Starting Process in the Nozzle of a Nonreflected Shock Tunnel

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Theme

RECENT experiments have shown that high performance shock tubes will produce flow speeds of 20 km sec^{-1}. If these shock tubes could be operated as nonreflected shock tunnels, hypersonic flows could be generated at stagnation enthalpies corresponding to speeds exceeding 20 km sec^{-1}.

Test times in such shock tubes are only of the order of 10 μsec, indicating that test time losses occasioned by the nozzle starting process must be kept to a minimum. Furthermore, this must be done without using a diaphragm at the nozzle entrance, as the times available are not sufficient to allow removal of diaphragm fragments from the flow. By using an approximate analysis of the nozzle starting process, together with experiments in a small free piston shock tunnel, it is shown that these conditions are satisfied by establishing steady supersonic flow in the nozzle prior to arrival of the primary shock wave.

Contents

Following the concepts summarized in a paper by Smith,[1] the nozzle starting process in a nonreflected shock tunnel can be represented on a wave diagram as in Fig. 1. Here u is the steady test gas flow velocity at station x, a is the associated speed of sound, U is the maximum steady flow velocity in the test gas, and z is the distance of the starting shock system from the origin at time t. The "resident" gas is the gas which is initially in the nozzle. On passing into this gas, the primary shock wave becomes the "principal starting shock" (P.S.S.). It is followed by a "secondary starting shock" (S.S.S.) which moves upstream in the test gas, but downstream in the laboratory frame of reference. To ensure minimum starting times, it is necessary to arrange that the secondary starting shock remains downstream of the upstream head of an unsteady expansion, which propagates into the steady flow.

For an approximate analysis of the trajectory of the secondary starting shock, the starting shock system can be regarded as a thin layer. At any station z, the momentum gained by the resident gas which has been swept up by this shock layer may be balanced against the momentum lost by the test gas which has passed into the shock layer through the secondary starting shock. If the impulse of the pressure difference across the layer is ignored, the resulting equation can be evaluated by assuming that $u = U$, and that the mass flow in the unsteady expansion is equal to the steady flow value. For large nozzle area ratios, this leads to the expression

$$(\Delta\tau)^2 = 2(U\dot{m}_e)^{-1}\int_0^z\int_0^{x=z}\rho(x)A(x)\,dx\,dz \qquad (1)$$

where $\Delta\tau$ is the delay in establishing steady flow at station z, arising from the passage of the starting shock system (see Fig. 1c), $\dot{m}_e$ is the mass flow of test gas at the entrance to the nozzle, $\rho(x)$ is the initial density of the resident gas at station x, and $A(x)$ is the associated nozzle area.

For the case where the initial density of resident gas is uniform throughout the nozzle, the integral in Eq. (1) shows that $\Delta\tau$ increases with increasing nozzle area. In fact, estimates made for cases in which there is no diaphragm at the nozzle entrance indicate that, for the large area ratios which are required for generation of hypersonic flow, the nozzle will not start within an acceptable time period.

However, if steady flow is established in the resident gas prior to arrival of the primary shock wave, then $\rho(x)A(x) = \text{const}$, and Eq. (1) yields the solution

$$\Delta\tau\, U/z = \{\rho_1{}^*a_1{}^*U/\rho_2 U_1 u_2\}^{1/2} \qquad (2)$$

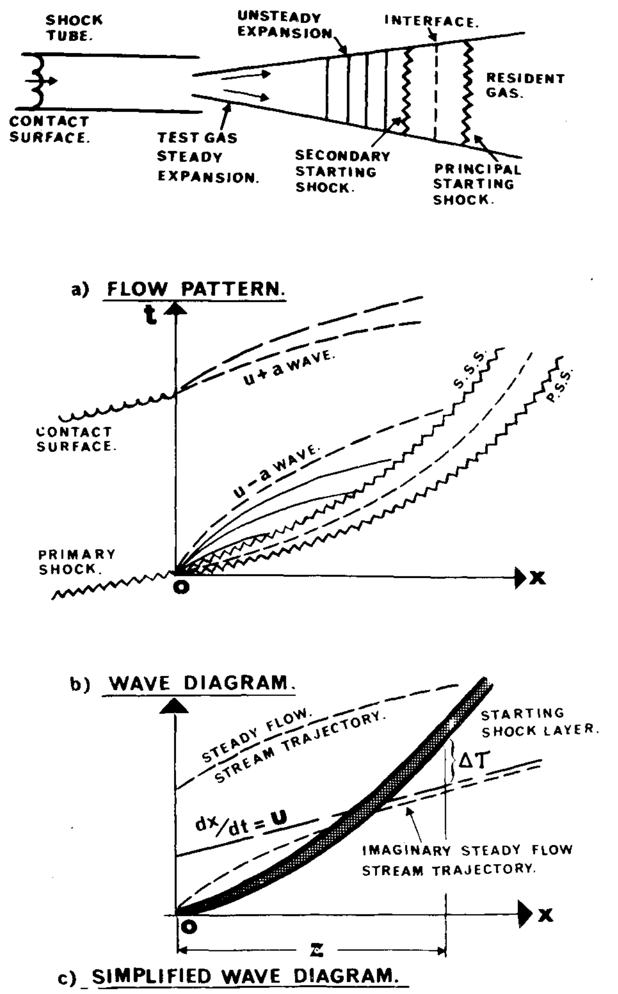

Fig. 1 Nozzle starting process.

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Index categories: Nozzle and Channel Flow; Research Facilities and Instrumentation.

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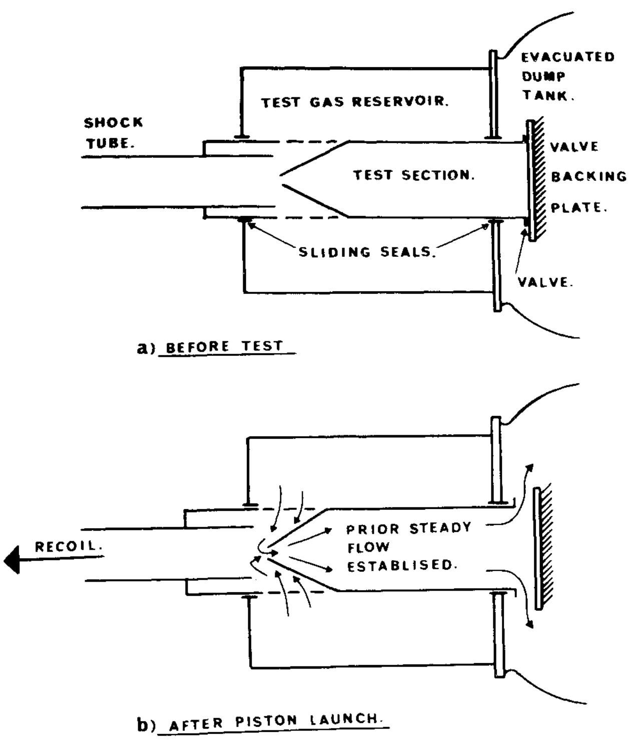

Fig. 2 Establishing prior steady flow.

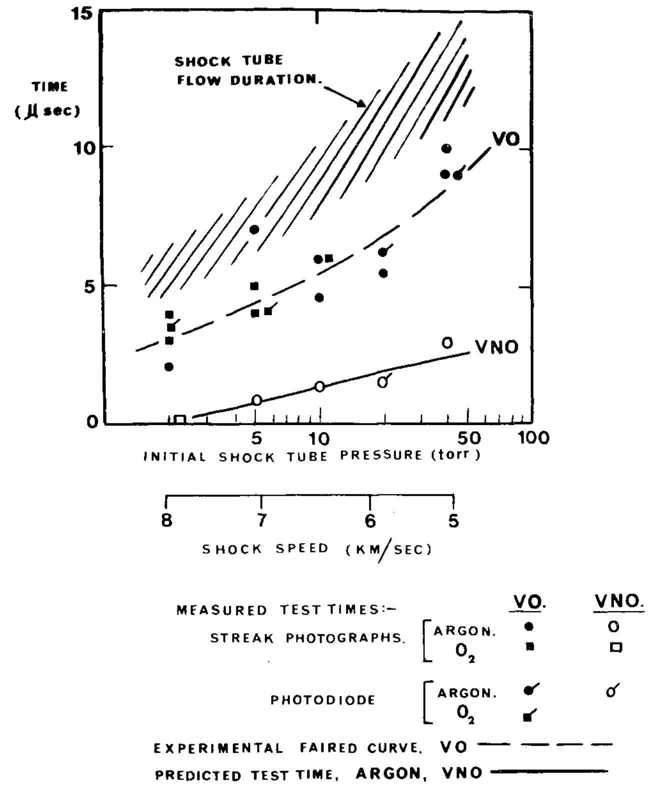

Fig. 3 Effect of prior steady flow on test time. (VO = valve operating; VNO = valve not operating.)

where U_1 is the maximum velocity in the prior steady flow of resident gas, ρ_1* and a_1* are the corresponding density, and speed of sound, at the nozzle entrance (minimum cross section of the prior steady flow), and ρ_2 and u_2 are the density and velocity behind the primary shock wave. As the nozzle area ratio does not appear in this equation, the delay due to passage of the starting shock system is independent of the hypersonic test section Mach number.

By taking examples, it can be shown from Eq. (2) that the minimum test time loss due to nozzle starting is achieved with a prior steady flow. Also, for a nozzle of length not too much greater than the distance between the primary shock and the contact surface, adequate test time is expected to remain after the starting process is complete.

The mechanism used to establish the prior steady flow is a matter of convenience. In the present case, a small free piston shock tunnel[2] was available for the experiments, and was fitted with a valve downstream of the test section. As illustrated in Fig. 2, this was opened by recoil of the compression tube-shock tube assembly when the piston was launched. Launching of the piston preceded rupture of the shock tube main diaphragm by the time required for the piston to traverse the length of the compression tube, and this allowed the prior steady flow to become established well before the primary shock wave arrived at the nozzle.

A two-dimensional nozzle was used, which was 19 mm wide. It was formed of two steel wedges, which were 3.2 mm apart at the nozzle entrance, and 38 mm at the test section. The test gas reservoir was 7.5 litres in volume, which was sufficient to ensure that the prior steady flow did not significantly reduce the initial test gas pressure in the shock tube. The shock tube was 2.1 m long, and 22 mm diameter.

Luminosity photographs of the nozzle starting process were obtained with an STL image converter camera. Results were obtained with the valve operating, so that a prior steady flow was established, and with the valve not operating, in which case the intial gas density was constant throughout the nozzle and shock tube. Test times were measured from streak photographs, by using the trace of radiation from the stagnation point of a hemispherical model in the test section. These measurements were checked by monitoring the same radiation with a photodiode. The duration of the shock tube flow following the primary shock wave also was measured from the streak photographs.

Results obtained with argon and oxygen as test gases are shown in Fig. 3. For comparison with the approximate theory, a curve was fitted to the points obtained with the valve operating, and Eq. (1) was used to calculate the reduction of test time for argon when the valve was not operating. As shown in the figure, this yielded a curve which was consistent with the experiments.

The results indicate that the prior steady flow considerably increased the available test time at all shock speeds. They also confirm that, with a nozzle of approximately the same length as the "slug" of test gas following the primary shock wave, a major fraction of the available test time can be realized in the test section. Equation (2) indicates that this conclusion is essentially independent of shock speed, suggesting that experimental high enthalpy hypersonic flow studies may be performed with apparatus based on present high-performance shock tubes.

References

[1] Smith, C. E., "The Starting Process in a Hypersonic Nozzle," *Journal of Fluid Mechanics*, Vol. 24, April 1966, pp. 625–640.

[2] Stalker, R. J., "A Study of the Free-Piston Shock Tunnel," *AIAA Journal*, Vol. 5, Dec. 1967, pp. 2160–2165.