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AUTOMATION OF THERMAL FLUX MEASUREMENTS WITH A
LINEAR CALORIMETRIC PROBE

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A system is developed to automate measurements of specific thermal flux in a plasma jet using a linear calorimetric probe. The effect of turbulence and gas flow rate on thermal flux is studied.

Contact methods are widely used to study thermal fluxes in plasma jets [1].

The linear calorimetric probe method was developed for measurement of local thermal flux values in a plasma of arbitrary configuration [2]. The essence of the method is that the probe (Fig. 1) is moved at constant velocity in the plasma jet in the direction in which the thermal flux distribution is being measured, and its local value at each point of the jet is given by

$$q = \frac{G_1 c}{\pi d_1} \frac{dt}{dx}. \quad (1)$$

In calculating q with Eq. (1), it is necessary to differentiate the experimentally obtained water temperature in the probe as a function of coordinate. As a rule, this operation is either performed manually using graphical methods or by using a computer, in which case the differentiation error can reach 30% [3]. This error can be decreased significantly by using analog differentiation circuitry. This reduces the error to 1% [3].

If we transform Eq. (1) to the form

$$q = \frac{G_1 c}{\pi d_1} \frac{1}{v_s} \frac{dt}{d\tau}, \quad (2)$$

then measurement of the thermal flux density distribution over coordinate can be reduced to differentiation of the signal recorded by the thermocouple with respect to time.

In calculating q with Eq. (2) significant dynamic error can develop in $t(x)$ if the probe velocity is chosen incorrectly. After several mathematical operations, the condition [4]

$$\frac{t_1 - t}{T_1} = \frac{dt}{d\tau} \quad (3)$$

provides us with the value of v_m for the probe:

$$v_m \leq \frac{\eta_{q_1}}{1 - \eta_{q_1}} \frac{t_m}{T_1 dt/dx}. \quad (4)$$

To calculate v_m with Eq. (4), we initially determine T_1 from a curve obtained by applying a Π -shaped thermal pulse to the probe. The value of dt/dx is estimated experimentally by moving the probe through a plasma at the smallest possible rate.

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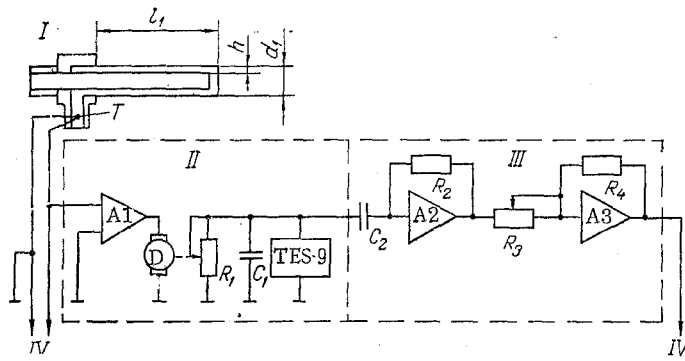


Fig. 1. Block diagram of measurement system: I) probe; II) signal preamplifier; III) signal processing circuitry; $R_1 = 150 \Omega$; $R_2 = 1 \text{ M}\Omega$; $R_3 = 100 \text{ k}\Omega$; $R_4 = 1 \text{ M}\Omega$; $C_1 = 2000 \mu\text{F}$; $C_2 = 25 \mu\text{F}$; IV) to input of data recorder.

TABLE 1. Plasmatron Operating Parameters and Calculated Plasma Jet Parameters

No. of curve in Fig. 3	I , A	U , V	G_2 , kg/sec	L , m	t_m , K
1	130	230	$3 \cdot 10^{-3}$	$2,2 \cdot 10^{-3}$	3800
2	130	250	$3 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	4000
3	130	250	$3 \cdot 10^{-3}$	$4,5 \cdot 10^{-3}$	4000
4	150	220	$2,1 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	5200

Available analog computer circuits (MN-7, MN-10) permit differentiation of an electrical signal with a frequency $f_{\text{lim}} = 1 \text{ Hz}$ given a sufficiently high input signal. The time required for measuring thermal flux in a plasma jet, calculated from the condition $\tau_m = D_1/v_m$, comprises $\tau_m = 8\text{--}15 \text{ sec}$, i.e., $f_{\text{lim}} \sim 0.1 \text{ Hz}$, with the signal from the probe being comparable in level to the input voltage drift of the analog circuit's operational amplifiers.

In the present study we will develop a system for automation of thermal flux measurement in a plasma jet using a linear colorimetric probe and study the effect of flow turbulence and flow rate on thermal flux.

The automatic measurement system (Fig. 1) consists of a thermal flux sensor probe, preamplifier, signal processing circuitry, and recording apparatus. The probe shown in Fig. 1 was described in detail in [5]. Basic dimensions and operating characteristics of the probe are as follows: $d_1 = 3.5 \cdot 10^{-3} \text{ m}$, $L_1 = 85 \cdot 10^{-3} \text{ m}$, $h = 0.3 \cdot 10^{-3} \text{ m}$, $G_1 = 5\text{--}9 \cdot 10^{-3} \text{ kg/sec}$, $v_w = 2\text{--}3 \text{ m/sec}$, $T_1 = 0.3 \text{ sec}$.

Preamplification of the input signal is performed by the amplifier of an ÉPR-09M electronic potentiometer, with output signal taken from the auxiliary slidewire R_1 , through which there flows a constant current from the TES-9 power supply, connected as a current regulator.

The signal processing system consists of circuits from an MN-7 computer, which permit differentiation, multiplication, and division of dc and ac signals, so that the device output indicates the actual value of the quantity measured.

In selecting the accurate differentiation range, the parameters R_2C_2 (op. amp. A2) are calculated from known expressions [6] for the upper and lower cutoff frequencies of the amplitude-frequency characteristic. The bandwidth of the measurement system is determined by graphicoanalytical expansion in a Fourier series [7] of the experimental curves of probe water temperature, obtained for various time intervals ($\tau = 8\text{--}15 \text{ sec}$). It was found that the basic signal information was carried by harmonics no higher than the 24th, with a fundamental frequency of $f_0 \sim 0.1 \text{ Hz}$.

To immediately produce the value of the thermal flux density q , a scale amplifier A3 was introduced, the gain of which was set by the condition

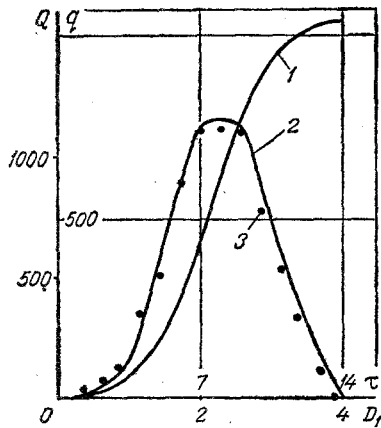


Fig. 2

Fig. 2. Integral thermal flux (1); specific thermal flux (2), obtained with measurement system; and specific thermal flux (3), calculated by graphicoanalytic differentiation. Q, W ; $q, W/cm^2$; τ, sec ; D_1, cm .

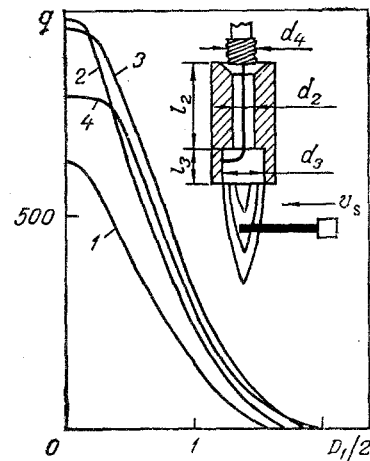


Fig. 3

Fig. 3. Effect of degree of turbulence and flow rate of plasma-forming gas on thermal flux distribution in plasma jet (parameters for curves 1-4 given in Table 1) and schematic diagram of plasmatron. $l_2 = 49 \cdot 10^{-3} m$, $l_3 = 36 \cdot 10^{-3} m$, $d_3 = 14 \cdot 10^{-3} m$, $d_4 = 18 \cdot 10^{-3} m$.

$$\kappa = \frac{G_1 c}{\pi d_1} \frac{1}{v_s} \quad (5)$$

The input and processed signals were continuously recorded with an N115 oscilloscope.

In signal processing, errors develop in the measurement circuit, which can be divided into dynamic and static errors [8]. The static error was determined by the following method. At the system input, a sawtooth voltage calibrated in °C was applied, with a rate of change $dt/d\tau$ from 3 to 14°K/sec. Analysis of the results obtained showed that static error in signal processing did not exceed $\eta_s = 3\%$. Dynamic error η_q in the system was essentially determined by the inertia of the ÉPR-09M electronic potentiometer

$$\eta_{q_2} = \frac{T_2}{\tau_m} \cdot 100\% \quad (6)$$

and reached 2% at $\tau_m = 15 sec$ [8]. The total error of the entire system was calculated with the expression

$$\eta_{\Sigma} = \eta_s + \eta_{q_1} + \eta_{q_2} \quad (7)$$

and did not exceed 9%.

Studies were performed with a type VPR-10 plasmatron with ratio $l_2/d_2 = 6$ and interchangeable gas swirlers, which allowed changing the amount of gas turbulence in the discharge cell. Air was used as the plasma generating gas. The plasmatron operating parameters and calculated plasma jet parameters are presented in Table 1.

Curves of the integral thermal flux and specific specific thermal flux together with specific thermal flux values calculated by graphicoanalytic differentiation with an error of ~10% [9] are shown in Fig. 2. As is evident from the figure, the thermal flux distribution curve shows a certain asymmetry. The deviation from a symmetrical curve comprises ~9%. Control measurements performed by introducing the probe into the plasma jet from the opposite side revealed that the character of the curve remained unchanged. Apparently, the observed asymmetry, although it lies within the limits of accuracy of the method, is produced by plasmatron construction and operating parameters, i.e., is the actual q distribution in the plasma jet.

The system was used to study the effect of degree of turbulence and plasma-forming gas flow rate on the thermal flux. Turbulence was changed by replacing the gas swirlers with ones having a different quadruple thread pitch. The total section of the output area remained unchanged in all cases. Reduction in the thread pitch led to an increase in tangential and decrease in axial components of the gas flow velocity. The effect of turbulence was studied at a constant jet section, $2.8 \cdot 10^{-2}$ m away from the nozzle.

Analysis of the results (Fig. 3) showed that with decrease in turbulence at each point of the jet the thermal flux in the probe increases, reaches a maximum value, and then ceases to grow (curves 1, 2, 3). However, reduction in the degree of turbulence leads to coarse scale flow pulsations, premature anodic erosion of the nozzle, and distortion of the jet form. Thus, further studies were performed with a gas swirler with $L = 3 \cdot 10^{-3}$ m for the VPR-10 plasmatron with $l_2/d_2 = 6$. With this swirler, reduction in gas flow rate leads to a reduction of thermal flux from the plasma jet into the probe, and the same effect is found as with reduction in the swirler pitch.

NOTATION

q , thermal flux density; G_1 , water flow rate through probe; c , specific heat of water; x , coordinate; v_s , probe velocity; τ , time; t_i , cooling water temperature with infinitely slow probe motion; t , cooling water temperature with finite probe velocity; η_{q1} , dynamic error produced by probe motion; T_1 , probe time constant; f_{lim} , lower limit frequency; τ_m , maximum measurement time; D_1 , jet diameter; l_1 , probe length; h , gap between coaxial probe tubes; v_w , cooling water flow rate in probe; l_2 , plasmatron channel length; d_2 , plasmatron channel diameter; L_1 , d_4 , pitch and diameter of swirler with quadruple rectangular thread; G_2 , plasma-forming gas flow rate; t_m , mean mass jet temperature; I , arc current; U , arc voltage.

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