DIFFUSION PROCESSES IN THE MIXING ZONE OF A SUPERSONIC JET OF LOW DENSITY

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Results of an investigation into the diffusion processes in a jet of low density behind a strongly underexpanded sonic nozzle, in the zone of mixing with the surrounding gas, are presented. By means of electron-beam methods, the structure of the jet was studied in the case of expanding N_2 into an atmosphere of $CO_2 + N_2$ in transient regimes of flow varying from solid to rarefied. The results of an analysis of the fields of concentration of the separate components are given in a generalized form.

In experiments on molecular-beam apparatus (Fenn and Anderson [1], Brown and Heald [2], Govers et al. [3]) the effect of penetration of molecules of the surrounding gas in the core of the jet was studied from the viewpoint of finding an optimal combination of the thermodynamic parameters and geometrical dimensions of the system in order to obtain intensive molecular beams. In the series of papers by Campargue, which includes one of the recent articles [4], the effect of penetration of molecules of the surrounding gas has been studied from the viewpoint of using it for the separation of the gases. The interpretation of the results of the papers [1-4] is difficult without an analysis of the field of concentration in the zone of mixing of the gases. The latter became possible with the use of electronic-beam methods and was started in the papers by Muntz et al. [5, 6] and one of the present authors [7].

The specific feature of the present work is the attempt to investigate diffusion processes in the zone of mixing of a jet of low density when the baro- and thermo-diffusion effects have been reduced to a minimum. This was possible, thanks to using a pair of gases (N_2 and CO) with closely related characteristics. The molecular weights of these gases are identical with accuracy up to the fourth digit. At a temperature of 273°K and a pressure of 1 atm abs. according to the data [8] the calculation coefficients are self-diffusive (N_2) and the diffusions N_2-CO coincide and are equal to 0.174 cm^2/sec, while the experimental quantities have closely related values:

$$D_{N_2-N_2} = 0.172 - 0.185\,\text{cm}^2/\text{sec},\; D_{N_2-CO} = 0.192\ \text{cm/sec}.$$

Thus, mixing of the gases N_2 and CO takes place practically with the same quantitative characteristics as in the case of self-diffusion of these gases. Precisely for the study of self-diffusion this peculiarity of a mixture of gases N_2 and CO was used earlier [9].

The experiments were carried out on a gas dynamic installation of low density with a capacity of about 50 m^3/sec at a pressure level of $1 \cdot 10^{-2}$ mm mercury. The diagram of the working part and the measuring equipment is shown in Fig. 1, where 1 is the source of N_2, 2 is the source of CO, 3 is the electron beam, 4 is a quartz window, 5, 6, and 7 are elements of an optical system, 8 is a monochromator, 9 is a photomultiplier, 10 is a cathetometer, 11 and 12 are coordinate adjusters with photo-registers, 13 is a vacuum chamber, 14 is a high-voltage rectifier, and 15 is a potentiometer.

The method of carrying out the experiments is as follows. Gas from a supersonic nozzle was expanded into the atmosphere of a slow stream (of the order 10 m/sec) of a mixture of CO and N_2 which was formed by mixing carbon monoxide, flowing from a supplementary source, with the gas of the jet being investigated (nitrogen). By means of an apparatus for electron-beam diagnostics, the longitudinal and trans-

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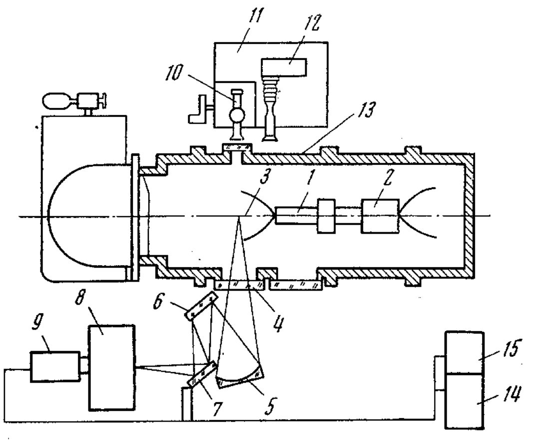

Fig. 1

verse concentration profiles of the components in the jet were recorded, and the longitudinal (axial) section of the jet was photographed by the electron beam.

The electron beam, the monochromator with an illuminating system, and the photo-register were fixed. The jet was displaced: the gas dynamic sources of N_2 and CO were mounted on a three-component coordinate adjuster which allowed a longitudinal displacement of ~1 m and a transverse displacement of 0.5 m.

The dimensions of the chamber and the flow of the gas allowed us to model approximately a jet expansion of a gas into a space filled with another gas. In all tests the relationship of flow of N_2 and CO was kept at the level 0.123-0.13. Here the average velocity of the flow in the space surrounding the jet was several meters per second. This cannot exert appreciable dynamic effect on the jet being investigated.

From the methodological side (for the detection) the gases N_2 and CO have definite advantages. In the spectrum of N_2 excited by the electron beam, the most intense band chosen for measurements (the band 00 of the first negative system of bands of N_2^+ with the edge wavelength 3914 Å) is located in the region where, in the case of pure CO, the 01 Herzberg band is weakly illuminated. Conversely, bands of the first negative system of CO^+: 01 with edge wavelengths of 2164 and 2300 Å respectively, are located in a region where no illumination of N_2 is detected.

In experiments with the N_2 of technical purity, it was discovered that the intensity of radiation of nitrogen on the segment 2299 ± 7.5 Å, which was used for measuring the partial density of carbon monoxide, is 200 times weaker than the intensity of radiation of pure carbon monoxide.

In addition, as was established by preliminary experiments, the spectrum of one of these gases is not altered when adding the other in the range of linear dependence of the illumination intensity on the density. For the conditions of the experiment this range at room temperature covers the pressure 0.001-0.15 mm mercury for the parameters of the electron beam used: current 1 mA, voltage 20 kV.

After calibration measurements and establishment of the conditions the monochromator with a photomultiplier was adjusted to a segment of the spectrum of one of the gases, and the distribution of the intensity of radiation along the axis and at five characteristic sections of the jet was recorded in succession: $x_+ = 0.1$, 0.4, 0.55, 0.73, 0.92, where $x_+ = x(d_* \sqrt{P_0/P_1})^{-1}$ is the normed coordinate along the axis of the jet, measured from the cutoff of the nozzle with diameter d_*; P_0 and P_1 are the braking pressure and the pressure in the vacuum chamber. After this the monochromator was readjusted to a segment of the spectrum of the gas, and the operation was repeated.

From measurements in the case of small flows, in particular, it was found that the concentration of CO varies along the length of the working chamber. On the length of the initial portion of the jet (up to the Mach disk) it varied approximately by 13-18%. In all sections the record showed a negligibly small value of density gradients of the individual components on the periphery. This indicates that the zone of mixing of the jet registered itself fully.

TABLE 1

Test No.	d_*, mm	G_{N_2}, g/sec	P_0, mm Hg	P_1, mm Hg	$\frac{P_0}{P_1} \cdot 10^{-4}$	R_*	R_L	G_{CO}, g/sec
1	1.09	0.61	2085	23.5	8.85	46500	157	0.078
2	1.09	0.408	1397	16.6	8.8	31100	107	0.053
3	1.09	0.176	610	6.9	8.85	13500	45.2	0.022
4	1.09	0.075	256	3.0	8.5	5710	19.5	0.0095
5	1.09	0.037	135.5	1.58	8.6	3000	10.2	0.0048
6	5.24	0.169	25.3	6.3	0.4	2680	42.6	0.0023
7	1.09	0.0362	126	31.5	0.4	2780	44.2	0.0048
8	2.15	0.174	156.5	6.9	2.26	6750	45.1	0.022

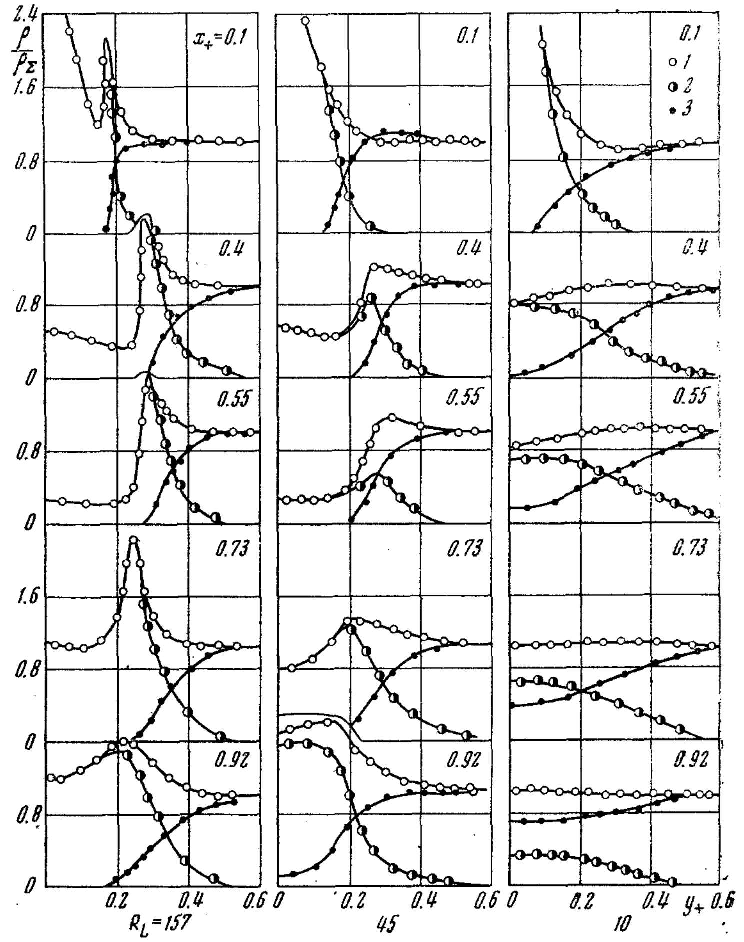

Fig. 2

When processing the experiments, use was made of the assumption that from the surrounding space the gases N_2 and CO diffuse into the jet perfectly identically. Therefore, from the profile of the CO concentration we determined the overall density of the gas diffusing into the jet by simply multiplying the readings for CO by a quantity which is reciprocal to the molar concentration of CO in the surrounding space.

In Fig. 2 we show the radial profiles of the relative overall density ρ_0 (points 1), the relative density of nitrogen (the gas of the source) ρ_1 (points 2), and the relative density of the gas diffusing into the jet ρ_2 (points 3), normed with respect to the overall density ρ, in the space of the vacuum chamber surrounding the jet. The radial coordinate y_+ is measured from the axis of the jet, and, analogously to the axial coordinate, is normed with respect to the diameter of the cutoff of the nozzle and the root of the pressure ratio. In the figure we have presented results corresponding to three values of the expression $R_L = R_* / \sqrt{P_0/P_1}$ (157, 45, 10), where R_* is the Reynolds number determined from the parameters in the critical section and the diameter of the cutoff of the nozzle.

In [11, 12] it was shown that the expression R_L can be used as a decisive criterion when analyzing a jet of a viscous gas. We note that the position of the Mach disk in the jet corresponds to $x_+ = 0.7$. The parameters of the jets investigated are presented in Table 1. In addition to the symbols introduced in the table, G_{N_2} and G_{CO} are flows of nitrogen and carbon monoxide.

It is characteristic that for $R_L = 157$ the gas from the surrounding medium does not penetrate into the zone of suspended shock wave. The front of the mixing zone is localized in the compressed layer which is to a large extent washed away even for these R_L numbers. Its position relative to the shock wave is approximately the same in all sections. In the region of space investigated, the outer gas does not penetrate to the axis of the jet. For $R_L = 107$ union of the mixing zone with the shock wave begins. In Fig. 2 we see that for $R_L = 45$ the shock wave already lies in the mixing zone. The regions with $R_L = 19.5$ correspond to such conditions, when union of the mixing zone with the shock wave has taken place, while the front of the shock wave has reached the axis of the jet into the core of the initial portion. The compressed layer is

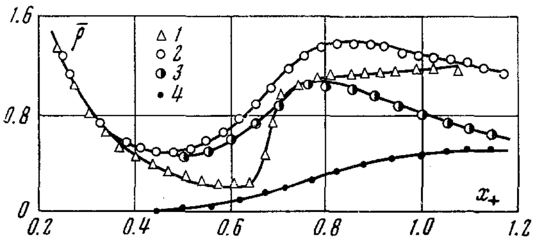

Fig. 3

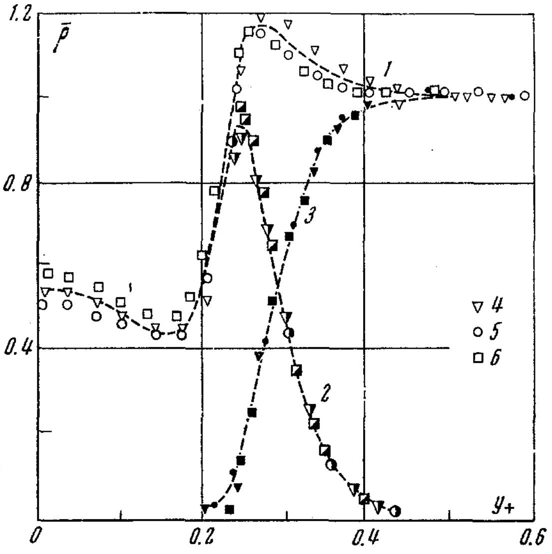

Fig. 4

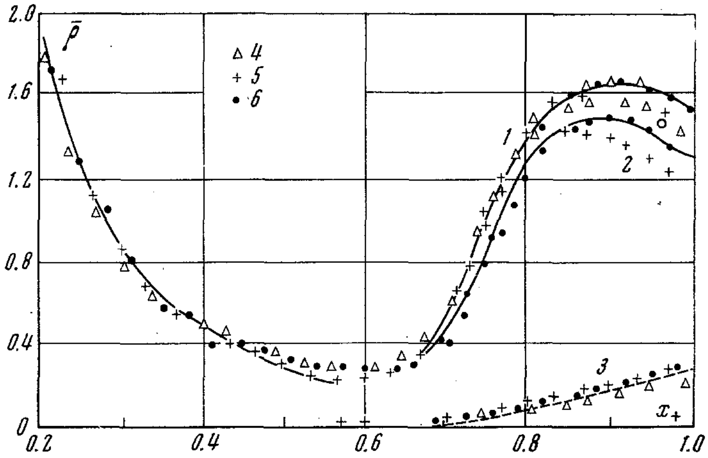

Fig. 5

substantially washed away. We note that the peak of the overall density in the compressed layer vanished for $19.7 > R_L > 10$. The flow for $R_L \approx 10$ corresponds to transition into the so-called dissipation regime [5]. The variation of the overall density in the suspended shock wave is of the order 10%. Individual zones of the jet are not separated from one another. Its structure is diffuse.

In Fig. 3 we have shown axial distribution of the relative density of the gas of the source (points 3 for $R_L = 19.5$), the penetrating gas (points 4 for $R_L = 19.5$) and the overall density (points 1 for $R_L = 157$ and points 2 for $R_L = 19.5$), which gives an idea about the structure of the shock wave of the Mach disk. The penetrating gas for $R_L = 19.5$ is discovered at the leading front of the shock wave.

The possibility of generalizing the experimental data was checked by a series of experiments with $R_L \approx 45$. In Fig. 4 we have shown the density distribution (1, overall density; 2, gas of the jet; 3, gas of the surrounding space; 4, $P_0/P_1 = 88{,}500$; 5, 22,500; 6, 4000) in the cross section of the jet $x_+ = 0.4$ for various pressure ratios (varying more than 20 times). As we see, the profiles are satisfactorily generalized. The longitudinal density distribution (Fig. 5; notation same as in Fig. 4) in the zone of the Mach disk has a representation which is not so well generalized. Therefore, it is possible that in regimes $R_L \approx 45$ the concentration of the penetrating gas on the axis of the jet is small and the accuracy of the experiments is not adequate for obtaining results which match.

With adequate definiteness we can talk about the position of the diffusion front on the axis of the jet. For $R_L \approx 45$ its coordinate is $x_+ \approx 0.65$-0.73. Estimating with the same accuracy the position of the diffusion front on the axis of the jet in other regimes, we can represent these results on the graph $x_{+D} = f(R_L)$ (points 1 in Fig. 6). Here we have also shown the graph of the position of the minimum of density in the shock wave (points 2). The affinity of these curves characterizes the penetration of the gas from the surrounding medium into the core of the jet.

The profiles of the penetrating gas in the compressed layer, where the effect of vorticity (entropy effects) is possible, in different regimes and in different sections are similar. This is illustrated by Fig. 7, where we have presented a unified profile of the distribution of the relative density of the penetrating component with respect to y/δ. Here y is the transverse coordinate measured from the point where $\rho_2 = 0.5$, and δ is the thickness of the mixing zone determined in the cross section of the jet as the distance between the points with the values $\rho_2 = 0.05$ and 0.95.

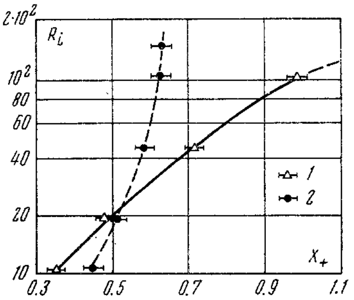

Fig. 6

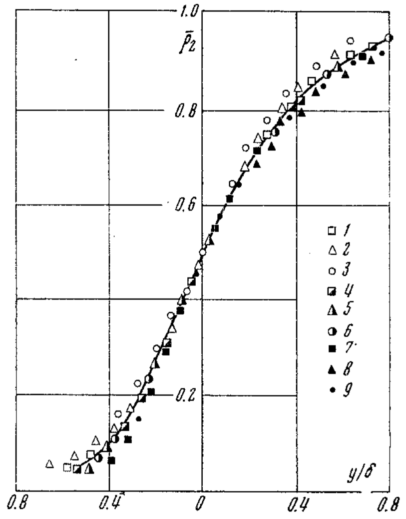

Fig. 7

In conclusion, we indicate the approximate boundaries of the characteristic regimes for jets of diatomic gases closely related to nitrogen in their properties. The inner front of the mixing zone for $R_L = 150$ is localized in the compressed layer. The range of transient regimes $R_L \approx 100$-10 corresponds to various degrees of union of shock waves and mixing zones; it commences for $R_L \approx 100$, while for $R_L \approx 20$-10 the jet becomes diffuse and the core of the jet before the Mach disk is filled by the penetrating gas in a quantity close to the quantity of the basic gas.

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