GASDYNAMIC STRUCTURE OF THE INITIAL SECTION OF SUPERSONIC JETS OF THE PLASMA OF A MAGNETOPLASMODYNAMIC SOURCE

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UDC 629.78.036.72

An experimental investigation was made of the gasdynamic structure of the initial section of supersonic jets of a plasma of argon and helium with outflow into a rarefied medium from a source of the magnetoplasmodynamic type. A study is made of the dependence of the gasdynamic structure on the kind of gas, the pressure in the surrounding medium, the inductance of the external magnetic field, the stagnation enthalpy, the mass flow rate, and the means used for feeding the gas.

The gasdynamic structure of supersonic jets of plasma depends to a considerable extent on the type of plasma source. In [1, 2] an experimental study was made of the structure of the plasma jets of electrothermal sources. The special characteristics of the acceleration of a plasma in magnetoplasmodynamic sources (MPDS) with an external magnetic field determine the specific character of the formation of the initial section of jets of this type. Individual questions in the gasdynamics of the jets of magnetoplasmodynamic sources were discussed in [3, 4]. In the present work, on the basis of experimental data an attempt is made to give a quantitative picture of the flow of a plasma in the initial section, with outflow into a low-pressure flooded space, and to clarify the connection between the gasdynamic structure and the parameters of the source. The experimental data were obtained during the course of gasdynamic, electric-probe, and optical measurements.

1. Source of Plasma and Experimental Conditions

The construction of the magnetoplasmodynamic source (Fig. 1) includes a tungsten cathode 1 and a coaxial pyrographite anode-nozzle 2, separated by a central insert 3, with a ring 4 made of boron nitride. Using the magnetic coil 5 and the magnetic circuit 6, a magnetic field is set up with an intensity at the end

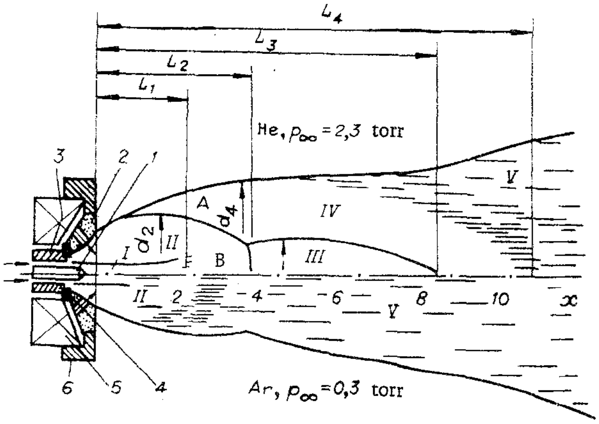

Fig. 1

Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 12-18, November-December, 1975. Original article submitted November 4, 1974.

of the cathode $B=30I_m G/A$, where I_m is the current in the cathode. The diameter of the cathode is equal to 5 mm, and the minimal inside diameter of the anode $d=40$ mm. The interelectrode gap is located in a diverging magnetic field. The construction of the source ensures an axial feed of gas along the cathode and a radial feed through the openings in the anode.

The magnetoplasmodynamic source is mounted inside a vacuum chamber on a positioning device with two degrees of freedom in the horizontal plane. The measuring devices were fixed with respect to the vacuum chamber. The gas was evacuated by a block of vacuum pumps, made up of two VN-6 mechanical pumps and a BN-15000 booster pump. For the experiments described the following conditions are typical: current of arc $I=250$-500 A; $B=250$-900 G; mass flow rate of gas $G=0.015$-0.3 g/sec. Under steady-state outlet conditions, the pressure in the vacuum chamber p_∞ is proportional to the mass flow rate of the gas and, with $G=0.1$ g/sec, is equal to approximately 0.2 torr for argon and 2 torrs for helium. In accordance with the data of the heat balance of the source, with $G=0.1$ g/sec and a current of 500 A, the mean-mass stagnation enthalpy is about $1.5 \cdot 10^5$ J/g for helium and 5×10^4 J/g for argon. Under these circumstances, there is complete primary and a considerable degree of secondary ionization of argon, and a considerable degree of primary ionization of helium. The spectra in the initial section of the jet are, respectively, the spectra of the argon ion and the helium atom [5, 6]. The pressure in the chamber of the magnetoplasmodynamic source was 0.3-3 torrs, with a concentration of particles 10^{14}-10^{15} cm^{-3} and an electron temperature of 5-10 eV.

2. Methods of Diagnosis

Gasdynamic, electric-probe, and optical methods were used to obtain quantitative information on the gasdynamic structure and the parameters of the plasma. The gasdynamic measurements included measurements of the total heads in the whole flow field and of the static pressure at the axis of the jet. The pickups for the total head were cylindrical water-cooled fittings with a flat end and a diameter of the receiving opening from 2 to 10 mm. Fittings with a small diameter were used for measurements near the outlet cross section of the nozzle of the source. The pickup for the static pressure was a cylindrical fitting with a diameter of 6 mm, with a head cone of 20° and lateral openings at a distance of 50 mm from the apex of the cone. The pressure was measured with VR-3 and VT-3 vacuum meters and BV-3 and LT-2 converters, respectively. The profiles of the total head and the static pressure were recorded continuously using a two-coordinate PDP-4-002 automatic recorder. The error in measurement of the pressure was 30-50%.

Electric-probe measurements were used to obtain data on the potential and velocity of the plasma, and the concentration and temperature of the electrons. Cylindrical and plane single probes were used. The electronic parameters and the potential of the plasma were found under the assumption of a Maxwellian distribution of the electrons and of free-molecular conditions of flow around the probe [7, 8]. The velocity of the plasma was measured by the method of two flat probes with collecting surfaces arranged parallel and perpendicular to the vector of the velocity [9]. The error of the electric-probe measurements was about 30%.

Optical diagnosis included photography of the jets and spectral measurements. The latter were carried out using an ISP-51 instrument with photographic and photoelectric recording. The optical methods ensured obtaining information on the dimensions of the gasdynamic structure of the jets, the spectrum of the radiation, the composition of the plasma, and the electronic parameters [5, 6].

3. Gasdynamic Structure

Under the conditions of the experiment, in the initial section there were mainly transitional flow conditions. With identical mass flow rates, jets of an argon plasma are considerably more rarefied than jets of a helium plasma. Figure 1 shows schematically the gasdynamic structure of the initial section of jets of argon and helium plasmas, constructed on the basis of photographs and visual observations, and corresponding to a mass flow rate of the gas on the order of 0.1 g/sec. From the cathode, along the axis of symmetry there is propagated a high-enthalpy and intense radiational flux of plasma I, usually called a cathode jet (see, for example, [10]). Beyond the outlet cross section of the source, there is a region of free expansion II, bounded by a hanging shock wave A and a Mach disk B. With equal mass flow rates and stagnation enthalpies, the dimensions of the region of free expansion in a jet of helium are considerably greater than in a jet of argon. As a result of the washing-out of the shock waves, a shock wave and a Mach disk are almost indistinguishable visually. In a jet of helium, the hanging and central shock waves are

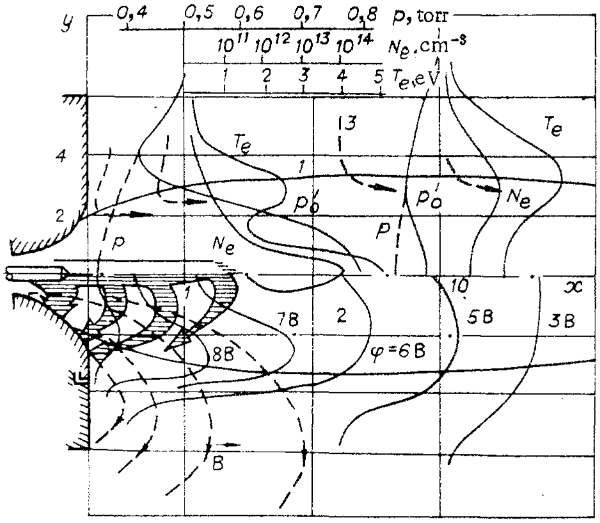

Fig. 2

rather clearly visible. The reflected shock wave B (see Fig. 2) is weakly expressed. Behind a Mach disk in a helium jet there is a region III, having a rose color. The central regions II and III are surrounded by region IV, of a blue color, going over gradually into the mixing zone V. The visually observed boundary between regions III and IV is obviously the limit of the boundary layer forming along a tangential discontinuity, which separates the plasma passing through the central shock wave from the plasma passing through the hanging and reflected shock waves. In the case of argon, as a result of its high degree of rarefaction, the region of mixing coalesces with the compressed layer, and the wave structure has a diffusional character. In Fig. 1 and below, the linear dimensions are referred to the inside diameter of the tube d.

We shall set forth briefly data on the effect of various parameters on the gasdynamic structure. With a decrease of the pressure in the vacuum chamber (for argon from 0.2 to $5 \cdot 10^{-3}$ torr), there is an increase in the longitudinal and transverse dimensions of the initial section, approximately proportional to $p_\infty^{-1/2}$. Simultaneously, there is washing-out of the boundaries of the characteristic regions.

An increase in the power of the magnetoplasmodynamic source leads to an increase in the linear dimensions of the jet; the cathode jet becomes more clearly expressed. With an increase in the external magnetic field, there is a transverse compression of the jet beyond the outlet cross section of the source, and an increase in the length of the cathode jet. There is a stronger effect of the magnetic field with small mass flow rates ($G < 0.1$ g/sec) and large currents of the discharge ($I > 300$ A). With very large values of the magnetic inductance $B = 900$ G, small values of G, and large values of I, there were observed working conditions of the source with a great length of the cathode jet, passing through the whole initial section. These conditions corresponded to a considerable increase of the voltage in the arc and to a sharp drop in the voltage between the cathode and the vacuum chamber. The end of the cathode jet is rather unstable, and there is tendency toward the formation of a wine-glass-shaped configuration (a bifurcation of the end in the meridional plane).

With $G \leqslant 0.1$ g/sec, the means of feeding the gas does not have any significant effect on the gasdynamic structure of the jets. The most stable work of the source is achieved with a mixed feed of the gas, where 0.6-0.8 of the mass flow rate is fed through openings in the anode, and the remaining part along the cathode.

Table 1 gives some data on the longitudinal and transverse dimensions (see Fig. 1) of the initial section of jets of argon and helium plasma with feeding of 0.7 of the mass flow rate through openings in the anode. In the case of argon, results are given for the greatest value of the mass flow rate $G = 0.3$ g/sec, where in a jet of argon plasma characteristic regions typical for a helium jet with $G \geq 0.05$ g/sec become visually distinguishable. Along with the values of G, I, B, and p_∞, the table gives data on the pressure at the wall of the anode p_W, in the cross section where the feed openings are located. We must note the decrease in p_W with an increase in B, which bears witness to the considerable role of electromagnetic forces in the formation of the jet.

An important special characteristic of the jets under consideration is the low density of the core of the jet in comparison with the density of the surrounding medium. Under transitional conditions, this fact

TABLE 1

Gas	G,g/sec	I, A	B,G	p , torr	p_W, torr	Dimensions						
						L_1	L_2	L_3	L_4	d_2	d_3	d_4
Ar	0,3	250	250	0,5	2,0	—	0,35	2,2	7,0	1,25	0,75	1,5
		500	250		3,2	0,5	0,65	5,0	10,0	1,5	0,75	1,75
		500	500		2,3	1,0	1,0	10,0	12,5	1,75	0,75	1,75
He	0,1	250	250	2,3	2,3	1,25	2,5	10,0	14,0	1,85	0,75	4,0
		500	250		2,5	2,0	2,75	12,5	21,5	1,85	0,75	4,5

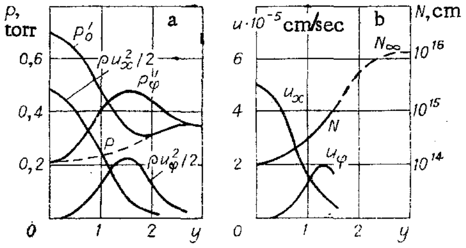

Fig. 3

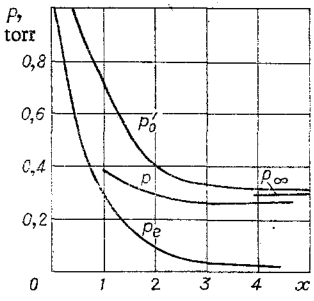

Fig. 4

ensures strong diffusion of atoms of the surrounding medium into the jet. As a characteristic of the conditions for the penetration of atoms of the surrounding medium into the jet, we can use the number $K_p = l/d$, where l is the length of the free-flight path of an atom of the surrounding medium with its motion across the jet in the plane of the outlet cross section of the source. Under the conditions G = 0.1 g/sec, I = 500 A, B = 250 G, for argon and helium $K_p \sim 0.1$ and 0.01, respectively. In evaluation of the K_p numbers, it was postulated that, for an atom of argon, collisions with argon ions are determining, and, for an atom of helium, with atoms. The difference of an order of magnitude in the K_p numbers explains the observed difference in the characteristic dimensions of the initial sections of jets of argon and helium plasma, with equal mass flow rates.

Under the conditions of the experiments, the propagation of a jet of argon plasma takes place under transitional conditions even at the outlet cross section. As a consequence of the scattering of the electrons and ions of atoms of the surrounding medium diffusing into the jet, there is formed a layer with a large gradient of the density, bounding the region of free expansion. For jets of helium, in distinction from argon jets, the flow conditions are mainly close to continuous. A transition to diffusional conditions took place with $G < 0.05$ g/sec.

4. Picture of Flow

The set of measurements presented makes it possible to give an approximate description of the picture of the flow of a plasma in the initial section. Figure 2 (1 is the visible boundary of the jet, 2 are entrainment currents, 3 are flow lines in the ejection zone), for a jet of argon plasma with G = 0.1 g/sec, I = 500 A, B = 250 G, and $p_\infty = 0.3$ torr, gives data on the profiles of the total heads with an axial orientation of the fitting p_0', the static pressure p, the concentration N_e and temperature T_e of the electrons, and the potential of the plasma with respect to the anode φ in two transverse cross sections x = 1, 10. The first cross section corresponds approximately to the middle, and the second to the end, of the initial section. The profiles of N_e, T_e, and p_0' in the first cross section have sharply expressed maxima, corresponding to a cathode jet. The monotonic decrease in N_e in a radial direction with increasing distance from the axis of the jet bears witness to a corresponding decrease in the degree of ionization. The profiles of T_e and φ have a maximum near the visually observed boundary of the jet. The increase in T_e in the mixing zone can be explained by heating of the plasma during its stagnation. The profile of p depends on the conditions of the source. With large currents and small mass flow rates of the gas, as a result of compression there is an axial maximum. In the zone of ejection of the surrounding medium $p < p_\infty$, and, within the limits of accuracy of the measurements, it is equal to p_0'.

In the cross section x = 10, the picture of the flow has a noticeably different character. There has been an equalization of the profiles in the region near the axis. At the periphery of the jet, the maximum

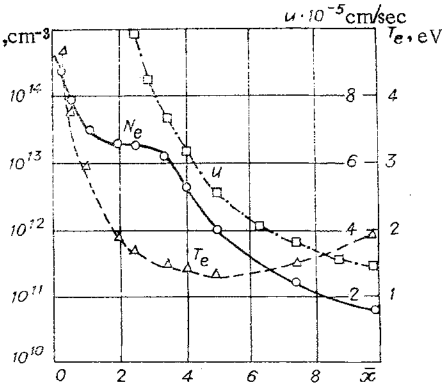

Fig. 5

of N_e has dropped out and a maximum of φ has appeared. The total head and the static pressure at the axis are less than the pressure in the surrounding medium. The main reason for the restructuring of the profiles of the gasdynamic parameters is twisting of the plasma by electromagnetic forces, arising with an interaction between the radial component of the current of the arc and the axial component of the magnetic field.

In the lower half of Fig. 2 there are given the equipotentials of the electrical field, the lines of force of the unperturbed magnetic field of the source, and a qualitative picture of the propagation of the entrainment currents. The part of the discharge current carried beyond the outlet cross section of the source is propagated predominantly along the axis of symmetry within the potential well.

To obtain data on the twisting of the plasma, measurements were made of the total heads using a fitting of rotated construction. The measurements also made possible an approximate determination of the direction of the lines of force. The latter was taken as the direction of the fitting corresponding to a maximum of p_0'. Measurements of the total head using a fitting oriented perpendicular to the axis of the jet in an azimuthal direction gave the profiles of p_φ' set up as a result of twisting of the plasma. Figure 3a gives the results of measurements of p_0' and p_φ' in the transverse cross section of a jet of argon plasma $x = 2,5$ with $G = 0.1$ g/sec, $I = 250$ A, $B = 250$ G, and $p_\infty = 0.35$ torr. With $y = 1$, near the visible boundary of the jet there is a maximum of p_φ' and equality of p_φ' and p_0'. Using the results of measurements of the longitudinal velocity u_x by the electric-probe method and the Bernoulli integral, we obtain the profiles of the concentration N and the azimuthal velocity u_φ (Fig. 3b). In the region near the axis of the jet, there is practically no twisting, $u_\varphi \ll u_x$; near the boundary $u_\varphi \simeq u_x$. The external part of the jet mainly performs a rotational motion. In the ejection zone, the gas first moves perpendicularly to the axis of the jet (here $p_0' \sim p \sim p_\varphi'$), the lines of flow then turn predominantly in an azimuthal direction ($p_\varphi' > p_0' \sim p$) and enter the boundary layer with an increase in the longitudinal component of the velocity.

We shall consider the laws governing the change in the parameters in a longitudinal direction using the example of a jet of argon plasma with $I = 500$ A, $G = 0.05$ g/sec, $B = 250$ G, and $p_\infty = 0.3$ torr (Figs. 4 and 5). Comparison of the electron pressure p_e and total static pressures shows that $p_e/p \simeq 1$ near the outlet cross section of the source, and decreases monotonically downstream along the jet. In the chamber of the source and the region of free expansion of the jet, the electrons make the principal contribution to the pressure of the plasma, since the ionization is complete and the temperature of the electrons under such conditions is considerably higher than the temperature of the ions [10]. The decrease in the ratio p_e/p downstream along the jet confirms the propositions advanced above with respect to the strong diffusion of atoms of the surrounding medium into the core of the jet, as a result of which, even with $x \geq 1$, the static pressure at the axis is determined by the atomic component. The rapid breakdown of the region of free expansion is confirmed also by the magnitude and the course of the change in the ratio p_0'/p along the axis. Under the assumption of isentropic flow, the value of p_0'/p with $x = 1$ for a monatomic gas gives a Mach number equal to 1.2, an experimental evaluation of which, from the angle of inclination of the attached shock wave in a wedge with an apex angle of 20° [11], gave a value of 1.5.

The connection between the distributions of N_e and T_e and the gasdynamic structure of the jet can be seen in Fig. 5. Near the outlet cross section of the source in region II (see Fig. 1) there is a rapid decrease in N_e and T_e, corresponding to an expansion of the plasma. With $x \geqslant 2$, there is a sharp slowing-down of the fall in the values of N_e and T_e, connected with stagnation of the plasma. Downstream in the mixing zone, N_e falls to a value on the order of 10^9 cm^{-3}, corresponding to the concentration of electrons in a vacuum chamber. At the end of the initial section there is a tendency toward a rise in the value of T_e. Analogous results were obtained in an investigation of the jets of electrothermal sources [2].

According to the data of measurements of the velocity u_x, the energy of the directed motion of argon ions near the outlet cross section of the source attains 20-30 eV and has the order of magnitude of the voltage in the source. Since the temperature of the electrons in the chamber of a magnetoplasmodynamic source does not exceed 10 eV, the observed velocities of the plasma cannot be explained by an electronic-thermal mechanism and, together with the factors discussed above, argues for the existence of electromagnetic effects in the formation of the initial section of the plasma jets of magnetoplasmodynamic sources.

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