Preliminary Results with a Free Piston Shock Tunnel

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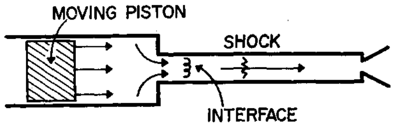
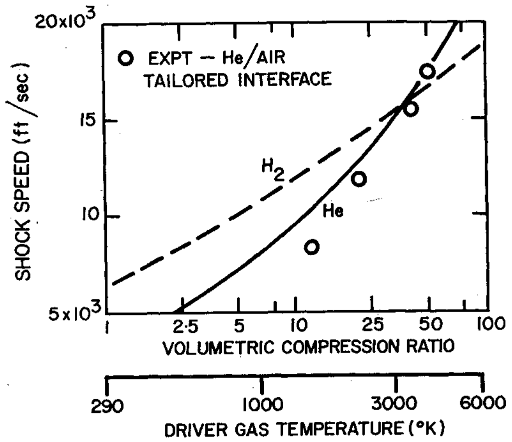
ONE widely used means of studying high-velocity gas flows is the shock tunnel, which involves a hypersonic nozzle supplied with test gas heated in a shock tube. The speed of the shock in the tube governs the nozzle stagnation enthalpy, and because present techniques limit this speed to about 11,000 fps, maximum enthalpies obtainable correspond to nozzle velocities of about 16,000 fps.

The free piston shock tunnel represents an attempt to increase these enthalpies by raising the shock speed. It derives from the free piston shock tube,[1] in which the shock is produced by a driver gas, initially contained in a large tube at relatively low pressure, which is isentropically heated and raised to high pressure by a single stroke of a relatively heavy free piston. The piston speed is sufficiently low that conditions are essentially uniform throughout the gas at any instant during compression. The shock tunnel modification is illustrated in Fig. 1a and is explained in detail in Ref. 2; only a brief description is given here. The shock tube diaphragm ruptures before the piston compression stroke is complete, at a moment when the piston velocity is such that subsequent movement of the piston face approximately compensates for the flow of gas from the driver volume into the shock tube. Provided that the area ratio of the driver compression tube to the shock tube is large enough to neglect the expansion wave generated in the driver by the bursting diaphragm, the driver conditions then remain approximately constant for a period, which is prolonged by the piston movement. This period is ultimately limited by the need to allow the piston to finally slow down and come to rest before striking the end of the tube. However, with a driver gas of $\gamma = 1.67$, it is theoretically possible to maintain the pressure constant to within 5% while half of the driver gas passes into the shock tube.



a) OPERATION



b) PERFORMANCE

Fig. 1 Free piston shock tunnel.

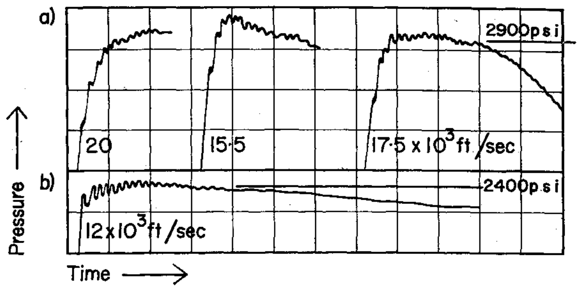


Fig. 2 Pressure vs time records (time scale 0.1 msec/division).

To avoid delay in establishing constant conditions in the test gas following reflection of the incident shock, it is desirable to eliminate reflection of disturbances from its interface with the driver gas, and so the shock tunnel is operated close to the "tailored interface" mode.[3] The driver gas temperature must therefore be matched to the shock speed, and since this temperature is determined by the degree of compression allowed before the diaphragm ruptures, there will be a particular volumetric compression ratio associated with each shock speed for a given driver gas. The theoretical variation of shock speed with driver gas volumetric compression ratio for tailored interface operation in air is presented in Fig. 1b for helium and hydrogen as drivers. The increase in volumetric compression ratio with shock speed is clearly evident, and this has the important consequence that the period of constant driver pressure, and hence the test time available, must fall with increasing shock speed.

Figure 1b also shows results obtained, using helium driver gas, in a small free piston shock tunnel. This embodied a piston, 2 lb in mass, moving in a compression tube 5 ft long and 2 in. in diameter, with a shock tube 4.2 ft long and 0.5 in. in diameter. The pressure following shock reflection was measured with an SLM HPZ-14 quartz pressure transducer, located in the side of the shock tube 0.30 in. from the downstream end, with the sensitive element at the bottom of a cavity approximately 0.15 in. in diameter and 0.25 in. deep. Shock speeds were measured by platinum thin-film heat-transfer gages 11.5 in. and 24.5 in. from the same end, with their outputs displayed on a Tektronix 551 Oscilloscope. The "tailored" shock speed could be determined approximately in each case by obtaining pressure records, with identical driver conditions, over a range of speeds. A typical group is shown in Fig. 2a and displays behavior that is characteristic of operation near "tailored" conditions; that is, a fall in pressure immediately following shock reflection at the lowest speed and a rise at the highest speed. The shock speed at which pressure remains constant is the "tailored" value, and in Fig. 1b this is plotted against a compression ratio derived from the driver gas temperature, calculated by assuming isentropic compression from the initial helium pressure in the compression tube to the known bursting pressure of the shock tube diaphragm.

The results constitute a small-scale test of this method of generating high-temperature gas for supply to a shock tunnel nozzle. They confirm theoretical expectations in two important respects. The first, evident from the incident shock speeds shown in Fig 1b, is that high test section stagnation enthalpies may be anticipated; for instance, a shock speed of 17,500 fps should yield a value corresponding to a flow velocity of 25,000 fps. The second, demonstrated by the pressure records in Fig. 2 at 12,000 and 17,500 fps, is that although the stagnation pressure in the test gas can be held approximately constant for a period, which is expected to be sufficient to operate a hypersonic nozzle, this period does decrease with increasing shock speed.

Received January 22, 1965. The assistance of D. Hartas, who constructed the apparatus, is gratefully acknowledged.

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Radar Absorption Effect in Hypersonic Ballistic Ranges

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Musal and Blore[1] have recently proposed an explanation for the anomalously large decrease in radar cross section that occurs when ½-in. diam spheres are observed by 4- or 8-mm wavelength radars at velocities near 13,000 fps and pressures of 10 mm Hg. This decrease is anomalous in that the plasma sheath around the sphere is far too thin to cause enough real power absorption in the lossy plasma layer. The new explanation hinges on the diffractive effect of sharp angular gradients in the plasma sheath surrounding the sphere. Some comparisons between this new theory and experiment are presented here for two different bodies and range conditions using General Motors Defense Research Laboratories (GM DRL) data.[2]

It can be shown,[1] using the techniques of physical optics, that the radar cross section of a metal sphere covered by a thin plasma layer is

$$\frac{\sigma}{\lambda^2} = \frac{\pi^3 a^2}{4\lambda^2}\left|\int_0^{4a/\lambda} (\Gamma_{TM} - \Gamma_{TE}) \times \left(1 - \frac{\lambda\chi}{4a}\right) e^{j(4\pi h/\lambda)}\, e^{-j\pi\chi[1+(h/a)]}\, d\chi\right|^2$$

where Γ_{TM} and Γ_{TE} are the *TM* and *TE* mode-reflection coefficients for a metal-backed plasma layer, given by

$$\Gamma_{TM} = \frac{\Gamma_{pTM} + e^z}{1 + \Gamma_{pTM}e^z} \qquad \Gamma_{TE} = \frac{\Gamma_{pTE} - e^z}{1 - \Gamma_{pTE}e^z}$$

$$\Gamma_{pTM} = \frac{[1 - \Omega_p{}^2/(1 - j\Omega_c)](1 - \chi\lambda/4a) - [(1 - \chi\lambda/4a)^2 - \Omega_p{}^2/(1 - j\Omega_c)]^{1/2}}{[1 - \Omega_p{}^2/(1 - j\Omega_c)](1 - \chi\lambda/4a] + [(1 - \chi\lambda/4a)^2 - \Omega_p{}^2/(1 - j\Omega_c)]^{1/2}}$$

$$\Gamma_{pTE} = \frac{(1 - \chi\lambda/4a) - [(1 - \chi\lambda/4a)^2 - \Omega_p{}^2/(1 - j\Omega_c)]^{1/2}}{(1 - \chi\lambda/4a) + [(1 - \chi\lambda/4a)^2 - \Omega_p{}^2/(1 - j\Omega_c)]^{1/2}}$$

and z is given by

$$z = -j(4\pi h/\lambda)[(1 - \chi\lambda/4a)^2 - \Omega_p{}^2/(1 - j\Omega_c)]^{1/2}$$

and λ is the radar wavelength, a is the radius of the sphere, and h is the thickness of plasma layer. The plasma properties are given by the normalized plasma frequency Ω_p and the normalized electron collision frequency Ω_c, which are

$$\Omega_p = \omega_p/\omega = (1/\omega)(q^2N/\epsilon m)^{1/2} \qquad \Omega_c = \nu_c/\omega$$

where ω is the radar angular frequency ($2\pi f$), ν_c is the electron collision frequency, ω_p is the plasma frequency, q is the electric charge carried by an electron and m is its mass, N is the electron number density, and ϵ is the capacitivity of free space. In the simplified case where the reflection coefficients of the layer are not functions of the angle of incidence, the preceding integral can be explicitly evaluated in closed form. The more interesting case of a plasma layer around a hypersonic sphere must be evaluated by numerical integration. In its present form, this equation can handle only angular plasma gradients, and radially nonuniform plasmas must be approximated by some equivalent "average" radially uniform plasma. The more general case is currently under development. Also, because of the physical optics assumptions used in its derivation the preceding equation is most accurate for large blunt bodies which have an angular plasma coverage of less than one radian.

The appropriate plasma parameters for each set of experimental results have been obtained either from the Cornell nonequilibrium bow shock program[3] or the GM DRL equilibrium flow codes,[4] appropriately modified to map streamline space into body-related shock space using the streamline-pressure relationships given in Gravolos[5] et al. For computation purposes, the actual flow fields were approximated as follows. The thickness of the plasma layer was taken to be the thickness of the overdense region of the plasma sheath around the body. The electron density and collision frequency within this overdense region were taken to be the values which existed in the stagnation region for the speed and ambient pressure considered. In order to obtain the dependence of the radar cross section on body speed, the way in which this overdense region thickens and spreads over the body as a function of speed was approximated by interpolation between sets of flow field calculations for various velocities. Using this approach, the radar cross section was calculated as a function of velocity for the ambient pressures used in the various ballistic range studies. The theoretical results are shown in Fig. 1, along with the experimental data for a 13-mm radius sphere at 10 mm Hg pressure. It can be seen that a large decrease in the radar cross section, of the order of 15 db, is obtained with the new theory. Previous theories gave approximately 3 db of absorption under these conditions. Figure 2 shows the same comparison for a

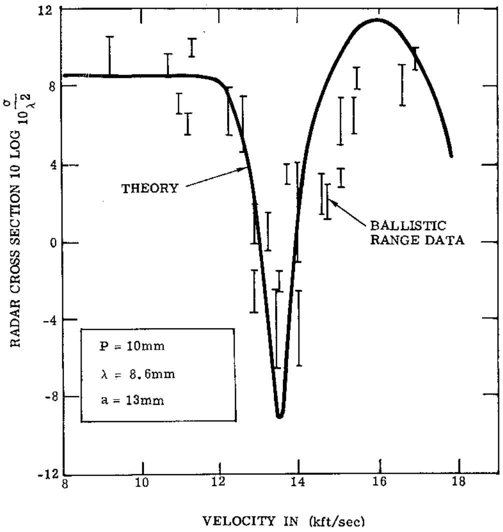

Fig. 1 **Comparison between theory and experiment for the backscattering radar cross section of 13-mm radius sphere observed in a hypersonic ballistic range at 10-mm-Hg pressure vs velocity.**

Received January 15, 1965. Part of the work described in this paper was sponsored by the Advanced Research Projects Agency, Department of Defense, U. S. Contract No. DA-04-495-ORD-3567(Z) as part of project Defender. Related corporation-funded research conducted at General Motors Defense Research Laboratories is also described.

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