HIGH-TEMPERATURE JETS OF LOW-DENSITY ARGON BEYOND A SONIC NOZZLE

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The gasdynamic structure of rarefied argon jets is studied in the range of stagnation temperatures of from 290 to 5200°K using the electron-x-ray method. The effect of the temperature factor on different zones of the jet is shown and the reorganization of the flow pattern with a change in the mode of flow from continuous to free-molecular is analyzed.

NOTATION

d_n, nozzle diameter; G, mass flow rate of gas per unit time; M, Mach number; $N = p_0/p_f$; pressure; Re_n, Reynolds number calculated for the parameters in the critical cross section of the nozzle; $Re_L = Re_n/\sqrt{P_0/P_f}$; T, temperature; x, distance along jet axis from nozzle cut; $\bar{x} = x/d_n$; y, distance from jet axis; $\bar{y} = y/d_n$; ρ, density; $\bar{\rho} = \rho/\rho_0$. Indices: 0, parameters in stagnation chamber; f, parameters in flooded space.

Experimental studies of the gasdynamic structure of low-density jets beyond a sonic nozzle at high pressure drops [1-3] have shown that in a wide range of parameters, including modes of rarefied flows, the geometrical configuration of the jet and the distributions of the density and total pressure are self-similar when the value of the complex $Re_L = Re_n/\sqrt{P_0/P_f}$ is constant.

When a gas escapes into a medium with a temperature different from the stagnation temperature of the gas of the jet the distribution of the parameters in the mixing zone depends on the temperature drop and on the temperature levels. In this connection it is possible for the temperature factor to affect the structure of the jet as a whole, especially at small values of Re_L which correspond to the transition to rarefied flow. The authors do not know of an analysis of these questions. It should be noted that no systematic studies of the gasdynamic structure of rarefied high-temperature jets have been performed at all. At present there are only single reports [4, 5] containing data on the measurement of the total pressure and density in individual modes of flow, and studies of the physical processes in gas streams expanding from a plasma source have been conducted without the necessary attention to the gasdynamic structure of the jets [6-8].

In the present article we describe the results of a study of the density distribution in jets beyond a sonic nozzle and analyze the effect of the temperature factor on the structure of the jets in the transition from the mode of continuous flow to the scattering mode. In order to exclude from consideration the effects leading to a change in the physicochemical properties of the gas at high temperatures (chemical reactions, dissociation, excitation of internal degrees of freedom with a marked change in the ratio of heat capacities) the study was conducted at relatively low temperatures on a monatomic gas – argon.

At $T \leq 16{,}000$°K the excitation of electron levels can be neglected, since under these conditions separation of the outer electrons (ionization) occurs preferably [9]. Under typical conditions with the use of plasma heaters the degree of ionization is small as a rule and does not exceed 1% [5]. The recombination coefficient is on the order of 10^{-10}-10^{-12} cm^3/sec [10, 11] and the relaxation rate is low [12]. This gives

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TABLE 1

Mode No.	T_0, °K	G, g/sec	p_f, μ Hg	d_n, mm	Re_n	N	Re_L
1	290	1,14	534	2,125	40100	1550	1010
2	290	1,14	185	2,125	40100	4480	600
3	290	0,74	104	5,0	10900	866	371
4	1510	1,39	1260	3,11	9900	860	341
5	290	0,68	85	3,135	16100	2680	312
6	290	0,56	98	2,125	19700	4150	307
7	290	0,423	41	3,115	10000	3520	168,5
8	2000	1,1	590	3,115	6600	1650	162,0
9	290	0,236	71	1,10	15750	9400	162,0
10	2030	0,666	970	3,135	3950	610	160,0
11	290	0,389	23	2,116	10100	9200	105,0
12	1500	1,036	146	2,116	10900	10800	105,0
13	1510	0,729	223	5,0	3220	950	104,5
14	290	0,222	30,8	5,0	3130	925	103,0
15	2970	1,13	407	5,0	3360	1110	101,0
16	4970	0,92	1290	3,11	3180	1010	100,0
17	290	0,196	20,6	2,116	6840	7050	81,5
18	290	0,118	34	1,10	7900	9400	81,5
19	3840	0,857	572	2,142	5060	3900	81,0
20	5170	0,898	920	3,21	2910	1300	80,6
21	5060	0,85	926	3,11	2890	1300	80,3
22	290	0,20	18,7	2,125	7020	7750	80,0
23	2000	0,666	239	3,135	3970	2460	80,0
24	2020	0,913	179	2,142	7900	9700	80,0
25	4910	0,295	413	3,115	1030	996	32,6
26	1510	0,156	33,8	1,10	3160	28500	18,7
27	290	0,0125	11,6	3,11	297	370	15,6
28	4710	0,302	41	3,115	1090	10000	10,9
29	4700	0,148	24.8	4,98	331	3230	5,6
30	290	0,005	2,67	1,10	332	5050	4,67
31	290	0,00275	1,95	2,125	100	1040	3,21

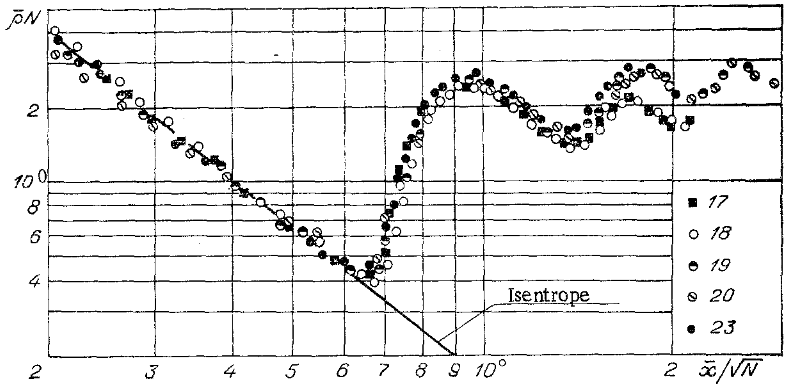

Fig. 1

reason to assume that the ionization in the jet is practically "frozen-in" and, consequently, the adiabatic index along a streamline corresponds to a monatomic gas.

The experimental studies of the present work were performed on a low-density gasdynamic stand using the electron-x-ray method of measuring the local gas density from the bremsstrahlung [13] and characteristic radiation [14] excited by an electron beam. An electric-arc plasmotron of single- chamber design with vortex stabilization of the arc and interchangeable stagnation chambers, mounted on a three-component coordinating mechanism, was used as the gasdynamic source. The electron gun was mounted immovably.

The principal operating parameters (see Table 1) were varied in the following ranges: T_0 = 290-5200°K; d_n = 1.1-5 mm; G = 0.003-1.4 g/sec; Re_n = 300-40,000; N = 300-30,000.

The possibility of generalizing the data on the density distribution in the jet at fixed values of Re_L and T_0/T_f in a wide range of values of Re_L (> 100) and N(>100) is shown, first of all, on the basis of the experiments.

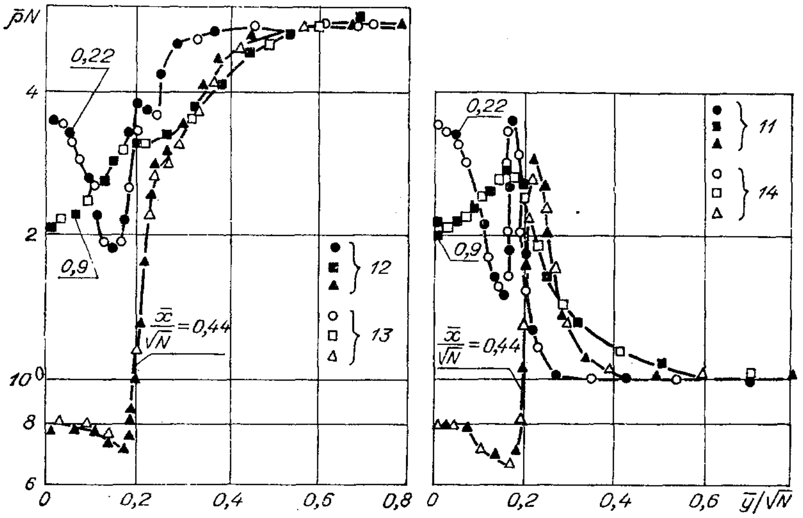

Fig. 2

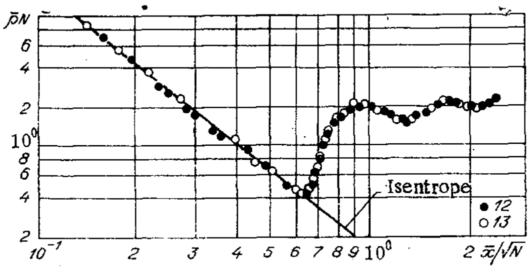

Fig. 3

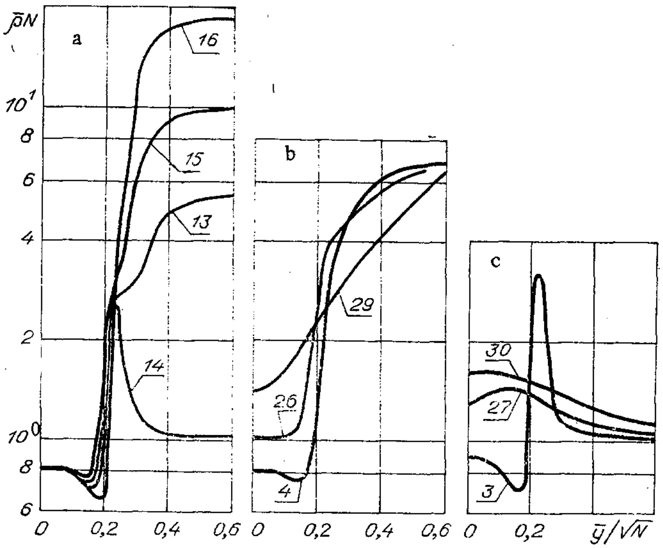

Fig. 4

As an example, the results of measurements of the axial density distributions are presented in generalized form in Fig. 1 (for $\mathrm{Re}_L = 100$), while transverse density profiles in three different cross sections of the jet are presented in Fig. 2 (the conditions are denoted by the corresponding mode number in Table 1). As is seen, the data are well generalized for fixed values of Re_L and T_0. Similar generalizations also occur for other values of Re_L (in the range of $\mathrm{Re}_L = 50$–1000). On the basis of the data obtained it can be concluded that in the indicated range of Re_L the density distribution along the length of the jets studied is self-similar with respect to N when the values of T_0 and Re_L are fixed. This is in agreement with the conclusions made on the basis of a study of nitrogen jets at $T_0 = T_f = 300$°K [3].

The next stage of the studies was the analysis of the effect of the temperature factor on the structure of low-density jets. The analysis of the experimental data is considerably facilitated thanks to the self-similarity with respect to N in the density distribution in the jets which was established above. The results of measurements of the axial density distributions with a fixed value $\mathrm{Re}_L = 80$ and different $T_0 = 290$–5200°K are presented in Fig. 3. As seen from the graph, agreement of the axial density distributions for different T_0 is observed in the first cycle of the jet. In the region behind the Mach disk the temperature factor begins to affect the axial density distribution and the experimental data become stratified. With an increase in the value of Re_L the region in which the temperature factor has no effect spreads down-

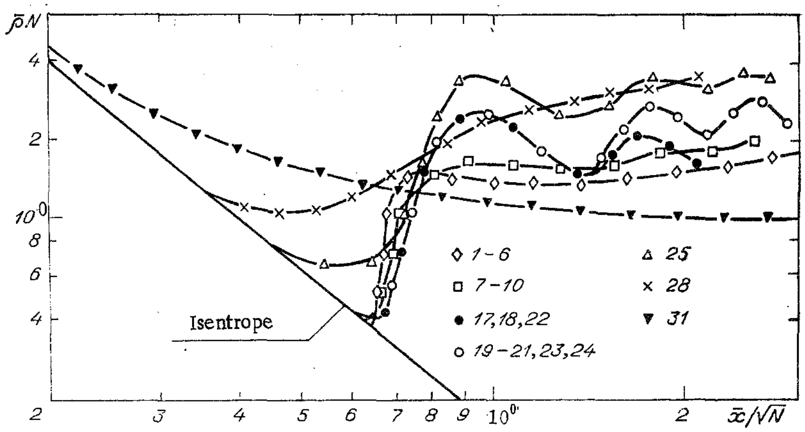

Fig. 5

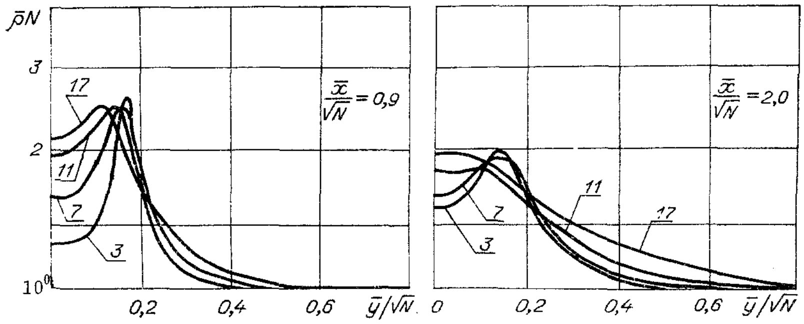

Fig. 6

stream, and when $\mathrm{Re}_L \geq 150$ generalization of the experimental data with respect to the axial density distributions at different values of T_0 ($T_0 = 290$-2000°K) is observed in the entire length of the jets studied ($\bar{x}/\sqrt{N} \leq 3$). With a decrease in Re_L ($\mathrm{Re}_L < 80$) the temperature factor already begins to affect the axial density distributions in the region of the initial section of the jet (the first cycle).

Transverse density profiles in the cross section $\bar{x}/\sqrt{N} = 0.44$ with $\mathrm{Re}_L = 100$ and $T_0 = \text{var}$ are presented in Fig. 4a. As is seen, the transverse density profiles for different T_0 are satisfactorily generalized only in the nonviscous zone of the core of the jet. In the region of the mixing zone, which merges with the zone of the compressed layer, the density profiles are stratified with respect to the temperature factor. The transverse density profiles at large values of Re_L have a similar form. At smaller values of Re_L the effect of the temperature factor on the generalized functions for the density already shows up in the core of the jet and at its axis (Fig. 4b, c).

The reorganization of the flow pattern with a change in Re_L can be traced on the basis of the data obtained (Fig. 5). At large values of Re_L ($\mathrm{Re}_L \geq 300$) the density distribution in the region of the nonviscous core of the jet is close to that calculated on the basis of a model of a nonviscous gas. The position of the Mach disk agrees with the data for high-density streams. In this case the width of the shock-wave front is small and the density ratio at the Mach disk is close to four, which is in accordance with the limiting value for a direct shock wave in a monatomic gas with $M \gg 1$. The measurements of the transverse density profiles at $\mathrm{Re}_L = 370$ and $T_0 = 290$°K show (Fig. 6) that an extended annular layer of compressed gas is retained behind the Mach disk and the mixing zone does not penetrate to the jet axis at least out to $\bar{x}/\sqrt{N} = 2$. A similar pattern is observed in high-temperature jets. The presence of annular flow behind the Mach disk (without passage through the speed of sound at the axis) was also noted in the studies of the authors of [3].

The reorganization of the described flow pattern occurs with a decrease in Re_L: the suspended shock waves, the Mach disk, and the mixing layer gradually become thicker; the merging of the mixing zone at the jet axis occurs behind the Mach disk and the region of merging moves upstream. This reorganization also leads to a change in the nature of the flow behind the Mach disk: the annular viscous layer becomes thicker and the merging of the mixing layer at the jet axis leads to an increase in the density behind the Mach disk, which is clearly seen in Figs. 5 and 6. This increase in density propagates upstream with a decrease in Re_L. At $\mathrm{Re}_L \simeq 80$ the merging of the mixing layer occurs close behind the Mach disk. The maximum density increase in the region of the Mach disk is reached with $\mathrm{Re}_L = 30\text{-}80$, which indicates the merging of the viscous layer directly in the region of the Mach disk and the latter cannot be considered as an isolated shock wave.

The thickening of the viscous layer strengthens the ejecting effect on the flow behind the Mach disk and the characteristic cyclicity of the flow ("barrels") appears. Such cyclicity is well seen, for example, in Fig. 5 at $\mathrm{Re}_L = 80$.

With a further decrease in Re_L the density shock waves degenerate, the flow becomes almost fully viscous (the merging of the viscous layer already occurs near the nozzle cut), and at $\mathrm{Re}_L \simeq 10$ the transition to the so-called scattering mode is observed. The rise in density at $\mathrm{Re}_L = 10$ and $T_0/T_f \gg 1$ is due to cooling of the gas in the mixing zone.

The qualitative changes in the structure of a jet of monatomic gas beyond a sonic nozzle with variation in the rarefaction and the temperature factor have been clarified as a result of the experiments and generalizations performed. The quantitative data obtained on the density distribution can be used for comparison with calculation in the development of a model of a jet.

LITERATURE CITED

1. V. S. Avduevskii, A. V. Ivanov, I. M. Karpman, V. D. Traskovskii, and M. Ya. Yudelovich, "Effect of viscosity on the flow in the initial section of a strongly underexpanded jet," Dokl. Akad. Nauk SSSR, 197, No. 1 (1971).
2. N. I. Kislyakov, A. K. Rebrov, and R. G. Sharafutdinov, "Diffusional processes in the mixing zone of a low-density supersonic jet," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1973).
3. V. V. Volchkov, A. I. Ivanov, N. I. Kislyakov, A. K. Rebrov, V. A. Sukhnev, and R. G. Sharafutdinov, "Low-density jets beyond a sonic nozzle at high pressure drops," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1973).
4. N. I. Yushchenkova, S. A. Lyzhnikova, and V. I. Nemchenko, "On the structure of supersonic jets of gas and low-temperature plasma," in: Transfer Effects in a Low-Temperature Plasma [in Russian], Nauka i Tekhnika, Minsk (1969).
5. R. B. Fraser, F. Robben, and L. Talbot, "Flow properties of partially ionized free jet expansion," Phys. Fluids, 14, No. 11 (1971).
6. M. Sinclair, A. A. Sonin, and J. H. de Leeuw, "Diffusive separation of ions and atoms in a shock wave," Phys. Fluids, 10, No. 4 (1967).
7. G. A . Luk'yanov and G. V. Petukhov, "Probe measurements in a rarefied plasma jet," Teplofiz. Vys. Temp., 7, No. 5 (1969).
8. V. M. Gol'dfarb and I. E. Kostygova, "Optical study of a supersonic nitrogen jet," in: Study of Low-Temperature Plasma Sources [in Russian], Vol. 466, Izd. LGPI, Leningrad (1971).
9. E. Resler, S.-C. Lin, and A. Kantrowitz, "The production of high temperature gases in shock tubes," J. Appl. Phys., 23, 1390 (1952).
10. W. A. Clayden, "Langmuir probe measurements in the R. A. R. D. E. plasma jet," in: Rarefied Gas Dynamics, Proceedings of Third International Symposium, Vol. 2, Academic Press (1963).
11. V. M. Gol'dfarb, E. V. Il'in, I. E. Kostygova, G. A. Luk'yanov, and V. A. Silant'ev, "Study of a supersonic rarefied argon plasma," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1967).
12. R. H. Kirchhoff and L. Talbot, "Experimental study of the shock structure in a partially ionized gas," AIAA J., 9, No. 6, 1098 (1971).
13. L. I. Kuznetsov and V. N. Yarygin, "X-ray bremsstrahlung of gas targets and its use for measuring the local density of a gas," in: Apparatus and Methods of X-Ray Analysis [in Russian], Mashinostroenie, Leningrad (1972), sec. 11.
14. L. I. Kusnetsov, A. K. Rebrov, and V. N. Varygin (Yarigin), "Diagnosis of ionized gas by electron beam in x-ray spectrum range," in: Eleventh International Conference on Phenomena in Ionized Gases, Prague (1973).