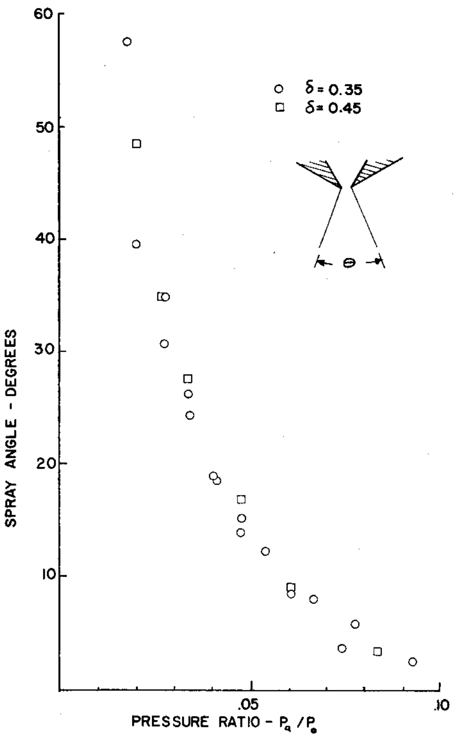

Fig. 3 Spray angle.

free expansion of a gas.[5] The jet exits at a pressure above ambient, expands to a pressure below ambient and contracts to recover the initial exit pressure. The process is then repeated giving the periodic jet boundary until the jet is dissipated.

As the pressure ratio across the jet is increased, the spray mode reported in Ref. 1 develops. The angle of the spray is quite sensitive to pressure ratio as shown in Fig. 3. Data for other nozzles and other concentrations show similar trends. At higher concentrations a secondary flow develops with the spray (see Fig. 1). This appears to be a thin fluid layer which separates at the edge of the nozzle and is sometimes entrained downstream in the spray.

Breakup occurred over a range of pressure ratios and was difficult to reproduce partially due to mechanical factors, i.e., nozzle configuration, vibration, etc. No detailed quantitative measurements of breakup were attempted. Tangren et al. have suggested that the jet is disrupted by the rapid expansion of the jet downstream of the nozzle. This explanation appears to be quite reasonable in view of the present experiment since breakup can be prevented by using a liquid of higher viscosity than water. Presumably the bubble expansion is less violent in the more viscous glycerine. We have further observed that some of the continuous jet structure remains even while the spray is developing. The jet structure for pressure ratios of $P_a/P_o = 0.11$ and 0.06 show this effect.

References

[1] Tangren, R. F., Dodge, C. H., and Seifert, H. S., "Compressibility Effects in Two Phase Flow," *Journal of Applied Physics*, Vol. 20, No. 7, July 1949, pp. 637–645.

[2] Campbell, I. J. and Pitcher, A. S., "Shock Waves in a Liquid Containing Gas Bubbles," *Proceedings of the Royal Society*, Ser. A, Vol. 243, Feb. 1958, pp. 534–545.

[3] Muir, J. F. and Eichorn, R., "Compressible Flow of an Air-Water Mixture Through a Vertical, Two-Dimensional Converging-Diverging Nozzle," FLD-10, March 1963, Dept. of Mechanical Engineering, Princeton Univ., Princeton, N. J.

[4] Eddington, R. B., "Investigation of Supersonic Phenomena in a Two-Phase (Liquid-Gas) Tunnel," *AIAA Journal*, Vol. 8, No. 1, Jan. 1970, pp. 65–74.

[5] Adamson, T. C., Jr. and Nicholls, J. A., "On the Structure of Jets From Highly Underexpanded Nozzles Into Still Air," *Journal of the Aerospace Sciences*, Vol. 26, No. 1, Jan. 1959, pp. 16–24.

A High-Performance Shock Tube with Air Driver

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To produce shock waves in a shock tube with Mach numbers of the order of 10 in air, it is usual to employ as driver gas either hydrogen, or a combustible mixture of oxygen and hydrogen diluted by helium. However, the use of air offers advantages. For example, in shock tunnel operation this would render the consequences of contamination of the test gas by driver gas less serious than they are in present high performance facilities,[1] while in shock tube operation it offers improved safety and economy.

The experiments reported here were associated with development of a shock tube for use in a university undergraduate laboratory. The purpose was to achieve shock speeds which would allow experiments involving substantial real gas effects, in a facility which would be both safe and economical when operated by undergraduate students. The facility is shown schematically in Fig. 1. Essentially, it is a double diaphragm or "buffered" free piston shock tube.[2,3] The free piston driver, shown in Fig. 1a, consists of a compression tube 1.98 m long and 80.5 mm in diameter, together with a piston driver reservoir 1.0 m long and of the same diameter. The primary diaphragm was located at the downstream end of the compression tube, and was followed by an intermediate shock tube 38 mm in diameter and 0.83 m long. The intermediate tube terminated at a flanged mount for the secondary diaphragm, and was followed by a test shock tube 38 mm in diameter and 2.75 m long. This opened into a dump tank at the downstream end.

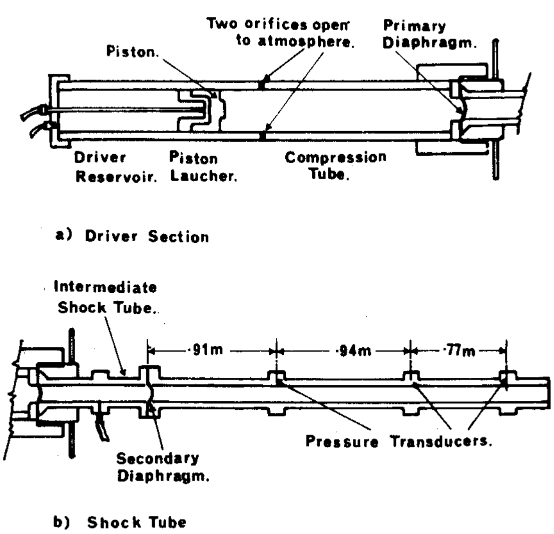

Fig. 1 Schematic general arrangement of shock tube facility.

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In all tests, the compression tube was initially filled with air at 1 atm, and a piston driver reservoir pressure of 40 atm was used. A test was initiated by releasing the piston from the launcher, whereupon it was driven rapidly along the compression tube, compressing the air in the tube until it reached a pressure such that the primary diaphragm ruptured. This diaphragm, which was made of mild steel, ruptured under static hydraulic tests at a pressure of 250 atm. Taking this as the rupture pressure under the conditions of the experiments, and assuming isentropic compression of the driver gas in the compression tube, it follows that the temperature of driver gas at rupture was 1400°K. Rupture of the primary diaphragm caused a shock wave to traverse the intermediate shock tube and reflect from the secondary diaphragm. This was made of aluminium, 1.27 mm thick, and was scribed to a depth of approximately 0.35 mm. Upon reflection of the shock wave this diaphragm would begin to yield. The process of yield prior to opening of the diaphragm was of time duration sufficient to allow formation of a quiescent slug of shock heated air adjacent to the diaphragm, and this acted as the driver gas for the test shock tube.

Shock speeds in the test shock tube were measured using three piezoelectric pressure transducers, which were manufactured in the laboratory and mounted with careful attention to requirements of vibration isolation. The transducers were located as shown in Fig. 1b, and their output was displayed on a Solarton CD1400 C.R.O., with precalibrated sweep. Initial shock tube pressures were read using a mercury manometer, with a micrometer screw reading attachment. The optimum initial pressure in the intermediate tube was determined by performing a series of tests with an initial pressure of 1 torr in the test shock tube, It was found that maximum shock speeds were achieved with an intermediate tube pressure of 0.56 atm, and this was used in all subsequent tests.

Shock speeds in the test shock tube were measured over a range of initial tube pressures. Results obtained for the shock speed between the two downstream timing stations are displayed in Fig. 2, where it can be seen that shock Mach numbers of 13 have been achieved. Shock attenuation varied with shock speed. For example, at $M_S = 6$ the shock decelerated by approximately 8%/m, at $M_S = 10$ no change in speed was observed, and at $M_S = 13$ the shock accelerated by approximately 5%/m.

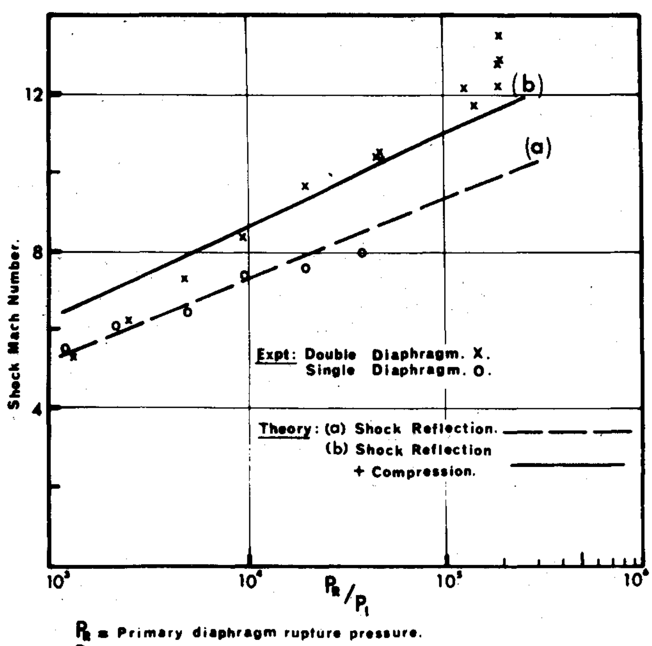

Fig. 2 Measured shock speeds in air.

The benefit conferred through use of the secondary diaphragm is illustrated in Fig. 2., by comparing the shock speeds plotted with those obtained in the absence of this diaphragm. It can be seen that at high shock speeds a gain exceeding 30% was achieved. Using the initial intermediate tube pressure employed in the tests, and shock speeds measured without the secondary diaphragm, it was calculated that a pressure of 79 atm and an ideal gas temperature of 2700°K would be reached in shock reflection from the secondary diaphragm. Assuming ideal gas behavior in the subsequent unsteady expansion of the shock heated gas, the shock speeds indicated by the theoretical curve (a), in Fig. 2, were obtained. These underestimate the measured values. However, calculations which were made by allowing isentropic compression to twice the shock reflection pressure before subsequent unsteady expansion in the shock tube produced the curve (b) in Fig. 2. Noting that the shock wave decelerated at low speeds, and accelerated at high speeds, it is clear that curve (b) provides reasonable estimates of the mean value of the shock speed over the length of the shock tube. Thus, the results suggest that compression subsequent to shock reflection in the gas in the intermediate tube plays a role in producing the high shock speeds measured.

The experiments reported show that strong shock waves can be produced with safety and economy by using a free piston shock tube with air as driver gas.

References

[1] Copper, J. A., Miller, H. R., and Hameetman, F. J., "Correlation of Uncontaminated Test Durations in Shock Tunnels," *Proceedings of the Fourth Hypervelocity Techniques Symposium*, Univ. of Denver, Denver, Colo., 1964, pp. 274–310.

[2] Stalker, R. J., "The Free-Piston Shock Tube," *Aeronautical Quarterly*, Vol. 17, Pt. 4, Nov. 1966, pp. 351–370.

[3] Stalker, R. J. and Plumb, D. L., "Diaphragm-Type Shock Tube for High Shock Speeds," *Nature*, Vol. 218, May 1968, pp. 789–790.

A New Assumed Stress Hybrid Finite Element Model for Solid Continua

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Introduction

IT is comparatively recent that several finite element models were formulated from different variational principles of solid mechanics, and their modifications, by systematically relaxing the continuity requirements at the interelement boundaries of adjoining discrete elements. A systematic classification of such finite-element methods is given by Pian and Tong,[1] and the author.[2] The commonly used assumed displacement models satisfy the requirements of interelement displacement field continuity and the rigid-body mode representation to various degrees; however, the strain and stress fields are discontinuous across the interelement boundaries. Tong[3] constructed a finite-element model, wherein an arbitrary smooth displacement field is assumed in the interior, and the interelement displacement compatibility is satisfied in the average by prescribing an independent compatible element-boundary displacement field and choosing an arbitrary set of boundary tractions as Lagrangian multipliers. In this

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