PLASMOIDS IN ELECTROMAGNETIC SHOCK TUBES

E. F. Lebedev and V. P. Formichev

Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 132–135, 1966

At the present time, many investigators are interested in processes in electromagnetic shock devices which enable one to obtain a moving ionized gas.

It has been discovered by a series of authors that a plasma discharge can move through the gas in a channel without accumulating in front of itself shock-heated plasma, for some distance from the discharge chamber [1–5]. As a rule this effect occurs for initial pressures less than 1 mm Hg and discharge currents of greater than 10^5 A, while the Mach number exceeds 20–30; we note that the type of gas and also the type of discharge chamber are of little importance.

If the initial pressure is increased or the magnitude of the discharge current is decreased, the plasma discharge begins to move like an impermeable piston considerably closer to the discharge chamber, forming a shock wave in front of itself [1, 2, 4, 6, 7]. In this case we may expect experiment to agree with the theory of a normal shock [4, 6, 7]. However, in the case when shock-heated plasma cannot be detected in pure form, the magnitudes of the plasma parameters differ significantly from the values calculated for a shock wave [1, 4, 5]. Some results are given below for the investigation of a plasmoid for a continuous discharge at a distance of 60–90 cm from the discharge chamber. These results confirm the assumption that there is no distinct boundary between the thermal plasma and the plasma of the continuous discharge.

An important parameter in the investigation of magnetohydrodynamic phenomena in a plasma is the magnetic Reynolds number, or the electrical conductivity of the plasma σ as its component. In the present paper values of σ are measured for a plasmoid obtained in a discharge tube with a T-source in air at initial pressures of p_0 = 0.2–1.0 mm Hg and plasmoid velocities of 8–13 km/sec. In these conditions experimental values of the pressure in the plasmoid were obtained.

The plasmoid was obtained in a T-tube of diameter 4 cm on discharging a bank of condensers (C = 1200 μF and U = 5 kV). The plasmoid velocity was determined from time-resolved photography and frame photography using a SFR camera (Fig. 1), and with the help of a special magnetic induction gauge composed of two magnetic probes arranged close to the moving plasma on a 100-mm base and located in separate constant magnetic fields perpendicular to the flow. The signals from these probes caused by the field deformation of the passing plasma were recorded on an OK-17m oscillograph.

As distinct from the time-resolved photographic records which registered the velocity of the bright "front" of the plasmoid, the induction gauge determined the velocity of its region of maximum conductivity, but the magnitudes of these velocities obtained by the two different methods agree with good accuracy (Fig. 2a). Frame photography confirmed the absence of a flat plasmoid front mentioned in the literature (Fig. 1b). The length of the "tongues" attains 1–2 cm.

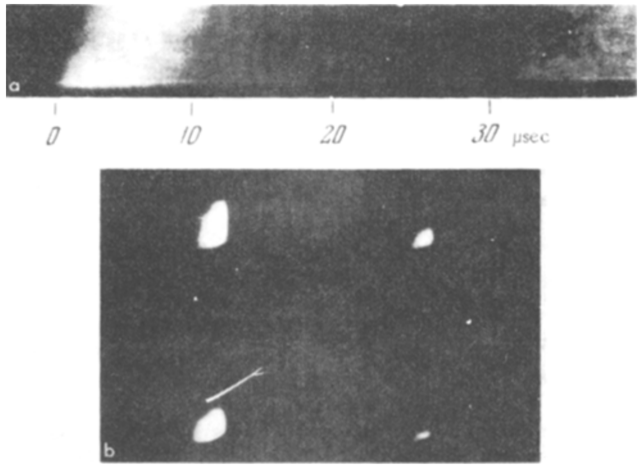

Fig. 1. Time-resolved and frame photography of the motion of a plasmoid in a tube at a distance of 90 cm from the discharge chamber; time between frames is 2.6 μsec.

The electrical conductivity was measured in a quartz section of the tube at a distance of 90 cm from the T-source by the displacement of the stationary magnetic field by the moving plasma [8]. The resolving power of the measuring device employed was 3 cm along the length of the plasmoid. This device does not register the "tongues" of the plasmoid, since the σ signal is roughly proportional to the fourth power of the diameter of the conducting region, and the diameter of the "tongue" is less than the diameter of the channel by a factor of two at least. For this reason the average value of the plasmoid conductivity is determined over the external annulus of tube cross section (of thickness about 1/3 of the radius). The internal part of the plasmoid has practically no interaction with the magnetic field of the measuring system if only the conductivity of these internal layers is not greatly in excess of the conductivity of the external layers, which is clearly so in the case under consideration.

From the time-resolved pictures of the flow behind the plasmoid front, it was established that the velocity of the plasma may be taken as constant up to distances of 30–40 cm from the main part of the plasmoid. Thus, according to the results of [8], the integral of the σ signals received is a direct indication of the variation of electrical conductivity along the plasmoid (taking into account the distortion caused by the resolving power of the measuring apparatus). Oscillograms of the σ signals are given in Fig. 3a and b. The electrical conductivity, which reaches its maximum value just at the main part of the plasmoid, or at a distance of 2–3 cm from it, later decreases,

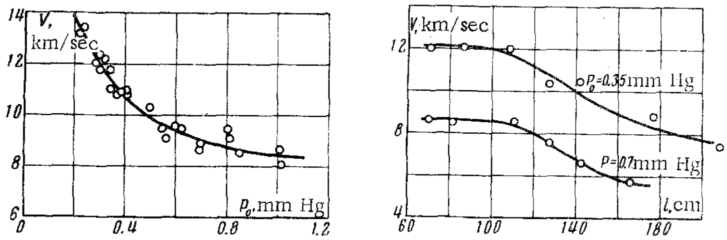

Fig. 2. a) Velocity of leading front of the luminescent plasmoid as a function of the initial pressure (l = 70 cm); b) variation of the velocity of the plasmoid along the tube, l – distance from discharge chamber.

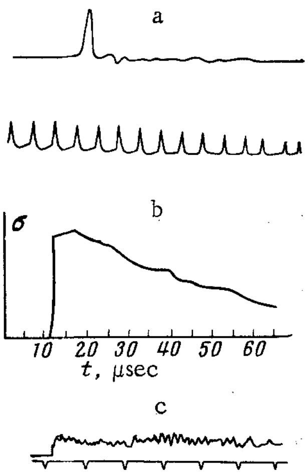

Fig. 3. a, b) The signal σ and rough behavior of the conductivity, p_0 = = 0.44 mm Hg; c) signal from the piezoelectric transducer, p_0 = 0.33 mm Hg. Time marks: a and b) 5 μsec. c) 10 μsec.

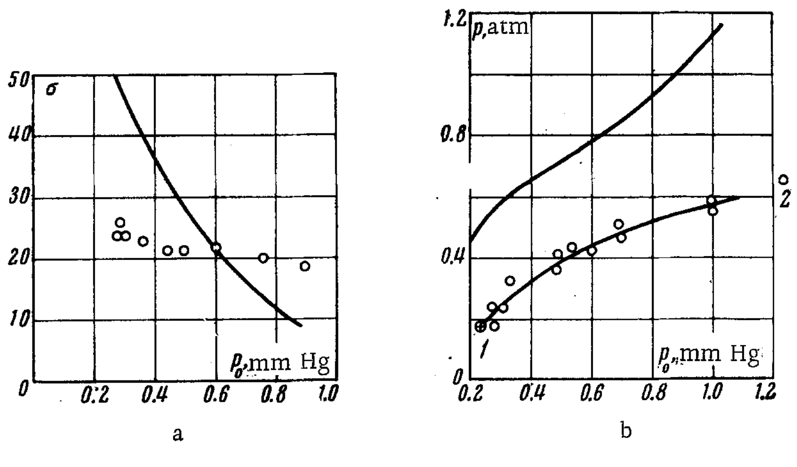

Fig. 4. a) Calculated curve of maximum values of the conductivity [$ohm^{-1}cm^{-1}$] in the plasma behind a shock wave and experimental results; b) calculated values of the pressure in air behind a shock wave (upper curve) and experimental results. 1) point taken from [5]; 2) point taken from [4].

falling roughly by a factor of two at a distance of 20–40 cm from the start of the plasmoid. The decrease occurs more slowly as the initial pressure increases. The maximum values of the conductivity were determined from the oscillograms by calibrating the measuring system using a metal cylinder, and are presented for various values of the initial pressure in Fig. 4a. The plasmoid velocity, essential in order to calculate the magnitude of σ, was measured by the induction gauge in each experiment (Fig. 2a). In order to make an estimate of the results obtained the magnitude of the electrical conductivity was calculated in the gas plug behind a plane shock wave moving at the velocity of the plasmoid with the mean free path of the electrons assumed constant [9]. The experimental values of σ° differ significantly from those calculated σ ($\sigma^\circ = \sigma/2$) for $p_0 = 0.3$ mm Hg; $\sigma^\circ \approx 2\sigma$ for $p_0 = 1$ mm Hg.

As a result of the obvious nonuniformity of the plasmoid the measured values of σ may be lower than the local values of the conductivity. If we make an estimate of the conductivity according to the law $\sigma \sim T^{3/2}$, taking into account the fact that the real temperature in the plasmoid is, according to [5], close to 1.5T, where T is the calculated temperature behind the front of a plane shock wave, we obtain the value $\sigma^\circ \sim 2\sigma$, which was obtained in the experiment in question for $p_0 \geqslant 1$ mm Hg. For these initial pressures a decrease of inhomogeneity in the plasmoid registered by the SFR camera is observed.

The pressure in the plasmoid was measured at a distance of 65 cm from the T-source. It should be noted that both the pressure and conductivity were measured in a section of the tube, where the velocity of the plasmoid changes insignificantly (Fig. 2a).

The piezotransducer which was employed, similar to that described in [10], had a piezoceramic TSTS-19 of diameter 3 mm and thickness 1 mm. The accuracy of the pressure measurements was about 10%.

In processing the pressure oscillograms (Fig. 3c) the average value of pressure was determined, which remained constant for a considerable time. Figure 4b shows this quantity as a function of the initial pressures. The experimental magnitudes of the pressures were roughly half the calculated values behind the front of a plane shock wave moving with the same velocity as the plasmoid [11]. As p_0 is raised, this difference increases.

Reference [5] gives the results of pressure measurements in a shock tube with a coaxial discharge chamber for $p_0 = 0.2$ mm Hg. Our pressure measurements for $p_0 = 0.2$ mm Hg coincide with the measurements of [5] (it should be remembered that in our case a T-source was employed).

If we assume that the gas density in the gauge is equal to 1/3 the calculated pressure for a one-dimensional shock wave, according to the estimates [12], then the region of gas compressed by the shock wave should have a length within the limits 15–25 cm. This quantity agrees with the length of the bright region obtained from the SFR-grams (Fig. 1a). However, the sharp fall off in conductivity which should be observed behind the contact surface is missing, and the quantity σ is about half the maximum value at this point. This confirms the assumption that there is no distinct boundary between the thermal plasma and the discharge plasma.

REFERENCES

1. Cloupeau, "Interpretation of luminous phenomena observed in electromagnetic shock tubes," Phys. Fluids., vol. 6, no. 5, 1963.

2. H. Brinkshulte and H. Muntebruch, "Interferometrische Untersuchungen an elektromagnetische beschleunigten Stosswellen," Z. Naturforsch, vol. 20, no. 2, 1965.

3. C. T. Chang, "Shock wave phenomena in coaxial plasma guns," Phys. Fluids, vol. 4, no. 9, 1961.

4. Yu. V. Makarov and A. M. Maksimov, "Investigation of the structure of shock waves in an electromagnetic shock tube," Zh. tekh. fiz., no. 4, 1965.

5. M. I. Vorotnikova and R. I. Soloukhin, "On the structure of flow in electromagnetic shock tubes," PMTF, no. 5, 1964.

6. H. C. Ahlstrom, "Observations of shock waves in an electrically driven shock tube," Phys. Fluids, vol. 7, no. 6, 1964.

7. W. Fucks and T. Czech, "Plasma motion and shock waves in Theta-pinch operated shock tubes," Phys. Fluids, vol. 8, no. 1, 1965.

8. Lin, Resler and Kantrovits, "The electrical conductivity of highly-ionized argon in a shock wave," Voprosy roketnoi tekhnologic, vol. 1 (31), 1956.

9. H. Nagamatsu and R. Sheer, "MHD results for highly dissociated and ionized air plasma," Phys. Fluids, 4, 9, 1961.

10. R. I. Slolukhin, Shock Waves and Detonation in Gases [in Russian], Fizmatgiz, 1963.

11. Thermodynamic Functions of Air for Temperatures from 1000 to 12 000° K and Pressures from 0.0001 to 1000 atm. [in Russian], Izd-vo AN SSSR, 1960.

12. E. McSean, G. Faneuft, A. Kolb, and H. Griem, "Spectroscopic study of helium plasmas produced by magnetically driven shock waves," Phys. Fluids., vol. 3, no. 6, 1960.

14 July 1965 Novosibirsk