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Rocketdyne Hypersonic Flow Laboratory as High-Performance Expansion Tube for Scramjet Testing

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Although current high-enthalpy test facilities are capable of generating the correct enthalpies associated with very high-speed atmospheric flight, they can not generate the large total pressures needed for the full simulation of the freestream conditions. For accurate aerodynamic, heating, and combustion testing in these ground-based facilities, it is desirable to increase their total pressure simulation capabilities. It is proposed that the hardware fabricated for the Rocketdyne Hypersonic Flow Laboratory (RHYFL) shock tunnel project be utilized in building a large-scale expansion tube: RHYFL-X. Performance predictions are presented of this proposed facility based on quasi-one-dimensional flow simulations. The validity of the numerical analysis is demonstrated by comparison with data from a currently operating expansion tube. The results indicate that the new facility will possess the unique capability of being able to generate test flows that duplicate the freestream conditions experienced by a scramjet during its atmospheric flight.

Nomenclature

a	=	sound speed, m/s
d	=	inside diameter of tube, mm
H	=	enthalpy, MJ/kg
L	=	length of tube, m
M	=	Mach number
p	=	pressure, Pa
R	=	gas constant, J/kg · K
T	=	temperature, K
u	=	velocity, km/s
γ	=	ratio of specific heats

Subscripts

A	=	accelerator tube
S	=	shock tube
0	=	stagnation
1	=	test gas, initial state
2	=	test gas, after primary shock
3	=	driver gas, after primary expansion
4	=	driver gas, initial state
5	=	test gas, fully expanded

I. Introduction

THE high cost associated with space travel can be attributed mainly to the fact that current launch systems require the fuel and oxidizer to be carried onboard the launch vehicle. The scramjet is a hypervelocity airbreathing engine that has the potential to reduce greatly the cost associated with the delivery of a payload to orbit.[1] The weight saved by obtaining the oxidizer from the atmosphere would allow for a more robust and, thus, fully reusable launch vehicle.

The hypersonic flight regime of a scramjet-powered vehicle would subject the craft to very large stagnation pressures and temperatures.[2] The generation of suitable flow conditions in a ground-based test facility is a challenging task, and because current material technologies prohibit the prolonged containment of gas at these extreme conditions, short-duration (or pulse) facilities such as shock tunnels[3] and expansion tubes[4] have been developed. Extensive scramjet testing has been performed in free-piston driven shock tunnels since the early 1980s.[5,6] These tests, however, can only produce full similarity of freestream flow parameters for the low-enthalpy end of the scramjet's proposed flight envelope.

The free-piston driven expansion tube is the only facility that has the potential to produce test flows that simulate flight conditions over the entire range of the scramjet's flight trajectory.[7,8] However, the capital cost of the free-piston driver exceeds the combined cost of all of the other components,[9] and the full potential of the free-piston driven expansion tube has not been realized. To enable the generation of scramjet flight conditions in a ground-based facility, a high-performance free-piston driver needs to be coupled to a large-scale expansion tube. An opportunity to increase our current ground-based hypervelocity testing capabilities lies in what was originally designed as a large-scale free-piston shock tunnel, the Rocketdyne Hypersonic Flow Laboratory (RHYFL).[10,11] Although all of the major components for this facility were fabricated, the project was suspended, and the RHYFL shock tunnel was never completed.

There is an opportunity, as suggested by Chinitz et al.,[8] for utilizing the components of the RHYFL shock tunnel, in particular the expensive, high-performance free-piston driver, to assemble the world's largest free-piston driven expansion tube, the RHYFL-X. This paper will look at the fundamental mechanisms of expansion tube operation and present one-dimensional transient flow simulations of both a currently operating expansion tube (X2) and the proposed RHYFL-X facility. These numerical simulations indicate that the RHYFL-X expansion tube would be capable of generating test flows with total pressures over an order of magnitude larger than that available today, allowing the full simulation of freestream flight conditions experienced by the scramjet. The duration of the test flows, however, will be restricted to the characteristically short periods associated with expansion tube operation.

II. Expansion Tube Operation

The expansion tube[12] is a pulse facility which can produce high-enthalpy flows without the dissociation and total pressure limitations of the shock tunnel. Space–time diagrams indicating the major wave proccesses during operation of a shock tunnel and an expansion tube from the instant of primary diaphragm rupture are illustrated in Figs. 1 and 2. In an expansion tube, hypersonic conditions are finally achieved at state 5 by the acceleration of the test gas through

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an unsteady expansion. This process adds energy and total pressure to the flow at the expense of test time,[4] enabling the generation of test flows with significantly higher total pressures than are possible using a shock tunnel. This arrangement for processing the test gas also avoids the high stagnation temperatures observed in reflected-shock tunnels and, thus, minimizes the dissociation levels in the test gas.

When test conditions for the expansion tube are calculated and true Mach number simulation is attempted, certain restrictions are placed on the operating parameters, which, in turn, limit the realizable pressures. To get an idea of the way in which the facility will be operated, the following analysis specifies a desired flow condition at the exit plane of the acceleration tube and then works upstream to estimate the necessary driver operating condition.

Starting with specified flow properties in the expanded test gas, one can determine the required flow conditions in the test gas after being processed by the primary shock. First, at high flight Mach numbers, the total enthalpy is dominated by the kinetic energy. This sets the total enthalpy in the expanded test gas as

$$H_{05} \approx \tfrac{1}{2}u_5^2 = M_5^2 a_5^2 / 2$$

Second, because the primary shock is very strong, the Mach number of the shock-processed test gas is approximately constant for all operating conditions and can be estimated as

$$M_2 \approx \sqrt{2/(\gamma_2 - 1)\gamma_2}$$

Setting the Mach number in the expanded test flow, M_5, then defines the total enthalpy ratio across the unsteady expansion as[13]

$$\frac{H_{05}}{H_{02}} = \frac{\gamma_2(\gamma_2 - 1)}{\gamma_2 + 1}\left[\frac{1}{\gamma_2 - 1} + \frac{M_5^2}{2}\right]\left\{\frac{1 + [(\gamma_2 - 1)/2]M_2}{1 + [(\gamma_2 - 1)/2]M_5}\right\}^2$$

Using a perfect-gas analysis and the strong shock approximation,

$$a_2^2 = H_{02}\frac{\gamma_2(\gamma_2 - 1)}{2 + \gamma_2}$$

Thus, the sound speed in the shocked test gas is given by

$$a_2 = \left\{\left(\frac{M_5^2 a_5^2}{2}\right)\left(\frac{H_{02}}{H_{05}}\right)\left[\frac{\gamma_2(\gamma_2 - 1)}{2 + \gamma_2}\right]\right\}^{\frac{1}{2}}$$

For the values $M_5 = 15$ and $\gamma_2 = 1.4$, this gives

$$a_2^2 \approx 0.05 H_{05}$$

With $\frac{1}{3} \leq H_{02}/H_{05} \leq \frac{1}{2}$ for the flight conditions of interest, values of a_2 will need to be in the range of 0.5–1.0 km/s.

To operate an expansion tube successfully, it has been shown[14] that the sound speed of the expanded driver gas, a_3, must be kept below that of the shock-heated test gas, a_2, by at least 20%. From this, the required driver sound speed can be estimated as[13]

$$a_4 = a_2 M_2 (f/F_1)[\gamma_2(\gamma_2 - 1)/2 + (\gamma_4 - 1)/2]^{\frac{1}{2}}$$

where $F_1 \approx 1$ is a function pertaining to the driver geometry and $f = a_3/a_2 < 0.8$ to avoid noise transmission to the test gas.[14]

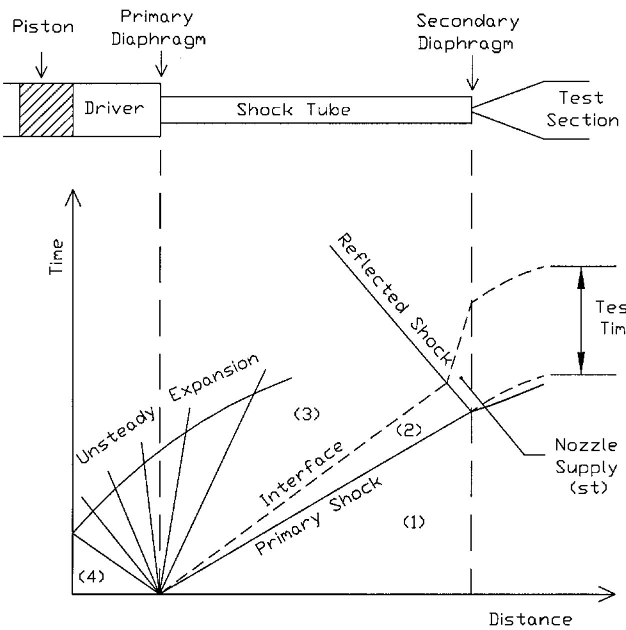

Fig. 1 Space–time diagram of shock tunnel operation: test gas, initial state, 1; shock-processed test gas, 2; expanded driver gas, 3; and driver gas, initial state, 4.

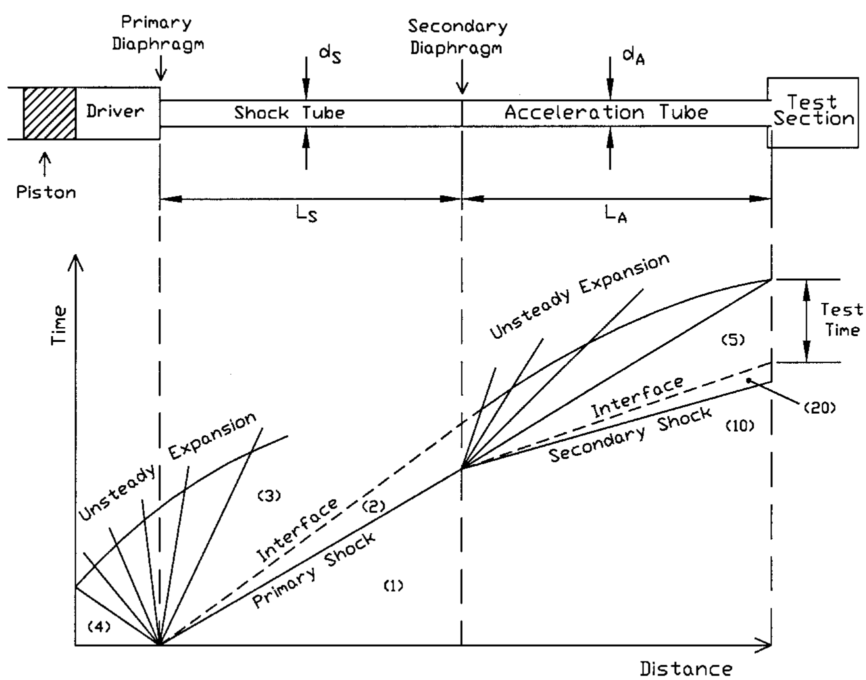

Fig. 2 Space–time diagram of expansion tube operation: test gas, initial state, 1; shock-processed test gas, 2; expanded driver gas, 3; driver gas, initial state, 4; expanded test gas, 5; accelerator gas, initial state, 10; and shock-processed accelerator gas, 20.

Applying this perfect gas analysis to a helium driver gas and air test gas shows that relatively low values of a_4 (in the range 800–1200 m/s) are needed to operate at scramjet flight conditions. This value of a_4 will be around 11–12% less if nitrogen is used for the driver gas instead of helium. The potential benefits of using nitrogen as the driver gas are presented later in the paper. These low driver sound speeds are significantly below the levels that free-piston drivers are capable of generating and represent a downgrading of performance. To compensate, the driver can be operated with extremely high driver pressures p_4, this being a feature of the RHYFL facility. Another performance enhancing feature of the RHYFL facility is a large 9:1 area ratio between the driver and the driven tubes.

III. Simulations of X2 Facility

Although adequate modeling of expansion tubes has been achieved in the past using Navier–Stokes solvers,[15,16] the magnitude of the computational effort required for axisymmetric simulations is large. Exploratory simulations found that a quasi-one-dimensional flow simulation using the code L1d[17,18] was around 300 times faster than the axisymmetric simulation. The difference between the types of simulation, in both shock and flow velocity, was less than 2%, and the difference in static pressure was less than 10%. Therefore, we were motivated to use the one-dimensional flow code to obtain the performance predictions for the proposed RHYFL-X facility. The remainder of this section tests the validity of the one-dimensional simulations by examining the performance of a currently operating facility.

The first condition modeled was a 7.2-km/s equivalent flight speed condition. The operating conditions for this shot are outlined in Table 1. Although the two-stage compression process of the helium driver gas was incorporated in this simulation, precise modeling of the high-performance driver on the RHYFL-X facility is not neccessary. The low driver sound speed required when targeting scramjet flight conditions could be readily attained through the adjustment of gas composition and driver compression ratio.

Initially, the idealization of instantaneous rupture and evaporation of the secondary diaphragm was assumed, and the flow was accelerated to hypersonic conditions undisturbed by the secondary diaphragm. However, experiments[19] have indicated that even the lightest practical diaphragm has sufficient inertia to drive a reflected shock back upstream into the oncoming gas. The simulation was run again with a 5-μs hold time imposed on the secondary diaphragm. Figures 3 and 4 show the reasonable agreement between experiment and the numerical simulations for the static and pitot pressure at the end of the acceleration tube. These numerical results indicate that the diaphragm hold time reduces the test flow pitot pressure, but has little effect on the static pressure.

Table 1 Initial conditions for X2

Condition	Value
Reservoir fill (air)	1.55 MPa
Driver fill (helium)	48 kPa
Shock tube fill, p_1 (air)	7.5 kPa
Accelerator tube fill, p_{10} (air)	46.6 Pa
Primary diaphragm rupture pressure p_4	24 MPa
Secondary diaphragm rupture pressure	45 kPa

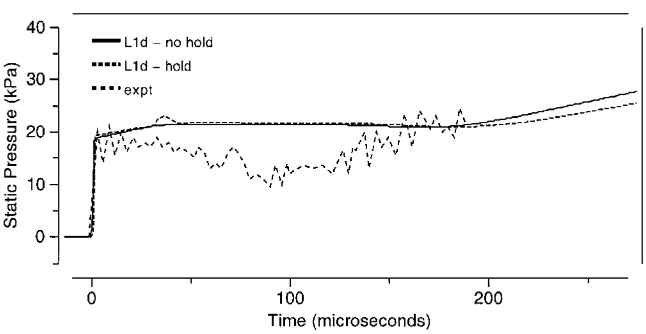

Fig. 3 Static pressure traces for diaphragm hold-time and no hold-time simulations compared with experimental data for X2 condition 1.

Table 2 Experimental conditions and L1d simulation results for X2 condition

Flow quantity	Experiment	Simulation No hold	Simulation Hold
Static pressure p_5, kPa	18	21.5	22
Pitot pressure p_{p5}, kPa	850	950	720
Temperature T_5, K	3392	3250	3900
Velocity u_5, km/s	6.4	6.3	6.4
Test time t, μs	90	130	115

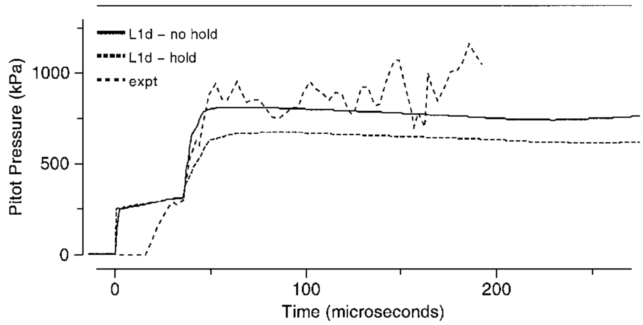

Fig. 4 Pitot pressure traces for diaphragm hold-time and no hold-time simulations compared with experimental data for X2 condition 1.

The simulated final shock speed at the end of the acceleration tube segment was 6.7 km/s, 5% larger than the experimentally obtained 6.4 km/s (Ref. 20). The simulated flow speed of the test gas at the exit of the acceleration tube was 6.3 km/s and increased by no more than 2% when the 5-μs hold time was applied to the secondary diaphragm. Table 2 shows the close agreement between simulation results and experimental data. See Ref. 20 for details on the experimental data. Very little difference in the numerical results (no more than 2% in pitot pressure, for example) was observed when the grid resolution was increased, verifying the independence of the solution to the grid resolution.

The second operating condition modeled used twice the thickness of cellophane for the secondary diaphragm with nitrogen as the test gas. Because of the extra diaphragm thickness, the 5-μs hold time incorporated into this simulation resulted in a simulated pitot pressure that is closer to that obtained experimentally. However, because of the larger gas densities and relatively low speeds that would be associated with the RHYFL-X facility when targeting scramjet test conditions, we believe that a light secondary diaphragm will have negligible effect on the final flow properties. As a result, RHYFL-X simulations presented later in this paper will assume an inertia-free secondary diaphragm.

These X2 results indicate that the one-dimensional approach used is sufficient to capture the important flow characteristics and adequately model an expansion tube. Because the viscous effects and three-dimensional phenomena primarily responsible for the discrepencies between L1d simulations and experimental measurements will be less significant in the larger RHYFL-X facility, we believe that the performance predictions of the RHYFL-X expansion tube obtained using the same one-dimensional flow model will be reliable.

IV. Simulations of RHYFL-X

To illustrate the performance of the proposed RHYFL-X facility, this section presents numerical results for three operating conditions: RX-1, an operating condition for the direct-connect testing of scramjet combustors; RX-2, a Mach 14 condition for a scramjet at an altitude of 35 km; and RX-3, a Mach 18 condition for a scramjet at an altitude of 40 km. Conditions 2 and 3 are intended for the true Mach number simulation of a flight vehicle.

Table 3 Flight conditions and nozzle-expanded test flow properties

Property	Flight	RX-1	Flight	RX-2	Flight	RX-3
Mach number	5–7	6.0	14	14	18	18
Static pressure, kPa	>100	305	0.60	5.8	0.30	1.47
Total pressure, MPa	360	18	1,300	12,500	9,000	33,000
Static temperature, K	<1,000	961	240	288	250	245
Flow velocity, km/s	3.60	3.60	4.35	4.65	5.70	5.59
Exit diameter, m	——	0.40	——	0.65	——	0.83

Table 4 Tube lengths for the proposed RHYFL-X facility

Test condition	Shock tube L_S, m	Acceleration tube L_A, m
RX-1, direct connect	15	16
RX-2, Mach 14	12	35
RX-3, Mach 18	10	35

Consider a hypothetical scramjet vehicle at an altitude of 40 km (RX-3). To fully duplicate this flow in a ground-based testing environment, the test flow must have the properties of approximately those shown in Table 3. The extreme nature of these freestream parameters results in many tests associated with the scramjet being aimed at generating flow conditions resembling those of the combustion chamber entrance.[21] This allows testing of the operation of just the combustion chamber in so-called direct-connect tests and avoids the entire intake process where large total pressures losses occur. Because RHYFL was originally designed for direct-connect tests, simulations were performed to determine whether RHYFL-X would still be capable of generating flows for these test arrangements without the dissociation encountered in shock tube flows.

The maximum design rupture pressure of the primary diaphragm of 250 MPa was used in all cases and the driver temperature was varied depending on the final flow properties required. Initially, helium was considered as the driver gas but, due to the restrictions on operating conditions, the high speed of sound properties of helium can not be utilized at these (relatively) low enthalpies. With helium as the driver gas, temperatures of $T_4 \approx 600$ K would be required at rupture when generating scramjet testing conditions. Combined with the compression ratios required to obtain 250 MPa in the driver gas, these low temperatures are not feasible. An advantage of the free-piston driver is that any gas or mixture of gases can be used as the driver gas. Nitrogen provides an ideal complement to helium because its low values of γ and R allow large compression ratios while maintaining a low sound speed. High compression ratios enable high values of p_4 for minimal amounts of work. Whereas the use of pure nitrogen would require compression ratios up to around 600 and temperatures at rupture of almost 4000 K, a nitrogen/helium gas mixture could be utilized to achieve a desired compression ratio and/or temperature at rupture. A 50% (by volume) nitrogen, 50% helium gas mixture would result in compression ratios of around 60 and temperatures at rupture of approximately 2300 K.

Because of the lower ratio of specific heats, the use of a diatomic gas such as nitrogen will also result in a smaller pressure drop through the unsteady expansion. However, after lowering the initial driver gas temperature so that the expanded driver gas sound speed remains the same, the increased pressure benefits of using a diatomic gas will only be realized at certain operating conditions. For the operating conditions presented here, the use of a 50/50 mixture of nitrogen and helium for the driver gas will result in a theoretical increase in test flow static pressure of around 8%. As well as the potential benefits of higher flow pressures, nitrogen is also cheaper than helium.

The driver tube of the RHYFL hardware has a diameter of 600 mm, whereas the shock and accelerator tubes both have a diameter of 200 mm. Table 4 lists the lengths of the shock and acceleration tube segments for the proposed facility. All simulations assume tuned operation of the piston[22] so that the maximum pressure at diaphragm rupture is maintained for a sufficient length of time. Based on this assumption, the length of the compressed driver gas was set at 2.5 m to ensure that the unsteady expansion reflecting off the front of the piston did not interfere with the test flow conditions.

A. Direct-Connect Condition

At moderate hypersonic speeds, combustion in the scramjet takes place at supersonic speeds, but as flight speeds approach Mach 18, hypersonic flow ($M > 5$) must be maintained in the combustor to ensure that the static temperature remains low enough for combustion.[23] Table 3 shows the approximate flow conditions required for hypersonic direct-connect testing, and Table 5 outlines the initial conditions for this simulation. Figures 5 and 6 show the static and pitot pressure traces for the first simulation at the exit of the acceleration tube. These traces indicate that test times of around 1.1 ms could be expected.

Because of the one-dimensional nature of L1d, the boundary layers are not modeled separately to the core flow. Instead, a calculated viscous shear is applied to the cell to represent momentum loss through the boundary layer. This introduces two distinct artifacts into the simulated flow properties. The first artifact is an increasing pressure gradient, both static and pitot, where there is constant velocity flow. Because there is a (viscosity-induced) shear stress being

Table 5 Initial gas states and flow properties at the end of the acceleration tube

Condition	RX-1	RX-2	RX-3
Primary diaphragm rupture pressure p_4, MPa	250	250	250
Rupture temperature (He) T_4, K	650	520	610
Shock tube fill (air) p_1, kPa	400	545	414
Initial test gas temperature T_1, K	295	295	295
Accelerator tube fill (air) p_{10}, kPa	14.0	0.631	0.220
Initial accelerator gas temperature T_{10}, K	295	295	295
Mach number M_5	4.3	8.5	10
Static pressure p_5, kPa	2200	160	80
Stagnation pressure p_{05}, GPa	1	10	32
Static temperature T_5, K	1690	750	760
Flow velocity u_5, km/s	3.43	4.50	5.50
Test time t, ms	1.1	0.6	0.5

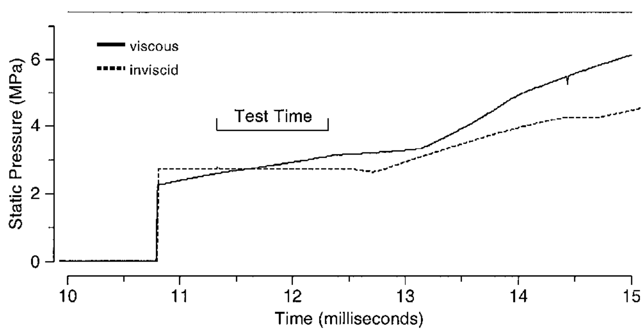

Fig. 5 RHYFL-X static pressure history for direct-connect condition RX-1.

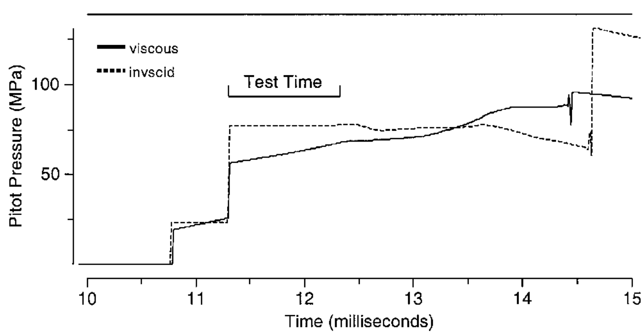

Fig. 6 RHYFL-X pitot pressure history for direct-connect condition RX-1.

applied to the edges of the cells, there must be a pressure gradient to maintain a constant velocity slug of gas. This can be seen in Figs. 5 and 6, where the test flow has a nonzero pressure gradient for the viscous simulations but a steady pressure level for the inviscid simulations. This does not appear in axisymmetric simulations where the boundary layer and core flow are distinct.[15,16]

The other artifact is that, as the flow travels down the tube and the boundary layers grow accordingly, the flow properties are increasingly influenced by the boundary-layer properties. Although this has little effect on the static pressure, the high temperatures in the boundary layer result in the static temperature of the bulk flow significantly increasing as the flow travels down the tube. Results from axisymmetric simulations show that, after expansion, the test gas temperature slightly decreases as the flow travels down the acceleration tube.

To compensate for these simulation artifacts, the test flow static pressure will be taken as the pressure at the start of the pressure history plot and the test flow temperature will be taken as the temperature of the flow immediately after expansion. The simulated test flow properties for condition RX-1 are presented in Table 5. These conditions are not immediately suitable for combustion testing because the static temperature is too high; however, the temperature can be lowered by expanding the flow through a hypersonic expansion nozzle.[24–26] This will not only increase the test section size, but it also has the effect of increasing the duration of steady test time.[27] For this particular set of conditions, the isentropic expansion of the flow to Mach 6 through a nozzle coupled to the end of the acceleration tube results in the attainment of direct-connect flow conditions in a test section approximately 400 mm in diameter. These nozzle-expanded properties (presented along side the target flight conditions in Table 3) indicate that the RHYFL-X facilty will be capable of producing dissociation-free direct-connect testing conditions in a test section approximately equal in size to the original RHYFL design.[10,11]

B. Conditions for True Mach Number Simulation

Whereas the majority of scramjet tests to date have focused on combustion and component testing, adequate testing of the operation of the scramjet engine will require full-model tests in which a complete model airframe, together with integrated scramjet combustor, is tested. Simulations of the RHYFL-X were conducted to determine whether this facility could produce freestream flow conditions that would allow the true Mach number simulation of the entire scramjet/aircraft arrangment.

Table 5 outlines the initial conditions and the test flow properties obtained for two true Mach number simulations, RX-2 and RX-3. Condition RX-2 was aimed at producing true Mach number test conditions for a Mach 14 scramjet by expanding the flow through a nozzle 650 mm in diameter, whereas RX-3 targeted the flight conditions for a scramjet at Mach 18 by expanding the flow through a 830-mm-diam nozzle. Table 3 shows the test conditions obtained by the isentropic expansion of the test gas through the appropriate nozzle, compared with target freestream flight conditions for a scramjet at the corresponding Mach number. In both cases, the flow velocity and temperature are well approximated, and the pressure is significantly higher than required. This will enable binary scaling for subscale models.

Table 6 shows a comparison of approximate maximum pressures for various major facilities (Refs. 20 and 27–36).

Table 6 Approximate maximum total pressure values for standard operating conditions of various facilities

Facility	Total pressure
Blowdown tunnels	
Ref. 28	10 MPa
Shock tunnels	
Aachen (TH2)[29]	63 MPa
T4[30]	60 MPa
High-Enthalpy Shock Tunnel[31]	70 MPa
T5[32]	70 MPa
High-Enthalpy Shock Tunnel Goettingen[33]	90 MPa
Arnold Engineering Development Center impulse facility[34]	172 MPa
Expansion tubes	
JX1[35]	300 MPa
X2[20]	600 MPa
HYPULSE[36]	1.6 GPa
X3 (estimated)	8 GPa
RHYFL-X (proposed)	40 GPa

V. Conclusions

If airbreathing engines are ever to be utilized as a viable propulsion system for high-speed atmospheric flight, ground-based testing facilities must be developed and built that can generate the high-energy flow associated with such flight. Whereas current expansion tubes enable the production of flows with total pressures orders of magnitude greater than shock tubes without the flow dissociation, they are still incapable of generating conditions matching those at the higher flight speeds. Table 6 presents the approximate maximum total pressures for standard operating conditions for various major reflected-shock tunnels and expansion tubes. When compared with the predicted total pressure capabilities of the proposed RHYFL-X facility, it is evident that RHYFL-X will be capable of generating flows with total pressures far greater than any facility in operation today.

The one-dimensional simulation results presented indicate that the proposed RHYFL-X facility will enable true Mach number testing of integrated engine/aircraft configurations in flows duplicating those that would be experienced during flight. The implementation of a hypersonic nozzle at the end of the expansion tube would increase the size of the models that could be tested in test flows exceeding 1 ms in duration.

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