3. L. M. Biberman, S. Ya. Bronin, and A. N. Lagar'kov, "Radiative–convective heat exchange during hypersonic flow over a blunt body," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5 (1972).
4. A. N. Rumynskii and V. P. Churkin, "Flow of a hypersonic stream of viscous radiating gas over a blunt body," Zh. Vychisl. Mat. Mat. Fiz., 14, No. 6 (1974).
5. V. P. Zamuraev, I. I. Maslennikova, and R. I. Soloukhin, "An investigation of radiative heat exchange behind shockwaves in air using the multigroup averaging method," in: Heat and Mass Transfer during Intense Radiant and Convective Heating [in Russian], Inst. Teplo-Massoobmena Akad. Nauk BSSR, Minsk (1977).
6. K. M. Magomedov, "Hypersonic flow of a viscous gas over blunt bodies," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2 (1970).
7. M. N. Rolin, F. B. Yurevich, and V. V. Kondrashov, "An approximate method of calculating transfer coefficients for partially ionized gas mixtures," Inzh.-Fiz. Zh., 24, No. 3 (1978).
8. K. S. Adzerikho, Lectures on the Theory of Radiant Energy Transfer [in Russian], Belorus. Gos. Univ. im. V. I. Lenina, Minsk (1975).
9. M. N. Rolin, "The approximate calculation of radiation transfer in spectral multiplets," in: Some Problems of Heat and Mass Exchange [in Russian], Inst. Teplo-Massoobmena Akad. Nauk BSSR, Minsk (1978).
10. R. M. Goody, Atmospheric Radiation, Clarendon Press, Oxford (1964).
11. V. I. Krylov, The Approximate Calculation of Integrals [in Russian], Nauka, Moscow (1967).
12. I. V. Avilova, L. M. Biberman, et al., Optical Properties of Hot Air [in Russian], Nauka, Moscow (1970).
13. M. N. Rolin and F. B. Yurevich, "An economical means of calculating flows in the vicinity of a stagnation point," in: Heat and Mass Transfer during Intense Radiant and Convective Heating [in Russian], Inst. Teplo-Massoobmena Akad. Nauk BSSR, Minsk (1977).
14. A. N. Zaidel' and E. Ya. Shreider, Spectroscopy of the Vacuum Ultraviolet [in Russian], Nauka, Moscow (1972).
15. I. K. Kikoina (editor), Tables of Physical Quantities. Handbook [in Russian], Atomizdat, Moscow (1976).

EXPERIMENTAL INVESTIGATION OF LOW-DENSITY PULSED SUPERSONIC JETS

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1. The present report is a continuation of [1, 2], in which we presented the results of an experimental investigation, by the method of electron-beam probing, of pulsed jets of Ar and N_2 formed by discharge from a sonic nozzle with a diameter $d_* = 0.25$ mm at an initial pressure $p_0 = 7$–8 atm, an ambient pressure $p_\infty = (1.5$–$2) \cdot 10^{-5}$ mm Hg, and temperatures $T_0 = T_\infty = 300$°K.

A description of the experimental complex and the procedure is given in [1]. In the present work we experimentally investigated pulsed Ar and N_2 jets discharging through a conical supersonic nozzle into a space with a counterpressure $p_\infty = 2 \cdot 10^{-5}$ mm Hg. The gas pressure p_0 in the reservoir was 2 atm and the expansion ratio was $N = p_0/p_\infty = 10^8$. The radii of the critical and exit cross sections of the nozzle were $r_* = 0.835$ and $r_a = 4$ mm, respectively, and the expansion angle was $\alpha = 43°$. The calculated Mach numbers were $M_a = 4.9$ for N_2 and 6.9 for Ar. An electromagnetic valve employed at the FIRÉ, Academy of Sciences of the USSR, was mounted at the nozzle entrance. The valve was opened by a powerful current pulse supplied to the solenoid of the valve. Then the plunger located inside the solenoid and covering the nozzle entrance was shifted and the gas entered the nozzle.

The signals of electron-beam absorption were recorded at distances $X = x/r_a = 50$–320 along the axis and up to $Y = y/r_a = 150$ from the axis of the stream in both directions.

Four stages of the process are recorded on oscillograms of beam-current absorption: the appearance and steep rise of the absorption signal, a region of sharp variation of the derivative of variation of the signal with a subsequent slow rise in the process of development of the flow, a relatively constant level of absorption,

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lasting about a fourth of the total time of existence of the jet, and a sharp decrease of the signal to the zero level, corresponding to the closing of the valve. The total time of recording of the absorption signal comprised ~3 msec in all the experiments.

As shown in [2], when the characteristic size of the flows is $L \approx 10$ cm the lower limit of the recordable variation in the density ρ is 10^{-10} g/cm^3. Since the initial ambient density is $\rho_\infty = 10^{-11}$ g/cm^3, while the shock wave forming ahead of the front of the escaping gas can raise the density by no more than six times, the first disturbance must be identified with the arrival of the front of escaping gas at the investigated point of space.

The treatment of the experimental data made it possible to determine: the equations of motion of the front of material; the time sequence of the variation in the shape of the pulsed jet; the density fields at different times for several cross sections.

To bring out the laws of formation and the properties of pulsed jets we compared the results obtained for a supersonic jet with the corresponding ones for a sonic jet.

2. The equations of motion of the gas front in physical coordinates were found by the method of least squares in the form of a quadratic binomial. The coefficient to the quadratic term is different from zero with a confidence coefficient of 70%. The equations of motion have the form

$$t = 11.1x + 0.023x^2 \ (\mathrm{Ar}); \tag{2.1}$$

$$t = 9.7x + 0{,}02x^2 \ (\mathrm{N_2}), \tag{2.2}$$

where t is the time in microseconds; x is the distance in centimeters.

A statistical analysis of the experimental data, carried out on the recommendations of [3], allowed us to determine the 98% confidence interval for (2.1) and (2.2). The maximum corridor width did not exceed 3% of the values of the functions.

On the basis of an analysis of the collection of available experimental data and the analysis contained in [2] we chose the dimensionless variables in which the empirical curves are generalized best.

As the characteristic velocity we took the gas velocity c_* at the critical cross section, while as the characteristic size we took the radius r_a of the nozzle exit cross section.

In the dimensionless parameters $T = tc_*/r_a$ and $X = x/r_a$ the functions (2.1) and (2.2) are expressed with an error of not more than 5% by the one equation

$$T = 0.31X + 5.3 \cdot 10^{-5} X^2.$$

It should be noted that the dimensionless variables suggested in [4], which generalize the calculated functions for the motion of the surface of a strong discontinuity for flow from a suddenly turned-on spherical source, do not give generalizations of the experimental data under our experimental conditions.

In the investigated interval of the coordinates the velocity of motion of the front of a jet, as in the case of discharge from a sonic nozzle [2], proves to be higher than the limiting velocity of steady discharge of the gas, $U_{\max} = \sqrt{\frac{2}{\gamma - 1}}\, c_0$, where γ is the ratio of heat capacities; c_0 is the speed of sound in the gas under stagnation conditions. At the same time, the velocity is higher for discharge from a sonic nozzle than for discharge from a supersonic nozzle and, as noted in [2], exceeds the limiting velocity of nonsteady discharge. A tendency for an increase in the velocity of motion of the front of the escaping gas may develop because of the influence of condensation on the flows being studied.

As shown in [5], devoted to a study of condensation, the complex $p_0 d_*^{0.55}$ is a generalizing one for the process of condensation in a steady jet of either Ar or N_2. A comparison of this complex for the cases of discharge from supersonic and sonic nozzles shows that condensation should have a greater degree of influence in the latter case.

Measurements in several cross sections permitted the construction of curves of space filling by the escaping gas at different times T (Fig. 1). Since the flow is symmetric relative to the nozzle axis in the pulsed jet under investigation, the curves for different gases are given in the same graph. The sequence of times corresponding to the separate curves comprises a series of values of T: 1) 40.9; 2) 47.9; 3) 54.9; 4) 61.9; 5) 68.9; 6) 86.4; 7) 121.4 for Ar; 1) 44.4; 2) 52.4; 3) 60.4; 4) 68.4; 5) 84.4; 6) 114.4; 7) 144.4 for N_2. It should be noted, however, that the curves of Fig. 1 characterize the spreading of gas having a density no lower than the sensitivity limit, which does not rule out the gas of lower density reaching the peripheral regions. At fixed

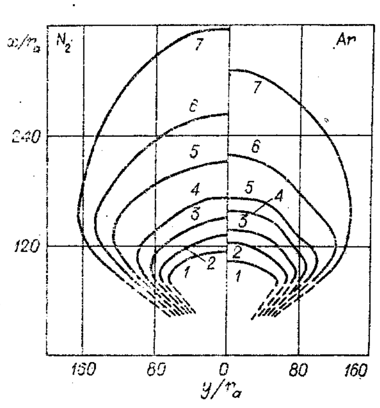

Fig. 1

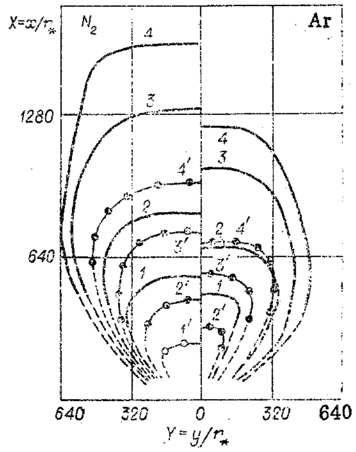

Fig. 2

times T in the proposed coordinates the pulsed jets of Ar and N_2 have the same sizes along the axis but differ along the radius. As follows from a comparison of the diameters, N_2 jets are somewhat larger than Ar jets. Variation of the boundaries of a jet occurs during the entire measurement process. Curves of space filling by a gas discharging from a sonic nozzle [2] are presented in Fig. 2. In this case the curves have a character analogous to the curves of Fig. 1. A comparison of Figs. 1 and 2 shows that in the chosen dimensionless coordinates, when the geometrical size of a jet is expressed in radii of the nozzle exit cross section, the relative transverse sizes of nonsteady jets discharging from a supersonic nozzle are less than those of jets from a sonic nozzle.

A second rise in absorption was observed on the oscillogram of beam absorption in the case of discharge from a sonic nozzle in [1]. The space–time dependence of the spreading of the front of this second disturbance is represented in Fig. 2 in the form of curves 1'-4'. The curves are similar in spatial coordinates to the curves corresponding to the front of the escaping material, while the velocity of motion of the second disturbance is lower than the velocity of the first.

3. A program for numerical integration of Abel's equation was compiled for calculating the density field from the integral absorption data. As in [2], the integral absorption curves were obtained from averaging a series of 6-10 experiments with the same conditions. The error of the integral absorption curves was ~20% with a confidence coefficient of 0.95; the error of the numerical integration did not exceed ~2%, while the total error of the determination of the density was ~25%. The calculated density distributions were verified by inverse numerical integration. The relative absorption curves thus obtained differed from the experimental ones by no more than 5%.

The distributions for Ar and N_2 jets with a relative density $\bar{\rho} = \rho/\rho_0$ for a supersonic nozzle in cross sections $X' = x/r_* = 380$, 485 (Ar), 500 (N_2), and 620 are presented in Fig. 3a-c. Since the flow is axisymmetric, half the density-profile field is given in each graph. Curves 1-3 correspond to times $T' = tc_*/r_*$ of 260, 326, and T'_{steady} for Ar and 326, 400, and T'_{steady} for N_2. The character of the variation of the density profile with time is the same for all the cross sections.

At times close to the moment of arrival of the gas at the test cross section the transverse density profiles have a bell shape, which is distorted after a certain time. Spreading with a density decreasing slowly away from the axis occurs in the peripheral sections of flow as a result of the subsequent variation. At later stages of discharge the jet broadens, the distribution flattens out more and more in the peripheral sections, and in the axial region a bell-shaped density distribution forms, a core, in which the main mass of gas of the jet lies. After a certain time the density profile in the core remains constant in each cross section, according to the behavior of the beam-absorption current, i.e., some "quasisteady" density distribution is established.

Relative density fields for a sonic nozzle [2] in the cross section $X' = x/r_* = 480$ are presented in Fig. 4. Curves 1-3 correspond to the times $T' = 235$, 336, and T'_{steady} for the flow of Ar, while for N_2 the series of values 251, 384, 512, and T'_{steady} corresponds to curves 1-4. A core with an increased density does not appear in this case, and the region in which the main mass of gas propagates is considerably wider than in the case of a supersonic nozzle. The distorted density profiles, observed in this case also, correspond to the time when an appreciable part of the stream, following behind the front of the second disturbance (curves 1'-4', Fig. 2), reaches the test cross section.

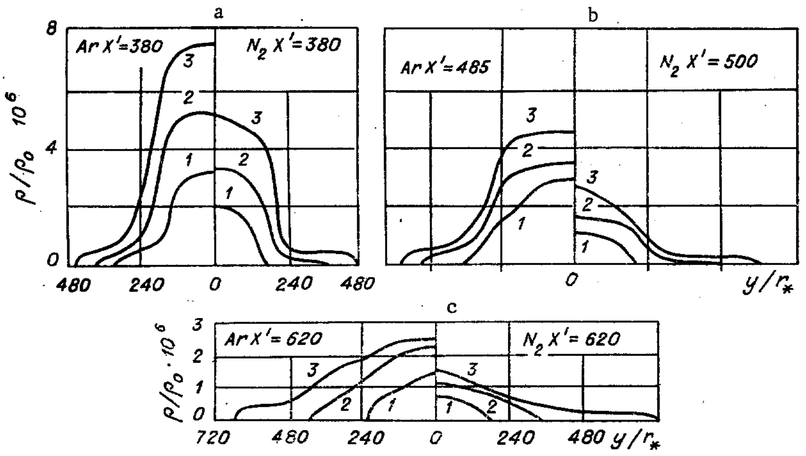

Fig. 3

At later times, just as for discharge from a supersonic nozzle, a constant "quasisteady" density distribution is established in the axial region, while the profile as a whole varies during the entire measurement time.

A comparison of Figs. 3 and 1, pertaining to the case of discharge from a supersonic nozzle, makes it possible to establish that a distorted density profile develops at that moment when the region of the jet with the maximum diameter is in the test cross section, which can be explained by the formation of vortex rings during discharge from a supersonic nozzle.

The analysis of the entire collection of experimental results of the present work, as well as those of [1, 2], allows us to suggest a model of the discharge of a pulsed jet. In the initial stage the gas coming behind the contact surface forms a vortex ring in the space near the nozzle cut as a result of the interaction with the rim, and it moves along the axis simultaneously as a whole and expands in the radial direction. The conditions of formation of this vortex are determined by the relation between the impulse of the jet, the drag forces of the ambient medium, and viscous forces. A second vortex cloud then begins to spread inside the cloud which has formed. The quasisteady density distribution is established as a result of the spread of the two interconnected vortex rings and the subsequent gas flow in the axial region.

An oscillogram of [1] for a sonic nozzle directly demonstrates the existence of two vortex rings. In many experiments a dip was recorded, corresponding to an increase in beam current and hence a decrease in absorption, before the second rise. Evidently, the rings which were discovered are analogous to those observed through direct visualization by the schlieren method in [6, 7], generated during the formation of a pulsed jet under the conditions of a counterpressure p_∞ = 10-40 mm Hg.

The fact that under the conditions of our experiments the discharge takes place into a deep vacuum allows us to conclude that the governing cause of the generation of vortices in the present case is the set of boundary conditions and the properties of a real gas.

An examination of the quasisteady density distributions in different cross sections allowed us to determine the character of the variation of the density $\bar{\rho}$ along the axis as a function of the distance from the nozzle. For both a supersonic and a sonic nozzle the variation of $\bar{\rho}$ is proportional to $(x/r)^2$ with a deviation of not more than 10%. A comparison of the quasisteady axial density distributions which were obtained with calculations made for a steady jet of nonviscous, thermally nonconducting gas discharging into a vacuum [8], as well as with isentropes, the coefficients for which were found from experiment in [9], showed that the experimental curves obtained lie below the calculated curves corresponding to them. The absolute values of the density are two to three times lower than the corresponding calculated ones.

From the density distributions in the test cross sections (see Fig. 3) we constructed lines of equal densities for a quasisteady N$_2$ jet from a supersonic nozzle (Fig. 5). Curves 1-4 correspond to $\bar{\rho} = 2.5 \cdot 10^{-6}$, 10^{-6}, $6 \cdot 10^{-7}$, and $2.5 \cdot 10^{-7}$. Curves 2'-4' are calculated curves from [8] and correspond to the same values of $\bar{\rho}$ as 2-4. The shapes of the experimental and calculated curves differ considerably. The former are flatter in the longitudinal direction and drawn out in the transverse direction. Condensation in the stream is the most likely reason for the broadening of the flow and the decrease in density along the jet axis. Condensation in steady jets was studied in [5, 10, 11] in modes close to those investigated in the present experiments. As noted in [10, 11],

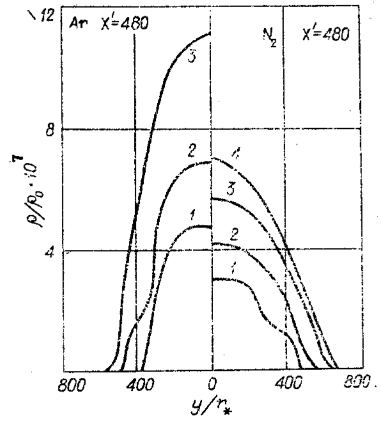

Fig. 4

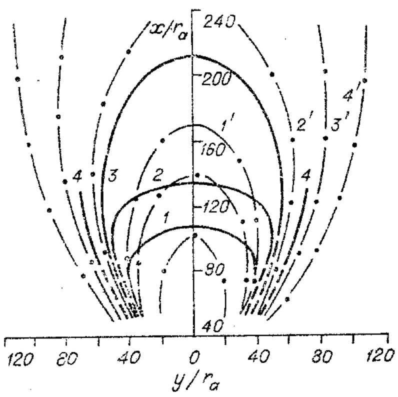

Fig. 5

the flow velocity can grow sharply, the stream expand, and the density decrease owing to the release of the heat of condensation.

An estimate of the fraction of condensate in the stream can be obtained if one knows the excess of the stream velocity relative to the maximum possible velocity in a noncondensing stream [5]. If the broadening of the jet is known, the increase in velocity is estimated with the help of the continuity equation. According to [8], the main mass of a jet expands within a cone whose half-angle is about half as large as the maximum deflection angle for expansion into a vacuum with the given γ_a and M_a. On the other hand, from the experimentally determined density profiles (see Fig. 3) we can determine the angle of the cone inside which the main mass of gas (~80%) is contained: the core of the jet. Thus, the amount of broadening of a condensing jet can be obtained from a comparison of the angles.

Estimates made for a quasisteady N_2 jet showed that the fraction of condensate is close to the maximum, which is in qualitative agreement with the results of [7].

In the above analysis the influence of the boundary layer forming on the nozzle walls on the flow in the jet was neglected. The small size of the boundary layer was shown by estimates made on the recommendation of [12], from which it follows that the possible reduction of the exit cross section of the nozzle due to the development of a boundary layer should not exceed 5%.

An analysis of the experimental data on the time variation of the density at the axial point of an individual cross section showed that up to times $T' = 0.4T'_{\text{steady}}$ the density variation has an uneven character, evidently connected with the influence of vortex formation. At $T' > 0.4T'_{\text{steady}}$ the density variation takes place with an exponential dependence. And this dependence, expressed through $(1-\bar{\rho})$, has its own equation for each gas, common to supersonic and sonic nozzles. The equation also incorporates a dependence on the axial coordinate X':

$$1-\bar{\rho}=K_1(X')^{-1/4}e^{-K_2T'(X')^{-1/4}},\quad K_1=\begin{cases}48.5 & (\mathrm{Ar}),\\ 21.2 & (\mathrm{N_2}),\end{cases}\quad K_2=4.26\cdot10^{-2}.$$

Thus, it is shown that the formation of a pulsed jet during the nonsteady discharge of gas through a nozzle into a rarefied space is complicated by processes of vortex formation and condensation. With the evident complexity of a theoretical analysis of the flows, the experiments and their analysis given in the present report prove to be useful for estimating the parameters of nonsteady jets, usable in the solution of a wide circle of scientific and technical problems.

LITERATURE CITED

1. A. V. Eremin, V. A. Kochnev, and I. M. Naboko, "An investigation of the formation of a gas jet during discharge into a rarefied space," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1975).
2. A. V. Eremin, V. A. Kochnev, A. A. Kulikovskii, and I. M. Naboko, "Nonsteady processes in the start-up of strongly underexpanded jets," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1978).
3. D. M. Himmelblau, Process Analysis by Statistical Methods, Wiley (1970).
4. S. F. Chekmarev, "Nonsteady radial expansion of gas into a flooded space from a suddenly turned-on steady source," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1973).
5. D. Golomb and R. E. Good, "Dimers, cluster, and condensation in free jets. II," J. Chem. Phys., 57, 3844-3852 (1972).

6. V. A. Belavin, V. V. Golub, I. M. Naboko, and A. I. Opara, "An investigation of the nonsteady flow structure in the discharge of a shock-heated gas," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1973).
7. I. M. Naboko, T. V. Bazhenova, A. I. Opara, and V. A. Belavin, "Formation of a jet of shock-heated gas outflowing into evacuated space," Astronaut. Acta, 17, 653-659 (1972).
8. G. I. Averenkova, É. A. Ashratov, T. G. Volkonskaya, et al., "Supersonic jets of an ideal gas. Part 1," Tr. Vychsl. Tsentr. Mosk. Univ. (1970).
9. I. B. Fenn and I. B. Anderson, "Velocity distributions in molecular beams of nozzle sources," Phys. Fluids, 8, No. 5 (1965).
10. N. V. Karelov, A. K. Rebrov, and R. G. Sharafutdinov, "Population of rotational levels of gas molecules with nonequilibrium condensation in the free expansion of a gas," Preprint Inst. Tekh. Fiz. Sib. Otd. Akad. Nauk SSSR, No. 20-77, Novosibirsk (1977).
11. N. G. Zharkova, V. V. Prokkoev, A. K. Rebrov, et al., in: Chemical Physics of Processes of Combustion and Explosion. Kinetics of Chemical Reactions [in Russian], Inst. Khim. Phys. Akad. Nauk SSSR, Chernogolovka (1977).
12. K. R. Enksnus, "Calculation of axisymmetric nozzles operating at high air-stream temperatures," in: Modern Technology of Aerodynamic Research at Hypersonic Velocities [in Russian], Mashinostroenie, Moscow (1965).