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OPTIMIZATION OF TEMPERATURE DISTRIBUTION IN THERMOELECTRIC MEASURING TRANSDUCER

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• *Computer model of thermoelectric measuring transducer based on a thermopile with a small number of thermocouples (3 to 5 pieces) has been built. Temperature distribution in the heater of a transducer with a nonlinear arrangement of thermocouples along the heater has been investigated. A non-uniform arrangement of thermocouples along the heater allows optimization of temperature distribution in the heater without the use of a large number of thermocouples (30 to 60 pieces). The use of a small number of thermocouples allows reducing the noise level. Optimal ratio between the thermopile and heater thermal resistances has been calculated, whereby the influence of the Thomson effect is minimized, the ratio between the heater thermal resistance (R_H) and thermopile thermal resistance (R_T), K, should be within 0.35 to 0.5. Design of thermoelectric transducer with the optimized temperature distribution has been proposed.*

Introduction

The accuracy and reliability of up-to-date electric and measuring instruments and setups for the determination of effective value of electric current, voltage, power and power factor in a wide frequency range is largely dependent on the parameters and characteristics of thermoelectric converters that underlie these instruments. The highest metrological and operating characteristics have been achieved in semiconductor thermoelectric measuring transducers that serve the element basis for creation of standards of units of electrical values in many countries [1, 2, 3].

A promising line of creating up-to-date measuring thermal transducers is the use of high-performance semiconductor materials optimized for thermal stability of the main parameters according to requirements of measuring technique and metrology [4]. Special demands to conversion accuracy are placed on thermoelectric measuring transducers that are used for creation of national standards of electric current units. Hence, the task of improving the accuracy of thermoelectric converters of metrological purpose is relevant.

The Thomson effect causes a violation of symmetry in the distribution of the heater temperature and a displacement of maximum heating area depending on current direction through the heater.

The influence of the Thomson effect on conversion accuracy has been proved experimentally: for constantan heaters at currents 0.1; 0.5; 1.0 A the error is no less than 0.06%, for nichrome and platinum-iridium at currents 1; 2; 5; 10; 20; 50; 200 mA – no less than 0.01%. Converters with a nichrome heater have a smaller error. These errors are reduced with a choice of material that has minimum Thomson effect. The best results were obtained for heaters of manganin or platinum-iridium alloy (85% *Pt* – 15% *Ir*); the error of transition from direct to alternating current in these cases does not exceed 0.005% [5].

Sometimes, to reduce the error due to the Thomson effect, a conductor is used which drains the electric current from the area close to the heater centre. With the help of shunting resistance it reduces power in that part of the heater where the Thomson effect results in excess heating [6].

A change in converter parameters in the temperature range is due to a number of reasons, primarily the temperature dependences of thermocouple and heater material properties, change in heat exchange conditions. Their effect can be reduced by introducing compensation elements into thermocouple circuit. Reduction of errors can be also achieved by the respective choice of thermocouple and heater materials [7, 8]. The temperature dependences can be almost completely compensated by using balanced differential circuits with two identical converters [9].

To obtain the necessary signal level and kind of temperature distribution, the up-to-date multi-element converters employ thermopiles with a large number of thermocouples (30 to 60 pieces) [3]. With a large number of thermocouples the thermopile resistance increases, which leads to noise level growth. For noise level reduction without reducing signal level, it is necessary to use thermopiles with a small number of thermocouples of high-performance semiconductor thermoelectric materials. Our purpose in this work is to study the possibility of temperature distribution optimization in the heater of a thermal converter with a small number of thermocouples.

Theoretical part

The kind of temperature distribution, hence the extent of the Thomson effect influence, can be controlled by means of thermal converter's geometrical parameters. To solve the formulated problem, we developed a thermal converter the design of which is shown in Fig. 1.

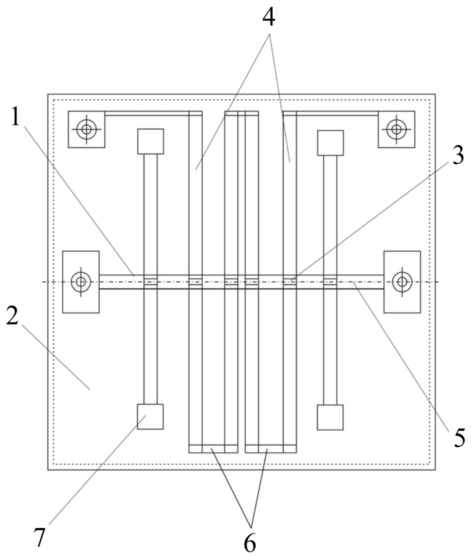

Fig. 1. Design of thermal converter with a non-uniform arrangement of thermocouples along the heater 1 – heater; 2 – package; 3 – hot junctions of thermocouples; 4 – thermocouple legs; 5 – heater symmetry axis; 6 – cold junctions of thermocouples.

A physical model of thermal converter under study was constructed. For the description of the physical model a system of equations was composed (1):

$$\kappa_i S_i^n \frac{d^2 T_i}{dx_i^2} - \gamma_i P_i (T_i - T_0) - \xi_i \sigma_0 P_i (T_i^4 - T_0^4) + \frac{\rho_i I_i^2 S_i^n}{S_{m_i}^2} = 0 \qquad (1)$$

where I_i is current, S_i^n is cross-section, P_i is perimeter of i-th element of converter, κ_i, ρ_i, γ_i, ξ_i is thermal conductivity, resistivity, coefficient of heat exchange with the environment, radiation incompleteness, respectively, σ_0 is the Stephan-Boltzmann constant.

The boundary conditions:

$$\begin{cases} T_0 = 293.15 \\ U\big|_{x=0} = 0 \\ U\big|_{x=a} = v \end{cases} . \quad (2)$$

the lateral surface of the heater and thermocouple legs is electrically insulated.

The thermal converter was studied by means of computer simulation in COMSOL Multiphysics medium, the system of differential equations was solved by finite element method.

In general, temperature distribution control was due to optimization of heat release along the heater length. The result was attained by a non-uniform arrangement of thermocouples along the heater, which lead to a non-uniform outflow of heat from the centre and edges of the heater.

Results of computer-aided studies

Computer simulation of thermal converter aimed at finding the kind of temperature distribution in the heater of thermal converters of different design. In particular, thermal converters with a non-uniform arrangement of thermocouples along the heaters and with profile heater.

The known values were: the length and diameter of the heater, the length and cross-sectional area of thermocouple legs, the electric and thermal conductivities of the heater and thermocouple materials, the Seebeck coefficients of thermocouple materials and the rated current. One had to obtain the graphical format of temperature distribution in a converter.

The results are given as a plot of temperature distribution (Fig. 2).

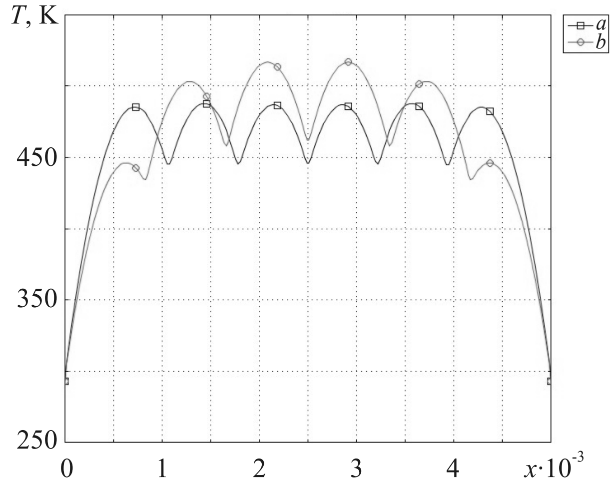

Fig. 2. Temperature distribution in the heater of optimized (a) and non-optimized (b) thermal converter.

As is evident from the plot, the above described method of thermal converter optimization yields minimization of temperature gradients between the contact points of the heater and thermocouple junctions.

Apart from geometrical parameters, the kind of temperature distribution is also affected by the ratio between the heater and thermocouple thermal resistances. To obtain the best results, the ratio of heater resistance (R_H) to thermocouple resistance (R_T), K, should be within 0.35 – 0.5. If $K < 0.35$, the general view of temperature distribution in the heater will retain the shape of a parabola. In so doing, conversion accuracy will be essentially affected by the Thomson effect. If $K > 0.5$, the influence of the Thomson effect on conversion accuracy will be minimized, but the power of thermocouple signal will be considerably reduced, and the value of heater overheat relative to thermocouple junctions will increase, which will reduce the thermal converter's overload capacity.

Conclusions

- Methods for control and optimization of temperature distributions in converters with a small number of thermocouples (up to 7 pieces) made of semiconductor materials with increased thermoelectric figure of merit have been developed.
- Computer simulation has been used to find the optimal temperature distribution in a heater that has thermal contacts with a thermopile with the number of thermocouples 3 to 7 pieces.
- It has been established that, to give the optimal result, the ratio between heater resistance (R_H) and thermocouple resistance (R_T), K, should lie within 0.35 to 0.5.

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