Construction of a Shock Tube for Metallic Vapors

Yong Wook Kim and Otto Laporte
The University of Michigan, Ann Arbor, Michigan

The construction and operation of a heated shock tube (often called mercury shock tube due to its immediate application) are described in some detail. Experimental observations of strong shocks in mercury gas are presented and discussed in the light of preliminary theoretical investigation. An observation of reflected shock bifurcation in the monatomic gas of mercury is also reported.

I. INTRODUCTION

A heated shock tube has recently been constructed at the University of Michigan. This facility is now in full operation, its primary application being the study of shock-generated mercury plasmas of high electron densities.

Our motivation in building a shock tube for metallic vapors is the following: The pressure-driven shock tube with a constant cross section has long proved to be an advantageous spectroscopic source,[1–5] mainly because the shock provides a well-defined discontinuity followed by a uniform flow at high temperature, and the thermodynamic variables of the flow are adequately predicted by the well-established shock theory.[6] Spectra are usually brought out by mixing a controlled amount of the element in equation with the shocked gas—usually an inert gas—and the metallic spectra, in particular, are obtained by using metallo-organic compounds as adulterants. The use of the inert gas as the shocked medium, of course, has a specific implication that one wishes to have an optically thin radiating gas in order to minimize the complication in analyses such as the self-absorption of spectral lines. Since these compounds are usually unstable, however, it is often questionable how much metal is actually present in the shocked zone. Furthermore, the metals which lend themselves to this type of investigation have very high melting and boiling points and possess complicated multiplet spectra.

Thermodynamic variables of the flow behind the shock are controlled by the choice of driving and driven gases and the pressure ratio p_c/p_0, where p_0 and p_c are the pressures in front of and behind the diaphragm before firing. According to the ideal shock-tube theory[7] and much experimental evidence, for a given initial pressure ratio a stronger shock can be produced the lower the sound speed in the shocked gas. This directed our attention to mercury, together with the fact that the mercury spectrum is simple and the pressure broadening of the lines has been well investigated under static conditions.[8] The ionization potential of neutral mercury being low also suggests that high electron density plasmas can be made readily available using strong shocks, and this in turn shows the possibility of an extensive investigation of the Stark broadening of spectral lines under optically thick plasma conditions.

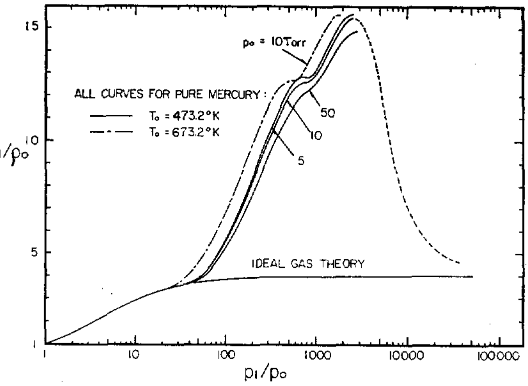

FIG. 1. The Rankine–Hugoniot relation for shocks in the monatomic gas of pure mercury. Calculation is done by assigning shock speeds for given p_0 and T_0 and includes corrections owing to such real gas effects as the internal excitation, lowering of ionization potentials, and the first and second ionizations.

Extensive numerical calculations of shock relations accordingly were carried out and an example is shown in Fig. 1. The Rankine–Hugoniot relation for the primary shocks in pure mercury gas is plotted for initial temperatures of 473.2 and

1 E. B. Turner, Ph.D. thesis, University of Michigan (1956).
2 T. D. Wilkerson, Ph.D. thesis, University of Michigan (1961).
3 G. Charatis, Ph.D. thesis, University of Michigan (1961).
4 L. R. Doherty, Ph.D. thesis, University of Michigan (1962).
5 W. A. Brown, Ph.D. thesis, University of Michigan (1964); Phys. Fluids 9, 1273 (1966).
6 O. Laporte, in *Combustion and Propulsion, Third AGARD Colloquium* (Pergamon Press, New York, 1958), p. 499.
7 W. Bleakney and R. J. Emrich, *High Speed Aerodynamics and Jet Propulsion* (Princeton University Press, Princeton, New Jersey, 1961), Vol. VIII, p. 600.
8 C. Füchtbauer, G. Joos, and O. Dinkelacker, Ann. Physik 71, 204 (1923).

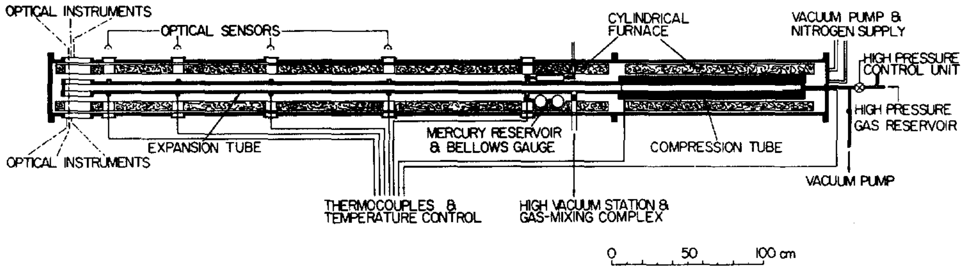

FIG. 2. A schematic side view of the heated shock tube.

673.2°K and pressures of 5, 10, and 50 Torr; it shows the role played by each stage of ionization in the behavior of shocked mercury gas. If there were no higher stage of ionization than the second, the curves would fall on the dotted line as the gas becomes a mixture of second ions and electrons only. ρ_0 and ρ_1 are the gas densities in front of and behind the primary shock and p_1 is the pressure behind. The case of $p_0 = 50$ Torr at $T_0 = 473.2$°K is unrealistic, but is considered for comparison.

At this point it is evident that the shock tube has to be heated to the temperature at which the saturated vapor pressure of mercury becomes some 10 Torr or greater in order to attain an appreciably long duration of the shock luminosity—long enough for the shocked gas to reach local thermodynamic equilibrium and to remain in this state so that various spectroscopic measurements can be carried out. For inert gases the optimum initial pressure lies in the vicinity of 10 Torr at room temperature. The fact that ρ_1/ρ_0 readily exceeds the ideal gas limit in mercury gas, however, indicates that the volume of shocked gas available in the expansion tube at the time the primary shock reaches the end wall is smaller than in the case of inert gases. The temperature of the tube should be kept substantially higher than that at which the saturated vapor pressure becomes p_0 so that the situation is not complicated by van der Waals corrections. For all practical purposes, in the p_0 range mentioned and at temperatures of 473 to 673 °K, one may indeed treat mercury as an ideal gas.

II. THE HEATED SHOCK TUBE

Figure 2 shows schematically a side view of the entire shock tube. It consists of three major parts: the main shock tube, the cylindrical furnace surrounding it, and the large outer tube within which both are contained.

The main shock tube is constructed entirely of stainless steel, Type 304. The expansion tube consists of five sections and two interchangeable test sections that are made of seamless rectangular tubing with inner dimensions 3.84 × 6.50 cm, wall thickness 0.95 cm, and inner corner radius 0.76 cm, the total length is 3.68 m. The inner surface of the entire expansion tube is highly polished with a specially designed tool. The interior of the test section is treated with molten sodium dichromate to reduce the surface reflectance. The sections are assembled so that they are both vacuum and high-pressure tight by squeezing a nickel-plated copper gasket between each pair of matching flanges. The quartz windows are sealed onto the test sections using O-rings of stainless steel and monel. Direct contact between optical quartz and metal O-rings is avoided by inserting a thin layer of Kapton polymide film, resulting in longer life of windows and an excellent vacuum. When the ambient temperature is varied extensively, this seal on the window fails but can be restored by adding additional layers of the film.

The compression tube is made of 1.22-m long tubing of the same kind as the expansion tube, enclosed within another cylindrical steel tubing of 15.23 cm diameter. The space between the two tubes is filled with refractory cement. Copper or aluminum sheets 1.27–2.03 mm thick are used as diaphragm material. Owing to the fact that the diaphragms are held within a pair of matching circular grooves cut in the flanges, no additional gaskets are needed. The diaphragms are scored diagonally. The entire tube proved to be well sealed from a vacuum of 5×10^{-5} Torr to a high pressure of 70 atm. The compression tube can be filled with H_2, He, or N_2 to 170 atm by means of a remote controlled high-pressure system.

The cylindrical furnace of 20.30 cm inner diameter is divided into six individually controlled electrical heating units, each with chromel "C" wire windings. The maximum total power is rated at 20 kW, making it possible to raise the shock-tube temperature continuously from room temperature to 400°C in a matter of 5 h. The furnace is wrapped

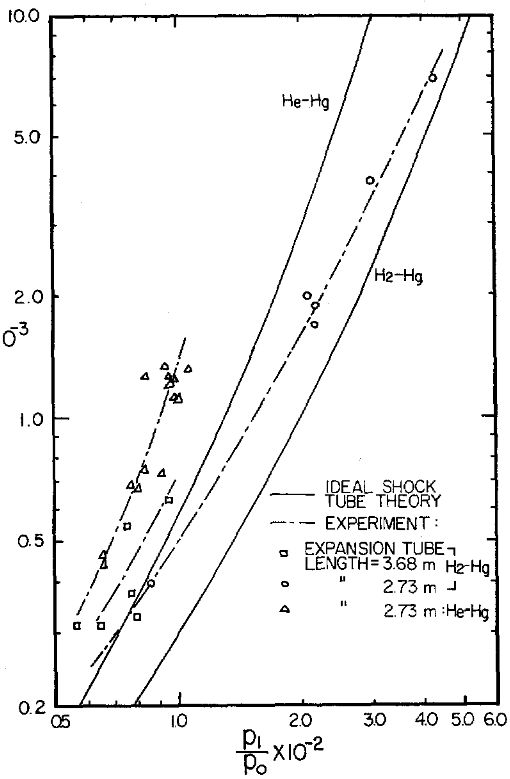

FIG. 3. Measured shock strengths p_1/p_0 are plotted as a function of initial pressure ratios p_c/p_0 and compared with the ideal shock-tube theory. Hydrogen and helium were alternately used as driving gases, while the shocked medium was pure mercury gas for all events. p_0 varied from 4 to 26 Torr, but T_0 was maintained at 506 ± 6 °K.

with fiberglass insulation and placed within an outer tube of 35.60 cm inner diameter. The outer tube likewise consists of sections and is again wrapped with fiberglass and asbestos insulation to an outer diameter of 46 cm. For safety reasons the pressure in the outer tube may be kept subatmospheric.

The mercury reservoir is installed within the furnace and connected to the expansion tube via a set of all metal valves. The pressure of mercury gas in the expansion tube is measured for each shot with a stainless-steel sylphon bellows gauge which is also installed within the furnace. This gauge is designed on the following principle: the space within the bellows is exposed only to the mercury gas present in the expansion tube, resulting in the expansion of the bellows along its axis. This can be counteracted by the build up of air within another vacuum tight chamber which houses the bellows. The change in the pressure of air needed to bring the bellows back to the initial position when there was no mercury gas present is a measure of the mercury gas pressure. It is independent of the temperature

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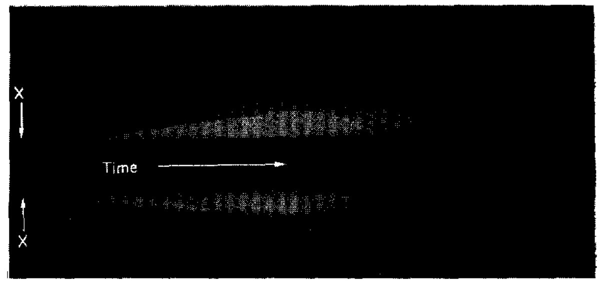

FIG. 4. Wave speed pictures taken using a horizontal slit 40.25 mm long. Primary shock speed = 1.357 mm/μsec, p_0 = 19.55 Torr, and T_0 = 509.7 °K. (a) A normal view and (b) an oblique view at an angle of 15° from the normal to the side wall. Time scale is identical for (a) and (b).

gradient in the air as long as the air pressure is kept high. When mixing mercury and other gases, another small metal container within the furnace is employed temporarily to keep premixed nonmercuric gases (prepared outside) at an appropriate pressure. After the mercury gas is introduced into the tube, the mixture in the container is released into the tube and the final total pressure is measured with the bellows gauge. The concentration of each component is thus accurately determined.

III. PERFORMANCE

Many shocks in mercury gas have been generated and observed, their shock Mach numbers ranging from 4 to 16 and the ambient temperature varying from 473.2 to 593.2°K. The pressure ratios p_1/p_0, across the primary shock front obtained for initial pressure ratios p_c/p_0, before firing, are shown in Fig. 3 for the two driver gases hydrogen and helium. The theoretically predicted relations are also plotted. The familiar disagreement between theoretical and experimental values is attributed to the opening of the diaphragm not being abrupt enough to establish a well-defined pressure discontinuity and to the shock attenuation while moving downstream due to boundary-layer growth. The latter is confirmed when two different lengths of the expansion tube were used; the results are presented in the figure by the different symbols.

Figure 4(a) shows wave speed pictures of the primary and reflected shocks. It should be noted that the point on the end wall where the primary shock terminates and the point where the strong luminosity due to the reflected shock begins do not coincide. But, when an additive such as tetramethylsilane is used (less than 0.06%), a wave speed picture shows the sharp luminosity beginning at the position of the primary shock front. In Fig. 4(a), since no tetramethylsilane was used and since the tube was baked extensively, no luminous line is seen. A generally bright region follows the shock front some time later, and the delay is considered to be the ionizational relaxation[1] of the shocked mercury gas. The measured relaxation time is of the order of 1–100 μsec for shocks dealt with thus far. One other notable point is that the time-resolved mercury spectrum shows no radiation overshoot, an effect which is frequently present in luminous shock-tube experiments due to the presence of many different electron donors as impurities in the tube during the relaxing period. The spectral intensity rises monotonically to reach a plateau.

A close examination of Fig. 4(a) seems to show two reflected shocks, which we should like to explain as a bifurcation effect. Figure 4(b) (space direction reversed!) is a wave speed picture taken not at right angles to the flow, but at an angle of 15° from the normal. In Fig. 4(a) the spreading legs of the bifurcated shock on the side wall can be seen apparently as two reflected shocks, while in Fig. 4(b) the diminishing size of the main or normal reflected shock shows up clearly as a diminishing bright triangle. This shock disappears completely even before the encounter with the interface. This explanation is consistent with the fact that many mercury lines are strongly reversed in this region, indicating that the forked portion of the reflected shock has a more complicated structure than the simple discontinuity and that the flow behind this forked portion is possibly even turbulent. Furthermore, it implies that the flow behind the primary shock has a growing boundary layer, growing much faster than expected in the monatomic gas, and this in turn agrees well with the observation that, in the time trace of the spectral intensity in the strong primary shock region, the intensity plateau reached after the relaxation period is maintained briefly and then deteriorates rapidly.

Different tests have been made in order of pinpoint the possible cause of bifurcation. It was learned that the length of the expansion tube plays no significant role and neither do the initial pressures. The roughness of the inner surface of the test section and the geometry of the test window mounting seem to be somewhat responsible, but only to a limited extent. However, it has been found possible to remove the bifurcation by either going to weaker shocks in pure mercury gas or diluting the mercury gas with an inert gas such as neon. What this amounts to is that the bifurcation in the monatomic gas of mercury, which is novel in itself,[9] is dependent indirectly on the equilibrium temperature of the flow behind the primary shock mainly through the ionization of the shocked gas.

For shock Mach numbers greater than 6.5 the reflected shock speed never exceeded 20% of the primary shock speed, owing to the strong ionization in this region and the energy loss to the end wall as expected. The empirical observation with other gases that for a given ratio p_c/p_0 a larger reflected region is attained the greater the pressure p_0 is not realized in the case of mercury because in most cases the significant range of the reflected shock is limited by the bifurcation independently of p_0, rather than being limited by the interface arrival. For the same reason no distinctive re-reflected shock at the interface is observed in the instances of strongly bifurcated shocks.

The problems where studies have either been completed or are currently underway utilizing the heated shock tube, are the following: the ionizational relaxation in mercury plasmas, the measurement of *gf* values of neutral mercury lines by means of the technique of curves of growth, the shock bifurcation in monatomic gases and its theoretical model, and the spectral line broadening in optically thick plasmas.

ACKNOWLEDGMENT

Financial support of this work by the United States Air Force Office of Scientific Research is acknowledged.

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[9] The reflected shock bifurcation in polyatomic gases had been observed earlier by many investigators. See H. Mark, Ph.D. thesis, Cornell University (1957); R. A. Strehlow and A. Cohen, J. Chem. Phys. **28**, 983 (1958); S. Byron and N. Rott, in *Proceedings of the 1961 Heat Transfer and Fluid Mechanics Institute* (Stanford University Press, Stanford, California, 1961), p. 38. Also refer to L. Davies and J. L. Wilson, Phys. Fluids Suppl. **12**, I-37 (1969).