METHODS OF MEASURING LARGE HEAT FLUXES

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Five methods of measuring heat fluxes are examined. Heat flux distributions across a jet of high-temperature gas are measured using two of these methods.

The problem of measuring large heat fluxes arises in many areas of technology. It is met, for example, in welding, in heating materials in high-temperature gas jets, and in a number of other cases.

Various techniques are used to measure heat fluxes in the range 1–10 kW/cm^2 and above. The object of this paper is to examine and compare the main methods applicable to a jet of high-temperature gas obtained with an electric-arc heater.

THE EXPONENTIAL (CALORIMETRIC) METHOD [1–7]

For small dimensions of the heated body and large thermal conductivity of the material or low values of the heat transfer coefficient, i.e., for small values of the parameter Bi = $\alpha l/\lambda$, the variation of body temperature (which under these conditions is the same at all points of the body) is decided by the rate of heat transfer between the body and the surrounding medium. In this case the body temperature is an exponential function of time. For this reason Kudryavtsev [1] refers to the "exponential method."

The amount of heat entering such a body in time $d\tau$ is equal to the change in heat content of the element.

$$Qd\tau = Gc_p dT \quad \text{or} \quad q = \delta\rho c_p \frac{dT}{d\tau} \tag{1}$$

(δ is the thickness of the element). For a given duration τ of the experiment there is a characteristic thickness $l = \sqrt{\alpha\tau}$, called the diffusion depth, which may be thought of as the approximate depth to which the heat flow has penetrated. If the thickness of the metal is of the same order as the diffusion depth, only a small amount of heat is transferred from the metal plate to the insulator.

The variation of temperature with time may be expressed in terms of the variation of the electrical values. If a current, which is held constant, is passed through a metallic specimen, the temperature variation may be related to the voltage variation as follows:

$$\frac{dT}{d\tau} = \frac{1}{\alpha_R R_0 I} \frac{dU}{d\tau}, \tag{2}$$

where α_R is the temperature coefficient of resistance.

Thus the expression for the heat flux takes the form

$$q = \frac{1}{IR_0} \left(\frac{\rho c_p \delta}{\alpha_R}\right) \frac{dU}{dt}. \tag{3}$$

The method of conducting the experiment depends on which of the two expressions given is used as the basis for the heat flux.

Models used to determine heat flux on the basis of expression (1) are hollow metal cylinders with plane, spherical and ellipsoidal ends of small wall thickness [2]. To reduce the error in heat flux determination arising from return flow of heat in the shell along the model generators, hemispherical models, made up of separate elements, have been used [3]. The temperature of each segment was measured with thermocouples. The slope of the curves $T_W = f(\tau)$ at zero time was used in the calculation, since the temperatures of the various segments changed at different rates, and isothermal conditions prevailed at zero time only.

When expression (3) was used, the sensor [4] consisted of platinum foil in contact with a pyrex model with a hemispherical head. The sensor covered 30° of the head. The foil had four leads—two current and two potential. The models were tested in a wind tunnel with air heated to a temperature of the order of 9000°K. The heat fluxes measured reached 40 kW/cm^2. These sensors were used in [6] under conditions where ionization of the gas was sufficient to cause electrical short-circuiting of the sensor. This effect was eliminated by insulating the sensor with a layer of silicon oxide of thickness 6×10^{-4} cm.

It was noted that a large error may arise from inexact evaluation of the time during which conditions were steady when the test time in the shock tube was 15–25 μsec.

HEAT FLUX DETERMINATION FROM CHANGE OF SURFACE TEMPERATURE [4, 8–11]

This method uses a solution of the heat conduction equation for a plate in perfect contact with a semi-infinite body [4].

If a metal plate is in contact with an insulator of semi-infinite thickness, and if, in addition, the metal thickness is very small, i.e., $l \ll l_{\text{insulator}} = \sqrt{\alpha\tau}$ (characteristic thickness of the insulator), the average temperature of the entire metal plate will be equal to the temperature of the contact.

$$T_{\text{met}} = \frac{2\sqrt{\alpha_{\text{ins}}}}{\sqrt{\pi}\,\lambda_{\text{ins}}}\, q_0 \sqrt{\tau}. \tag{4}$$

The metal temperature is determined by measuring its resistance, and the heat flux is found from (4). The thermal properties of the metal film and of the backing are assumed to be constant in deriving the theoretical relation, but, since the temperature of bodies in supersonic flow often reaches several hundred degrees, the validity of this assumption has been checked [8].

For constant heat flux, the change of surface temperature of a semi-infinite body is given by (4). A heat flux was produced by passing through the sensor a current pulse.

$$q = I_0^2 R(1 + \alpha_R T_{\text{met}}) \qquad (5)$$

and

$$\Delta U = R_0 I_0 \alpha_R \Delta T. \qquad (6)$$

Combining relations (4), (5), and (6), we obtain an expression for the product $\rho c \lambda$ in terms of values measured in the experiment:

$$(\pi \rho c \lambda)^{1/2} = \frac{2\alpha_R R_0 (1 + \alpha_R T) I_0^3 R_0}{4.18 A} \frac{t^{1/2}}{\Delta U}, \qquad (7)$$

where A is the area of the film.

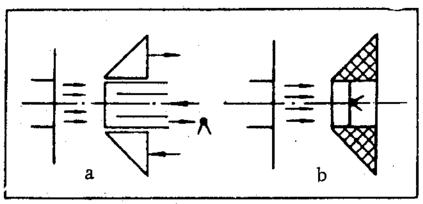

Fig. 1. Cooled (a) and uncooled (b) heat flux sensors.

The authors of [8] checked measurements of this kind for a number of substrate materials, and it was shown that there may be appreciable errors in calculating heat transfer rates from the dependence of surface temperature on time if the properties are assumed to be constant. Corrections to the temperature may be evaluated from an approximate solution of the one-dimensional heat conduction equation, taking into account the dependence of λ and c on temperature. The value of the correction determined using the expression obtained was 45% for a pyrex substrate and about 15% for quartz and glass substrates, at 150° C.

The authors of [9] used a resistance thermometer in the form of a platinum film 10^{-6} cm thick to measure the model surface temperature.

THE METHOD OF SURFACE POINTS [2]

The heat flux to a flat plate is given by the heat conduction law

$$q = -\lambda \left(\frac{\partial T}{\partial x} \right)_{x=0}. \qquad (8)$$

The gradient at the surface may be determined by solving the heat conduction equation for an infinite plate of thickness δ for the case of an initial distribution T (x, 0) = const and boundary conditions T (0, τ) = $\varphi_1(\tau)$ and T (δ, τ) = $\varphi_2(\tau)$. Differentiating the expression for the temperature with respect to x and substituting it into (8), we obtain an expression relating the heat flux to the change of temperature with time at the front and back surfaces [2].

To achieve test conditions approximating the heating of an infinite plate, the authors of [2] used a model in the form of a steel cylinder surrounded by two annuli of thermally insulating material to avoid heating the cylinder from the lateral surface. A thermocouple passes along the cylinder axis in a porcelain tube of diameter 1 mm, its junction being located on the heated end and covered by a silver plate of thickness 0.1 mm. The second junction of the thermocouple is located at the opposite end of the cylinder.

DETERMINATION OF HEAT FLUX FROM THE TIME AT WHICH THE MATERIAL STARTS TO MELT [12]

This method uses the solution of the one-dimensional heat conduction equation for a semi-infinite body with a constant heat flux at its surface (4) [13]. In the time interval τ_1 from the start of heating, the surface temperature reaches the melting point of the material, T_f. Substituting these values in (4), we obtain a formula for calculating the heat flux

$$q = \frac{\sqrt{\pi}}{2} \sqrt{\frac{\rho c_p \lambda}{\tau_1}} \cdot T_{f(\text{usion})}. \qquad (9)$$

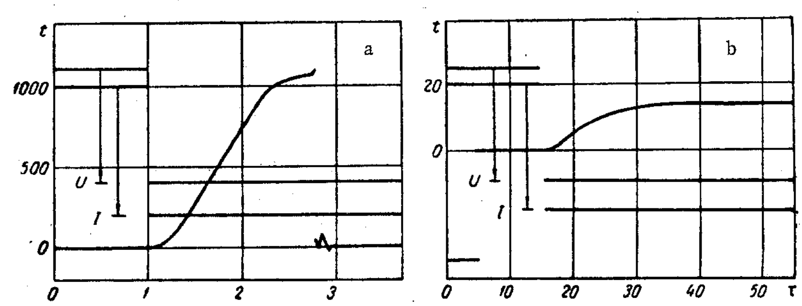

Fig. 2. Variation with time τ (sec) of the temperature t (°C) of an uncooled specimen (a), and of the temperature of the cooling water (b) recorded using a thermistor: a) with gas flow rate G_{N_2} = 5 g/sec; d_{cal} = 20 mm; specimen thickness δ = 7 mm; I = 590 a; U = 240 V; b) d_{cal} = 10 mm; flow rate of cooling water G_{cal} = 0.048 kg/sec; I = 570 a; U = 240 V.

Models consisting of copper and aluminum cylinders with their lateral surfaces protected by fiberflass were tested in a wind tunnel with an electric-arc air heater. The time to the start of melting was measured by taking photographs or with a timer.

THE COOLED CALORIMETER METHOD [14–17]

The heat flux to the cooled calorimeter is determined by the flow rate and heating of the cooling water. Thus

$$q = \frac{G \Delta t c_p}{f}, \tag{10}$$

where G and Δt are the flow rate and temperature rise of the cooling water, and f is the area of the heated surface of the sensor. The sensor used, for example, in [15], was a hollow copper cylinder with its lateral surface protected by a cooled annular screen.

The existing methods of measuring heat flux may be divided into unsteady and steady methods. Of the methods examined, the cooled calorimeter method is a steady one, while the remainder are unsteady. In applying unsteady methods, difficulties arise from the need to allow for the temperature dependence of the physical parameters of the specimen, and, in shock tube measurements, for the unsteadiness of the gas flow. On the other hand, very real errors may arise in the steady method, due to heat currents not conforming to the calculation model.

A comparison of the different methods is in order.

Measurements of heat flux were made in [4] by the exponential method and the change of surface temperature method. Both methods are unsteady and were used for measurements in a shock tube.

It is of interest to compare the two types of methods examined above under conditions of steady gas flow, and, in fact, in a gas jet heated to a temperature of the order of 7000° K and above in an electric-arc heater [18, 19].

Two methods were used for measuring heat flux in the present study: the cooled calorimeter method and the exponential method. The first, as noted above, is steady, while the second, which is the most widespread and convenient for our conditions, is an unsteady method.

The specimens used in the unsteady method were copper cylinders of thickness 5–8 mm. A schematic of the cooled calorimeter is shown in Fig. 1. The diameters of the calorimeter and of the specimen were 5, 10, 15, and 20 mm, and the thickness of the annular wall of the calorimeter was 3–5 mm. The temperature of the water cooling the calorimeter was recorded, using a type MMT-1 thermistor and a thermocouple, with an oscillograph and an electronic potentiometer, respectively, while the specimen temperature was recorded with a thermocouple (as shown in Fig. 1) and an oscillograph (Fig. 2). The specimens were mounted at distance L = 25 mm from the exit section of the nozzle of the discharge chamber, diameter 15 and 20 mm. All the measurements examined were made for one set of operating conditions of the electric-arc heater, in terms of power and gas flow rate.

The measurements showed (Fig. 3, curve 2), that in the core of the jet, diameter roughly 10 mm, the specific heat flux was constant over the section, and twice as large as the mean specific flux for the whole jet. The use of a cylindrical mixing chamber, length 100 mm, internal diameter 50 mm, and exit section diameter 20 mm, did not result in equalization of the heat flux over the jet section (Fig. 3, curve 1). Moreover, the presence of the mixing chamber reduced the heat flux by a factor of four, both in the core and over the whole section of the jet.

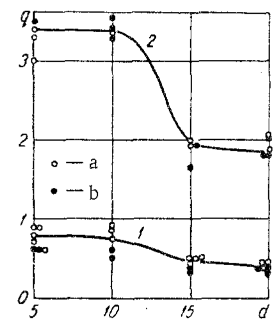

Fig. 3. Dependence of heat flux q (kW/cm^2) on sensor diameter d (mm): 1) with a mixing chamber, $d_{m.ch.}$ = 20 mm (mean mass enthalpy of the gas (nitrogen) at the exit $\overline{H}$ = 8700 J/g, mean mass velocity $\overline{W}$ = 270 m/sec); 2) without mixing chamber (d_{anode} = 15 mm, $\overline{H}$ = 13400 J/g, $\overline{W}$ = 600 m/sec); a) for a cooled sensor, b) uncooled.

The heat flux values measured by the two methods at various sensor diameters and jet parameters (Fig. 3) showed sufficiently good agreement.

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