NOTATION

ε, thermal emf; q, specific heat flux; l, length of thermoelement; φ, angle of inclination of layers; $\delta^* = \delta_2/\delta_1$, layer thickness ratio; α_{xy}, $\varkappa_{yy}$, ρ_{xx}, nondiagonal components of thermoelectric coefficient, thermal conductivity, and electrical resistivity tensors; α_{x_0}, α_{y_0}, $\varkappa_{x_0}$, $\varkappa_{y_0}$, components of thermoelectric coefficient and thermal conductivity tensors; α_1, α_2, $\varkappa_1$, $\varkappa_2$, ρ_1, ρ_2, thermoelectric coefficient, thermal conductivity, and electrical resistivity of initial materials; Z_{xy}, Z_{1-2}, thermoelectric quality of anisotropic and longitudinal classical thermoelement; D*, detectivity; K, volt — watt responsivity; $\bar{T} = (T_h + T_c)/2$, mean temperature.

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EFFECT OF NONUNIFORMITY OF HEATING OF FILM RESISTANCE THERMOMETERS ON MEASUREMENTS OF PULSED HEAT-FLUX DENSITIES

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UDC 536.24.08

A method of correction for the nonuniformity of heating of metal and semiconducting film resistance thermometers of the calorimetric type in the measurement of pulsed heat flux densities is proposed.

Measurements of heat flux densities by means of film resistance thermometers (FRT) of the calorimetric type are based on determination of the mean excess temperature of the heated electrically conducting film and its first derivative with respect to time. If the film has an initial temperature t_0, °C (T_0, °K) in the unheated state the mean excess temperature of the film, heated in the absence of heat loss, is

$$\bar{\vartheta}^*(\tau) = \bar{t}^*(\tau) - t_0 = W(\tau)/c\gamma v, \quad (1)$$

where W is the amount of heat, in J, received by the film; τ is the time, in sec, measured from the start of the heat pulse.

When the heat flux density q is the same over the entire heated surface of a film of area s,

$$W(\tau) = s\int_0^\tau q(\omega)\,d\omega, \quad (2)$$

where ω is the time. Substituting the value of W from (2) in (1) and taking the film thickness as l, we obtain

$$\bar{\vartheta}^*(\tau) = \frac{1}{c\gamma l}\int_0^\tau q(\omega)\,d\omega. \quad (3)$$

If we differentiate (3) with respect to τ, we easily obtain

$$q(\tau) = \frac{d\bar{\vartheta}^*(\tau)}{d\tau}\,c\gamma l. \quad (4)$$

The heat loss by the film by the time of measurement is due to conduction of heat into the electrically insulating substrate and wire, and also to heat transfer to the surroundings. Reduction of heat loss is achieved primarily by the use of films which are not appreciably heated through by the time of measurement. This inevitably leads to a temperature gradient over the film thickness. Heat loss to the wire and surroundings can lead to temperature gradients along and across the film. The primary measured quantity is the varying difference in voltage

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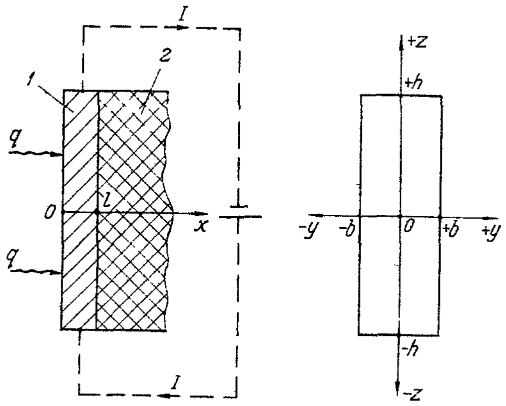

Fig. 1. Schematic of FRT and adopted system of coordinates: 1) film; 2) substrate; 3) direction of heat flux; I) direction of electric current.

drops on the heated and unheated film of the FRT, with the electric current kept constant.* The voltage drop depends on the electrical resistance of the film, which is related to its temperature field. The temperature of the unheated film is uniformly distributed and has a unique effect on its resistance. The resistance of the heated film even with an identical mean temperature depends on the temperature field. This obvious fact is usually ignored and the electrical resistance of the nonuniformly heated FRT film is uniquely related to its mean temperature, and the heat loss is ignored, as was done, e.g., in [1, 2]. This leads to indeterminate errors in the measurement of pulsed heat flux densities.

In this paper we obtain relations between the electrical resistance and the temperature field of the film with due allowance for the heat loss. These relations enable us to eliminate or evaluate the above-mentioned errors. The subsequent account relates to a flat FRT consisting of a two-layer parallelepiped of length 2h and width 2b. The FRT and the adopted system of coordinates are schematically shown in Fig. 1. The physical properties of the film and substrate are assumed constant. The pulsed heat flux acts on the y0z plane. The electric current flows in the direction of the axis 0z, and the cross-sectional area of the conductor (film) is $2lb$. For metal films in the range of positive temperatures allowed by metrological requirements we can use in the general case, according to [3], a quadratic relationship connecting the electrical resistivity ρ and the excess temperature $\vartheta = (t - t_0)$

TABLE 1. Values of Correction Factor H in Relation to K and Fo

Fo	K					
	0,02	0,03	0,04	0,08	0,09	0,1
0,1	1,000	1,000	1,000	1,000	1,000	1,000
0,2	1,003	1,003	1,003	1,006	1,006	1,006
0,3	1,005	1,007	1,007	1,011	1,013	1,015
0,4	1,008	1,010	1,012	1,019	1,020	1,023
0,5	1,009	1,012	1,014	1,024	1,028	1,029
0,6	1,011	1,014	1,017	1,029	1,032	1,035
0,7	1,011	1,015	1,019	1,034	1,037	1,042
0,8	1,013	1,017	1,022	1,038	1,043	1,047
0,9	1,014	1,019	1,024	1,042	1,047	1,050
1	1,015	1,019	1,026	1,046	1,052	1,056
3	1,028	1,038	1,049	1,095	1,106	1,117
4	1,032	1,045	1,058	1,112	1,126	1,140
5	1,035	1,050	1,066	1,127	1,143	1,160
6	1,038	1,055	1,073	1,142	1,159	1,177
7	1,042	1,061	1,079	1,155	1,174	1,192
8	1,044	1,064	1,086	1,166	1,186	1,206
9	1,047	1,068	1,089	1,177	1,199	1,221
10	1,049	1,072	1,094	1,188	1,211	1,235
20	1,070	1,103	1,135	1,271	1,306	1,339
50	1,109	1,161	1,217	1,439	1,495	1,550
100	1,153	1,230	1,309	1,629	1,709	1,792

*The voltage drop on the other parts of the electric circuit of the FRT remains constant during the measurement and, hence, has no effect on the measured value.

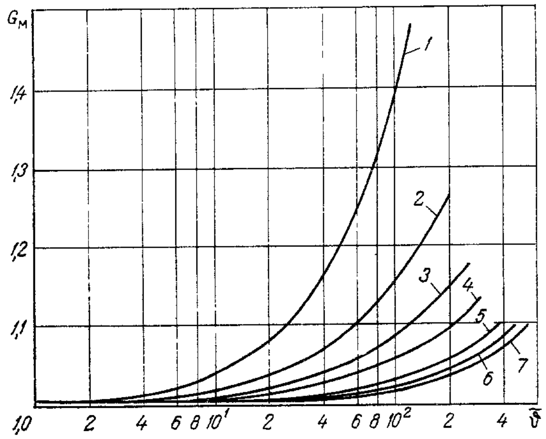

Fig. 2. Correction factor G_M as function of approximate mean excess temperature $\tilde{\vartheta}$°C of a platinum film at different Fo of the film for K = 0.02...0.1 [1) Fo = 0.1; 2) 0.2; 3) 0.3; 4) 0.4; 5) 0.7; 6) 1; 7) 10; 100].

$$\rho = \rho_0 (N + D\vartheta + B\vartheta^2), \tag{5}$$

where

$$N = 1 + At_0 + Bt_0^2, \tag{6}$$

$$D = A + 2Bt_0. \tag{7}$$

In (5)-(7) ρ_0 is the resistivity at t = 0°C; A and B are the thermal resistance coefficients.

In approximate calculations, and also for some metals (copper, etc.), we can take B = 0 and relationship (5) becomes linear. For semiconducting (thermistor) films, according to [4], an exponential relation between ρ and the absolute temperature is suitable:

$$\rho = \rho_0 \exp [C/(T_0 + \vartheta)], \tag{8}$$

where ρ_0 is the resistivity at the characteristic absolute temperature.

It follows from (5)-(8) that with increase in temperature the resistivity of metal films increases, while that of semiconducting films decreases.

The excess temperature field of the heated film at each instant is given by the solution of the heat conduction boundary-value problem for a two-layered model representing the FRT with boundary conditions corresponding to the heating and heat loss of the film. The local excess temperature ϑ of the film can always be related to its mean excess temperature $\bar{\vartheta}$ by means of a dimensionless factor R on the basis of an analytical or numerical solution of the heat conduction boundary-value problem, as was done in [5], for instance. Converting to dimensionless coordinates and the quantities $\bar{x}=x/l$, $\bar{y}=y/l$, $\bar{z}=z/l$, $\bar{b}=b/l$, $\bar{h}=h/l$, we obtain

$$\vartheta(\bar{x}, \bar{y}, \bar{z}, \tau) = \bar{\vartheta}(\tau) R(\bar{x}, \bar{y}, \bar{z}, \tau), \tag{9}$$

$$\bar{\vartheta}(\tau) = \frac{1}{4\bar{b}\bar{h}} \int_0^1 \int_{-\bar{b}}^{+\bar{b}} \int_{-\bar{h}}^{+\bar{h}} \vartheta(\bar{x}, \bar{y}, \bar{z}, \tau)\, d\bar{x} d\bar{y} d\bar{z}. \tag{10}$$

Using the known physical relations given in [6], e.g., we can easily write the expression for the electric current I flowing through the film and keeping a constant value:

$$I = \int_0^l \int_{-b}^{+b} j(x, y)\, dxdy = \int_0^l \int_{-b}^{+b} \frac{E(x, y, z, \tau)}{\rho(x, y, z, \tau)}\, dxdy, \tag{11}$$

where j is the local electrical current density in the cross section of the film; E is the local electric field strength; ρ is the local resistivity. The values of E and ρ vary in time along with the temperature field of the film.

With sufficient accuracy for engineering calculations, neglecting transverse and eddy currents, we can assume that the electric field strength is constant in each cross section of the film and take E(z, τ) out of the integrand in (11), and then determine its value:

$$E(z,\ \tau) = I\left[\int_0^l \int_{-b}^{+b} \frac{dxdy}{\rho(x,\ y,\ z,\ \tau)}\right]^{-1}. \tag{12}$$

The voltage drop U along the film at each instant is

$$U(\tau) = \int_{-h}^{+h} E(z,\ \tau)\, dz. \tag{13}$$

Substituting in (13) the value of E from (12) and converting to dimensionless coordinates and dimensions, we obtain

$$U(\tau) = (I/l)\int_{-\bar{h}}^{+\bar{h}}\left[\int_0^1 \int_{-\bar{b}}^{+\bar{b}} \frac{d\bar{x}d\bar{y}}{\rho(\bar{x},\ \bar{y},\ \bar{z},\ \tau)}\right]^{-1} d\bar{z}. \tag{14}$$

The value of ρ from (5) or (8) is substituted in (14) using (9), which allows us to write

$$U(\tau) = (I\rho_0/l)\, J(\bar{\vartheta},\ \tau) \tag{15}$$

dimensionless integral for metal films is

$$J_{\text{M}}(\bar{\vartheta},\ \tau) = \int_{-\bar{h}}^{+\bar{h}}\left[\int_0^1 \int_{-\bar{b}}^{+\bar{b}} \frac{d\bar{x}d\bar{y}}{N + D\bar{\vartheta}(\tau)R(\bar{x},\ \bar{y},\ \bar{z},\ \tau) + B\bar{\vartheta}^2(\tau)R^2(\bar{x},\ \bar{y},\ \bar{z},\ \tau)}\right]^{-1} d\bar{z}, \tag{16}$$

and for semiconducting films is

$$J_{\text{s}}(\bar{\vartheta},\ \tau) = \int_{-\bar{h}}^{+\bar{h}}\left\{\int_0^1 \int_{-\bar{b}}^{+\bar{b}} \exp\left[\frac{-C}{T_0 + \bar{\vartheta}(\tau)R(\bar{x},\ \bar{y},\ \bar{z},\ \tau)}\right] d\bar{x}d\bar{y}\right\}^{-1} d\bar{z}. \tag{17}$$

The voltage drop U(0) on the unheated film is easily determined from (15) by substituting $\bar{\vartheta}(0) = 0$ in the dimensionless integrals and performing the integration. The difference in voltage drops on the heated and unheated film $\delta U(\tau) = U(\tau) - U(0)$. For metal films

$$\delta U_{\text{M}}(\tau) = (I\rho_0/l)\left[J_{\text{M}}(\bar{\vartheta},\ \tau) - N\frac{h}{b}\right] > 0, \tag{18}$$

and for semiconducting films

$$\delta U_{\text{s}}(\tau) = (I\rho_0/l)\left[J_{\text{s}}(\bar{\vartheta},\ \tau) - \frac{h}{b}\exp(C/T_0)\right] < 0. \tag{19}$$

We note incidently that the heating of films by electric current can be assessed more accurately if (15) is used to determine the increase in the mean excess temperature of the film:

$$\delta\bar{\vartheta}(\tau) = (I/4lbhc\gamma)\int_0^\tau U(\omega)\, d\omega = (I^2\rho_0/4l^2bhc\gamma)\int_0^\tau J(\bar{\vartheta},\ \omega)\, d\omega. \tag{20}$$

The approximate mean excess temperature $\tilde{\vartheta}$ of the film, which is determined without regard to the effect of the temperature field and heat loss, and for metal films, in addition, by linearization of relation (5), can be related to the effective resistivity of metal films

$$\tilde{\rho}(\tau) = \rho_0[1 + At_0 + A\tilde{\vartheta}(\tau)] \tag{21}$$

and semiconducting films

$$\tilde{\rho}(\tau) = \rho_0\exp[C/(T_0 + \tilde{\vartheta}(\tau))]. \tag{22}$$

The voltage drop on the film at each instant is

$$U(\tau) = I\tilde{\rho}(\tau)h/lb. \tag{23}$$

The voltage drop U(0) on the unheated film corresponds to the values of $\tilde{\rho}(0)$ obtained from (21) or (22) with $\tilde{\vartheta}(0) = 0$. The difference in voltage drops on the heated and unheated metal film is

$$\delta U_{\text{M}}(\tau) = I\rho_0 hA\tilde{\vartheta}(\tau)/lb \tag{24}$$

and on the semiconducting film is

$$\delta U_{\text{s}}(\tau) = (I\rho_0 h/lb)\{\exp[C/(T_0 + \tilde{\vartheta}(\tau))] - \exp(C/T_0)\}. \tag{25}$$

Since the left-hand sides of (18) and (24) or (19) and (25) contain equal, measured values, we can, accordingly, equate the right-hand sides, thus connecting the approximate mean excess temperature with the true temperature by the following relations. For metal films

$$\tilde{\vartheta}(\tau) = \frac{1}{A}\left[\frac{b}{h} J_{\text{M}}(\bar{\vartheta}, \tau) - N\right], \tag{26}$$

and for semiconducting films

$$\tilde{\vartheta}(\tau) = C \ln^{-1}\left[\frac{b}{h} J (\bar{\vartheta}, \tau)\right] - T_0; \tag{27}$$

whence it is easy to find the correction factor G by which the approximate mean excess temperature must be multiplied to determine the true temperature. For metal films, according to (26),

$$G_{\text{M}}(\bar{\vartheta}, \tau) = \frac{\bar{\vartheta}(\tau)}{\tilde{\vartheta}(\tau)} = A\bar{\vartheta}(\tau) \Big/ \left[\frac{b}{h} J_{\text{M}}(\bar{\vartheta}, \tau) - N\right], \tag{28}$$

and for semiconducting films, according to (27),

$$G_{\text{s}}(\bar{\vartheta}, \tau) = \frac{\bar{\vartheta}(\tau)}{\tilde{\vartheta}(\tau)} = \frac{\bar{\vartheta}(\tau) \ln\left[\frac{b}{h} J_{\text{s}}(\bar{\vartheta}, \tau)\right]}{C - T_0 \ln\left[\frac{b}{h} J_{\text{s}}(\bar{\vartheta}, \tau)\right]}. \tag{29}$$

The value of the correction factor when $\bar{\vartheta}(\tau)$ tends to zero tends to a constant $G_{\lim}$. Convincing evidence of this is obtained by determination of the errors arising in the right-hand sides of (28) and (29) when $\bar{\vartheta}(\tau) = 0$. The determination of the errors requires the differentiation of the dimensionless integrals with respect to parameter $\bar{\vartheta}$. Omitting the deduction we will indicate that $G_{M\ \lim} = (1 + 2Bt_0/A)^{-1}$ and differs little from unity, while $G_{s\ \lim} = 1$.

It is important to note that there is a fairly wide region of comparatively low heatings of the films where $G \approx G_{\lim}$ and the effect of temperature fields on measurements of heat flux densities is negligible. On the other hand, at high heatings of films, close to the maximum permissible, the value of the correction factor differs greatly from the limiting value and depends on the structure of the temperature fields.

Calculating the correction factor as a function of $\bar{\vartheta}$ we can conveniently make the substitution $\tilde{\vartheta} = \bar{\vartheta}/G$ and obtain $G(\tilde{\vartheta}, \tau)$. The values of $\tilde{\vartheta}$ are determined according to (24) or (25) and depend only on the measured values and constants of the FRT. For metal films

$$\tilde{\vartheta}(\tau) = \delta U_{\text{M}}(\tau)\, lb/I\rho_0 hA, \tag{30}$$

and for semiconducting films

$$\tilde{\vartheta}(\tau) = C \ln^{-1}[\delta U_{\text{s}}(\tau)\, lb/I\rho_0 h + \exp(C/T_0)] - T_0. \tag{31}$$

Errors in determination of $\tilde{\vartheta}$ have little effect on the accuracy of calculation of G_M; i.e., function $G_M(\tilde{\vartheta})$ is very stable.

To determine the required mean excess temperature of the film in the absence of a heat loss $\bar{\vartheta}^*$ in the general case we must introduce a second correction factor to compensate for the heat loss of the film by the time of measurement:

$$H(\tau) = \bar{\vartheta}^*(\tau)/\bar{\vartheta}(\tau). \tag{32}$$

On the basis of (3), (10), and (32) for films of any materials

$$H(\tau) = (4bh/c\gamma l^3)\int_0^{\tau} q(\omega)\, d\omega \left[\int_0^1 \int_{-\bar{b}}^{+\bar{b}} \int_{-\bar{h}}^{+\bar{h}} \vartheta(\bar{x}, \bar{y}, \bar{z}, \tau)\, d\bar{x} d\bar{y} d\bar{z}\right]^{-1}. \tag{33}$$

Dimensionless conversion of the time function q contained in the integrands of the numerator and denominator of the right-hand side of (33) allows the use of only the dimensionless analog in the integration, and the conversion scales are reduced. In some cases the value of the heat pulse $u = \int_0^{\tau} q(\omega)\, d\omega$ is known and it can be substituted in (33). If heat losses can be neglected, then H = 1. Thus, according to (28), (29), and (32),

$$\bar{\vartheta}^*(\tau) = \bar{\vartheta}(\tau)\, G(\tilde{\vartheta},\ \tau)\, H(\tau). \quad (34)$$

After determination of $\bar{\vartheta}^*(\tau)$ calculation of the heat flux density from (4) requires differentiation, performed numerically or graphicoanalytically, and $\frac{d\bar{\vartheta}^*}{d\tau} = GH\ \frac{d\tilde{\vartheta}}{d\tau}$ if the correction factors in the differentiation interval are practically constant.

As an example, from the data of [7] we give the values of the correction factors, calculated by computer, for an FRT with a film of "Ékstra" platinum ($A = 3.94 \cdot 10^{-3}$; $B = -5.8 \cdot 10^{7}$), heated by a rectangular heat pulse ($q = \text{const}$) from $t_0 = 20°C$ to local temperatures not exceeding 660°C. For the calculations we used the solution of the unidimensional (in x) problem of heat conduction in the case of ideal thermal contact of the film (infinite plate) with the substrate (semiinfinite body) and the absence of heat loss in the wires and surrounding medium. The dimensionless parameters of the solution are the Fourier number $Fo = a\tau/l^2$ of the film and the similarity number $K = \sqrt{\lambda_1 c_1 \gamma_1 / \lambda c \gamma}$, where a is the thermal diffusivity and λ is the thermal conductivity of the film, and the symbols for the thermophysical parameters of the substrate are distinguished only by the subscript 1.

Figure 2 shows graphs of $G_M(\tilde{\vartheta},\ Fo)$ for $K = 0.02\ldots0.1$, $G_M \lim \approx 1.006$. The values of $\tilde{\vartheta}$ corresponding to $G_M = 1.05$ increase from 12.5 to 280°C with increase in Fo from 0.1 to 10...100. At maximum heatings $G_M = 1.1\ldots1.48$.

Table 1 gives values of H(K, Fo) suitable for films of any materials. The data of Table 1 indicate negligible heat loss by the film ($H \approx 1$) when $Fo \leqslant 0.3$.

In conclusion, we note that the correction factors remove the systematic error due to the use of $\tilde{\vartheta}$ instead of $\bar{\vartheta}^*$. Hence, they should be used in calculations mainly in cases where the absolute difference $|GH - 1|$ exceeds the random relative error of determination of $\tilde{\vartheta}$, or is at least comparable to it.

In addition, we recall that the solution of the heat-conduction boundary-value problem requires calculation of the correction factors and the assignment of boundary conditions, including the dimensionless analog of the time function of the heat flux density. The boundary conditions can usually be assigned only approximately, which affects the values of the correction factors. The most reliable are calculations for limitation of the region of parameters within which the correction factors are close to unity, since the effect of inaccuracy of the boundary conditions on the results of calculations here is much less. In planning measurements in which high heatings of the films are expected, and a satisfactory approximation of the boundary conditions is impossible, one must consider whether it might be better to replace FRT of the calorimetric type by thin-film resistance thermometers, where the heating of the film is isothermic, the thermophysical principles of the application of which are described in [5].

NOTATION

t, temperature, °C; t_0, °C (T_0, K), initial temperature; $\bar{t}$, mean temperature; ϑ, excess temperature; $\bar{\vartheta}^*$, mean excess temperature in absence of heat flux; $\bar{\vartheta}$, mean excess temperature with heat loss taken into account; $\tilde{\vartheta}$, approximate mean excess temperature; R, dimensionless excess temperature factor; τ, ω, time; q, heat flux density, W/cm^2; W, amount of heat; u, heat pulse, J/cm^2; c, heat capacity, J/(g·°K); γ, density, g/cm^3; λ, thermal conductivity, W/(cm · °K); a, thermal diffusivity, cm^2/sec; Fo, Fourier number of film; K, similarity number; l, 2b, 2h, thickness, width, and length of film, cm; s, v, area of heated surface, cm^2, and volume of film, cm^3; x, y, z, coordinates; $\bar{x}$, $\bar{y}$, $\bar{z}$, $\bar{b}$, $\bar{h}$, dimensionless coordinates and dimensions; ρ, ρ_0, electrical resistivity, Ω· cm; $\tilde{\rho}$, effective resistivity; A, B, C, thermal resistance coefficients, deg^{-1}, deg^{-2}, deg; N, D, dimensionless coefficients; I, electric current, A; j, electric current density, A/cm^2; E, electric field strength, V/cm; U, voltage drop, V; J, dimensionless integral; G, H, correction factors. Subscripts: M, metal; s, semiconductor; 1, substrate.

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ANALYSIS OF MEASUREMENT ERRORS OF CONVECTIVE HEAT-TRANSFER COEFFICIENT USING A THIN-WALLED HEAT-FLUX SENSOR

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A theoretical analysis of the errors is made and it is shown that the convective heat-transfer coefficient in steady conditions on a rotating object of investigation can be measured by thin-walled sensors.

Thin-walled heat-flux sensors [1] have so far been used mainly for measurement of radiative heat fluxes [1, 2]. An account of the method of investigating convective heat transfer in steady conditions by means of these sensors and the results of experimental tests of them are given in [3].

For a further investigation of the potential of sensors we analyzed the errors of measurement of the heat-transfer rate and experimentally tested the sensors on a rotating object — a steel disk of diameter 500 mm and thickness 15 mm. Thirty sensors of the construction illustrated schematically in Fig. 1 were mounted in the disk.

A thin element 1 in the form of a disk of constantan foil 0.05 mm thick was soldered into a copper case 2 in the form of a cylindrical bush with a hole 5 mm in diameter. A copper thermoelectrode 3 of diameter 0.05 mm was welded to the center of the thin element. The copper parts of the sensor — the case 2, the thermoelectrode 3, the wire 4 connected to the case, and the thin constantan element 1 — form a differential thermocouple with junctions at the center of the thin element and at its effective radius r_1.

The interior of the case was filled with heat-insulating material 5 and was closed by a copper plug 6. The investigated surface of the disk was subjected to jets of air from perpendicular nozzles of a radius of 200 mm. On the opposite side heat was delivered to the disk from a stationary electric heater.

The airflow rate, number and diameter of nozzles, angular velocity of the disk, and the distance from the nozzles to the investigated surface were varied in wide ranges. In 20 sensors plastic foam was used as heat insulation, and in the rest Kel-F was used. Heat transfer at the face of the thin element gives rise to a temperature difference between its periphery at effective radius r_1 and the center, which can be determined from the thermal emf of the differential thermocouple of the sensor. The connection between this difference and the heat-transfer coefficient on the face of the thin element is given by the relation

$$I_0(m) = 1/(1 - \Delta\overline{T}_0), \tag{1}$$

obtained in [3] from the equation

$$\frac{\theta_p}{\theta_e} I_0(m\overline{r}) = I_0(m) = \text{const} \tag{2}$$

for the temperature field of a thin element in the case of convective heat transfer. Here the parameter $m = r_1\sqrt{\alpha/\lambda_e\Delta}$, including the required quantity α, characterizes the thermophysical and geometric parameters of the sensor.

The sensors on the object of investigation were placed in groups of six at radii 160, 180, 200, 215, and 232 mm. To increase the accuracy of measurement of α and reduce the effect of the stray emf of the current-removing device the sensors of each group were connected in series and formed differential thermopiles, consisting of six sensors, electrically insulated from the disk by Textolite collars 7. A constantan wire 8 of

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