STRUCTURE OF A SUPERSONIC JET OF AN ARGON-HELIUM MIXTURE IN A VACUUM

A. A. Bochkarev, V. A. Kosinov, V. G. Prikhod'ko, and A. K. Rebrov

Results of an experimental investigation of barodiffusion processes in supersonic jets of argon and helium mixtures by using an electron beam are presented.

Becker [1] first disclosed the barodiffusion effect of separation in a jet of a gas mixture. Results of investigating this effect by gasdynamical methods are elucidated in a series of subsequent papers [2-4]. Zigan [5] and Sherman [6] attempted a quantitative analysis. The papers [7-9] are based on applying electron-beam diagnostics, which introduce no perturbation into the supersonic flow and permit a real picture of the gas mixture flow to be obtained.

New results of investigating effects in gradient flows are elucidated below.

1. EXPERIMENTAL TECHNIQUE AND METHOD

The experimental apparatus is a low-density gasdynamic shock tube of about 50,000 liters/sec productivity, equipped with an electron beam apparatus to measure the density. The schematic diagram of the apparatus is shown in Fig. 1a. The working chamber 1 is attached to the receiver 3 through the valve 2. The receiver and chamber are evacuated by steam diffusion 5 and mechanical pumps 6 through the valve 4. The electron gun 13 with electron collector 9 is mounted on the coordinator 7 in the working chamber. The injection chamber with nozzle 8, placed in the chamber on the coordinator with $300 \times 300 \times 300$ mm^3 displacement, is the jet source. An electron beam with 10 kV energy and 1-3 mA current intersects the jet in the transverse direction and excites a glow in the gas. This radiation drops on the entrance slit of the ISP-51 spectrograph 11, operating in a unit with the photomultiplier 12 and the recorder EPPV-60, through an illuminator, the lens 10. The spectograph is mounted in such a manner that its entrance slit is perpendicular to the electron beam. For a maximum 0.4 mm width of the entrance slit, quadruple diminution of the image, and 1.5 mm beam thickness, the received signal is averaged over the volume of a gas column 1.6 mm high and 1.5 mm in diameter, which assures localness of the measurement.

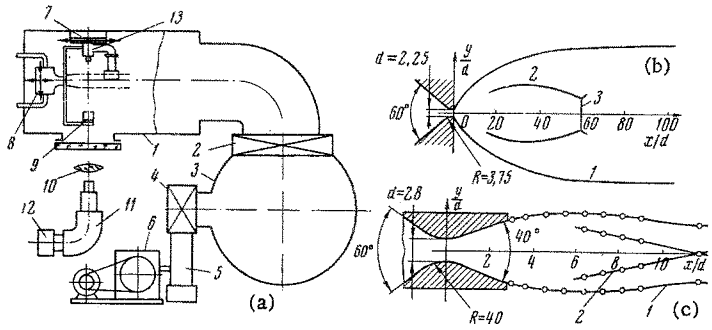

Fig. 1

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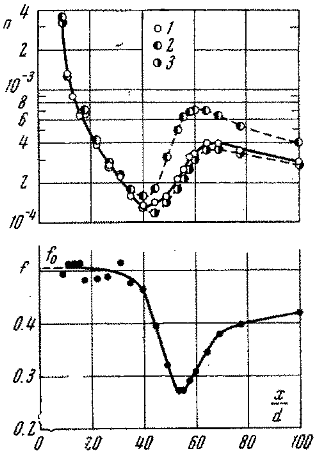

Fig. 2

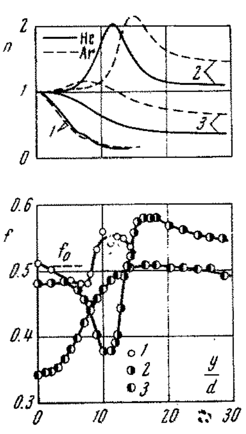

Fig. 3

The measurement of the partial densities of the components n(Ar) and n(He) and the argon concentration f are based on a linear dependence between the measured intensities I(Ar) or I(He) of the components excited by the electron beam and its partial density and the beam current i.

The following dependences are hence used:

$$f = \frac{n(\mathrm{Ar})/n(\mathrm{He})}{1 + n(\mathrm{Ar})/n(\mathrm{He})}, \qquad \frac{n(\mathrm{Ar})}{n(\mathrm{He})} = B\frac{I(\mathrm{Ar})}{I(\mathrm{He})} \tag{1.1}$$

where B is a proportionality coefficient.

To check the character of the dependence of the component glow intensity on the density, the calibration was carried out at 300°K in a 0.0147-0.441 mm Hg pressure range. The injection chamber nozzle pictured in Fig. 1c was used in the calibration.

The glow was observed after the critical section of the nozzle. The 5016 Å line (the transition $3^1p_1 - 2^1S_0$) was utilized to record the helium glow, and the 4200 ± 50 Å spectrum band for argon.

The dependence of the argon glow intensity on the density is linear in the whole calibration band, where linearity is retained for helium just to the density n(He) = 0.6×10^{16} atoms/cm^3 (0.19 mm Hg pressure).

The proportionality coefficient B = 2.89 in (1.1) was determined on the linear section from the calibration results.

All the experimental results quoted herein lie within the limits of calibration linearity for the density level.

To clarify the possibility of utilizing the electron-beam method in the nonlinear domain, the spectra of Ar, He, H_2, N_2, and their mixtures were studied at pressures when the influence of collision processes is possible. The results of this investigation reduce to the following:

1) As the density increases, the probability of collisions between the excited and unexcited particles rises, and therefore, so does the probability of radiationless transitions between excited particles in the normal state, which is manifest in the diminution of the total intensity of the spectrum;

2) A change in the character of the collisions, associated with the change in density and composition of the gas excited by the electron beam, results in a redistribution of the excited particle energies over the terms.

In particular, analysis of the spectrum of a helium mixture with argon shows that as the argon concentration increases the intensity of the helium lines belonging to the singlet transitions decreases, but increases for the multiplet transitions;

3) The spectrum of molecular hydrogen excited by an electron beam, just as the spectrum in a glow discharge, has no very definite vibrational structure bands. A peculiarity of the spectrum is the presence of the atomic hydrogen lines H_α = 6552.8 Å, H_β = 4861.3 Å, H_γ = 4340.5 Å.

The needed concentration was obtained in the stagnation chamber by the method of a separate supply of the components. If p_0(Ar) and p_0(He) are the pressures in the injection chamber for the flow of the individual components, then a mixture with the partial density ratio

$$\frac{n(\mathrm{Ar})}{n(\mathrm{He})} = \frac{p_0(\mathrm{Ar})}{p_0(\mathrm{He})}\sqrt{\frac{m(\mathrm{He})}{m(\mathrm{Ar})}} \tag{1.2}$$

and pressure

$$p_0 = \left[[p_0(\mathrm{Ar}) + p_0(\mathrm{He})]^2 + p_0(\mathrm{Ar})\, p_0(\mathrm{He}) \frac{[\sqrt{m(\mathrm{Ar})} - \sqrt{m(\mathrm{He})}]^2}{\sqrt{m(\mathrm{Ar})\, m(\mathrm{He})}} \right]^{1/2} \tag{1.3}$$

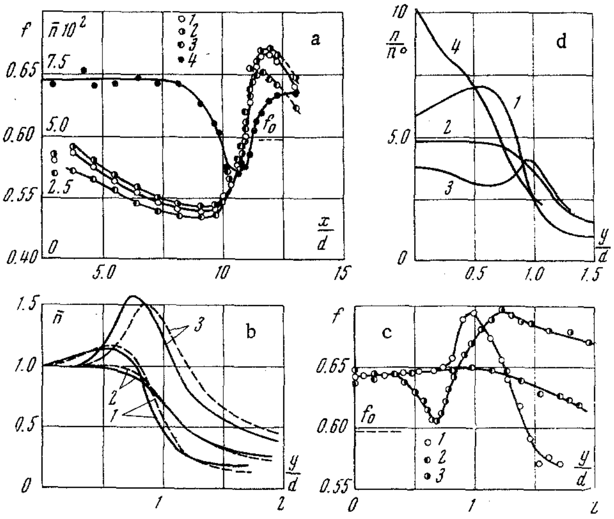

Fig. 4

will exist in the injection chamber for their combined delivery with the same discharges.

Here m(Ar) and m(He) are the molecular weights of argon and helium. The relationships (1.2), (1.3) have been obtained within the scope of inviscid continuous gas flow of the same atomicity.

The pressure in the stagnation chamber is measured by a U-shaped oil manometer. The level was measured by using a scale microscope MIR-12 with error not exceeding ± 0.01 mm. A VT-2 thermocouple vacuum meter was utilized to measure the pressure in the chamber.

2. JETS FROM A SONIC NOZZLE

A mixture with an initial $f_0 = 0.51$ argon concentration was taken to investigate the configuration of a jet from a sonic nozzle. The nozzle diagram and jet configuration are shown in Fig. 1b. A system of shocks is clearly formed for the stagnation temperature T = 300 °K, stagnation pressure $p_0 = 124.6$ mm Hg and the chamber pressure $p^0 = 1.43 \times 10^{-2}$ mm Hg selected in the experiment: the jet boundary in the figure is 1, the lateral compression shock is 2, the Mach disc is 3. Certain results are presented in Figs. 2 and 3 for the mentioned values of the parameters.

Presented in Fig. 2 for the same values of the parameters are the longitudinal profiles of the partial relative component densities $n(\mathrm{He})/n_0(\mathrm{He})$ and $n(\mathrm{Ar})/n_0(\mathrm{Ar})$ (curves 2, 3), the relative mass density of the mixture ρ/ρ_0 (curve 1) and also the molar concentration of argon f. The densities are referred to the corresponding values in the stagnation chamber. The initial concentration f_0 is no worse than ± 5%.

The Mach disc has a significant thickness (20-25 mm). The point $x_m/d = 0.67\sqrt{p_0/p^0} = 62.5$, corresponding to the location of the Mach disc, coincides according to the Sherman [7] generalization with the maximum of the helium density in the shock. The leading front of the shocks is helium enriched in conformity with their configuration in a binary mixture.

The helium in the Mach disc is elevated 4.5-fold, which exceeds the limit of density variation in conformity with the Hugoniot adiabat. The argon density in the shock is increased 2.92-fold along the jet axis, and the total mass density 2.91-fold.

Shown in Fig. 3 are the transverse profiles of the relative partial densities of the components and the concentration profiles calculated with them for different x/d. Curves 1, 2, and 3 correspond to x/d = 11.1, 35.6, 64.5.

The flow picture presented in Figs. 2 and 3 for the separate components agrees qualitatively with the Rothe [7] results for a jet with d = 15 mm, $f_0 = 0.12$, $p_0 = 2.56$ mm Hg, $p^0 = 0.017$ mm Hg and Reynolds number R = 533. Enrichment in the inviscid expansion zone was not detected in the experiments. This also corresponds to the data in [7], since the expected enrichment for the case under consideration is $f - f_0 = 0.002$ for R = 5600, which is less than the experimental error.

The minimal argon concentration 0.27 is observed on the axis in the forward zone of the Mach disc.

According to the character of the profiles recorded directly behind the front of the Mach disc (x/d = 64.5) (Figs. 2, 3), the impression is created that the lateral compression shocks specify helium enrichment on the jet axis. A "semitransparent funnel" for the light component seems to originate.

Physically, this apparently means the effect of concentration diffusion of helium to the jet axis from the helium-enriched zone in front of the lateral shock.

The diameter of a Mach disc in a monatomic gas is small compared to the jet size. Hence, additional helium enrichment from the shock layer zone of the transverse shocks is possible on the jet axis in the Mach disc because of the curvature of the streamlines to the axis. This can appear to be the reason for the

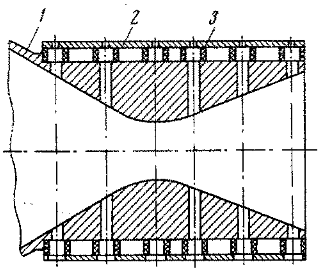

Fig. 5

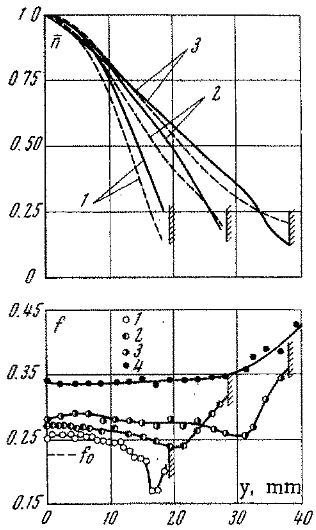

Fig. 6

anomalously high density ratio on the Mach disc for helium (4.5). The effect mentioned was not observed in the Rothe [7] experiment, where the Reynolds number was an order of magnitude less, the system of shocks was diffuse, and the helium could diffuse into the surrounding space from the shock zone. Under the conditions of the experiments described this latter effect is already felt behind the Mach disc where argon enrichment is observed. Further expansion of the mixture only results in equilibrium in the jet inhomogeneity.

3. JETS FROM A SUPERSONIC NOZZLE

The jet configuration was investigated for the escape of a He + Ar mixture under the following conditions: $f_0 = 0.60$, $p_0 = 2.57$ mm Hg, $p^0 = 1.8 \times 10^{-2}$ mm Hg, $T_0 = 300°K$. The geometric value of (the discontinuity) (without taking account of boundary layer displacement) is $p_\alpha/p_0 = 0.725$. The configuration of the compression shocks and the jet boundary obtained in this mode are shown together with the nozzle geometry in Fig. 1c in the same scale. Here 1 is the jet boundary, 2 the compression shock. Shown in Fig. 4a, b, c are the longitudinal and transverse profiles of the partial relative component densities and the concentration profile. Curve 1 in Fig. 4a is the mass density, 2, 3 are the partial argon and helium densities, respectively, 4 is the concentration. Corresponding to curves 1, 2, 3 in Fig. 4b, c are x/d = 3.0, 4.61, 8.18, where the solid line is helium and the broken line is argon. The errors in determining the coordinate x do not exceed ± 2 mm, and ± 1 mm for the coordinate y. The accuracy of measuring the concentration in this experiment is not worse than ± 10%.

Marks for the values of the initial concentration are superposed on the vertical axis (Fig. 4a, b, c). It is seen from Fig. 4a that an elevated argon concentration is already observed in the jet at the exit from the nozzle. This fact is qualitatively not in conformity with the results of Sebacher [8] in an investigation of the escape of a He + N_2 mixture from a d = 3.56 mm nozzle. The strong helium enrichment on the jet axis detected but not explained by Sebacher is visibly the result of an error in determining the initial concentration of a mixture composed of the discharges of pure components.

Exactly as in the jet from a sonic nozzle, helium enrichment of the leading front is characteristic for the shocks. Moreover, a noticeable rise in argon concentration is observed in the peripheral domain of the jet (Fig. 4b, c), which is caused by the escape of helium from the jet boundaries because of the high rates of helium evacuation by the vacuum system.

In the zone of compression shock intersection the mass density in the shock is elevated 4.34-fold along the jet axis; the density of the individual components varies by approximately the same amount, i.e., the rise in density is more intense than the limit value for a normal shock.

There is a valley (a low density domain on the axis) in the transverse profiles of the partial relative densities of the components x/d = 3.0, where the compression shocks are not formed. The reason for such a profile shape has not been clarified finally. Let us assume that this is the influence of perturbations passing through the nozzle boundary layer. For x/d = 4.61 the density profile at the axis is equilibrated.

In order to clarify the jet singularities, an experiment was conducted with a pure argon jet escaping from a supersonic nozzle with $p_0 = 2.08$ mm Hg, $p^0 = 1.4 \times 10^{-2}$ mm Hg, and $p_\alpha/p° = 0.755$. The transverse density profiles n referred to the density in the chamber n°, are shown in Fig. 4d. The curves 1, 2, 3, 4 correspond to x/d = 3.0, 4.50, 6.65, 10.67. A sharp density peak in the zone of shock intersection (x/d = 10.67) is visible. In this case the rise in density at the shock intersection is 3.56. A comparison between this quantity and that presented above for the mixture (4.34) indicates that the addition of a light component results in a growth of shock intensity, which can be a direct consequence of diffusion processes in the shock zone.

The density trough on the jet axis observed in the mixture in the profile recorded at the nozzle exit ($x/d = 3.0$) is duplicated also in the experiment with pure argon.

A general comparison of the jet configuration from a sonic and a supersonic nozzle shows that gas separation at the shocks is weaker in the second case than in the first. This means that barodiffusion effects in the jet from a supersonic nozzle are weaker as the primary reason for gas separation.

4. FLOW IN A SUPERSONIC NOZZLE

Separation of the components in the flow of a binary mixture in a nozzle is possible at low pressures. In order to investigate the expansion of gas mixtures in a channel, the nozzle pictured in Fig. 1c was utilized. An Ar + He mixture with the initial concentrations $f_0 = 0.24$, $p_0 = 0.27$ mm Hg, $p^0 = 1.5 \times 10^{-3}$ mm Hg was the working gas.

The nozzle construction is shown in Fig. 5. An electron beam is introduced through the holes in the nozzle walls 1. The cowling 2 mounted on insulators 3 stop down the electron beam preventing it from falling on the nozzle wall. The nozzle is mounted in the working chamber in such a way that its axis is parallel to the optical axis of the radiation detector and the glow of the gas excited by the electron beam is recorded through the exit section of the nozzle.

Results of measuring the transverse profile of the partial component densities at different sections of the supersonic part of the nozzle are shown in the upper Fig. 6. The solid line is helium, and the dashes are argon. The density profiles at each section are referred to values on the nozzle axis. The curves 1, 2, 3 correspond to x = 20, 45, 70 mm. The results show that the flow mode is essentially viscous (there is no inviscid stream nucleus). This circumstance permits the hope that perturbations from holes in the nozzle walls do not propagate deeply into the stream and can be neglected. The Reynolds number computed by means of the stagnation parameters and the radius of the critical section is $R = 55.6$.

Transverse profiles of the argon concentration are presented in the same Fig. 6. The initial concentration is superposed on the vertical axis. A common argon enrichment, which grows downstream, is observed for all profiles. This fact is a direct consequence of the barodiffusion separation of the mixture components in the gradient stream; in other words, the lag of argon atoms behind the helium atoms is observed as the gas is accelerated.

An increase in the argon concentration at the walls is noticeable in all sections. The trough in the argon concentration, which gradually levels out at the nozzle exit, precedes this increase. There is already no such trough in the jet at 5 mm from the nozzle exit (curve 4 for x = 80). A transverse pressure gradient whose magnitude and distribution are determined by the shape and viscosity is produced in the flow over the rounded critical section of the nozzle. This pressure gradient specifies the stream inhomogeneity in the transverse direction because of barodiffusion.

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