NOTATION

ρ_m, ρ_{ph}, ρ_e, densities of dispersion medium, dispersed phase, and emulsion, respectively; kg/m^3; μ_m, μ_{ph}, μ_e, viscosities of dispersion medium, dispersed phase, and emulsion, respectively, N·sec/m^2; μ_{ef}, effective viscosity of emulsion, N·sec/m^2; Φ, volumetric concentration of dispersed phase; d_{av}, average volumetric diameter of globule, mm; n_i, number of globules with diameter d_i; k, number of globule sizes; w, average velocity of emulsion in a tube, m/sec; Q, volumetric emulsion flow rate in a capillary, m^3/sec; r, l, radius and length of capillary, m; Δp, pressure differential on capillary, N/m^2; v_s, shear rate, sec^{-1}; P_s, shear stress, N/m^2; P_{min}, P_{max}, limiting minimum and maximum shear stresses, N/m^2; P_0, additional shear stress, N/m^2.

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IMPROVEMENTS IN THE DYNAMIC THERMOCOUPLE TECHNIQUE

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The paper describes an improved method for measuring the temperature of a low-temperature plasma. The method has been verified experimentally. An electronic method for inserting the thermocouple into the plasma is described. An error analysis is given.

Reiser and Olsen [1] describe a method of measuring the temperature of a low-temperature plasma using a periodically heated thermocouple. The essence of the method is that a thermocouple is inserted into the plasma for a time t_1, and then cools for a time t_2. The process is repeated a number of times, and then the experiment is changed so that the time spent in the plasma is t_3 and in cooling, t_4. For this situation the energy-balance equation is

$$\int_0^{t_1} Q_1 dt = \int_0^{t_2} Q_2 dt, \quad \int_0^{t_3} Q_3 dt = \int_0^{t_4} Q_4 dt. \tag{1}$$

The heat flux values in Eq. (1) are replaced by the expressions

$$Q_1 = \alpha_1 S (T_c - \overline{T}_1),\ Q_2 = \alpha_2 S(\overline{T}_1 - T_0),$$
$$Q_3 = \alpha_1 S (T_c - \overline{T}_2),\ Q_4 = \alpha_2 S (\overline{T}_2 - T_0). \tag{2}$$

From Eqs. (1) and (2), using the fact that T_0 is known, we finally obtain

$$T_c = \overline{T}_2 + \frac{T_1 - T_2}{1 - \dfrac{\overline{T}_1 t_1 t_4}{\overline{T}_2 t_2 t_3}}. \tag{3}$$

To implement the technique we developed a device for periodically exposing the thermocouple to the test plasma. The periodicity is generated by a light beam, interrupted by a synchronous rotating shutter and a photodetector, which controls the periodic insertion of the thermocouple.

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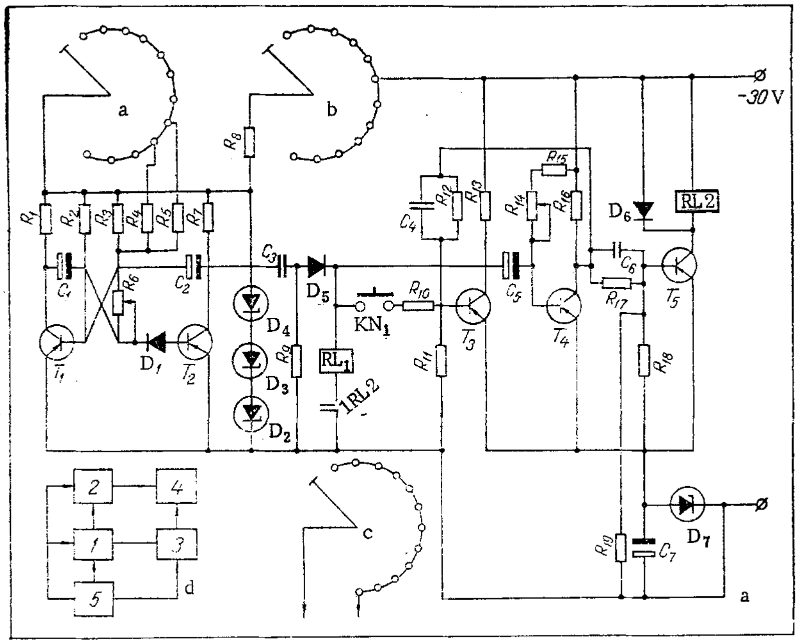

Fig. 1. Schematic electrical diagram of the control unit (a) and of the temperature measurement unit, using the improved dynamic thermocouple method (b): 1) control unit; 2) high-speed electromagnetic; 3) recording device; 4) Pt — Pt + 10% Rh thermocouple; 5) power supply.

The main defect of this method is the long measurement time (on the order of 3-4 min), and this introduces considerable error when one measures the temperature of turbulent swirling jets. The use of a slow recorder leads to a reduced equilibrium temperature, and this temperature varies for different cyclic frequencies. In addition, there is a large uncertainty in choosing the mean temperature, which introduces a method error into the measurement.

In the opinion of the authors, it is more favorable, in measuring the temperature of a periodically heated thermocouple, to use the fact that at a given instant the rate of thermocouple temperature increase is less, the larger its initial temperature. To derive the mathematical relation between the plasma temperature and the hot thermocouple junction temperature, we use the well-known equation [2, 3]

$$\frac{c\rho d}{6}\frac{dT}{dt}=\alpha(T_c-T). \tag{4}$$

As was done in [1], we shall assume that c, ρ, d, and α do not vary during the measurement. Then from Eq. (4) we have

$$T_2=T_c-(T_c-T_1)\exp(-kt_1), \tag{5}$$

where $k = 6\alpha/c\rho d$. Here the thermocouple is heated from temperature T_1 to T_2 in time t_1. If the thermocouple is heated from T_3 to T_4 in the same time t_1, then

$$T_4=T_c-(T_c-T_3)\exp(-kt_1). \tag{6}$$

After several simple transformations, and using the fact that kt_1 = const, from Eqs. (5) and (6) we can obtain

$$T_c=\frac{T_1T_4-T_2T_3}{\Delta T_1-\Delta T_2}, \tag{7}$$

where $\Delta T_1 = T_4 - T_3$ and $\Delta T_2 = T_2 - T_1$.

Since we did not account for additional gas heating due to flow stagnation in deriving Eq. (7), we must consider the temperature to be that for jets with Mach number M < 1 [6]. Equation (7) was used in [4] for the special case $T_2 = T_3$ in determining plasma temperature from measurements of the heating rate of a point calorimeter under conditions where T = f(t) is not linear. However, it is very difficult to determine

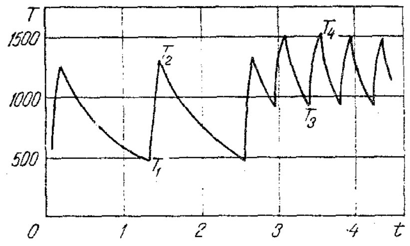

Fig. 2. Oscillogram of the temperature variation of a Pt — Pt + 10% Rh thermocouple, inserted into an air jet plasma with temperature $T_c = 3000°K$, where T_1, T_2, and T_3, T_4 are the lowest and highest temperature values at heating frequencies of $F_1 = 0.81$ Hz and $F_2 = 2.32$ Hz, respectively.

T_c from the relation $T = f(t)$ satisfactorily, since this nonlinearity in the heating curve can be observed only if the thermocouple is placed in the plasma jet for a long period, which can result in destruction of the thermocouple.

In order to determine the plasma temperature using a periodically heated thermocouple and Eq. (7) we developed a control program for inserting the thermocouple into the plasma (Fig. 1a). The scheme allows: 1) the heating frequency to be varied automatically from 0.2 to 3 Hz; 2) steady temperatures to be measured at three cyclic frequencies; 3) the device itself, as well as a type N-700 oscilloscope or some other recording system, to be automatically switched on and off at the time of measurement; 4) the dwell time of the thermocouple in the plasma to be adjusted smoothly from 20 msec to 1 sec; 5) the heating frequency to be varied smoothly; and 6) the temperature to be measured in a time 1.5-2 sec.

The control unit is made up of the following subunits: a low-frequency generator, embodying transistors PT_1 and PT_2 with automatic frequency adjustment; a time relay based on the multivibrator formed by transistors PT_3 and PT_4; the electronic switch represented by transistor PT_5 whose load is the relay RL2, which controls the operation of a high-speed magnet; and the stepping switch with three banks of non-separating contact groups *a*, b, and c. When button KN_1 is depressed, transistor PT_5 opens for a time $t_1 = 0.7(R_{14} + R_{15})C_5$, relay RL2 operaties — it switches on the stepping switch to relay RL1, which operates in the pulse-count mode (without a mechanical chopper). The frequency of inserting the thermocouple into the plasma jet is equal to the generator frequency. Variation of this frequency from 0.2 to 3 Hz is achieved by switching resistors R_5 or R_4 in parallel with resistor R_3 via contact group *a*. Contact group b switches off the generator supply, which is stabilized by means of the semiconductor stabilizers D_2 and D_4. Contact group c switches on and off the recording device during the measurement. Resistor R_{14} provides for smooth control of the swell time of the detector in the plasma from 20 msec to 1 sec. Resistor R_6 provides smooth control of the frequency of insertion of the thermocouple into the plasma. The system provides for the detector to be inserted with three different frequencies during a single measurement, thus reducing the measurement error. At the expense of reduced accuracy of plasma temperature measurement one can accelerate the measurement process, using only resistors R_3 and R_5 to vary the frequency. A measurement duration of four periods is used at each frequency to measure steady thermocouple temperatures. This is sufficient time for the detector to reach dynamic equilibrium with the plasma.

A block diagram of the experiment is shown in Fig. 1b. An oscillogram of values of $T = f(t)$, recorded on a type N-700 oscilloscope, is shown in Fig. 2. As can be seen from the figure, as the frequency of insertion of the thermocouple into the plasma jet is varied, keeping the dwell time of the detector in the plasma constant, the T_1, T_2, T_3, and T_4 obtained are different and can be used to determine T_c using Eq. (7).

In this way we found a temperature of 3000°K for an air plasma at distance of 20 mm from the nozzle exit on the axis, with a plasmotron power of 25 kW, 80% efficiency, nozzle diameter 10 mm, and flow rate 1.5 g/sec. The temperature at the same point was measured by the cooled calorimeter [5]. The two methods gave good agreement within experimental error. It is clear that the temperature method using the periodically heated thermocouple gives a value close to the true one, since the method requires no data other than the measured quantities T_1, T_2, T_3, and T_4.

The error in plasma temperature measurement by this method is due mainly to error in measurement of the thermocouple temperatures T_1, T_2, T_3, and T_4 and to the fluctuations in the dwell time of the thermocouple in the plasma in the two cases. The first error is given by the relation

$$\varepsilon_1 = \frac{2(T_1 + T_2)\Delta T}{T_1T_4 - T_2T_3}, \tag{8}$$

which may be simplified to the form

$$\varepsilon_1 = \frac{8\Delta T}{T_1 + T_2}.$$

The error due to fluctuations in the swell time of the thermocouple in the plasma is $\varepsilon_2 = (2\Delta t/t)$ [$\varepsilon_1 = \pm(3.5\text{-}4)\%$, $\varepsilon_2 = \pm(0.5\text{-}1)\%$], i.e., the error in determining the plasma temperature using this method does not exceed $\pm 5\%$.

NOTATION

Q_1, Q_3, heat fluxes to the thermocouple in the plasma; Q_2, Q_4, heat fluxes given out by the thermocouple to the cooler; α_1, α_2, heat transfer coefficients in the plasma and in the cooler; S, thermocouple surface area; T_c, plasma temperature; $\overline{T}_1$, $\overline{T}_2$, average temperatures of the thermocouple for different heating frequencies; T_1, T_2, initial and final temperatures at frequency F_1; T_3, T_4, initial and final temperatures at frequency F_2; T_0, temperature of the cooler; c, ρ, d, specific heat, density, and diameter of the Pt — Pt + 10% Rh thermocouple, respectively.

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