анализ холодильного коэффициента реальной модели модуля с его "идеальным" значением, не учитывающим влияние электрических и тепловых сопротивлений контактов, коммутационных и изоляционных пластин. Библ. 7, рис. 4, табл. 2.

Ключевые слова: термоэлектрический охлаждающий модуль, холодильный коэффициент, электрическое контактное сопротивление, тепловое сопротивление коммутационной и изоляционной пластин

References

1. Anatychuk L.I., Vikhor L.M. (2013). The boundaries of thermoelectric cooling for photodetectors. *J.Thermoelectricity*, 5, 58–63.
2. Vainer A.L., Moiseev V.F. (2000). *Sovmeshchennyie pribory kriotermoelektricheskoi elektroniki [Combined devices of cryothermoelectric electronics]*. Odessa: Negotsiant studio [in Russian].
3. Mansour K., Qiu Y., Hill C.J., Soibel A., Yang R.Q. (2006). Mid-infrared interband cascade lasers at thermoelectric cooler temperatures. *Electron. Lett*. 42 (18), 1034-1036.
4. Chein Reiyu, Huang Guanming (2004). Thermoelectric cooler application in electronic cooling, *Appl. Therm. Eng*., 24, 2207-2217.
5. Zhou Yuanyuan, Yu Jianlin (2012). Design optimization of thermoelectric cooling systems for

applications in electronic devices. *Int. J. Refrig*. 35,1139-1144.

6. Zhang H.Y., Mui Y.C., Tarin M. (2010). Analysis of thermoelectric cooler performance for high power electronic packages. *Appl. Therm. Eng*. 30, 561-568.
7. Phelan Patrick E., Chiriac Victor A., Tom Lee Tien-Yu (2002). Current and future miniature refrigeration cooling technologies for high power microelectronics. *IEEE Trans. Compon. Packag. Technol.* 25 (3).

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