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Survey of Short Duration, Hypersonic and Hypervelocity Facilities (invited paper)

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Survey of Short Duration, Hypersonic and Hypervelocity Facilities

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Hypersonic and hypervelocity testing relies to a large extent on short duration facilities—specialized facilities which possess distinct advantages compared to longer duration, blowdown or continuous facilities. A review is made of the basic operating principles of a number of facilities such as the shock tunnel, the gun or free piston tunnel and the expansion tube. Some recent developments to improve understanding and operation of these facilities are highlighted.

Nomenclature

a	= speed of sound
A	= cross-sectional area
M	= Mach number
p	= pressure
T	= temperature
u	= velocity
1, 2, 3, ...	= regions in wave diagram, Fig. 2b
γ	= specific heat ratio

Subscripts

cs	= contact surface
s	= shock
rs	= reflected shock
∞	= freestream

Introduction

Aerodynamic testing using short duration facilities is a highly specialized testing activity confined mostly to hypersonic and hypervelocity regimes. Early development of such facilities is summarized in Ref. 1 and a short review can also be found in Ref. 2. Recent revival of widespread hypersonics activity has brought a renewed demand for short duration facilities. Although this new era of hypersonics relies heavily on computations, experimentation is still necessary for exploring and understanding flow phenomena[3-14] and for supporting numerical code development.[15-19]

Special requirements in hypersonic testing have spawned a number of exotic facilities, many of which trace their ancestry to the shock tube.[20] These facilities share the common trait of short test times in contrast to blowdown or continuous (that is, "conventional") facilities. In this paper, the duration of the test time is chosen as less than a second; in the majority of the facilities, test times are closer to the 0.1–10 ms range. In any case, the key characteristic of these facilities is that they are all derived from the shock tube or its operating principle.

The variety of facilities found in hypersonic testing can be attributed to the large number of conditions encountered in hypersonic flight and the large number of phenomena to be investigated. The idea of a facility capable of fulfilling all these requirements is attractive but admittedly difficult to realize.[21] For example, at the low hypersonic regime, simulation of perfect-gas flows (Mach and Reynolds numbers only) is adequate. At the extremely high-speed, hypervelocity regime, real-gas simulation becomes necessary. At high altitudes, rarefied conditions exist. In addition, hypersonic laminar-turbulent transition and compressible turbulence, both poorly understood, are not adequately addressed in ground testing. It goes without saying that no single facility can simulate all of the flow conditions and many ingenious attempts have been made to develop ground-based facilities for studying various aspects of hypersonic flight.[1]

Renewed interest in hypersonics has certainly created a demand for short duration facilities and, in fact, such facilities are favored for certain types of testing. Research using short duration facilities is making a comeback from the doldrums of the 1970s, as noted above. Examples of some recent large-scale developments include the restoration of an expansion tube in the U.S.[10] and the construction of a free-piston shock tunnel at Göttingen, Germany.[22] Also, many old facilities have been resurrected, some through donations by industry and government to educational institutions.

Possibly, the main attraction of short duration facilities is that they provide a high-enthalpy slug of test gas at reasonable cost. The underlying principle is to store energy over a long period of time, with low input power requirement, and then releasing the accumulated enthalpy rapidly. The test gas is compressed and subsequently expanded to the desired conditions. There are many practical challenges arising from this principle and these have been tackled most recently through numerical modeling of the flow process and through implementation of advanced, high-speed diagnostics to improve understanding of tunnel operation.

The alternative to short duration facilities may be extremely costly, especially if large blow-down tunnels are contemplated. (Even a small university facility requires power in the megawatt range.) Additionally, one may even argue that for certain purposes, there is no other reasonably viable alternative, such as in simulating near-orbital flight or flight through extraterrestrial atmospheres. The latter application exploits a feature of short duration facilities, that is, they are not restricted to using air as the test gas and can readily

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use other gases as well. Another familiar use of short duration facilities is in heat-transfer studies where the appropriate cold-wall boundary conditions encountered in flight is simulated. The short time of passage of the hot gas enables one to dispense with elaborate thermal protection of the test model or of the instrumentation.

There are, on the other hand, difficulties revolving around the short test time. These difficulties have, fortunately, been greatly reduced with modern high-speed data-acquisition systems. The short test times have also produced ingenious solutions. Diagnostics capabilities have been enhanced over the years through development of electro-optic technologies. In certain areas, such as in optical diagnostics, progress has been impressive but in others, such as in force measurements, there is still room for improvement. Moreover, a major preoccupation of operators and users of short duration facilities remains in understanding the flow quality.

The tenor of this review is, thus, a brief sketch of a number of short duration facilities based on the shock tube since substantial reviews are available already[1,2] and unsteady flow principles can be found in a number of texts, e.g., Ref. 23. Some of these facilities include the shock tunnel, the gun tunnel, the piston tunnel and the expansion tube as shown in Fig. 1. The lineage from the shock tube in all these facilities is clearly seen by the presence of a high-pressure driver separated from the driven tube by a diaphragm. The nonreflected shock tunnel,[24] the reflected shock tunnel,[25] the gun tunnel[26] and the free piston tunnel[27] have a test section connected to the driven tube via a nozzle and, additionally, for the latter two tunnels, a piston is also present. Unlike the shock tunnel in which the test gas is compressed by shocks, in gun and piston tunnels, a piston is used for compression—in the former case, of the test gas, and in the latter, of an intermediate gas which then compresses the test gas—in addition to shock compression. The piston motion can range from slow via a heavy piston whereby the compression is nearly isentropic, or can be fast via a light piston. For the expansion tube, the test section is connected to the driven tube via an "acceleration tube," a scheme which can produce very high speed flows.[28] This paper outlines the authors observations on a number of design and operational problems, emphasizing recent developments. To begin the discussion, a short summary of shock-tube principles will be given next.

The Shock Tube

Gasdynamics texts usually include a description of the shock tube to illustrate unsteady expansion and shock propagation. The shock tube consists of a high-pressure driver tube separated from a low-pressure driven tube by a diaphragm. Typically, the two sections are of the same bore, as shown schematically in Fig. 2a. A test section or a dump tank may be connected to the end of the driven tube. In the latter case, the free jet emanating from the driven tube may be used for testing. A means is provided for pressurizing and, sometimes, heating the driver tube. To provide the proper pressure ratio p_2/p_1, the driven tube, with the appropriate test gas, can be pressurized or evacuated.

Precise control of test conditions is achieved by breaking the diaphragm suddenly to simulate the instantaneous, theoretical initiation of the flow when the desired initial conditions are reached. In some tubes, a diaphragm cutter, such as a pointed rod, is used to pierce a scored diaphragm. Bogdanoff et al.[29] reported the firing of detonation cord taped to the diaphragm to produce rupture. These authors also used a single diaphragm with a precisely milled scoring pattern to produce clean rupture. Alternatively, a double-diaphragm section with a chamber at an intermediate pressure is vented to start the flow.[30] This technique also ensures precise control of the initial pressure ratio p_4/p_1.

Assuming that the diaphragm ruptures instantaneously and that a quasi one-dimensional flow of an inviscid, perfect gas is established, the flow can be easily analyzed. After diaphragm rupture, an unsteady expansion propagates into the driver tube, serving to "empty" it. The process is illustrated by a wave diagram shown in Fig. 2b. The numbering in the wave diagram, *1–5*, follows convention. The high-pressure driver gas propagates to the right, compressing the low-pressure gas in the driven tube. The driver and driven gases are separated by a contact surface. The quiescent driven gas in region *2* moves to the right as indicated by a particle path in Fig. 2b. Testing can be performed utilizing the induced flow, with models placed toward the end of the driven tube. If the driven tube is capped at its end, the shock is reflected whereas an open end causes an unsteady expansion to be reflected.

A point not clearly made in gasdynamics texts is that the tail of the unsteady expansion may move into the driven tube if this tail is supersonic, as shown in the inset to Fig. 2b. This occurs if $u_3 > a_3$ and is encountered in high-performance test facilities. The head of the unsteady expansion, however, always propagates into the driver tube.

Some analytical details of shock-tube flows can be found in Ref. 23 and only a few points will be highlighted here. For a closed driven tube, theoretically, a maximum test time t_{max} can be computed for a driven tube of length L_1 as

$$t_{max} = \frac{(u_s - u_2)(u_s + u_{rs}) L_1}{u_s^2 (u_2 + u_{rs})}. \qquad (1)$$

Since, typically, $L_1 = \mathcal{O}(1\text{–}10\,\mathrm{m})$, $u_s = \mathcal{O}(1\,000\,\mathrm{m\,s^{-1}})$ and u_s, u_2 and u_{rs} are of comparable order, it is clear that $t_{max} = \mathcal{O}(0.1\text{–}10\,\mathrm{ms})$, an extremely short time indeed, but which is the hallmark of all derivatives of the shock tube. (Early experience with shock tubes has shown that viscous effects reduce the inviscid estimate by an order of magnitude.[31,32] A further consideration of test times and their impact on aerothermodynamic testing will be given later.)

It is usual to use the shock Mach number M_s to discuss shock-tube performance since, given initial conditions, M_s must be known to compute the flow in region *2*: large values of M_s are required to achieve hypervelocity conditions. Moreover, the pressure ratio p_2/p_1 is important in discussing shock tube performance and it is given implicitly by

$$\frac{p_4}{p_1} = \frac{p_2}{p_1}\left\{1 - \frac{(\gamma_4 - 1)(a_1/a_4)(p_2/p_1 - 1)}{\sqrt{2\gamma_1[2\gamma_1 + (\gamma_1 + 1)(p_2/p_1 - 1)]}}\right\}^{-2\gamma_4/(\gamma_4 - 1)} . \quad (2)$$

From the simple inviscid model sketched above and with air in the driver and driven tubes, as $p_4/p_1 \to \infty$, $M_s \to 6.16$ and $p_2/p_1 \to 44.1$. A practical limiting shock Mach number, however, is lower at about 3. Although only low shock Mach numbers can be achieved, the shock tube was used successfully for blunt body, stagnation region studies in which test conditions closely follow the Mach-number independence principle.[23]

The practical limitation of $M_s \approx 3$ using air can be overcome by various means, resulting in so-called high-performance shock tubes. It was thought that a stronger shock may be generated by an area reduction from the driver to the driven section, using either a monotonically convergent or a convergent-divergent diaphragm section. Improvements in having an area convergence are not substantial. For example, under the conditions of $p_4/p_1 \to \infty$ and $T_4/T_1 = 1$, the increase in M_s when $A_4/A_1 \to \infty$ is only about 9–15 percent for a number of different driver-and-driven gas combinations, with the larger gains coming from using a driver gas with a high acoustic speed, namely, helium or hydrogen.[33] Thus, the gain in M_s is not especially remarkable. However, a recent study suggested improvements can be gained using a driven tube with a converging taper.[34] Aerodynamics testing using short-duration facilities has favored the use of shock tube derivatives instead of the shock tube because of improved performance. Some of these facilities, shown schematically in Fig. 1, will be briefly discussed next.

Shock Tunnel

The deficiencies of the shock tube in simulating high Mach number flows led to the development of the shock tunnel.[24] Returning to the wave diagram of Fig. 2b, it can be noted that the high-enthalpy gas in region *2* can be expanded to hypersonic speeds. A supersonic nozzle attached to the end of the shock tube suffices, thereby resulting in a shock tunnel. A shock tunnel with such an arrangement is operating in a *nonreflected* mode: a wave diagram illustrating this is shown in Fig. 3. The inherent problem of an extremely short run time found in shock tubes remains for nonreflected shock tunnels. However, an attractive feature of nonreflected operation is that, because the incident shock in the driven tube is not reflected, the hot, test gas does not stagnate; thus, possible nonequilibrium test conditions are avoided.

Unlike the nonreflected mode, the more popular method of operating a shock tunnel is the *reflected* mode in which a convergent-divergent nozzle is attached to the end of the driven tube. The throat of the nozzle is small because, in hypersonic flow, the area ratio between test section and throat is very large, being in the hundreds or thousands. (For a given test Mach number, the actual area ratio is even larger than simple predictions from quasi one-dimensional inviscid theory.) The small opening provides an excellent approximation to the closed shock tube. Within the nozzle-throat region is a secondary diaphragm to separate the driven tube from the test section, the latter being at an initial pressure lower than the former to ensure that the tunnel can be started.

When the primary shock arrives at the nozzle throat, it is partly reflected and partly transmitted, trapping the test gas (region *5* in Fig. 4). This pressurized and heated gas is most likely in chemical equilibrium. The high enthalpy is obtained via compression by two major shock systems. The reflected shock interacts with the oncoming contact surface and is then partly reflected back toward the nozzle. Further weak reflections occur in region *5′* in the wave diagram. The high enthalpy reservoir in region *5* is drained through the nozzle to provide the test flow. Region *5′* also provides a test flow, the gas in this region possessing higher stagnation enthalpy than that in region *5*. Although the flow appears to be subjected to a rising pressure with oscillations due to multiple shock reflections, recent studies[35] suggested that the shocks are weak and a gradual pressure rise is encountered.

Under certain conditions, the reflected shock interacts with the contact surface and is totally transmitted. Regions *5* and *5′* in Fig. 4 then become one, and a long test time—typically an order of magnitude longer than otherwise—is achieved. The shock tunnel is then said to be operating in the "tailored interface" mode.[25] Using this terminology, the wave diagram of Fig. 4 depicts an "overtailored" condition. If the interaction between the reflected shock and the contact surface results in secondary reflection in the form of an unsteady expansion, the process is "undertailored."

Minucci and Nagamatsu[35] re-examined the equilibrium interface operation of a reflected shock tunnel to achieve useful, high enthalpy conditions. In this method of operation, progressively weaker shock reflections between the contact surface and the end of the driven tube produce the required test conditions. Referring to Fig. 4, the test conditions are achieved toward the end of region *5′*. Early experience with the equilibrium interface mode of operation was disappointing, with the test gas being cooler and with shorter test times than expected. Careful analysis showed that the equilibrium interface condition, with acceptable test times and high enthalpy conditions, can be achieved. In supporting experiments, reservoir pressures of 5.8 MPa (840 psia) and 4 100 K (7,400 °R) were obtained.[35]

Shock tunnels have found a useful niche in hypersonic testing, possessing many advantages over shock tubes or conventional hypersonic tunnels. Reflected tunnels have test times longer than shock tubes. In comparison with conventional tunnels, the shock tunnel can achieve higher stagnation enthalpies of importance in hypervelocity testing. The high stagnation temperatures also overcomes the problem of air liquefaction.

The short test time, compared to conventional tunnels, can be both advantageous or disadvantageous. The advantage is that the tunnel (especially the throat), model and instrumentation do not need elaborate thermal protection. The major disadvantages are that fast instrumentation is required, dynamic stability measurements are difficult and, in many instances, a quasi-steady flowfield, with a duration shorter than the starting process, is generated which needs a detailed understanding of tunnel flow processes to extract useful data from experiments.

As highlighted in the Introduction, a broad range of flow regimes is encountered in hypersonic flight. Experience has shown that shock tunnels are ideally suited for Mach and Reynolds number simulation, rather than for simulating real-gas effects, and are thus seldom operated with maximum test section velocities above 5–7 km s^{-1} (16–23 kft/sec).

Gun Tunnel

In a gun tunnel, a piston is set into motion when the primary diaphragm is ruptured. Multiple shock reflections occur between the end of the driven tube and the piston face, thereby compressing and heating the gas in region *2*; see the x-t diagram in Fig. 7. This gas ruptures a secondary diaphragm and is then expanded into the nozzle. The piston provides a larger degree of flexibility compared to the shock tunnel. The piston mass can be small or large, giving rise to different operating conditions. Compared to shock tunnels, the run time of a gun tunnel is longer, frequently being in the 0.1–0.01 s range, because all of the test gas is exhausted out of the driven tube by the piston. In a modification of the gun tunnel, the free piston tunnel (Fig. 1) uses a heavy piston to compress the driver gas adiabatically to high enthalpy conditions.[13,36]

Expansion Tube

Figure 8 is an x-t diagram illustrating the operation of an expansion tube. The expansion tube consists of a shock tube with a third, so-called expansion, section beyond the driven tube. This section is evacuated and separated from the driven tube by a thin diaphragm. When the expansion tube is started, the arrival of the primary shock at the secondary diaphragm causes its rupture. The test gas originally in region *1* is accelerated by the shock (region *2*) and then expanded into the expansion section (region *5*). The test flow is at a relatively high enthalpy.

The expansion tube suffers from a number of drawbacks, unfortunately. The test time remains quite short which limits its use in hypersonic configuration testing since only small models can be tested. The test flow quality is regarded as poor. One reason is that the test flow travels through a long distance and viscous effects diminishes the inviscid test core substantially. Another reason is that the state of test flow is poorly defined because the gas is processed by two nonequilibrium processes, namely, a shock followed by an unsteady expansion. A recent theoretical study[37] provided some understanding as to why only certain operating conditions result in acceptably steady test conditions. Nonetheless, the high enthalpies that are achievable in an expansion tube makes it useful for real gas simulation, such as in supersonic combustion research.[10] Paull et al.[38] reported the use of a free piston driver for an expansion tube facility to improve performance. Finally, the expansion tube appears similar to a nonreflected shock tunnel, the difference being that the expansion tube possesses a second diaphragm and lacks a nozzle. Hence, the expansion tube may be modified to include a nozzle to accelerate the test flow even further.

Some Recent Developments

High Performance Drivers

Equation (2) shows that p_2/p_1 can be greatly increased, with a corresponding increase in stagnation enthalpy, if $a_4 \gg a_1$. High performance drivers utilize elaborate techniques for achieving hypervelocity flows by increasing the acoustic speed of the driver gas. This increase can be achieved by using a light driver gas, such as helium or hydrogen, or by heating the driver gas.

Theoretically, for a uniform shock tube with $p_4/p_1 \to \infty$, $T_4/T_1 = 1$ and helium driving air, $M_s = 10.9$, a 77 percent improvement over using air as the driver gas. With H_2 as the driver gas, $M_s = 22.6$, a 270 percent improvement. Further improvements are obtained by heating the driver gas. Thus, with $T_4/T_1 = 2$, a helium driver produces a theoretical $M_s = 14.8$ while a hydrogen driver produces a theoretical $M_s = 31.9$.

The illustrations above show that, in principle, a high-performance driver relies on a technique of discharging a hot, pressurized ("high enthalpy"), low density gas to drive another gas to hypervelocity conditions. The techniques include resistive,[39] combustion,[29] explosive,[40] electric arc,[41] or compressive[13] heating of the pressurized driver gas—recently, Bogdanoff[42] suggested novel techniques to improve shock-tube performance. However, a high-enthalpy, stagnant gas, when accelerated, may produce a nonequilibrium flow of poor quality for simulating extremely high velocity conditions. To ensure that the test gas remains in chemical equilibrium, some of the energy can be added to a flowing gas instead of a stagnant gas, such as by adding an MHD accelerator in the nozzle.[43,44] Recent proposals include optical[45] energy addition. Some other suggestions can be found in Ref. 46.

Flow Establishment Time

The discussion here concerns tunnels which possess nozzles, particularly those with a diapraghm separating the driven tube from the nozzle. Flow enters the nozzle when this diaphragm is ruptured. The idealized nozzle starting process described above is depicted by a wave diagram in Fig. 5.[47,48] In the figure, the transmitted shock is labelled as the primary shock and it can be seen that an expansion wave dominates the process instead of the starting shock system.[47] The secondary shock moves upstream relative to the test gas, but downstream in the laboratory frame of reference. These wave systems, captured by recent numerical simulations,[49,50] are in actuality highly distorted—an example from Jacobs' full Navier–Stokes simulation at 0.5 ms after nozzle start is shown in Fig. 6.[49]

Since test times are extremely short, it is crucial to minimize the nozzle flow establishment time. This time is minimized if the secondary shock remains downstream of the upstream head of the unsteady expansion, Fig. 5. Smith[47] also mentioned the need to maintain a low, initial reservoir pressure, and pointed out that the pressure must be below the steady-flow static pressure at the nozzle exit. However, a definite criterion on the actual pressure level is not known.

Moreover, it is not merely the nozzle flow establishment time that is relevant but, additionally, the flow establishment time around the test model, this time being the result of either molecular or turbulent diffusion instead of adjustment by wave propagation in the external flow. This flow establishment time is described by the nondimensional parameter

$$G = \tau u_\infty / L, \tag{3}$$

where τ is the flow establishment time and L is a characteristic length.[51] There are two points worth noting through the application of Eq. (3). The first is that for hypervelocity testing, the flow establishment time around a model is reduced and this can be used to advantage. On the other hand, flow establishment around long, slender models, such as for aerospace plane development, takes a longer time and data obtained from such tests may be compromised.

Laminar flow over a flat plate is established when $G \approx 2$ (Ref. 52) but Navier–Stokes simulations show that, among a number of configurations, flow establishment for a circular cylinder at $G = 46$ is the longest because of the large region of flow separation.[53] For turbulent, flat plate flow, $G \approx 1$ although this may be insufficient if flow separation exists.[52] Flow establishment in conditions of shock-induced separation is especially pertinent in recent research. Holden[54] suggested that the establishment time in laminar separation is determined by the time for an acoustic wave to traverse the total length of the interaction region and not primarily by mixing. It is likely that the establishment time in turbulent separation will be less because of the more intense mixing and the laminar criterion can be used as a conservative upper bound. An important point here is that the characteristic length for studies of shock boundary-layer interactions is not the length of the flat plate where such interactions are typically studied but is the length of the shorter interaction region.[55–57]

Test Conditions

The amount of time available for testing is affected by unsteady wave propagation through the shock tube and nozzle. For a nonreflected shock tunnel, the test time is bracketed by the end of flow establishment and by either the arrival of the contact surface between the driver and the driven gases or the arrival of the reflection of the unsteady expansion wave. The test time is usually determined by examining transducer records, an example of which can be found in Ref. 58.

A time lag arises between detection of the start of the test time at the end of the driven tube and the arrival of test flow at the test section. If this time lag is not properly accounted for, errors will arise in data analysis. For a number of facilities, the quasi-steady test time is sufficiently long that this problem is not encountered, the initial time lag being considered to be part of the model starting process. However, for a reflected shock tunnel that is operating far from tailored conditions or a gun tunnel, the stagnation pressure measured at the end of the driven tube changes drastically with time, to produce a wide variation in measured test pressures. A proper normalization procedure takes into account the time lag between a stagnation pressure measurement and a test pressure measurement to yield acceptable results; this is described in Ref. 56. A consequence of this procedure is that the measurements are not sensitive to Reynolds number. Thus, care must be taken to ensure that such a lack of Reynolds number sensitivity is actually the case.

Nozzle Design

Although nozzle design is not restricted to short duration facilities but is of broader interest, it is worthwhile to review some recent developments. Historically, hypersonic nozzle design is an extrapolation of supersonic practice, being based on the method of characteristics with a boundary-layer correction.[59] The characteristics are assumed to be reflected off the displacement surface whereas in actuality the characteristics reflect from positions nearer to the wall.[60] The difference in the design and actual characteristics is not critically important in supersonic nozzles because these have thin boundary layers. In hypersonic nozzles, where the boundary layers can fill half the nozzle, the difference between design and actual characteristics becomes significant. (Modern methods in designing high performance nozzles will be discussed later.)

Conical and contoured axisymmetric nozzles prevail in hypersonic testing following realization that three-dimensional, rectangular or two-dimensional nozzles produce highly nonuniform boundary layers.[1] In a large number of hypersonic facilities, a conical nozzle (instead of a contoured nozzle) is used with a throat insert of variable area to obtain a wide Mach number capability economically. The nozzle is kept short to minimize boundary layer growth by having a large conical angle. But the conical angle cannot be too large for axial flow gradients to be acceptable because a conical nozzle produces radial, source flow in the test section. In practice, the nozzle boundary layer produces a contouring effect to counteract the source flow[61] and typical semi-angles are in the 5–15 deg range.

The problem of obtaining a uniform test flow of reasonable size becomes a serious issue for Mach numbers above 10. High-quality flows are especially necessitated by stringent CFD code validation requirements. A comparison of nozzles designed by the traditional coupled-characteristics-and-displacement-correction method and a Navier–Stokes solver reveals that the former method is acceptable up to Mach 8.[62] At higher Mach numbers, the Navier–Stokes solver found that compression waves originate near an inflection point required by the method of characteristics.

The parabolized Navier–Stokes (PNS) equations[23] appear suitable for designing hypersonic nozzles, possessing the necessary sophistication without exorbitant cost. Korte et al.[63] applied an optimization procedure based on the PNS equations, together with an algebraic turbulence model, to design hypersonic nozzles. For a Mach 10 conical nozzle, the design showed a slight Mach number gradient as might be expected from the conical shape. For a Mach 6 contoured nozzle, there was a negligibly small Mach number gradient toward the nozzle exit while a Mach 15 contoured nozzle showed some Mach number variations toward the nozzle exit. Korte et al. suggested that an uncancelled wave still existed in the nozzle. Subsequently, Korte et al.[64] designed a contoured Mach 15 axisymmetric nozzle for a helium tunnel with laminar flow. The laminar design is more sensitive to the number and location of knots for cubic spline fits than the turbulent design. Korte et al. attributed the decreased sensitivity in the latter case to the dampening of small surface curvature changes by the large turbulent shear stresses.

An aspect of nozzle design which may be important is the relaminarization of turbulent flow due to the favorable pressure gradient.[65,66] The different laminar and turbulent boundary-layer growth rates may affect the test flow quality. But, relaminarization is not well understood and a recent computation shows unexplained discrepancies between two turbulence models.[67] The possibility of relaminarization is one more complication in developing high-quality nozzles.

Another feature of nozzles attracting recent attention is surface smoothness. Surface waviness can cause strong disturbances which can interfere with a model downstream. This problem is particularly important in designing so-called quiet tunnels for boundary-layer stability and transition research[68] and highly polished surfaces are needed to maintain laminar flow. Beckwith et al.[68] suggested a smoothness criterion given by a roughness Reynolds number of

$$Re_k = \rho_\infty u_\infty k_{max}/\mu \approx 10 \tag{4}$$

where the flow properties are evaluated at the maximum roughness height of $y = k_{max}$. Other requirements for achieving a quiet test core are discussed in Ref. 69. At Mach 3.5 and a unit Reynolds numbers of 40–60 million per meter, $k_{max} = 0.8\,\mu$m.[68] Equation (4) indicates that the allowable roughness height decreases with an increase in unit Reynolds number. Mach number effects are still not explored but are expected through testing in a helium tunnel at Mach 18.[70] Perhaps a criterion based on some sort of viscous interaction parameter should be appropriate.

For high enthalpy testing, the rapid expansion in a hypersonic nozzle causes the vibrational energy of the gas to be frozen,[2] producing a nonequilibrium flow. Canupp et al.[71] recently examined the nonequilibrium, laminar, nitrogen flow in a Mach 14 nozzle. They found that a nozzle designed assuming equilibrium, perfect gas flow will produce a nonuniform flow when there is vibrational nonequilibrium. Comparisons between computations and experiments for nitrogen nozzle flows[72,73] revealed discrepancies due to freezing of the vibrational mode.

Research utilizing hypersonic tunnels can be viewed as serving two broad goals, namely, to provide physical understanding through broad parametric experiments and to provide high-quality data to support numerical modeling and design. The traditional use of conical nozzles remains very much a part of the hypersonic scenery due to their versatile, parametric capability and generally acceptable flow qualities. The design and fabrication of contoured nozzles are expensive propositions when one realizes that a nozzle designed for a particular Mach number and a given stagnation enthalpy will be off-design at any other test condition. Such a nozzle may be of limited utility if off-design flow quality deteriorates unacceptably because hypersonic testing frequently requires testing through wide parametric ranges. Thus, an investigation of off-design nozzle performance is worthwhile. In summary, although recent studies have heightened awareness of the problem of obtaining high-quality flow, a compromise has to be made between obtaining good flow quality and versatility. The nature of the particular study would dictate the desire of using a conical or a contoured nozzle.

Future Challenges

The development of hypersonic flight vehicles employing airbreathing propulsion systems will severely tax the capabilities of available hypersonic test facilities, especially in real gas simulation. The discrepancy between existing facility capabilities and flight conditions is shown in Fig. 9. Indicated in this figure are the flight region of interest and current capabilities. The facility stagnation temperature and pressure requirements needed for simulation of flight conditions at the higher Mach number portion of the map represent severe challenges to facility designers. In the authors' opinion, high-performance impulse facilities with augmentation in the form of direct thermal or kinetic (MHD) energy addition to the supersonic flow downstream of the nozzle throat represent one of the few methods available to achieve the requisite temperature and pressure levels. This and other novel concepts are elaborated by Chinitz et al.[74] Although research into these concepts has been done on a small scale, additional research is needed to develop these concepts to the point of justifying the development of a full-scale test facility. In particular, the issue of acceptable flow quality in facilities of this type must be addressed.

Conclusions

A review of principles of short duration tunnels and some pertinent problems was provided. It is evident that recent developments have attempted to improve understanding of the flow processes. This improvement will result in an improved ability to interpret test data. Advanced optoelectronic diagnostics, not reviewed presently, have also broadened the capability of short duration facilities and increased data accuracy.

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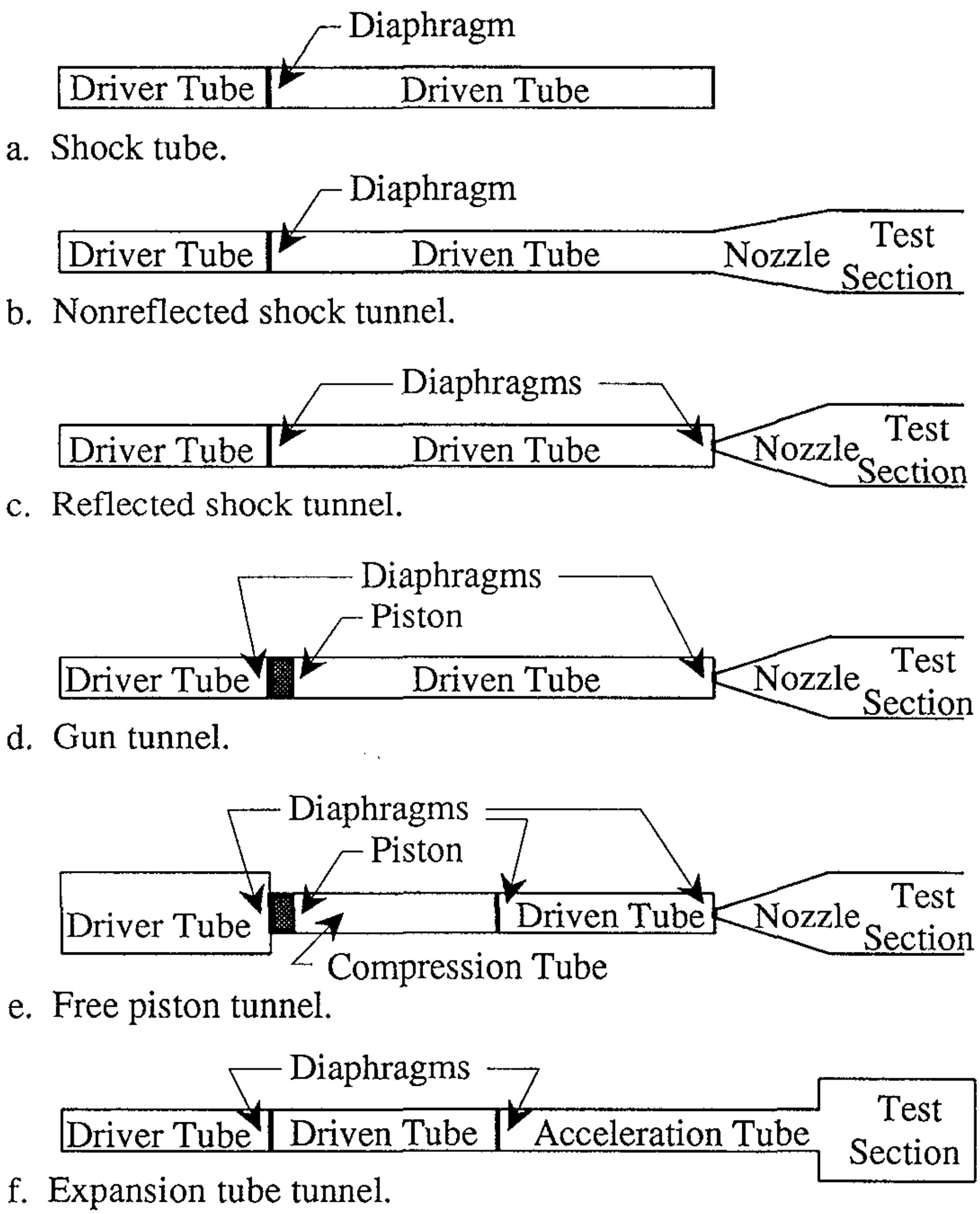

Figure 1: Examples of short duration facilities.

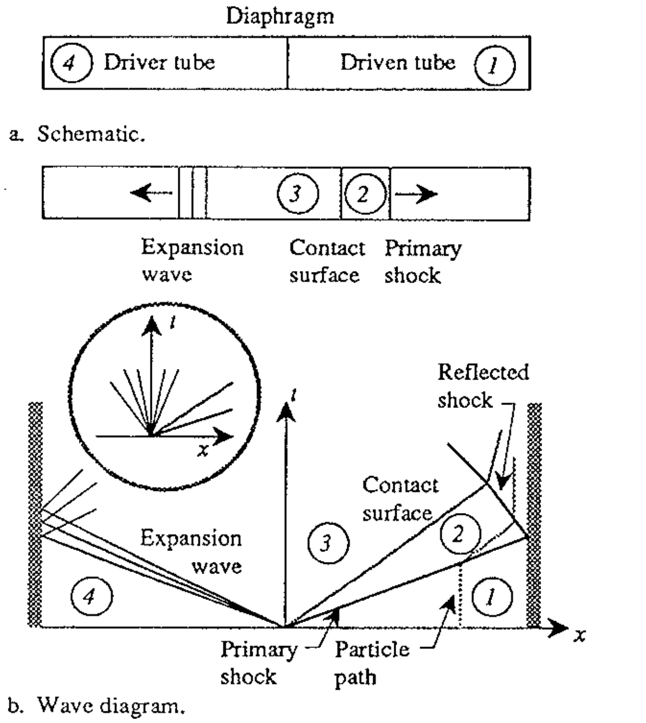

Figure 2: Schematic of shock tube and wave diagram.

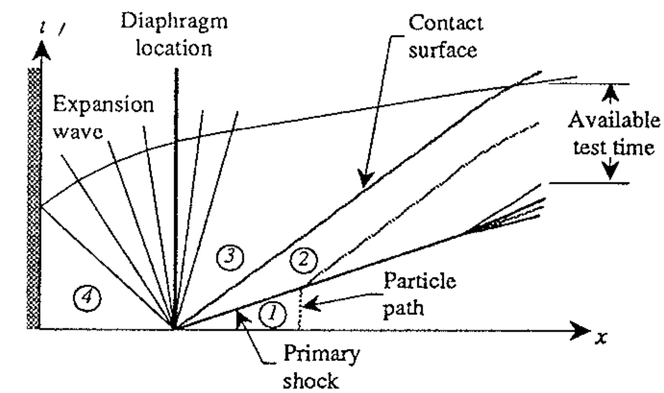

Figure 3: Wave diagram for a nonreflected shock tunnel.

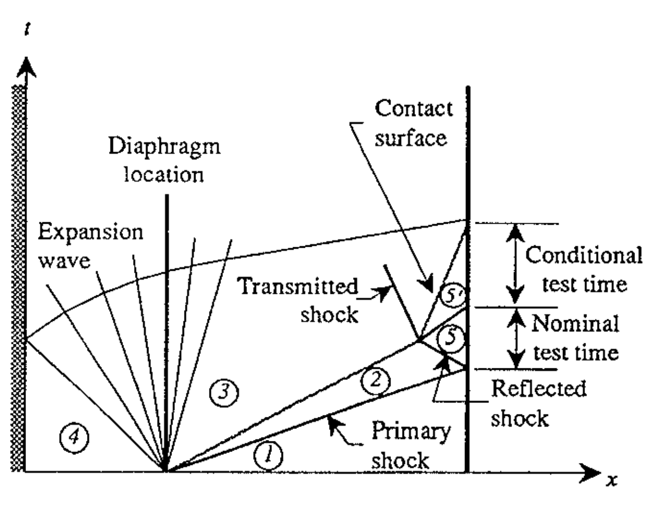

Figure 4: Wave diagram for a reflected shock tunnel.

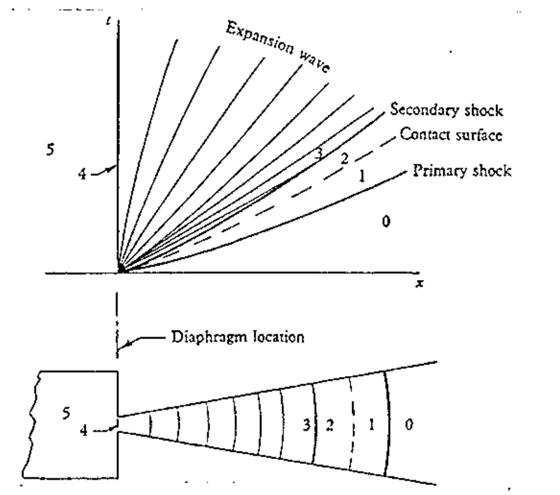

Figure 5: Nozzle starting process (from Ref. 47).

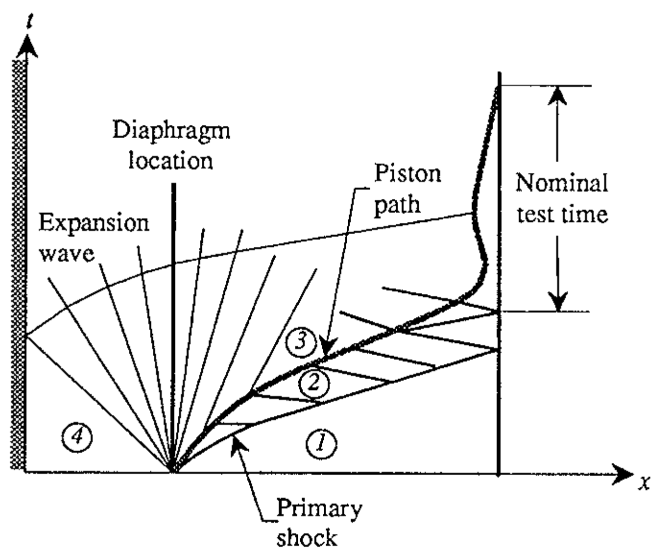

Figure 7: Wave diagram for a gun tunnel.

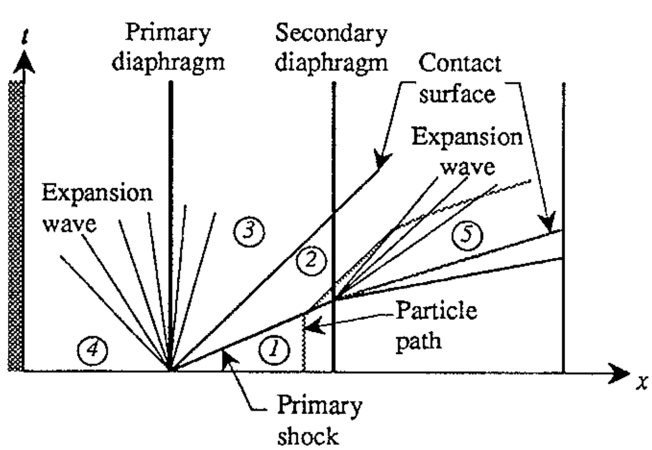

Figure 8: Wave diagram for expansion tube.

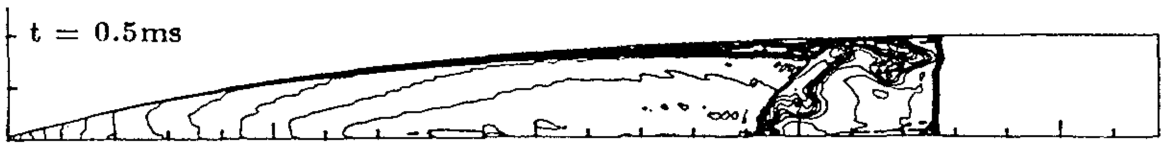

Figure 6: Mach number contours in an axisymmetric nozzle (from Ref. 49).

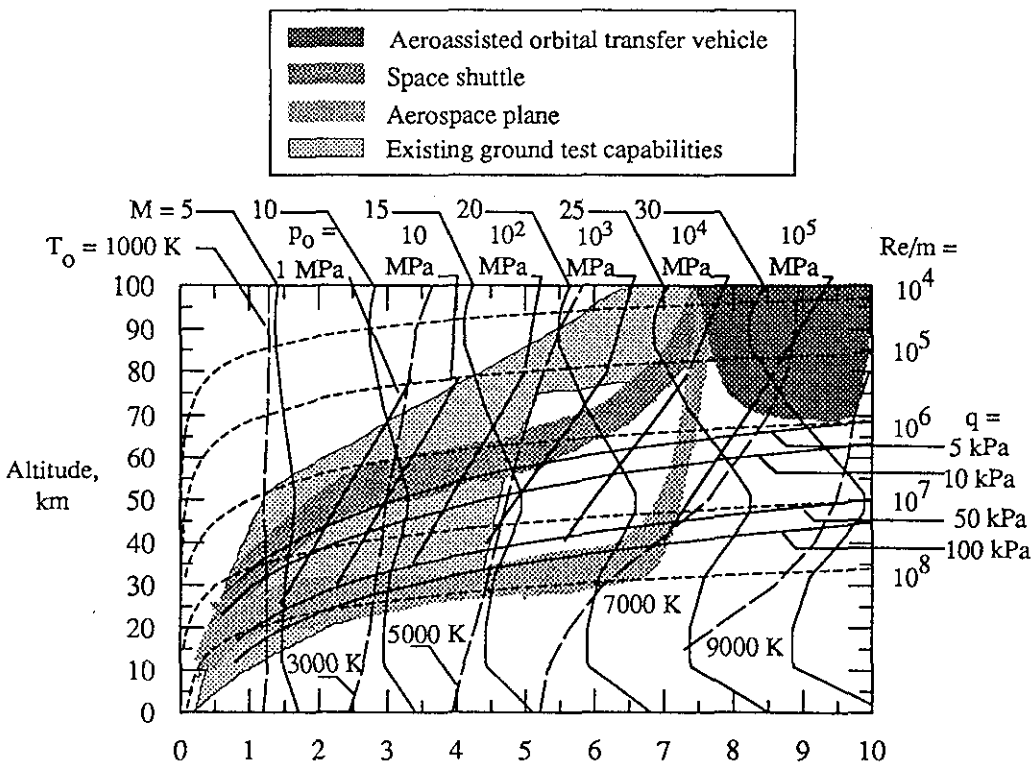

Figure 9: Existing ground test capabilities and requirements for airbreathing flight.