IMPROVEMENT OF THE DYNAMIC THERMOCOUPLE METHOD

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An instrument is described for automated heat-flux measurement. Experimentally measured results are presented for heat flux, heat-transfer coefficient, and gas phase temperature in an air plasma jet.

The use of thermal plasma jets in technological processes (spheroidizing, vapor deposition, etc.) raises the problem for investigators of studying the energy and physical interaction between a high-temperature flow and a material [1]. In terms of obtaining full and reliable information required to solve this problem, contact methods [2, 3] are the most suitable. The dynamic thermocouple method [4-6] is often used to model the heat-transfer process to particles of a disperse material. This method has been developed in many papers [4-8] which have described techniques for determining the basic errors in measuring heat flux and gas temperature with this method, errors due, e.g., to loss of heat from the thermocouple junction to the leads [7], and to temperature fluctuations and scatter in the calibration characteristics [8]. In all these cases the heat flux to the thermocouple junction is given by the expression

$$q = A\rho c_p \frac{dT}{dt}. \tag{1}$$

Thus, in calculating q from Eq. (1) and the heat-transfer coefficient as the tangent of the slope of the curve q(T), one must differentiate the experimental thermocouple junction temperature T(t) with respect to time. As a rule, the differentiation is performed by quantizing the experimental curve manually by a graphical method or by using a computer. However, the error in determining the derivative by such a method, even on a computer, may be 25% or more [9]. Analog differentiating devices have considerably less error (less than 1% [9]).

The present paper investigates the possibility of simplifying and accelerating the data processing, and enhancing the reliability in the use of the dynamic thermocouple method by automatic differentiation of the experimental thermocouple junction curve.

Differentiation can be obtained with a simple RC circuit, if the output signal is taken from the resistor. For minimum error in the differentiation one must choose the time constant $\tau = RC$ so that $\tau \leqslant 100\tau_0$ [10], where τ_0 is the input signal duration. Analysis of the use of an RC circuit for differentiation shows that choosing the circuit time constant to reduce the differentiation error is accompanied by a considerable decrease in the output voltage. This, along with other defects of the RC circuit, makes it impossible to apply it for accurate differentiation. One can compensate for RC circuit differentiation error by using a high-gain amplifier employing deep negative feedback. Analysis of the dynamic and static errors of such differentiators shows [10, 11] that the error in differentiation does not exceed 1% with suitable choice of the system parameters.

The heat flux from a plasma jet to a solid surface was measured in our work by the dynamic thermocouple method, using the instrument shown schematically in Fig. 1a. The differentiator was incorporated in a type K284UD1 operational amplifier, whose basic parameters are: gain at frequency 1000 Hz is $2 \cdot 10^4$, mean dc input $I \leqslant 10^{-9}$ A, input resistance at frequency 1000 Hz is 5-6 MΩ, and at dc it is 150 MΩ.

The specific parameters of the differentiator circuit were computed from the known relations [11] for the low and high cutoff frequencies of the amplitude—frequency characteristic:

$$f_l = \frac{1}{2\pi R_1 C_D}, \quad f_u = \frac{1}{2\pi R_{in} C_1}. \tag{2}$$

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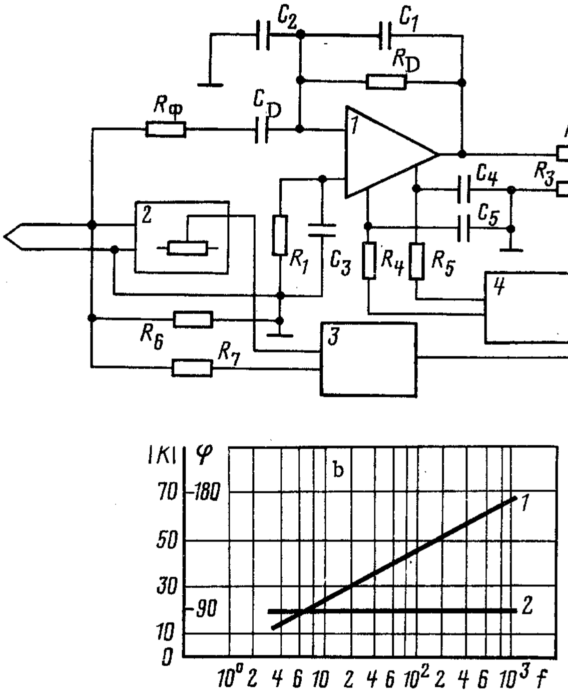

Fig. 1. Schematic diagram of an instrument for measuring unsteady heat flux: a) [1) type K284UDI microcircuit; 2) input system; 3) type K-115 oscillograph; 4) supply unit; C_1 = 33 pF; $C_2 = C_3$ = 470 pF; $C_4 = C_5$ = 5.0 μF; C_D = 0.1 μF; $R_1 = R_D$ = 300 kΩ; R_2 = 2.2 kΩ; $R_3 = R_4 = R_5$ = 1.1 kΩ; $R_6 = R_f$ = 27 kΩ; R_7 = 2.2 kΩ]; b) amplitude–frequency (1) and phase–frequency (2) characteristics of the differentiator [K is the gain, db; φ is the frequency shift, deg; and f is the frequency, Hz].

A preliminary harmonic analysis of thermocouple heating rate curves, for various junction diameters (0.3-0.5 mm), performed by the method of graphicoanalytical expansion in Fourier series [12], showed that the main information is carried by harmonics not exceeding the fourth, at a basic frequency of from 8 to 30 Hz. On the basis of these data, for accurate differentiation one must choose $f_l \leqslant 5$ Hz, $f_u \geqslant 100$ Hz in Eq. (2). In practice, the accurate differentiation range is determined from the amplitude–frequency characteristic [10, 11], and is roughly equal to $f_u - f_l$. A calculation using Eq. (2) and the specific parameters of the system (Fig. 1a) gives $f_l = 0.8$ Hz, $f_u = 1000$ Hz. The actual characteristics of the differentiator are shown in Fig. 1b. In the accurate differentiation range (up to 1000 Hz) the deviation of the amplitude–frequency characteristic (curve 1 of Fig. 1b) from linearity does not exceed 1%. The phase shift in differentiating a sinusoidal signal was constant and equal to 90° (curve 2 of Fig. 1b).

Thus, one can say that the error introduced by the differentiator in measuring the heating rate of the thermocouple does not exceed 1%. The system for injecting the thermocouple into the jet was arranged so that the injection time was a minimum, at the most no more than 0.1 of the time to heat the thermocouple junction to the maximum allowed temperature. As a monitor the injection rate was recorded with a type K-115 oscillograph. The thermocouple signal and its derivative were recorded simultaneously. Electrical pickup was completely eliminated by careful screening of all supply leads and by introducing the antinoise resistor R_f (Fig. 1a).

The experimental results in measuring the heating rate of the thermocouple junction and the heat flux are shown in Fig. 2. The plasmajet was obtained from an axial type plasmatron with gas-vortex arc stabilization. Its operating parameters were: arc current, 140 A; voltage, 200 V; flow rate of plasma-generating air, $2.9 \cdot 10^{-3}$ kg/sec; mean bulk jet temperature, 3800°K; bulk mean flow velocity at the plasmatron exit, 250 m/sec.

The thermocouples were made of wire (NMtsAK2-2-1 and NKh9.5) of diameter 0.27 mm. The junction diameter was 0.3-0.6 mm. For this Bi < 0.05. The thermocouple was inserted to the center of the jet at a distance 40 mm from the rim of the plasmatron nozzle.

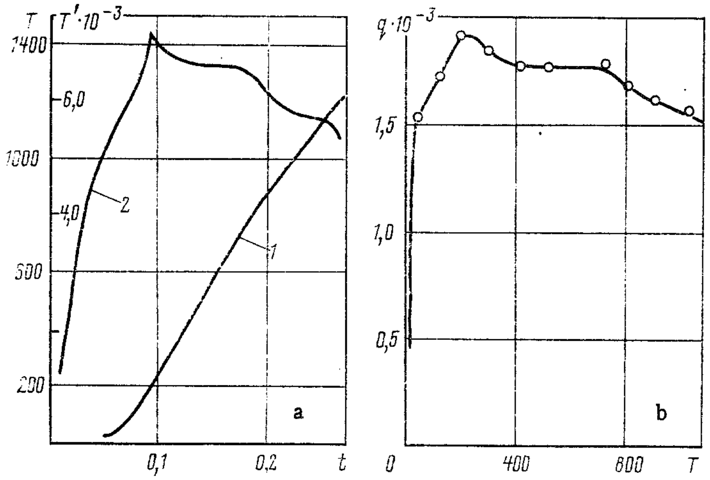

Fig. 2. Relationships: a) junction temperature T, °K, as a function of time t, sec (1), and its derivative T', deg/sec (2); b) heat flux $q \cdot 10^{-3}$ W/cm^2 as a function of temperature T, °K.

It can be seen from Fig. 2 that the maximum heat flux from the air plasma jet to the solid surface was 1.9 kW/cm^2. The gas phase temperature, determined at the point of intersection of a continuation of the q(T) curve with the abscissa axis (Fig. 2b) was (3.4-3.5)·10^3 °K. The heat-transfer coefficient is then 0.59 W/cm^2·deg.

We compared the curves of dT/dt, one obtained automatically and the other by the method of graphicoanalytical differentiation, which has a low error [13]. The discrepancy did not exceed 10%.

Automatic differentiation of the dependence T(t) for the thermocouple junction yields the frequency and amplitude of heat-flux fluctuations. In our case the heat-flux fluctuation frequency was 10-15 Hz, which is apparently linked to rotation of the anode spot of the arc on the plasmatron channel wall.

It should be noted that a sensor for direct recording of the heating rate with the instrument described can be a calorimeter with a linear characteristic, a thin-film sensor, etc., as well as the dynamic thermocouple.

Thus, with the instrument described for automatic measurement of unsteady heat flux one can significantly decrease the time spent in reducing the experimental results, while substantially decreasing the heat flux measurement error.

NOTATION

q, heat flux, W/m^2·deg; T, temperature, °K; ρ, c_p, density, kg/m^3, and specific heat, J/kg·deg, of thermocouple material; A, a constant, dependent on thermocouple structure; f_l, f_u, lower and upper cutoff frequencies of the differentiator amplitude–frequency characteristic, Hz; R_{in}, input resistance, Ω.

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MEASUREMENT OF THE MAIN PARAMETERS OF A HIGH-PRESSURE, HYDROGEN—LITHIUM PLASMA

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The pressure along the capillary length, its dependence on the capillary diameter, the time dependences of the temperature and pressure, and the radial dependences of the temperature are measured in a capillary discharge with a vaporizing wall (material: lithium hydride).

The interest in the investigation of the optical properties of gases at temperatures of tens of thousands of degrees is connected with the clarification of the role of radiant energy transfer in a number of phenomena: electric arcs, shock waves developing upon the entry of a body into the earth's atmosphere with a hypersonic velocity, a laser flash, etc. Thanks to the self-similarity of Coulomb properties, data on plasma properties in a model range convenient for experiment can be carried over to another natural region of parameters.

To investigate the properties of a high-pressure, hydrogen—lithium plasma we used a capillary discharge with a vaporizing wall (CDVW), developed at the State Optical Institute [1], permitting the obtainment relatively simply and for a sufficiently long time (~500 μsec) of a plasma of known composition in a wide pressure range, from 10 to 500 bar, at temperatures on the order of 4 eV.

During the passage of a current pulse through a capillary the space of the capillary is filled with material violently vaporized from the walls. The dissociation and then the ionization of the vaporized material occur, and a high-pressure plasma, at tens or hundreds of atmospheres, forms in the capillary. Simultaneously with vaporization of the wall in a CDVW one observes the escape of plasma jets through the open ends of the capillary, with the gas which initially filled the capillary, open to the atmosphere, being entirely displaced and only the elements entering into the composition of the wall remaining in the discharge. It has been established [2] that in forced modes of discharge the quantitative ratios of elements in the solid and gaseous phases coincide. This property of a CDVW is extremely attractive for obtaining a plasma of a given composition, since usually in installations of any type the plasma is contaminated by impurities entering the discharge from the walls and from the electrodes. Lithium hydride served as the working substance.

The installation consisted of an airtight chamber mounted on an optical track and a unit for supplying rectangular current pulses. Briquettes of lithium hydride were pressed into a Textolite casing. Rods 9 mm in diameter made of fine-grained graphite of spectral purity were used as the electrodes. In those experiments where it was necessary to measure the pressure, the LiH briquette was placed in a cylindrical Textolite plug and was pressed from the open end by a metal cylinder, which simultaneously served as the current-carrying electrode. The working LiH briquettes were obtained by pressing them from powder with a particle size of not more than 0.2 mm at a pressure of 9.5 tons/cm^2. The percentage content of impurities in the working substance was: Na 0.06, Mg 0.06, SiO_2 0.02, Ca 0.01. The supply unit of the installation included an artificial LC-line (L = 8 μH, C = 150 μF × 5 kV).

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