MEASUREMENT OF TRANSLATIONAL TEMPERATURE IN LOW-DENSITY JETS

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A technique and method for measuring the velocity-distribution function of the atoms in rarefied gas flows are described. Some results obtained with flows of binary gas mixtures behind a sonic nozzle are presented. The temperature of the light component (helium) is determined from the half width of the distribution function. Incomplete restoration of the helium temperature occurs in the Mach disk. This effect is examined in relation to concentration. A qualitative explanation is proposed for the effect in question.

The experimental apparatus used for the present investigation comprises a low-density gas-dynamic tube with a delivery of about 50,000 liters/sec, equipped with an electron-beam system for measuring the density and temperature. The gas-dynamic tube and the method of measuring the density were described earlier [1].

In order to determine the translational temperature, we used a method based on measuring the Doppler contour of the spectral line of the cold gas after excitation by an electron beam, as proposed by Muntz [2, 3]. It is well known that if the velocity distribution of the emitting atoms is F(v), then the distribution of the emission frequencies in the direction of the observer is

$$I(w)\,dw = F\left(\frac{w-w_0}{w_0}c\right)\frac{c}{w_0}\,dw \tag{1}$$

where c is the velocity of light, w_0 is the emission frequency of the atom at rest. From the contour of the spectral line I(w), it is easy to determine the velocity distribution function of the atoms in any chosen direction.

In the measurements we used the helium line with wavelength $\lambda = 5015.67$ Å (transition $3^1p_1 - 2^1s_0$). The mode of excitation of this line is quite well known [4]. Resonance diffusion of the radiation does not appreciably worsen the spatial resolution. The excitation of helium by electrons with energies of 15 keV takes place without any substantial transfer of momentum. This confirms the investigations carried out in [3], and also the methodical experiments of the authors under equilibrium conditions.

In order to measure the spectral-line contour, we used a Fabry–Perot interferometer, together with a monochromator having a dispersion of 10 Å/mm. The light excited by the electron beam was focused on the monochromator slit by means of lenses with focal lengths of 600 mm. The interferometer, situated in a pressure chamber, operated with parallel beams. The distance between the interferometer mirrors was $t_0 = 10$ mm. The signal was recorded with a photomultiplier, using an automatic-recording potentiometer. The entrance slit of the monochromator was a circular diaphragm of radius r = 1 mm placed at the focus of the exit lens. The center of the diaphragm coincided with the center of the interference pattern, so that only part of the first order of interference passed through to the photomultiplier. The contour of the spectral line was recorded by scanning the interference pattern. Scanning was affected by varying the gas pressure between the plates of the interferometer. The experimentally obtained line contour was distorted by apparatus broadening.

The experimental intensity distribution recorded over the line contour u(z) constitutes a convolution of the Doppler contour $f(s)$ and the apparatus function K(z) [5]

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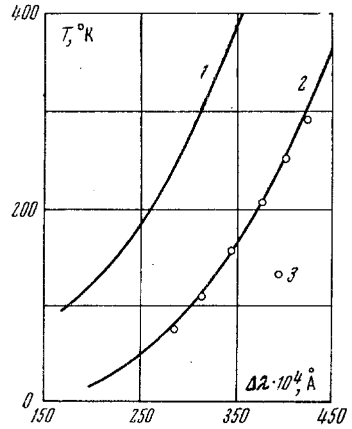

Fig. 1

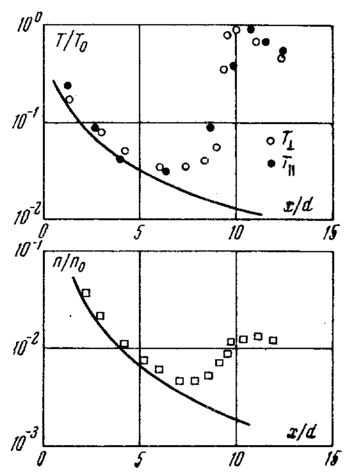

Fig. 2

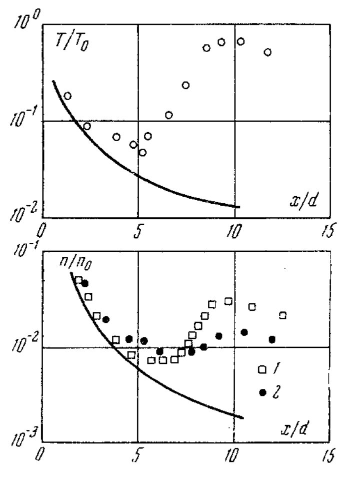

Fig. 3

$$u(z) = \int_{-\infty}^{\infty} K(z-s) f(s)\, ds\,. \tag{2}$$

The problem of determining the function $f(s)$ belongs to the class of incorrectly posed problems [6]. The use of the method of regularizing the functions proposed in [7], with subsequent construction of an algorithm for the numerical determination of $f(s)$, constitutes an independent problem.

In order to determine the temperature when studying equilibrium gas flows, we may make use of a preliminary calibration representing the temperature dependence of the half width of the spectral line. Such calibrations were in fact carried out under equilibrium conditions with a known helium temperature. Equilibrium conditions were ensured by means of an independent thermostated vessel. The gas temperature was varied from 80 to 300°K, the temperature fluctuations during the measurement not exceeding 1°K. For temperatures below 80°K the results of the calibration were extrapolated by a numerical computer integration of Eq. (2). The apparatus function was here taken in the form of an Airy function [5]

$$K(z) = [1 + 4R(1-R)^{-2}\sin^2 \pi p]^{-1} \tag{3}$$

where R is the reflection coefficient of the interferometer mirrors, p is of the order of interference ($p \sim z$). The function $f(s)$ was regarded as Maxwellian. The results of the calibration are presented in Fig. 1, in which curve 1 corresponds to the temperature dependence of the Doppler half width of the spectral line, curve 2 to the convolution of the Doppler contour with the Airy function, while curve 3 represents the experimental values. Simultaneous measurements of the helium temperature and the density on the axis of the helium and helium-argon jets were carried out under conditions which were transitional between continuous and rarefied. The experimental conditions were: nozzle diameter d = 9.1 mm, retardation temperature T_0 = 300°K, retardation pressure P_0 = 1600 N/m², pressure in the chamber P_k = 10 N/m². The Reynolds number was kept constant at Re_0 = 750. (The number Re_0 was determined from the retardation parameters and the nozzle diameter.)

The electron beam was set on the axis of the jet and the distance from the nozzle was reckoned to an accuracy of 0.1 mm in each case. The discreteness of the measurements was determined by the diameter of the electron beam (≈3 mm) and the area of the field of observation (a circle of radius 1 mm). The temperature in the preliminary chamber was measured with a thermocouple and taken as representing the retardation temperature.

The error in the temperature measurement for those parts of the jet in which the velocity distribution function of the atoms was locally Maxwellian equalled 12%. In the Mach disk the error reached 25%. The error in measuring the temperature in the Mach disk was determined on the basis of the results of [8], with due allowance for the apparatus error.

The nozzle was set so as to make the direction of the flow parallel or perpendicular to the axis of the optical system. The parallel ($T_\parallel$) and perpendicular ($T_\perp$) temperatures were measured accordingly.

Figure 2 shows the results of measurements made on the axis of a jet of pure helium in relation to the reduced distance x/d (x is the distance from the end of the nozzle). The vertical axes give the relative temperatures T/T_0 and density n/n_0 (n_0 is the density in the preliminary chamber of the nozzle). The continuous lines represent calculations for an isentropic flow [9].

Within the limits of experimental error, there was no difference between the parallel and perpendicular temperatures. In the core of the jet the temperature profile was practically isentropic. The increase in temperature and density relative to the isentropic values for x/d = 6-10 corresponds to restoration (recovery) in the Mach disk. The maximum temperature in the Mach disk equals the retardation temperature T_0. The temperature front (leading edge) slightly precedes the density front. The fall in temperature and density behind the Mach disk is due to subsequent expansion of the flow.

The mixed argon–helium jet was studied under the same conditions. The results of the measurements on the axis of the jet for a mixture with a volumetric concentration of argon in the preliminary chamber f = 10% are presented in Fig. 3. The horizontal axis gives the x/d ratio, the vertical axes give the reduced helium temperature T/T_0 and the partial densities n/n_0 (1 – helium density; 2 – argon density). The continuous lines represent the isentropic curves.

The course of the partial density curves on the axis of the jet indicate the existence of a pressure-diffusion separation of the mixture into components. The total picture of the flow agrees qualitatively with the results of [1, 10].

The maximum value of the helium temperature in the region of the Mach disk is slightly below the corresponding temperature in the pure gas. In Fig. 4 the points represent the results of our measurements of the maximum relative helium temperature in the Mach disk in relation to the volume concentration f of argon supplied to the preliminary chamber of the nozzle. We see that the reduction of temperature in the Mach disk relative to the retardation temperature bears a systematic character. Since the geometry of the jet remained constant in all the experiments, the reason for the observed fall in temperature is to be sought in a translational deviation of the mixture from equilibrium.

Using appropriate estimates as to the number of collisions between atoms of the same and different types, and also the condition of energy conservation for the flow in the one-dimensional case, we may now attempt the creation of a qualitative model of the process for the flow of a mixture of components with different atomic weights.

In the absence of "slippage" of the components in the jet in front of the Mach disk (equal velocities of the components), the velocity of the mixture u_Σ is related to the velocity for the outflow of pure helium u_0 by the relation $u_\Sigma = u_0/\sqrt{1 + 9f}$. The difference $(u_0 - u_\Sigma)$ corresponds to the proportion of the velocity (and energy) of the helium expended in accelerating the argon in the initial part of the jet. Thus the Mach number $M_1 = u_\Sigma/a(T_1)$, where $a(T_1)$ is the velocity of sound in pure helium, T_1 is the minimum temperature in front of the Mach disk measured experimentally. This is slightly lower than the Mach number for the mixture.

Let us assume the absence of translational relaxation between the components in the initial part of the shock front (two-liquid model). Such an approximation may quite properly be made for low concentrations of the heavy component, since even for f = 10% the number of collisions of the helium atoms with each other is an order of magnitude greater than the number of collisions with argon atoms. In addition to this, the difference between the masses of the helium and argon atoms increases the relaxation time between the components by comparison with the time in the pure gas by a factor of more than two [11]. This means that the establishment of translational equilibrium between the two components takes place more slowly than between the atoms of the light component only. Then the helium temperature in front of the relaxation zone T_2 may be approximately determined from the Hugoniot relations

$$\frac{T_2 - T_1}{T_1} = \frac{2(\gamma - 1)}{(\gamma + 1)^2 M_1^2}(M_1^2 - 1)(1 + \gamma M_1^2) \tag{4}$$

where γ is the adiabatic index. The values of the relative temperature T_2/T_0 calculated from Eq. (4) are shown in Fig. 4 (continuous line).

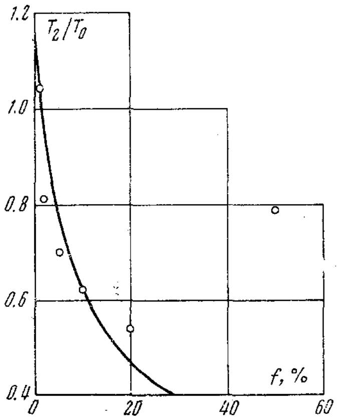

Fig. 4

For argon concentrations of f = 0-10% the calculated values of T_2 agree qualitatively with the experimental values, despite the approximate nature of the calculation. The expected rise in helium temperature behind the relaxation zone remained undetected in the argon case, since further expansion (and hence cooling) of the flow occurred in the same zone. For high argon concentrations the number of collisions between atoms of the same and different types became comparable with one another and estimations based on the model here described were no longer valid.

The foregoing consideration does not allow for a number of subsidiary effects, such as the distribution of the components in the jet and the influence of lateral jumps in compression (shock waves); it is only proposed in a qualitative interpretation.

A qualitatively similar effect (a reduction in helium temperature) was obtained in [12] in calculations relating to the structure of a plane shock wave.

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