STRUCTURE OF UNDEREXPANDED JETS OF ARGON PLASMA IN THE TRANSITIONAL MODE

G. A. Luk'yanov, V. V. Nazarov, and V. V. Sakhin

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A considerable number of experimental investigations have been devoted to the study of the gasdynamic structure of supersonic jets of gas and plasma. For example, underexpanded rarefied jets of cold air, nitrogen, and argon beyond sonic nozzles with discharge into a flooded space were investigated in [1-3]. The investigations of [4-6] pertain to jets of plasma with a low degree of ionization and a stagnation temperature $T_0 \lesssim 4.5 \cdot 10^3$°K. The authors obtained rather detailed data on the flow pattern and the characteristic size of the initial section. Such investigations are absent for jets of plasma with a considerable degree of ionization, however. The experimental investigations of such jets (see [7, 8], for example) mainly contain data on the laws of free expansion of the plasma and the behavior of electron–ion processes in jets. There is considerable interest in clarifying the properties of the gasdynamic structure of plasma jets in comparison with those of gas jets and attempting to generalize the data on the characteristic size of the initial section of such a jet.

The flow pattern in the initial section of a supersonic gas jet discharging from a sonic nozzle into a flooded space is determined by the expansion ratio N (the ratio of the pressure p_0 in the stagnation chamber to the pressure p_∞ in the ambient medium), the ratio γ of specific heats of the gas, the Reynolds number $Re_L = Re_* N^{-0.5}$ [1] (Re_* is the Reynolds number calculated from the parameters in the critical cross section), and the temperature factor $\tau = T_0/T_\infty$ (T_0 and T_∞ are the stagnation and ambient temperatures, respectively).

There are a number of important features in the case of sufficiently strongly ionized plasma jets of electrothermal sources. First of all, the conditions of discharge from the nozzle are considerably different, which is expressed, in particular, in the nonisentropic character of flow through the nozzle owing to Joule heating in the arc and the strong nonequilibrium of the parameters in a cross section. In the general case, relaxation processes have a considerable influence on the gasdynamic parameters at the nozzle cut and in the flow field of the jet.

1. Range of Investigations and Diagnostic Methods. A jet of argon plasma discharging in a steady state from a sonic nozzle of a direct-current electric-arc source with gas stabilization of the arc into a vacuum chamber with a volume of 10 m^3 was studied. A diagram of the source is presented in Fig. 1. The cathode with a tungsten tip 1 and body 2 was separated from the copper nozzle-anode 4 by an insulating gasket 3. The cathode and anode are water-cooled. The sonic nozzles had a diameter d of 2 and 5 mm and a cylindrical section with a length d.

The investigations were conducted in the range of $p_0 = 10^4$–10^5 Pa and $T_0 = (6\text{–}12) \cdot 10$°K with variation of the arc current from 75 to 500 A and of the argon flow rate G from 0.1 to 1 g/sec. The mass-average stagnation temperature was determined from the data of heat balance of the plasmotron. For this the determining dimensionless parameters were varied within the following limits: N = 25–750, τ = 20–40, $Re_* = 4G/\pi d\eta$ = 100–2000, and $Kn_L = 1.26\gamma^{0.5} Re_L^{-1}$ = 0.01–0.1. The coefficient of dynamic viscosity η is determined from the temperature and pressure in the critical cross section, calculated under the assumption of isentropic expansion in the plasmotron nozzle and that $\gamma = 1.67$. A characterization of the individual modes is given in Table 1.

The total pressure fields and photographic negatives of the jets served as the basis for the analysis of the gasdynamic structure. Cylindrical water-cooled tubes having a flat end and an outside diameter of from 2 to 6 mm were used as the Pitot tubes. The ratio of the outside diameter to the diameter of the receiver opening was 1.25. The small-diameter tubes were used for measurements near the nozzle cut. The pressure was recorded with vacuum gauges of types VT and VSB. The vacuum-gauge converters of types MT-6 and LT-2 were placed inside hermetic constant-temperature boxes and connected directly with the tubes. Tilted liquid manometers were also used for measurement. Dibutyl phthalate was used as the working liquid. The error of the pressure measurement did not exceed 20%.

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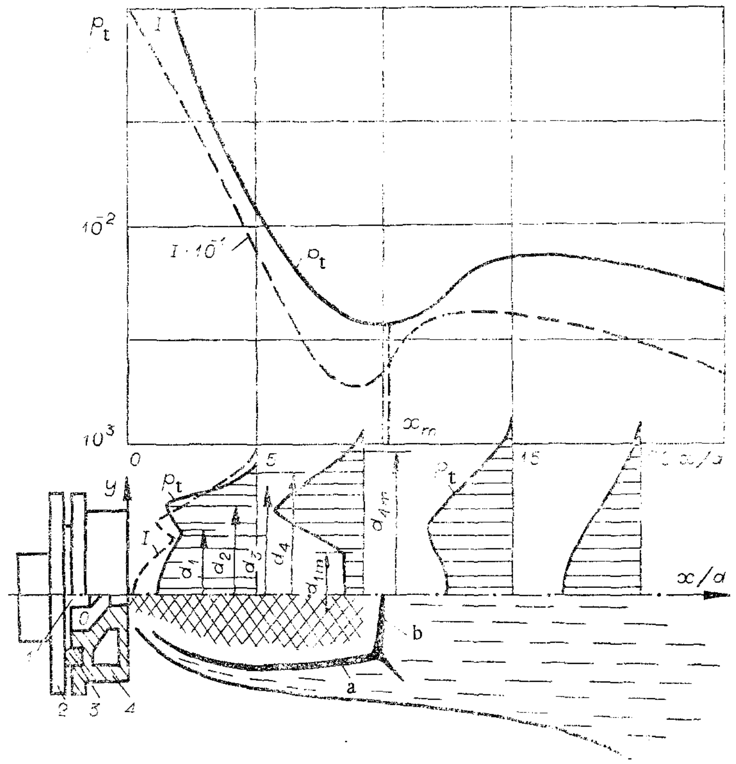

Fig. 1

As a methodological experiment using Pitot tubes of different diameter showed, the correction to the receiver readings, allowing for the rarefaction of the stream and determined using the results of [9, 10], did not exceed the measurement error and we ignored it. The measured pressures were no lower than 65 Pa, which made it possible, in accordance with [11], to ignore the correction for thermal transpiration in the tube.

The jet was photographed with a Zenit-4 camera on type KN-2 movie film. Photometry of the negatives was performed on an MF-4 microphotometer in order to obtain curves of emission intensity.

2. Flow Pattern. The gasdynamic structure of the investigated plasma jets is similar in its main features to the structure of supersonic gas jets. In the jet one can distinguish initial, transitional, and main sections. The characteristic wave structure is observed in the initial section. The initial section (see Fig. 1) consists of one "barrel," formed by the suspended (a) and central (b) compression shocks. The position of the compression shocks is emphasized visually by the presence ahead of them of a "dark" region, a zone of reduced emission intensity (unhatched zone in Fig. 1). The formation of the "dark" space is explained by the fact that because of the increase in electron temperature ahead of a shock wave there is a decrease in the rate of collisional radiative recombination and a corresponding decrease in the intensity of the emission, which basically has a recombination character under the given conditions [12].

In the investigated range of the parameters a laminar mode of flow occurred in the initial section. The range of Knudsen numbers $Kn_L = 0.01$–0.1 corresponds in degree of rarefaction to a transitional mode of flow. The number Kn_L has the approximate meaning of the ratio of the mean free path in the region behind the central compression shock (the Mach disk) to its distance from the nozzle cut. For $Kn_L < 0.01$ the wave structure of the initial section is observed rather clearly. With an increase in Kn_L there is a gradual smearing out of the wave structure. For $Kn_L > 0.1$ the suspended shock merges with the mixing layer, and the wave structure can no longer be considered as isolated compression shocks.

Characteristic longitudinal and transverse distributions of the relative total head $p_t = p_0'/p_0$ (p_0' is the total head measured by the tube) and of the integral emission intensity I, normalized to its value at the nozzle cut, are shown in Fig. 1.

In observing the dependence of the gasdynamic structure of the jet on the determining parameters we measured a number of the characteristic dimensions of the initial section. As the characteristic longitudinal dimension we chose the distance x_m to the Mach disk. It was measured as the distance from the nozzle cut to the minimum in the axial distribution $p_t(x)$ or the inflection point of the I(x) curve (see Fig. 1). According

TABLE 1

Mode number	$p_0\cdot10^{-4}$, Pa	$T_0\cdot10^{-3}$, °K	$\mathrm{Re}_*\cdot10^{-2}$	$N\cdot10^{-2}$	$\mathrm{Kn}_L\cdot10^2$
1	3,57	0,3	20	0,94	0,78
2	5,09	6	14	1,02	1,20
3	3,99	7	9,9	1,14	1,80
4	5,97	9	9,9	1,57	2,10
5	7,33	11.2	8,1	2,07	2,90
6	2.53	6	5,24	0,95	3,00
7	2,06	10	2,54	0,44	4,00
8	4,10	11,0	4,46	1,65	4,70
9	4,74	12,5	4,05	1,91	5,50
10	2,19	10,5	2,54	0,84	5,80
11	2,95	9,6	4,25	3.53	7.25
12	1,99	10	2,54	3,00	11,5
13	2.70	12,2	2,30	4,06	14,3
14	1,09	10	1.3	2,05	18,5
15	1,06	9,0	7,0	7.5	6,43
16	1.46	7,2	2,8	1,24	6,43
17	2,26	10,0	2,54	1,06	6,5
18	2,46	12,0	2.35	0.8	6,4
19	2,26	10,0	2,54	2,5	10,3
20	2.53	12,3	2,3	1.4	10.2
21	1.33	12.0	1.2	2,66	22.3

to [2], for gas jets under similar conditions the minimum of p_t in the axial distribution corresponds approximately to the inflection point of the curve of gas density in the region of the Mach disk. On the other hand, according to [12], in the region of the central compression shock the variation of I(x) is similar to the variation of electron density. This relationship was investigated experimentally in [13, 14]. Thus, under the experimental conditions we can expect that the dimensions x_m determined from the $p_t(x)$ and I(x) curves will be close. Experience confirmed this assumption.

In the cross section $x = 0.35dN^{0.5}$, approximately corresponding to the middle of the first "barrel" of the initial section of the jet, we measured the following conditional characteristic dimensions (see Fig. 1): d_1, the minimum diameter of the suspended compression shock [the distance between minima on the $p_t(y)$ curve or between inflection points on the I(y) curve]; d_2, the diameter of the compressed layer (the distance between maxima on the $p_t(y)$ curve]; d_3, the diameter of the supersonic core of the jet [the distance between points on the $p_t(y)$ profile where $p_0'/p_\infty = p_tN = ((\gamma+1)/2)^{\gamma/(\gamma-1)}$ for $\gamma = 1.67$]; d_4, the diameter of the jet [the distance between points on the $p_t(y)$ curve where $p_tN = 1.05$]. The diameter d_{1m} of the suspended shock and the jet diameter d_{4m} (analogous to d_1 and d_4, respectively) were measured in the cross section $x = 0.9x_m$.

<u>3. Experimental Results and Their Analysis.</u> In the investigated range of the parameters the values of x_m do not depend on Kn_L or τ and are generalized sufficiently well by the dependence (curve I in Fig. 2)

$$x_m = (0.65 \pm 0.03)dN^{0.5}. \tag{3.1}$$

In Fig. 2 modes with the same T_0 are denoted by points: 1) $T_0 = 7\cdot10^3$°K; 2) 10^4°K; 3) $1.1\cdot10^4$°K; 4) $1.2\cdot10^4$°K. The values of x_m obtained from axial profiles of p_0' and I are in satisfactory agreement with each other. The dependence (3.1) gives the distance from the nozzle cut to the center of the thickened Mach disk. A comparison of Eq. (3.1) with the results of [3] ($x_m = 0.645dN^{0.5}$) and [15] ($x_m = 0.67dN^{0.5}$), obtained for dense, strongly underexpanded gas jets with discharge from a sonic nozzle, when the central shock actually is a gasdynamic discontinuity, reveals rather good agreement. It should be noted, however, that in the investigated transitional mode of flow the extent of the region of free expansion along the jet axis is less than x_m in the initial section, in contrast to the continuous mode.

The tests do not reveal a significant influence of Kn_L or τ on the quantity d_1. The experimental data are approximated by the dependence (curve II in Fig. 2)

$$d_1 = (0.33 \pm 0.02)dN^{0.5}.$$

The variation of the rarefaction has a relatively weak influence on the quantities d_2 and d_3 (Fig. 3; the numbers of the modes from Table 1 are given at the top). The influence becomes noticeable for $\mathrm{Kn}_L > 0.1$. The test data for d_2 and d_3 are generalized by the empirical dependences

$$d_2 = 0.45\,(1 - 0.3\,\mathrm{Kn}_L^{0.5})\,dN^{0.5},\quad d_3 = 0.52(1 - 0.3\mathrm{Kn}_L^{0.5})\,dN^{0.5}.$$

The influence of Kn_L on the position of the conditional boundary of the jet is more significant. For d_4 and d_{4m} we obtain the empirical equations

$$d_4 = 0.57(1 + 2.3\,\mathrm{Kn}_L)dN^{0.5},\ d_{4m} = 0.7(1 + 1.85\,\mathrm{Kn}_L)dN^{0.5}.$$

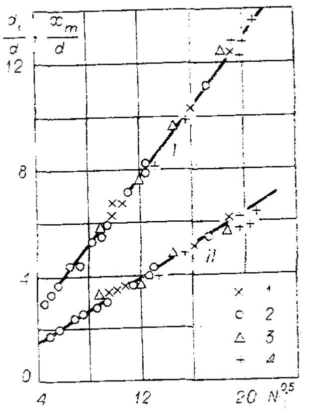

Fig. 2

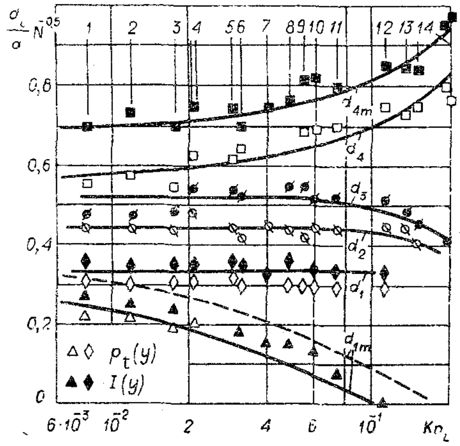

Fig. 3

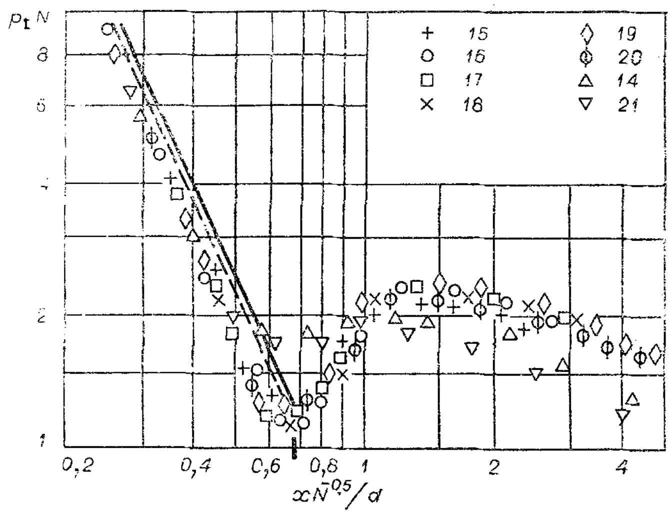

Fig. 4

Displacement of the suspended shock toward the jet axis and expansion of the viscous mixing layer occur with an increase in Kn_L. This effect is most pronounced in cross sections located immediately ahead of the Mach disk. The test data for d_{1m} are generalized by the dependence

$$d_{1m} = 0.33\left(1 - 3\,Kn_L^{0.5}\right) dN^{0.5}.$$

The data presented for d_{1m} are close to the results obtained for analogous gas jets. In Fig. 3 the dashed curve corresponds to the data of [1] for an air jet ($\tau = 1$), reduced to $\gamma = 1.67$ using the approximate dependence $d_{1\tilde{m}} \sim \gamma^{-1}$ [16].

The results of measurements of the total head at the jet axis for $Kn_L \lesssim 0.1$ are generalized sufficiently well in the coordinates p_tN and $x/dN^{0.5}$, not only in the region of free expansion but also behind the Mach disk. For $Kn_L > 0.1$ one observes separation of the curves into layers with respect to Kn_L and their smoothing in the region of the Mach disk.

Within the region of free expansion the experimental values of p_t are about 20% lower than the values of p_t for an ideal monatomic gas (solid curve in Fig. 4; the number of the mode from Table 1 is given at the top). The numerical estimates show that the observed difference cannot be explained by a possible decrease in the effective value of γ. In Fig. 4 the position of the minimum of $p_t(x)$, marked on the abscissa, corresponds to the dependence (3.1).

To determine the influence of viscous effects on the flow in the nozzle we measured the pressure p_w at the wall of the cylindrical part of the nozzle (Fig. 5) for the following cases: 1) $Re_* = 120$, $T_0 = 9 \cdot 10^3$°K; 2) $Re_* = 250$, $T_0 = 9 \cdot 10^3$°K. The tests showed that p_w decreases along the nozzle and at the nozzle cut it is considerably less than the value $p_*/p_0 = ((\gamma + 1)/2)^{-\gamma/(\gamma-1)}$ corresponding to isentropic expansion up to a Mach number M = 1. (The values of p_*/p_0 for different γ are given by horizontal bars in Fig. 5.)

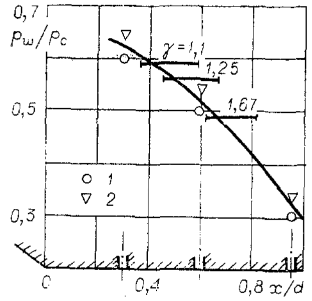

Fig. 5

The observed character of the variation of p_w (dashed line) can be explained by a decrease in the effective displacement thickness of the boundary layer near the nozzle exit cross section for discharge in the mode of underexpansion [17]. In this case the critical parameters are reached higher along the flow from the nozzle cut, and supersonic discharge occurs at the nozzle cut. Under the assumption of isentropic expansion with $\gamma = 1.67$ the measured values correspond to a Mach number $M_a = 1.3$ in the nozzle exit cross section. It should be noted that such an increase in M_a cannot explain the observed departure of p_t from the model of an ideal gas. In Fig. 4 the dashed curve corresponds to the case of $M_a = 2$ and $\gamma = 1.67$. In our opinion, the main reason for the decrease in p_t in the investigated plasma jets in comparison with the case of the expansion of an ideal gas is the loss of total pressure during the motion of the plasma through the cylindrical nozzle in the presence of a heat supply [18, 19].

A comparison of the empirical dependences obtained for the characteristic dimensions of the initial section with the analogous results for gas jets beyond a sonic nozzle [1, 3, 4] shows that the characteristic dimensions of the investigated jets are 10-20% smaller than for gas jets. The agreement can evidently be improved by allowing for the total pressure loss in the plasmotron nozzle. The influence of the expansion ratio N and the rarefaction Kn_L on the parameters and characteristic dimensions of the initial section is analogous to the influence of these factors on the parameters of such gas jets. Within the limits of the experimental accuracy the influence of the temperature factor ($\tau = 20$-40) on the gasdynamic structure is weakly expressed.

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RADIAL EXPANSION OF A PERFECT AND VIBRATIONALLY RELAXING GAS DUE TO A SUDDENLY CONNECTED SOURCE IN A VACUUM

N. V. Stankus and S. F. Chekmarev

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Radial expansion of a gas due to a suddenly connected stationary source is the model for a theoretical investigation of the process of stationary flow shaping in supersonic nozzles and strongly underexpanded jets during their onset [1, 2]. A flow is usually started up either by means of shock or explosive gas compression in the forechamber or by disruption of the diaphragm between the high-pressure chamber and the nozzle. In the former case the gas has a high temperature, in which connection the question of relaxation of the vibrational degrees of freedom of the molecules [3] becomes important, while in the latter case of high density, the question of gas condensation arises [4]. In their energetic characteristics both of these phenomena may exert significant influence on the gas flow. The question of vibrational relaxation is also important for gasdynamic lasers with shock heating of the gas [5].

The problem of the flow of a vibrationally relaxing gas due to a suddenly connected source during expansion into a vacuum is considered in this paper. For a perfect gas this problem was examined in [1], where the main attention was paid to calculating the buildup time of the stationary flow. A numerical solution is obtained below for the problem for a perfect gas, which corresponds to the case of a "frozen flow," and a vibrationally relaxing gas (up to equilibrium flow). It is shown that an approximate self-similar representation exists for the gas velocity and density distribution at large times. By using this representation, an estimate is obtained of the location of the vibrational temperature "freezing" point which describes its dynamics and agrees well with results of numerical computations. The results presented can be used to estimate the influence of the condensation process.

1. Statement of the Problem. There is a radial gas source with a surface of radius r_1. The pressure is $p_\infty = 0$ in the surrounding space. At the time $t = 0$ the source is connected, and the gas velocity v, the pressure p, the temperature T and the vibrational energy ε_V on the surface of the source $r = r_1$ acquire the given values $v_1 > 0$, p_1, T_1, ε_{V1}, which do not change with time, by a jump. Determine the behavior of the gas parameters with time for $r > r_1$.

Taking account of vibrational relaxation, the nonstationary one-dimensional gas flow is described by the following system of equations (in a Lagrange coordinate system) [6, 7]:

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