ELECTRON TEMPERATURE AND CONCENTRATION IN INITIAL REGION OF A SUPERSONIC JET OF ARGON PLASMA FROM A MAGNETOPLASMADYNAMIC SOURCE

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UDC 533.9.082.76

The flow picture and the parameters in supersonic plasma jets depend significantly on the type of source and its characteristics. In [1] we investigated experimentally the gasdynamic structure of the initial region of argon and helium plasma jets issuing into a rarefied atmosphere from a magnetoplasmadynamic source (MPDS). Data on the distribution of electron concentration and temperature, ion composition, and kinetics of electron—ion processes in MPDS jets are of considerable independent interest.

The results of measurements of the electron parameters in plasma jets of sources without an external magnetic field are discussed in [2, 3]. Data for plasma jets of sources with an external magnetic field are given in [4, 5]. It should be noted, however, that the results of these investigations do not give a complete picture of the distributions of the electron parameters in the initial region, and in the analysis of the results the gasdynamic structure of jets of this type was not taken into account.

In this paper we attempt to explain the variation of the electron parameters in an argon plasma jet of an MPDS with an external magnetic field, taking into account the gasdynamic structure of the initial region and the kinetics of electron—ion processes. The construction of the plasma source and a diagram of the initial region of the jet are shown in Fig. 1a. The source consists of a tungsten cathode 1, a nozzle anode 2, a neutral insert 3, a magnetic coil 4, and a magnetic circuit 5. The minimum internal anode diameter d = 40 mm. The source was mounted on a coordinate device with two horizontal degrees of freedom inside a vacuum chamber with a volume of about 10 m^3. The measuring instruments were stationary relative to the vacuum chamber.

In the jet we can distinguish several characteristic regions: I) the high-enthalpy flow, usually called the cathode jet; II) the expansion zone; III) the layer of mixing of the jet with the surrounding medium. The flow conditions correspond to propagation of a free jet in an immersed space.

In the experiments the flow regime was of the transition type in which the initial region had a smeared wave structure. A detailed description of the source and jet structure is given in [1].

The following conditions are typical of the described experiments: arc current I = 250-500 A, magnetic-field induction at cathode face B = 250-500 G, argon-flow rate G = 0.05 g/sec, pressure in vacuum chamber p_∞ = 0.25 mm Hg, mass-average stagnation enthalpy $(0.5-1)\cdot 10^5$ J/g. The medium into which the jet flowed consisted of 65% argon and 35% air. The presence of air in the vacuum chamber was due to its imperfect sealing.

Diagnostic Methods

To obtain quantitative information about the electron concentration N_e and temperature T_e we used the electric-probe technique. We used a single cylindrical probe of tungsten wire 0.3 mm in diameter and 5 mm long. The reference electrode was the cooled copper holder with an expanded collecting surface. Voltage was applied to the probe (see Fig. 1b) by a mechanical sawtooth generator powered by a B1-8 stabilized dc supply. The current—voltage characteristic of the probe was recorded by a PDP-4-002 two-coordinate recorder.

Preliminary methodological experiments revealed that the source magnetic field had a significant effect on the probe characteristic, mainly reducing the electron current to the probe (see Fig. 1c). To determine T_e we used the straight-line portion of the current—voltage characteristic, undistorted by the magnetic field, on a semilogarithmic scale [6].

Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 22-28, January-February, 1978. Original article submitted January 10, 1977.

0021-8944/78/1901-0017$07.50

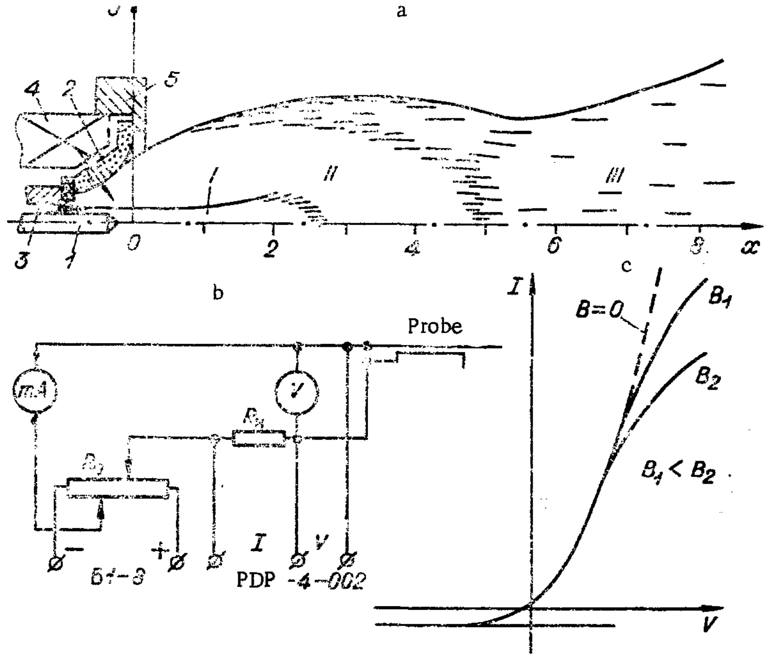

Fig. 1

Taking into account the quasineutrality of the plasma we determined the electron concentration from the Bohm formula [7]

$$N_e = \frac{i}{0{,}4e\,[2kT_e/m]^{1/2}},$$

where i is the saturation ion current density, e is the electron charge, k is the Boltzmann constant, and m is the ion mass.

The plasma velocity u was measured by the method involving two flat probes with their collecting surfaces set parallel and perpendicular to the velocity vector [8]. The value of u was determined from the measured saturation ion current densities $i_\parallel$ and $i_\perp$ with the aid of the formula

$$u = 0{,}4\frac{i_\perp}{i_\parallel}\left(\frac{2kT_e}{m}\right)^{1/2}.$$

To obtain information about the plasma ion composition we used the data of spectroscopic measurements. The emission spectra were recorded by two ISP-51 instruments with photographic and photoelectric recording. The technique and the results of the spectroscopic measurements are described in detail in [9].

The concentration N_{i_1} of singly charged argon ions on the assumption of the coronal population model [9] was determined from the measured populations N of the $4p^2D_5/_2$ Ar^+ level. For the calculation we used the plots of $N(4p^2D_5/_2) = f(N_eN_{i_1}, T_e)$ from [10], obtained for $T_e \geq 2$ eV. In determining the population of the $4p^2D_5/_2$ Ar^+ level on the jet axis we took into account the effective optical thickness of the plasma. The concentration N_{i_2} of doubly charged ions was determined from the measured populations of the upper Ar^+ states on the assumption that Saha–Boltzmann equilibrium exists between free electrons and electrons in the upper bound states [11]. The values of N_e and T_e required for calculations of the Ar^+ and Ar^{++} concentrations were taken from the results of the probe measurements.

Results of Measurements and Their Analysis

A general idea of the distributions of N_e and T_e in the initial region of the jet is provided by the results (Figs. 2 and 3) for three operating regimes of the source: 1) I = 250 A, B = 250 G; 2) I = 500 A, B = 250 G; 3) I = 500 A, B = 500 G. The longitudinal and transverse dimensions are expressed in terms of d.

Near the mouth of the source I and B had a strong effect on the axial distributions of the electron parameters. An increase in I and B led to an increase in N_e and T_e at the mouth

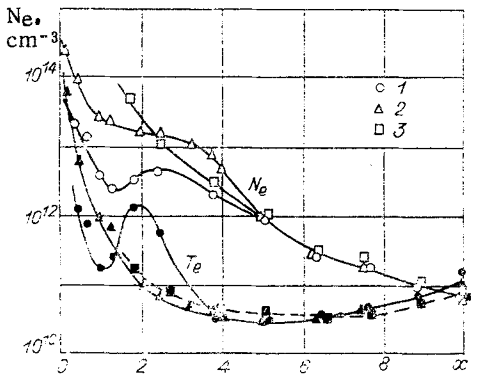

Fig. 2

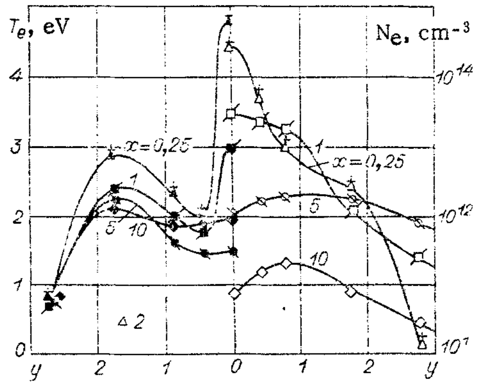

Fig. 3

of the MPDS. Beyond the mouth of the source, in the plasma expansion region, N_e and T_e were reduced. Further downstream the axial profiles of the electron parameters in some regimes of the MPDS (e.g., regime 1) had local maxima, whose position corresponded approximately to the end of the cathode jet. An increase in I and B led to smoothing out of the longitudinal distributions of N_e and T_e. With increasing distance from the mouth, the effect of the source regime on the distributions of electron parameters rapidly diminished. In the mixing region N_e decreased steadily in the downstream direction to a value of the order of 10^9 cm^{-3}, corresponding to the electron concentration in the vacuum chamber. In the region $5 < \kappa < 10$ the electron temperature on the axis increased slightly.

The transverse distributions of N_e and T_e (see Fig. 3) were characterized by large gradients. In region II there were distinct axial maxima corresponding to the cathode jet. With increase in I and B the transverse gradients of the electron parameters increased. In addition to the axial maximum on the transverse profiles of T_e there was a distinct peripheral maximum, whose position coincided with the boundary of the luminescent region of the jet. With increasing distance from the source mouth the axial maximum on the transverse distributions of N_e and T_e gradually decreased and was absent in region III. With increase in B and G the length of the zone of occurrence of the axial maximum increased.

The results of measurement of the ion velocity along the jet axis ($x \geq 2.5$) and in the cross section ($x = 2.5$) are given in Fig. 4. No measurements were made at $x < 2.5$ in view of the limited thermal stability of the probes.

In region III the velocity steadily decreased with increase in x and y. Increase in I and B led to an increase in u. As in the case of the N_e and T_e distributions, the effect of the source parameters was significant close to the MPDS mouth and decreased with increasing distance from it.

At the nozzle mouth we give the results of an estimation of the velocity u, based on the assumption of complete single ionization of argon, from the experimental values of the mass-average enthalpy, gas flow, and N_e profile at the source-outlet section.

The observed variation of the electron parameters and ion velocities can be explained within the framework of the qualitative flow picture, described in [1], for the initial region of an MPDS jet. The form of the longitudinal and transverse distributions of N_e, T_e and u is due to the existence of characteristic regions of gasdynamic structure — the cathode jet, the expansion region, and the mixing region. The main cause of alteration of the electron-parameter profiles with increasing distance from the source mouth is reduction of the role of electromagnetic compression, which forms the cathode jet, and an increase in the role of longitudinal acceleration and azimuthal twisting. The increase in N_e and T_e in the axial region beyond the source mouth with increase in I and B is due to an increase in compression forces resulting from the interaction of the azimuthal Hall current with the axial component of the external magnetic field and the axial component of the discharge current with its own azimuthal magnetic field. The presence of a lateral maximum of T_e in the mixing zone can be attributed to heating of the plasma as it decelerates. The appearance of a lateral maximum on the transverse profiles of N_e with increasing distance from the source mouth is due to twisting of the plasma and to a corresponding reduction of pressure on the jet axis [1].

Figure 5 shows data illustrating the variation of the concentration of singly and doubly charged argon ions along the jet axis. Results were obtained for $x \leq 2.5$. The obtention of data for large x was limited by methodological difficulties. Beyond the source mouth the

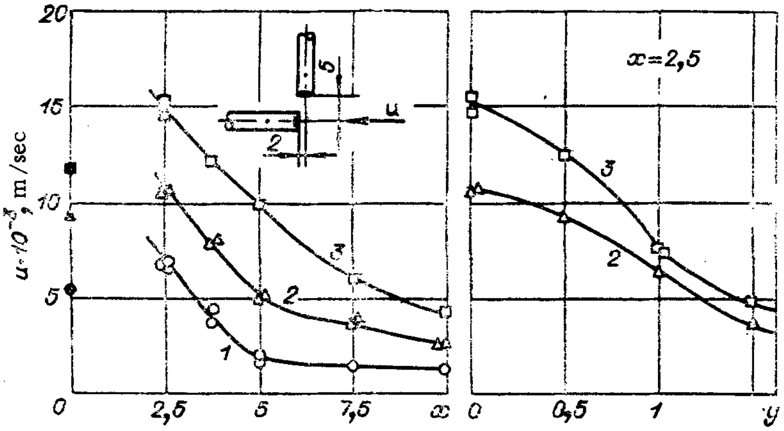

Fig. 4

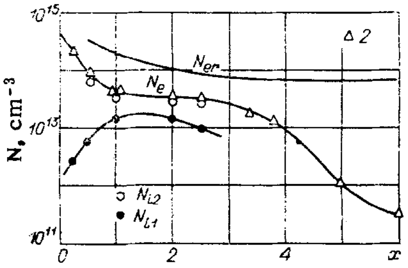

Fig. 5

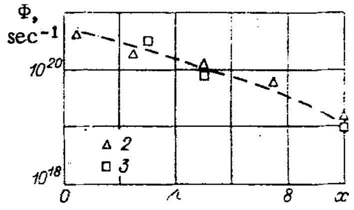

Fig. 6

concentration of doubly charged ions was much higher than the concentration of singly charged ions. The increase in N_{i_1} near the mouth can probably be attributed to the ionization of argon atoms entering the axial zone of the jet from the surrounding space.

The observed values of N_e are well below the equilibrium N_{er} determined from the Saha formula for known plasma pressure [1] and electron temperature.

The equilibrium electron concentration corresponds in the experimental conditions to complete double ionization. The slight variation of N_{er} along the jet axis is due to the slight change in plasma pressure and electron temperature. With increasing distance from the source mouth the difference between the experimental and equilibrium values of N_e increases.

The set of gasdynamic [1], spectroscopic [9], and probe measurements provides an approximate picture of the course of electron—ion processes in the initial region of an MPDS plasma jet. According to spectroscopic data [9], in the source arc chamber at $T_e = 5 - 10$ eV and $N_e \approx 10^{15}$ cm^{-3} there is complete single and significant double ionization of argon. An estimate of the characteristic times of the first and second ionization τ_{I_1} and τ_{I_2}, using the hydrogen-like model [12], shows that at the source mouth the first-ionization times τ_{I_1} are smaller, while the second-ionization times τ_{I_2} are comparable with the gasdynamic time $\tau_G = d/u$. With increasing distance from the source mouth the ionization rates sharply decrease and the ionization process becomes "frozen." The times of first and second collisional-radiative recombination τ_{r1} and τ_{r2} in the whole initial region are several orders greater than τ_G. For instance, in regime 2 of an MPDS with source-mouth parameters $N_e \approx 5 \cdot 10^{14}$ cm^{-3}, $T_e \approx 5$ eV, and $u = 5 \cdot 10^3$ m/sec the characteristic ionization and recombination times are, respectively, $\tau_{I_1} \approx 10^{-6}$ sec, $\tau_{I_2} \approx 10^{-5}$ sec, $\tau_{r1} \approx 10^{-3}$ sec, $\tau_{r2} \approx 10^{-4}$ sec for $\tau_G \approx 10^{-5}$ sec.

Beyond the source mouth the plasma composition rapidly changed due to mixing with the neutral surrounding medium. To determine the degree of "freezing" of the ionization and recombination processes from the results of measurements of N_e and u we calculated the electron fluxes $\Phi = \int N_e u dS$, passing through jet cross sections S (Fig. 6). There is a steady reduction of Φ in the downstream direction. According to the above estimates, the mechanism of collisional-radiative recombination cannot account for the observed variation of Φ. There is some other (more effective) recombination channel. An investigation of the distribution of electron concentration and temperature in argon plasma jets from electrothermal sources in similar conditions showed that the air in the medium surrounding the jet has a decisive effect on the course of electron–ion recombination. It was suggested that the reduction of the electron flux is due to dissociative recombination: $N_2^+ + e \rightarrow N + N$. The N_2^+ ions can be formed by charge transfer from argon ions. The spectra of the investigated jets show molecular bands of N_2 (first and second positive) and N_2^+ (first negative). An approximate estimate of the N_2^+ concentration from measured values of the population of the excited state $B^2\Sigma_u^+ (v=0)$, made on the assumption of the existence of coronal equilibrium, gives a value of the order of 10^{11} cm^{-3} in the cross section $x = 1.5$.

With a dissociative recombination coefficient of 10^{-7} cm/sec [14] the obtained N_2^+ concentration is sufficient to account for the observed reduction of electron flux along the jet. Definite conclusions regarding the recombination mechanism will require further investigations.

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