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METHOD AND APPARATUS FOR ACCURATE MEASUREMENT OF TEMPERATURE OF A HOT PLATE BY A COMPENSATION THERMOSENSOR

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A method is described for accurate temperature measurement by a contact thermosensor, based on eliminating heat loss through the sensor during measurement. The error in measurement of the temperature of heated thermally "thin" plates comprises 1.6°K.

The technique of thermophysical experimentation is simplified significantly when the specimen to be investigated is chosen in the form of thermally "thin" plates or cylinders. However, as a rule, accurate measurements of temperature then present great difficulty. In a number of cases accurate temperature measurements on thin plates may be performed by radiation pyrometry methods which do not require a knowledge of the material's emissivity [1, 2]. However, the area in which such techniques may be employed is limited to optically opaque bodies and requires special experimental conditions.

Contact methods of measurement provide highly accurate information if special measures are taken to eliminate the disturbing influence of the thermoprobe on the ribbon temperature field.

The appropriate corrections may be calculated, for example, with the formula presented in [3].

For the case where the thermoprobe can be approximated by a bar, the formula relating the actual temperature of the ribbon t_0 before contact of the thermoprobe with that after contact t_e, as measured by the thermoprobe, is written in the form

$$t_0 = t_e\left[1 + \sqrt{\frac{\lambda\alpha h_0}{\lambda_0\alpha_0 R}} \cdot \frac{K_0(\nu)}{K_1(\nu)}\right], \quad (1)$$

where $K_0(\nu)$ and $K_1(\nu)$ are modified Bessel functions of the second kind of zero and first orders.

The parameter

$$\nu^2 = \frac{2\alpha_0}{h_0\lambda_0} R^2; \quad (2)$$

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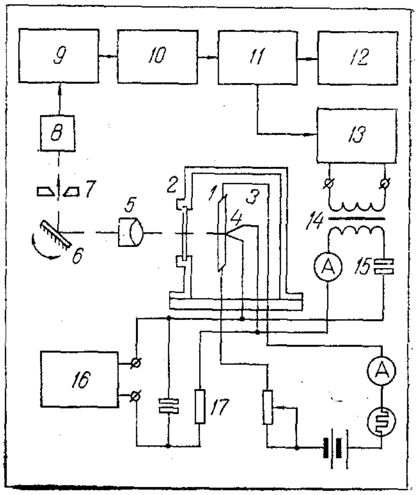

Fig. 2. Schematic diagram of experimental apparatus for accurate temperature measurements on heated plates: 1) object to be measured; 2) chamber; 3) current leads; 4) thermocouple; 5) objective; 6) scanning mirror; 7) slit; 8) photodetector; 9) preamplifier; 10) phase-sensitive amplifier; 11) slave mechanism; 12) generator; 13) power amplifier; 14) matching transformer; 15) blocking capacitor; 16) dc potentiometer; 17) low-frequency filter.

λ_0 and λ are thermal-conductivity coefficients of the ribbon of thickness h_0 and thermoprobe of radius R.

Equation (1) is valid under the condition of equality of the coefficient α_0 on both ribbon surfaces heated by the current, and the heat-exchange coefficient α is taken constant over the entire extent of the thermoprobe. Also, Eq. (1) does not consider thermal resistance in the thermoprobe — ribbon contact area of radius R.

Thus, the real model of the temperature experiment only reflects the theoretical model to a certain approximation, and in estimating necessary corrections significant methodic error can develop, depending on the degree of this noncorrespondence.

Calculations with Eq. (1) reveal that the error due to temperature distortion, for example, with a platinum ribbon 50 μ thick and a platinum — rhodium thermoprobe 0.2 mm in diameter, reaches 10% and more of the measured temperature.

Since there appear in the formula together with the physical characteristics of the thermoprobe and specimen, the heat exchange coefficients α_0 and α, which are not always possible to measure to an accuracy of even 20%, attempts to increase the accuracy of temperature measurements on thin ribbons and wires by introducing corrections for heat lost to the thermoprobe are, as a rule, ineffective, even if the theoretical heat-exchange model of the specimen — thermoprobe — surrounding medium system is made more detailed.

Attempts to increase accuracy by decreasing heat loss through use, for example, of microthermocouples with thermoelectrode diameter of 0.05 mm and less, as is often done by experimenters, is still questionable, because of the significant thermoelectric inhomogeneity of thin thermoelectrodes. Moreover, difficulties develop in calibrating such thermocouples under conditions approximating their intended use.

Thus, those methods are useful in which the error can be determined experimentally, for example, by measuring the temperature with two thermoprobes differing in construction and physical properties [3].

However, a shortcoming of such methods of increasing accuracy is that they do not eliminate disturbance of the initial temperature field, which is undesirable in thermophysical experiments.

Thus, methods in which the distorting influence of the thermoprobe is eliminated by supplementary heating of the latter [4-6] are deserving of attention.

We describe below the use of a contact thermosensor, for example, a thermocouple, with compensation for heat loss by direct heating by an ac current, for measurement of the temperature of a thin metallic ribbon 1 (Fig. 1) 50 μ in thickness, heated by an electric current in either a gas atmosphere or under vacuum conditions in chamber 2. The current leads 3 consist of massive copper electrodes which slide against copper tubes cooled by water. Such construction permits use of specimens of differing lengths, and since the lower large electrode can slide freely along the current supply tube, the ribbon specimen will be in a constant state of tension during the experiment.

Such a system with a thin plate or cylinder with its thermal regime determined by a current is widely used in thermophysical experiments.

The actual specimen temperature is measured by thermocouple 4, for example, type PR-30/6.

To eliminate distortions of the ribbon temperature field by the thermocouple due to heat loss to the thermoelectrodes, the following system of compensation by direct thermocouple heating by ac current is employed. The control signal for the compensation heating signal can be formed by the distorted temperature field on the ribbon surface near the contact point [7].

In fact, assuming that for a sufficiently long thin ribbon in the middle region there will be a zone with homogeneous temperature t_0, then upon contact with this zone of a cylindrical thermoprobe, heat loss to the surrounding medium will disrupt the homogeneity of the ribbon temperature field. The radial temperature distribution from the point of contact will be described by the equation [8]

$$t(r) = t_0 + \frac{Q_0}{2\pi\lambda_0 h_0 \nu_0 R} \cdot \frac{K_0(\nu_0 r)}{K_1(\nu_0 R)}, \tag{3}$$

where Q_0 is the quantity of heat removed from the ribbon by the thermoelectrodes; $K_0(\nu_0 r)$ and $K_1(\nu_0 R)$ are modified Bessel functions of the second kind of zero and first orders.

The parameter

$$\nu_0^2 = \frac{\alpha_0 P_0}{\lambda_0 \sigma_0},$$

where P_0 and σ_0 are the perimeter and cross section of the ribbon. This parameter, defined as the ratio of surface conductivity to internal conductivity for a ribbon width $l_0 \gg h_0$, is equal to

$$\nu_0^2 = \frac{2\alpha_0 (h_0 + l_0)}{\lambda_0 h_0 l_0} \simeq \frac{2\alpha_0}{\lambda_0 h_0} \simeq \frac{\nu^2}{R^2}. \tag{4}$$

Taking $t(R) = t_e$, from Eq. (3) we obtain an expression for evaluating the distorting influence of the cylindrical thermoprobe on the ribbon temperature field:

$$\frac{t(r) - t_0}{t_e - t_0} = \frac{K_0\left(\nu_0 \frac{r}{R}\right)}{K_0(\nu_0)}. \tag{5}$$

The maximum distortion at the contact point $(t_e - t_0)$ for a given cylindrical thermoprobe radius depends on the heat loss and will obviously increase with decrease in h_0 and λ_0 of the plate and, conversely, with increase in R and λ of the thermoprobe.

Using Eq. (5), we choose points r_1 and r_2 $(r_1 < r_2)$ along a radius near the contact point such that by reduction of the temperature difference

$$t(r_2) - t(r_1) = (t_e - t_0)\frac{K_0\left(\nu_0 \frac{r_2}{R}\right) - K_0\left(\nu_0 \frac{r_1}{R}\right)}{K_0(\nu_0)}$$

to zero by heating the thermosensor, the sensor temperature t_e approaches the actual temperature t_0 which the ribbon had before intrusion of the thermoprobe.

Thus, for example, in measuring the temperature of a nickel ribbon 50 μ thick with a platinum – rhodium/platinum – rhodium PR-30/6 thermocouple with thermoelectrode diameter of 0.5 mm with a scanning step $\Delta r = (r_2 - r_1) = 1$ mm near the contact point

$$\frac{t_e - t_0}{t(r_2) - t(r_1)} \simeq 2.$$

Thus, if we have a temperature difference measurement system with a resolving power of 0.1°K at $\Delta r = 1$ mm, the methodic error due to heat loss, reaching tens of degrees, will be reduced to 0.2°K after compensation by additional thermoprobe heating.

In the method described here for accurate measurement of heated ribbon temperatures by a thermosensor, for example, a thermocouple, the control signal for automatic heat-loss compensation is generated by periodic measurement of the temperature gradient near the contact point using the difference in luminosity of points r_1 and r_2 in the following manner.

An image of a portion of the ribbon is projected by objective 5 and movable mirror 6 onto the plane of slit 7, behind which photodetector 8, for example, an FD-3, is located. The mirror is mounted to the armature of a type RP-5 polar relay so that the armature axis of rotation passes through the center of the mirror and oscillates at a frequency of ~50 Hz. Thus, operating at the modulation frequency the photodetector successively "looks at" different points along a radius from the point of thermoprobe contact with the surface. The signal from the photodetector, proportional to grad t, is amplified by preamplifier 9. That stage also matches the photodiode parameters to the input impedance of phase-sensitive amplifier 10. The output of the latter is connected to slave mechanism 11, which varies the voltage from the output of audio frequency generator 12 applied to the input of power amplifier 13, whose load is the thermocouple 4, connected through matching transformer 14 and blocking capacitor 15, to avoid shunting the thermocouple by the matching transformer for dc. Complete heat-loss compensation (grad t = 0) corresponds to zero control signal and under this condition the true ribbon temperature is measured by the thermocouple. Since the thermocouple heating current is at a frequency of 20 kHz, the thermocouple thermo-emf is separated by RC filter 17 with time constant 0.001 sec and measured by potentiometer 16.

As was noted above, the distorting influence of heat loss to the thermosensor on the ribbon temperature field decreases rapidly with removal from the contact spot, and so compensation is performed by measuring grad t near the contact. In practice, appropriate points are chosen as follows. With the aid of a special electromagnet mechanism the thermocouple sensitive element can be touched to or removed from the surface.

In the contact position in the presence of heat loss a dark spot is observable from the opposite side of the ribbon. A lamp with ground glass is installed in place of the photodetector linking the ribbon to the control system and slit 7 is focussed on the dark spot. Then with the scanning system operating the system is adjusted for maximum ac output signal at the mirror oscillation frequency to select the segment with maximum grad t. The distance between the points chosen is determined by the mirror oscillation amplitude. The amplitude and polarity of the control signal depend on the amount of under- or overcompensation of heat loss. By measuring stationary temperatures, heat-loss compensation can be determined with an oscilloscope.

If for any number of reasons (varying thickness, state of the surface, etc.) there exists an initial grad t with the thermocouple absent, it can be allowed for by correction of the control signal.

In practice, the following sources of systemic error remain in realization of this system.

As for normal thermoelectric methods, there is a calibration error of 0.2°K and thermostatic maintenance of the thermocouple free ends to 0.05°K. Moreover, we have error due to inaccurate heat-loss compensation (0.2°K), nonconstant heating current (0.1 — 0.2°K), uncertainty as to temperature drop in the contact zone (0.5°K), and also due to incomplete elimination of thermocouple shunting by the power amplifier for dc, uncertainty in consideration of thermal flux screening by the sensitive element, and a number of other error sources, not exceeding 0.1°K.

Random errors are determined mainly by inconstancy of ribbon temperature and heat-exchange conditions both in the contact zone and in the entire system of ribbon — thermocouple — surrounding medium.

An estimate of the total error in measurement of an actual ribbon temperature by a compensation thermocouple with the apparatus described above can be made using the assumption that the limiting values of the uneliminated systemic errors have an equal probability distribution, and that random errors have an asymptotic normal distribution, with subsequent quadratic summation [9].

Then the reliability (P = 0.95) of measurement of a ribbon temperature of 1000-1500°K by the compensation thermocouple will be

$$\Delta = \frac{Q + \tau_{\bar{x}} \cdot S_{\bar{x}}}{S_Q + S_{\bar{x}}} \sqrt{S_Q^2 + S_{\bar{x}}^2} \simeq 1.6\ K,$$

where

$$S_{\bar{x}} = \sqrt{\frac{\sum^{n} (t_i - \bar{t})^2}{n(n-1)}}; \quad S_Q = \sqrt{\frac{1}{3} \sum^{n} Q^2}; \quad Q = k \sqrt{\sum^{m} Q_j^2}.$$

The quantile of the residual systemic error distribution Q_j at a reliability of P = 0.95, weakly dependent on the number of terms m, is equal to k = 1.1. The quantile $\tau_{\bar{x}} = 4.3$ is determined using the Student distribution as a function of number of measurments n = 3 and P = 0.95; $\bar{t}$ is the mean of the measured temperatures t_i.

The validity of the ribbon temperature measurements performed with the compensation thermocouple were verified experimentally with the use of a method differing in principle, based on determining the moment of heat-loss compensation by measuring the brightness temperature at the contact point with a type IKP-57 spectrometer [10]. Both methods agreed, not exceeding the above error estimate of 1.6°K.

The method and apparatus described can be used not only for temperature measurements on thermally "thin" plates, but also for any heated body surfaces.

NOTATION

t_0, t_e, temperatures of ribbon and thermoprobe; λ_0, λ, coefficients of thermal conductivity of ribbon and thermocouple; R, thermocouple radius; h_0, l_0, thickness and width of ribbon; α_0, α, heat-exchange coefficients for ribbon and thermoprobe.

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