INVESTIGATION OF UNSTEADY FLOW STRUCTURE DURING DISCHARGE OF A SHOCK-HEATED GAS

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This paper examines the structure of the near-gasdynamic section of a jet discharging into a rarefied volume. The experimental part of the article deals with unsteady discharge of a high-temperature gas. Discharge from a slot and from a circular aperture is investigated for air, nitrogen, CO_2, and argon with nonuniformities from 20-200. Approximate relations are obtained to describe the motion of the front of a discharging substance in dimensionless coordinates and the associated perturbation along the flow axis. It is established that the time for a steady geometric structure to form in the gasdynamic section of the jet is greater than the values obtained from data available in the literature.

Starting processes in nozzles and the initial phases of discharge into free space have received little investigation. The problem is usually solved in the one-dimensional approximation, and there is agreement with experimental data only along the axis of the nozzle and the jet in the initial stages of the process. The experimental data on starting processes can be divided into two groups: data on flow in nozzles and near the nozzle exit, and data on the discharge of the primary shock wave, observed at distances of several nozzle diameters. The literature contains no experimental and numerical data pertinent to the formation of a jet and its gasdynamic section.

The formation of flow in a nozzle has been investigated experimentally [1-3]. A few papers have described investigation of the initial stage of discharge into free space [4-7].

The formation of steady flow in a jet and a nozzle can be divided into two stages: the stage where all the perturbations accompanying the front of the discharging gas pass through a given point in space, and the stage where established flow is formed in the discharging gas.

The process of establishing stationary parameters in a discharging gas in the region upstream of the secondary shock wave occurs independently of the presence of an opposing pressure. The time to establish stationary flow in the discharging gas can be evaluated from the results of [6]. Reference [6] examined the problem of formation of stationary flow under the assumption that the discharge takes place in a vacuum, that the discharging gas is perfect, inviscid, and non-heat conducting, and that there are no physical or chemical transformations in the gas during the discharge. It is assumed that the flow depends on one spatial coordinate, i.e., axisymmetric and centrosymmetric flows are considered. The time to establish stationary discharge into vacuum for axisymmetric and centrosymmetric flows at a distance of several tens of calibers from the throat differ by two orders of magnitude and more. At this distance appreciable differences exist in the time to establish steady conditions, depending on $\gamma = C_p/C_V$. The time to establish stationary flow for a gas with $\gamma = 1.4$ is less than the corresponding time for $\gamma = 1.2$ by a factor of 4-5.

The present work was performed using a shock tube of cross section 40×40 mm, a low-pressure-chamber length of 3.5 m, and the IAB-451 shadowgraph unit. A nozzle was mounted at the end of a shock tube with two-dimensional or cylindrical symmetry, and the shock-heated gas discharged through the nozzle. The nozzle throat area was $\leq 5\%$ of the area of the end of the tube, so that the gas parameters in the "test slug" could be calculated with sufficient accuracy. The tube and the pressure chamber were filled with the test gas to a pressure of 20 torr. The Mach number of the incident shock was $M = 2.5$-4.

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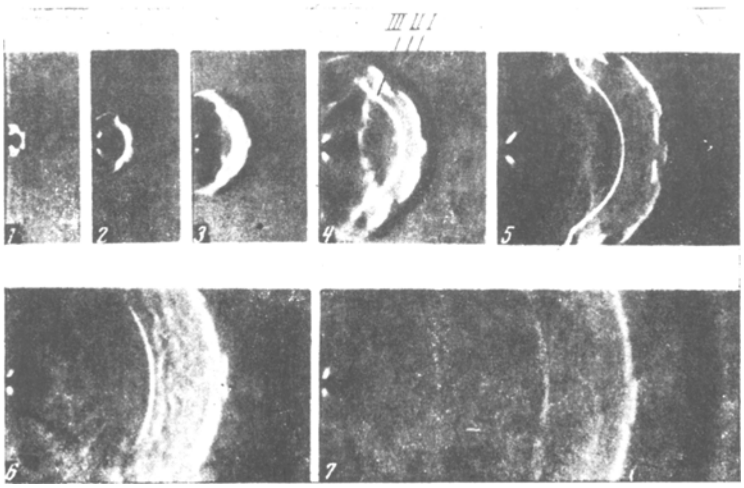

Fig. 1

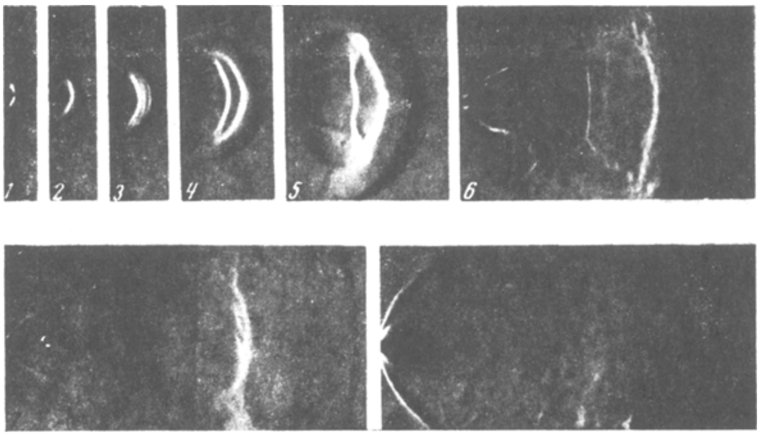

Fig. 2

The photographs (Figs. 1-3) show successive stages in the change of structure of the unsteady flow of N_2, Ar, and CO_2 discharging from a slot. Frames 2, 3, and 4 and also frames 5 and 6 for CO_2 show typical pictures of perturbations accompanying the front in the discharging gas.

The front surface of the discharging gas (frame 2 of Fig. 1) is a contact discontinuity separating the pressure-chamber gas and the gas which arrives through the slit from the volume heated by the reflected shock in the tube. The surface has a typical structure, similar for Ar and N_2 and somewhat different for CO_2. In CO_2 this surface is more complex and more perturbed in the initial stages. The photographs for successive stages show that it is more stable and better defined at later times, and that it is smeared somewhat later than for Ar, N_2, and air.

Ahead of the contact surface a layer of dense gas forms as the discharge process develops; the dense gas originates in the pressure chamber and is displaced by the heated gas discharging from the shock tube. The front of the perturbation thus formed (Fig. 1) separates further and further from the contact surface as the process develops and the speed of the front diminishes as distance from the slot increases. In the initial stage of development of the process there is no evidence of spatial separation of the contact surface and the forward boundary of the dense layer. After a time of the order of 5-10 μsec from the start of the discharge, a smooth boundary is clearly seen (on the Schlieren photograph) and the motion of the front for the first 10-15 μsec takes place at the maximum velocity.

The photographs relating to 10-15 μsec from the beginning of the discharge clearly show, for the gases examined, a second compression wave (3 in Fig. 1), arising in the discharging gas.

We shall comment on some special features of the structure of the unsteady picture of the CO_2 discharge (Fig. 1). In the CO_2 jet a clearly distinguishable secondary compression wave (3) is observed at

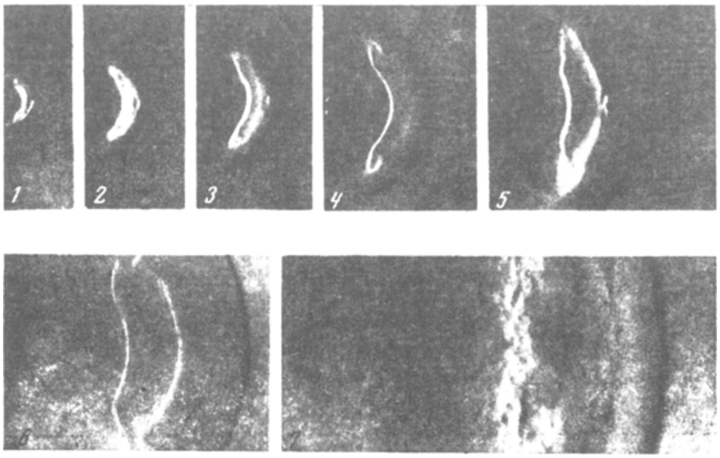

Fig. 3

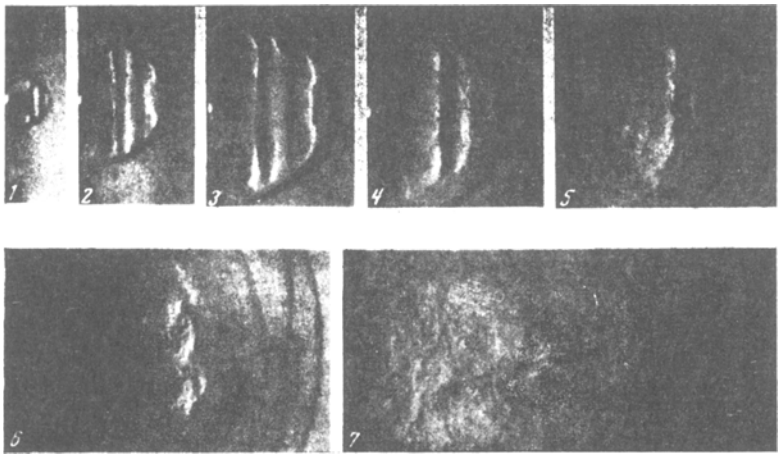

Fig. 4

200 μsec in the discharge; for Ar, N_2 and air after 125-150 μsec the secondary shock wave is not seen in the photographs. For discharge of CO_2 for almost the whole time investigated one does not see a wave structure like a stationary flow picture. The unsteady suspended discontinuities change their position and the angle of their inclination to the jet axis varies from frame to frame.

In the photographs obtained at 1.5-2 μsec from the start of the flow, the picture appears practically identical for all the gases, and corresponds to discharge of a mixture of the driver and the driven gases. When this time is over, the initial nonuniformity of the regimes considered changes, since the gas which has now reached the pressure chamber increases the pressure in the chamber, and the wave front traveling ahead of the discharge gas front reaches the pressure-chamber wall, and disturbs the original conditions in the chamber.

The discharge from a circular aperture proceeds analogously to discharge from a slot in the initial stages of the unsteady regime. In the immediate vicinity of the edge of the aperture there are perturbations accompanying the discharge gas front (Fig. 4). The latter forms a system of vortex rings, there being three, as a rule, in the course of the first 45-75 μsec in these conditions. The size of the second and third rings increases noticeably with time, while that of the first ring remains unchanged, and after 100-125 μsec we cannot distinguish it against the turbulent structure which results from the growth and decay of the second ring. In the 25-μsec picture the perturbation forming ahead of the discharge gas front is a front representing interference of perturbations from each of the vortex rings, i.e., the envelope of the perturbed region is not smooth and follows the structure of the ring system. After 35-45 μsec the leading front of the perturbed region is quite far from the contact surface, becomes smooth, and has a shape like an ellipse with major axis elongated along the flow axis.

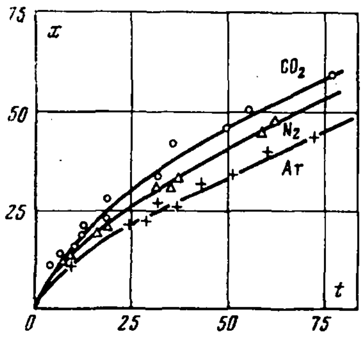

Fig. 5

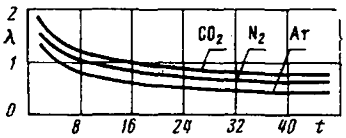

Fig. 6

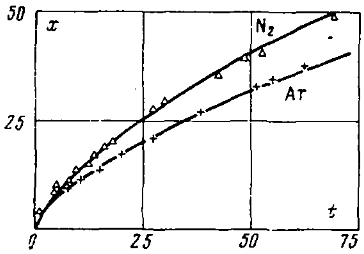

Fig. 7

After 75-100 μsec, when the second and third vortex rings merge, forming a developed turbulent structure, a system of perturbations arises in the region between the contact surface and the front (Fig. 4). The perturbations closest to the contact surface repeat their shape at a given time, and since this shape becomes complicated as time goes on, the system of perturbations seen on the Schlieren photographs also becomes complex. The perturbations interact amongst themselves, and if they are not attenuated, the leading front is distorted, since in the limit the speeds of all the perturbations are equal to the speed of sound, but in the medium behind the leading front sound is propagated with somewhat greater speed than in the unperturbed gas. These considerations are valid when the visible perturbations are not compression waves having an absolute velocity in the upstream direction.

The secondary compression wave in the discharging gas, clearly seen for the case of discharge from a slot, is not visible on the photographs (Fig. 4), since the internal structure of the cloud of discharging gas is closed by the vortex rings of the outer flow region. On the individual frames of Fig. 4, inside the volume between the third and second vortex rings of characteristic shape, one can see a nonuniformity which is a secondary shock wave. The sequential photographs of the discharge processes, with evenly spaced recording times for each stage, enable us to describe the quantitative motion of the material front and the perturbations which precede it.

The numerical processing of the experimental data takes the form of constructing approximate formulas to describe the change in position of the perturbation front with time. It was convenient to express all the results in a dimensionless coordinate system: the distance in calibers (X/r_0) where there is a nonuniformity under investigation, at a time expressed as a function of the dimensionless time $t = \tau C^*/r_0$, where C^* is the critical speed of sound for the discharging gas. The time t shows how the time of observation is related to the time required for the flow to travel the characteristic dimension at the critical sound speed. The critical sound speed, which enters into the determination of t brings information about the original conditions of the discharge gas, since it is a unique function of temperature in the reservoir for a perfect gas.

In the case of discharge of shock-heated gas the gas parameters in the reservoir are the parameters of the gas behind the reflected shock. The equilibrium and the fully frozen state behind the reflected shock waves in CO_2 for regimes corresponding to Mach numbers $M \leq 4$ differ by 20-25% as regards the temperature. These differences are less in N_2, and in Ar for $M \leq 4$ the ionization does not produce noticeable change in temperature behind the reflected shock.

In reducing the experimental data it was assumed that the condition in CO_2 and N_2 behind the reflected shock corresponds to equilibrium excitation of the gas molecules. The critical speed of sound was calculated without accounting for relaxation effects.

These calculations were based on the relative smallness of the numerical effect of the influence of variation in γ and the value of the speed of sound in the conditions examined (6-7%). In principle there should be a real gas effect in determining C^*, particularly where the gas discharge is created by reflection of shock waves with $M \cong 4$ in the gases listed.

In the coordinates $x = X/r_0$, $t = \tau C^*/r_0$ the experimental points lie on a single curve, different for each of the test gases (a difference in γ is apparent).

The experimental curves can be described by exponential functions of the type

$$(1)\ X / r_0 = A\ (\tau C^* / r_0)^{\alpha} \qquad (1)$$

in the section of X/r_0 and $\tau C^*/r_0$ considered, where A and α are given in Table 1.

TABLE 1

Gas	Coefficients			
	front 1		front 2	
	A	α	A	α
CO_2	3.8	0.71	3.2	0.68
Ar	3.1	0.69	2.5	0.65
N_2	3.1	0.71	2.6	0.71

TABLE 2

Gas	Coefficients			
	front 1		front 2	
	A	α	A	α
N_2	3.04	0.66	3.00	0.54
Ar	2.72	0.63	2.62	0.52

The corresponding curves constructed using these formulas and the experimental points are shown in Fig. 5.

From these approximate relations one can obtain formulas for the velocity

$$dx / dt = A \alpha t^{(\alpha-1)}$$

The graphs of velocity for the case of discharge from a slot are shown in Fig. 6 for front 2. The speed is given as a ratio to C^* [$\lambda = (dx/dt) \times (1/c^*)$]. The relations assumed only hold in the region corresponding to the experimental points, and do not indicate the limiting stage of the motion, since the conditions for transition to the limit have not been imposed on relations of this type. The front of the compression wave propagating in the pressure chamber must move in the limit with the speed of sound right up to the point of complete attenuation resulting from dissipation. The intensity of this perturbation can diminish according to different laws, depending on the properties of the gas, and the speed cannot remain less than the speed of sound in the unperturbed medium. Therefore the approximate curves for dx/dt are valid in the region $\tau \leq 75$ for N_2; $\tau \leq 100$ for CO_2, and $\tau \leq 175$ μsec for Ar.

The photographs of the initial stage of the discharge ($\tau \leq 15$ μsec) do not show the perturbation front in the pressure-chamber gas, nor the boundary of the discharging gas (1 and 2). The perturbation front follows the shape of the boundary of the discharging gas, becomes smooth, and differs markedly from the discharging gas after at a time 20-30 μsec from the start of the discharge.

Using the approximations and the dependence derived from them for dimensionless velocity as a function of time, it has been established that during the period corresponding to values of τ for which the dimensionless speed dx/dt is less than 1.5 C^*, the wave front (and the front of the discharging gas, since they are not resolved) moves with a speed greater than that of the shock wave in the tube before reflection from the end wall.

The experimental relations for variation in the position in the shock wave which propagates ahead of the front in the gas discharging from a circular aperture are shown in Fig. 7.

The curves given in the figures describe the approximate dependence of the type of Eq. (1), where A and α are given in Table 2.

From the approximations in the data of [6] one can estimate the expected time for establishment of a stationary discharge in these specific conditions. The experiment for the cases of discharge from a slot and from an aperture shows that the theory gives underestimated times. Since the time for the material front and the perturbations associated with it to pass have been established experimentally, the discrepancy should be attributed to the second term, which was obtained from results of computations in [6].

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