STUDY OF HIGH-VELOCITY GAS FLOWS BY ELECTROMAGNETIC MEANS

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We present some results of electromagnetic measurements of velocity characteristics of gas flows moving in a channel with velocities of tens of kilometers per second. Flows were investigated in which the gas density was greater than air density at standard conditions by factors of 10-50.

1. There are several well-known methods for obtaining high-velocity flows of a dense gas. We mention two: the production of a shaped gas jet by explosion of a tubular cylindrical charge of high explosive [1]; the production of a gas jet by compression of gas in an acute-angle geometry [2]. In the first method, the velocity of the shock wave in the charge channel ahead of the jet of detonation products is $D \approx 12$-15 km/sec (under vacuum conditions of 1-2 mm Hg, $D \approx 18$-20 km/sec). In the device described in [2], $D \approx 20$-30 km/sec. The velocity of the front is usually measured by means of streak photography [2-4]. This method gives no information about flow velocities behind the front. Another purpose of the experiments described below is the measurement of mass velocity in the flow.

Flow velocity was determined from the emf induced by motion of ionized gas in a transverse magnetic field. For electrodes perpendicular to the field direction and flow velocity, and an open circuit, we have

$$E = uB\,d \cdot 10^{-8} \tag{1.1}$$

where E is the emf (V), u is the velocity (km/sec), B is the field induction (G), and d is the distance between electrodes (cm).

The voltage in a circuit closed by a load R is

$$V = ER\,/\,(R_p + R) \tag{1.2}$$

Here, R_p is the plasma resistance. When $R \gg R_p$, we have $V \approx E$ from (1.2) and, consequently, the flow velocity is determined by the quantity E by virtue of (1.1).

2. The measured value [5] of the resistance of the gap between electrodes along the length of a shaped jet in high-explosive charges with channel diameters $d_1 = 10$ and 20 mm fell within the range 1.5-3 Ω, changing little with time of measurement. With electrodes arranged at angles $\alpha_0 = 45$, 90, and 135°, the value of R_p changed by no more than ±10% in comparison with $\alpha_0 = 180°$. This can be explained by a reduction in conductivity to the outer layer. The question of radial distribution of electrical conductivity in a shaped gas jet is far from simple and requires further investigation.

The electrical conductivity of the flow in the device [2] was not determined experimentally but was estimated from the data in [6]. We used the approximation

$$\frac{1}{\sigma} = \frac{1}{\sigma_0} + \frac{1}{\sigma_d} \tag{2.1}$$

$$\left(\sigma_0 = \frac{0.532\alpha e^2}{(m_e kT)^{1/2}}\,\frac{1}{Q},\ \sigma_d = \frac{0.591\,(kT)^{3/2}}{m_e^{1/2} e^2 \ln (h\,/\,b_0)},\ h^2 = \frac{kT}{8\pi n_e e^2},\ b_0 = \frac{e^2}{3kT}\right)$$

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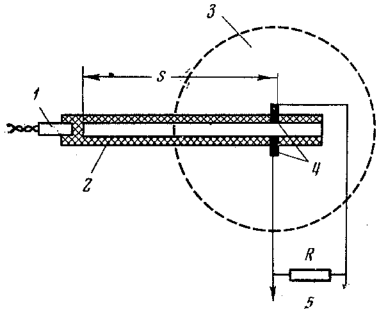

Fig. 1

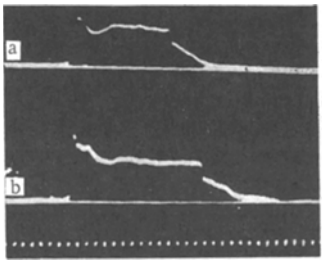

Fig. 2

Here, $1/\sigma_0$ is the specific resistance for a weakly ionized gas, $1/\sigma_d$ is the same [6] for a completely ionized gas, α is the degree of ionization, m_e and e are the mass and charge of the electron, k is the Boltzmann constant, T is the absolute temperature, Q is the cross section for the collision of electrons with gas atoms, h is the Debye screening radius, and n_e is the electron density.

The effective collision cross section Q was determined from [6]; the temperature behind the wave front and the degree of ionization were determined from [7] on the basis of the known velocity of the front ($D \approx 18$ km/sec). The conductivity corresponding to these values is $\sigma \approx 10^3$ mho/m. The plasma resistance between electrodes was a few ohms in this case also.

3. A magnetic field was created by a permanent magnet with an induction of $5 \cdot 10^3$ G. The pole diameter was 250 mm and the gap 30 mm. During the experiments, the field distribution was monitored and absolute calibrations were made (IMI-3).

The scheme for measurements of emf in experiments with shaped charges is shown in Fig. 1, where 1 is a detonator, 2 is a shaped charge of high explosive, 3 is the magnet pole, 4 is the electrodes, and 5 is the leads to an oscilloscope. The copper electrodes (2.5 mm in diameter) were fastened flush with the internal surface of the channel, either in the charge or in an insulating tube which extended the channel. Jets were produced by tubular charges of TG 50/50 explosive (Fig. 1) with external diameters $d_2 = 12$, 24, and 36 mm with corresponding channel diameters $d_1 = 5$, 10, and 15 mm. The ratio of channel length to diameter was always 25. The induced emf was determined from the voltage drop across the load $R = 100\ \Omega$. At any cross section of the flow, $R \gg R_p$. The signal was fed to the plates of an oscilloscope. Under experimental conditions, the time to establish a polarizing electric field was no more than 0.25 μsec.

The electrodes were located at the center of the magnet pole faces at a distance $s = 17\text{-}60\, d_1$ (Fig. 1). For $s > 25\, d_1$ (and always for $d_2 = 36$ mm), the electrodes were installed in a tube which extended the channel. Experiments were performed in air under standard conditions and at pressures of 1-2 mm Hg.

Figure 2 shows data from two experiments (*a* at standard pressure and b at pressures of 1-2 mm Hg). Here, $s = 22.5\, d_1$, $d_1 = 5$ mm, and $d_2 = 12$ mm. The time scale is at the bottom; the marker frequency is 2.5 MHz. For $d_1 = 10$ and 15 mm, the amplitude and duration of the signals increase similarly. In Fig. 2a, $D = 13.1$ km/sec and in Fig. 2b, $D = 16.5$ km/sec. Correspondingly, the plateaus behind the fronts on the traces are 10 and 10.9 km/sec. The velocities of the fronts in both cases are in agreement with data from streak photography. When the distance is increased to $s = 60\, d_1$, the velocities at the front and in the flow fall to 1.5-2 km/sec.

The arrangement of the device described in [2] is shown in Fig. 3, where 1 is a plane-wave generator, 2 is the high-explosive charge, 3 is a copper plate, 4 is the chamber wall, 5 is the compressed gas (air), 6 is the exit tube, and 7 is the electrodes. During detonation, the metal plate moves to the vertex of the hemispherical chamber. The compressed gas (air) is expelled into the tube in the form of a high-velocity jet. The measuring circuit is similar to that in Fig. 1; measurements were made for $s = 14\, d_2$ (in the experiments, $d_1 = 5$ mm and $d_0 = 40$ mm). For these dimensions, $D = 18$ km/sec; the nature of the velocity variation behind the front is seen from the trace in Fig. 4. The signal duration $t \approx 8$ μsec; 3 μsec after the beginning of the signal $u \approx 10$ km/sec. Measured values for the velocity of the front agree with data from streak photography; the quantity D drops sharply with further increase in s.

4. One can determine the actual flow velocity from the induced emf when the flow is nearly uniform, which also assumes little effect from the boundary layer at the wall. In the opposite case, the existence of velocity nonuniformity over the cross section leads to a drop in emf and values that are too low for the core of the flow. Deceleration of the flow at the walls should give rise to an increase in the temperature of the outer layers and to an increase in their electrical conductivity. The existence of a skin effect may then offer no opportunity for the magnetic field to reach an equilibrium value, which may also lead to understate-

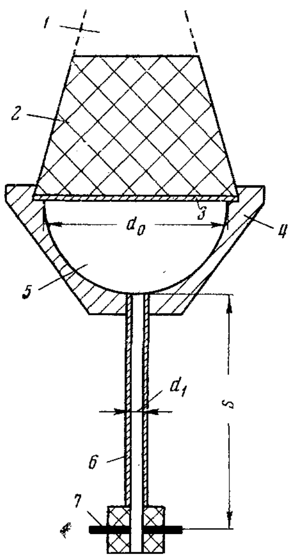

Fig. 3

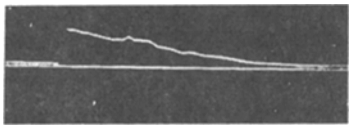

Fig. 4

ment of the measured quantities. When the flow velocity is constant over the cross section and there is a drop in electrical conductivity toward the outer layer, it is sufficient that the magnetic field be established in the outer layer in order to obtain true velocity values. In this case, it is assumed that the increase in the magnetic field because of the displacement of a portion of it from the central zone is small and that the resistance of the load is much greater than the resistance of the outer layers.

Measurement of the resistance of a shaped jet with electrodes arranged at an angle in the flow cross section leads one to suppose that the presence of a core flow with increased conductivity is characteristic of a shaped jet. A similar conclusion was reached in [8],where it was shown that a plasma jet from a shaped high-explosive charge exhibits nonuniform electrical conductivity over its cross section but has a plane wave front.

Under the experimental conditions, the time of plasma motion in the magnetic field was very much greater than the time of field penetration into the flow. The measurements were made in the center of the magnet poles (Fig. 1) and consequently the flow was already polarized when approaching the electrodes. The presence of a velocity gradient along the length of the jet should lead to redistribution of the potential. Analysis of the equivalent electrical circuit shows that the signal at the load is equal to the emf within 2-5%: the flow velocity was measured with the same kind of accuracy.

The considerations presented above make it possible to consider that the mass velocity of the flows investigated can be determined from the induced emf with acceptable accuracy.

5. Gas jets with velocities of tens of kilometers per second can be used as a working substance for the acceleration of solid particles to meteoritic velocities (flow of detonation products, plasma in a discharge device, gas in a shock tube, etc.). The flow surrounds the particle and accelerates it. The flow velocity u and the density are determining factors in estimating the possibilities of acceleration. In order that the particle velocity be comparable to the flow velocity, it is necessary that [1]

$$l\rho / \delta\rho_1 \geqslant 1 \tag{5.1}$$

where l is the length of the flow, ρ is its density, δ is the dimension of the solid, and ρ_1 is the density of the solid material. A considerable mass of gas is required to project a body with a dimension of a few millimeters. The loads during acceleration must not exceed the critical destructive stresses for the material. Calculation shows that for a spherical solid [9]

$$\rho u^2 \leqslant a\tau \tag{5.2}$$

where $a \approx 3.5$ and τ is the maximum strength of the material.

The oscilloscope traces (Fig. 2) indicate the extent of the portion of the jet where $u > 10$-11 km/sec is small in comparison with the total length of the jet. This explains why, for actual dimensions of laboratory devices, shaped charges in the form of tubular high explosive can achieve particle acceleration to only 8-9 km/sec [1] because the flow length l, according to (5.1), is important for acceleration. (Jet density $\rho \approx 0.025$-0.06 g/cm^3 according to estimates [3].) Charges of more complex geometry [1] are necessary for accelerations in the range 9-12 km/sec, where portions of a jet with increased velocity are created repeatedly. One can also assume (Fig. 2) that particle velocity will not change markedly for projection of sufficiently large particles in air or in vacuum since the signal amplitudes in Fig. 2a, b in the "plateau" region are nearly the same. (Experiment gives an increase of velocity in vacuum of about 10%.)

Equation (5.2) indicates that for a stable solid material it is necessary that $\rho \sim 1/u^2$ as the velocity increases. For conservation of the solid during projection by a shaped explosion (spheres of steel or glass), we must have $\rho \approx 0.005$-0.01 g/cm^3 when $u \approx 25$ km/sec. The length of the flow should increase, according to (5.1), $l \sim u^2$. For projection of solids in this velocity range, therefore, it is necessary to combine the conditions of relatively low density and considerable duration of flow. The problem of producing flows with such parameters is extremely complex.

In particular, experiments on the acceleration of steel spheres by the system sketched in Fig. 3 showed that even for $D = 18$ km/sec the condition (5.2) was not satisfied; disintegration of the solid occurred. The oscilloscope trace (Fig. 4) also shows that the duration of flow where $u > 10$ km/sec is relatively short under laboratory conditions. Some improvement in flow parameters (in terms of duration) is observed with the introduction of additional portions of gas into the chamber ahead of the compression (jet of detonation products). In that situation, however, the velocity level is reduced ($D = 14$-15 km/sec) and becomes comparable to the flow parameters of a shaped high-explosive charge.

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LITERATURE CITED

1. V. M. Titov, Yu. I. Fadeenko, and N. S. Titova, "Acceleration of solid particles by a shaped detonation," Dokl. Akad. Nauk SSSR, 180, No. 5, 1051 (1968).
2. A. E. Voitenko, "Production of high-velocity gas jets," Dokl. Akad. Nauk SSSR, 158, No. 6, 1278 (1964).
3. A. S. Zagumennov, N. S. Titova, Yu. I. Fadeenko, and V. P. Chistyakov, "Detonation of elongated hollow charges," Zh. Prikl. Mekhan. i Tekh. Fiz., No. 2, 79 (1969).
4. A. E. Voitenko, "Strong shock waves in air," Zh. Tekh. Fiz., 36, No. 1, 178 (1966).
5. G. V. Pryakhin, V. M. Titov, and G. A. Shvetsov, "Use of shaped high-explosive charges in pulsed generators," Dinamika Sploshnoi Sredy, No. 3, Inst. Gidrodinamiki, Sibirsk. Otd. AN SSSR, Novosibirsk (1969).
6. S. C. Lin, E. L. Resler, and A. Kantrowitz, "Electrical conductivity of highly ionized argon produced by shock waves," J. Appl. Phys., 26, No. 1, 95 (1955).
7. N. M. Kuznetsov, Thermodynamic Functions and Shock Adiabats of Air at High Temperature [in Russian], Mashinostroenie, Moscow (1965).
8. M. W. Burnham and S. J. Marshall, "Some experiments related to explosive driven MHD converters," Proc. Conf. on Megagauss Field Generation, Frascati (1965), pp. 367-386.
9. Yu. I. Fadeenko, "Disintegration of meteorites in the atmosphere," Fizika Goreniya i Vzryva, 3, No. 2, 276 (1967).