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Reflected Wave Reverse Flow in an Electromagnetic Shock Tube

David S. Scott*
University of Toronto
and
Thomas P. Anderson†
University of Iowa

Introduction

Several considerations led us to investigate the possible existence of reverse flow within the plasma generated in a conical electromagnetic shock tube (EMST) after reflection from a downstream bulkhead. These were as follows:

1) Various investigators[1,2] have reported the one-dimensional blast wave behavior of EMST produced flows. Our data was in agreement with these previous observations and, moreover, showed that, after reflection from a downstream bulkhead, the velocity of the reflected luminous front increased with distance from the bulkhead.[3] This increasing velocity had been predicted for one-dimensional blast wave reflection[4] and, hence, its existence further supported the presence of blast wavelike mechanisms within the flows produced by our EMST.

2) If we assume the densities within the wave incident upon the bulkhead resemble those characteristic of a one-dimensional blast wave, the density of the gas into which the reflected plasma moves drops off very rapidly. After the reflected plasma has traveled several diameters from the bulkhead, the density of the incident plasma at the reflected plasma front becomes sufficiently low that there is complete shocked gas diffusion into the reflected plasma. Under these circumstances it is the mass crossing the wave front that is important for determining the velocity behind the wave front, rather than the shock strength as is the case in higher density flows. At this point in the flow it may be assumed, with small error, that the reflected plasma is moving into a vacuum and, hence, that the plasma velocity at the reflected front is equal to the reflected front velocity.

Using standard photomultiplier techniques, reflected luminous front velocities were found to range over 1900–3500 m/sec. depending upon shock tube initial conditions. Therefore, by previous arguments, it was felt that there might exist reverse plasma velocities as high as 3500 m/sec.

3) Makarov and Makismov[5] investigated the thermodynamic state of a plasma after reflection from a downstream bulkhead in a conical EMST and reported temperatures in the order of 13,000°K. It was recognized that temperatures of this order coupled with the plasma velocities indicated by considering 2), suggested that not only should there be a reverse flow but that it might also be supersonic which, if true, could be easily established by image camera photography.

4) Finally, although like many other investigators, we found that in all cases the incident flows exhibited marked instabilities, our data (see Fig. 1) indicated that the reflected plasmas were remarkably stable and reproducible. It was recognized, therefore, that if the reflected wave yielded a supersonic reverse flow its stability would enhance its suitability for a wide range of further studies.

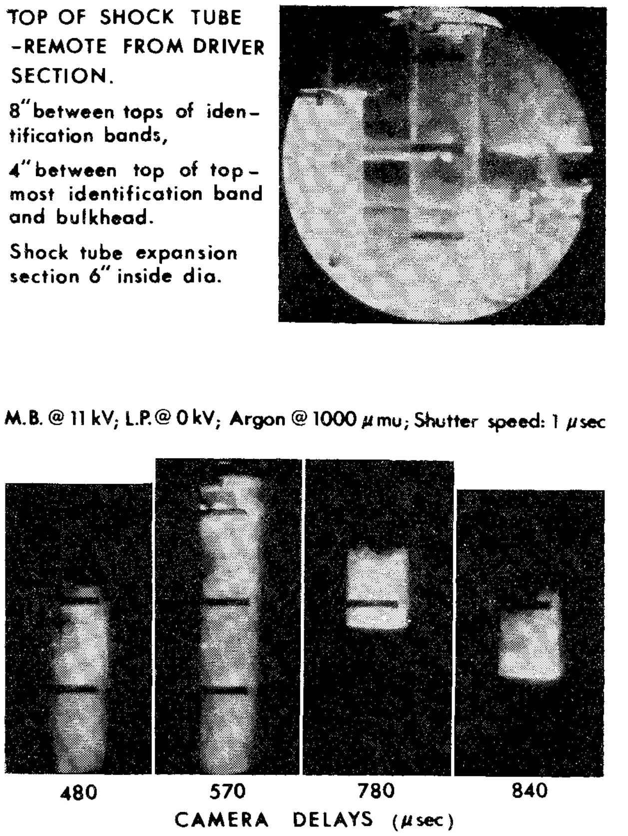

Fig. 1 Sequential development of luminosity.

Facility

The familiar conical driver[2] geometry was chosen. However, to eliminate current streamer wondering and yield a more symmetric energy addition, the usual full-ring electrode was replaced by twelve electrically-isolated electrode-pins, evenly spaced round a shock-tube section and each individually supplied energy from a single 14 μF, 20 kv capacitor. The expansion-section i.d. was 15.25 cm and its length (distance between the bulkhead and the 12 pin-electrode section) was 173 cm. The driver section length (distance between the plane of the 12 pin-electrodes and the tip of the ground electrode) was 59 cm. The EMST had preionize and crowbar capabilities,[3] however, these are unimportant to this note.

Experimental

Image-converter camera and photomultiplier data was used to study the reproducibility, plasma homogeneity and symmetry, of the incident and reflected waves. Figure 1 is representative of a portion of the data.

In all incident front profiles a high degree of asymmetry existed and became even more conspicuous at lower pressures. Our data, however, showed the reflected wave front to be not only symmetric but reasonably planer, with a tendency for

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* Associate Professor of Mechanical Engineering. Member AIAA.

† Professor and Chairman of Mechanical Engineering. Member AIAA.

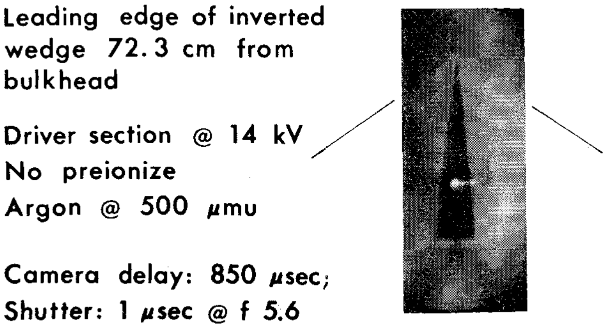

Fig. 2 Reflected wave enveloping inverted aerodynamic wedge.

both to improve with increasing pressure. The plasma homogeneity was good towards the front of the reflected wave but deteriorated somewhat toward the rear. With decreasing pressure, the length of the luminosity decreased while the homogeneity tended to improve.

At 570 μsec delay in Fig. 1, an intense luminosity standoff may be seen in front of the reflecting bulkhead. Because in an EMST the temperature of the driver gas exceeds that of the driven gas,[2] this luminosity indicates the existence of an interaction zone and its extent after reflection. Intense luminosity stand-off was not observed during runs in which the pressure was less than 1000 μ, indicating the absence of an interaction zone at these pressures and confirming observations of others.[6,7]

The reflected wave was photographed, at shutter speeds of 1 μsec, as it enveloped an inverted aerodynamic wedge of half-angle 6.3°. Two series of runs were made with the wedge leading edge 72.3 cm from the bulkhead. Data from the first series (capacitor bank at 12 kv) indicated a region of constant Mach angle flow approximately 60 μsec long; however, the shock was not sharp and the Mach angle approached the largest allowable limit compatible with a wedge half-angle of 6.3°. The second series, with the wedge in the same position but the shock tube at 14 kv, indicated a constant Mach angle flow of 80 μsec duration, within an experimental accuracy of ±10 μsec. The Mach angle for this period was 54.24 ± 1.0°, and Fig. 2 is a typical of the data. Because the data from the second series of runs lies in a region of high shock-shape dependence, an error of 1° in the Mach angle would result in a Mach number error of order 0.025, if the gas remained at constant temperature.

A final two series of runs were performed with the wedge leading edge 40.2 cm from the bulkhead and the shock tube voltage at 12 kv and 14 kv, respectively. No shocks were observed in any of the data; which is not surprising since one of the boundary conditions is that the plasma velocity at the bulkhead be zero for all time.

Assuming an electrically neutral plasma in thermal equilibrium, an iterative procedure (to account for the variation of the ratio specific heats with temperature and pressure) involving the 54.25° Mach angle and plasma velocity was used to estimate the temperature of the reflected plasma. Since for this case, the luminous front velocity was 3500 m/sec the temperature was evaluated over a 3500–2500 m/sec plasma velocity range. The variation of temperature with velocity was almost linear and yielded for a velocity of 3500 m/sec, Mach 1.510, T = 13,430°K, and for a velocity of 2500 m/sec, Mach No. = 1.415, T = 11,000°K.

Discussion

Although at this time we propose no detailed mechanism to account for the markedly increased stability of the reflected wave, it appears likely to result from a reproducible energy addition followed by an inertially unstable expansion toward the bulkhead and, after compression against the bulkhead, an inertially stable expansion away from the bulkhead. It should be noted that, except in its early stages, the reflected wave propagates into the tail of the incident wave which, although probably still nonuniform is sufficiently rarefied that it has negligible effect upon the motion of the reflected wave.

A complimentary investigation of the temperature by a method independent of the shock shape, could be used to substantiate the shock shape data. Although such an investigation has not been performed, the present results are in good agreement with Makarov and Makismov's[5] measurements of the thermodynamic state behind the reflected shock in their conical EMST.

The blast wave reflection theory of Chang and Laporte[4] gives an analysis of the position of the reflected shock and the flow variables immediately either side of it. Although flow variables a finite distance from the shock were not given, the authors make the statement, "that in all probability, a reverse flow will be induced behind the reflected shock." If the flow in our EMST approximates that of a one-dimensional blast wave (with the exception of temperature), this research experimentally substantiates their findings.

Summary

Experimental evidence indicates that: 1) the plasma generated in an EMST is considerably more stable and uniform after reflection off a downstream bulkhead than it is as it initially moves away from the driver section, and that 2) there exists a reverse flow within the reflected plasma which under some circumstances is supersonic.

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Nonsimilar Behavior of Ablating Graphite Sphere Cones

Eugene P. Bartlett*
Aerotherm Corporation, Mountain View, Calif.

RESULTS obtained by the method of Ref. 1 are presented for the nonsimilar laminar chemically-reacting boundary layer over ablating graphite sphere cones under typical bal-

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* Manager, Aerochemistry Department, Analytical Services Division. Member AIAA.