JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 7, No. 2, April–June 1993

Hypersonic Shock-Tunnel Testing at an Equilibrium Interface Condition of 4100 K

M. A. S. Minucci*
Instituto de Estudos Avançados—CTA, São José dos Campos, São Paulo, 12231 Brazil
and
H. T. Nagamatsu†
Rensselaer Polytechnic Institute, Troy, New York 12180

An investigation has been conducted on the operation of the RPI 0.61-m-diam hypersonic shock tunnel at an equilibrium interface condition of 5.8 MPa and 4100 K. The numerical analysis shows a strong dependence of the equilibrium interface pressure and temperature on the initial driver temperature and incident interface speed. A fairly good agreement was observed between the measured equilibrium pressure and the predicted value for the shock-tunnel conditions. For the particular test conditions investigated, useful test times of up to 6 ms were detected by ionization and radiation intensity measurements.

Nomenclature

A = cross-sectional area
a = local speed of sound
h = enthalpy
M = Mach number
p = pressure
T = absolute temperature
U = velocity
γ = ratio of specific heats

Subscripts
rt = transmitted conditions
s = incident shock conditions
t = shock-tube conditions
0 = reservoir conditions
1 = driven tube initial conditions
2 = conditions downstream of the incident shock wave
3 = conditions downstream of the interface
4 = driver tube initial conditions
5 = reflected conditions

Superscripts
' = equilibrium interface conditions
n = conditions existing after nth interactions
* = nozzle throat conditions

Introduction

THE development of hypersonic vehicles like the national aerospace plane (NASP), NASP derived vehicles (NDVs), and aeroassisted orbit transfer vehicles (AOTVs), will rely heavily on the parallel progress of ground testing and computational fluid dynamics (CFD). Undoubtedly, the former will play an important role not only as a "CFD validator," but also in understanding the complex high temperature hypersonic flow phenomena.

Due to the extremely high reservoir conditions, pressure, and temperature needed for an "on the ground" flight condition duplication,[1-3] only impulse facilities appear to be the possible candidates.

Although impulse facilities may vary in shape and size, all of them share the same characteristic of useful test times limited to a few milliseconds. A good description of such facilities can be found in Ref. 4. The investigation on a particular type of impulse facility, namely the hypersonic shock tunnel,[5] operating at an equilibrium interface condition of 5.8 MPa and 4100 K is the objective of this article.

The equilibrium interface technique was first suggested by Hertzberg[6] and later investigated by Copper,[7] Lapworth,[8,9] Dunn,[10] and more recently by Neumann.[3] By this technique, high temperatures and pressures are obtained through the successive shock wave reflections occurring between the moving interface and the end of the driven tube. These reflections become successively weaker as the interface is continuously decelerated and eventually brought to rest. When the reflected shocks become weak enough, so that no appreciable changes in the temperature or pressure occur, the equilibrium condition is reached.

Copper[7] investigated the equilibrium interface technique for incident shock wave Mach numbers ranging from 3.29 to 7.26 using ambient temperature helium as the driver gas and air as the driven gas. He observed from pressure history measurements conducted at the end of the driven tube that an equilibrium condition was reached for the complete Mach number range investigated. He also noticed some discrepancy between the measured equilibrium pressures and those calculated from the measured M_s using a perfect gas wave diagram. Copper verified that the successive shock compressions after the first shock wave-interface interaction could be approximated by an insentropic compression process. Using this result he was able to calculate the equilibrium enthalpy and temperature from the measured pressure value. The maximum equilibrium enthalpy and temperature from the measured pressure value. The maximum equilibrium enthalpy was more than six times the reservoir produced using the tailored-interface technique (one shock wave interface interaction) and lasted for about 2.4 ms. This time was taken from the moment the equilibrium was achieved (constant pressure) until the arrival of the front of the expansion waves, which has been reflected off the driver tube end wall. The driver and driven tubes were both 3.66-m long and circular in cross section. Their inside diameters were 7.62 and 5.40 cm, respectively.

Presented as Paper 91-1707 at the AIAA 22nd Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, HI, June 24–26, 1991; received September 16, 1991; revision received April 6, 1992; accepted for publication April 8, 1992.

*Captain Brazilian Air Force, Research Engineer, Divisão de Lasers. Member AIAA.

†Active Professor Emeritus of Aeronautical Engineering, Department of Mechanical Engineering. Fellow AIAA.

Lapworth,[8,9] using ambient temperature hydrogen as the driver gas and ambient temperature nitrogen as the test gas, conducted both pressure and temperature measurements near the driven tube end wall for below tailoring conditions (M_s = 4.3) and close to tailoring conditions (M_s = 5.8). Based on these measurements, he observed that the duration of the high temperature was always very much less than the duration of the high pressure plateau. Furthermore, he verified that the duration of the hot gas decreased as the incident shock wave Mach number was increased. He experimentally determined that for an incident shock wave Mach number of 5.8, the duration of the high temperature was little longer than 2 ms while the steady pressure lasted for about 10 ms. The shock tube used by Lapworth had driver and driven tubes measuring 8.53 and 5.49 m in length, respectively.

Later, Dunn[10] using heated hydrogen (680 K) as the driver gas and air in the driven tube, conducted pressure and radiation-intensity measurements near the end wall for an incident shock wave Mach number of 12.2. As observed by Lapworth,[8,9] Dunn also verified that the duration of the hot gas was much less than that based on pressure measurements alone. However, he detected the existence of an expansion wave as a result of the first shock wave contact surface interaction where a shock is theoretically predicted. This was assumed by the author to be caused by a local heating of the interface produced by hydrogen-oxygen combustion, which altered the local speed of sound. As a pertinent conclusion to the equilibrium interface technique, Dunn concludes that although significant gains in enthalpy appear to have been achieved on the basis of the pressure data alone, radiation-intensity measurements show the test gas is quite cool. This investigation was conducted in the Calspan 0.82-m-diam hypersonic shock tunnel. This facility had a 2.74-m-long driver section and a 29.6-m-long driven tube. The inside diameters were 7.62 and 15.24 cm, respectively.

Although the results reported by Lapworth and Dunn seem to negate the advantages of the equilibrium interface technique, some important aspects have to be pointed out. First of all both investigators used hydrogen as the driver gas; therefore, the dramatic drop in temperature observed by these authors may have been caused by an excessive contamination of the test gas by the driver gas. This would cause a premature arrival of a cold gas mixture to the end of the driven tube and a consequent rapid decrease of the temperature. In addition to that, Dunn used air as the test gas and as acknowledged in his article, combustion may have taken place at the interface region. Based on these facts, the writers believe that the conclusion drawn by Dunn[10] regarding that the test gas produced by the equilibrium interface technique is quite cool—although the pressure data shows otherwise—should not be generalized.

More recently, as reported by Neumann,[3] investigators at Boeing have been quite successful in operating their 0.76-m-diam combustion driver hypersonic shock tunnel in an equilibrium interface condition of 39 MPa and 6657 K. In the experiments, a mixture of H_2-O_2-He is ignited in the driver section producing an incident shock wave Mach number of 8.2 in air. According to this author, useful test times of 300 μs have been achieved by this technique. This shock tunnel (as reported in Ref. 11) has a 4.06-m-long driver and a 7.62-m-long driven tube. Both sections have inside diameters of 7.62 cm.

In the present study, the Rensselaer Polytechnic Institute (RPI) 0.61-m-diam hypersonic shock tunnel was operated at an equilibrium interface of 5.8 MPa and 4100 K. For this purpose cold helium was used as the driver gas and air as the test gas. Pressure measurements along with ionization and radiation-intensity measurements indicate useful test times in the 3–6-ms range depending on the nozzle throat used. The achievement of the above-mentioned equilibrium reservoir temperature and pressure permitted the successful tests of a two-dimensional Scramjet inlet over the flow Mach number range of 8–18[12] with real gas effects (T_0 = 4100 K, p_0 = 5.8 MPa, h_0 = 6.3 MJ/kg). More recently the equilibrium interface technique was used to produce the above high enthalpy reservoir conditions for the hypersonic high temperature tests of a three-dimensional Scramjet inlet.[13]

In order to better understand the physics of the equilibrium interface condition, a computer code for equilibrium air was written to model the shock wave end wall reflections and the shock wave interface intersections. Although the code assumes an inviscid one-dimensional flow, a reasonably good agreement was verified between the predicted pressure history and the experimental data.

Review of the Equilibrium Interface Condition

Shock-Wave Interface Interaction

Let us assume the initial condition given in Fig. 1 which corresponds to a head-on collision between a normal shock wave and an idealized sharp contact surface. When adequate conditions[14] are present the interface shock wave interaction produces a transmitted shock into the driver gas and a reflected shock back to the nozzle entrance. This situation is shown in Fig. 1a. The condition depicted in this figure is of particular interest since the reflected shock wave will increase both the pressure and the temperature of the test gas.

However, as pointed out by Glass and Hall,[14] the one-dimensional head-on collision between a shock wave and a contact surface can produce two other possible final states. Once the incident shock "crosses" the interface, either a Mach wave or a rarefaction wave, in addition to the shock wave case, can be generated. A simple way to understand this phenomenon is, e.g., to imagine that the pressure behind the interface, immediately downstream of the transmitted shock, is lower than that existing upstream of the interface. This situation will lead to an expansion wave propagating toward the nozzle entrance (Fig. 1b) lowering both the pressure and the temperature of the test gas slug. The interface is then said to be "undertailored." This also corresponds to the particular situations investigated by Lapworth[8,9] and Dunn.[10]

The reflected Mach wave case will correspond to the situation where the pressure existing behind the interface is identical to the one in front of it (Fig. 1c). As a consequence, both the temperature and pressure of the test gas slug remain unchanged. When this "equilibrium" is reached, the interface is said to be "tailored." If such an equilibrium is reached after the first shock wave interface interaction, the shock tunnel is

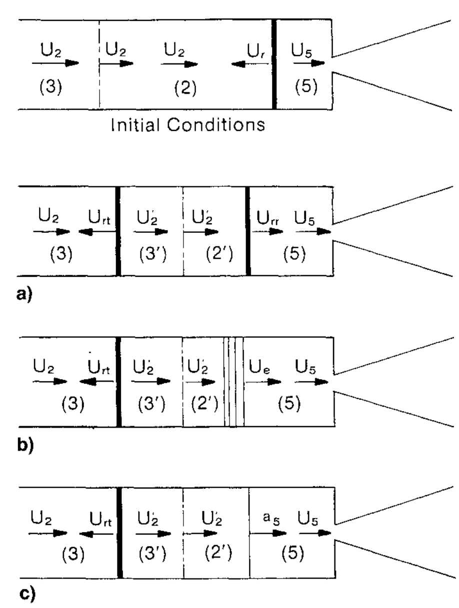

Fig. 1 Possible conditions resulting from the head-on collision between the reflected shock wave and the contact surface.

said to be operating at a tailored interface condition. On the other hand, if the equilibrium requires a multiple number of interactions (>1) the shock tunnel is said to be operating at an equilibrium interface condition.

By using the same reasoning adopted in the above paragraphs it is quite straightforward to see that the case of the reflected shock wave will occur when the pressure downstream of the interface becomes instantaneously higher than the one upstream of it. This situation corresponds to an "overtailored" interface.

When the reflected wave is an expansion or a Mach wave, the contact surface is also said to be "soft." This usually happens when the gas behind the interface has a high acoustic speed which is the case of helium, hydrogen, hydrogen/oxygen combustion products, or electrically heated drivers. On the other hand, when the reflected wave is a shock wave, the contact surface is called "hard," since it approaches the behavior of a "solid wall" moving downstream in the shock tube.

Although hydrogen, helium, and even heated drivers exhibit very high accoustic speeds, the reader must be reminded that the temperature behind the interface can be many times lower than the initial driver temperature. This is because of the insentropic expansion existing between the undisturbed driver gas and the driver gas adjacent to the interface.

The relationship between temperatures T_3 and T_4, and U_2 for a calorically perfect driver gas is given by

$$T_3 = T_4[1 - 0.5(\gamma_4 - 1)U_2/a_4]^2$$

Therefore, the right combination of initial driver temperature and incident shock strength will make the use of hydrogen, helium, and even heated drivers suitable for the equilibrium interface technique. In other words, the achievement of an equilibrium interface condition for a specified state and gas composition of the driver and the driven gases, is theoretically possible for incident shock wave Mach numbers greater than that required for the corresponding tailored interface.

Calculation of the Equilibrium Interface Temperature

The actual measurement of the reservoir temperatures generated by shock tunnels or shock tubes is by no means an easy task and can be subject to appreciable experimental error.[8,9] A relatively recent work developed by Chang et al.[15] using a laser-based absorption technique for temperature measurements in shock tubes seems promising. However, the complexities associated with the laser absorption system and the necessity of a seeding level of 100–500 ppm of OH do not make this technique very suitable or affordable.

Another possibility is the calculation of the equilibrium interface temperature based on the measured equilibrium interface pressure. At this stage it is of interest to point out that an agreement within 3% has been reported[15] to exist between the actual measured reflected temperature and that calculated from the measured M_s. This result encourages the computation of the equilibrium interface temperature from other measured quantities such as pressure. One way is to make the assumption that the compression existing between the reflected pressure and the equilibrium is isentropic.[7] This assumption is based on the fact that the successive shock waves involved in the compression process are rapidly decreasing in strength as the contact surface becomes "softer."

Copper[7] noticed that the approach to equilibrium is not done by a series of discrete shock waves decreasing in strength. Instead, as will be seen later, the pressure increases in a rather smooth fashion. Copper explained this observation on the basis of the existence of a constant pressure mixing region of finite width, instead of a sharp discontinuity, separating the driver and driven gases. Therefore, the entering reflected shock wave gradually increases in strength as it passes through this region and the re-reflected disturbance consists of a family of converging characteristics. The consequent absence of discrete shock waves, and the result instead of a gradual compression, provides additional support to the isentropic compression hypothesis presented above. Another possible way of calculating the final equilibrium interface temperature is the one discussed in the numerical section of this article. In this method, the end wall reflections and the reflected shock interface interactions are actually modeled using the one-dimensional Euler equations for equilibrium air.

Problems Associated with the Equilibrium Interface Technique

So far, with the exception of the negative aspects observed in the experiments conducted by Lapworth[8,9] and Dunn,[10] the equilibrium interface technique has only shown advantages. These advantages are higher reservoir temperatures and pressures than the tailored-interface technique while possibly retaining some of its test time attractive features. Unfortunately, this is not completely true. As for both techniques, the "steady-state" conditions will eventually end upon the arrival of either the rarefaction waves from the driver or the contact surface. The latter will physically happen due to the presence of the nozzle throat at the end wall of the driven tube. However, the arrival of the interface to the nozzle entrance will occur sooner than ideally predicted due to 1) diffusion of the driver gas into the driven one through the interface; and 2) the so-called "jetting" phenomenon.

The diffusion through the interface causes the latter to spread out due to the contamination of the driven gas with the driver gas. This process is accelerated by the large temperature difference across the contact surface and, eventually, by the driver gas low molecular weight.[16]

On the other hand the jetting phenomenon[3] is caused by viscous effects. Cold gas flow behind the contact surface moves through this surface faster near the walls, inside the boundary layer, than in the inviscid core creating a jetting effect.[3] As a consequence of this the driver gas penetrates the driven gas—contaminating the latter and spreading the contact surface even more.

As a result of these effects, although the boundary layer is being physically decelerated by the successive reflected shocks, the spreading causes the edge of the contaminated region to reach the nozzle entrance. This causes the useful test time to be terminated sooner than theoretically predicted. Since there is no pressure difference across the interface, the detection of the exact moment when the contaminated gas starts flowing cannot be made through pressure measurements. Instead, spectroscopic,[3] temperature,[8,9] radiation intensity,[10] ionization, or heat transfer measurements must be used.

Regarding the diffusion problem, it is known from the kinetic theory of gases[16] that it can be considerably minimized by operating the driven tube at higher pressures and by employing a heavier driver gas—helium instead of hydrogen. The use of higher driven pressures will also attenuate the jetting phenomenon by increasing the Reynolds number and, therefore, thinning the boundary layer over the shock-tunnel walls. In addition to that, the utilization of large diameter driven tubes can also minimize viscous effects which enhance the jetting.

Recent results[17] indicate that the use of a thin layer of a high molecular weight gas (i.e., argon) initially separating the driver gas from the test gas, can indeed reduce the spreading of the mixing layer.

Numerical Modeling of the Equilibrium Interface Condition

Computer Programs EQUINT, HSTR, and HSTR1

In order to better understand the physics of the equilibrium interface condition and to tentatively predict its performance for different test conditions, two numerical approaches were developed. The first one uses the simple but efficient isentropic assumption discussed in the previous section. In this first approach, the measured equilibrium interface pressure, in conjunction with the measured p_5 and M_s, are used to determine the equilibrium interface temperature. For this purpose a computer routine, equilibrium interface (EQUINT), was written[18] having inputs T_5, p_5, and p_5'. By assuming an isentropic process between the reflected and equilibrium states and using the equilibrium thermodynamic properties for air (curve-fitted by Tannehill and Mugge[19]), the program determines T_5' and other relevant air properties.

The reflected temperature and pressure used by EQUINT are calculated by another computer program, hypersonic shock tunnel with real gas effects (HSTR),[18] developed previously. This code requires the incident shock wave Mach number, the initial driven temperature and pressure, and both the driven and nozzle throat cross-sectional areas. The last two inputs permit the modeling of the partial reflection of the shock wave off the nozzle entrance. The airflow in the shock tunnel is assumed to be inviscid, one-dimensional, and in thermodynamic equilibrium. As for the EQUINT code, the thermodynamic equilibrium properties for air were taken from Ref. 18. Since p_5 is experimentally measured, it can be compared to the value predicted by HSTR. The agreement between the experimental and numerical value has been verified to be within 4%.

As a result, the code EQUINT can calculate the air properties at the equilibrium interface condition and, therefore, the reservoir conditions for the hypersonic airflow in the nozzle. Although this is a great feature for the data reduction for actual shock tunnel testing, EQUINT does not give any information about the mechanism of the equilibrium interface technique itself. In order to "fill this gap," a third computer code, HSTR1, is being developed.[18]

The HSTR1 code actually models the reflected shock wave contact surface interactions that take place during the approach to the equilibrium. As for the HSTR program, the airflow is assumed to be one-dimensional, inviscid, and in thermodynamic equilibrium. In this code, helium, at a specified (by the user) temperature, is the driver gas and it is modeled as a calorically perfect gas. The reflections of the shock wave off the nozzle entrance are modeled in the same manner[18] as done for HSTR.

The interactions of the reflected shocks with the helium interface are numerically modeled by simultaneously solving two sets of one-dimensional Euler equations: one for the transmitted shock (in helium) and the second one for the rereflected shock (in the equilibrium air) as shown in Figs. 1a and 1c. The computation is terminated when a Mach wave is produced from either the shock wave nozzle reflection or from the shock wave interface interaction. As a result, HSTR1 does not yet model the situation described in Fig. 1b where expansion waves are reflected back to the nozzle entrance. When the computer program runs into this situation, the calculation is aborted and an error message is issued. The criterion used to predict whether reflected shock waves or rarefaction waves will be generated is the one suggested by Glass and Hall.[14]

Numerical Results

As will be seen from the following numerical simulations, several parameters affect the performance of the equilibrium interface technique. Therefore, in order to obtain some fundamental information regarding the operation of the RPI shock tunnel at this condition, the incident shock wave Mach number was kept 5.8, whereas, the initial driven temperature and pressure were kept at 25°C and 3.4 KPa, respectively. These values correspond to typical operational conditions of the RPI facility. Additionally, a driven tube to nozzle throat area ratio of 16 was also prescribed. In these experiments, only the initial driver state was varied by increasing T_4 from 0 to 500°C. Since both M_s and T_1 are to be kept constant, this corresponds to physically adjusting the initial driver pressure in such a way that the strength of the produced shock will not be altered.

Figures 2 and 3 show the variation of the equilibrium interface pressure and temperature, respectively. As would be expected, by increasing the initial driver gas temperature, the

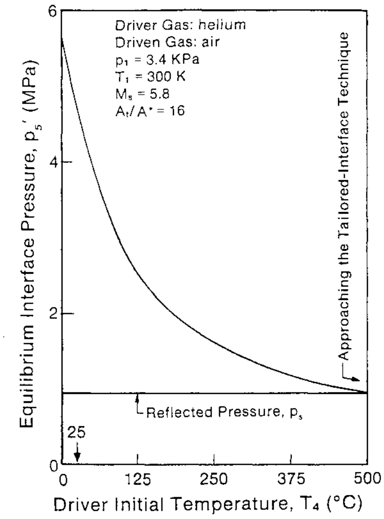

Fig. 2 Variation of the equilibrium interface pressure with the driver gas initial temperature.

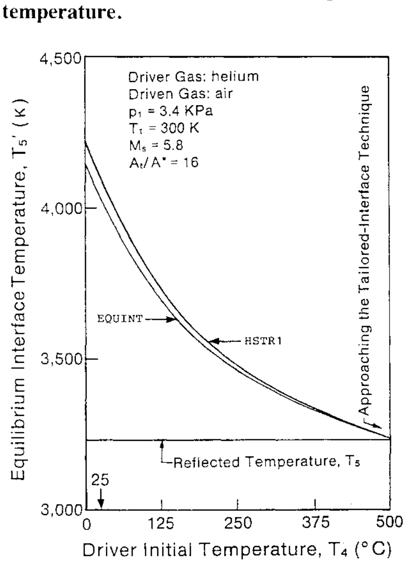

Fig. 3 Variation of the equilibrium interface temperature with the driver gas initial temperature.

interface becomes softer and increasingly less overtailored. As a result of that, both the equilibrium interface pressure and temperature decrease with the increasing driver temperature. At 500°C we practically achieve the tailored interface condition for an incident shock wave Mach number of 5.8 and heated helium as the driver gas.

It is important to point out that the curves shown in Figs. 2 and 3 do not asymptotically approach the lines representing the reflected pressure and temperature. They actually will cross them at some temperature a little above 500°C. This is due to the fact that beyond this point the interface will be undertailored and rarefaction waves will result from the reflected shock wave interface interaction. These rarefaction waves will bring both the final pressure and temperature to values below the initial reflected ones.

Figure 3 also presents the equilibrium temperature calculated through the use of the EQUINT code. For this purpose p_5, T_5, and p_5' (Fig. 2) were used as the input data. From this figure it becomes evident that under the present conditions the isentropic compression assumption is indeed valid.

Although the decrease of the equilibrium interface pressure and temperature with the increasing initial driver temperature was expected, the rate of this decrease was not. It is of particular interest to notice the slope of the curves in Figs. 2 and 3 near the driver gas temperature of 25°C (ambient). The very steep slope of the curves in this region indicate that small increments in T_4 will cause considerably large losses in p_5' and

T_5'. This observation seems to have been accidentally verified in practice. Fluctuations in the initial driver gas temperature, introduced by the high pressure helium compressor,[18] caused some scattering in the measured equilibrium interface pressure. It is important to point out that no appreciable changes were observed in the measured M_s.

Also of interest is how the transmitted shock wave velocity after the first shock-interface interaction $U_{rt}^{(1)}$ behaves. The variation of this velocity with T_4 is presented in Fig. 4. The observation of this figure leads to a startling fact. For low values of T_4 (lower than 67°C), the transmitted shock wave velocity assumes a negative value. This means that the transmitted wave moves toward the nozzle entrance—trailing the refracted interface—instead of moving toward the driver end. Since the ambient temperature, 25°C, is still lower than the 67°C, the operation of the driver gas (helium) at such temperature will produce a transmitted shock with the above characteristic. This particular situation is shown in the x-t diagram of Fig. 5. As seen in Fig. 4 for an initial driver temperature of about 67°C, the first transmitted shock will be stationary and beyond that point the transmitted shock will propagate toward the driver end.

The type of motion imparted to the transmitted shock wave after the first reflected shock contact surface interaction is more important than the reader may think. From Fig. 5 it becomes clear that when $U_{rt}^{(1)} < 0$, the first transmitted shock will intersect the next transmitted ones much sooner than when $U_{rt}^{(1)} > 0$. This means that the shock overtaking processes (as discussed by Glass and Hall[14]) may take place close enough to the tunnel end wall (nozzle entrance) to influence the equilibrium interface condition during the useful test time. These shock overtaking processes may increase the equilibrium interface pressure even more and the temperatures predicted by the present model. However, due to the relatively more complex calculations involved, these processes have not been introduced in the HSTR1 code yet.

An issue of paramount importance for the shock-tunnel overall performance is the useful test time. As stated previously in this article, when operating at an equilibrium interface condition, one of the parameters limiting the duration of the useful test time is the arrival of the contact surface (mixing layer) to the nozzle entrance. Therefore, the deceleration of the interface resulting from the interactions with the reflected shocks becomes important. Figure 6 shows the variation of the interface initial speed to the interface final speed ratio resulting from the first contact surface reflected shock interaction. The deceleration of the interface becomes more efficient as T_4 is increased. This is due to the correspondingly higher helium temperatures T_3 existing downstream of the contact surface causing the interface to become softer.

Although soft interfaces can be easily decelerated, a quick look at Figs. 2 and 3 reminds us that they are equally inefficient

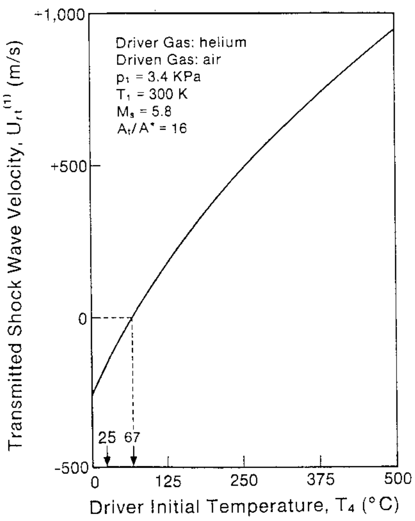

Fig. 4 Variation of the transmitted shock velocity, after the first reflected shock interface intersection, with the driver gas initial temperature.

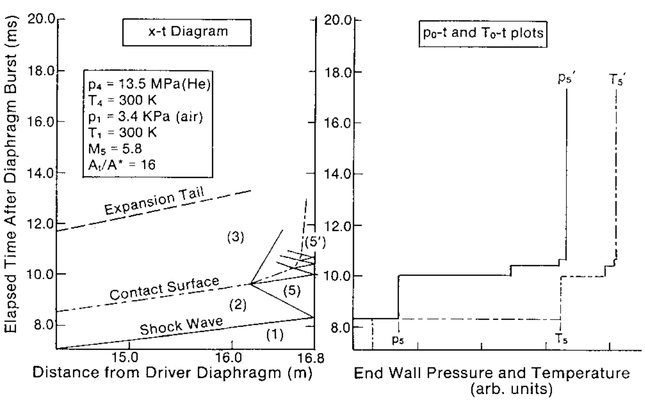

Fig. 5 Wave diagram and end-wall pressure and temperature histories at the equilibrium interface condition (T_4 = 25°C).

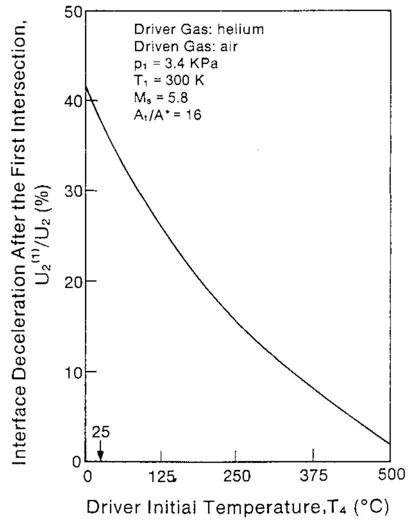

Fig. 6 Variation of the interface velocity, after the first intersection with the reflected shock wave, with the driver gas initial temperature.

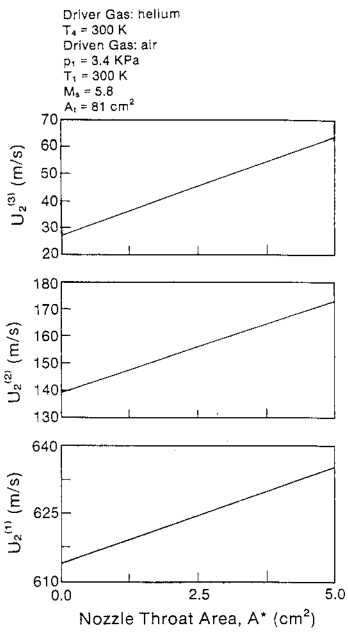

Fig. 7 Dependence of the contact surface deceleration on the nozzle throat area.

in producing high equilibrium interface pressures and temperatures. Moreover, the jetting phenomenon discussed previously becomes more pronounced at low interface speeds,[3] which is highly undesirable.

In order to investigate the contact surface deceleration dependence on the nozzle throat area, Fig. 7 shows the variation of $U_2^{(1)}$, $U_2^{(2)}$, and $U_2^{(3)}$ with the mentioned parameter. As could be expected, the deceleration suffered by the contact surface increases as we decrease the nozzle throat area, other conditions stayed the same. In other words, for a given initial mass of air in the driven tube, the time required to flow this mass through the nozzle throat decreases as we increase A^*.

Another interesting result from Fig. 7 is that for a given A^* the minimum interface deceleration occurs after the first reflected shock contact surface intersection. This is evident since after each interaction the gas temperature behind the interface increases causing it to become less overtailored.

Experimental Data Obtained at an Equilibrium Interface of 4100 K

Experimental Apparatus

The shock-tunnel stainless steel driver tube is 4.6-m long with an internal diameter of 10.2 cm. The maximum driver tube operational pressure is 20.7 MPa with a safety factor of 2 and it is designed for operation with a near room temperature driver gas. The driven tube is 16.8-m long with the same internal diameter of the driver. The tube material is stainless steel and it is separated from the driver tube by a double diaphragm section. Separating the driven tube end from a 30 deg included angle conical nozzle, there is a clamping section which houses a thin scored aluminum diaphragm. This diaphragm bursts upon the arrival of the incident shock wave and the resulting flow in the nozzle is exhausted into a 5.7-m^3 dump tank. Test models can be installed at the exit of the 0.61-m exit diameter conical nozzle inside the dump tank. Figure 8 shows an overview of the RPI hypersonic facility.

Three pressure transducers installed upstream of the nozzle entrance in a reinforced section, are used to trigger the data recording system, to pulse the schlieren light source, to measure the shock wave speed, and to determine the reservoir pressure history. One ionization gauge[5,18] and a RCA silicon photodiode model C30807E are installed 20-cm upstream of the nozzle entrance to indicate the duration of the high temperature gas and the arrival of the contact surface. Further upstream from the nozzle entrance, two thin film platinum heat transfer gauges[5,16] supplied additional information on the incident and reflected shock wave velocities as well as determined the propagation and spreading of the contact surface.[17]

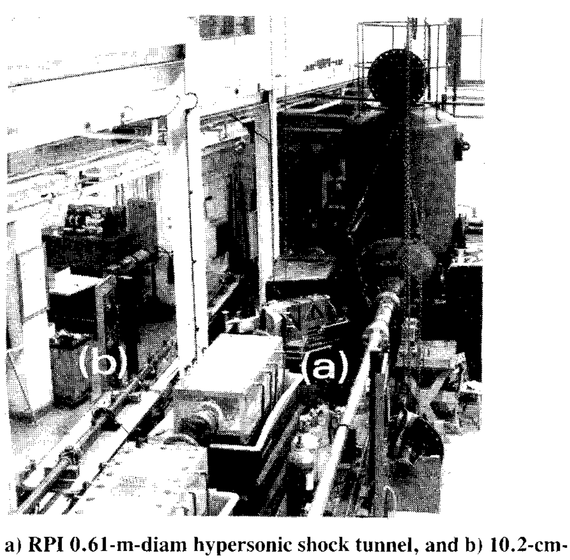

Fig. 8 a) RPI 0.61-m-diam hypersonic shock tunnel, and b) 10.2-cm-diam low pressure shock tube.

A second photodiode, identical to the one described above, was used at the test section so that information on the start, duration, and end of the hot airflow in this section could be obtained. Figure 9 shows a schematic view of the relative location of the above-described instrumentation. In all tests, the driven and driver initial pressures were 3.4 KPa (air) and 13.5 MPa (helium). Prior to each test, the driven section was evacuated, flushed with dry high purity air, and then pumped to the desired final pressure.

A 23-m long, 10.2-cm inside diameter low pressure shock tube is used to calibrate the sensors installed in the hypersonic shock tunnel. This facility is shown in the left corner of Fig. 8. A more detailed description and the operation of the RPI hypersonic shock tunnel and shock tube are discussed in Ref. 18.

All pressure histories, both in the model in the test section and in the shock tunnel, are measured by piezoelectric pressure transducers. The outputs from these transducers and from the other sensors are fed into a Tektronix test lab 2520 data acquisition system and a Nicolet model 4094C digital oscilloscope.

Optical investigation of the flow over test models is made possible through thick optically selected 20-cm-diam plate glass windows. A single-pass schlieren arrangement can be used to obtain the photographic records of shock waves and the boundary layers. Due to the high enthalpy reservoir conditions (h_0 = 6.3 MJ/kg; T_0 = 4100 K), air becomes luminous over the model surfaces. Air-luminosity photographs were taken simultaneously with the schlieren photographs through the use of a Canon 35-mm still camera and a Sony 8-mm video camera. A schematic view of the optical recording set up can be seen in Fig. 9.

Experimental Results

Figure 10 shows typical pressure histories recorded during the Scramjet inlet tests.[18] The top trace corresponds to the reservoir (equilibrium interface) pressure history as seen by a pressure transducer located at the nozzle entrance. The subsequent pressure traces correspond to pitot-pressure histories obtained for the different flow Mach numbers tested. Each one of these traces belongs to a different shock-tunnel run and they were obtained by a reference pitot-pressure probe located at the nozzle exit plane.[12,18] The pitot-pressure histories are aligned in time with respect to the reservoir pressure trace. In this way, the time delay existing between the former traces and the latter is representative of the nozzle flow starting time, which is of the order of 350 ms. It is of interest to notice the excellent pressure constancy reached at the equilibrium interface condition.

The traces shown in Fig. 10 do not completely characterize the useful test time available. Important information concerning the duration of the hot gas flow is presented in Fig. 11. This figure shows again the reservoir and pitot-pressure histories for reference. In addition to these, the output of the photodetector installed at the test section observation window was also included. This trace clearly indicates a constant radiation emission for roughly 6 ms which is indicative of the test time. This emission corresponds to the self-luminescence produced by hypervelocity hypersonic airflow coming to a dead stop at the test section end wall. Photographic records,[18] as the one shown in Fig. 12, do indicate that the intensity of the light emission is strong enough to light up the whole interior of the dump tank.

Figure 11 provides relevant information concerning the net effect of the produced equilibrium interface conditions on the hot gas flow in the test section. On the other hand, Fig. 13 gives some idea of how the reservoir conditions were attained. This figure shows the outputs from a pressure transducer, an ionization gauge, and a photodiode located 20-cm upstream of the nozzle entrance. The ionization gauge starts to react when the incident shock wave arrives at that location. The subsequent rather strong fluctuations in the output voltage

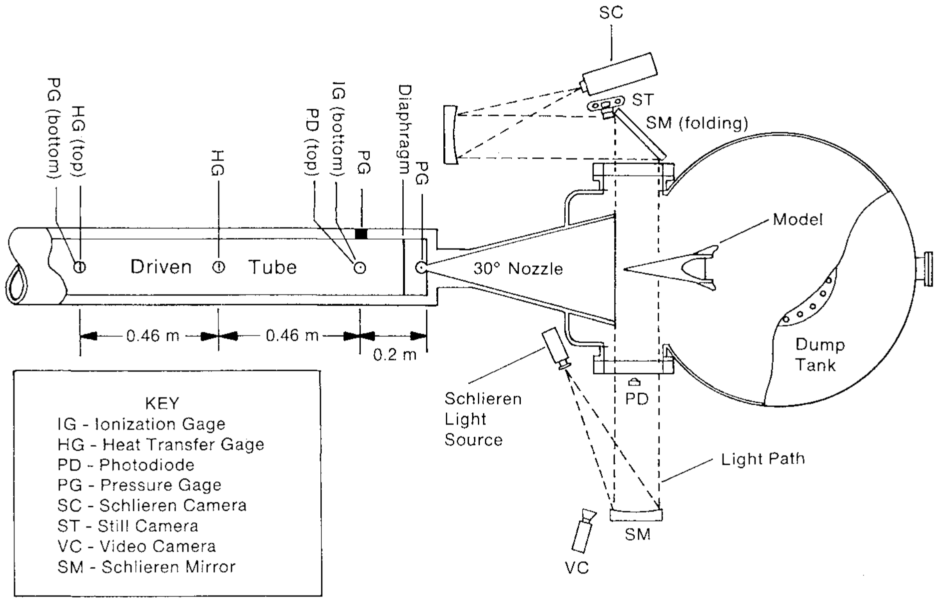

Fig. 9 Schematic view of the hypersonic shock tunnel instrumented section and test chamber.

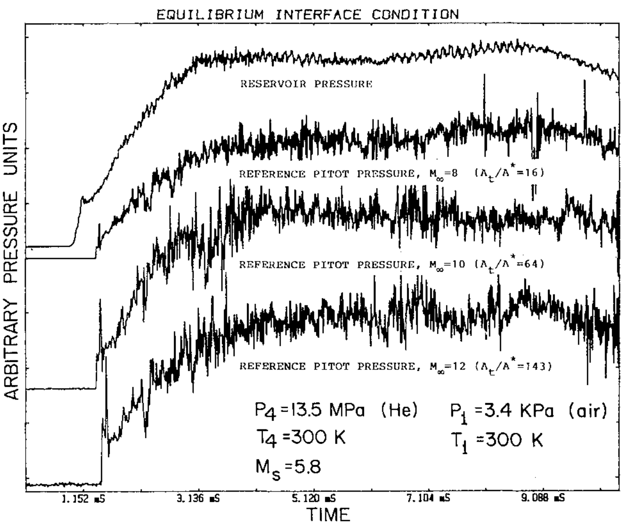

Fig. 10 Typical reservoir pressure (top) and test section pitot-pressure traces obtained for the operation of the shock tunnel in the equilibrium interface condition.

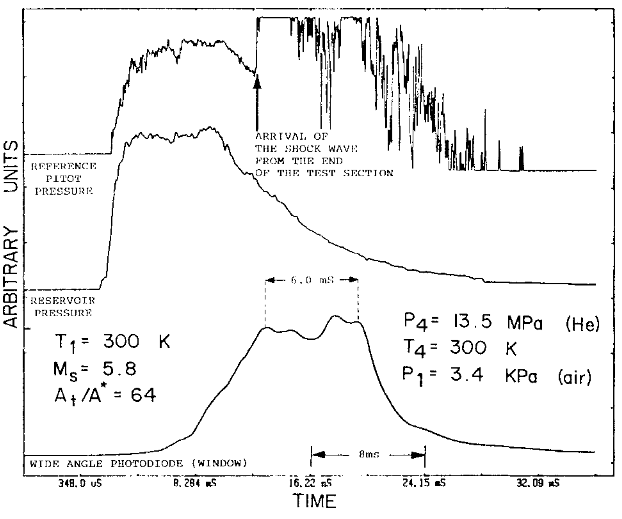

Fig. 11 Pressure and radiation—intensity traces obtained for the operation of the shock tunnel in the equilibrium interface condition.

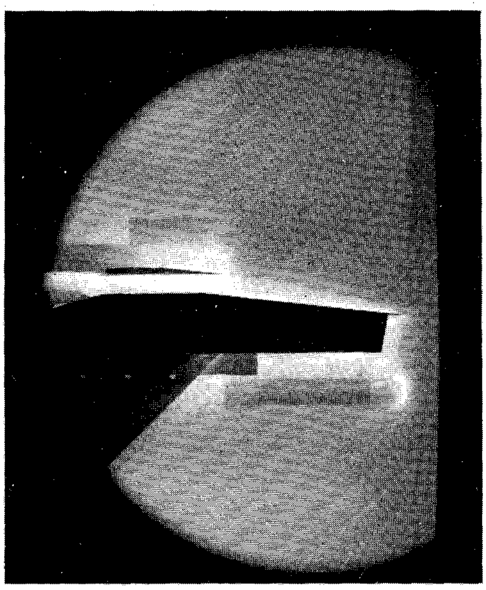

Fig. 12 Air-luminosity photograph of a Mach 12 airflow over a two-dimensional scramjet inlet, p_0 = 5.9 MPa and T_0 = 4200 K.

are caused by the boundary-layer effects over the shock-tunnel wall where the gauge is mounted. The drop to zero voltage observed in this trace at about 1.3 ms from the initial jump seems to indicate the arrival of the cold gas (helium) behind the interface.

A similar trend is indicated by the photodetector trace shown in Fig. 13. Since the optical detector is not as influenced by the shock-tunnel wall boundary layer as much as the ionization gauge, the output of the former is much "cleaner" than the latter. Due to the fact the photodetector response time is only 3 ns, the slopes exhibited by the output trace are representative of the changes in the gas temperature at that location. Consequently, the rather gradual rise in the radiation intensity corresponds to the smooth rise in the gas temperature (and pressure) resulting from the weak re-reflected shock waves.

Conversely, the gradual decrease in the photodiode output seems to be representative of a corresponding gradual decrease in the gas temperature. Such a smooth decrease in temperature may possibly indicate a temperature gradient within the mixing layer. However, this observation has to be further investigated.

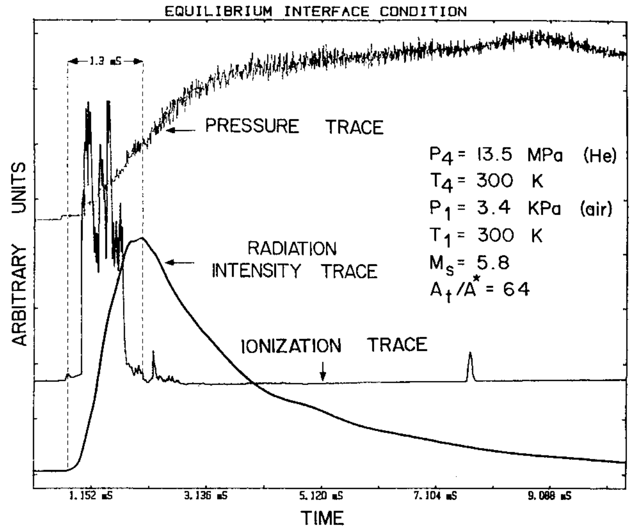

Fig. 13 Pressure, ionization, and radiation intensity histories measured at 20 cm from the nozzle entrance.

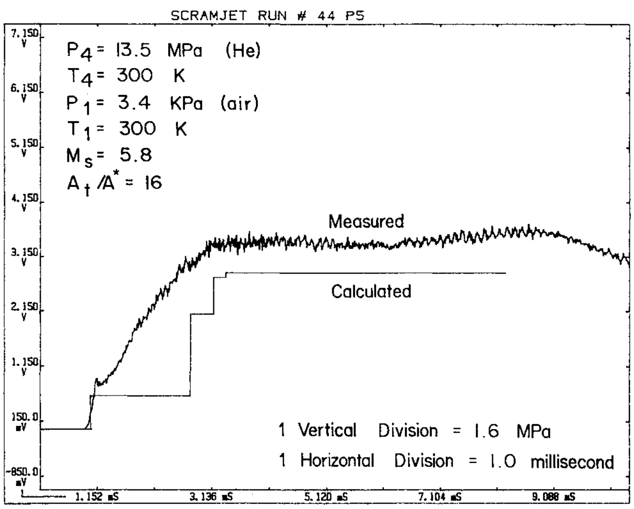

Fig. 14 Comparison between the measured and the calculated endwall equilibrium interface pressures.

The duration of the hot gas, at 20-cm upstream of the nozzle entrance, indicated by the photodetector is in agreement with that indicated by the ionization gauge. However, the particular traces shown were obtained with a nozzle throat area of 1.27 cm^2. For this value, code HSTR1 predicts the arrival of the contact surface at the station investigated at about 1.9 ms after the passage of the incident shock wave. This shows that the interface has been accelerated and/or spread out due to viscous and diffusion effects[4,14] as discussed previously.

Comparison Between the Experimental and Numerical Results

In this section the numerical prediction for the equilibrium interface pressure at the nozzle entrance and 20-cm upstream from that location will be compared with the experimentally measured values. These comparisons can be seen in Figs. 14 and 15, respectively. As observed in these graphs, the numerical model underpredicts the final equilibrium pressures at both locations investigated and does not reproduce the smooth approach to the final equilibrium state. This very same problem was also noticed by Copper[7] and it is shown in Fig. 16. This figure shows both the theoretical and the experimental values for the equilibrium interface pressure as determined by Copper and the results obtained from the HSTR1 code. The minor discrepancies observed between the two predictions can be attributed to 1) imprecisions related to the

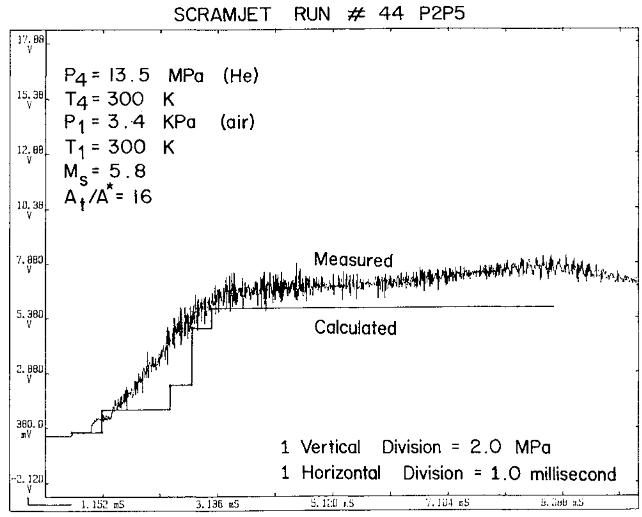

Fig. 15 Comparison between the measured and the calculated equilibrium interface pressures 20-cm upstream of the nozzle entrance.

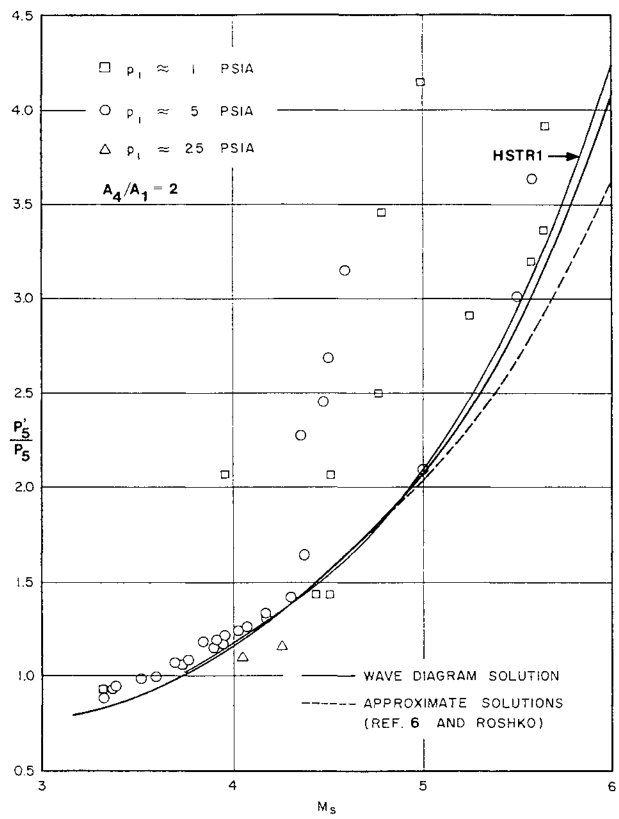

Fig. 16 Comparison between the HSTR1 predictions and the results reported by Copper.[7]

construction of the wave diagram; and 2) the real gas effects not considered by Copper.[7] Interestingly enough, the higher equilibrium pressures predicted by HSTR1 at the higher Mach numbers seem to agree better with the measured data.

In the present investigation, the underestimated pressure levels are believed to be caused mainly by the absence of viscous and shock overtaking effects in the relatively simple model used in the analysis. As is well known,[4,14] the viscous effects accelerate the interface while decelerating the incident shock wave by removing air from the inviscid core of the shock-tunnel flow. Although the deceleration of the shock wave is automatically taken into account in the model by actually using the measured value, the contact surface speed is calculated using that value and a one-dimensional inviscid approximation. As a consequence, U_2 may be less than the actual interface velocity. This observation seems to be cor-

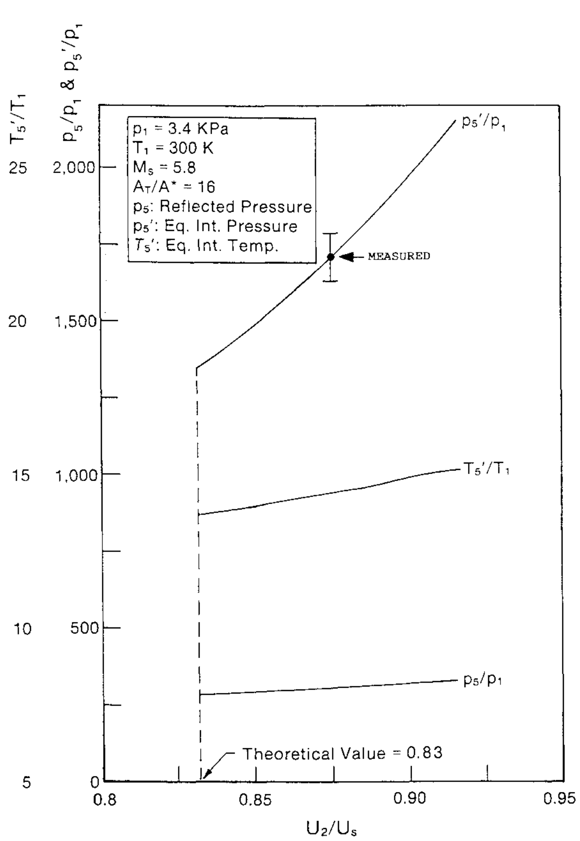

Fig. 17 Effect of the interface velocity on the equilibrium interface pressure and temperature.

roborated by the observed premature arrival of the interface as discussed in the previous section.

In order to obtain a feeling for the effect of the contact surface acceleration on the final equilibrium interface pressure and temperature, the interface speed was artificially increased. This numerical exercise is shown in Fig. 17. In this figure, p_5'/p_1, T_5'/T_5, and p_5/p_1 are plotted against U_2/U_s. The minimum value for U_2 used corresponds to the theoretical value predicted based on the measured U_s. On the other hand, the maximum value of U_2 investigated corresponds to a value 10% higher than the one theoretically predicted. The influence of this rather small variation in U_2 did not considerably affect the reflected pressure. However, the same is not true for the equilibrium condition. This shows the large influence of a possible acceleration of the interface on the conditions achieved by the technique investigated. The difference between the predicted pressure value and the actual measured one (as shown in Figs. 14 and 15) can be reduced to zero by just increasing the theoretical interface speed by less than 5%. This level of acceleration could be easily attained in the RPI hypersonic shock tunnel on the basis of its driven length, 16.8 m, and internal diameter, 10.2 cm. The trend indicated in Fig. 17 becomes of particular importance at high incident shock Mach numbers and low driven initial pressures in long driven tubes.[4,14] This is due to the pronounced boundary-layer growth along the shock-tunnel walls.

Conclusions and Future Research

Numerical and experimental investigations have been conducted in the RPI 0.61-m nozzle exit diameter hypersonic shock tunnel operating at an equilibrium interface condition of 5.8 MPa pressure, and 4100 K temperature. These particular conditions correspond to the reservoir pressure and temperature used to drive a high enthalpy, 6.3 MJ/kg, hypersonic equilibrium airflow over a two-dimensional Scramjet inlet in the flow Mach number range of 8–18.

The numerical study was made possible by development of a computer code. This code assumes the shock-tunnel airflow to be one-dimensional, inviscid, and in equilibrium. From the initial shock-tunnel conditions and the measured incident shock wave velocity, the code computes the final equilibrium interface state. This is done by modeling the several partial shock wave reflections off the nozzle entrance and the subsequent reflected shock contact surface intersections.

The study revealed that the equilibrium interface pressure and temperature strongly depend on the driver gas (helium) initial temperature. The equilibrium pressure and temperature were also shown to be dependent on the interface terminal speed. Although not very pronounced, the nozzle throat area does have some influence on the deceleration of the interface close to the entrance to the nozzle.

The experimental tests conducted in the RPI hypersonic facility produced higher equilibrium interface pressure values than those predicted by the numerical study. This is believed to be due to the theoretical model, it does not include either viscous effects or shock wave overtaking processes, and assumes that the approach to equilibrium is done exclusively by discrete compressions.

The output traces from an ionization gauge and photodiodes indicated useful test times ranging from 3 to 6 ms. These relatively long test times associated with high reservoir pressures (5.8 MPa) and temperatures (4100 K) make the equilibrium interface technique quite attractive.

Further investigation is required in order to actually determine the contact surface terminal speed. This will permit a more accurate modeling of the reflected shock wave interface interaction and, as a consequence, a better understanding of the physics of the equilibrium interface condition.

Acknowledgments

The authors wish to express their gratitude to Watervliet Arsenal, Tektronix, Inc., PCB Piezotronics, and RCA-General Electric for their technical support and donations. They also thank L. N. Myrabo, R. A. Jones, F. Tesman, and C. Vannier for their efforts to make this investigation possible. Finally M. A. S. Minucci wishes to thank the Brazilian Air Force for supporting his Doctoral Program at the Rensselaer Polytechnic Institute.

References

[1]Anderson, G., Kumar, A., and Erdos, J., "Progress in Hypersonic Combustion Technology with Computation and Experiment," AIAA Paper 90-5254, Oct. 1990.

[2]Thomas, S. R., and Guy, R. W., "Scramjet Testing from Mach 4 to 20 Present Capability and Needs for the Nineties," AIAA Paper 90-1388, June 1990.

[3]Neumann, R. D., "Requirements in the 1990's for High Enthalpy, Ground Test Facilities for CFD Validation," AIAA Paper 90-1401, June 1990.

[4]Lukasiewicz, J., *Experimental Methods of Hypersonics*, Marcel Dekker, New York, 1973, pp. 21–32.

[5]Nagamatsu, H. T., Geiger, R. E., and Sheer, R. E., Jr., "Hypersonic Shock Tunnel," *American Rocket Society Journal*, May 1959, pp. 332–340.

[6]Hertzberg, A., Smith, W. E., Glick, H. S., and Squire, W., "Modifications of the Shock Tube for the Generation of Hypersonic Flow," Arnold Engineering Development Center TN 55-15, Tullahoma, TN, March 1955.

[7]Copper, J. A., "Experimental Investigation of the Equilibrium Interface Technique," *Physics of Fluids*, Vol. 5, No. 7, 1962, pp. 844–849.

[8]Lapworth, K. C., "Temperature Measurements in a Hypersonic Shock Tunnel," *High Temperature Aspects of Hypersonic Flow*, edited by W. C. Nelson, AGARDograph 68, Pergamon, Oxford, England, UK, 1964, pp. 255–269.

[9]Lapworth, K. C., "Investigation of the Physical Properties of Gases at High Temperatures," *Journal of the Royal Aeronautical Society*, Vol. 68, March 1964, pp. 189–197.

[10]Dunn, M. G., "Experimental Study of High Enthalpy Shock-Tunnel Flow. Part I: Shock Tube Flow and Nozzle Starting Time," *AIAA Journal*, Vol. 7, No. 8, 1969, pp. 1553–1560.

[11]Rogers, R. A., "Workshop on the Application of Pulse Facilities

to Hypervelocity Combustion Simulation," Eighth NASP Technology Symposium, NASP WP-1008, Monterey, CA, March 1990.

[12]Minucci, M. A. S., and Nagamatsu, H. T., "Experimental Investigation of a 2-D Scramjet Inlet at Mach Numbers of 8 to 18 and Stagnation Temperatures of 4,100 K," AIAA Paper 91-0013, Jan. 1991.

[13]Jones, R. A., Myrabo, L. N., Nagamatsu, H. T., and Minucci, M. A. S., "Experimental Investigation of a 3-D Scramjet Inlet for Laser Propulsion at Mach Numbers of 10 to 25 and Stagnation Temperatures of 800 to 4100°K," AIAA Paper 91-0012, June 1991.

[14]Glass, I. I., and Gordon Hall, J., *Handbook of Supersonic Aerodynamics, Section 18 Shock Tubes*, Navord Rept. 1488, Vol. 6, U.S. Navy, White Oaks, MD, Dec. 1959, pp. 82–98.

[15]Chang, A. Y., Rea, E. C., Jr., and Hanson, R. K., "Temperature Measurements in Shock Tubes Using a Laser-Based Absorption Technique," *Applied Optics*, Vol. 26, No. 5, 1987.

[16]Kennard, E. H., *Kinetic Theory of Gases*, McGraw-Hill, New York, 1938, pp. 60–100.

[17]Minucci, M. A. S., Nagamatsu, H. T., and Myrabo, L. N., "Combustion Shock Tunnel and Interface Compression to Produce Stagnation Temperatures of 20,000 K and Mach Numbers of 35," AIAA Paper 92-0569, Jan. 1992.

[18]Minucci, M. A. S., "An Experimental Investigation of a 2-D Scramjet Inlet at Flow Mach Numbers of 8 to 25 and Stagnation Temperatures of 800 to 4,100 K," Ph.D. Dissertation, Rensselaer Polytechnic Inst., Troy, NY, Aug. 1991.

[19]Tannehill, J. C., and Mugge, P. H., "Improved Curve Fits for the Thermodynamic Properties of Equilibrium Air Suitable for Numerical Computation Using Time-Dependent or Shock-Capturing Methods," NASA CR-2470, Oct. 1974.