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Double-Diaphragm Shock Tube: Comparison between Theory and Experiment

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THE double-diaphragm shock-tube technique developed by Holbeche[1,2] is an ideal way to cool shock-heated gases and vapors rapidly. It has been used to study vibrational relaxation[1-4] and atomic recombination reactions,[5,6] and is also suitable for the study of homogeneous nucleation.

The usefulness of the technique, however, depends on knowing the flow properties throughout the region of interest. Treatments so far have assumed that shock reflection from the second diaphragm can be ignored. We describe a series of experiments performed to establish the presence of a reflected shock from the second diaphragm and give brief details of the theoretical analysis used to obtain flow properties.

The shock tube of 76 mm diameter (see Fig. 1) has been described elsewhere.[6] A scored aluminum disk and two sheets of 0.025 mm aluminum foil were used for primary and secondary diaphragms, respectively. Pressure was measured by Kistler piezoelectric pressure transducers mounted 80 mm upstream and 100 and 455 mm downstream from the secondary diaphragm. Light scattered at 90 deg from an argon ion laser beam (476.5 nm) was also recorded 455 mm downstream from the secondary diaphragm. In each run high-purity argon and nitrogen were used as test and driver gas, respectively.

Pressure measurements upstream from the secondary diaphragm indicate that shock reflection has occurred. A typical oscilloscope trace showing pressures upstream and downstream of the secondary diaphragm is given in Fig. 2. Previous analyses assumed no shock reflection. Inclusion of shock reflection in the flow analysis necessitates a full method of characteristics analysis, similar to that of Rudinger.[7]

In our analysis, the incident shock reflects from the secondary diaphragm (assumed planar) and travels back upstream into the test gas. At a later stage, the secondary diaphragm bursts instantaneously due to the increased pressure behind the reflected shock. A rarefaction wave is thus generated, the head of which travels upstream into the test gas; the tail travels downstream into the evacuated expansion section. The rarefaction wave head eventually catches up to the reflected shock front, and the resulting interaction causes the shock wave to decay.

Particle paths are constructed through the characteristics mesh so that gas properties at any point in time and space are known. In particular, gas temperature and pressure at the point where each path passes an observation position are calculated and theoretical pressure profiles thus obtained. The various features of the flow are shown in Fig. 1.

Comparison of experimental pressure traces with theoretical profiles where shock reflection has and has not been considered is made in Fig. 2. It may be seen that downstream of the secondary diaphragm both theoretical treatments fit the trace well apart from a timeshift (discussed later). However, upstream there is a marked difference—the arrival of the reflected shock front can clearly be seen in the experimental pressure trace.

In the analysis described above, the time between shock reflection and secondary diaphragm bursting (the bursting time) is not directly determinable. However, the time between the arrival of the incident and reflected shocks at the upstream window (Δt) is a function of bursting time. Bursting time can therefore be obtained by fitting a theoretical Δt value to the experimental value. It was found that bursting times were typically between 15 and 35 μs.

In each run it was possible to fit the downstream theoretical pressure profiles to the experimental trace by shifting it by times of between 60 and 180 μs. Profiles where shock reflection was and was not taken into account fitted the experimental data equally well. This time shift has been observed by a number of earlier workers.[1,2,6,8] Beck,[6] using the same apparatus, found time shifts of between 85 and 175 μs were necessary, while Nasser[8] needed about 45 μs to fit his data. In their study of water condensation in a driver expansion, Glass et al.[9] also found it necessary to shift their

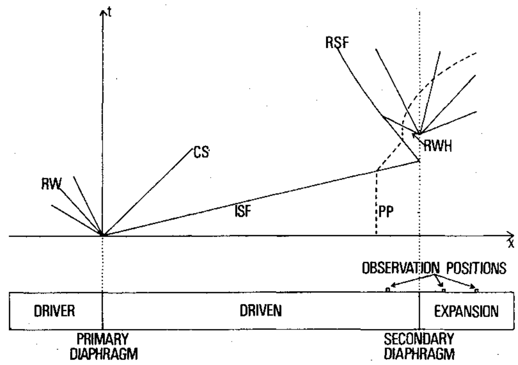

Fig. 1 Gas flow in double-diaphragm shock tube (incident (ISF) and reflected (RSF) shock fronts, contact surface (CS), rarefaction wave generated by rupture of primary diaphragm (RW), head of rarefaction wave generated by rupture of secondary diaphragm (RWH), and particle path (PP) are shown).

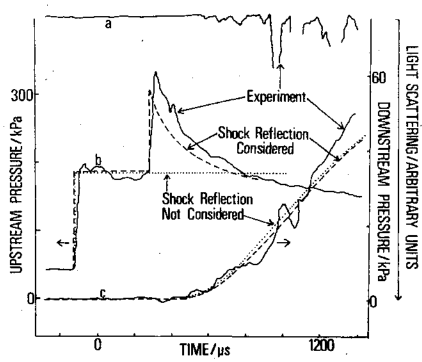

Fig. 2 Typical oscilloscope traces: a) light scattering, and pressure at b) upstream and c) downstream observation positions. Experimental pressure traces (——) are compared to theoretical profiles where shock reflection has (– – –) and has not (· · · · ·) been considered. (Time shift of 120 μs was made in theoretical downstream pressure profiles; zero in time corresponds to rupture of secondary diaphragm.)

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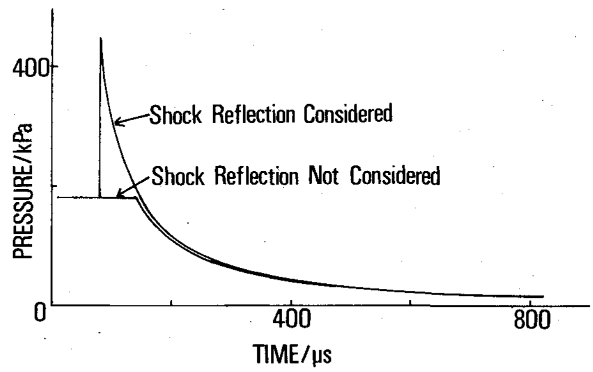

Fig. 3 Pressure changes along particle path where shock reflection has and has not been considered (zero in time corresponds to rupture of secondary diaphragm).

theoretical profiles to fit their experimental traces. This time shift can be attributed to the finite opening time of the diaphragm and a detailed investigation of this has been performed by Hall et al.[10] Experimental pressure traces at 100 and 455 mm downstream from the secondary diaphragm require the same time shifts to fit the corresponding theoretical profiles. This suggests that the model is least reliable during the earliest stages of expansion—the region where neglect of reflection gives completely incorrect results (see Fig. 3).

It is clear that our analysis adequately describes the important aspects of the flow, but it is appropriate to consider possible sources of error in the above treatment. The assumption of shock reflection from a plane surface does not allow for bulging of the secondary diaphragm caused by the pressure differential across it prior to rupture. It was found that aluminum foil diaphragms subjected to test gas pressures of about 40 kPa stretched to form a dome about 10 mm high. Assuming reflection to take place from a plane surface at the most stretched point of the diaphragm (i.e., 10 mm downstream) we found little effect on the computed pressure profiles. Errors in measuring Δt had negligible effect.

In using the double-diaphragm shock-tube technique it is necessary to know the period over which ideal flow occurs. The end of ideal flow may be caused by the arrival of the contact surface or reflected rarefaction head (generated by the driver expansion) or by the arrival of secondary-diaphragm fragments. The reflected rarefaction wave can be retarded so that it does not interfere with the flow by using a low-sound-speed driver gas such as nitrogen rather than the more usual hydrogen or helium. The arrival of diaphragm fragments, observed by light scattering (see Fig. 2) often coincides with the arrival of the contact surface.

Bursting times of secondary diaphragms are very dependent on the nature and thickness of the diaphragm material. For 0.009 mm thick aluminum foil the reflected shock had decayed completely before reaching the upstream window. Cellulose acetate film 0.17 mm thick gave reflected shock waves of long persistence. The apparent failure of others to observe shock reflection from the secondary diaphragm can now be explained by the occurrence of shock decay before arrival at the pressure measuring station.

The importance of taking into account shock reflection can best be seen in Fig. 3. The pressure change along the particle path reaching the downstream position at a given time is plotted for cases where shock reflection is and is not considered. It can be seen that the major differences occur immediately behind the reflected shock front and that for most of the expansion the rate of change of pressure is roughly the same.

We conclude, therefore, that shock reflection does occur. Agreement between pressure traces measured downstream from the secondary diaphragm and theoretical profiles in which shock reflection has not been considered cannot be taken as evidence that shock reflection is insignificant. Pressure measurements upstream from the secondary diaphragm need to be made. The omission of shock reflection from analyses can lead to serious inaccuracies in the earliest parts of the expansion where significant chemical or physical changes can occur at the much higher temperatures and pressures behind the reflected shock.

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Pressure-Coupled Response of Composite Solid Propellants

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Introduction

WITH the advent of standardized stability prediction codes[1] acquisition of adequate response function data has become a major impediment to routine inclusion of realistic linear stability analyses in the motor design process. This is a particularly difficult problem for motors destined for tactical applications.[2] A practical solution path is to employ results from combustion models to provide a framework for correlating data. This path has been pursued for composite propellants by employing both homogeneous and heterogeneous propellant models. (Reference 3 has recently reviewed response function theories that account for heterogeneity.) Limited success has been achieved as both models can correlate the available T-burner data about

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