MEASUREMENT OF VELOCITY OF RAREFIED GAS JETS FROM THE DRIFT OF AN ION MARKER FORMED BY AN ELECTRON BEAM

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The physical aspects of the formation of an ion marker in a low-density gas jet are examined. The properties of the method of measuring velocity by using a known base of two double probes to record the flight time of a marker are studied. A comparison of the results of the measurements with data obtained using a pitot tube shows that measurement of the velocity by the indicated method can be conducted not only in the core of a supersonic jet but also in nonisentropic zones of flow under certain conditions.

The need for independent measurement of the velocity of gas jets of low density arises principally from two circumstances. The first of these is determined by the significantly nonequilibrium nature of the flow at high rarefaction. The second is determined by the nonisentropic nature of the flow in considerable regions of the jet.

Electron-beam methods of measuring the density and temperature under such conditions are rather well developed and are successfully applied [1, 2], but methods of measuring the velocity have still not received the necessary degree of development and wide distribution.

Measurements of velocity from the drift of an ion marker are usually conducted in the following way. The current strength of the electron beam which intersects the region of the gas jet being studied is modulated with short pulses. The ion cloud produced in this case is a marker which drifts along with the jet and whose velocity is determined by measuring the time it takes the marker to traverse a known base.

At present the principal area of application of the method of velocity measurements is limited at present to the zone of the core of the jet [3, 4].

The physical aspects of the formation of the ion marker are examined in the present article, and the results of experimental studies on the application of the method to the measurement of velocity both in the core of the jet and in the nonisentropic regions of flow are also presented.

1. Gas ionization occurs during the propagation of an electron beam having an energy higher than the ionization potential. A radial electric field acts on the ions owing to the presence of a space charge. When $n_i < n_e$ (n_i and n_e are the concentrations of the ions and electrons, respectively) the ions move toward the center of the beam. When $n_i > n_e$ overcompensation of the negative space charge sets in and the ions begin to leave the zone of the beam because of diffusion and electrostatic repulsion. The effect of the longitudinal electric field on the motion of the ions can be ignored since the anode of the electron beam is screened from the pressure chamber by the exit diaphragm and the field from the anode–cathode gap cannot penetrate into the pressure chamber. The relative magnitude of the increase in kinetic energy of an ion in a collision with an electron is negligibly small because of the large difference in the masses of the colliding particles. Therefore, the ion which is formed continues to move together with the gas in the jet ("drifts" with the jet).

Let us estimate the effect of each of the phenomena mentioned in the formation of an ion marker.

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In studying rarefied streams, electron beams with an energy of about 10 keV are usually used. The accelerating voltage in the experiments described was 6 kV. The characteristic value of the gas density in the jet was equal to $2 \cdot 10^{-7}$ g/cm^3.

The accumulation time of the ions after which the beam is fully neutralized can be estimated from the equation [5]

$$t = 1.69 \cdot 10^{-8} / p\varepsilon V^{1/2} \tag{1.1}$$

Here ε is the relative ionization, i.e., the number of ion pairs formed by one electron along a 1-cm path at a pressure of 1 mm Hg and a temperature of 0°C, p is the gas pressure in mm Hg, and V is the accelerating voltage in volts. Under these conditions $t \approx 1.5 \cdot 10^{-3}$ μsec. The duration of the modulating pulse was usually about 1 μsec. Therefore, the beam can be considered under conditions of overcompensation of the negative space charge.

The ion concentration in the zone of the beam during a current impulse is determined by the balance equation

$$\left(\frac{dn_i}{d\tau}\right)_1 + \left(\frac{dn_i}{d\tau}\right)_2 + \left(\frac{dn_i}{d\tau}\right)_3 + \left(\frac{dn_i}{d\tau}\right)_4 = 0 \tag{1.2}$$

The indices 1, 2, 3, and 4 refer to the processes of formation, drift, diffusion, and repulsion, respectively. Since the electron energy considerably exceeds the thermal energy and the gas density is low, one can neglect volume recombination.

The determination of the exact value of the terms of the equation which determine the decrease in concentration is a very complex problem, so we will confine ourselves to an estimate of the relative role of these terms.

The number of ions formed in a unit time per unit volume along a unit beam length is equal to

$$\left(\frac{dn_i}{d\tau}\right)_1 = \frac{\varepsilon}{e} \frac{\rho}{\rho_0} \frac{i_0}{\pi r_0^2} f(\tau) \tag{1.3}$$

Here ρ is the gas density, ρ_0 is the gas density at 1 mm Hg and 0°C, equal to $1.7 \cdot 10^{-6}$ g/cm^3 in air, i_0 is the maximum current strength of the beam during a pulse, r_0 is the beam radius, and $f(\tau)$ is a function describing the shape of the pulse of current strength. From the condition of obtaining the maximum number of ions during the ionization process, it is advantageous for the modulating pulse to have a rectangular shape, i.e., $f(\tau) = 1$. In the given experiments the modulating pulse had an abrupt leading front and a decline after reaching the maximum. The pulse shape could be approximately written as

$$f(\tau) = 1 - \tau/\tau_0 \tag{1.4}$$

Here τ_0 is the duration of the pulse, equal to 3 μsec. The radius of the electron beam was ~0.5 mm.

The concentration of ions formed up to the time τ is equal to

$$n_i(\tau) = \frac{\varepsilon}{e} \frac{\rho}{\rho_0} \frac{i_0}{\pi r_0^2} \int_0^\tau f(\tau')\, d\tau' \tag{1.5}$$

Assuming that the distribution of ions formed in the zone of the beam is isotropic, for the term which determines the decrease in ion concentration because of drift with a velocity v we obtain

$$\left(\frac{dn_i}{d\tau}\right)_2 = -\frac{2}{\pi} \frac{v}{r_0} n_i \tag{1.6}$$

In order to determine the effect of drift on the change in ion concentration we find the equation

$$a = \left(\frac{dn_i}{d\tau}\right)_2 \left[\left(\frac{dn_i}{d\tau}\right)_1\right]^{-1} = -\frac{2}{\pi} \frac{v}{r_0} \frac{1}{f(\tau)} \int_0^\tau f(\tau')\, d\tau' \tag{1.7}$$

If $f(\tau) = 1$, then for $v = 10^5$ cm/sec we have $a = -1$ when $\tau = 0.78$ μsec. If $f(\tau)$ has the form (1.4) and $\tau_0 = 3$ μsec, then $a = -1$ when $\tau = 0.68$ μsec. Thus, the drift of the ions during their formation significantly affects the ion distribution in the marker, giving it a shape drawn out along the direction of flow.

It is complicated to analytically determine the change in ion concentration as a result of electrostatic repulsion and diffusion. However, one can obtain an expression for the radius of a cylindrical cloud containing ions having a total charge q per unit length and which is expanding because of repulsion or diffusion.

Using an ion-mobility equation and employing the Gauss–Ostrogradskii theorem we obtain an equation for the radius of an ion cloud which is spreading because of electrostatic repulsion:

$$r^2 - r_0^2 = 4q\eta t \tag{1.8}$$

Here η is the ion mobility and t is the spreading time.

Since $\eta\rho$ = const,

$$\eta = \frac{\rho_0}{\rho}\eta_0 \tag{1.9}$$

Here η_0 is the ion mobility at a pressure of 1 mm Hg and a temperature of 0°C. In air, $\eta_0 = 1.4 \cdot 10^3$ $cm^2/V \cdot sec$ [6].

The charge of the cloud per unit length for an initial isotropic ion distribution is equal to

$$q = en_i\pi r_0^2 \tag{1.10}$$

Substituting the values of η and q from (1.9) and (1.10) into (1.8) and taking (1.5) into account, we obtain

$$r \simeq \left(4\varepsilon\eta_0 i_0 t \int_0^{\tau_0} f(\tau')\, d\tau'\right)^{1/2} \tag{1.11}$$

Thus, the radius of the cylindrical ion cloud spreading because of electrostatic repulsion which is formed in passing the electron beam does not depend on the gas density and is determined only by the current strength of the beam, the energy of the electrons, and the duration of the pulse.

Setting $f(\tau) = 1$ and taking a pulse duration of $\tau_0 = 1$ µsec, we obtain

$$r \simeq 2.7 \cdot 10^3 \sqrt{t} \tag{1.12}$$

If t is the drift time of the ion cloud after the end of the pulse, then for v = 10^5 cm/sec the diameter of a cross section of the cloud is about 17 cm at a distance of 10 mm from the beam. Thus, static repulsion has a very powerful effect on the dimensions of the ion cloud.

Let us now estimate the role of diffusion. From kinetic theory we have for the radius of a cylindrical column whose wall the diffusing particles reach in a time t

$$r_1 = 2.4\sqrt{D_i t} \tag{1.13}$$

Here D_i is the diffusion coefficient. For nitrogen and air at a pressure of 1 mm Hg and a temperature of 0°C, D_{i0} = 22-25 cm^2/sec [6]. Since $D_i \sim T^{1/2}/\rho$, for the characteristic conditions in a supersonic rarefied jet ($\rho = 2 \cdot 10^{-7}$ g/cm^3, T_∞ = 50°K) we have $D_i \approx 200$ cm^2/sec. Then

$$r_1 = 34\sqrt{t} \tag{1.14}$$

It can be seen by comparing (1.12) and (1.14) that the effect of diffusion can be neglected in comparison with electrostatic repulsion.

As shown above, as a result of repulsion the transverse dimension of the drifting ion cloud very quickly begins to exceed the characteristic size of supersonic rarefied streams, which is usually from several millimeters to several dozen millimeters. However, a study* of the longitudinal (in the direction of flow) and transverse distribution of the ion concentration in a cloud spreading in the zone of the isentropic core of the jet showed that the ion concentration in the cloud has a radial dependence. Characteristic transverse distributions of the signal I in relative units, corresponding to distances of 10 mm (curve 1) and 20 mm (curve 2) from the beam, are presented in Fig. 1. In the time it takes for the edges of the dis-

*The experiment was conducted by A. S. Nekhoroshev.

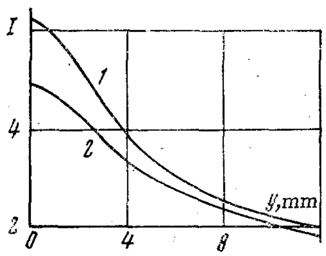

Fig. 1

Fig. 2

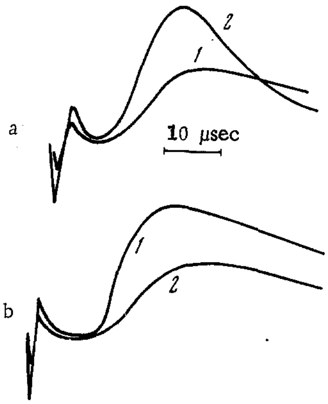

Fig. 3

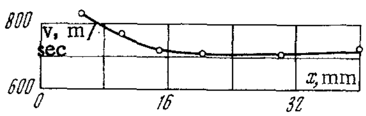

Fig. 4

tributions to depart to infinity their half widths become ~11 and 15 mm. The position of the maximum can be given with an accuracy of 1-2 mm.

Thus, it becomes possible to measure the velocity from the time it takes the zone of maximum ion concentration in the cloud to traverse the base. We note that the ratio of half widths of the signal at distances of 10 and 20 mm is approximately equal to the square root of the ratio of the distances to the beam, which agrees with Eq. (1.12) for the radius of a cylindrical cloud spreading because of electrostatic repulsion.

The analysis conducted permits a qualitative examination of the effect of a change in the experimental conditions and the parameters of the test apparatus on the characteristics of the method.

The duration of the modulating pulse has a great influence on the shape of the marker. It can be related to the magnitude of the measured velocity. In supersonic rarefied jets with a velocity of $5 \cdot 10^4$–10^5 cm/sec the pulse duration evidently must not exceed 0.5-1 μsec. Note that a reduction in the pulse duration also leads to a decrease in the spreading of the ion cloud caused by electrostatic repulsion [see (1.11)].

The ion concentration in the zone of the beam is directly proportional to the gas density. Since the spreading does not depend on the density, the signal strength depends linearly on the density.

The ion concentration in the zone of the beam is directly proportional to the current strength of the beam, while the spreading is proportional to the square root of the magnitude of the current strength. Therefore, it can be assumed that the measured signal is proportional to $\sqrt{i}$, i.e., other conditions being equal, an increase in the current strength of the beam leads to an increase in the signal.

The accuracy of the velocity measurement also depends on the base of the measurement. Since the velocity of the jet is

$$v = (x - x_0)/(t - t_0) \tag{1.15}$$

($x - x_0$ is the base and $t - t_0$ is the time taken to traverse it), then

$$\frac{\Delta v}{v} = \frac{v}{x - x_0} \sqrt{v^{-2}\left[(\Delta x)^2 + (\Delta x_0)^2\right] + (\Delta t)^2 + (\Delta t_0)^2}$$

i.e., with the errors in measuring the coordinates and time determined, the error in measuring the velocity is inversely proportional to the base.

2. The measurement of the velocity of the rarefied gas jets was conducted according to the following system. An electron beam with a current strength of 1 mA and an energy of 6 keV was introduced into the pressure chamber perpendicular to the axis of the gas jet. The beam was focused on the zone being studied using an electromagnetic lens. To record the time of flight we used two double probes made of wires 0.1 mm in diameter fastened to a coordinator perpendicular to the jet axis and the direction of propagation of the electron beam. The distance between probes in a pair was 3 mm; the second pair was located 10 mm downstream along the jet from the first. Double probes were used in an effort to decrease the disturbing effect of their electric field on the measured velocity of the ion marker.* A constant voltage was placed on the probes. The signal from the probes was amplified and observed on the screen of an IO-4 oscillograph. The interval corresponding to the positions of the maxima of the ion current pulses on the oscillograph screen with alternate connection of the probes to the measuring circuit was taken as the time the marker took to traverse the base. The second pair of probes simplifies the measurements, although when the disturbance of the jet by the first pair of probes becomes so great that it

*A. S. Nekhoroshev, Yu. V. Petrov, V. G. Stepchenkov, and B. K. Sukhomlinov, "An instrument for measuring the velocity of low-density gas jets," Author's Certificate No. 248358.

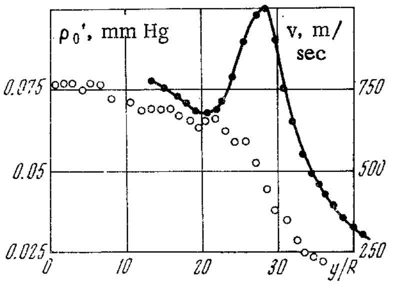

Fig. 5

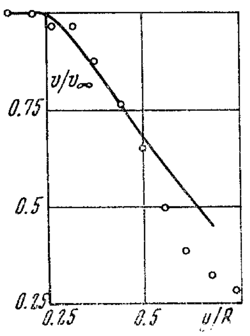

Fig. 6

is not able to die out along the length of the measuring base, one must be confined to the use of one pair of probes, placing it alternately at the end points of the base.

A sonic nozzle with a large overpressure and a supersonic nozzle were used to produce the gas jet. The velocity gradient in the measuring regions was small for all the nozzles on the base used. An example of the pattern observed on the oscillograph screen for one pair of probes is presented in Fig. 2. The pulse was calibrated with markers having a 1-μsec interval. It should be noted that the shape of the recorded pulse depends considerably on the flow parameters and the operating conditions of the instrument.

The velocity measured in the core of the jet was compared with the results obtained with a pitot tube which was also placed on the coordinator bracket at fixed distances from the probes. The comparison was made by superimposing the profiles obtained by the two methods.

In using the two-probe system of recording the ion marker, just as for the one-probe method [3], the shape and position of the ion signal on the oscillograph screen relative to the moment of modulation depend on the magnitude of the voltage u applied to the probes, although less strongly. In Fig. 3a, curve 1 corresponds to u = 25 V and curve 2 to u = 65 V. It was established experimentally that although an increase in u does cause a shift in the pulse maximum, nevertheless the results of measuring the velocity in the core of the jet by the system described above agree with the data obtained with a pitot tube with an accuracy of ~10% at $u \leq 70$ V in the range of densities studied ($6 \cdot 10^{-8}$ g/cm$^3 \leq \rho \leq 1.5 \cdot 10^{-7}$ g/cm^3).

In the course of the experiments it was discovered that the magnitude of the bias voltage on the beam control electrode, and consequently the depth of modulation m of the electron beam, affects the position of the pulse maximum relative to the moment of modulation. Oscillogram pulses corresponding to m = 100% (curve 1) and 75% (curve 2) for a local gas density of $\rho \approx 9 \cdot 10^{-8}$ g/cm^3 are shown in Fig. 3b. A change in the modulation depth from 100% to 75% led to a change of 6-7% in the measured velocity in the core of the jet. The shift in the maximum was greater in the region of the boundary layer than in the core.

The results of the velocity measurement can depend on the distance x between the beam and the probes. An apparent increase in velocity is observed when measuring the velocity near the beam (Fig. 4). At a large distance from the beam the accuracy of the velocity measurement decreases because of spreading of the marker.

The peculiarities of the measurement presented resulted in the following method of conducting the experiments:

1. the distance from the first pair of probes to the beam was chosen within the limits of 10-30 mm;
2. the lowest possible voltage was applied to the probes, sufficient, however, to distinguish the drifting pulse;
3. the modulation depth was chosen as 75%.

3. A characteristic velocity profile in a strongly underexpanded jet with discharge into the flooded space from a sonic nozzle is presented in Fig. 5. The experimental points are marked by circles. A pitot tube profile is also presented. The pressure in the forechamber was 76 mm Hg. The distance from the nozzle mouth to the midpoint of the base was 18 times the nozzle caliber. The distance y from the axis of the nozzle is relative to the nozzle radius R = 1.4 mm.

Let us note the principal characteristics of the profile:

1. the velocity at the jet axis corresponds to the maximum for the given stagnation temperature $T_0 = 293°K$;
2. the drop in velocity toward the periphery of the jet is explained by the conicity of the flow in the core of the strongly underexpanded jet, while the measuring system used is able to measure only the component of velocity along the jet axis;
3. the velocity profile is not fully measured, with the minimum velocity measurement being ~ 200 m/sec for the indicated system.

For the region of the boundary layer a comparison was made between the velocity measurements and the results calculated from the pitot tube readings on the assumption that the pressure across the boundary layer in a jet escaping from a supersonic nozzle is approximately constant.*

The rather good agreement between the velocity profile obtained by the electron beam method with the calculations is confirmation of the hypothesis of a constant pressure. The experimental points and the calculated curve (velocity relative to the velocity at the axis) are plotted in Fig. 6. It can be seen that satisfactory agreement is observed for $v \geq 0.5v_\infty$. The divergence of the results at lower velocities is evidently explained by the reduced accuracy of the measurement in the near-sonic and subsonic parts of the boundary layer.

Thus, velocity measurement from the drift of an ion marker can be conducted not only in the core of a supersonic rarefied jet but also under certain conditions in the nonisentropic zones of flow. With such measurements it is useful to conduct a supplementary diagnosis of the flow (for example, visualization and density measurement) in order to choose the optimum experimental conditions.

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* The calculated data were presented by I. V. Popov.