ACCELERATION OF A GAS COMPRESSED UNDER CONDITIONS OF ACUTE-ANGLED GEOMETRY

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In obtaining high velocities (10–100 km/sec) by methods employing the mechanical motion of compressible media it is customary to use the flow scheme obtained with shaped charges [1–4]. This paper presents the results of a study of an apparatus that can be used to obtain gas jets in the same velocity range but at higher densities by means of a different type of flow.

1. Experiment. Several variants of the proposed flow scheme are possible. Certain results obtained with apparatus of the type considered were presented in [5, 6]. One of the chambers used in that study is shown schematically in Fig. 1 with the typical dimensions indicated in millimeters. The working gas 1 is contained in the cavity formed by a metal spherical segment 2 and a metal compression plate 3. Plate 3 rests on an explosive charge 4 with a plane detonation front. At the top of the chamber is an opening beyond which the outlet 5 is located. The outlet tube is separated from the gas in the chamber by a thin membrane 6 and is evacuated. When the charge is exploded, plate 3 is accelerated and forces the gas to the top of the chamber.

On being compressed the gas is heated and escapes through the opening in the form of a high-temperature high-density plasma. The velocity of the front of the luminous jet in the transparent outlet tube was determined by means of a SFR-2M moving-image camera, similar in design to that described in [7]. The initial pressure of the working gas in the chamber was usually 1 atm abs., the volume 100–200 cc.

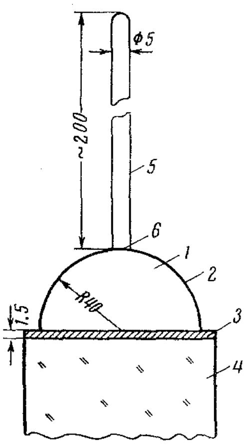

Fig. 1

Figure 2 presents a photograph of the operation of the appratus shown in Fig. 1, obtained with the camera shutter open without time resolution (integrated luminosity); 1) position of charge, 2) outlet tube, 3) plasma passing from end of tube into the atmosphere. In this experiment the chamber and the tube contained air under normal conditions. The luminosity of the plasma is much more intense than that of the explosion products and of the shockwave that they produce in the air, a qualitative indication of the higher temperature of the plasma. The pictures in Fig. 3, obtained by frame photography, represent the motion of the gas jets in an apparatus similar to that shown in Fig. 1, but having nine radial outlet tubes located at different distances from the top of the chamber. All these tubes and the chamber contained air under normal conditions.

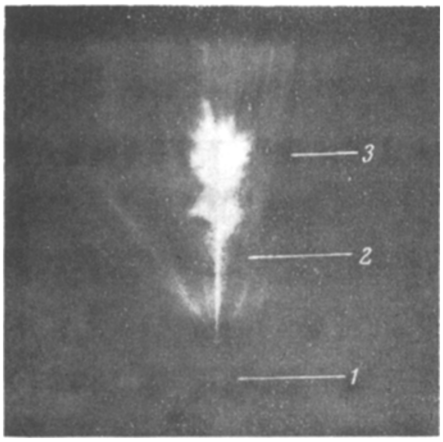

Fig. 2

The time lapse between frames was 2 μsec. The velocity of the jet in the central tube was several times greater than that in even the closest lateral tubes, which were located 10 mm from the top of the chamber.

As the outlet tube fills with gas, a strong shock wave passes through it, and the velocity of the jet is reduced. Figure 4 shows time-resolved photographs obtained at different initial air pressures in the outlet tube: a) 1 mm Hg, velocity over first 10 cm of tube 59 km/sec, b) 10 mm Hg, 50 km/sec, c) 100 mm Hg, 41 km/sec. The time axis is horizontal, the longitudinal stripes on the photographs are scale marks on the outlet tube at intervals of 50 mm. At low pressures the decrease in velocity on a length equal to several tens of centimeters is not very great. The inside diameter of the tube is 5 mm. In experiments with super high-speed shaped-charge jets similar velocities were obtained only when the jet entered a space evacuated to a residual pressure of $\leqslant 10^{-1}$ mm Hg [1–3]. Thus, the density of the jets obtained with the apparatus described is evidently much greater (this assertion does not extend to low velocities of about 10 km/sec).

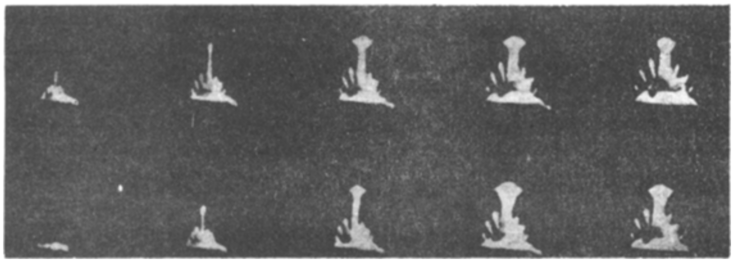

Fig. 3

Figure 5 shows the jet velocity as a function of the radius of curvature R of the spherical segment. Curves 1 and 2 correspond to chambers with outlet tubes 5 and 28 mm in diameter. The decrease in jet velocity at radii of curvature $\geqslant 8$ cm excludes what would appear to be a very simple method of increasing it by going over to ever greater radii of curvature.

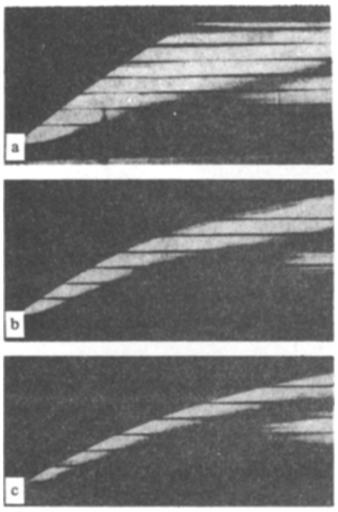

Fig. 4

It was experimentally established that at velocities up to 60 km/sec the material of which the chamber is made (copper, steel, aluminum, glass, plexiglas) has no effect on the jet velocity. Beginning with a chamber wall thickness of about 2 mm, further increases in thickness do not affect the jet velocity. The influence of the material was not investigated at higher velocities. All the chambers were made of copper, a stable and technically convenient material in the presence of high heat flows.

Tests performed on several types of chambers with a nonspherical surface failed to give a significant increase in jet velocity. Rounding the sharp edge of the outlet opening to a radius of 5 mm increases the velocity by about 5 km/sec.

Figure 6 shows the jet velocity as a function of the mass of the membrane ΔM, divided by the mass of working gas M. An evaluation of the heat fluxes at the boundary of the plasma shows that the membrane in contact with the plasma was vaporized. If the mass of the membrane is not more than a few percent of the mass of the gas, the presence of a membrane, irrespective of its material, does not affect the jet velocity. In our experiments we used mica and dacron membranes 8–15 microns thick.

The dependence of velocity on outlet tube diameter is presented in Fig. 7. The radius of curvature of the spherical segment was 60 mm, the initial chamber diameter 103 mm. We note the possibility of obtaining gas flows at high velocities of about 50 km/sec in tubes of considerable diameter (~30 mm), which makes the experiments easier to perform.

When expanding tubes with an aperture angle of 10°–50° are used, the jet velocity is reduced by a factor of about 2. Contracting tubes with various tapers have almost no effect on the jet velocity: in this case the wall friction increases. All the above relations were obtained with air. With hydrogen we obtained jet velocities of up to 90 km/sec. The velocity depends only slightly on the nature of the working gas and its initial density [5]. The experiments were so designed and conducted that the jet velocity could be reproduced with an accuracy of ±5%.

2. Acceleration scheme and rough calculations. As the plate approached the top of the chamber, the compressed gas was forced to flow out of a narrow wedge-shaped gap (acute-angled geometry) formed by the plate and the chamber wall (Fig. 8). The most important factor from the viewpoint of obtaining high velocities can be qualitatively explained without a knowledge of the details of the very complex gas flow pattern. Namely, the mass velocity of the gas close to the point of contact between plate and chamber (point A in Fig. 8) must be approximately equal to the phase velocity of that point. In principle, the velocity of the contact point is not limited by dynamic factors, so that the mass velocity of the gas may also be assumed to be very large.

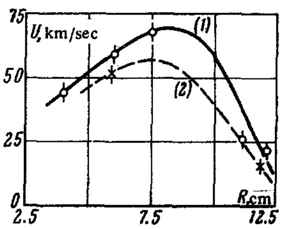

Fig. 5

Unfortunately, there are factors that limit the mass velocity of the gas. In the experiment described the mass velocity does not exceed several tens of km/sec, although the phase velocity of the contact point may be much greater. The velocity-limiting factors will not be examined in this paper.

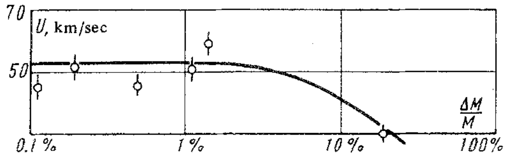

Fig. 6

The flow of gas compressed in the apparatus shown in Fig. 1 is two-dimensional and nonstationary, oblique shocks are present, and the equation of state must take into account dissociation and ionization. An exact solution of the corresponding gas-dynamic problem in analytic form is almost impossible. The acceleration and compression of the gas can be treated approximately as follows.

The gas in front of the plate is traversed by a normal shock (1 in Fig. 8, where the direction of the waves is noted by arrows), whose intensity is determined by the fact that the mass velocity of the gas is equal to the velocity of the plate. Reflection of the normal shock from the front wall of the chamber produces a reflected wave 2, whose parameters at small angles between the plates and the tangent to the segment at the contact point A are similar to the wave parameters in the case of normal reflection. In its turn, the reflected wave is reflected from the plate and so on, creating the system of oblique shocks shown schematically by the broken lines in Fig. 8. With each successive reflection the angle of incidence of the waves increases, so that, starting from a certain wave, reflection becomes irregular (Mach reflection), which further complicates the flow pattern. The intensity of the successive waves decreases, which enables one approximately to replace all the waves starting from the third by the single wave 3. Since the results of calculation are in agreement with experiment, the introduction of this simplification is justified. The intensity of the third comprehensive shock must be determined not from the reflection condition but from the condition that the mass velocity of the gas behind the front be equal to the phase velocity of the contact point A.

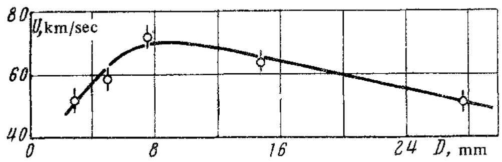

Fig. 7

We will carry out the calculations for the case when the radius of curvature of the segment is 60 mm, the initial distance of the plate from the top of the segment is 30 mm, the plate velocity is 5 km/sec, and the working gas is air under normal conditions with $\rho_0 = 1.3 \cdot 10^{-3}$ g/cc.

The density of the air behind the normal shock-front ρ_1 exceeds the initial density ρ_0 by a factor of about 10 [8]. Thus, at the moment the shock wave approaches the outlet opening, the plate is 3 mm from the top of the segment, while the average phase velocity of the contact point A on the remainder of the path to the top of the segment u = 23 km/sec. Unfortunately, we lack data on the shock compression of air at high initial temperatures, which complicates the exact determination of the parameters of the second and third shocks. Assuming that the Poisson adiabatic exponent $\gamma = 1.3$ (region of dissociation and ionization [9]) and that the shock waves are strong, we find the density behind the second and third shock fronts:

$$\rho_2 = \left(\frac{\gamma+1}{\gamma-1}\right)\rho_1 = 10\left(\frac{\gamma+1}{\gamma-1}\right)\rho_0 \approx 80\rho_0, \qquad \rho_3 = \left(\frac{\gamma+1}{\gamma-1}\right)\rho_2 \approx 600\rho_0.$$

At the moment in question, when the plate is 3 mm from the top of the segment, the average gas density is about 100 times greater than the initial density. The value of ρ_3/ρ_0 obtained above is greater; however, it cannot be compared directly with the average density, since a considerable part of the volume is occupied by gas shock-compressed not by three but only by one or two waves.

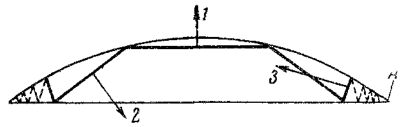

Fig. 8

The pressure behind the third shock front

$$p_3 = {}^1/_2(\gamma + 1)\,\rho_2 u^2,$$

where u is the mass velocity of the gas, is approximately equal to the phase velocity of the contact point.

Substituting the above numerical values, we obtain $p_3 = 6 \cdot 10^5$ atm abs. The speed of sound behind the third shock front can be estimated from the equation

$$c = \sqrt{\gamma p_3/\rho_3} = 10 \text{ km/sec}.$$

In the case of nonstationary expansion in an evacuated outlet tube the velocity of the expanding gas front is equal to [9]

$$v = \frac{2}{\gamma - 1}c.$$

For the above values of c and γ we obtain v = 67 km/sec. The velocity obtained experimentally was 70 km/sec (this coincidence of the calculated and experimental velocities correct to a few km/sec must be considered a matter of chance, since it is not guaranteed by the accuracy of the calculations). Thus, our simplified scheme of gas acceleration by a triple shock

(Fig. 8) accounts for the gas jets with velocities of 50–90 km/sec obtained in the appratus described.

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