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ON THE ISSUE OF CHOOSING THERMOCOUPLE MATERIAL FOR THERMAL CONVERTERS OF METROLOGICAL PURPOSE

In this paper, we consider ways to increase the sensitivity of a thermoelectric converter for metrological purposes due to design improvements in the thermoelectric converter and optimization of thermal operating modes. The features of the requirements for thermoelectric material intended for designing thermoelectric converters as measuring instruments are shown. Bibl. 11, Fig. 1.

Key words: *thermoelectric converter, heater, thermocouple, sensitivity, thermoelectric material*

Introduction

The creation of high-precision devices for measuring alternating current values is a fundamental task of modern thermoelectric instrumentation. An increase in the sensitivity of such devices is directly related to an increase in the sensitivity of a thermoelectric converter (TC) for metrological purposes.

Increasing the sensitivity of TC is mainly achieved by improving the parameters of thermoelectric material (TEM). However, along with the search for new TEMs and improving the quality of known materials, the possibilities of increasing the figure of merit (z) of which are practically exhausted at this stage, there are opportunities to increase the parameters of the TC due to their design improvements, optimize thermal operating modes in order to increase the efficiency of using the heat generated by the TC heater. The task of optimal application of TEM specifically for TC remains relevant, because in this case there is a significant difference from the use of TEM for other thermoelectric devices – thermal generators (TEG), radiation receivers, coolers, etc.

Therefore, an important task and purpose of this work is to establish the features of the application of TEM in the development of TC.

Differences in the choice of TEM for different types of thermoelectric devices

It is known [2] that the use of a semiconductor material for thermal into electrical energy converters has led to a sharp improvement in their coefficient of performance (COP) and created good prerequisites for the widespread use of such converters. The possibilities of improving the parameters of TC for metrological purposes have been studied to a much lesser extent. Often, attempts to use thermoelectric materials (TEMs) developed for energy applications have not met with the expected success. This is due to the fact that TEMs intended for measurement technology and metrology must satisfy a number of additional requirements that are not taken into account when developing TEMs for other applications, such as TEG, thermoelectric coolers (TEC) and thermoelectric heating devices.

When choosing a TEM for TC thermocouples, the TEM optimization criteria are modified. In TEG, TEC and thermoelectric heating devices, the main parameter that determines their quality is the efficiency. For TEG, the efficiency (η_{Max}) in the maximum power mode is determined by the expression [3]:

$$\eta_{\max} = \frac{1}{2}\frac{T_1 - T_2}{T_1 + \frac{2}{z} - \frac{1}{4}(T_1 - T_2)}\ , \tag{1}$$

where T_1 and T_2 are the temperatures of the hot and cold junctions, respectively, z is the thermoelectric figure of merit of TEM which is determined by the formula:

$$z = \frac{\alpha^2\sigma}{x}, \tag{2}$$

where α is the Seebeck coefficient, σ is electric conductivity, x is thermal conductivity.

To characterize the TEC, the coefficient of performance ε_{Max} is used, which is determined from Eq.[4]:

$$\varepsilon_{\max} = \frac{T_2}{T_1 - \mathrm{T}_2}\cdot\frac{\sqrt{1+0{,}5z(T_1+T_2)} - T_1/T_2}{\sqrt{1+0{,}5z(T_1+T_2)} + T_1/T_2}. \tag{3}$$

The heating coefficient K_{T} for thermoelectric heating devices is determined as [5]:

$$K_T = \frac{1}{4}\left(\frac{T_2}{2} - \frac{T_1 - T_2}{zT_2}\right). \tag{4}$$

Formulae (1), (2), (3), (4) remain correct regardless of which type of device is considered. In these formulae, the main parameter that characterizes the efficiency of the device is z. Therefore, the main requirement for the TEM is to achieve the maximum possible value of z.

Another, no less important, requirement is to maintain the figure of merit of the TEM in a wide range of temperatures.

Only for a small group of measuring devices – radiation receivers, microcalorimeters, thermocouples - a relation has been found from which the relationship between the parameters of the TEM and the main characteristics of the device is determined, taking into account the possibility of reaching their boundary values, limited only by thermal and temperature noises [5].

The main parameters describing radiation receivers are signal detection capability and volt-watt sensitivity. Similar parameters are introduced for microcalorimeters. These parameters have long been studied and described in [3,4]. Mathematical expressions to determine these parameters do not take into account a number of additional factors inherent in various thermoelectric devices. Expressions for real structures are much more complicated [5]. They include TEM parameters in different combinations: α, σ, x. In addition to the requirements for achieving maximum sensitivity, a number of additional conditions are imposed on TEM and TC: stability in a given temperature range, high temporal stability, etc.

From the above it can be seen that the requirements for TEM, designed for TEG, TEC and heat pumps, differ significantly from the requirements for TEM, designed for the design of TC as measuring instruments. For example, the figure of merit of a TEM is decisive for a TEG, and its efficiency at small values of ZT depends on the figure of merit according to a law close to linear. Whereas for measuring instruments, the expressions that include z are determined by the power dependence [6] and other coefficients. For this reason, the conditions for optimizing the TEM to achieve the maximum value of sensitivity, speed, etc., will differ. In addition, there are differences in the requirements for TEM and for different measuring instruments [7]. Due to this, a universal TEM suitable for various thermoelectric products cannot be created.

However, the requirements for TEM to achieve the extremely important parameters of the TC are either not fully investigated and defined, or are chosen from considerations that do not always follow from the physical principles of the TC operation, but are determined by operational approaches. As a result, it is often difficult to choose the best TEM for TC.

The relationship of the main parameters of TC with the properties of TEM

To determine the method of selection and optimization of TEM for TC, consider the main parameters of TC.

The most influential parameters describing the properties of TC are those that determine the relationship between the initial values (current, voltage) and the output values (thermoEMF of thermocouples, thermoelectric current, power in the thermocouple circuit). To describe this connection, the following is accepted in the literature [5]:

a) sensitivity $S_I = \frac{\partial E_T}{\partial I_H}$, as the ratio of the increase in thermoEMF of the thermocouple E_T to the increase in current I_H through the heater;

b) sensitivity $S_U = \dfrac{\partial E_T}{\partial U_H}$, as the ratio of the increase in thermoEMF of the thermocouple E_T to the increase in voltage U_H;

c) sensitivity $S_W = \dfrac{E_T}{P_H}$, as the ratio of E_T to power P_H dissipated by the heater.

To determine S_I and S_U, use formulae [10, 11]:

$$S_I = 2K_1 I_H, \tag{5}$$

$$S_U = 2K_2 U_H. \tag{6}$$

Conversion factors K_I and K_2 are related by the ratio:

$$K_I = K_2 R_H^2, \tag{7}$$

where R_H is the resistance of the heater.

Conversion factor K_I can approximately written as [10]:

$$K_I = \frac{\alpha R_H}{S\lambda}, \tag{8}$$

where S is heat exchange surface, λ is heat transfer coefficient.

Expressions (5) and (6) for sensitivity S_I and S_U include only one parameter of TEM – α. Formulae (5) and (7) are valid only for some types of TC in which heat dissipation by the heater is much greater than heat dissipation by the thermocouple.

In most TC designs, the thermocouple and the heater are similar in both geometric dimensions and thermophysical parameters of the materials. In this case, as shown in [8], the thermal conductivity of the thermocouple affects the temperature distribution along the heater. Therefore, expressions (5) and (6) do not fully take into account the physical processes that take place in the TC.

The volt-watt sensitivity [9] for small temperature differences is equal to

$$S_W = \frac{\alpha r_T}{S\lambda}, \tag{9}$$

where r_T is thermal resistance of thermocouple which is determined by the formula:

$$r_T = \frac{l_T}{x S_T}, \tag{10}$$

Where l_T and S_T are the length and cross-section of thermocouple leg.

The volt-watt sensitivity is related to conversion factor K_I by the ratio:

$$S_W = \frac{K_1}{R_H}. \tag{11}$$

With regard to (11), the general expression for TC sensitivity can be written as:

$$S_I = \frac{r_\alpha r_T R_H I_H}{S\lambda}. \tag{12}$$

Thus, E_q.(12) determines the relationship between the main parameters of the thermocouple. It can be seen from formula (12) that S_I makes it possible to establish with greater certainty the dependence of the properties of the TC on the parameters of the TEM, however, the sensitivity S_I does not fully characterize them either.

To most fully determine the dependence of TC parameters on the properties of TEM, we introduce the sensitivity parameter

$$S_\eta = \frac{P}{P_H}, \tag{13}$$

which is the ratio of the power obtained on the electric load of the thermoelement to the AC electric power supplied to the TC. To find S_η, consider the equivalent schematic of a contactless TC with the load r_H, Fig. 1.

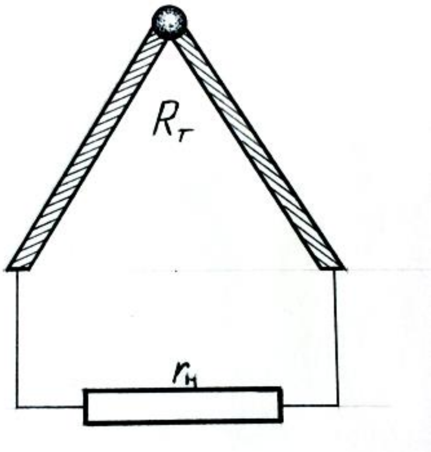

Fig. 1. Schematic of a contactless TC with the load

If the load resistance is matched with the thermocouple resistance ($r_H = R_T$), then TC works in a mode close to maximum efficiency mode, and then

$$S_\eta = \frac{E_T^2}{4R_T R_H I_H^2}. \tag{14}$$

On the other hand, the watt-watt sensitivity S_η can be recorded through the thermophysical parameters of the thermocouple TEM in the form:

$$S_\eta = \frac{z(T_1 - T_2)}{4F_p}, \tag{15}$$

where F_P is coefficient that characterizes the rationality of using heat dissipated by the heater in TC. In so doing,

$$F_p = \frac{2P_H r_T}{T_1 - T_2}. \tag{16}$$

Formula (15) according to [3] corresponds to the expression for TEG efficiency under the condition of small temperature differences in the thermocouple and under the condition that the TEM parameters for the thermocouple do not depend on temperature. Moreover, the expression for can be written [5] in the form:

$$S_\eta = \eta = \frac{(T_1 - T_2)\sqrt{1+zT} - 1}{(T_1\sqrt{1+zT} - T/T_1)F_P}. \tag{17}$$

From the analysis of (15) and (17) it follows that the main operational characteristics of the TC are set by the thermoelectric figure of merit of the TEM *z*, the operating drop $\Delta T = T_1 - T_2$ and the coefficient F_P dependent on the concentration of the TC.

Therefore, an increase in the sensitivity of the TC can be achieved by increasing z and ΔT and decreasing the coefficient F_P. However, an increase in ΔT unambiguously worsens the TC parameters: the squareness of the conversion (the K_I coefficient in formula (5) becomes temperature dependent), the ability to overcurrent, the stability over time due to the aging of the heater metal and the acceleration of diffusion processes at the thermocouple junctions. Therefore, a significant increase in ΔT is impractical.

Evaluation of the rationality of the TC design, taking into account the possibility of reducing heat losses due to the evacuation of the TC body or filling it with inert gases with low thermal conductivity (for example, xenon) [10], the optimal ratio of the geometric dimensions of the heater and thermocouple, the use of a heater with a variable cross section [11], which optimizes the use of heat from the heater, etc., significantly improve the parameters of the TC. But the main increase in sensitivity is still provided by using TEM with the maximum value of z and the Seebeck coefficient α.

Conclusion

The combination of various options for increasing the TC parameters using effective materials based on Bi_2Te_3 creates favorable opportunities for the development of TC with boundary sensitivity values.

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ДО ПИТАННЯ ВИБОРУ МАТЕРІАЛУ ТЕРМОПАРИ ДЛЯ ТЕРМОПЕРЕТВОРЮВАЧІВ МЕТРОЛОГІЧНОГО ПРИЗНАЧЕННЯ

У даній роботі розглянуто способи збільшення чутливості термоелектричного перетворювача метрологічного призначення за рахунок конструктивних удосконалень термоелектричного перетворювача та оптимізації теплових режимів роботи. Показано особливості вимог до термоелектричного матеріалу, призначеного для конструювання термоелектричних перетворювачів як вимірювальних приладів. Бібл. 11, рис. 1.

Ключові слова: термоелектричний перетворювач, нагрівник, термопара, чутливість, термоелектричний матеріал

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К ВОПРОСУ ВЫБОРА МАТЕРИАЛА ТЕРМОПАРЫ ДЛЯ ТЕРМОПРЕОБРАЗОВАТЕЛЕЙ МЕТРОЛОГИЧЕСКОГО НАЗНАЧЕНИЯ

В данной работе рассмотрены способы увеличения чувствительности термоэлектрического преобразователя метрологического назначения за счет конструктивных усовершенствований термоэлектрического преобразователя и оптимизации тепловых режимов работы. Показаны особенности требований к термоэлектрическому материалу, предназначенному для конструирования термоэлектрических преобразователей как измерительных приборов. Библ. 11, рис. 1.

Ключевые слова: термоэлектрический преобразователь, нагреватель, термопара, чувствительность, термоэлектрический материал

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