FEATURES OF THE MEASUREMENT OF MICRO-RATES OF FLOW OF LIQUID METALS WITH THERMOELECTRIC TRANSDUCERS

P. A. Korotkov, V. V. Prokhorov,
A. A. Tkachev, and V. N. Shutov

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The design and characteristics of a thermoelectric transducer for measuring small steady flows of liquid metals are examined.

Problems of measuring small flows of gaseous and liquid media are encountered in different areas of science and technology. The most complex problem is measuring flows of liquid metals, particularly alkali metals. Thermoelectric transducers are best for this purpose. They meet several current requirements, in that they are monolithic and sufficiently accurate, have a relatively simple design, and have a compact input element [1].

The calorimetric thermoelectric steady-state transducers now used to measure small (to $50 \cdot 10^{-6}$ kg $\cdot$ sec^{-1}) flows of liquid metals with an external heater have several shortcomings. First, a change (an increase, for example) in the flow rate is accompanied by a change (decrease) in the temperature at the location of the heater, which leads to a significant change in the sensitivity of the flow-rate meter [1]. Second, the above type of transducer is fairly inertial, since its operation requires complete thermal stabilization of the entire design, i.e., not only the pipe section, but also the heater and the heat shielding system (to reduce heat loss to the environment). Also, due to the complexity and insufficiently precise thermal design of the transducer, it has to be carefully calibrated within a broad range of flow rates.

The above problems can be solved if the temperature of the heater is stabilized and it is kept at the maximum level by installing a thermostatting element on the pipe of the transducer. Here, each liquid metal flow rate will correspond to a certain temperature distribution along the measurement section of the pipe, located ahead (upstream) of the thermostat. The results of measurement of the temperature distribution can be used to reliably determine the flow rate. A change in flow rate leads to distortion of this temperature distribution, i.e., to a change in the readings of the thermoelectric transducer.

Such a device (Fig. 1) includes the measurement section 3 of the pipe, a heat-exchanger—radiator 2 installed on the pipe, a heater 1, and a differential thermocouple. The latter consists of the section of the pipe between the junctions 4 and 5, performing the function of a natural thermoelectrode with properties similar to those of a standard thermoelectrode, and two Copel electrodes 6. The liquid metal flow enters the pipe from the unit 7 with the temperature t_{in}. The temperature of the radiator t_r is chosen in relation to the boiling point of the given liquid metal and the operating conditions.

Much of the power of the heater is consumed as radiation from the surface of the heat-exchanger—radiator. The proportion of power spent on heating the flow and transferring heat along the pipe is roughly two

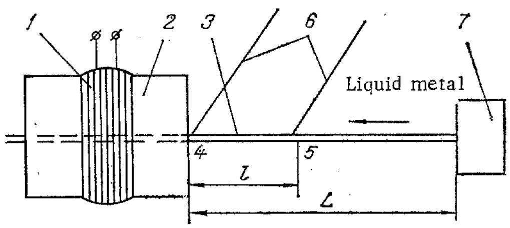

Fig. 1. Diagram of thermoelectric transducer.

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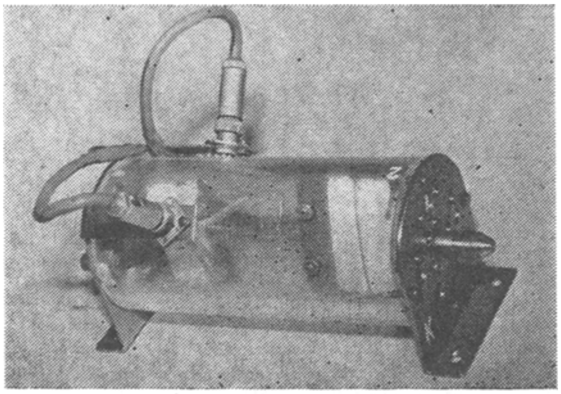

Fig. 2

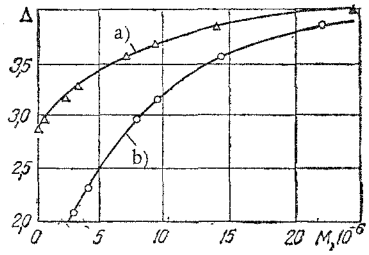

Fig. 3

Fig. 2. General view of thermoelectric transducer in its shield (the transducer is shown with two radiators for measuring forward and reverse flows of liquid metal).

Fig. 3. Calibration curves of the thermoelectric transducer: a) gallium–indium eutectic, air environment, $t_r = 398 \pm 2°K$; b) potassium, vacuum, $t_r = 433 \pm 3°K$ (Δ denotes a reading of the transducer, mV; M denotes the flow of the liquid metal, $kg \cdot sec^{-1}$).

orders less. Here, the heat-exchanger-radiator is actually a thermostat, since the energy radiated by the radiator is proportional to the fourth power of the temperature of the radiator t_r. This ensures that t_r will be almost constant at relatively low flow rates of the liquid metal $(5\text{-}50) \cdot 10^{-6}\ kg \cdot sec^{-1}$. Thus, with a change in flow rate, the temperature around the junction 4 remains constant, while there is a change in the temperature at the junction 5. The temperature difference at the locations of the junctions 5 and 4 on the pipe is the quantity which determines the flow rate of the liquid metal.

To determine the optimum design parameters of the transducer and obtain its calibration curve, it is necessary to solve the problem of steady-state heat exchange along the pipe. We made the following assumptions: the temperatures of the radiator t_r and the unit t_{in} during measurement of the flow rate were constant; the temperatures of the wall of the pipe t_w and of the liquid metal flow t_q were equal to each other in all sections; the thermophysical coefficients λ and c of the wall and liquid metal were independent of the temperature and did not change along the pipe; radiation from the outer surface of the pipe was negligibly small; the flow was steady and laminar.

Given these assumptions, the equation describing the temperature distribution along the axis of the transducer pipe on the section between the heat-exchanger–radiator and the unit (located a sufficient distance L from each other) has the form

$$\frac{d^2t}{dx^2} + \frac{c_q M}{\lambda_w F_w + \lambda_q F_q} \frac{dt}{dx} = 0. \qquad (1)$$

The x axis corresponds to the pipe axis, and the coordinate on the axis is reckoned from the junction 4 counter to the direction of the flow. In the absence of flow, i.e., when M = 0, Eq. (1) takes the form

$$\frac{d^2t}{dx^2} = 0. \qquad (2)$$

The solution of (2) for the point $x = l$, corresponding to juntion 5, will be

$$t_l = \frac{l}{L} t_r + \left(1 - \frac{l}{L} \right) t_{in}. \qquad (3)$$

The solution of Eq. (1), with allowance for (3) for the point $x = l$, will be as follows with $M \neq 0$:

$$\frac{t_l}{t_r} = \frac{\exp(-AMl)}{1 - \exp(-AML)} - \frac{\exp(-AML)}{1 - \exp(-AML)}, \qquad (4)$$

where $A = c_q/(\lambda_w F_w + \lambda_q F_q)$. For convenience in the calculation, the temperatures are reckoned from t_{in}, i.e., it is assumed that $t_{in} = 0$. The measured temperature difference at points 4 and 5, with allowance for (4), is determined from the relation

$$\Delta = t_r - t_l = t_r \frac{1 - \exp(-AMl)}{1 - \exp(-AML)},$$

which is a statistical characteristic of the transducer and makes it possible to theoretically construct its calibration curve.

We will write the expression for the sensitivity of the transducer:

$$S = \frac{d(t_l/t_r)}{dM} t_r = \frac{t_r AL \exp(-AML)}{1 - \exp(-AML)} \times \left[1 - \frac{l}{L} \frac{\exp(-AMl)}{\exp(-AML)} - \frac{\exp(-AMl) - \exp(-AML)}{1 - \exp(-AML)} \right], \quad (5)$$

from which it is evident that the sensitivity of the transducer is linearly dependent on the temperature of the heat-exchanger–radiator t_r and is a function of the thermophysical and design parameter. Evaluation of the sensitivity of the transducer with Eq. (5) shows that the sensitivity will be greater at higher values of the complex AML, i.e., at large L. In the case AML ≥ 5, the small quantity exp(–AML) in Eqs. (4) and (5) can be ignored. Then we obtain

$$\frac{t_l}{t_r} = \exp(-AMl), \quad (6)$$

$$S = -At_r l \exp(-AMl). \quad (7)$$

Differentiating Eq. (7) with respect to l and finding the optimum value l_{opt}, we obtain the condition for correspondence of the design parameters of the transducer to maximum sensitivity during measurement of flow rate at a specific temperature t_r = const:

$$AMl = 1 \quad (8)$$

Thus, within the chosen range of flow-rate values, Eqs. (6)-(8) can be used to determine the basic geometric parameters of the thermoelectric transducer and its theoretical calibration curve, ensuring the required sensitivity of the transducer.

The theoretical data obtained was used to design a thermoelectric transducer, a general view of which is shown in Fig. 2. The design parameters of the transducer were chosen with allowance for Eqs. (6)-(8). The pipe, made of steel Kh18N10T, has an inside diameter of $1.2 \cdot 10^{-3}$ m and a wall thickness of $0.2 \cdot 10^{-3}$ m. The distance between the junctions of the thermoelectrodes is $l = 22 \cdot 10^{-3}$ m, while the distance between the copper radiator, with an area of $3 \cdot 10^{-3}$ m^2, and the feed unit L = $40 \cdot 10^{-3}$ m. The heater, made of grade POZhNKh 0.3 wire, has a resistance of 10 Ω and consumes 4-8 W of electric power (depending on the required temperature t_r). The transducer was tested in both air and a vacuum.

It is apparent from the calibration curve of such a transducer, obtained on a liquid gallium–indium eutectic in air at t_r = 398 ±2°K (Fig. 3), that the measurement sensitivity at a mass flow rate M ≈ $3 \cdot 10^6$ kg·sec^{-1} reaches S = $0.1 \cdot 10^6$ mV·kg^{-1}·sec. When the transducer is calibrated on liquid potassium in a vacuum at t_r = 433 ±3°K at a mass flow rate M ≈ $3 \cdot 10^{-6}$ kg·sec^{-1} (Fig. 3), we obtain a measurement sensitivity S = $0.2 \cdot 10^6$ mV·kg^{-1}·sec. It should be noted that if the differential thermocouple is replaced by special heat-sensitive elements the transducer can be made even more sensitive.

The transducer is distinguished by the ease of its use and its satisfactory accuracy in measuring microrates of liquid metal flow. The reliability and ease of repair of the transducer compared to other types of transducers (rotametric, turbine, etc.) is the result of the lack of direct contact between the measurement elements and the flow. The measurement accuracy of the transducer depends on the following factors: the stability of the condition of the internal surfaces of the pipe, the calibration error of the differential thermocouple, the stability of the voltage supply to the heater, and stray currents in the thermoelectrode leads.

Three years of continuous use of a traditional thermal-type flow meter in a flow of liquid potassium showed [2] that the inside surface of the pipe remains almost unchanged. Thus, we may take γ_1 = 0.00% for the error of the transducer on the heat-exchange section between the pipe and the liquid metal.

The instability of the temperature of the heat-exchanger–radiator is determined by the instability of the heater power supply and the conditions of heat exchange by the radiator with the environment. The power supply instability is taken as 0.01% [3]. In using a thermoelectric transducer in air, the heat-transfer coefficient changes by about 0.03% with a 1°K change in ambient temperature. We can therefore assume that a ±10°K change in ambient temperature will produce a measurement error γ_2 = 0.01–0.6 = 0.61%.

The permissible calibration error of standard thermocouples with a thermostatted cold junction is 0.16 mV for Chromel—Copel [4]. For a differential thermocouple, we can assume a relative error $\gamma_3 = 1.50\%$ at $\Delta t = 2°K$. Since the transducer will be used in compact equipment, we need not consider the effect of long leads.

Thus, in using the thermoelectric transducer in control systems, i.e., without a recorder, the total relative measurement error will be: $\gamma = \gamma_1 + \gamma_2 + \gamma_3 = 0.00 + 0.61 + 1.50 = 2.11\%$. If the transducer is used with a class 0.5 recorder, the total error of the system in measuring microrates of flow will not exceed 2.11%.

NOTATION

A, coefficient determined in context; c, specific heat; F, cross-sectional area; L, distance between radiator and unit; l, distance between junctions of thermoelectrodes; M, mass flow rate of the liquid metal; S, sensitivity of the transducer; t, temperature; t_{in}, temperature of the flow at the transducer inlet; x, coordinate along the pipe; γ, measurement error; Δ, temperature difference of the thermoelectrode junctions; λ, thermal conductivity. Indices: w, pipe wall; q, liquid metal flow; r, heat-exchanger—radiator.

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FILM-TYPE THERMOELECTRIC AND THERMOMAGNETIC THERMAL RADIATION SENSORS AND THEIR OUTPUT PARAMETERS

V. V. Borodin, D. M. Gel'fgat,
and Z. M. Dashevskii

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Voltage—power sensitivity and time constant of a "star"-type film thermoelectric sensor and time constant of a film thermomagnetic sensor are calculated.

Thermal radiation sensors are widely used in thermometry as primary transducers. Their most important output parameters are the conversion coefficient or voltage—power sensitivity and their response time or time constant. In recent years interest has increased in thermal-type sensors, in particular, in film thermoelectric and film thermomagnetic sensors [1, 2]. Such sensors are small in size, reliable in operation, and of high technological quality. Decrease in geometrical dimensions and use of high efficiency film materials permits achievement of high-quality output parameters.

Using two types of film radiation sensor construction (thermoelectric and thermomagnetic), the authors have analyzed the transient thermal processes which occur within the sensor when radiation is incident on the receiver area. The relationships thus obtained have been used to calculate the output parameters of sensors using the most efficient working materials.

One of the most widely used film thermoelectric sensor constructions is the "star" type [1]. The "star" construction (Fig. 1) consists of a substrate 1 in the form of a disk with a film thermobattery 2 deposited on its surface by vacuum technology methods. The branches of the thermobattery have the form of tapered segments which converge at the center, with the gaps between these branches being quite small in comparison

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