CFD analysis of early diaphragm removal in expansion tubes

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Keywords: Expansion tube, secondary diaphragm, early opening, impulse facility

Abstract. Impulse facilities generate transient high-velocity gas flows for ground testing in aerodynamics. The expansion tube is the facility type with the highest performance capability in terms of total flow enthalpy and total pressure, and is particularly useful for studies of atmospheric re-entry, chemical kinetics, scramjet flight and supersonic combustion. In operation, a thin film diaphragm that initially partitions two tube sections is required to rupture under the force of a shock-wave. Fragmented pieces are accelerated with the flow and can damage test models and instrumentation, and the rupture process itself affects flow properties. It has been proposed to replace the diaphragm with a fast open valve that clears the tube prior to shock arrival. This paper investigates the effect of early valve opening on the test flow.

An inviscid, axisymmetric model was created using Eilmer3, a compressible CFD solver developed at the University of Queensland. Early valve opening was simulated at varying times for instantaneous diaphragm removal. The result was the formation of a secondary shock and expansion wave. The primary shockwave reaches the test section at a higher velocity due to passing through the expansion wave, creating a faster, higher-pressure test flow, but also higher temperature, leading to substantially reduced Mach number. The interactions with the secondary waves were found to cause unsteadiness in test flow properties.

Introduction

High speed gas flows begin to demonstrate phenomena outside of ideal gas models at around Mach 5, at which point they are considered *hypersonic*. Gas processed by a shock wave in front of a hypersonic vehicle reach stagnation conditions sufficient to cause dissociation, ionisation and finite-rate chemical reactions. These conditions are relevant to flows associated with atmospheric entry capsules and high-velocity, air-breathing propulsion vehicles like scramjets.

Computational modelling of complex hypersonic processes requires experimental validation in wind tunnels. Extreme energy requirements mean that only transient flows can be produced, with test times typically less than 1ms. Expansion tubes are a class of impulse facilities, which have the highest potential for producing high total enthalpy and total pressure flows [1, 3].

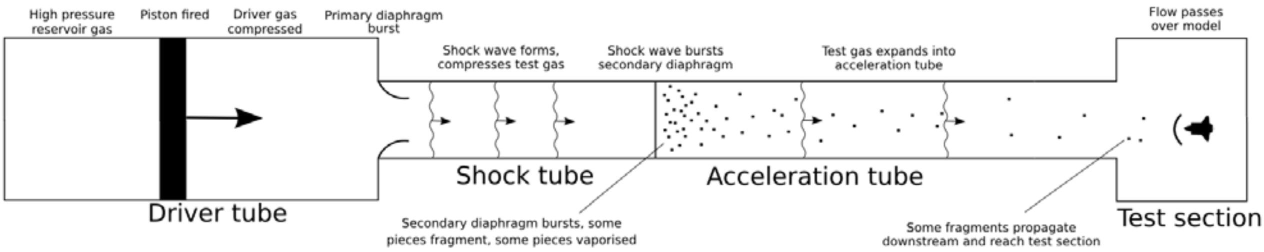

Fig. 1 Expansion tube operation and diaphragm fragmentation problem (not to scale)

In simple terms, a piston is fired into a sealed *driver* tube, compressing a high sound-speed gas, like helium [1]. The pressure becomes sufficient to burst a metal diaphragm separating the driver from a *shock* tube containing a low pressure test gas. A shock wave forms, and heats and accelerates the gas as it propagates down the tube. It reaches a comparatively weak secondary diaphragm, which bursts, exposing the gas to an even lower pressure *acceleration* tube. The gas undergoes unsteady expansion into this next section, adding total flow enthalpy.

The mechanism of secondary diaphragm failure is shear around the tube periphery. It fragments and the pieces either vaporise or remaining solid. Solid pieces may entrain in the boundary layer, but some may propagate downstream, potentially damaging test models or instrumentation [3].

A proposed solution is to replace the diaphragm with a sliding gate valve. The point of shock arrival cannot be exactly determined, so it is necessary to remove it some finite time before that. Early valve removal will create shock and expansion waves that interact with the primary wave processes, ultimately affecting the test flow. The facilities of interest are the X2 and X3 at the University of Queensland. Full facility descriptions can be found in [2, 3]. Timescales for expansion tube flows tend to scale with characteristic length. As X3 is a larger facility, it is anticipated that similar wave processes will be observed for proportionately earlier valve opening times.

Test Cases. The test flow cases reflect the common operation modes at the University of Queensland. High enthalpy flows are characterised by very high flow velocities and relatively low total density. They are relevant to atmospheric entry experiments, and generalised finite rate chemistry studies. Low enthalpy cases are relevant to scramjets and other access to space vehicles. They have lower velocity but higher total pressure, due to high gas density in air-breathing flight.

This paper analyses a representative low enthalpy, X2, scramjet condition in detail, Case *2f*, as documented in [2] (see Figure 2 for fill conditions). Some data is presented for the high enthalpy Case *4e*. [2]. Expansion tubes may operate in other modes, such as with a shock-heated secondary driver, or a nozzle [2]. This paper focuses only on the simplest mode described in Figure 1.

Expansion Tube Models. The only effect of interest is early diaphragm removal on an otherwise ideal operation of an expansion tube, so full simulation of all processes is not a priority. Gildfind et al [6] showed that flow upstream of the secondary diaphragm is well modelled assuming a fixed-volume driver, with initial conditions defined to produce results matching experiment. This model is acceptable for *tuned operation*, where the piston is fired in such a way that the outflow into the shock tube is effectively steady at the critical times, allowing piston dynamics to be ignored.

Initially longitudinal wave processes were studied using the 1-D Lagrangian code, L1d [4]. A 2-D axisymmetric model was then developed in Eilmer3, an explicit compressible flow solver [5]. Both codes used inviscid perfect gas models.

One-dimensional CFD Analysis

Simulations using the L1d code ran into a fundamental problem in accurately simulating early opening. Time-history data at the tube exit showed anomalous behavior at the interface between the test and accelerator gas. In an expansion tube the shock wave subjects the accelerator gas to high compression ratio, significantly heating it, so the gas initially exiting the tube is very hot (typically order of 10 000K). This is followed by the expanded test gas which is much cooler (typically order of 1000K, depending on flow condition). The temperature across the interface between these gas regions is theoretically a discontinuous drop, but this was not the result seen in the simulations. There was unexpected property smearing across the interface that changed significantly with cell desicretisation. In the nominal case (no early diaphragm removal), this behavior could be prevented by initially clustering cells around the diaphragm. This model was then used for early diaphragm removal simulations, but the non-physical variations in temperature history were observed again.

It was concluded that the cause was the Lagrangian nature of the solver. Following diaphragm removal, cells initially near that diaphragm expand into the acceleration tube and their cell size increases significantly. When the shock passes through the test gas cells, they are very large, so the grid resolution is poor for this critical wave process. It is not able to adequately capture flow processes over the interface. Discontinuities appear smeared.

An adaptive meshing technique was trialled where cells are subdivided if they become too large, but this did not return good results. The function may require further development in L1d.

Two-dimensional CFD Analysis

Wave and Property Results. The 2-D Eulerian model avoided issues with representing the test-accelerator gas interface seen in L1d. As stated, this analysis will focus on case *2f*, comparing the nominal to 1ms early opening. The primary waves are visualized with x-t plots in Figures 2 and 3. The x-axis is position along the tube, with the primary diaphragm at 0m. The y-axis is time since primary diaphragm burst. The expansion tube fill conditions for Case *2f* are shown in Figure 2. Figure 4 shows property traces over time at the tube end. They are equivalent to the data on the right-hand vertical axis on the x-t plots, starting from the point of shock arrival. These show the state of the flow in the test section and are the crucial outputs to an expansion tube study.

Nominal Case.

N1 – Primary diaphragm bursts. Primary shockwave propagates downstream. The shock compresses and accelerates the stagnant test gas to approximately constant speed.

N2 – Expansion waves propagate upstream from the diaphragm and reflect off the driver end wall. They propagate downstream as rarefaction waves, causing complex wave interactions. The driver length chosen was somewhat arbitrary, so this process is not exactly simulated.

N3 – Rarefaction waves catch up to the primary shock, passing through the shock-compressed test gas. This affects the uniformity of test gas properties. The shock is bent slightly by the waves.

N4 – Primary shock reaches secondary diaphragm which instantaneously bursts (no inertia or opening time effect considered). Shock velocity increases due to lower acceleration tube pressure.

N5 – Shock propagates through acceleration tube, compressing and accelerating the stagnant gas.

N6 – The test gas that was compressed behind the accelerator gas expands into the acceleration tube. An expansion fan propagates against the flow, but the flow velocity is sufficient to convect the wave downstream. The expansion wave head is a straight line joining N4 to N9.

N7 – Primary shock arrives at test section. In Figure 4, this time is set to 0. The first gas is accelerator gas. It is processed by the strongest shock and has the highest temperature.

N8 – First test gas arrives at test section, starting test time. There is a temperature discontinuity, but pressure and velocity are approximately continuous, so the Mach number increases. This is an important criterion for a useful test flow. There is a small drop in pressure, a result of rarefaction waves in N4 passing through the test gas at around x=2m to 4m.

N9 – The expansion wave head reaches the tube-end. This is test gas that has not been fully expanded, and each subsequent particle has undergone less expansion. Therefore the pressure over time increases and the velocity and Mach number begin to decrease. Test time is over when there is sufficient departure from the target test flow properties.

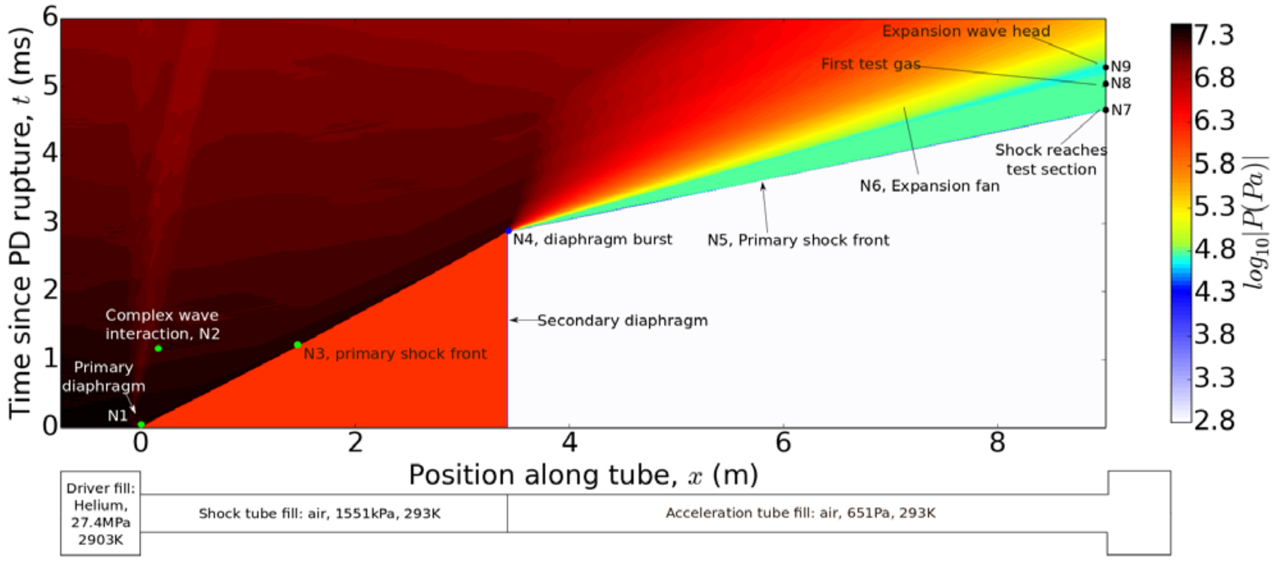

Fig. 2 Pressure contour plot for case *2f*, (X2, centerline), and expansion tube with fill pressures

Early Open, 1ms, Case *2f*. For the early open case, an x-t temperature plot is included.

E1 to E3 are equivalent to N1 to N3 in the nominal case. For E3, the temperature plot better illustrates the driver-test gas interface at the tube start (red-yellow boundary). Ideally the shock-compressed test gas region between 0m and 3m would be uniform colour, but the contours in this range show variation due to complex wave interactions. This is likely caused by the reflected rarefaction waves described in N3. A possible contributing cause is radial waves formed from the driver-shock tube area change.

E4 – Secondary diaphragm removed before primary shock arrival. Weak secondary shock propagates into still acceleration gas (E5), compressing and accelerating it. Test gas expands into acceleration tube, and so an expansion wave moves against the flow, while been convected downstream. Flow velocity is such that the expansion wave tail moves up the tube slightly.

E6 – Primary shock meets the expansion fan tail, and begins continuously accelerating until reaching the wave head (E7).

E7– Primary shock reaches expansion wave head and accelerator gas. Exact point is not clear from Fig. 3 due to contour scaling, but is clear in Fig. 4. Shock begins moving through accelerator gas that had been compressed by the weak shock, and so now moves at constant velocity.

E8 – Primary shock catches up to the secondary shock and begins moving through the stagnant accelerator gas, which has lower pressure and accelerates.

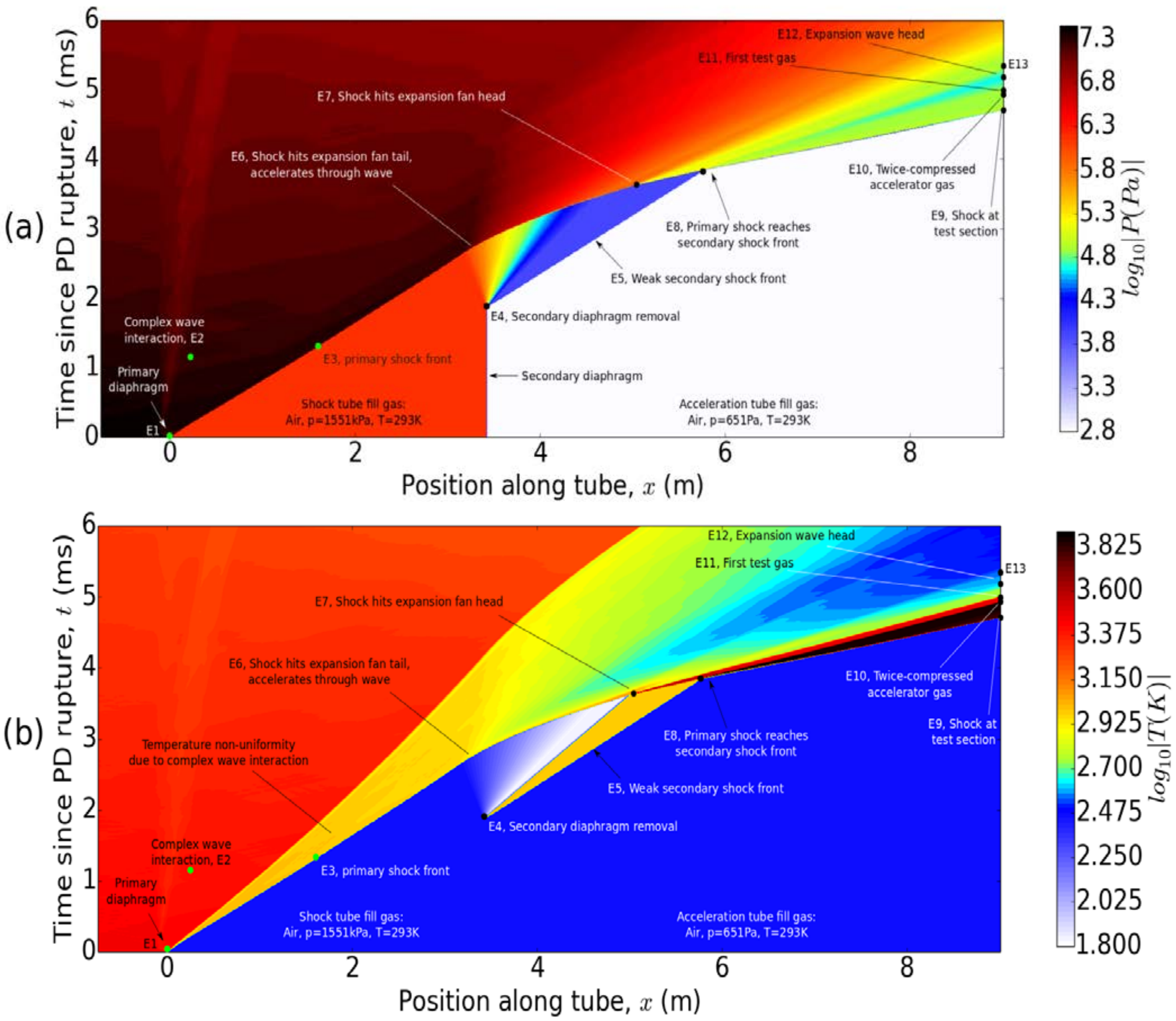

Fig. 3(a) and (b) Pressure and temperature contour x-t plot for case 2f, nominal

E9 – Shock arrival at test section, bringing accelerator gas with the highest temperature. Compared with the nominal, the shock is stronger, so this gas is hotter and faster.

E10 – Arrival of accelerator gas that, due to early opening, was compressed by the secondary, and then the primary shock (red gas in Fig. 4). This gas is much colder than accelerator gas processed by one shock only, and causes a step in the temperature and Mach number plots. For the period of accelerator gas flowing in the test section (E9 to E11), the pressure gradually drops (in the nominal this is constant). There is therefore a very weak expansion wave passing here.

E11 – Arrival of fully-expanded test gas. Because the test gas was expanded before been shock-processed, it was compressed by a stronger shock (compared to the nominal). The velocity, pressure and temperature are therefore all greater, but the temperature increase is such that the Mach number is much less (Mach 6 compared to Mach 9.8). For the nominal case, test gas properties are approximately constant until the head of the expansion wave arrives (N9). Furthermore, because the first test gas particles were allowed to expand the most before been shock-treated (at E7), the pressure and temperature decays for each subsequent test gas particle over time.

E12 – Corresponds to N9, the arrival of gas that is not fully processed by the expansion wave (the point is the expansion wave head). The pressure increases. The velocity, that was already decreasing due to the effect described in E11, decays more severely, as does the Mach number. In the nominal case, the temperature increases slightly, but for early open, it continues to decrease.

E13 to E14 –In the nominal case, the pressure continues to increase as the expansion fan is convected through to the test section, but for early opening the pressure drops again between 0.63 and 0.69ms. Correspondingly, the velocity becomes steady over this period, and the Mach number slightly increases. Looking at the x-t pressure plot, Figure 3(a), this point can be traced to a pressure wave beginning where the shock passed over the test-accelerator gas interface, which is also the head of the weak expansion wave (E7). So this pressure wave is likely caused by the shock passing over this density discontinuity

E14 – The pressure continues to ramp, and the Mach number drops. Test time ends, as stated, when there is sufficient departure from test flow properties and the remaining wave processes are of no interest.

Test Section Property History: Nominal and 1ms Early Open, Case *2f*

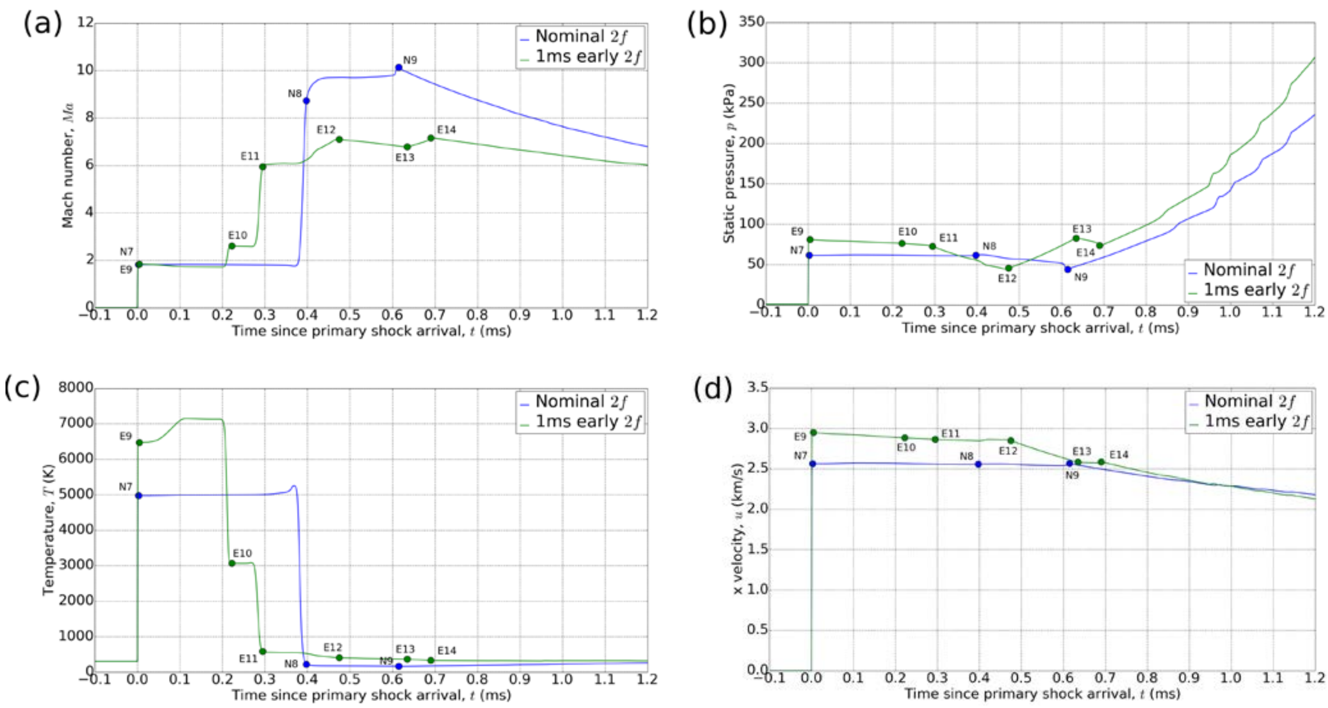

Fig. 4 Annotated property traces of (a) Mach number, (b) pressure, (c) temperature and (d) velocity respectively at tube end; nominal and 1ms early open in case *2f*; primary shock arrival set to t=0s

Figure 4 is the tube exit property traces, which show the final test flow performance. Early opening leads to a higher primary shock velocity. This analysis has focused on a single case, but this was observed for the high (4e) and low (2f) enthalpy cases in X2. The velocity increased further with earlier opening times (Figure 5).

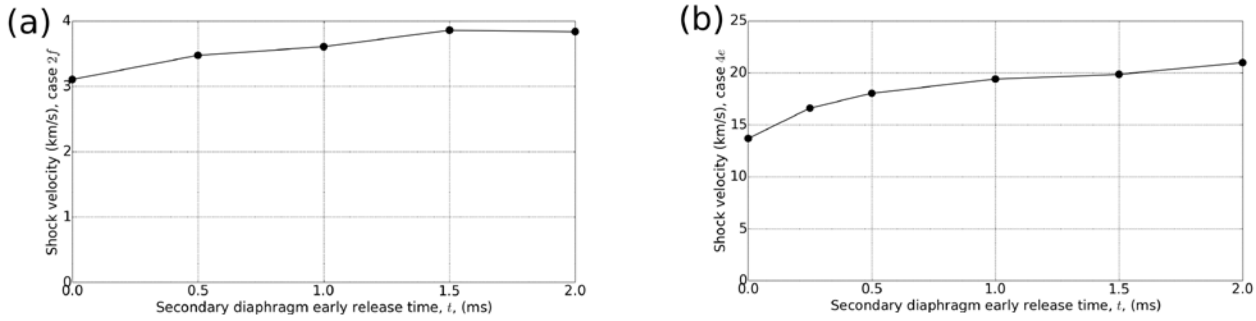

Fig. 5 Primary shock velocity for varying early open times for cases (a) *2f* and (b) *4e* respectively

The faster shocks produce higher velocity flows, but the corresponding increase in temperature causes the Mach number to reduce. This may in itself be acceptable as flow conditions can be modified by adjusting initial gas fill pressures [3]. The secondary pressure waves that result from early opening cause unsteadiness in properties over test time (after E13). For the nominal case, Mach number remains approximately steady before arrival of the expansion wave, but it should be noted that this is for an ideal model. The period over which the Mach number remains high before dropping with the un-expanded test gas (test time), does not appear to be reduced for this case, though this is an effect that requires further study for other opening times and flow conditions.

Summary

This paper presents results for a preliminary study of wave processes due to early diaphragm removal and its effect on the test flow in an expansion tube, compared with nominal operation. It was found that secondary waves lead to unsteadiness in properties in the test-section flow. Shock strength was found to increase, but Mach number was reduced due to higher temperature.

More general findings regarding feasibility of a fast open gate valve, especially relating to test time, require further study into alternate flow cases. It is of particular interest to find if acceptable early-open times will scale with increasing facility size. Further study is also required into the effects of viscous interface mixing, especially on the flow uniformity.

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