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OPTOSPECTROSCOPIC STUDIES OF THE CATHODIC JET OF A LAMINAR PLASMATRON

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The structure and temperature field of a cathodic jet near the external surface of the nozzle in a laminar plasmatron are studied.

Plasmatrons with a laminar flow in highly heated gas are used in plasma technology, in particular, in gas-thermal hardening of machine parts and mechanisms [1, 2]. They intensively heat and accelerate powder particles and thereby ensure that the powder is used efficiently [3]. As is well known, plasma atomizers in which the powder is injected at the cutoff of the nozzle have the longest lifetime. Because of the low plasma temperature in the zone of injection of the powder (7000-10,000°K), however, in such atomizers the efficiency of heating is several times lower than when the atomized material is injected into the nozzle directly near the cathode [4-6]. For this reason, a promising direction of development of long-lifetime atomizers, which at the same time heat particles to high temperatures, is to use plasmatrons with a short distance between the cathode and the exterior surface of the nozzle and to inject powder onto the nozzle cutoff.

In this work, employing optospectroscopic methods we studied the structure and temperature field of the plasma flow in a nitrogen atmosphere near the exterior surface of the nozzle at a distance of one unit from the cathode (Fig. 1). The working conditions of the discharge are: $1 = 200\text{-}500$ A, $U = 33$ V, and $G = 0.003\text{-}0.077$ g/sec. The structure of the flow was observed both visually and with the help of a motion picture film using an SKS-1M camera.

The plasma formation under study consists of a high-intensity conical, cathodic jet emanating from the nozzle with two symmetrically positioned expanding jets with a transverse size in the zone of contact with the anode of ~1 mm lying next to it. Under optimal conditions, which are achieved primarily by adjusting the gas flow, the electrode spots assume stationary positions on the surface of the anode within several tens of seconds. Then a jumplike change occurs in their spatial position with the symmetry mentioned above preserved. As the duration of the operation of the plasmatron increases the residence time of the spots at one location gradually decreases. Reliable observation of the spatial position of the cathodic and anodic jets was facilitated by their different color, which is determined by the different composition of the plasma.

Motion-picture photography of the plasma formation indicates that the stationariness of the plasma depends substantially on the geometry of the discharge chamber and the working conditions of the generator, and especially on the flow rate of the gas. The probability of transverse displacements of the cathodic jet increases appreciably with the diameter of the nozzle cutoff at a distance $L > 10$ mm. With the help of the SKS pictures, obtained with continuous photographic scanning, we estimated the velocity of the anodic plasma jets. For zones lying quite far away from the nozzles ($l > 20$ mm) it falls in the range 5-20 m/sec. We could not determine by an analogous method the velocity of the cathodic jet because the amplitude of the pulsations in the brightness of the jet was too low.

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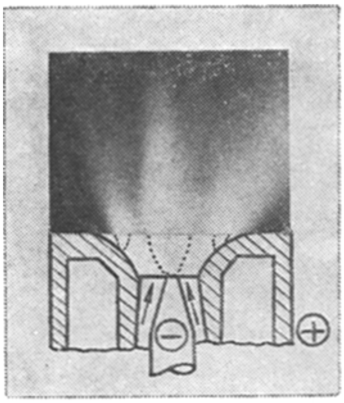

Fig. 1

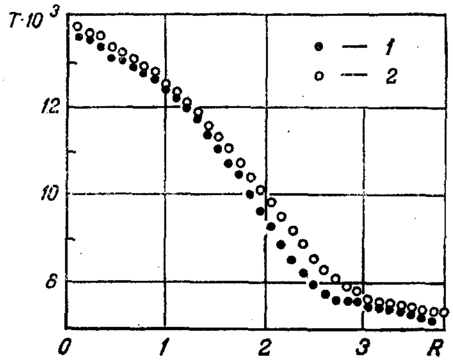

Fig. 2

Fig. 1. Schematic diagram of the plasmatron.

Fig. 2. Radial distribution of the temperature in the jet of a laminar plasmatron; NI 742.36 nm line: 1) i = 300; 2) 400 A. T, K; R, mm.

The formation of two electrodic spots on the end face of the anode of the plasmatron under study is apparently determined by the following. After the discharge is ignited the nearly cylindrical current-conducting channel becomes curved, at first under the action of the gas flow and then owing to the magnetic interaction between separate zones of the arc channel. As a result, a plasma filament in the form of a loop with anodic and cathodic jets is obtained, analogously to a two-jet plasmatron [7]. Because of the magnetic effect of the anodic jet the cathodic jet is displaced from the nozzle axis in a direction away from the anodic spot and forms with the anode a second current-conducting channel, coexisting with the first channel. Then, as a result of the interaction with both anodic jets, the cathodic jet returns to the axis of the nozzle and a stable configuration of the plasma flow is thus obtained. At the same time the axes of symmetry of the cathodic and anodic jets lie in the same plane. The random displacement of the cathodic jet, for example owing to erosion processes occurring at the cathode, causes the anodic spots to move toward one another along the edge of the nozzle, coalesce into a single spot, and form one current-conducting channel. In accordance with the foregoing analysis, however, this configuration of the arc in the plasmatron design under study is spatially unstable. The cathodic jet moves away from the anodic spot and forms a second current-conducting channel.

For plasmatrons in which the cathode is moved away from the exterior surface of the nozzle by more than one unit the current density in the cathodic jet is appreciably lower at the level of the anodic spot. This lowers the efficiency of the magnetic interaction of the anodic and cathodic jets and, as a consequence, reduces the probability for the formation of two anodic spots. This is also facilitated by the limitedness of the displacement of the spot within the nozzle, and it emerges onto the exterior surface with gas flow rates which substantially destroy the laminar nature of the plasma flow.

The experimentally determined outflow of mass from a copper nozzle for optimal operation of the plasmatron turned out to be less than $1 \cdot 10^{-5}$ g/C, which is comparable to the magnitude of the specific erosion of copper tubular electrodes accompanying rapid motion of the anodic spot [8]. Apparently, the cathodic plasma flow under these conditions has a weak convective effect on the region near the anode. Based on this it may be conjectured that the principle of rapid motion of the reference spot of the arc along the anode in order to decrease the erosion [9], used by the designers of plasmatrons, is not always optimal. If the outflow of plasma, including of copper atoms, from the region near the anode is small (insignificantly higher than the rate of diffusion processes), then current transport at the metal-plasma boundary requires a very small inflow of copper atoms from the surface of the anode.

The emission spectra of the generated plasma formation were recorded at visible and IR wavelengths with the help of a DFS-8 spectrograph and an ASK-3 automated spectrometric complex [10] with a spectral resolution of ~0.1 and 3 Å, respectively. From the emission spectrum of the anodic flame it was established that the composition of its plasma is determined by copper vapor. The emission spectrum of the cathodic jet includes an intensive continuum, molecular bands of N_2, and the lines of nitrogen and oxygen atoms and ions. There are no lines from the most likely impurity W. Taking this into account, it may be assumed that the composition of the plasma of the cathodic jet is determined by the working gas (nitrogen) and the air sucked in from the surrounding atmosphere.

Comparison of the emission spectra showed that the plasma temperature in the cathodic jet is much higher than in the anodic jet. The purpose of this work is to determine the maximum parameters of the plasma responsible for the heating of solid particles in the jet, so that the radial distributions T(r) were obtained for the cathodic jet only. The measurements were performed under the assumption that LTE exists in the jet by the method of absolute intensities based on the line NI 742.3 nm. The assumption of LTE is fully justified, since other authors have shown that LTE exists in electrical discharges in a nitrogen atmosphere under less favorable conditions [11-13].

The image of the zone of the cathodic jet under study — a disk 0.5 mm thick at a distance of 0.15 mm from the nozzle cutoff — was projected with an illuminating system having a magnification of ~4× onto the input slit of a monochromator and was moved in discrete steps with the help of a scanning device in a direction perpendicular to its geometric axis. This enabled recording the transverse distribution of the intensity I(x) at 32 equally spaced points x. From the output of the monochromator the signal, after analog-to-digital conversion, was fed in the form of a corresponding block into the working memory or onto the magnetic tape of a 15 VSM-5 computer. The distribution I(x) was accumulated with a resolution time of $\sim 2 \cdot 10^{-3}$ sec sequentially in separate groups based on six contours in each group with an interval of several seconds. The input time of one contour was equal to ~50 msec with a spacing of ~0.1 sec in a group. The number of groups reached 30. The existence of a link between ASK-3 and the system for complex study of the plasma [14] enabled the following analysis of the experimental data with the available mathematical software for the SM-3 computer.

Pulsations of the electrical characteristics of the power supply, erosion processes on the electrodes, and other factors could cause the jet to be displaced in a transverse direction accompanied by a change in brightness. The effect of jet displacements on the reliability of the determination of T(r) was eliminated by selecting only symmetrical contours I(x), and since the problem of this work was to determine the maximum parameters of the plasma, to make a substantive analysis symmetrical contours, whose intensity at the center $I(x = 0) \geq 0.9 \cdot I_{max}(x = 0)$, where $I_{max}(x = 0)$ is the maximum value of all quantities $I(x = 0)$ recorded for the conditions used, were employed.

The quantum-mechanical constants required for calculating the pyrometric dependences E(T) were taken from [15], and the values of the partition functions were taken from [16]. The plasma generated was assumed to consist of nitrogen [17]. The possibility of making such an assumption is supported by the close values of the concentrations of atomic nitrogen in the temperature range under study for nitrogen and air plasmas [18]. In addition, from a comparison of the relative intensities of the NI and OI lines for the plasma of the cathodic jet and air at approximately the same temperatures [19] it follows that the plasma under study contains several percent oxygen. The radiation in the wings of the diagnostic lines was taken into account employing the technique presented in [20].

The role of the reabsorption of radiation within the jet was evaluated by additionally measuring the local plasma emissivities $\varepsilon(r)$ in the line NI 744.2 nm. Its excitation energy is equal to the excitation energy of the main pyrometric line NI 742.3 nm, while the probability of a spontaneous transition and therefore also the coefficient of absorption within the line profile differ approximately by a factor of two. The agreement between the ratio $A = \varepsilon^{744.2}(r)/\varepsilon^{742.3}(r)$ and the theoretical value A = 2.03, taking into account the errors in the measurement of $\varepsilon(r)$, enabled drawing the conclusion that the absorption of radiation in the jet in the direction of observation can be neglected.

The results of the measurements of the radial temperature distribution in a plasmatron jet are presented in Fig. 2. We estimated the total (systematic plus random) relative rms error of the measurements to be $\Delta T/T \sim 10\%$.

As is evident from Fig. 2 when the discharge current changes from 300 to 400 Å the temperature of the plasma does not increase appreciably: the distributions T(r) remain practically unchanged as the power input P increases by a factor of 1.3. The maximum temperature (T ~ 14,000°K) is reached at the center of the jet and drops to 7500°K at a distance of ~3 mm from the axis.

An analogous dependence of the axial temperature of the plasma $T(r = 0)$ on the discharge current was observed in [21-23], where in order to increase $T(r = 0)$ in a cascade arc from 13,000 to 14,000°K a very substantial increase (by more than a factor of two) in P was required. Such a weak dependence of the plasma temperature in the zone under study on the current strength can explain the observed insignificant effect of current pulsations on the plasma parameters near the nozzle.

The transverse gradient $\partial T/\partial r$ evaluated for the central, median, and peripheral sections did not exceed $2 \cdot 10^4$ K/cm and was several orders of magnitude smaller than $\partial T/\partial r$, at which deviations from ionization equilibrium in the arc in a nitrogen atmosphere owing to diffusion of charged particles is observed [24].

Thus the jet plasmatron with the cathode surface located at a distance of approximately one unit from the nozzle cutoff enables obtaining a nitrogen plasma temperature of 14,000°K at the outlet from the nozzle. A higher temperature and therefore enthalpy of the jet in the given zone of the generator, compared with the existing designs, makes the setup described here promising for plasma hardening of hard to melt powdered materials.

NOTATION

i, Current strength; u, discharge voltage; P, electrical power fed into the discharge; G, flow rate of the plasma-forming gas; L, distance from the surface of the cathode to the nozzle cutoff of the plasmatron; l, distance from the cutoff of the plasmatron nozzle to the zone of the cathodic jet under study; r, instantaneous radius of the jet; x, transverse coordinate of the jet in the scanning direction; T, plasma temperature; I, plasma radiation intensity integrated along the line of sight; E, energy of the radiation in the pyrometric line; ε, local emissivity of the plasma; A, ratio of the local plasma emissivities; $\Delta T/T$, relative rms error of the measurements of the plasma temperature; and dT/dr, transverse temperature gradient.

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BREAKDOWN OF AN ORGANICALLY BASED COMPOSITE MATERIAL IN A HIGH-TEMPERATURE GAS FLOW

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The authors analyze a mechanism for breakdown of a composite material of the textolite type, composed of the chemical elements H, C, N, and O in an air stream of stagnation enthalpy 14,000-73,000 kJ/kg. A comparison of the theory and the experimental data show that the accuracy of the theoretical model is 25%.

Recently, many papers have appeared with mathematical models for breakdown of heat shield materials in high enthalpy gas flow. The physics of the breakdown process have been analyzed in detail [1]. It has been established that the error in the theoretical model depends to a greater extent than had been suggested earlier on the accuracy of calculating the transfer coefficients of the mixture in the boundary layer, and on the use of a correctly chosen kinetic condition for breakdown of the material at the body surface.

The literature makes wide use of the boundary layer model with the approximation of frozen chemical reactions within the flow and under the hypothesis of a catalytic wall [2], lead-

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