AIAA Journal
Vol. 48, No. 8, August 2010

Comparison of Mach 10 Scramjet Measurements from Different Impulse Facilities

Matthew McGilvray,* Rainer Kirchhartz,† and Thomas Jazra†
University of Queensland, St. Lucia, Queensland 4072, Australia

DOI: 10.2514/1.J050025

A comparison is made between scramjet pressure data taken in two different impulse facilities, a reflected shock tunnel and an expansion tunnel, to provide verification of flow similarity. A two-dimensional hydrogen-fueled scramjet was tested in both facilities at a Mach 10, 66 kPa dynamic pressure, flight-replication condition. The entire flowfield was reproduced, including the inlet, combustor, and thrust nozzle. The expansion-tunnel model was a 40%-scaled model of that investigated in the shock tunnel, as the generated core flow was smaller. Applying density-length scaling, the density of the freestream was increased by a factor of 2.5 in the expansion tube to maintain similarity between the experimental setups. Results show agreement within the experimental uncertainty between the two data sets at similar fuel equivalence ratios, indicating the repeatability of scramjet pressure measurements, independent of the experimental facility used. It is further demonstrated that density-length scaling is appropriate for the flows generated in the investigated scramjet engines. Verification is also provided of the analysis technique used to process experimental scramjet data sets that involve transient inflow conditions.

Nomenclature

H	=	stagnation enthalpy, J/kg
L	=	length, m
M	=	Mach number
$\dot{m}_{\mathrm{air}}$	=	mass flow rate of air, kg/s
p_p	=	pitot pressure, Pa
p_s	=	static pressure, Pa
p_{stag}	=	reflected shock tunnel stagnation pressure, Pa
Re_u	=	unit Reynolds number, 1/m
T_s	=	static temperature, K
U	=	flow speed, m/s
U_{norm}	=	normalization velocity, m/s
U_s	=	shock speed, m/s
ρ	=	density, kg/m^3
ϕ	=	fuel equivalence ratio

I. Introduction

THE proven capability and robustness of conventional chemical rockets could be superseded in the future by more cost effective scramjet-rocket-based delivery systems [1]. Scramjets have the potential to reduce access to space costs by using air from the Earth's atmosphere as an oxidizer, allowing for larger payload mass fractions. However, there are many complex technical issues that still need to be explored and overcome for these engines to become operable. Proposed access to space trajectories requires the scramjet to accelerate the vehicle from approximately Mach 7 to Mach 14 [2]. As the bulk of the research and development to date has investigated scramjet operation below Mach 8, there is currently a lack of understanding of the fundamental flow physics and chemistry involved at higher flight Mach numbers.

To explore the performance of scramjets at higher speeds on the ground, it is required that test capabilities directly match flow properties incurred during an anticipated flight trajectory. Although testing can currently be undertaken for individual components (inlet, fuel injection, and combustor direct connect) at the lower end of the flight regime, full configuration testing is also required to capture the coupling between engine parts [3] and simulate integrated engine behavior. Limits are imposed by the large energy and total pressure requirements at higher speed conditions, constraining ground tests to impulsive facilities. Simulating realistic flight conditions above Mach 10 is limited in reflected shock tunnels due to total pressure and dissociation constraints [4]. However, testing at lower total pressure conditions can still produce meaningful results [5]. Ultimately, the viability of access to space by combined scramjet-rocket propulsion systems may largely depend on the proportion of the trajectory for which the scramjet can be used, since a rocket must be used for the final ascent. This issue needs to be addressed promptly to determine the limitation point for scramjet engines, which requires ground-test capabilities to be extended.

Experiments testing a complete *nose-to-tail* scramjet configuration have been shown to be feasible in an expansion tube [6] at Mach 10. This is at the lower end of the facility's advantageous operating range. Replicating higher-Mach-number flight conditions has previously been demonstrated in expansion tubes [7]. However, questions concerning the precision of measurements in expansion tubes have been raised as the level of freestream fluctuations has yet to be measured in the harsh flow environment. To give researchers/designers confidence in scramjet data produced from expansion tube testing, a comparative set of measurements were obtained from a more commonly used reflected shock tunnel facility. This paper presents the comparison of static pressure measurements taken in the University of Queensland's impulse facilities, the T4 reflected shock tunnel and the X2 expansion tunnel.

II. Experimental Setup

Two separate sets of experiments were conducted in T4 and X2. The T4 shock tunnel has been used extensively for fundamental scramjet component testing [8], as well as testing of complete engine configurations. In contrast, the X2 campaign was the first attempt at conducting scramjet experiments in an expansion tube at the University of Queensland. The latter is discussed in full detail in the preceding paper by the present author [6].

As T4 could produce both a core flow and test times to allow testing of an engine size comparable to current subscale flight-test models [5], direct duplication of Mach 10, 30-km-alt flow conditions was created. In X2, the available test time limited the engine size to a 2/5 scaled version of the T4 model. The X2 condition was scaled according to the density-length scaling law proposed by Pulsonetti

Received 7 July 2009; accepted for publication 17 March 2010.

*Research Fellow, Division of Mechanical Engineering, Centre for Hypersonics. Member AIAA.

†Ph.D. Candidate, Division of Mechanical Engineering, Centre for Hypersonics. Student Member AIAA.

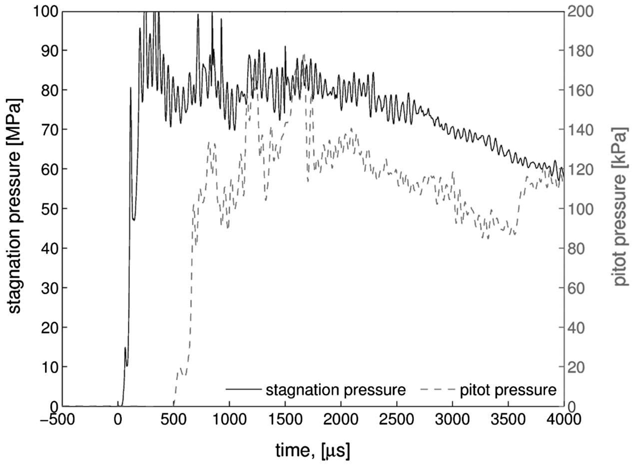


Fig. 1 Stagnation and pitot pressure–time histories for Mach 10 T4 condition. Taken from shot 8481.

[9], increasing the density by a factor of 2.5 relative to the flight condition.

A. Flow Conditions

A baseline condition was created in the T4 shock tunnel, replicating Mach 10 flight at 66 kPa dynamic pressure. Using a fully contoured nozzle, the tunnel dynamics were refined and the conditions verified by Abdel-Jawad [10]; further adjustment was undertaken more recently [11]. The stagnation pressure and pitot pressure for the T4 condition investigated are shown in Fig. 1. The X2 condition was determined using ρL-scaling [6,12].

For the scramjet data presented, all plots are shown for a given time interval, following the slug-tracking method [6]. It takes an average of each measurement over a small slug of gas that is tracked through the engine at a constant speed and normalized against its initial pressure. This approach is required due to the transient nature of the freestream properties in both facilities. The flow conditions entering the scramjets are presented at 450 μs after the arrival of the incident shock for X2, and at 2500 μs for T4. These are presented in Table 1. The X2 inflow conditions are taken from numerical simulations using MB_CNS [13] of the flow at 450 μs [12]. The T4 inflow conditions were inferred from the stagnation conditions using ESTCj, an updated version of the STN code [14], at 2500 μs, and processed using the nonequilibrium flow nozzle calculator, NENZF [15]. Slight deviations were found in static temperature and velocity data between the two flow conditions.

B. Scramjet Models

The primary motivation for conducting the engine tests was to determine whether or not scramjet experiments in impulse facilities are viable above Mach 10. Therefore, a simple two-dimensional engine design was employed. Figure 2 gives a cross-sectional view of the T4 model; the two-fifths-scaled X2 version was described in full detail in the preceding paper [6]. Investigating a simple engine design was deemed to be the most promising approach mainly for two reasons: ease of design modification during the test campaign, making the engine robust to offdesign freestream flow conditions; reduced complexity of the internal flow path to minimize after experimentation analysis. However, due to the presence of side walls and porthole injection, the flowfield is not truly two-dimensional. Hydrogen was injected from the third ramp of the intake (Fig. 2) through a series of four holes ($\phi = 2$ mm). Pressure measurements were taken along the body wall. Apart from the different scale of the T4 and the X2 models, there were additional slight differences between the two: first, the sensor locations were varied as the transducer size was the same in both engines; also, the inlet ramp sizing differs by millimeters to allow passing of the bow shock on the external cowl surface; and finally, the X2 model was fitted with a longer combustor. Pressure measurements on the thrust surface were only obtained in the X2 experiments.

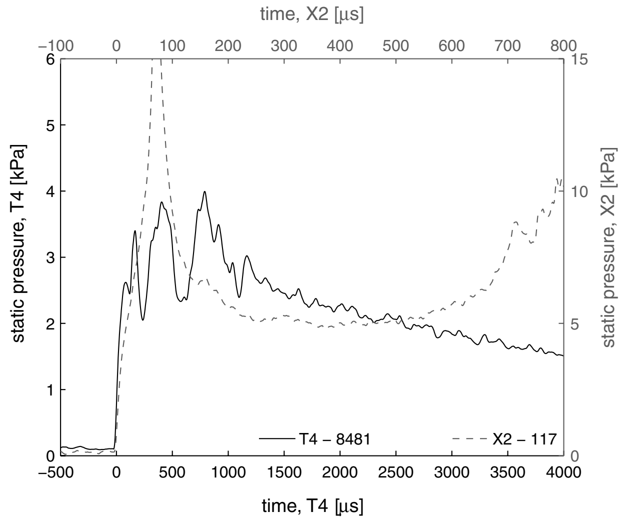


Fig. 3 Comparison of inlet pressure traces used for normalization. First transducer in X2 experiment and seventh transducer in T4 experiment.

III. Comparison of Experimental Results

To allow direct comparison between the two experiments, axial distance is normalized by the overall length of the X2 engine and the scaling factor of 2/5. The results obtained from T4 are presented as average values for a period of 25 μs, which equates to 10 μs for X2 in order to keep the slug of gas constant. In terms of normalized

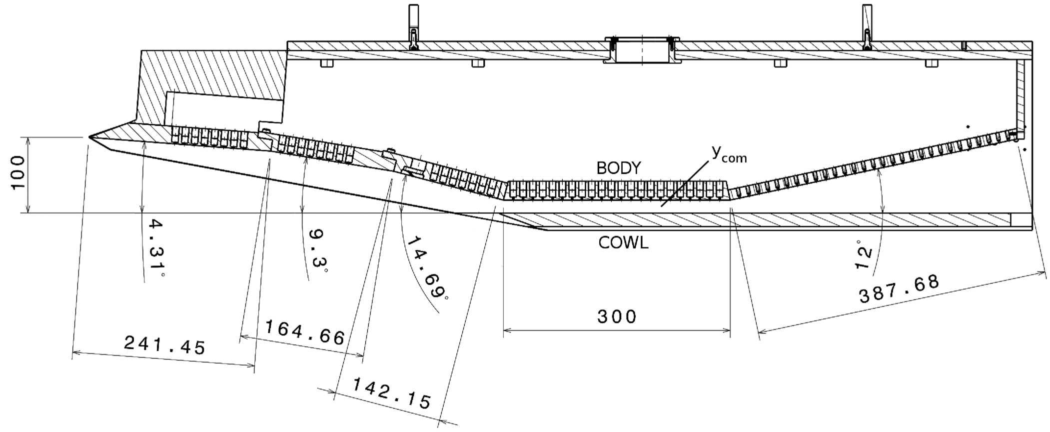


Fig. 2 Scramjet model used in T4 experiments, with 10 mm combustor height setup (y_{com}). Dimensions are in millimeters. (Modified from original drawings by M. Frost and A. Paull, 2005.)

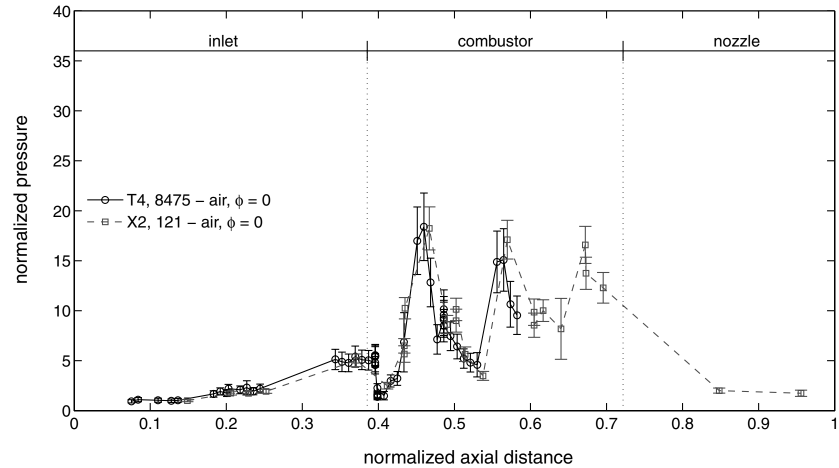


Fig. 4 Comparison of normalized pressure axially along engine for fuel-off shot into air.

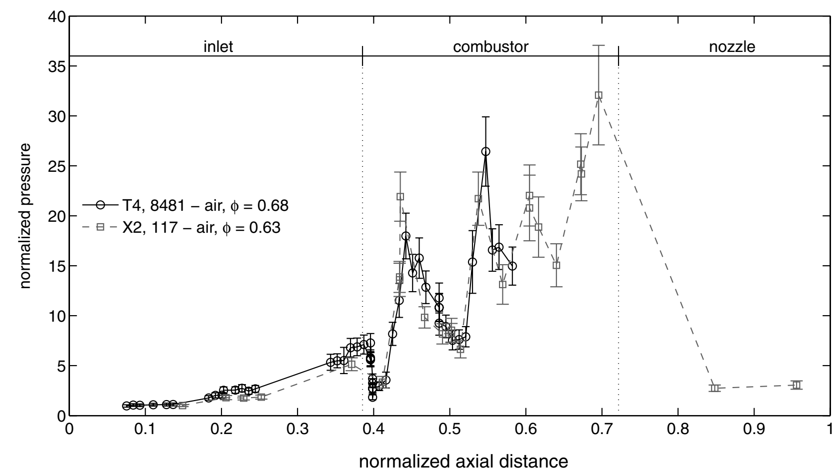


Fig. 5 Comparison of normalized pressure axially along engine for fuel-on shot into air for cases with a high fuel equivalence ratio.

distance, the T4 model allowed measuring pressure closer to the leading edge; the seventh pressure sensor was used for normalizing the T4 data, whereas the first one was employed for the X2 data. From each experimental campaign, two comparable data sets were obtained: a fuel-off case and a fuel-on case at a fuel equivalence ratio of $\phi \approx 0.65$.

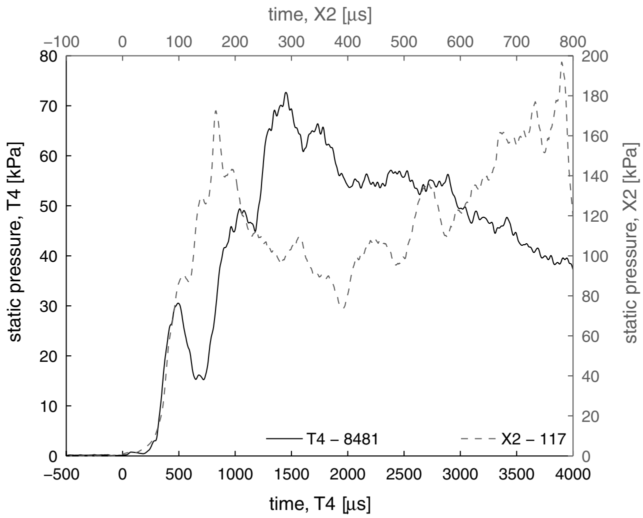
Figure 3 shows a comparison of inlet pressure traces that were used for normalization; in both facilities, the test flow is preceded by an initial slug of startup gas. Both experiments show a similar shift in static pressure of approximately 250 Pa for the time it takes a slice of gas to reach the equivalent position of the last transducer in the T4 experiment (295 μs for T4 experiment and 118 μs for X2 experiment), starting at the analysis time. However, in the T4 experiments, this value corresponds a larger percentage of the static pressure level (9%) due to a lower freestream pressure.

A comparison of normalized pressure results along the engine axis at fuel-off conditions is plotted in Fig. 4. From the equivalent characteristics of the two traces it can concluded that density-length scaling can be applied to internal flows that do not experience fuel mixing or combustion. Although the T4 experiments involve longer test times and lower rates of change of the freestream flow properties, the data sets can be compared directly by means of quasi-steady flow analysis. The larger size of the T4 model enables greater spatial resolution of measurements, and hence it gives a more detailed representation of the flow.

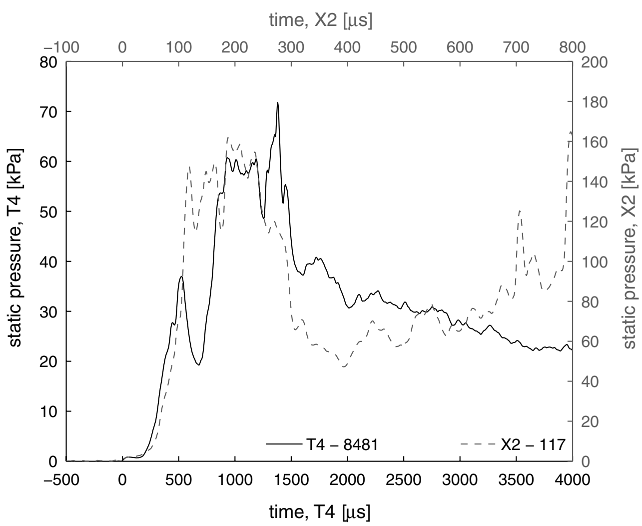
For the fuel-on case, the pressure distributions along the body wall (Fig. 5) agree to within the experimental uncertainty.[‡] From the fuel-on comparison, a number of findings can be concluded: density-length scaling can also be applied to this scramjet for fuel mixing and supersonic combustion cases; steady combustion can be established even within the very short test times in X2; slug tracking can be applied to appropriately scaled conditions, regardless of the slope of the time history of the transient freestream flow. The increase in combustor length of the X2 engine results in a higher pressure level at the end of the combustor, which may indicate that combustion is not complete at the end of the combustor investigated in T4.

The inflow properties into the engine are transient in both facilities, with a decreasing freestream pressure in T4 and a freestream pressure increase in X2. The pressure measurements towards the end of the combustor exhibit the cumulative effects of the unsteady inflow conditions together with fuel mixing and combustion. Turbulent boundary layers, which are also of unsteady nature, further promote variations in the pressure measurements over time. Figures 6a and 6b present a comparison of pressure histories taken at an axial location that corresponds to the end of the T4 combustor, respectively, illustrating a peak and a trough in the pressure distribution shown in Fig. 5. While the X2 results display an overall increase in pressure during the test time, the pressure trace from T4 declines, which is in accord with the time history of the freestream static pressure. Pressure fluctuations are observed for both experiments during the test time, with larger amplitudes and frequencies in the X2 results. These fluctuations can be driven by turbulence in the freestream, which is deemed higher for X2 based on a higher unit Reynolds number, and amplified through the flow compression process. Ultimately, this may cause a shift in the shock/expansion pattern through the combustor and hence affect the fuel

[‡]Experimental uncertainty is not constant at each transducer location and is discussed in the preceding paper [6].



a) Normalized axial position of 0.547



b) Normalized axial position of 0.582

Fig. 6 Transient behavior of pressure measurements at the end of the combustor for cases with a high fuel mass flow rate.

mixing and combustion process. Apart from the freestream turbulence, shorter test times further increase experimental uncertainties in X2, since less complete cycles of fluctuations become available for data averaging.

Table 1 Flow conditions for Mach 10 condition in both facilities

Property[a]	X2 at 450 μs		T4 at 2500 μs	
	Experiment	Computation (MB_CNS)	Experiment	Computation (ESTCj/NENZF)
p_s, kPa	2.4 ± 0.17	2.2 ± 0.28	——	0.99 ± 0.15
p_p, kPa	265 ± 19	260 ± 39	120 ± 8	122 ± 15
M	——	10.2 ± 0.4	——	9.8 ± 0.5
ρ, kg/m^3	——	0.032 ± 0.004	——	0.013 ± 0.002
T_s, K	——	251 ± 15	——	263 ± 32
U, ms^{-1}	——	3270 ± 100	——	3180 ± 160
$\dot{m}_{\mathrm{air}}$, kg/s	——	0.152 ± 0.020	——	0.384 ± 0.053
H, MJ/kg	——	5.6 ± 0.4	——	5.3 ± 0.29
Re_u, 10^6/m	——	5.55 ± 0.7	——	2.64 ± 0.14
p_{stag}, MPa	——	——	81.5 ± 5.7	——
U_s, m/s	——	——	2320 ± 60	——

[a]Experimental properties are averaged over a period of 20 μs, at 450 μs after flow startup for X2, and at 2500 μs for T4.

IV. Effect of Assuming Steady Flow

Analysis is required to ensure that the errors induced by the local transients [6] in the scramjet pressure measurements are significantly lower than other uncertainties. A quasi-steady analysis technique must be applied to the experimental data to produce quasi-steady results. Figure 7 compares pressure distributions along the engine wall for a fuel-on case, if one assumed the flow was at steady state. A significant difference between the two traces can be seen, with an increasing deviation in the downstream direction. As the flow entering the engine is appropriately scaled, the two data sets are in good agreement at the start of the inlet. Further downstream, the variance in initial flow properties of each gas slice between the two facilities (Fig. 3) results in divergence of the normalized pressure distributions. Applying the assumption of steady flow (Fig. 7), the X2 and T4 pressure distributions are significantly lower and higher, respectively, than those presented using the slug-tracking method (Fig. 5). This exemplifies the importance of using an adequate quasi-steady analysis technique for the presentation of experimental scramjet data.

V. Conclusions

Comparative scramjet engine pressure tests between a reflected shock tunnel and an expansion tube were conducted at Mach 10 flight conditions. The pressure measurements taken along the body-side engine wall were in close agreement between the two facilities for both the fuel-off and fuel-on cases investigated. The viability of scramjet engine testing in expansion tubes at the lower end of the facility's operating range has hence been proven. Based on the above,

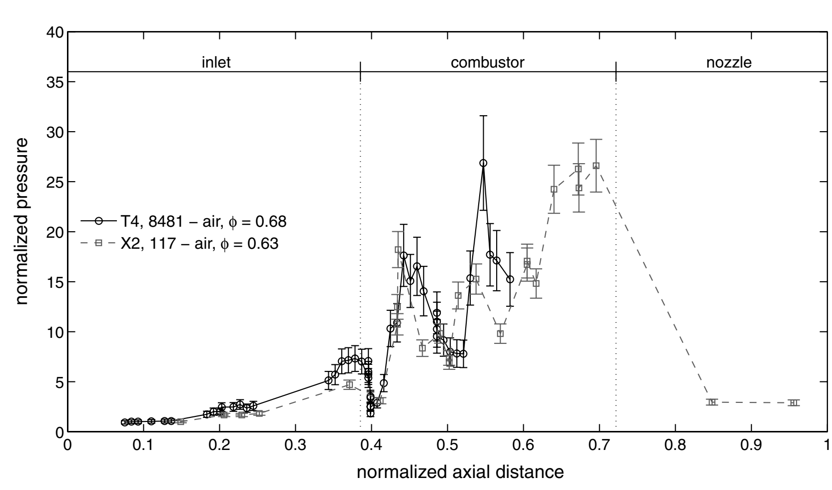


Fig. 7 Comparison of normalized pressure axially along engine for fuel-on shot into air for the high-fuel-equivalence-ratio case. Normalized assuming steady flow, error bars show combined measurement and sampling uncertainty levels.

confidence is increased for ground-testing scramjet engines in their upper operating regime, for which only expansion tubes can currently provide a testbed.

Acknowledgments

The authors would like to acknowledge the financial support of the Australian Research Council. We would like to thank Allan Paull, Madhat Abdel-Jawad, Myles Frost, and the other members of the HyShot team for their original contributions to the model design and valuable input into the experiments. The help of the T4 operators and the facility maintenance by Keith Hitchcock were also much appreciated. Finally, we acknowledge the valuable contributions of Richard Morgan and Peter Jacobs to the engine design and analysis.

References

[1] Curran, E. T., "Scramjet Engines: The First Forty Years," *Journal of Propulsion and Power*, Vol. 17, No. 6, November–December 2001, pp. 1138–1148.
doi:10.2514/2.5875

[2] Tetlow, M. R., and Doolan, C. J., "Comparison of Hydrogen and Hydrocarbon-Fueled Scramjet Engines for Orbital Insertion," *Journal of Spacecraft and Rockets*, Vol. 44, No. 2, March–April 2007, pp. 365–373.
doi:10.2514/1.24739

[3] Heiser, W. D., and Pratt, D. T., *Hypersonic Airbreathing Propulsion*, AIAA Education Series, AIAA, Reston, VA, 1994.

[4] Chinitz, W., Erdos, J. I., Rizkalla, O., Anderson, G. Y., and Bushnell, D. M., "Facility Opportunities and Associated Stream Chemistry Considerations for Hypersonic Air-Breathing Propulsion," *Journal of Propulsion and Power*, Vol. 10, No. 1, 1994, pp. 6–17.
doi:10.2514/3.23705

[5] Suraweera, M. V., and Smart, M. K., "Shock-Tunnel Experiments with a Mach 12 Rectangular-to-Elliptical Shape-Transition Scramjet at Off-Design Conditions," *Journal of Propulsion and Power*, Vol. 25, No. 3, 2009, pp. 555–564.
doi:10.2514/1.37946

[6] McGilvray, M., Morgan, R. G., and Jacobs, P. A., "Scramjet Experiments in an Expansion Tunnel Analyzed Using a Transient Flow Normalization Procedure," *AIAA Journal* (submitted for publication).

[7] Erdos, J., Calleja, J., and Tamango, J., "Increase in the Hypervelocity Test Envelope of the HYPULSE Shock-Expansion Tube," AIAA Paper 94-2524, June 1994.

[8] Stalker, R. J., Paull, A., Mee, D. J., Morgan, R. G., and Jacobs, P. A., "Scramjets and Shock Tunnels: The Queensland Experience," *Progress in Aerospace Sciences*, Vol. 41, No. 6, 2005, pp. 471–513.
doi:10.1016/j.paerosci.2005.08.002

[9] Pulsonetti, M. V., "Scaling Laws for Scramjets," Ph.D. Thesis, Univ. of Queensland, St. Lucia, Australia, 1995.

[10] Abdel-Jawad, M. M., "The Mach 10, 30 km Altitude Condition in the T4 Shock Tunnel Using a New Mach 10 Nozzle," Univ. of Queensland, Mechanical Engineering, Rept. 2005/05, St. Lucia, Australia, 2005.

[11] McGilvray, M., Jacobs, P. A., Morgan, R. G., Gollan, R. J., and Jacobs, C. M., "Helmholtz Resonance of Pitot Pressure Measurements in Impulsive Hypersonic Test Facilities," *AIAA Journal*, Vol. 47, No. 10, 2009, pp. 2430–2439.
doi:10.2514/1.42543

[12] McGilvray, M., "Scramjet Testing at High Enthalpies in Expansion Tube Facilities," Ph.D. Thesis, Univ. of Queensland, St. Lucia, Australia, 2008.

[13] Jacobs, P. A., "MB_CNS: A Computer Program for the Simulation of Transient Compressible Flows, Dept. of Mechanical Engineering, Univ. of Queensland, Rept. 10/96, St. Lucia, Australia, 1996.

[14] Krek, R. M., and Jacobs, P. A., "STN: Shock Tube and Nozzle Calculations for Air," Univ. of Queensland, Mechanical Engineering, Rept. 93/2, St. Lucia, Australia, 1993.

[15] Lordi, J. A., Mates, R. E., and Moselle, J. R., "Computer Program for the Numerical Solution of Non-Equilibrium Expansions of Reacting Gas Mixtures," NASA, CR-472, 1965.

N. Chokani
Associate Editor