LINEAR CALORIMETRIC PROBE OF IMPROVED SENSITIVITY

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A linear calorimetric probe of improved sensitivity has been developed. It permits measurement of heat flux and pulsations in heat flux up to a frequency of 160 Hz.

Contact methods of measuring thermal flux are widely used in investigations of the interaction of a thermal plasma with a material [1-6]. The linear calorimetric probe (LCP) is the simplest of these methods to use. It permits determination of local values of heat flux for a stationary axisymmetric stream by the conversion of empirical values using Abel's integral equation [1-4]. Recently probe designs and methods of using them have been proposed that make it possible to determine the local value of heat flows from a stationary plasma stream of any configuration without conversions [5-6]. However, these probes are characterized by a relatively high degree of inertia and are unsuitable for measuring pulsating thermal flows from a thermal plasma stream.

Our goal was to develop a high-sensitivity linear calorimetric probe (HSLCP) for measuring pulsating and local values of heat flux.

We used as a prototype the LCP design in [5] and added a second thermocouple C_2 in the annular gap between the tubes at a distance l from the probe end (Fig. 1) to improve its sensitivity. The width of the gap was chosen so that at a distance l from the probe end it would be equal to the thickness of the thermal boundary layer calculated from the formula in [7]

$$k = 4.64 l \sqrt{\mathrm{Re}} \sqrt[3]{\mathrm{Pr}}.$$

The diameter of the bead of thermocouple C_2 was chosen from the condition

$$\varnothing \approx k/(1.5-2).$$

The thermocouple beads were located close to the outer tube but in such a way as to preclude direct contact with the tube. To reduce overflows of heat through the inner tube, the latter was made of a material with a low coefficient of thermal conductivity (Alundum).

A layer of alumina $(0.2\text{-}0.3)\cdot 10^{-3}$ m thick was deposited on the outside end of the probe, reducing the contribution of heat flow from the probe end to the total heat flow into the probe to 0.1%. This contribution was subsequently ignored. The location of the thermocouple in the annular gap in LCP leads to the fact that it records pulsations in the temperature of the boundary-layer water from a small region of the probe surface. The boundary of the heat-sensing region of the HSLCP was determined by moving a point source of heat over the probe surface. The region runs lengthwise along the probe from the end to thermocouple C_2 and is limited in the annular gap by the diameter of the thermocouple junction.

The location of the thermocouple junction in the thermal boundary layer of the annular gap leads to the fact that the resulting measurements cannot be used to calculate local heat flux q. Thus, to calculate the latter the following formula is used

$$q = B\frac{G_1 c \Delta T''}{2\pi r l}, \tag{1}$$

in which the value of coefficient B must be determined by experiment. For this purpose, the end of the HSLCP was placed in a medium with a fixed temperature and the readings of both thermocouples were recorded. Here, B was determined as follows

$$B = \Delta T' l/\Delta T'' L. \tag{2}$$

For the conditions under which the HSLCP was calibrated (probe diameter $\varnothing$ = 3.5 mm, depth of

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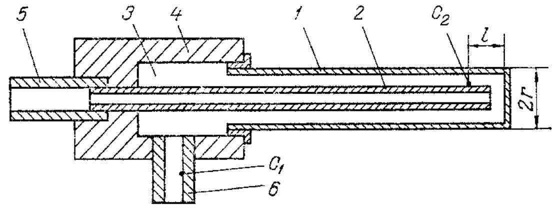

Fig. 1. Linear calorimetric probe of improved sensitivity: 1) outer copper jacket; 2) inner Alundum tube; 3) mixing chamber; 4) mount; 5, 6) water inlet and discharge nozzles, respectively; C_1, C_2) thermocouples.

immersion of the probe in dry stream L = 50 mm, thickness of annular gap b = 0.35 mm, diameter of thermocouple bead ∅ = 0.2 mm), B proved to have a value of 0.2.

In calculating local values of heat flux with Eq. (1), coefficient B will introduce a systematic error into the measurement results. The value of this error may be determined from the expression

$$\varepsilon = \frac{dB}{B} + \frac{dT'}{T'} + \frac{dT''}{T''} . \tag{3}$$

Estimates show that $dT'/T' = dT''/T'' \leqslant 2.5\%$, $dL/L \leqslant 5\%$ and $\varepsilon \leqslant 10\%$.

The total error in determining unit values of heat flux with the HSLCP may be computed from the formula

$$\frac{dq}{q} = \varepsilon + \frac{dT''}{T''} + \frac{dr}{r} . \tag{4}$$

Taking Eq. (3) into account, in accordance with Eq. (4) $\eta \approx 17.5\%$.

Experience in using the HSLCP has shown that its sensitivity depends considerably on the location of the thermocouple bead relative to the thickness (width) of the annular gap. The size of the heat-sensitive region decreases with a decrease in gap size.

Let us examine the thermophysical characteristics of the HSLCP compared to the LCP. All calculations will be performed for the HSLCP and known numerical values of these characteristics for the LCP will be displayed alongside in parentheses for the sake of comparison. The principal thermophysical characteristics that will be considered here are: time constant, phase—frequency characteristic, sensitivity, and measurement limits. The time constant τ, being a measure of the thermal inertia of the probe and determining its dynamic characteristics, is the time in which the recorder shows 0.6231 the value of the measured quantity starting from the beginning of the measurement [8,9]. If regular thermal conditions are established in the working volume of the probe, then we can proceed on the basis of the determination of the time constant τ at the thermocouple measurement point to describe the temperature with the equation [8,9]

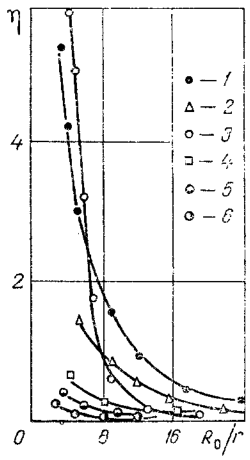

Fig. 2. Dependence of value of error η (%) in measurement of heat flux due to averaging through probe radius: 1, 4) $R = 0.1R_0$; 2, 5) $R = 0.5R_0$; 3, 6) $R = 0.9R_0$; 1, 2, 3) $R_0 = 1.7 \cdot 10^{-2}$ m; 4, 5, 6) $R_0 = 2.5 \cdot 10^{-2}$ m.

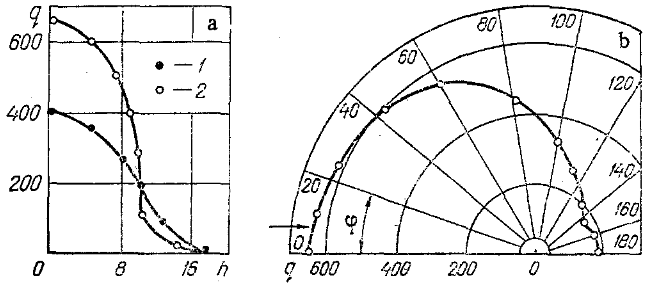

Fig. 3. Distribution of heat flux q, W/cm², over a distance h from the edge of the plasmatron nozzle: a) through radius of plasma stream [1) heat flux obtained with LCP; 2) same, HSLCP]; b) with rotation of HSLCP about its own axis (arrow denotes direction of inflowing plasma stream).

$$T = T_0\left(1 - \exp\frac{t}{\tau}\right).$$

The time constant of the probe was determined according to its response to a thermal P-pulse by the following method. A heat-insulating gate moved by an electromagnet was installed between the probe and heat source. The operating time of the gate did not exceed $8\cdot10^{-3}$ sec. With the gate open, we recorded the rate of increase in the temperature of the cooling water determined with thermocouples C_1 and C_2. The measurements were used to plot the function $\ln(T - T_0)$ versus time. The time constant τ was found from the slope tangent of the straight line $\ln(T - T_0) = t/\tau$. The time constant of the probe changed within the range 0.04–0.01 sec (0.3–0.7 sec) in relation to the rate of flow of the cooling water.

The phase–frequency characteristic determines the phase shift introduced into the measurements in relation to the frequency of the signal at the input [10]

$$\frac{Q_1}{Q_0} = \frac{1}{\sqrt{1+\omega^2\tau^2}}\sin(\omega t - \operatorname{arc\,tg}\omega t). \qquad (5)$$

Under the condition $Q_1/Q_0 = 0.1$, from Eq. (5) we determine the boundary frequency $\nu_2 = 160$ Hz. Thermal signals with a frequency no greater than 8 Hz are reproduced without distortion of the pulse shape. The applicability of Eq. (5) for the HSLCP was verified empirically. To this end, the probe was placed under the influence of a pulsating thermal flux with a smoothly changing frequency. The shape and repetition frequency of the thermal pulse were determined simultaneously by means of a photodiode. The experiments confirmed the validity of Eq. (5) for the HSLCP.

Probe sensitivity was determined from the relation

$$\delta = \frac{\Delta T}{T_m}\cdot 100\%,$$

and proved to be equal to $\delta = 0.5$–7.5% (1–15%). We will designate as the sensitivity threshold the minimum change in heat flux in the region of the thermocouple sufficient to cause a detectable change in the temperature of the coolant water.

The measurement limits are determined by the sensitivity threshold and the greatest thermal flux that can be recorded without physical damage to the probe. The upper limit was determined by the rate of flow of coolant water through the probe, the geometric dimensions of the probe, and the thermal conductivity of the material of the outer tube. For a probe of the design under discussion, the measurement range is 0.2–2500 W.

In measuring thermal flux with the LCP, the flux across the diameter of the LCP is averaged. Let us find the error introduced into the measurement by averaging:

$$\eta = \left(1 - \frac{q_{av}}{q_l}\right)\cdot 100\%,$$

where

$$q_{av} = \int_R^{R+2r} q(R)\,dR/2r.$$

Finally

$$\eta = \left[1 - \frac{\int\limits_{R}^{R+2r} q(R)\,dR}{2rq(R+r)} \right] \cdot 100\%. \qquad (6)$$

The value of q(R) for an air-plasma stream with vortical stabilization can be approximated by a third-order polynomial with an error no greater than 2%:

$$q(R+r) = q_0 + q_1(R+r) + q_2(R+r)^2 + q_3(R+r)^3. \qquad (7)$$

Calculations were performed with Eq. (6) with allowance for Eq. (7) on an ES1020 computer (Fig. 2). As can be seen from Fig. 2, even at $R_0/r \geqslant 10$ the error in the measurement of thermal flux due to averaging through the probe diameter does not exceed 1%.

Heat flux was measured in the air streams of a thermal plasma created by an indirect-action single-chamber plasmatron ($I = 119$ A; $U = 176$ V; $G_2 = 1.31^2$/sec; $D = 1.5 \cdot 10^{-2}$ m).

When introducing the probe into the high-temperature stream, we moved it along its own axis at a constant speed computed from the formula in [11]. Here, thermocouple C_2 was turned toward the direction of stream flow. As can be seen from Fig. 3a, the heat flux distribution on the axis of the plasma stream obtained with the HSLCP was 1.5 times greater in magnitude than that obtained with the LCP. This is understandable, since the braking thermal flux is being measured when thermocouple C_2 is positioned counter to the direction of the stream. We also made measurements of heat flux in the HSLCP on the stream axis with rotation of the probe about its own axis. The character of heat flux distribution for the thermal plasma stream in this case (Fig. 3b) is similar to curves obtained earlier for a stream of heated air [12,13].

NOTATION

Re, Reynolds number with characteristic dimension b; Pr, Prandtl number; q, heat flux density; G, mass flow of cooling water; c, specific heat of water; T", excess temperature of thermocouple C_2; r, probe radius; L, depth of immersion of probe in heated medium; T', excess temperature of thermocouple C_1; T_0, initial temperature of thermocouple; t, time; Q_1, heat flux recorded with thermocouple; Q_0, heat flux acting on the probe; ω, angular frequency; $Q = Gc\Delta T$, sensitivity threshold; $Q_m = Gc\Delta T_m$, maximum heat flux recorded by probe; $q_l = q(R + r)$, local heat flux; R_0, radius of plasma jet; R, current radius of plasma jet; q_0, q_1, q_2, q_3, approximation coefficients; h, size of the outlet nozzle of the plasmatron; φ, angle of orientation of thermocouple C_2 relative to incoming stream; G_2, rate of of air through plasmatron; D, outlet orifice of plasmatron nozzle.

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