Plasma Motion and Shock Waves in θ-Pinch Operated Shock Tubes

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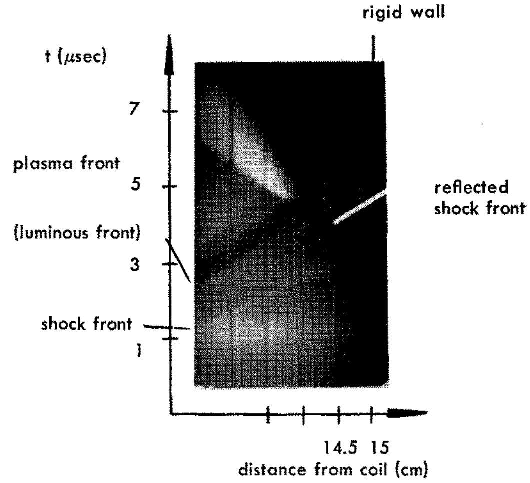

FIG. 1. Schlieren streak record of reflection and refraction process of a shock wave in helium (10 mm Hg).

Plasma Motion and Shock Waves in θ-Pinch Operated Shock Tubes

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IN electromagnetically operated shock-tubes, luminous fronts have been observed, their velocities as a function of basic pressure and distance from the shock-generating discharge have been measured, as well as the physical state behind the moving front, especially electron temperature and density.[1,2]

In other papers[4,12] the luminous front has been tacitly supposed to be a contact surface. In the papers cited above,[1,2] however, the luminous front has been treated as a shock front to which the Hugoniot equations have been applied. This theory has been questioned especially by Cloupeau.[3] In this paper, therefore, the question is taken up again and the nature of the luminous front and a discontinuity separating itself from the luminous front have been studied by application of the schlieren method.

The measurements of this report have been made in helium, argon, and hydrogen, basic pressure from 0.5 to 100 Torr, with conical θ-pinch devices in tubes of 30 mm diam, lengths up to 1 m, and having bank energy of 1.5 kJ, peak currents up to 450 kA, current rise rate up to 10^{13} A/sec, coil magnetic field increasing along the axis of the tube from 50 to 300 kG.[5–8]

Luminous fronts of good planarity have been observed with very good reproducibility, and front velocities have been measured with streak camera, image converter, schlieren-technique and time resolved spectroscopy up to Mach 100. Temperatures up to 4.5 eV and electron densities up to 2.5×10^{17} per cm^3 of a helium plasma behind the luminous front have been measured in time resolved form with the relative intensity method of two appropriately chosen lines, line profile analysis and with a time-resolved Langmuir-probe method. The temperature drops only slightly after the luminous front for 1 μsec, whereas electron densities drop to $\frac{1}{3}$ within the same time.[9]

Time-resolved schlieren pictures show that a shock wave separates itself from the luminous front at a distance of a few tube-diameters from the coil. The shock moves ahead of the luminous front. For the ratio of the luminous front velocity to the shock velocity we find values between 0.7 and 0.8 with Mach numbers up to 15.[10] For higher Mach numbers this value approaches unity.

The shock was reflected at a rigid wall (see Figs. 1 and 2). The reflected shock interacts with the follow-

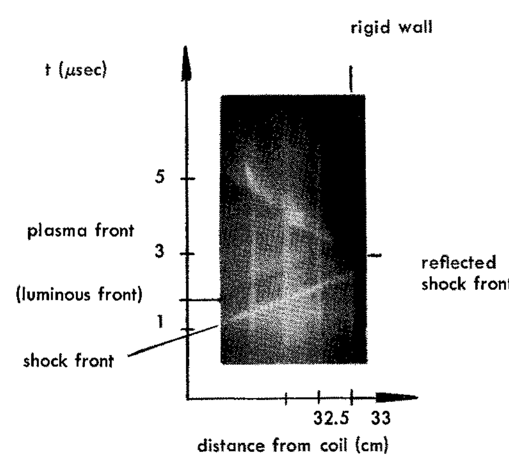

FIG. 2. Schlieren streak record of reflection and refraction process of a shock wave in hydrogen (2 mm Hg).

ing luminous front in a refraction process. Part of it is reflected at the plasma and a part moves into the plasma heating the plasma to a higher temperature. The velocity of the luminous front of the plasma is slowed down in the refraction process.

To determine the nature of the observed density jump we discuss the velocity ratio at the reflection (see Fig. 3). The measurements range from 1 to 100 Torr and are made at distances from the coil ranging from 10 to 80 cm.

Theoretically we expect for the velocity ratio at the reflection

$$\frac{V_R}{V_S} = \frac{2(\gamma - 1)M^2 + 3 - \gamma}{M^2(\gamma + 1)},$$

where $\gamma = c_p/c_v$, M is the Mach number, and dissociation and ionization are neglected. For hydrogen at M values between 2 and 5 we expect $V_R/V_S = 0.33$, for higher values of M dissociation occurs and we expect a decrease of the velocity ratio. For helium at M values between 2 and 10 we expect $V_R/V_S = 0.5$, similarly for argon up to $M \approx 6$.

The experiments show the expected results in helium with an error of about 10%. With argon, ionization causes a decrease from the value 0.5 to 0.25 at Mach numbers 11 to 18, which is theoretically expected beginning with Mach numbers of about 6.[11] The higher values in these two cases may result from energy transport from the plasma region into the region between the shock and the luminous front.[2] With hydrogen, a decrease from the classical value of $\frac{1}{3}$ caused by dissociation is observed according to the theoretical expectation.

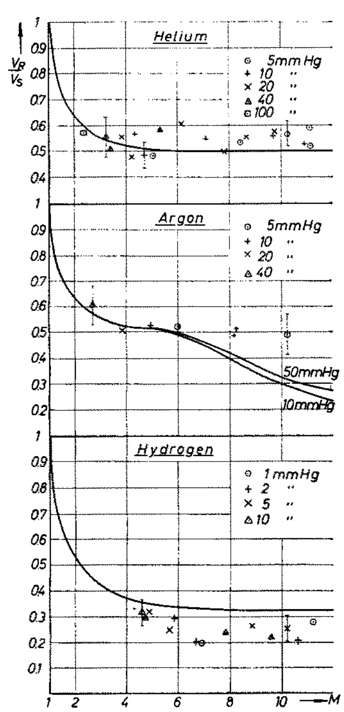

FIG. 3. Measured velocity ratio of the reflected and incident shock. The solid line for helium and hydrogen indicates the theoretical value without ionization and dissociation, for argon with ionization (see Ref. 11).

Our results allow the following conclusions: The luminous front is the edge of a moving plasma generated by the discharge in the coil region. From this plasma a shock wave separates itself at a distance from the coil, where the ratio between shock and luminous front velocity begins to differ from unity, i.e., in our experiments at a distance between three and five times tube diameter and with Mach numbers about equal to 20. If reflected, the reflected shock interacts with the following luminous front of the plasma in a refraction process very similar to the refraction of a shock at the contact surface of classical shock-wave theory.

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Loss of Plasma from Cesium Devices

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IN 1961 D'Angelo and Rynn[1] reported that a thermally-produced, low temperature cesium plasma diffused across a magnetic field according to the classical laws, i.e., by electron–ion collisions. Their analysis rested on an important assumption; namely, that there existed a rapid process of volume recombination which was primarily responsible for the loss of plasma if the magnetic field were greater than ~4000 G. The recombination coefficient required to fit their data was $\alpha \sim 10^{-10}$ cm^3 sec^{-1}, which is more than an order of magnitude greater than the computed rates of both radiative (two body) and collisional-radiative (three body) recombination and the experimental rates found by Knechtli and Wada[2] at higher plasma concentrations ($n > 10^{12}$ cm^{-3}).

Recently von Goeler,[3] in an analysis similar to one done by Knechtli,[4] has pointed out that the rapid