GENERALIZATION OF THE TEMPERATURE CHARACTERISTICS OF THE PLASMA JET OF A LINEAR PLASMATRON

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Contact and noncontact methods are used to measure the temperature of the plasma jet of a linear vortex-type plasmatron. The results are compared with the literature data. Generalized relations are obtained.

When a plasma jet generated by an electric-arc gas heater is used in production processes, it is important to know the temperature characteristics of the jet.

We experimentally studied and generalized the temperature distribution over the length and radius of a plasma jet in relation to the regime parameters and the geometry of the heater for the most common linear plasmatron design. The experiments were conducted with atmospheric pressure at the nozzle outlet. A tangential gas feed was employed.

Temperature was measured by two noncontact methods and two contact methods, based on laws governing the interaction of a plasma flow with a solid. In the first contact method of temperature measurement, we measured the heat given up to water during the passage of the gas inside a water-cooled pipe. We then determined the temperature of the gas at the pipe inlet (the method used by Grey et al., [1]). In the second contact method, we measured the heat flux to a bluff body, while the temperature of the flow was determined by employing laws governing heat exchange between a high-temperature gas flow and a bluff body in the region of the stagnation point (the relations derived by Fey and Riddell in [2] and by V. S. Avduevskii and G. A. Glebov in [3]).

In spectroscopic studies of the plasma jet, we photographed sections of the jet located 2-3 mm from the edge of the nozzle or near the surface of the transducer. We determined the temperature on the axis of the jet, the radial temperature distribution, and electron density.

The temperature of a gas in thermal equilibrium, such as nitrogen in a plasma jet at atmospheric pressure [4], was determined by the method of relative spectral-line intensity [5]:

$$T = \frac{E_1 - E_2}{k}\left[\ln\left(\frac{I_2\lambda_2 A_1 g_1}{I_1\lambda_1 A_2 g_2}\right)\right]^{-1}, \tag{1}$$

where the intensity ratio I_2/I_1 was found from the density curve obtained by photographing a standard light source through a multistage reducer with stages haivng known transmission factors. The light source was photographed on the same plate as the spectrum of the jet. The remaining notation in (1) is given in [5]. We used the lines of singly-ionized carbon and nitrogen for the measurement. Assuming that the plasma jet was cylindrically symmetrical, we used Abel's method to convert the observed distribution of spectral-line intensities into a radial distribution and we accordingly found the true temperature distribution over the radius of the jet.

Another method employed was temperature determination from electron density, which can be established from the broadening of the H_β line [4].

This method makes use of the fact that particle interaction — which can be characterized by the strength of the field — causes a change in pressure (density) to be accompanied by spectral line broadening. The amount of broadening which takes place for the H_β line is proportional to the field strength and is unambiguously related to the ion concentration. Assuming that $n_e = n_i$, we have the following expression for electron density

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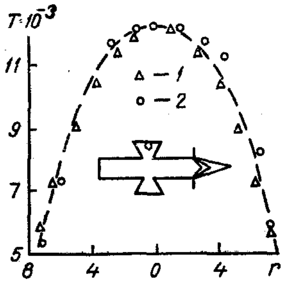

Fig. 1. Temperature distribution over the radius of the jet: 1) method of determining temperature from the heat flux to the body in the region of the stagnation point and the stagnation pressure; 2) spectroscopic method; N = 270 kW, G = 12 g/sec, d_0 = 15 mm, ℓ = 100 mm; working gas – nitrogen. T, K; r, mm.

$$n_e = (\Delta\lambda/2{,}61e\alpha)^{3/2}, \tag{2}$$

where Δλ is the half-width of the H_β line found experimentally; α is a coefficient calculated in [6] for the theoretical contour of the line. The electron density determined from (2) was used to determine the temperature from the known composition of the plasma as a function of temperature and pressure. The appearance of the lines of hydrogen, carbon, and copper in the spectrum of the plasma jet showed that the jet contained a small amount of impurities from the electrodes and linings – which is a favorable circumstance in the present case. It must be noted that the impurities were insignificant in terms of concentration and were estimated to have had no appreciable effect on the thermodynamic functions of the plasma.

In checking the reliability of the results, it is important to compare the values of temperature we obtained by different methods.

We used the exponential method in [7] to measure the constant heat flux on the jet axis. Heat flux was determined by the rate of change in the temperature of a copper cylinder with a diameter of 3 mm and a length δ = 5 mm, as well as by the thermophysical parameters of the cylinder material cρ:

$$q = \delta c\rho\,\frac{dT}{d\tau}. \tag{3}$$

The calorimeter we used was protected from lateaal heating by a 20-mm-diameter textolite sleeve with a spherical blunting.

To determine the enthalpy (temperature) of the gas acting on the heat-flux sensor, we used a relation which approximates the results of calculations and experiments involving determination of heat transfer at the stagnation point [8]:

$$q = 4{,}5\cdot 10^{-4} R^{-0,5} p_s^{0,25} (p_s - p_\infty)^{0,25} (h_s - h_w). \tag{4}$$

Along with axial values of temperature, the above-described contact method was used to measure the temperature distribution over the diameter of the jet. Here, we employed a combination sensor which allowed us to simultaneously determine three parameters which vary with time: heat flux, stagnation pressure, and the enthalpy (temperature) of the flow [9]. The sensor was a relatively long copper rod that was thermally insulated on its sides. The presence of the rod in the flow simulated the measurement of a semiinfinite body. The sensor was 5 mm in diameter and 50 mm in length. A hole 0.4 mm in diameter was drilled in the copper cylinder of the calorimetric element. The working rear end of the channel was connected to a membrane-type extensometric pressure sensor. The ratio of the area of the hole to the area of the end was 1/100. The sensor made it possible to measure the pressure change in tenths to hundredths of an atmosphere at frequencies up to 400 Hz.

The signal generated by an imbalance of the extensometric bridge due to deformation of the membrane was amplified by a model F 1510 5-channel semiconductor amplifier. The amplified signal was recorded over time by an N030A oscillograph with an M014A-1200 galvanometer having a sensitivity of 9 mm/mA. To measure the variable heat flux with the sensor, we positioned the junctions of Chromel–Alumel thermocouples 1 mm from the working and rear ends of the calorimetric element. The emf of the thermocouples was recorded on an N030A oscillograph with the aid of an M017-400 galvanometer with a sensitivity of 134.6 mm/mA. The method of a semi-infinite body [10], based on the solution of the inverse heat conduction problem,

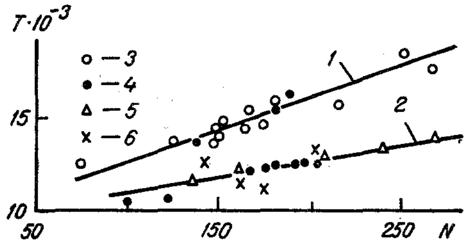

Fig. 2. Comparison of different methods of measuring the temperature in the core of a jet: 1) ℓ = 50 mm; 2) ℓ = 100 mm, G = 6.5 g/sec; 3, 4) spectroscopic methods (3 – from H_β broadening; 4 – method of relative intensity); 5) from the heat flux to the body and the stagnation pressure; 6) with the sensor developed by Grey et al.; heated gas – nitrogen. N, kW.

was used to determine the heat flux from the thermocouple readings. The sensor allowed us measure heat fluxes varying with a frequency of up to 150 Hz. The variable enthalpy present as the sensor was moved over the diameter of the jet was determined with Eq. (4) from the measured heat flux and stagnation pressure. This determination was based on the previously established [12] quasi-stationariness of the heat-transfer process under the conditions being considered. The sensor was rigidly attached to a lever connected with a rod. The rod was moved by an electric motor. The displacmeent was determined with a slide-wire resistor and was recorded on the N030A oscillograph. The errors of measurement of the main quantities were evaluated and reported in [8, 12].

Figure 1 presents an example of the measurement of temperature by contact and noncontact methods along the diameter in a section of a plasma jet. In the case of the contact method, we used the displacement of the above-described combination sensor over the jet diameter. The noncontact method was spectroscopic and involved determination of the relative intensity of the spectral lines of carbon. Despite some difference in the rates of temperature change over the radius, the two methods yielded results which agreed satisfactorily.

When plasma jets obtained from linear discharge chambers with vortical stabilization of the arc column are used to treat refractory, heat-insulating materials and perform other operations, a special feature of such jets is employed. Specifically, the temperature of the jet core is considerably greater than the jet's mean mass temperature. Moreover, it is the core that governs the interaction of the flow with the solid being treated in the region of the stagnation point. Measurement of temperature in the jet core (Figs. 2 and 3) and comparison of these measurements with the mean mass temperature (Fig. 3) show that, depending on the discharge power and gas flow rate, the ratio of these temperaures lies within the range from 1.4 to 2.1. Thus, by changing the regime parameters, it is possible to form a jet core with the necessary temperature. Core temperature increases with an increase in power and, to a greater extent, with an increase in gas flow rate. The latter method of increasing core temperature is restricted by the forcing of the arc from the channel as gas flow rate is increased. Also, as was shown by spectroscopic measurements, at flow rates higher than 12 g/sec and a power of 250-300 kW, a valley appears near the axis in the radial temperature distribution. The presence of the valley is connected with an increase in the tangential component of flow velocity at the outlet. The left ends of the temperature characteristics in Fig. 3 correspond to the boundary of ejection of the discharge from the channel (extinction), while the right sides correspond to the permissible values of current for the cooled copper electrodes. The characteristics in Fig. 3 were obtained for a discharge chamber with electrodes 100 mm long. Core temperature can be further increased by shortening the electrodes. Visual observations have shown that, in this case, the chamber usually operates in a regime whereby the reference spot is located on the end surface at the anode outlet. In connection with this, the temperature in the jet is close to the temperature in the arc column. Thus, a temperature within the range 15,000-18,000 K was attained for a nitrogen plasma (line 1 in Fig. 2) with electrodes 50 mm in length. Temperature was measured by the two spectroscopic methods described above. Also shown in Fig. 2 (points 4, 5, and 6) is the temperature of the core for the same flow rate and an electrode length of 100 mm. This data was obtained by the two contact methods described previously, as well as from the relative intensity of lines of singly ionized nitrogen.

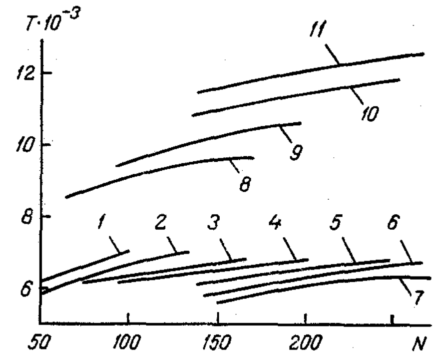

Fig. 3. Dependence of the temperature of jet air at the nozzle edge on the discharge power and gas flow rate: 1-7) mean mass temperature (from the heat balance of the discharge chamber); 8-11) temperature in the jet core (from the heat flux to the sensor ∅ 3 and the stagnation pressure); the curves show averaged values of the measurement results; the gas flow rates: 1) 1.8 g/sec; 2) 2.5; 3, 8) 3.5; 4, 9) 4.5; 5, 10) 6; 6, 11) 7; 7) 10; the gas — nitrogen.

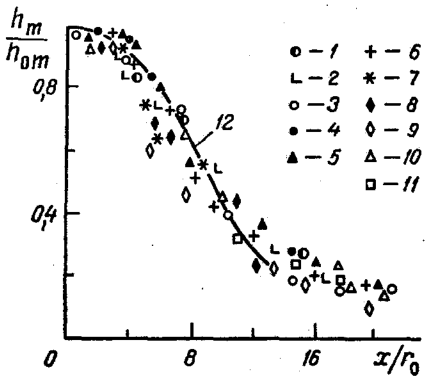

Fig. 4. Change in enthalpy along the jet axis: 1-6) data from [13], 1) T_{0m} = 6900 K, u_{0m} = 350 m/sec; 2) 7100 and 300; 3) 9100 and 410; 4) 9700 and 640; 5) 11,200 and 700; 6) 12,100 and 850; 7) data from [14], T_{0m} = 5800 K, u_{0m} = 220 m/sec; 8) data from [15], T_{0m} = 6300 K, u_{0m} = 480 m/sec; 9) data from [16], T_{0m} = 3800-5200 K; 10) data from [17], T_{0m} = 4000 K; 11) data from [18], T_{0m} = 1200 K; 12) calculation with Eq. (7); heated gas —air.

The measurements obtained by the three methods agree well with each other. For later systematic studies of the temperature in a plasma air jet, this result allowed us to select measurement of the heat flux and stagnation pressure as the simplest and most reliable method of investigation. Studies were conducted in the power range 40-350 kW at air flow rates of 2.5-13 g/sec [13].

The study showed that the radial temperature distribution is described by an expression of the form

$$\frac{T_r - 5600}{T_m - 5600} = \exp\left[-\ln 2\left(\frac{r}{r_*}\right)^2\right], \tag{5}$$

where r_* corresponds to $T_* = 0.5\sqrt{(3.17 \cdot 10^4 T_m - 1.79 \cdot 10^8)}$; T_m is the temperature on the axis.

The temperature on the axis at the nozzle edge T_{0m} is determined by the following expression as a function of current I, gas flow rate G, and nozzle diameter

$$T_{0m} = 0{,}363\, d^{-0{,}706}\left(\frac{G}{d_0}\right)^{0{,}794}\left(\frac{I^2}{Gd_0}\right)^{0{,}256} + 5600, \tag{6}$$

while the temperature distribution near the axis along the jet is described by the equation

$$T_{xm} = (T_{0m} - 5600) \exp[-0{,}004 (x/r_0)^{2{,}3}] + 5600. \quad (7)$$

Our measurements of the temperature distribution over the length and radius of the jet agree with the measurements made by other authors on plasmatrons of similar designs. In particular, Fig. 4 shows results of a comparison of calculation of the temperature along the jet using Eq. (7) and data reported in the literature. The overall ranges of values the parameters, embracing both our work and the literature data which confirms the generalized relations obtained here, are as follows: d_0 = 3.5-25.4 mm; ℓ/d_0 = 4-10; N = 3-400 kW; G = 0.375-21 g/sec. The relations presented for temperature are also restricted to the range of approximation (with a maximum error of 6%) of the temperature dependence of enthalpy – 6000-12,000K. The investigated jet was laminar up to 6-8 diameters from the nozzle edge [13]. The gas-dynamic characteristics of the jet were examined in greater detail in [13].

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