INFLUENCE OF THE CALORIMETRIC-ELEMENT CHARACTERISTICS ON THE RESULTS OF HEAT-FLUX MEASUREMENTS

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The results of an experimental study of the influence of the dimensions of the calorimetric element and the properties of its material on the measured heat flux are examined. Recommendations for calculating the thickness of a heat-flux sensor are made, and two methods of measuring the thermal conductivity of various metals in the case of samples heated by a plasma jet are proposed.

When an exponential technique is used for measuring heat fluxes, it is imperative to know the influence of the calorimetric element, the type of material from which it is made, and the properties of the material of the protective sleeve on the magnitude of the measured heat flux.

These problems are of primary importance when studying heat-transfer intensity by this or other techniques. Study of these problems is also of interest in the determination of the laws governing heat transfer between solid bodies and plasma flows. It is well known that heat-transfer intensity under nonstationary conditions can differ appreciably from heat transfer under stationary conditions. This leads to the question of whether results of heat-flux measurements performed by nonstationary methods are suitable for establishing heat-transfer laws for stationary conditions.

Some of these questions have been studied in [2] by analyzing the solution to a one-dimensional heat-conductivity equation for boundary conditions of the second kind.

In this paper we present the results of an experimental verification of the laws established, and we examine the conclusions which derive from these laws.

Influence of sample length on the measurement of heat-transfer intensity. The rate at which an infinite plate is heated by a steady heat flux can be computed from expression (20) in reference [1, p. 155]. The laws which govern heating are given in dimensionless form in Figure 5.3 of this book. Analysis of the relations plotted in the figure showed that, starting with $F_0 = 0.3$, neglect of the series in expression (20) leads to an error of less than 1%. Hence, for $F_0 \geq 0.3$, we have

$$t = \frac{q\tau}{\rho cl} + \frac{ql}{\lambda}\,\frac{3x^2 - l^2}{6l^2}. \qquad (1)$$

Taking the time derivative of the temperature, we get a formula for calculating the heat flux by an exponential technique,

$$q = \rho cl \frac{dt}{d\tau} \quad \text{for Fo} \geqslant 0.3. \qquad (2)$$

From expression (1), it follows [2] that there exists an optimal and a limiting thickness of the calorimetric element which are defined, respectively, by the relations

$$l_{\text{opt}} = 0.73\,\frac{\lambda t_m}{q} \qquad (3)$$

$$l_{\text{lim}} = 1.46\,\frac{\lambda t_m}{q}. \qquad (4)$$

The time required for the temperature curve to become linear, and the time to the onset of melting at the heated surface can be determined, respectively, from the expressions

$$\tau_1 = 0.3\,l^2/a \qquad (5)$$

$$\tau_2 = \frac{l\lambda t_m}{aq} - \frac{1}{3}\,\frac{l^2}{a}. \qquad (6)$$

It is obvious that in the case of a steady flux (the specific heat and density of the material are practically constants), the temperature measured in any cross section of the plate (x = const) must be a linear function of time (1). Hence, if the experimentally obtained relations between temperature and time are linear, it may be safely assumed that the experimental conditions were one-dimensional and that the heat flux was steady.

In [3] it was shown that the heat flux under nonstationary conditions is affected by the dimensions of the body measured in the direction of the heat flux; however, when the dimensions diminish to a certain value, heat-transfer intensity is no longer influenced by the dimensions. These findings were checked by experiments in which copper samples of various lengths were heated in a plasma jet.

The samples were cylinders measuring 10 mm in diameter and 1, 2.5, 5, 10, 25, 50, and 100 mm long. One-dimensional heating was accomplished by protecting the lateral surface of the samples from heating by textolite sleeves shaped as a truncated cone and provided with an axial hole into which the sample fitted tightly. The sleeve, in turn, was fixed in a metallic tube which was aligned with the jet axis by means of the sensor bracket.

The electric-arc heater in which the gas was heated is described in [4]. All samples were tested under the same experimental conditions characterized by the following parameters: power expended in the arc—80 kW, gas consumption—2 g/sec, diameter of the noz-

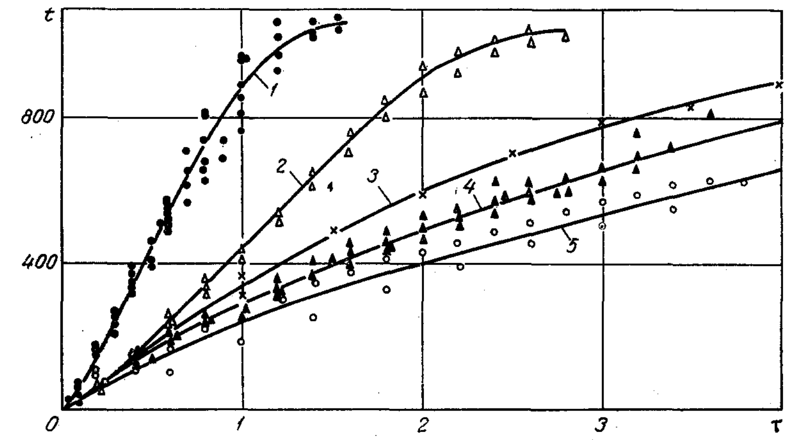

Fig. 1. Sample temperature, t (°C) vs. time τ (sec) for $l - x = 5$ mm: 1) $l = 5$ mm, 2) $l = 10$ mm, 3) $l = 25$ mm, 4) $l = 50$ mm, 5) $l = 100$ mm.

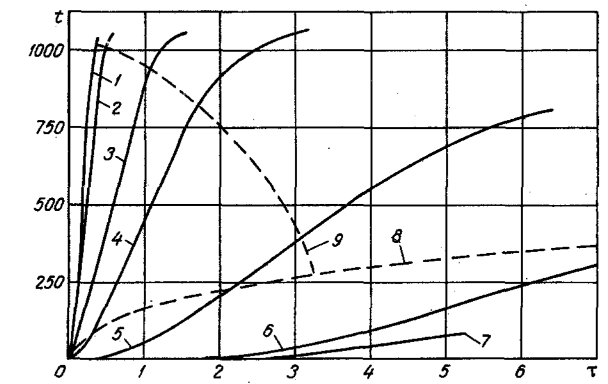

Fig. 2. Sample temperature t (°C) vs. time τ (sec) for x = 0: 1) $l = 1$ mm, 2) $l = 2.5$ mm, 3) $l = 5$ mm, 4) $l = 10$ mm, 5) $l = 25$ mm, 6) $l = 50$ mm, 7) $l = 100$ mm, 8) τ_1, 9) τ_2.

zle exit section—15 mm, spacing between the nozzle exit section and the sample—25 mm. These parameters correspond to an enthalpy of 14 600 kJ/kg (T = 6300°K) of the gas flow acting on the sample and to a stagnation pressure of 1 atm. The maximum deviation of the power and the gas enthalpy from the mean value was 10%. Samples measuring 1, 2.5, and 5 mm in length were provided with one thermocouple. Each of the longer samples was provided with two thermocouples at distances of l (l is the sample length) and 5 mm from the end face exposed to the jet.

In order to minimize the random error, samples of all sizes were subjected to heating 3 to 8 times.

The averaged heating characteristics obtained for copper samples are given in Figs. 1 and 2. Linear segments on the temperature curves can be observed for samples of small dimensions. A comparison of the curves in Figs. 1 and 2 shows that the linear segments of the curves obtained for various cross sections of 10- and 25-mm-long samples have the same slope. For 50-mm-long samples, the curves deviate over the entire heating time.

Analysis of the temperature vs. time curves obtained for the $l - x = 5$ mm and $x = 0$ sections across the sample (Figs. 1 and 2) shows that a dimension of roughly 25 mm separates the family of temperature curves into two parts. For smaller sample dimensions, linear segments can be observed on the temperature vs. time curves, while for large dimensions linear segments are absent.

The time to the commencement and termination of the linear segments and the limiting sample thickness can be computed from the formulas given above. The results of computations performed for copper samples confirm the conclusions made on the basis of measurements. The computed and measured values of τ_1, τ_2, l_{lim}, and l_{opt} are in satisfactory agreement (Fig. 2, Table 1).

The optimal sample length for the heat flux employed is 14.8 mm; this corresponds to a maximum duration of the linear segment equal to 1.54 sec (Table 1). For sensor dimensions of 30 mm and more, a linear segment is not observed under the given conditions.

Table 1

Calculation of Sensor Dimensions for Various Metals

Material	q, kW/cm²	l_{opt}, mm	l_{lim} mm	$\Delta\tau_{max}$, sec	t_m, °C	
					from the literature	experiment
Aluminum	1.4	7.8	15.7	0.51	660	640
Tin	0.49	1.9	4.43	0.085	232	220
Copper	1.92	14.8	30.0	1.54	1083	1060
1Cr18Ni9Ti steel	1.58	1.75	3.51	0.05	1535 (iron)	—
Brass	1.73	3.06	6.15	0.228	850	830

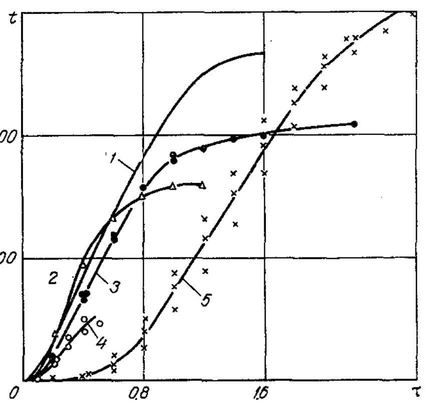

Fig. 3. Sample temperature t (°C) for various materials vs. time τ (sec), for l = 5 mm: 1) copper, 2) aluminum, 3) brass, 4) tin, 5) stainless steel.

Formal determination of heat fluxes by an exponential technique (formula (2)) leads to faulty results for sample dimensions greater than l_{lim} (and, in practice, for smaller dimensions close to l_{lim}).

The heating curves obtained were used for calculating heat fluxes for various sample lengths (Fig. 4a). The deviation of the measured values from the mean value for a length of 25 mm does not exceed 10%. An exception is the 1-mm-thick sample for which the diameter of the thermocouple junction (0.2-mm-diam wires were employed) is compatible with the sample thickness.

With an increase in dimensions to 50 mm, the deviation of the measured heat flux from the actual value reaches 30%. As has been noted above, this deviation may be attributed to sample melting prior to the commencement of a linear segment.

The results of the determination of heat fluxes from temperature gradients measured for various sample cross sections agree with each other within an error of less than 12%.

Influence of the material properties of the calorimetric element on the results of heat-transfer-intensity measurements. The value of the steady heat flux determined from expression (2) should be independent of the properties of the calorimetric element. When the parameter ρc varies, the value of $dt/d\tau$ should vary in such a way that their product would remain constant.

With expression (2), however, its range of applicability should be kept in mind. Formal application of an exponential technique may lead to incorrect results.

Samples for use in heat-flux measurements were prepared from copper, aluminum, brass, tin, and stainless steel in the form of 5-mm-long cylinders. The cylinder diameter and the method of achieving one-dimensional heating were the same as in the case of copper sensors of various length. The sample temperature was measured at the cross section x = 0.

On the temperature vs. time curves obtained (Fig. 3), one can distinguish linear segments whose duration depends on the melting point of the material. Heat flux calculations on the basis of expression (2) and of the relations obtained showed that the heat flux varies depending on the type of material, in spite of the fact that all the parameters of the hot gas flow were kept constant in all tests (Fig. 4b). Specifically, for tin, the ratio of the heat flux to the heat flux measured with a copper calorimeter is equal to 0.26.

The heat flux values measured with sensors made from other materials lie within ±10–12% of the mean value; this does not exceed the error involved in the determination of heat fluxes by an exponential technique.

The results obtained may be explained by examining the manner in which the optimum and limiting sensor lengths depend on the type of material (Table 1).

In the case of tin and steel, the sensor dimension (5 mm) employed exceeds the limiting value for these materials. Consequently, on the temperature vs. time curves for these materials, linear segments are essentially absent, but the curves exhibit an inflection from concave to convex. Formally, this inflection region can be taken as a linear one. Heat flux determi-

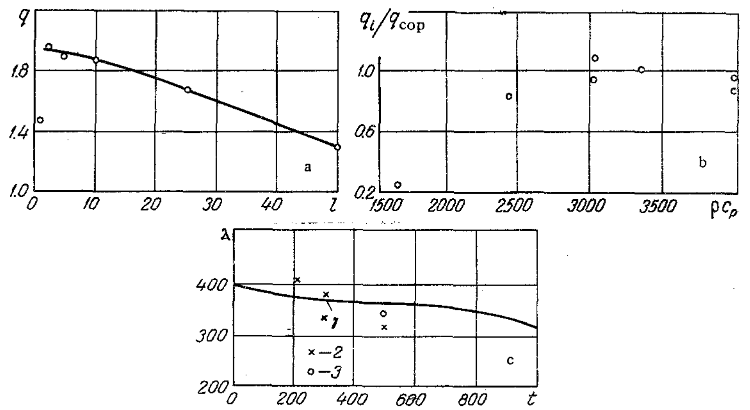

Fig. 4. Results of an analysis of the temperature curves: a) heat flux q (in kW/cm²) vs. sample length l (in mm), b) relative heat flux q_i/q_{cop} vs. the parameter ρc_p (in kJ/m³ · deg), c) thermal conductivity coefficient λ of copper (W/m · deg) vs. temperature t (°C); (1—from paper [5], 2—first method, 3—second method).

nation from the gradient at this region leads to arbitrary heat flux values.

Thus, for correct determination of heat fluxes, it is necessary that the thickness of the calorimetric element for a given material and a given heat flux lie within limits which ensure the presence of a linear segment on the temperature curve. There is an optimal thickness of the calorimetric element in each case.

The experimentally obtained melting points of materials can serve as an indirect accuracy index for temperature measurements on samples of various materials heated in a plasma jet (Table 1). A comparison shows good agreement between the measured values and literature data.

Comparison between the exponential technique and the method of successive intervals. The method of successive intervals was developed in [3] for determining time-variable heat fluxes. In the determination of heat fluxes by this method, it is necessary to provide one-dimensional heating conditions for cylindrical samples, and to record the time variations of the temperature in an arbitrary cross section of the sample.

The formula for calculating heat fluxes is

$$q_n = \frac{\left[t(x,\tau) - t_0\right]\frac{\lambda}{l} - \sum_{i=1}^{i=n-1} q_i\,\mathrm{Fo}_i}{\mathrm{Fo}_n - \frac{1}{6} + \frac{x^2}{2l^2}}. \quad (7)$$

This formula is also applicable to the case examined in this paper. Heat fluxes can be determined by this method with the aid of the temperature vs. time curves obtained for the determination of heat fluxes by an exponential technique (Figs. 1,2).

Proceeding from expression (7), we can show that if the relation $t = f(\tau)$ is a straight line, the heat flux does not change in time and is a constant.

If q = const, the time intervals into which the process is divided are equal, and $t_0 = 0$, then

$$t = \frac{a}{\lambda l} q \sum_{i=1}^{n} \tau_i - \frac{l}{\lambda}\frac{q}{6} + \frac{l}{\lambda} q \frac{x^2}{2l^2} = \frac{q\tau}{c\rho l} + \frac{qx^2}{2\lambda l} - \frac{ql}{6\lambda}, \quad (8)$$

i.e., we have obtained expression (1) which represents a linear relation between temperature and time.

The method of successive intervals was used for calculating heat fluxes for 2.5-, 5-, and 10-mm-long samples heated in a plasma jet.

The computational formulas are

$$l=2.5 \text{ mm } \Delta\tau=0.02 \text{ sec}; \; q_n=0.68\cdot 10^6\,\Delta t - 1.89\,\Sigma q_i;$$
$$l=5 \text{ mm } \Delta\tau=0.1 \text{ sec}; \; q_n=2.3\cdot 10^5\,\Delta t - 1.6\,\Sigma q_i;$$
$$l=10 \text{ mm } \Delta\tau=0.3 \text{ sec}; \; q_n=1.93\cdot 10^5\,\Delta t - 2\,\Sigma q_i.$$

The difference between heat fluxes determined by both methods did not exceed 10%. This accuracy may be considered satisfactory for the given conditions.

It should be emphasized that for small sample lengths the value of the heat flux measured remains constant in time. Consequently, the results of heat-transfer-intensity measurements performed by a nonstationary method, such as the exponential method employed, are applicable in the case of heat transfer under stationary conditions.

For samples of greater length, a relation between the heat flux and time could not be established in our experiments, because samples of large dimensions began to melt prior to the onset of the segment on the temperature curve of interest to us.

Influence of the properties of the material of the protecting sleeve on the results of heat-flux measurements. The computational relations of the exponential method (formula (1) and others) were obtained under the assumption that the expansion of heat in a sample is one-dimensional. As has been said above, in order to obtain a one-dimensional heat flux, the lateral surface of the samples was protected by a textolite sleeve. The contact surface between the sample and the sleeve was a 4-mm-wide ring in the proximity of the front face of the sample. Beyond this ring, there was a 1-mm-wide air gap between the sample and sleeve.

The experimentally observed linear segments on the temperature curves confirm that heat expansion in the samples was one-dimensional. The short duration of the tests and the pronounced difference in the thermal-conductivity coefficients of the sample and sleeve were factors favorable for obtaining one-dimensional heat expansion.

Additional heating tests were performed with samples protected by sleeves made of textolite, hard rubber, and asbestos cement. The thermal-conductivity coefficients of these materials differed by as much as a factor of three. In the presence of appreciable radial heat fluxes, such changes in the properties of the protective sleeve are bound to lead to substantial changes in the quantity being measured. Measurements showed that the deviations of the heat-flux values are compatible with the conventional measurement error (±10–12%). This result is confirmed by the heating curves obtained for the samples. The temperatures measured in samples protected by hard-rubber and asbestos-cement sleeves lie on either side of the curve obtained for samples with a textolite sleeve.

Application of sample heating in a plasma jet to the determination of the thermal-conductivity coefficient of metals. With the aid of expressions (1) and (2), it is possible to obtain a relation for calculating thermal-conductivity coefficients (first method):

$$\text{for } x=0 \quad \lambda = \frac{l^2 \rho c_p dt/d\tau}{6\tau\, dt/d\tau - 6t} \quad (9)$$

and a relation for calculating thermal-diffusivity coefficients

$$a = \frac{l^2 dt/d\tau}{6\tau\, dt/d\tau - 6t}. \quad (10)$$

In order to determine λ and a from the expressions obtained, it is necessary to measure the temperature gradient at the linear segment of the temperature curve and the temperature at an arbitrary moment of time within the linear segment at the end face of the sample (x = 0). Thermal-conductivity and -diffusivity coefficients can be determined also by a different method.

Under the conditions studied, the temperature at the cross section x of a sample is

$$t_x = \frac{q\tau}{\rho cl} + \frac{qx^2}{2\lambda l} - \frac{ql}{6\lambda}.$$

For the cross section x = 0, the temperature is

$$t_{x=0} = \frac{q\tau}{\rho cl} - \frac{ql}{6\lambda}.$$

By subtracting the second expression from the first, after certain transformations and substitution of q, from (1), we get (second method)

$$\lambda = \frac{\rho cx^2 dt/d\tau}{2(t_x - t_{x=0})} \tag{11}$$

and

$$a = \frac{x^2}{2(t_x - t_{x=0})} \frac{dt}{d\tau}. \tag{12}$$

For determining λ and a in this case, it is necessary to measure the temperature difference at two cross sections of the sample and the temperature gradient at the linear segment of the heating curve.

By using the methods studied, it is possible to determine mean values of the thermal-conductivity coefficient for temperatures lying within the linear segment.

The samples used for determining thermal-conductivity coefficients had a simple configuration, quite similar to that of the heat-flux sensors discussed above.

To determine the thermal-conductivity coefficient of copper by the first method, use was made of the heating curve obtained for a 10-mm-long sample (Fig. 2). The density of copper in the temperature range between 25 and 670° C is taken as 8800 kg/m³, and the specific heat as 0.42 kJ/kg-deg. The rate at which the temperature varies over a linear segment is

$$\frac{dt}{d\tau} = \frac{670 - 25}{1.4 - 0.2} = 540 \text{ deg/sec}.$$

The thermal conductivity coefficient (τ = 0.4 sec, t = = 130° C) is $\lambda_{300^\circ\,C}$ = 383 W/m-deg. The value obtained differs by 2.8% from the value of the thermal-conductivity coefficient of copper for 300° C taken from the handbook.

The first method was used also to determine the thermal-conductivity coefficients of 2.5-, 5-, and 25-mm-long copper samples. The values obtained deviate by 6 to 13% from the corresponding tabulated values (Fig. 4c). For a 25-mm-long sample, the thermal-conductivity coefficient was determined also by the second method. The calculated value differs by 9.2% from the tabulated value for pure copper at t_{mean} = 200° C.

Table 2

Results of the Determination of the Thermal-Conductivit Coefficients of Some Metals

Material	λ_1 from [5, 6]	λ_2 experimental	$\frac{\lambda_2-\lambda_1}{\lambda_1}$, %
1Cr18Ni9Ti steel	20.4 (t=600 °C)	24.3 (t_m=600 °C)	19
Tin	55 (t=0 °C)	57 (t_m=100 °C)	3.6
Aluminum	195—127 (t=200 °C)	148 (t_m=200 °C)	—
Brass	110 (t=400 °C)	95 (t_m=400 °C)	—14

Thus, the properties of the copper employed in the experiments approach rather closely those of electrolytic copper. The methods developed yield satisfactory results. They were used to determine the thermal-conductivity coefficients of other metals from which calorimetric elements were made. The density and specific heat of materials are taken from [5, 6]. The rate of temperature variation was determined from the curves in Fig. 3.

The thermal conductivities determined for four metals (Table 2) confirm the effectiveness of the method discussed. It is possible that the error of 19% involved derives not only from measurement errors but also from a difference in the types of steel compared.

NOTATION

t is temperature, q is the specific heat flux, τ is time, l is the length of calorimetric element, x is the distance from the rear face of a sample to the cross section studied, t_m is the melting point of the material, $\Delta\tau_{max}$ is the maximum time interval for a linear segment, n is the number of the time interval, t_0 is the initial temperature of a sample.

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