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Recent Advances in Detonation Techniques for High-Enthalpy Facilities

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Detonations can be used to generate a high-pressure gas of high acoustic speed to drive a shock tube. Recently, detonation driven facilities have been implemented for meaningful hypervelocity testing. These facilities can be operated with the detonation wave propagating either downstream or upstream. The advantages and problems associated with these methods are discussed. In addition to a performance comparison between these two modes, comparisons with other high-performance techniques, such as free piston and gun tunnels, are also made. At present, detonation driven facilities are generally of lower performance than free piston tunnels. However, they appear easier to operate and have a lower capital investment.

Nomenclature

a = acoustic speed
M = Mach number
$P_{i,j}$ = p_i / p_j, pressure ratio
$P'_{i,j}$ = $p_i / p_j - 1$
p = pressure
T = temperature
u = velocity
γ = specific heat ratio

Subscripts

CJ = Chapman–Jouguet
s = shock
0 = stagnation conditions
1, 2, 3, ... = regions in wave diagram corresponding to different gas states

Introduction

AERODYNAMIC testing using short duration facilities is a highly specialized technique confined mostly to hypersonic and hypervelocity regimes with their high-enthalpy requirements. The main characteristic of these facilities is that they are derived from shock-tube principles. Consequently, these facilities have short test times, typically in the 0.1–10-ms range. This short test time contrasts drastically from those achievable using continuous or blowdown (that is, conventional) facilities.[1] Despite this limitation, short duration facilities appear to be the primary means for achieving hypervelocity flows at present. The underlying principle is to store energy over a long period of time, lessening the input power requirement, and then releasing the accumulated energy rapidly. The tradeoff between flow duration and flow enthalpy is clearly manifested.

The alternative to impulse facilities can be extremely prohibitive in cost, especially if large conventional tunnels are contemplated. Additionally, one can even argue that for certain purposes there is no other really viable alternative, such as in simulating orbital flight or flight through planetary atmospheres.[2] The latter application exploits the fact that impulse facilities can easily use test gases other than air. Moreover, elaborate thermal protection of the test model or of the instrumentation can be dispensed with because of the short time of passage of the heated test gas.

Windows and optical elements can be inserted in or near the model to allow flow visualization and optical diagnostics despite the high-enthalpy flow environment. Further, the inherent cold-wall boundary conditions allow highly accurate heat-transfer measurements to be made at freestream total temperature to wall temperature ratios similar to those encountered in flight.

Testing in impulse facilities requires careful attention to the need to establish steady flow over the model and make measurements within the brief test time available. Criteria have been developed that ensure establishment of steady model flow based on verification experiments and computational studies.[3,4] Recent advances in instrumentation, data acquisition systems, and measurement techniques allow time-resolved flow visualization,[5] planar flowfield measurements,[6] and integrated force measurement[7] all within millisecond test durations.

Perhaps the greatest recent interest in high-enthalpy, impulse facilities stems from the need to test advanced, high-Mach-number, airbreathing propulsion systems at energies and pressures beyond the reach of long-duration facilities.[8] Only impulse facilities offer the combination of high stagnation pressure and enthalpy that are necessary for replicating the conditions flowing over and through the engine of a slender airbreathing vehicle such as hypersonic scramjets[9] and oblique detonation wave engines.[10,11] Recent proposals for achieving high stream enthalpies considered radiative energy addition to a supersonic flow[12] or the incorporation of a magnetohydrodynamic accelerator.[13] Although proposed for continuous or blowdown operation, the feasibility of these facility advances can be studied using shock tubes.

In view of the enthalpy requirements for hypervelocity testing, the shock tube must incorporate a high performance driver. Warren and Harris[14] classified high performance drivers as 1) conventional drivers using high-pressure and high acoustic speed gases, 2) electric and magnetic field interaction drivers, 3) detonation, that is, explosive drivers, and 4) those that derive their flow characteristics from the coupling of energy addition and wave processes in an unconventional manner. Examples of conventional drivers, which are well developed, include electrical energy discharge, internal or external heating of hydrogen or helium driver gas, and piston compression. The last technique is found in free piston[15] and gun tunnels.[16] Electric and magnetic field interaction drivers and detonation drivers

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appear to be less well developed. The final class of techniques includes the expansion tube[2] and the use of shock waves or detonation waves to produce a high-pressure, hot driver gas.[17]

Although Warren and Harris[14] listed many high-performance techniques, only a few of these appear feasible. The free piston technique appears to be the most developed and has been implemented in different institutions, including the High Enthalpy Shock Tunnel, the largest such facility at Kakuda, Japan. The free piston technique is generally thought to be capable of achieving extremely high enthalpies. However, there is recent interest in using detonation techniques to achieve high enthalpies. To date, detonation driven facilities have achieved enthalpies somewhat lower than that achievable by free piston techniques, although there does not appear to be serious practical difficulties in achieving higher enthalpy levels. Some practical limitations include thermal and mechanical loading to the tube structure, including erosion and ablation. More fundamentally, the maximum temperature of the high-pressure state is limited because of the limitation in the Chapman–Jouguet (CJ) temperature—and, hence, the maximum shock strength—in the detonation of a given gas mixture and initial temperature. Nonetheless, detonation techniques possess a number of favorable features, which ensure that they occupy a useful niche in hypervelocity testing. Before a review of recent developments in detonation drivers, a brief summary of shock-tube principles will be given next.

Background

A shock tube, shown schematically in Fig. 1a, consists essentially of a high-pressure, driver section separated from the low-pressure, driven section by a diaphragm. Gases fill both sections. When the diaphragm is ruptured, the high-pressure gas, at an initial state 4, expands into the low-pressure section, filled with gas at an initial state 1. Propagating into the driven gas ahead of this expansion is a shock wave, as shown schematically in Fig. 1b. This shock compresses the driven gas, thereby changing its state from 1 to 2. This slug of shock processed, driven gas—between the propagating shock and the arrival of the contact surface between the driver and driven gas—forms the test gas. (The test gas can be further processed; for example, it can be accelerated by a nozzle, as in a shock tunnel.) By using different driver gases or by having the driver and driven gases at different initial pressures and temperatures, the shocked state of the driven gas can be preset. Quasi-one-dimensional theory yields the following implicit expression for the pressure ratio of the test gas after shock passage as

$$P_{4,1} = P_{2,1}\left\{1 - \frac{(\gamma_4 - 1)(a_1/a_4)(P'_{2,1})}{\sqrt{2\gamma_1[2\gamma_1 + (\gamma_1 + 1)P'_{2,1}]}}\right\}^{-2\gamma_4/(\gamma_4 - 1)} \tag{1}$$

where $P'_{2,1} = P_{2,1} - 1$. The key parameter governing shock-tube performance is the shock Mach number M_s, defined as the shock speed referred to the initial speed of sound in the driven gas. The shock Mach number is given by

$$M_s = \sqrt{1 + (\gamma_1 + 1)/(2\gamma_1)P'_{2,1}} \tag{2}$$

The theoretical performance of a shock tube is displayed in Fig. 2, where helium is the driver gas and air is the driven gas. Both gases are assumed perfect because real gas effects in the test gas up to a shock Mach number of eight are not large. In the figure the initial driver-to-driven pressure ratio p_4/p_1 is plotted as a function of M_s for different values of a_4/a_1. Also plotted as a dotted line is the pressure ratio across the propagating shock p_2/p_1.

Figure 2 shows that a cold driver, with a low sonic speed (with a sonic speed ratio of unity, say), can attain a practical shock Mach number of only about three. This limited shock Mach number led to schemes to improve driver performance in order to provide adequate hypervelocity, real gas simulation. The figure shows that to achieve large shock Mach numbers without incurring an exorbitant initial pressure ratio the sonic speed of the driver gas must be raised. In other words, the driver gas must be of low molecular weight and must be heated. For example, to achieve a shock Mach number of eight the theoretical initial pressure ratio needs to be only 1300 and 260 for acoustic speed ratios of 5 and 10, respectively. In practice, using a value of $p_1 = 10$ kPa for instance, $M_s = 8$ can be achieved with a value of p_4 of only 2.6 MPa for an acoustic speed ratio of 10. Unfortunately, if the driven tube is filled with air at room temperature, the helium must be at a temperature of 3500 K. The only practical means of achieving this high temperature without destroying the facility is to heat the gas in a transient manner.

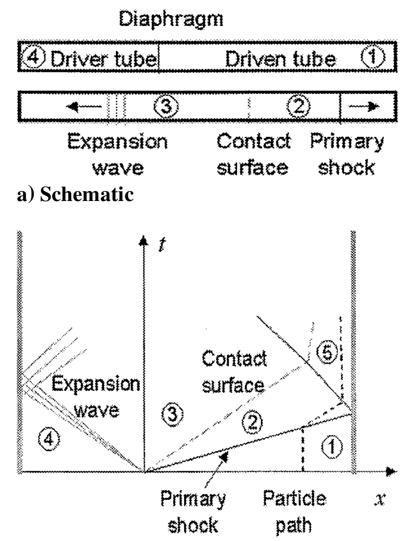


Fig. 1 Ideal wave processes in a shock tube.

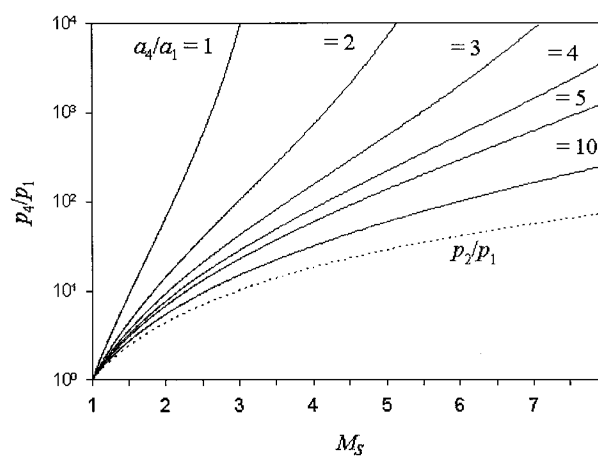


Fig. 2 Effect of acoustic speed and initial driver pressure ratio (helium driver gas and the air test gas).

Detonation Wave Drivers

In ground-test applications the free piston technique for producing a hot driver gas is well developed. Nevertheless, detonations can also be used to obtain a hot driver gas with a large acoustic speed. Detonation drivers are an inexpensive, simple, viable alternative to free piston drivers for obtaining high enthalpies because the technique dispenses with a fast moving, heavy piston. Detonations are also attractive compared to deflagrative combustion as a transient, heating method.[18] The low velocity combustion depends on factors such as ignition energy, number of igniters, initial turbulence, flame propagation, and size of tube, all of which cause difficulties in reproducibility.

The detonation driven shock tube was first proposed by Bird[19] and was subsequently studied by several investigators.[20–22] This concept has recently been further developed.[17,23–30] A detonation process is typically established in a driver tube filled with a near-stoichiometric oxyhydrogen mixture, although other gas combinations, such as acetylene and oxygen,[22] are possible. The mixture pressure can be quite low, thus eliminating the need for thick metal diaphragms. Thick diaphragms are still desirable to avoid losing material as the

Table 1 Summary of detonation drivers[a]

Facility	Detonation driver	Driven tube	Approx. max. test conditions
University of Texas at Arlington[30] (up/downstream propagation, arc initiation)	152-mm (6-in.) bore 3 m (10 ft) long 41 MPa (6,000 psi) $2H_2 + O_2$ (0.5–8 atm)	41.2-mm (1.62-in.) bore 9 m (30 ft) long 19 MPa (2,800 psi)	p_0 = 2.8 MPa T_0 = 2,450 K M_s = 10.7
University of Texas at Arlington (downstream propagation, shock initiation)	152-mm (6-in.) bore 3 m (10 ft) long 41 MPa (6,000 psi) $2H_2 + O_2$ (0.5–8 atm)	41.2-mm (1.62-in.) bore 9 m (30 ft) long 19 MPa (2,800 psi)	p_0 = 40.5 MPa T_0 = 7,000 K
GASL,[b] Ronkonkoma, New York (downstream propagation, shock initiation)	150-mm (6-in.) bore Up to 12 m (39 ft) long 140 MPa (20,300 psi) $2H_2 + O_2 + Ar$ (1–17 atm)	150-mm (6-in.) bore Up to 21 m (69 ft) long 53 MPa (7,700 psi)	p_0 = 34 MPa T_0 = 5,000 K h_0 = 7 MJ/kg
RWTH[c] Aachen, Germany[23] (upstream propagation, shock initiation, with damping tube)	140-mm (5.5-in.) bore 6.2 m (20.3 ft) long 150 MPa (21,700 psi) $2H_2 + O_2 + x\mathrm{Ar} + y\mathrm{He}$ (1.5–7 MPa) x = 0–65% vol., y = 0–65% vol.	140-mm (5.5-in.) bore 6.2 m (20.3 ft)	p_0 = 32.4 MPa T_0 = 7,930 K h_0 = 15.6 MJ/kg M_s = 11
Institute of Mechanics, Chinese Academy of Sciences, Beijing, People's Republic of China[24] (upstream propagation, shock initiation, with damping tube)	100-mm (4-in.) bore 5.6 m (18.4 ft) long $3H_2 + O_2$ (10 atm)	100-mm (4-in.) bore 5.6 m (18.4 ft) long	M_s = 10.7

[a]Dimensions and fill conditions are representative. These may have changed.
[b]GASL: light gas driver = 2.4 m long; pressure up to 140 MPa.
[c]RWTH Aachen: damping tube = 140-mm diameter, 6.1 m long; initiation tube = 30-mm diameter, 900 mm long.

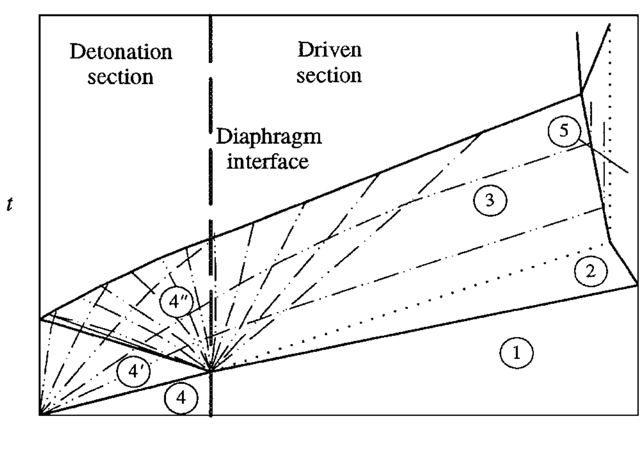


Fig. 3 Downstream propagation mode.

diaphragm ruptures and petals (M. Habermann, private communication, University of Technology, Aachen, Germany, 1998). The detonation process produces a low molecular weight driver gas at high temperature and pressure, all of which are desirable features. The sudden pressure rise produced by the detonation causes the primary diaphragm to rupture, thus establishing a shock wave in the driven tube.

Implementation

At present, detonation driven facilities have been reported by the University of Technology, Aachen, Germany[23,24]; the Institute of Mechanics, Chinese Academy of Sciences[24]; GASL, Ronkonkoma, New York[25–28]; and the University of Texas at Arlington.[29,30] These facilities use an oxyhydrogen mixture as the driver gas, with helium or argon dilution as necessary. Table 1 summarizes the major characteristics of the detonation drivers in the four institutions mentioned, indicating the propagation mode of the detonation wave. The detonation wave can propagate either downstream or upstream. Thus, the mode of propagation can serve as a means of classifying detonation wave drivers.

In the downstream propagation mode the ignition source is located at the upstream end of the driven tube, producing a detonation wave that propagates downstream. The main wave processes are shown schematically in Fig. 3. The detonation wave, depicted as a solid line from the lower-left-hand corner in the diagram, propagates downstream into region 4. Momentum of the burned gas following the detonation wave is also in the downstream direction. This produces a stronger shock for a given detonation overpressure than if the gas were moving opposite to the wave propagation. However, the detonation wave is followed by Taylor rarefaction, shown as chained lines in region 4′. The Taylor rarefaction satisfies the no-flow boundary condition at the upstream end of the detonation section, which progressively attenuates the pressure behind the detonation wave. The detonation wave propagating into 4 is reflected at the diaphragm to yield an effective, unsteady condition given by 4″. The reflection of the detonation wave at the diaphragm interface generates a shock that propagates into region 1, being driven by the high-enthalpy detonation products at state 4″. The burned gas then exhausts into the driven section to reach state 3. This gas is separated by an interface, shown in Fig. 3 as a dotted line, from the postshock driven gas at state 2. Further wave processes are not shown but can be important, such as in creating a high-pressure, stagnant region 5.

An example of detonation tube pressure traces for the downstream propagation mode is shown in Fig. 4 (Ref. 30). The detonation tube was filled with a stoichiometric oxyhydrogen mixture at 6 atm. Transducer (3) was closer to the igniter than transducer (4) and thus recorded an earlier arrival of the detonation wave. Time-of-flight calculations indicated that the detonation wave eventually reached CJ velocity. The pressure records showed a rapid pressure rise. However, the transducers were unable to resolve the von Neumann spike, the maximum pressure of the detonation front. This is typical of pressure measurements using off-the-shelf piezoelectric or piezoresistive transducers, which typically have bandwidths of 100 kHz. The records show a rapid pressure drop associated with the Taylor rarefaction, as indicated in the figure. The Taylor rarefaction reduces the effective pressure pumping the driven gas to below the CJ pressure at the trailing edge of the detonation front. This means that there is a reduction in shock-tube performance. The records also show peaks within the rarefaction region. These peaks are attributed to waves reflecting off the upstream flange of the detonation tube because the igniter was placed on the tube wall adjacent to the end flange.

In the upstream propagation mode the ignition source is just upstream of the primary diaphragm, producing a detonation wave that propagates upstream. The detonation tube process is shown schematically in Fig. 5. The detonation wave propagates to the left into region 4. The pressure rise following the detonation wave is fairly constant, but the momentum imparted to the driver gas by the

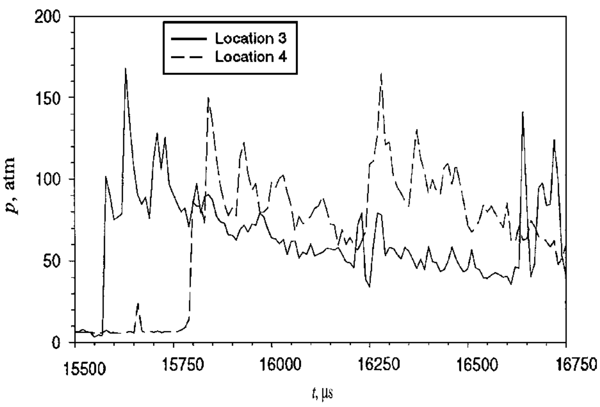


Fig. 4 Pressure traces for downstream propagation mode (stoichiometric oxyhydrogen mixture at initial pressure of 6 atm, electric arc ignition). Location 3 = 1.067 m (42.0 in.) upstream of diaphragm interface; location 4 = 0.406 m (16.0 in.) upstream of diaphragm interface.

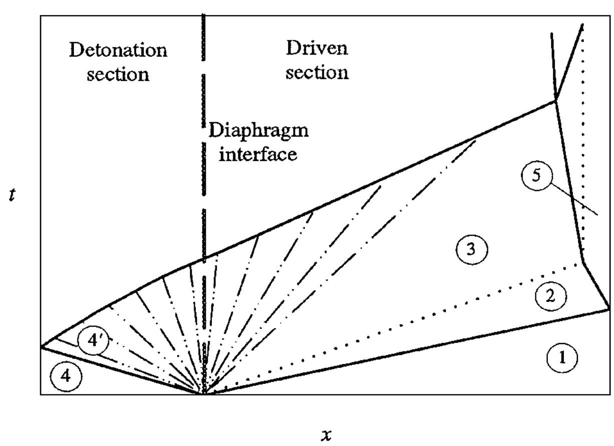


Fig. 5 Upstream propagation mode.

detonation wave is directed upstream. This has potentially adverse loading consequences on the shock tube.

An example of detonation tube pressure traces for the upstream propagation mode is shown in Fig. 6 (Ref. 30). The detonation tube was filled with a stoichiometric oxyhydrogen mixture at 6 atm. Transducer (4) was now closer to the igniter and thus recorded the arrival of the detonation wave before transducers (2) and (3). However, transducer (4) detected some precompression ahead of the detonation wave, indicating that the detonation wave did not reach the CJ velocity, a phenomenon also reported in Ref. 31. Transducer (3) as well as subsequent transducers upstream (not shown in Fig. 6 for clarity) did not detect any precompression. Time-of-flight calculations indicated that the detonation wave eventually reached CJ velocity. The pressure records indicated a rapid pressure rise after the precompression, but the von Neumann spike was not resolved. The Taylor rarefaction and additional peaks in this region are also indicated in the figure.

For either propagation mode further performance enhancement is possible by helium dilution to the oxyhydrogen mixture. Helium dilution raises the sonic speed in the driver gas and also somewhat reduces the danger associated with premature detonation of the oxyhydrogen mixture. Performance calculations by Yu[24] indicate that the performance degradation caused by the slight lowering of the detonation temperature caused by helium dilution is more than adequately offset by the increased sonic speed of the driver-tube gas.

Two of the institutions that have recently implemented detonation drivers make use of downstream propagation, whereas the other two make use of upstream propagation (Table 1). Means of implementing these techniques to enable them to be used for test facilities are now elaborated separately in the following subsections.

Downstream Propagation

Downstream propagation using arc ignition[29] yielded shock speeds considerably lower than those predicted by a simple, one-dimensional model, thus producing drastically lower pressure and temperature levels in state 2 of the driven gas. The primary reason was attributed to the Taylor rarefaction wave associated with the arc-ignition process.

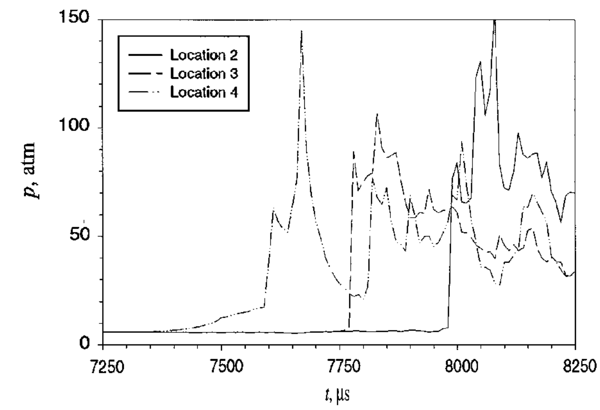


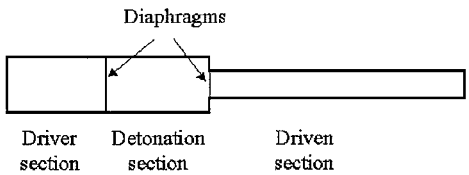
Fig. 6 Pressure traces for upstream propagation mode (stoichiometric oxyhydrogen mixture at initial pressure of 6 atm, electric arc ignition). Location 2 = 2.248 m (88.5 in.) upstream of diaphragm interface; location 3 = 1.664 m (65.5 in.) upstream of diaphragm interface; location 4 = 1.080 m (42.5 in.) upstream of diaphragm interface.

The decrease in pressure following the detonation front can be overcome by adding a driver tube ahead of the detonation tube to initiate a shock-induced detonation.[32] A detonation wave is generated in the combustible mixture by rupture of a diaphragm between the driver tube and the detonation tube. This method was apparently first used by Coates and Gaydon.[20] These authors made use of the shock wave from a cold hydrogen driver to ignite a detonable mixture. Recently, shock-induced detonation was reintroduced by Bakos et al.[26] and adopted by Stuessy et al.[30]

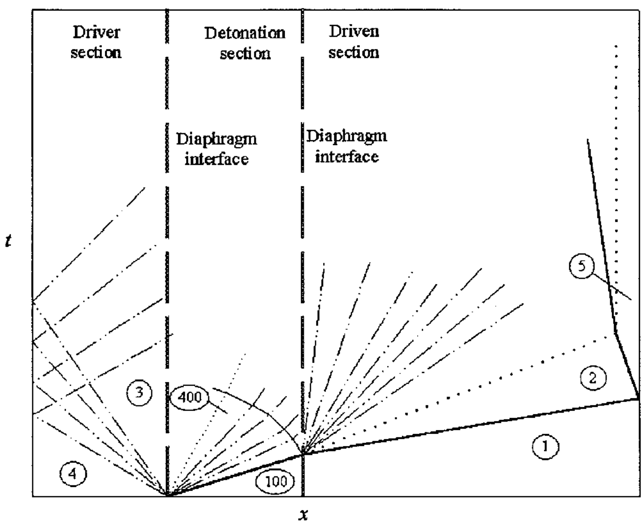
A schematic of the method, including an idealized wave diagram, is shown in Fig. 7. The detonation and driven sections are shown with different diameters. This causes a slightly more complicated wave process. Labeling of the different regions in the wave diagram remains consistent with shock-tube nomenclature. A high-pressure air or helium driver is placed upstream of the detonation tube. When the primary diaphragm is ruptured, a shock wave is driven into the detonation tube, labeled region 100 in Fig. 7b. This shock wave quickly initiates detonation. Unlike the closed-end operation (see Fig. 5) the driver tube serves to reduce or eliminate the Taylor rarefaction wave, thus resulting in a higher pressure available to drive the primary shock wave in the shock tube. In effect, the driver tube exhaust acts like a gas piston to sustain the pressure behind the incident detonation wave at a higher level than would occur if the detonation propagated away from a closed end wall.

Depending on the driver-to-detonation tube pressure ratio and the composition of the detonable mixture, the gas piston will alter the pressure history behind the shock-induced CJ detonation. If the driver is weak, the Taylor rarefaction behind the propagating detonation still occurs, although it is less severe than the arc-ignited detonation already described. In this so-called underdriven condition (not to be confused with an underdriven detonation that is experimentally inaccessible) the Taylor rarefaction expands the detonated gas to a pressure and velocity just sufficient to match those at the driver gas interface. A uniform region of detonation products forms giving rise to a pressure plateau behind the Taylor rarefaction. This is labeled region 400 in Fig. 8a. If the driver pressure is raised (that is, if p_4/p_{100} is raised), a point will be reached such that the pressure of the expanding driver gas just balances that at the rear of the detonation wave p_{CJ}, annihilating the Taylor rarefaction. In this perfectly driven mode the full CJ pressure level can ideally be maintained behind the detonation wave, as shown in Fig. 8b. A further increase in p_4/p_{100} causes the expanded driver gas pressure to be higher than the CJ wave pressure. This forces the detonation to travel faster than the CJ speed, resulting in an overdriven detonation (Fig. 8c). Taylor rarefaction also does not exist in this case.

Pressure traces typifying underdriven and nearly perfectly driven detonation operation are shown in Figs. 9 and 10. In both cases the



a) Schematic with area reduction between detonation and driven sections

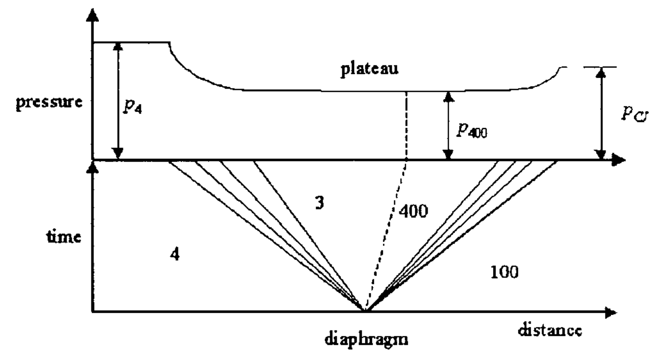


b) Wave diagram

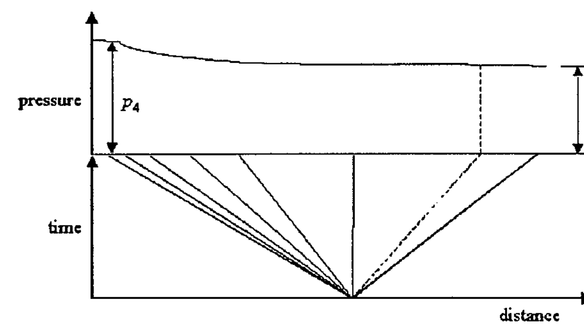
Fig. 7 Downstream propagation mode using shock-induced detonation.

driver section that forms the gas piston is filled with helium, and the reactants in the detonation tube are a stoichiometric mixture of oxygen and hydrogen. Figure 9 shows an underdriven case where the ratio of fill pressures between the helium driver and the detonation tube is 33:1. The pressure trace, measured in the detonation tube, is shown normalized by the initial helium pressure p_4. The initial pressure spike is the arrival of the CJ detonation wave and is followed by a pressure decay through the Taylor rarefaction. A plateau of pressure forms subsequently at approximately 30% of the p_4 level. In the pressure trace of Fig. 10, the pressure decay through the Taylor rarefaction has been nearly eliminated by increasing the initial pressure ratio between the helium and the detonable mixture to 50:1 and by diluting the detonable mixture with argon. The combination of the higher helium pressure and the slower detonation wave speed in the argon diluted mixture serves to support the pressure behind the detonation at a higher level. Overdriven detonations have apparently not been reported in the literature.

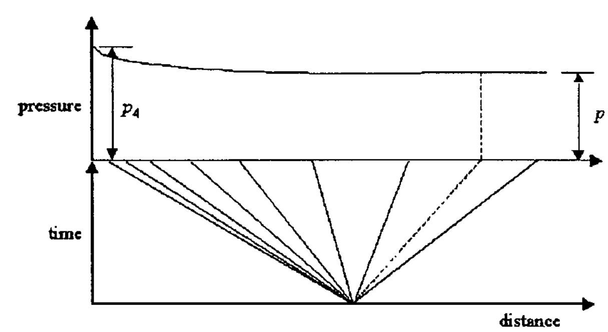
Further examples of an underdriven detonation are shown in Fig. 11. The driver section was filled with air and helium, respectively, with both gases at room temperature and at 210 atm. For both these cases the detonation section contained a stoichiometric oxyhydrogen mixture at room temperature and at a pressure of 1.5 atm. The driven tube was filled with air at room temperature and at a pressure of 0.14 atm. The drop in pressure through the Taylor rarefaction wave is clearly indicated in both these figures. The next increase in pressure recorded by the transducer is because of the arrival of the reflected detonation wave. Although both traces show the same rate of pressure drop with time, the use of helium yielded an improved driver performance. The driven-tube Mach number achieved in this latter case was 7.65 compared to 6.70 with an air driver. Driven-tube pressure traces for these two cases are shown in Fig. 12. Approximately 1 ms of adequately steady pressure downstream of the propagating shock was obtained for these two cases. Thus the shock-induced detonation mode offers substantial gains in performance by reducing or possibly eliminating the Taylor rarefaction wave. Finally, the postshock pressures in Fig. 12b show a slight rise. This was thought to be caused by the unsteady expansion arising from the area contraction between the detonation and driven sections. This unsteady expansion depends on the strength



a) Under-driven detonation



b) Perfectly driven detonation



c) Overdriven detonation

Fig. 8 Different modes for shock-induced detonation.

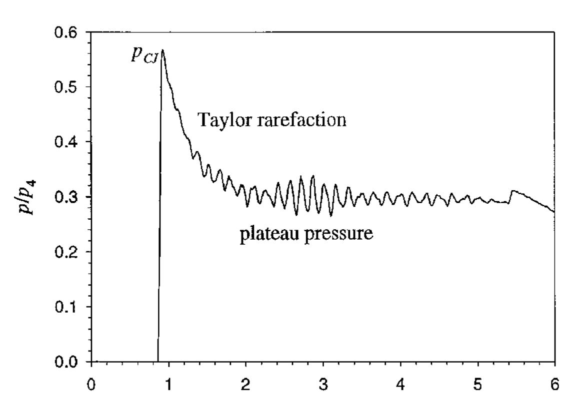


Fig. 9 Normalized underdriven pressure trace.

of the detonation wave and can be sufficiently weak to cause the postshock pressure to decrease slightly.

The pressure plateau region behind the Taylor rarefaction can be used to drive a nonattenuating shock wave. Thus, the shock-induced detonation mode of operation can be optimized to achieve the highest pressure postshock conditions and the maximum steady flow test time for a driver and detonation tube of a given design pressure. The first requirement for operation of the shock-induced detonation driver is that p_4/p_{100} is sufficiently high to quickly initiate detonation. Detonable mixtures with diluent fractions up to 65% are

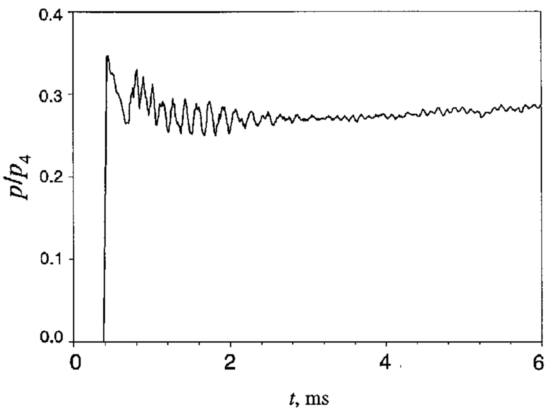
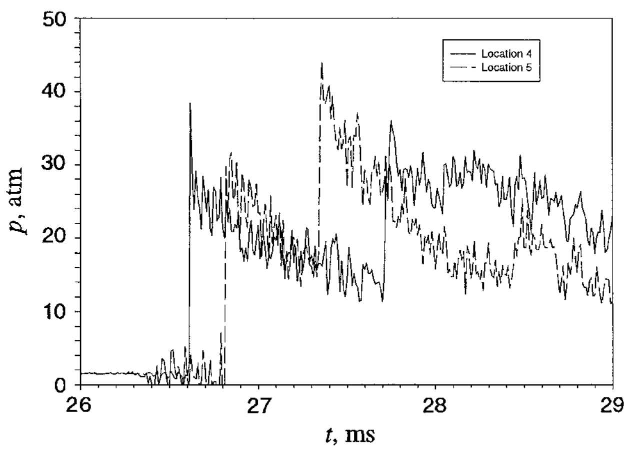
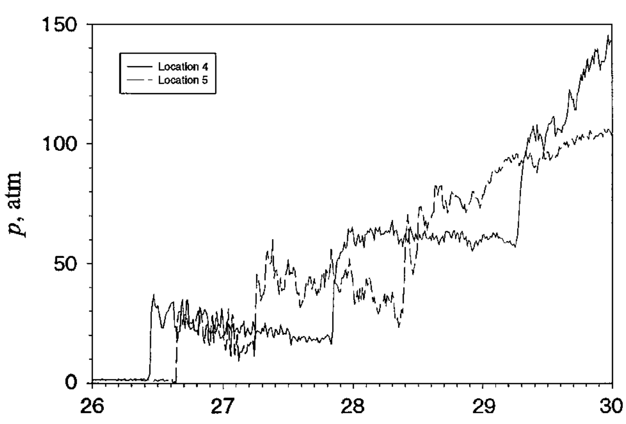


Fig. 10 Normalized nearly perfect driven GASL.

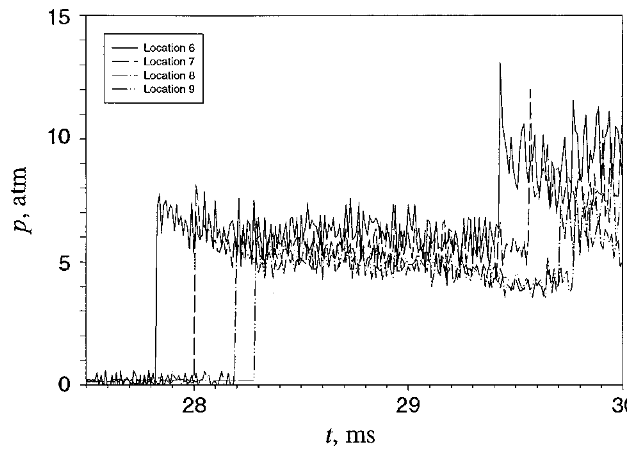


a) Driver tube filled with air at room temperature and 210 atm

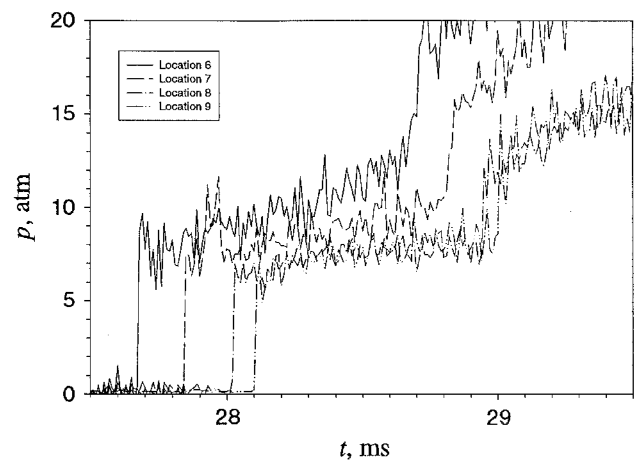


b) Driver tube filled with helium at room temperature and 210 atm

Fig. 11 Example of an underdriven pressure trace: location 4 = 1.080 m (42.5 in.) upstream of diaphragm interface: location 5 = 0.495 m (19.5 in.) upstream of diaphragm interface.



a) Driver tube filled with air at room temperature and 210 atm



b) Driver tube filled with helium at room temperature and 210 atm

Fig. 12 Pressure trace in driven tube corresponding to Fig. 11a: location 6 = 2.146 m (84.5 in.) downstream of diaphragm interface; location 7 = 2.604 m (102.5 in.) downstream of diaphragm interface; location 8 = 3.061 m (120.5 in.) downstream of diaphragm interface; location 9 = 3.416 m (134.5 in.) downstream of diaphragm interface.

sufficiently sensitive for achieving detonations at pressure ratios as low as 20 (Ref. 29). The strength of the driven shock wave depends on the gas velocity, the sound speed, and the pressure in region 400. These three parameters then depend on the initial pressure ratio and the composition of the driver and detonable gases.

To simplify the optimization, an effective pressure p_e and sound speed a_e can be defined for the propagating detonation products. The effective values are those of a conventional static driver that would deliver the same shock strength in a given shock tube. They are related to the actual values in region 400 by

$$p_e = p_{400}\{1 + [(\gamma - 1)/2]M_{400}\}^{2\gamma/(\gamma - 1)} \tag{3}$$

$$a_e = a_{400}\{1 + [(\gamma - 1)/2]M_{400}\} \tag{4}$$

The preceding equations show that the downstream propagation velocity augments the pressure and sound speed relative to the static values.

For reflected shock-tunnel operation the optimization proceeds by choosing the effective sound speed that will tailor the driver-test gas interface in order to yield maximum test time. Then the effective pressure is maximized relative to the peak pressure that occurs in the driver during the operating cycle. Naturally, it is this pressure that must be maintained within the design pressure limit of the driver vessel. Referring to Fig. 8, depending on the initial fill pressure ratio, the peak pressure will be either the initial driver fill pressure or the pressure immediately following the CJ wave.

Figure 13 is an example from the optimization process for a stoichiometric oxyhydrogen mixture with 30% argon diluent. The driver gas is helium. The effective pressure of the detonation products, normalized by either the driver pressure or the CJ pressure (whichever is higher), is shown as a function of the fill pressure ratio. This normalization is chosen under the assumption that the light-gas driver tube and the detonation tube have the same design pressure rating, and therefore the maximum of these two pressures limits the maximum equivalent driver pressure. At the lowest fill pressure ratio the driver does not push on the detonation products and provides no forward velocity. This yields an effective pressure that is less than 40% of the peak pressure behind the CJ wave. At the highest fill pressure ratio shown the driver pressure is sufficient to maintain the pressure behind the CJ wave constant, that is, in the perfectly driven state. However, the effective pressure achieved is only 35% of the fill pressure. In between these extremes at a fill pressure ratio of approximately 20, the normalized effective pressure reaches a maximum of 75%. Because the pressure ratio generated by the CJ

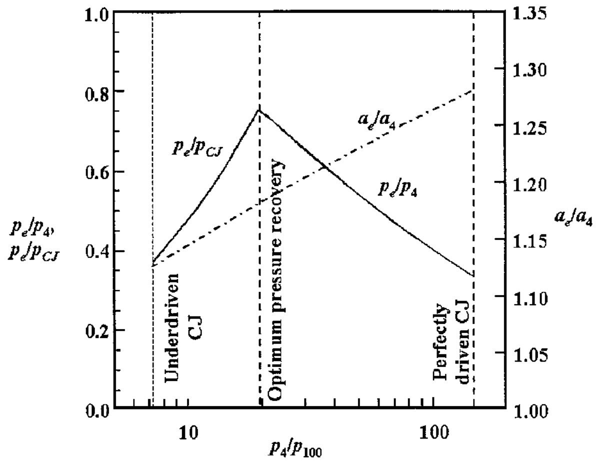


Fig. 13 Dependence of normalized p_e and a_e on the light-gas driver to detonation fill pressure ($4.67H_2 + 2.33O_2 + 3Ar$).

wave for this mixture is also approximately 20, optimum performance occurs when the drive fill pressure and the post-CJ pressures are equal.

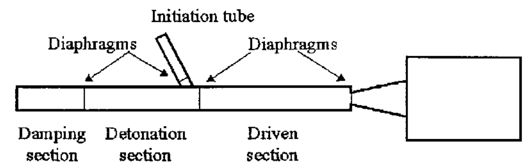
Figure 13 shows that the effective sound speed of the detonation products changes slowly with the fill pressure ratio for a given composition. This effective sound speed needs to be considered for tailored shock-tunnel operation. Of note is that the sound speed of the detonation products is greater than that of the ambient temperature helium driver gas, indicating that the detonation technique allows tailored operation at higher enthalpy than does the helium driver alone. This is consistent with the aims of high-performance driver techniques as elaborated earlier.

Upstream Propagation

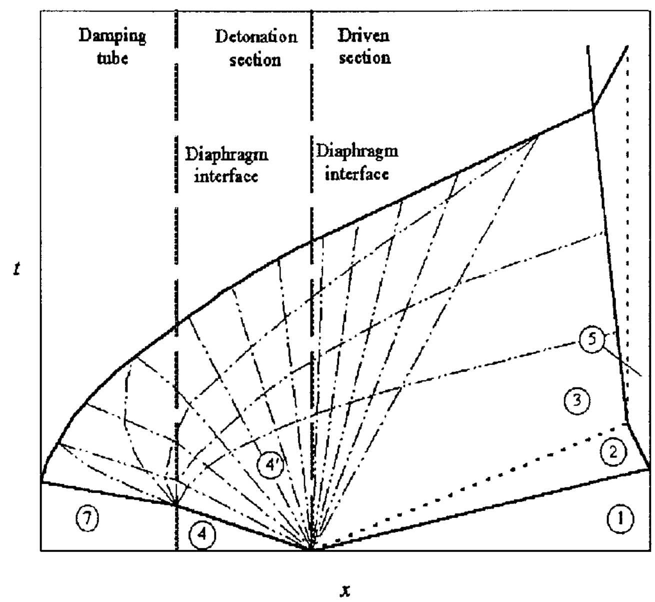
As already highlighted, the upstream propagation mode has an advantage in that it provides a fairly steady supply pressure for driving the shock wave into the driven tube. However, shock reflection at the closed end of the driver tube produces a structural problem. The reflected wave pressure may exceed 200 times the initial driver pressure.[33] For initial driver pressures of 10 MPa or more, the high value of the reflected wave pressure can destroy the facility. This can be overcome by adding a damping tube to the upstream end of the driver tube.[23] A schematic of the test facility and an accompanying, ideal wave diagram are shown in Fig. 14. The damping tube is separated from the driver tube by a light diaphragm. Figure 14b indicates that an upstream propagating detonation wave would break this diaphragm and continue to propagate into the damping tube. The high pressure that would otherwise occur because of shock reflection is well attenuated. The damping tube absorbs the shock loading and helps to reduce the structural load.

The damping pressure and damping gas can be optimized to minimize the end-wall loading. The wave structure in the damping tube depends on the ratio of the CJ pressure to the initial pressure in the damping tube. The high predicted peak end-wall pressure is shown in Fig. 15, indicating the need for a damping tube. Nitrogen is suitable as the damping medium. It has the advantage over air for avoiding reactions with possibly unburned hydrogen. Calculations indicate that p_7 needs to be no less than $p_{\mathrm{CJ}} \times 10^{-4}$ or, equivalently, $0.002p_4$. Tailoring to maximize the test time, unlike conventional shock tubes which is achieved by a unique value of p_4/p_1, is achieved by adjusting the helium/argon dilution rate to stoichiometric oxyhydrogen.

Finally, Yu[24] found that helium addition in general does not improve the operation of the detonation tube in the upstream propagation mode. They used a rich mixture of hydrogen and oxygen. This mixture is ignited by the detonation of a combustible gas in an initiation tube, which breaks the diaphragm and starts a detonation wave moving leftwards. The reflection of the extinguished detonation wave can be influenced by the choice of the gas and the pressure in the damping tube.



a) Schematic of detonation driven shock tube in upstream propogation mode[20]



b) Wave diagram

Fig. 14 Shock tube with detonation driver and additional initiation and damping tubes.

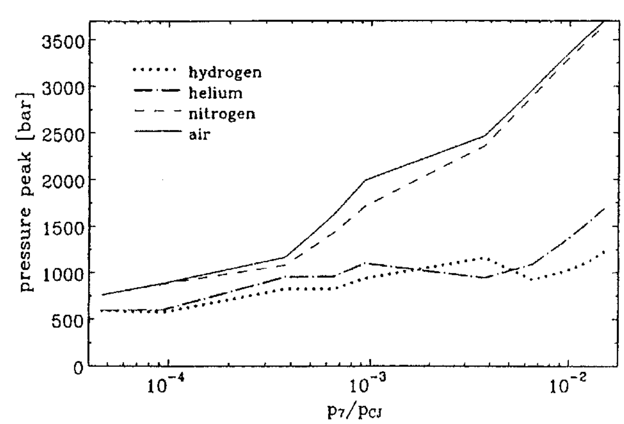


Fig. 15 End-wall peak pressure of the damping tube as a function of p_{CJ}/p_7.

Ignition

There are two methods of ignition,[34] a slow or self-initiation by a low energy source and a fast or direct initiation by an energetic source. In self-initiation a deflagration front transitions to a detonation. The underlying mechanisms for deflagration-to-detonation (DDT) remain unclear, and the DDT length can vary substantially depending on how well the gases are mixed and other factors. Hence, this process is not considered viable for facility development because it may not yield reproducible conditions.

Development of a viable technique for detonation drivers centers on direct initiation, where the detonation forms almost instantaneously at the immediate vicinity of the igniter. The ignition process is crucial to the success of detonation drivers. In general, the ignition energy must exceed a certain threshold. This critical amount of energy for direct initiation depends on the mixture ratio for given pressure and temperature and igniter. Its minimum occurs at stoichiometric ratios.[35] However, Yu[24] suggested that a gain in shock Mach number can be achieved with a hydrogen-rich mixture up to a H_2/O_2 ratio of 5 at high initial pressure $P_{41} \gtrsim 100$. Obviously, an energetic igniter is necessary in such a situation. In a private communication (University of Technology, Aachen, Germany, 1998) Habermann reported fully developed detonation in an initiation tube with a bore of 30 mm and a length of 900 mm, with a turbulence generator, with more than a 60% volumetric dilution by helium or argon. Initial mixture pressure was 4–7 MPa. Ignition was by an exploding wire with an electrical energy release of about 4 J.

Methods used for direct initiation include the use of an exploding wire, electric arc ignition (sparks), explosives, lasers, and shock-induced detonation. Lee[22] exploded a 75-μm copper wire near the face of a diaphragm to initiate detonation in an equimolar acetylene-oxygen mixture at atmospheric pressure. A shock Mach number up to about eight was obtained at a pressure ratio P_{51} of 50. Higher shock Mach numbers were thought possible by increasing the driver pressure. Yu[24] found that sparks and exploding wires yielded weak detonations. Instead, they directly initiated detonations in oxyhydrogen mixtures using a 20-mg tetryl pellet. However, there was significant contamination and erosion of the facility. Stuessy et al.[29] used an energetic arc source capable of delivering 20–25 J in 60 μs.

In shock-induced detonation the shock is generated either by using an auxiliary driver filled with high-pressure gas such as air, nitrogen, helium,[27,30] or hydrogen,[36] or it is generated by a detonation using an initiation tube or preigniter.[23,24] Shock-induced detonation appears to be the most attractive for the downstream propagation mode, with the potential of minimizing the adverse Taylor rarefaction.

Comparison of High Performance Facilities

The fundamental difference between the upstream and downstream modes is the direction of the detonation-induced velocity relative to the detonation wave propagation direction. To assess the effect of this difference on performance, the effective static driver concept can be used. For the upstream mode the effective driver state is related to the CJ state by

$$p_e = p_{CJ}\{1 - [(\gamma - 1)/2]M_{CJ}\}^{2\gamma/(\gamma - 1)} \tag{5}$$

$$a_e = a_{CJ}\{1 - [(\gamma - 1)/2]M_{CJ}\} \tag{6}$$

Performance of the two cycles, with the same initial conditions as in Fig. 13, is compared in Fig. 16. For the upstream mode the peak cycle pressure is the CJ pressure, whereas for the downstream mode the cycle is assumed optimized as shown in Fig. 13 such that the CJ pressure and the light-gas driver pressure are equal and represent the peak cycle pressure. The downstream mode delivers approximately double the pressure performance over the effective sound speed range of interest in comparison to the upstream mode. The temperatures are greater than room-temperature helium.

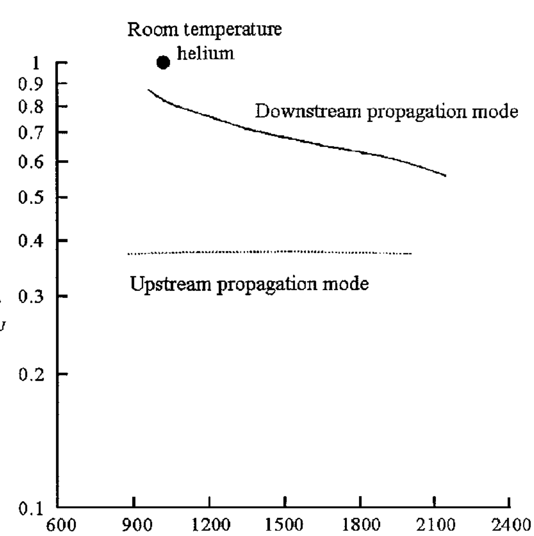


Fig. 16 Pressure recovery of upstream and downstream modes.

Table 2 Comparison of maximum performance of different facilities

Facility	Stagnation pressure, MPa	Stagnation temperature, K	Stagnation enthalpy, MJ/kg
	Shock tunnels		
TH2, University of Technology, Aachen, Germany	63	4,700	6.8
LENS, Calspan, Buffalo, New York	130	8,000	14.4
Rennselaer Polytechnic, Troy, New York	5.8	4,100	6.3
	Free piston tunnels		
HEG, Göttingen, Germany	91	9,730	22.3
TCM2, Marseille, France	123	7,000	25
T4, University of Queensland, Brisbane, Australia	200	8,600	15.8
T5, Caltech, Pasadena, California	62	9,050	22
	Gun tunnels		
Longshot, VKI, Brussels, Belgium	400	2,500	3
C2, LBRA, Vernon, France	35	2,400	2.8
UTIAS, Toronto, Canada	36	2,100	2.4
No. 2, Imperial College, London, U.K.	55	1,070	1.1
University of Southampton, U.K.	60	1,100	1.2
	Hot shot tunnel		
F4, Le Fauga, France	200	5,500	16
	Detonation-driven tunnel and tubes		
University of Texas at Arlington	40.5	4,400	12.5
HYPULSE (Reflected Shock Tunnel Mode) GASL, Ronkonkoma, New York	34	5,000	7
HYPULSE (Shock Expansion Tunnel Mode) GASL	7,000	11,000	26
TH2-D, University of Technology, Aachen, Germany	28	7,460	15.5

Table 1 summarizes the detonation driven facilities known to the authors. The University of Texas at Arlington facility is a shock tube and is currently used for high-pressure plasma, combustion, and detonation research.[30] The other facilities are devoted to aerodynamics testing. Table 2 (adapted from Ref. 37) shows that, among the different impulse techniques for generating high-enthalpy flows, detonation driven facilities occupy an important niche. Detonation driven facilities currently produce enthalpies below that of free piston tunnels but above that of gun tunnels. The enthalpies, when expressed in terms of the binary scaling parameter, are in the range of the reentry corridor.[24] Even though the performance is below that of the free piston tunnel, detonation driven facilities have a few attractive features. First, they are relatively easy to operate, without the problems associated with a heavy piston, such as piston erosion and rebound. Also, there is no need for thick diaphragms to contain high-pressure gas. However, the safe handling of large amounts of hydrogen must be carefully considered.

Conclusions

Recent developments in detonation drivers have indicated that high performance can be obtained for meaningful hypervelocity testing. There are two preferred ways of implementing detonation techniques, namely, a downstream and an upstream detonation mode, depending on the direction of the detonation wave. The downstream propagation mode makes use of shock-induced detonation and can be operated as underdriven, perfectly driven or overdriven, this classification being governed by the subsequent wave structure. Ideally, the Taylor rarefaction should be annihilated by the high-pressure driver. In the upstream propagation mode the Taylor rarefaction problem does not truly exist. However, structural problems require the use of a damping tube. The wave processes in the upstream propagation mode also results in a potentially longer run time than the downstream mode. Theoretical considerations indicate that a higher performance can be obtained by the downstream propagation mode.

The operation of detonation driven facilities is thought to be simpler than that of free piston tunnels. However, the enthalpies that are obtained at present are somewhat lower. Nevertheless, detonation driven facilities can make a useful contribution to the study of various gasdynamics problems. There remains the potential for developing new ways of operating detonation driven facilities with better understanding of detonations. Finally, the possibility of hybrid drivers, combining pistons and detonations, can open up a new class of high-performance facilities.

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