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Using the test method for optimization the Peltier device for achievement superconducting transition temperatures

***Abstract**: A new method for determining electric and thermal characteristics of Peltier devices is analyzed with the aim of optimization of Peltier devices. Obtained results give the possibility to optimize thermoelectric cooler systems to reach most efficient operating state and to achieve the lowest possible temperature. In optimized by proposed method four stage Peltier cooling cascade the achieved temperature could be near to the superconducting transition temperature of $HgBa_2CaCu_2O_{6+\delta}$. Peltier device is not damaged during the test process and still can be used.*

Streszczenie:** W artykule przeanalizowano nową metodę wyznaczania elektrycznych oraz termicznych parametrów ogniw Peltiera. Otrzymane wyniki dają możliwość optymalizowania chłodziarek termoelektrycznych w celu osiągnięcia najbardziej efektywnego punktu pracy. W czterostopniowej chłodziarce termoelektrycznej zoptymalizowanej przy użyciu proponowanej metody otrzymana temperatura może być bardzo bliska temperaturze nadprzewodnictwa $HgBa_2CaCu_2O_{6+\delta}$. Badany element Peltiera nie ulega uszkodzeniu podczas testu i może być dalej używany.* ***(Wykorzystanie metody badań ogniw Peltiera do optymalizacji ich punktu pracy w celu osiągania temperatur nadprzewodnictwa)

Keywords: *thermoelectric coolers, thermoelectric properties, Peltier device, test method of Peltier device, superconductor temperature*
Słowa kluczowe: *chłodziarki termoelektryczne, moduł termoelektryczny, charakterystyki ogniw Peltiera*

Introduction

Thermoelectric modules are widely used in military equipment, aeronautics and industry. They owe their popularity to simple construction without any mechanical elements, that increases the reliability. Peltier cooling devices have special place in superconductor electronics. Superconducting microelectronic circuits are largely miniaturized and only a small cooling power of the order of milliwatts is needed. In multi-stage thermoelectric coolers the temperature as low as 149 K can be reached [1,2]. This temperature approaches the superconducting transition temperature of 124 K which can be achieved in thin films of $HgBa_2CaCu_2O_{6+\delta}$ However, the designing of high performance cooling systems or thermoelectric generators is very difficult because the characteristics of modules provided by manufactures do not fit the required cooling levels [3,4]. The optimization of cooling or generating systems, based on ΔT_{max}, I_{max} or Q_{max} , is hard to realize.

In this article, the new concept for testing method of the Peltier devices [5] is analyzed. The proposed method allows determining Peltier device characteristics [6], including thermal and thermoelectric material characteristics and electric resistance without affecting the device structures, unlike classic methods do [7-11]. The accuracy of different versions of the method was analyzed and the most accurate version was chosen. The results obtained from the proposed method give the possibility to optimize the thermoelectric cooler systems towards the most efficient operating state.

Method

In the experimental setup, the thermoelectric module is placed between a heat source (1) and a cooler (5), that causes heat flux through the tested element. The temperatures T_{h0} and T_{c0}, the heat flux Q_0, the electromotive force E_0 and the current I_0 (generated immediately after the circuit is shortened) are measured when the thermoelement approaches a thermally stable state. After the measurements are conducted, the circuit is shorted and I_0 is measured with an ammeter of the lowest available resistance. Then, a change in the temperature distribution inside the Peltier device, caused by Peltier effect, takes place. When the Peltier device reaches a new thermally stable state, the temperatures T_{hz} and T_{cz}, the current I_z , the heat flux Q_z and the voltage E_z (generated immediately after the circuit is opened) are measured.

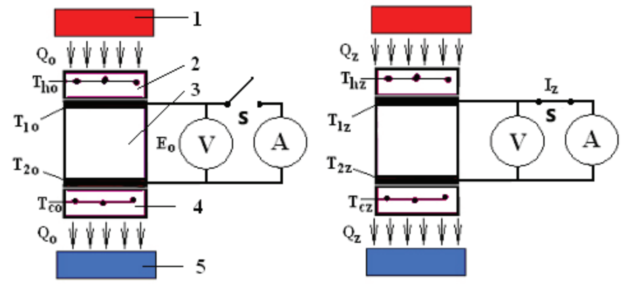

Fig. 1. The test system for Peltier device: 1 - electric heater; 2, 4 - heat conducting and temperature equalizing plates; 3- the Peltier device under test; 5 – cooler; V – voltmeter; A-ammeter; K-switch

The basic principle of the proposed method is that the heat fluxes through the surfaces at temperatures T_h and T_c are equal when no external electric load is inserted into the circuit. There are two states of the Peltier device which meet abovementioned condition: when the electrical circuit, fed from the device, is shorted, and when it is opened.

For a single thermoelectric element of Peltier device, the heat equation can be written as follows:

$$Q_{h,c} = \frac{(T_1 - T_2)}{\psi_p} + AIT_{1,2} \mp \frac{1}{2} RI^2 , \qquad (1)$$

where $Q_{h,c}$ are the heat fluxes on the hot and cold sides respectively, T_1 and T_2 are the temperatures at the contact points between thermoelectric material and copper connectors, Ψ_p is the thermal resistance of thermoelectric material, A is the real electromotive force, I is the current, R is the electric resistance of the Peltier device (the true electric resistance of the thermoelectric material added to the electric resistance of the contact layer R_c).

$$R = nh\left(\frac{\rho_n}{s_n} + \frac{\rho_p}{s_p}\right) + R_c . \qquad (2)$$

n is the number of semiconductor blocks, h is the height of semiconductor blocks, ρ is resistivity, s is the cross-section area of semiconductor blocks.

When the circuit is short, and assuming that mutual dependence of heat fluxes can be applied and written down using average values of thermoelectric material properties, the following set of equations can be written:

(3)
$$\begin{cases} Q_z = (T_{hz} - T_{1z})/\psi_t \\ Q_z = (T_{1z} - T_{2z})/\psi_p + I_z A T_{1z} - I_z^2 R/2 \\ Q_z = (T_{1z} - T_{2z})/\psi_p + I_z A T_{2z} + I_z^2 R/2 \\ Q_z = (T_{2z} - T_{cz})/\psi_t \\ I_z = E_z/R \\ E_z = A(T_{1z} - T_{2z}) \end{cases}$$

where Ψ_t is the total thermal resistance of copper connections, contact surfaces adjacent to the structure of a heating or cooling system at the level of temperature measurement points T_h or T_c. From equations (3) the following relationship can be obtained:

(4)
$$Q_0 = \frac{\Delta T_0}{\psi_p + 2\psi_t},$$

(5)
$$E_0 = A Q_0 \psi_p,$$

where $\Delta T_0 = T_{h0} - T_{c0}$.

Taking into account that, $\overline{T}_z=(T_{hz}+T_{cz})/2=(T_{1z}+T_{2z})/2$ for heat fluxes in the contact point between the thermoelectric material and the copper connection layer, the following formula can be written:

(6)
$$Q_z = \frac{E_z Q_0}{E_0} + I_z A \overline{T}_z.$$

From the aforementioned equations, one can obtain:

- for the true electromotive force:

(7)
$$A = \left(\frac{Q_z}{I_z} - \frac{Q_0}{E_0/R}\right)\frac{1}{\overline{T}_z},$$

- for the thermal resistance of semiconductor elements of the Peltier device:

(8)
$$\psi_p = \frac{E_0}{A Q_0},$$

- for the summary thermal resistance of copper connections, joint surfaces with the structure of the heating/cooling system:

(9)
$$\psi_t = \frac{1}{2}\left(\frac{\Delta T_0}{Q_0} - \psi_p\right),$$

- for the electric resistance:

(10)
$$R = \frac{E_0}{I_0} = \frac{E_z}{I_z}.$$

Equation (6) shows that it is possible to conduct the experiment in several ways. The tests can be performed:

- at a constant average value of temperature during the experiment: $A = \left(\frac{Q_z}{I_z} - \frac{Q_0}{I_0}\right)\frac{1}{\overline{T}}$ - *that makes possible eliminating the inaccuracy resulting from thermal dependencies of constructional materials and the temperature*,

- at equal heat fluxes $Q_0 = Q_z : A = \left(\frac{1}{I_z} - \frac{1}{I_0}\right)\frac{Q}{\overline{T}_z}$ - *that gives possibility to make experiment faster*,

- at equal currents $I_z = I_0 : A = \frac{Q_z - Q_0}{\overline{T}_z I}$.

In order to compare the accuracy of abovementioned variants, they are analyzed using the maximum approximation error formula:

(11)
$$\Delta_A = \sqrt{\left(\frac{\partial A}{\partial Q_0}\cdot\Delta_{Q_0}\right)^2 + \left(\frac{\partial A}{\partial Q_z}\cdot\Delta_{Q_z}\right)^2 + \left(\frac{\partial A}{\partial I_z}\cdot\Delta_{I_z}\right)^2 + \left(\frac{\partial A}{\partial I_0}\cdot\Delta_{I_0}\right)^2 + \left(\frac{\partial A}{\partial T_h}\cdot\Delta_{T_h}\right)^2 + \left(\frac{\partial A}{\partial T_c}\cdot\Delta_{T_c}\right)^2}$$

The derivatives for each term of equation (11) and for each variant of the experiment are given in Table 1.

Table 1. Expressions for derivatives coefficients

	$\frac{\partial A}{\partial Q_z}$	$\frac{\partial A}{\partial Q_0}$	$\frac{\partial A}{\partial I_z}$	$\frac{\partial A}{\partial I_0}$	$\frac{\partial A}{\partial T_h}$	$\frac{\partial A}{\partial T_c}$
$\overline{T} = const$	$\frac{1}{\overline{T} I_z}$	$-\frac{1}{\overline{T} I_0}$	$-\frac{Q_z}{\overline{T} I_z^2}$	$\frac{Q_0}{\overline{T} I_0^2}$	$-\left(\frac{Q_z}{I_z} - \frac{Q_0}{I_0}\right)\frac{1}{\overline{T}^2}$	
$Q_0=Q_z$	$\frac{1}{\overline{T}}\left(\frac{1}{I_z} - \frac{1}{I_0}\right)$		$-\frac{Q}{\overline{T} I_z^2}$	$\frac{Q}{\overline{T} I_0^2}$	$\frac{Q}{\overline{T}^2}\left(\frac{1}{I_z} - \frac{1}{I_0}\right)$	
$I_z=I_o$	$\frac{1}{\overline{T} I}$	$-\frac{1}{\overline{T} I}$	$-\frac{Q_z - Q_0}{\overline{T} I^2}$		$-\frac{Q_z - Q_0}{\overline{T}^2 I}$	

After substitution the experimental data into relationships from Table 1, the values of derivative coefficients can be obtained.

Table 2. Values of derivative coefficients

	$\frac{\partial A}{\partial Q_z}$	$\frac{\partial A}{\partial Q_0}$	$\frac{\partial A}{\partial I_z}$	$\frac{\partial A}{\partial I_0}$	$\frac{\partial A}{\partial T_h}$	$\frac{\partial A}{\partial T_c}$
$\overline{T} = const$	0,001	0,001	0,4	0,04	$1\cdot10^{-4}$	
$Q_z=Q_o$	0,001		0,2	0,2	$5\cdot10^{-5}$	
$I_z=I_o$	0,009	0,009	0,12		$1\cdot10^{-4}$	

Let the accuracy of the research setup equipment is as follows: ΔT = ± 0,5 °C, ΔQ = ± 0,5 W, ΔI = ± 0,01 A.

From equation (11) and the coefficients given in Table 2, the accuracy for each variant of the method can be expressed as: ΔA = 2,26% (for T_s=const), ΔA = 1,13% (for Q_z=Q_0), and ΔA = 0,7%. (for I_z=I_0)

From the obtained results It can be seen that the experiment conducted at I_z=I_o is the most accurate. In this variant ΔA should be about 0,7%; that gives very good support for precise optimization.

Conclusions

The proposed method allows determining Peltier device parameters, and it is possible to determine the total thermal resistance of copper connections, contact surfaces with structure of a heating or cooling system and thermal resistance of semiconductor material. This feature gives the possibility to obtain the true electromotive force (A) based on the temperatures T_1 and T_2. There are several ways to conduct the experiment, and each one has own advantages. The analysis shows that the accuracy of each variant of experiment is different. The most accurate is the variant for I_o=I_z which gives ΔA about 0,7%. The variant of experiment to be chosen depends on the result that is preferred, e.g. a short time of experiment, a high accuracy or elimination of the inaccuracy resulting from thermal considerations of constructional materials, and the temperature. Results obtained using the proposed method give the possibility to optimize the thermoelectric coolers systems for most efficient operating state, and to achieve the lowest possible temperatures. For a four-stage Peltier cooling cascade optimized by this method, it could be possible to achieve the temperature as low as 124 K which is sufficient for superconducting transition of thin films of $HgBa_2CaCu_2O_{6+\delta}$.

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