THEORETICAL AND EXPERIMENTAL TEST TIMES AVAILABLE IN AN EXPANSION TUBE

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ABSTRACT

New theoretical bounds which are in good agreement with centreline pitot pressure measurements are obtained for the test time in an expansion tube. One-dimensional ideal inviscid gas relationships are used across shocks and unsteady expansions, and boundary layer entrainment effects are included to predict the driver-test gas interface trajectory. A greater understanding of the mechanisms which control the test time is obtained and used to widen the range of conditions at which an expansion tube will produce a steady flow.

INTRODUCTION

An expansion tube is an impulse hypersonic facility which can produce high enthalpy steady flows. A number of these facilities have been built, however, most have since been discarded as only a narrow window of test conditions for each test gas was ever obtained. This was in contrary to the then theoretical results which indicated that a large variety of test conditions were available.

The new analysis presented here explains the discrepancy between Trimpi's (1962) theoretical maximum test time and the test times observed in the University of Queensland's expansion tube (Morgan et.al. (1988)) and other facilities. This analysis explains why the window of steady test conditions is small and indicates how this window can be widened so as these facilities could be used for a variety of hypersonic research. In addition to the theoretical results, centreline pitot pressure measurements for an air test gas are also presented. Good agreement exists between experiment and theory.

GENERAL THEORY

An expansion tube consists of three sections; the driver, the shock tube and the acceleration tube, with the acceleration tube emptying unrestrictively into a dumptank-test section (see figure 1). Initially the three sections are separated by two diaphragms. The heavier of these is the primary diaphragm which resides between the driver and shock tube while the shock and acceleration tubes are initially separated by the secondary diaphragm. Ideally the secondary diaphragm is massless. The three regions are initially filled with the driver, test and acceleration gases, respectively.

If the driver gas pressure is increased and the primary diaphragm ruptures, a shock is produced which travels through the test gas towards the secondary diaphragm. It is assumed that this shock ruptures the secondary diaphragm without reflecting, instantaneously accelerates, then travels down the acceleration tube with constant velocity. The test gas follows the shock and accelerates through an unsteady expansion centred at the secondary diaphragm rupture point. The test time is the period of steady flow following the arrival of the test-acceleration gas interface at the test section.

Trimpi (1962) obtained a theoretical maximum test time by assuming the steady flow is terminated by the arrival of the unsteady expansion. This indeed gives an upper limit for the test time, however, the test time can be further limited by the reflection of the unsteady expansion off the driver-test gas interface (see figure 2).

The analysis presented here determines the theoretical arrival times of the unsteady expansion and the reflection of the unsteady expansion off the driver-test gas interface. To obtain a realistic limit on the test time an accurate estimation is required of the elapse time between the secondary diaphragm rupture and the intersection of the driver-test gas interface with the unsteady expansion's trailing edge. Mirels' (1964) boundary layer entrainment analysis is used to obtain this elapse time as ideal inviscid gas theory is inadequate.

UNSTEADY EXPANSION LIMITATIONS

The invariants along the characteristics

$$\frac{dx}{dt} = u \pm a \qquad (1)$$

for a one-dimensional flow of an ideal inviscid gas are $u \pm 2a/(\gamma+1)$, where u and a are respectively the gas and local sound speed. It follows that within an unsteady expansion

$$u = \frac{\gamma-1}{\gamma+1} u_3 + \frac{2}{\gamma+1}\left(a_3 + \frac{x}{t} \right) \qquad (2)$$

and

$$a = \frac{2}{\gamma+1} a_3 + \frac{\gamma-1}{\gamma+1}\left(u_3 - \frac{x}{t} \right) \qquad (3)$$

The origin of the (x,t) space is at the rupture of the secondary diaphragm and γ is the specific heat ratio (see figure 2 for numbered subscripts).

If the test time is limited by the unsteady expansion the test time, T, is the time elapsed between the arrival of the test-acceleration gas interface and the leading edge of the unsteady expansion. This interface and expansion have velocities u_5 and $u_5 - a_5$ respectively. Hence, the test time is

$$T = \frac{x_A a_5}{u_5(u_5 - a_5)} \quad (4)$$

where x_A is the acceleration tube length.

REFLECTED EXPANSION LIMITATIONS

If the test time is limited by the reflected expansion then the test time is determined analytically as a function of the elapse time, t_0, between secondary diaphragm rupture and the intersection of the driver-test gas interface and the unsteady expansion's trailing edge. Within the expansion the characteristic curve which marks the leading edge of the reflected expansion is obtained from integration of equation 1+ with u and a given by equations 2 and 3 respectively. The intersection of this trajectory and the expansions leading edge gives the time for the front of the reflected expansions to emerge from the expansion as

$$t_1 = t_0\left(\frac{a_5}{a_3}\right)^{\frac{\gamma+1}{2(1-\gamma)}} \quad (4)$$

The reflected expansion front then travels in the simple region ahead of the expansion with constant velocity $u_5 + a_5$ until it strikes the test section or the test-acceleration interface. In the later case there is no test time, otherwise the test time is

$$T = \frac{a_5}{u_5 + a_5}\left(2t_1 - \frac{x_A}{u_5}\right) \quad (5)$$

The relationships between the conditions in the different regions of figure 2 are determined assuming the flow is one-dimensional, ideal and inviscid (see Liepmann et.al. (1967)).

BOUNDARY LAYER ENTRAINMENT

The boundary layer behind the shock acts as a mass sink and accelerates the driver-test gas interface towards the shock (Mirels (1964)).

If the product of the shock tube filling pressure, P_4, and the shock tube inside diameter, d, is greater than 0.17 m.kPa then turbulent boundary layer theory is applicable. In the experiments reported here $3.7 > P_4 d > 0.11$ m.kPa. In the test time predictions made here Mirels (1964) ideal gas analysis for turbulent boundary layers has been used to predict t_0 (see Paull (1989)).

RESULTS AND DISCUSSIONS

In this section theoretical results are compared with experiments in which centreline pitot pressure measurements were recorded. The following four parameters were varied; (i) the shock tube filling pressure, (ii) the acceleration tube filling pressure, (iii) the primary diaphragm rupture pressure and (iv) the driver gas. Air test and acceleration gases and either helium or argon driver gases were used. The temperature of the driver gas was increased above ambient by using a free piston driver, and the test and acceleration gases were initially at room temperature.

Acceleration Tube Filling Pressure Dependence

Figure 3 displays the theoretical variation of test time with acceleration tube filling pressure, P_7, where the primary diaphragm rupture pressure, P_0, is 34.5 Mpa, the driver gas (argon) is compressed to a volumetric compression ratio, λ, of 28 and the shock tube filling pressure, P_4, is 3.4 kPa. Figures 4a-4d are the corresponding experimental results. The shaded region in figure 3 represents the available test time and the cross hatched region covers the additional test times which may be expected had the reflected expansion been ignored. It can be seen from figure 3 that at the lower filing pressures (P_7<11 Pa) the test time is terminated by the unsteady expansion. However, at higher filling pressures the test time is limited by the reflected expansion. Furthermore, test time decreases, and is eventually zero, as the acceleration tube filling pressure is increased. In contrast, predictions which ignored the reflected expansion predict an increase in test time with an increase in P_7. It can be seen that the intrusion of the reflected expansion leaves only a very narrow window of acceptable test time.

From figure 4b it is observed experimentally that after the initial shock and test-acceleration gas interface the pressure remains constant for approximately 100 μs and then fluctuates about a rising mean. From figures 4b-4d it can be seen that these fluctuations arrive earlier as P_7 is increased. It can also be seen that there is good agreement between predicted arrival times of the reflected expansion and measured arrival times of this disturbance. It is concluded that this disturbance is the reflected expansion.

Figure 4a has different characteristics to 4b-4d. Subsequent to a very short test time a more pronounced and more steady pressure rise is followed by the rapidly fluctuating disturbance seen at larger P_7 (the reflected expansion). This is consistent with predictions for this acceleration tube filling pressure as a steady pressure rise associated with the unsteady expansion should indeed arrive before the reflected expansion.

The reflected expansion has a higher frequency disturbance superimposed on its pressure rise than the unsteady expansion because the characteristics for the reflected expansion pass through the expansion. Hence, any disturbance which exists in the expansion would be reflected off the driver-test gas interface and then would experience additional modifications by other disturbances encountered in the expansion, and thus produce more erratic flow.

Shock Tube Filling Pressure Dependence

A series of experiments have been done in which only the shock tube filling pressure was varied. The driver was helium with P_0=34.5 MPa , λ=29 and P_7= 16 Pa. Figures 7a-7d are the pitot pressure records and figure 6 displays the predicted projectories of the unsteady expansion and the reflected unsteady expansion as a function of shock tube filling pressure. Time t=0 is the arrival of the test-acceleration gas interface at the test section.

It is predicted that at the lower values of P_4 the test time is terminated by the reflected expansion and as P_4 is increased test time is limited by the unsteady expansion and remains approximately constant for all values of P_4 considered here.

From figures 7a-7d it can be seen that these trends are measured experimentally. For P_4=3.5 kPa the pitot record shows an initial steady period which is terminated by a disturbance which is characteristic of a reflected expansion and for P_4= 7 kPa or 27.6 kPa the initial steady period is terminated by a steady rising trace:- the unsteady expansion. At these conditions the disturbances superimposed on the unsteady expansion are relatively small, however, at P_4= 101 kPa the disturbances are significant and have lower frequency. It can be seen that this new disturbance does not significantly alter the test time at these conditions, however, it is important to note that additional results of Morgan et.al.(1988) show that this disturbance prematurely terminates the test period at higher acceleration tube filling pressures. The source of this new disturbance is not understood at this stage.

Test Time Contours

Figure 8 displays test times as a function of shock tube shock speed and acceleration tube filling pressure for a helium driver, P_0=34.5 MPa, λ=29. At high enthalpy conditions these theoretical results are consistent with the experimental results of Morgan et.al.(1988) where the shock and acceleration tube filling pressures where systematically varied. At lower enthalpies the new disturbance discussed above prematurely terminates the predicted test time.

Pressure Scaling

The x-t diagram for an ideal gas (figure 2) is dependent only upon
(i) the ratio of the primary diaphragm burst pressure to the shock tube filling pressure,
(ii) the ratio of the shock tube filling pressure to the acceleration tube filling pressure and
(iii) and the driver, test and acceleration gas sound speeds when the primary diaphragm ruptures.
The x-t diagram does not dependent upon the actual pressure levels. Hence, for an ideal gas, the test static pressure may be changed without altering the test time by maintaining the above three quantities and changing the overall pressure levels. However, for a non-ideal gas, boundary layers exist and the quantity of core flow entrained by the boundary layer is pressure dependent and thus affects the trajectory of the driver-test gas interface. If the pressures are scaled and the overall pressure is decreased then the driver test gas interface is closer to the shock. Hence, if the test time is limited by the reflected expansion then the test time decreases as the filling pressures decrease. The separation of the interface and the shock approaches a maximum as the pressure increases, hence, the test time changes less when the pressure is scaled at higher pressures. Fortunately, the dependence of t_0 on the scaled pressures is generally small, thus the test time is relatively unaffected by pressure scaling.

Figures 5a-5d display the experimental results when filling pressures are scaled.

CONCLUSIONS

Ideal gas theory can be used to give a good estimate for test time if the effects of boundary layer entrainment are included in the driver-test gas trajectory predictions.

The test time is terminated by one of at least three disturbances:
(i) At low shock tube filling pressures the test time is limited by the unsteady expansion's reflection off the driver-test gas interface
(ii) At intermediate shock tube filling pressures the test time is limited by the unsteady expansion.
(iii) At high shock tube filling pressures the test time limited by another disturbance which is not fully understood.

Pressure scaling will effect the test time as boundary layer entrainment is pressure dependant. However, if the scaling is moderate the effect on test time is small.

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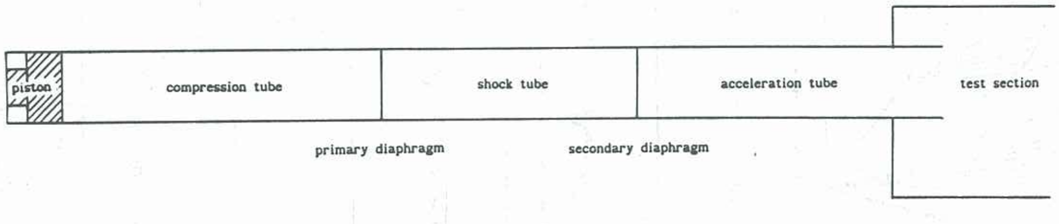

FIGURE 1. SCHEMATIC OF AN EXPANSION TUBE

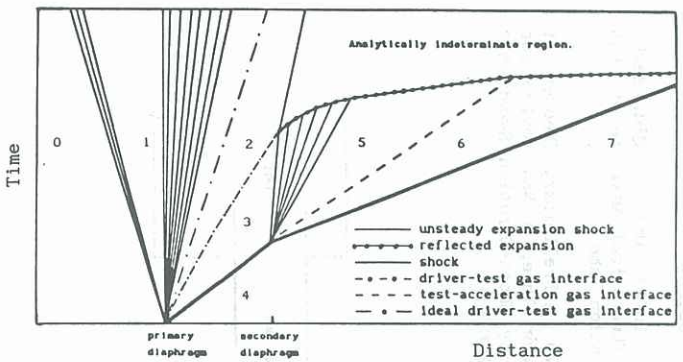

FIGURE 2. X-T DIAGRAM FOR AN EXPANSION TUBE

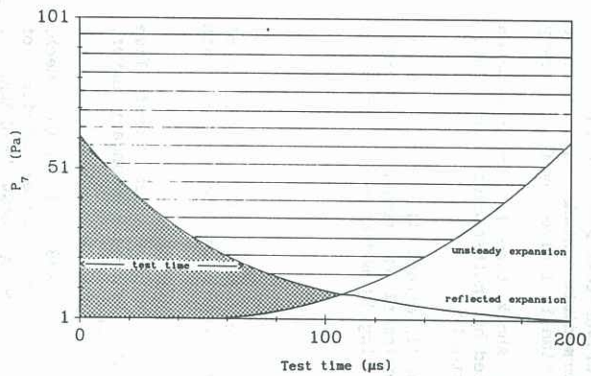

FIGURE 3. TEST TIMES AS A FUNCTION OF ACCELERATION TUBE FILLING PRESSURES

A driver, λ=29, P_0=34.5Mpa, P_4=3.5kPa

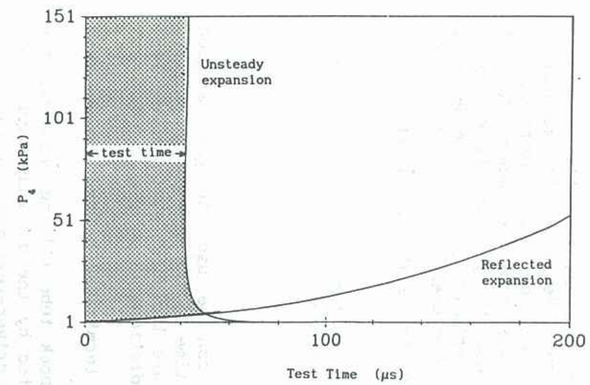

FIGURE 6. TEST TIMES AS A FUNCTION OF SHOCK TUBE FILLING PRESSURES

He driver, λ=28, P_0=34.5Mpa, P_7=16Pa

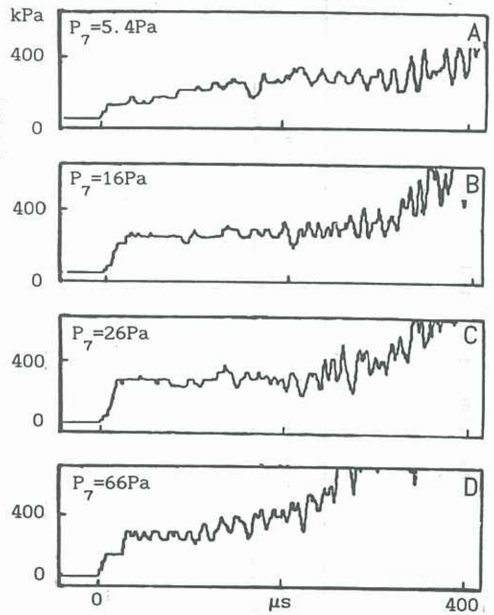

FIGURE 4.

PITOT PRESSURE RECORDS AT DIFFERENT ACCELERATION TUBE FILLING PRESSURES

A driver, λ=29, P_0=34.5MPa, P_4=3.5kPa

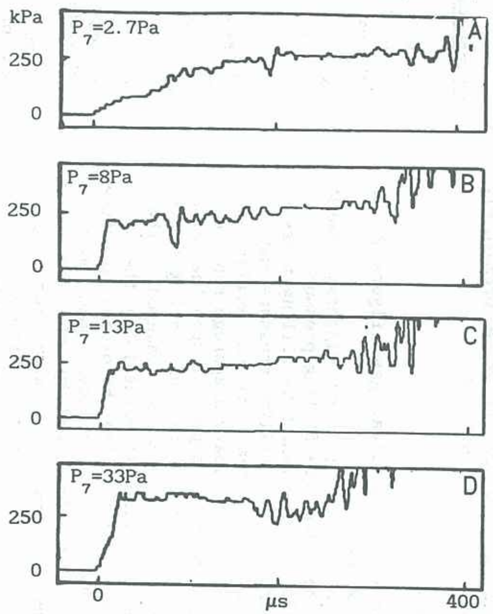

FIGURE 5.

PITOT PRESSURE RECORDS AT DIFFERENT ACCELERATION TUBE FILLING PRESSURES

A driver, λ=29, P_0=17MPa, P_4=1.7kPa

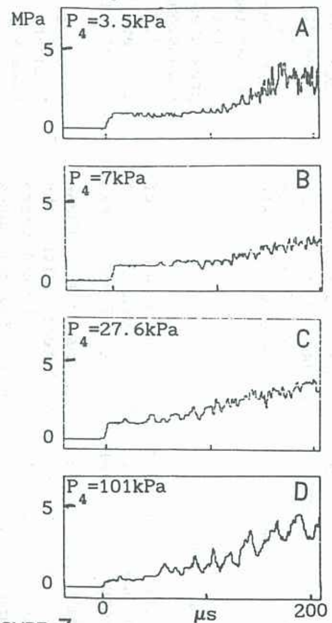

FIGURE 7.

PITOT PRESSURE RECORDS AT DIFFERENT SHOCK TUBE FILLING PRESSURES

He driver, λ=28, P_0=34.5MPa, P_7≅16Pa

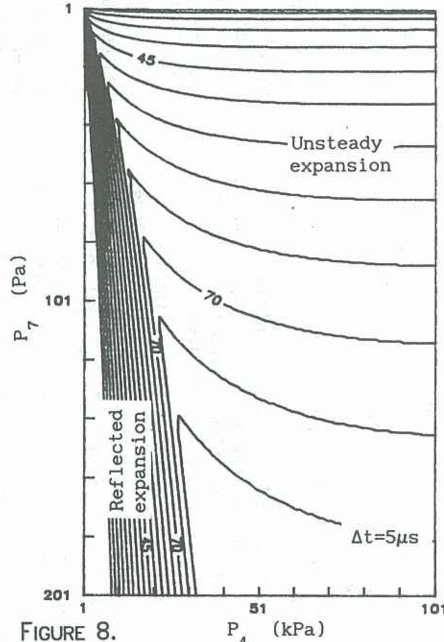

FIGURE 8.

TEST TIMES AS A FUNCTION OF SHOCK AND ACCELERATION TUBE FILLING PRESSURES

He driver, λ=28, P_0=34.5MPa