*13th Australasian Fluid Mechanics Conference*
*Monash University, Melbourne, Australia*
*13-18 December 1998*

# PILOT STUDY FOR A RAREFIED HYPERVELOCITY TEST FACILITY

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## ABSTRACT

This paper reports the current results from a pilot study into the development of a rarefied hypervelocity test facility. The aim is to produce a rarefied hypersonic flow in which gas speeds are in excess of the earth orbital velocity of 7 km/s. In the experiments undertaken so far, the X1 expansion tube has been used with a conical nozzle to produce a flow of Argon at 8.8 km/s with a test flow duration of 60 μs. A central core of 50 mm diameter with Pitot pressure variation of 30% was produced. Experimental data are compared with results from a CFD code with only reasonable agreement being obtained. Further CFD simulations indicate that a larger region of more uniform flow may be obtained with no nozzle by allowing the flow from the expansion tube to expand freely into a large reservoir.

## INTRODUCTION

Aerobraking in the upper atmosphere of Venus was used to circularize the orbit of the Magellan probe with an expenditure of propellant which was less than 5% of what would have been required if thrusters only were used. The flight speed was 9 km/s and the flow was in the transition regime between continuum and free molecular flow (Rault, 1994). Eventually Magellan was allowed to fly even deeper into the atmosphere of Venus and, during this last (higher density but still rarefied flow) phase of its flight, the observed sequence of thruster firing required to maintain the stability of the satellite indicated that the aerodynamic forces were different from those predicted. Similar aerobraking manoeuvres, with flight speeds in excess of 10 km/s, were used in the Mars Pathfinder mission. In view of the anomalous Magellan results an improved understanding of the aerodynamics of high-speed, rarefied flow is required.

Compared to other areas of fluid mechanics, there is a paucity of experimental data for the aerodynamics of rarefied gases. The standard numerical method for these flows, the Direct Simulation Monte-Carlo (DSMC) method (Bird, 1994), whereby the motions and collisions of the gas molecules are simulated on a computer, has assumed the role of surrogate for experiments (Muntz, 1989). Molecule-molecule and molecule-surface collision models, which can involve exchange of energy amongst translational, rotational, vibrational and chemical energy modes have been developed for DSMC. These models often incorporate some assumptions of near equilibrium conditions in their derivation. It is very important that the accuracy of DSMC be assessed in the extreme conditions presented by aerobraking manoeuvres where the collision models can be expected to be severely tested. Present experimental facilities for rarefied gas flows are limited to stagnation temperatures of about 2000 K and hence are limited to test speeds of 1.5 to 2.0 km/s. The development of a high-speed test-facility which spans the range from rarefied to continuum flow will represent a significant increase in the range of experimental testing for DSMC.

The purpose of this paper is to present the results of an ongoing investigation into the development of a test facility for producing a uniform flow spanning the transition regime from continuum to rarefied. The X1 expansion tube of the Centre for Hypersonics at The University of Queensland is proposed for producing the flow. This paper reports the methods proposed for producing a hypervelocity rarefied flow, preliminary experimental results obtained in the expansion tube and a comparison of these results with numerical simulations of the facility.

## CONDITIONS FOR RAREFIED HYPERVELOCITY FLOWS

Bird (1994) argues that the continuum description of an expanding flow is no longer valid when a parameter, which he calls the *breakdown parameter*, is greater than 0.04. The relevant length-scale in Bird's breakdown parameter, $P$, is based upon the macroscopic flow gradients,

$$P = \frac{\sqrt{\pi}}{2} S \frac{\lambda}{\rho} \left| \frac{\partial \rho}{\partial x} \right|$$

where $\lambda$ is the mean-free path, $\rho$ is density, $x$ is distance and $S$ is the speed ratio, $u/(2RT)^{0.5}$.

In the case of the flow around an object such as an aerobraking shield, the importance of rarefaction (non-continuum effects) is indicated by the ratio of the collision time, $\tau$, to the characteristic flow time $D/u$, where $D$ is the characteristic size of the object in the test flow and $u$ is the characteristic flow speed (Macrossan, 1995). This can be expressed as

$$\frac{\tau}{D/u} = \frac{\sqrt{\pi}}{2} KnS$$

where $Kn$ is the Knudsen number, $\lambda/D$. This ratio is the same as Bird's breakdown parameter but with the length-scale equal to the characteristic model size. It is convenient to drop the constant, which is approximately unity, and define a rarefaction parameter, $P_D$, as

$$P_D = KnS\,. \qquad (1)$$

Bird's critical value of $P = 0.04$ corresponds to only 25 collisions over the characteristic length scale and it is reasonable to assume a similar value of $P_D = 0.04$ would indicate the onset of transition when an object of characteristic length $D$ is placed in the flow.

The mean-free path can be related to viscosity by

$$\lambda = \frac{2\mu}{\rho\sqrt{2RT}}\,.$$

Therefore $P_D$ can also be expressed in terms of the more familiar parameters of Mach number, $M$, and Reynolds number, $Re_D$, as

$$P_D = \frac{\sqrt{\pi\gamma}M^2}{2\,\mathrm{Re}_D}$$

The aim of this work is to produce an experimental facility capable of producing rarefied flow with a test flow speed in excess of earth orbital speed (7 km/s) with $P_D$ of the order of 0.04.

## POSSIBLE METHODS FOR PRODUCING RAREFIED HYPERVELOCITY FLOWS

One of the few facilities capable of producing the required flow speeds is the expansion tube, first proposed by Resler and Bloxsom (1952). An expansion tube uses a shock tube as the source of the test gas and accelerates this gas through an unsteady expansion in a constant area tube (see Fig. 1).

The expansion tube shown in Fig. 1 has a free-piston driver (Paull and Stalker, 1989). The wave diagram for such a facility is shown in Fig. 2. Initially the piston is located at the left-hand of the facility. The driver gas is contained between the piston and the primary diaphragm. The test gas (at state 1) is contained between the primary diaphragm and a light secondary diaphragm. The dump tank and acceleration tube initially contain the acceleration gas (at state 10).

A test is started by release of the piston which isentropically compresses the gas in the driver tube. The pressure of the driver gas is eventually high enough to cause the primary diaphragm to rupture. After rupture of the primary diaphragm a shock wave processes the test gas in the shock tube compressing it from state 1 to state 2. This shock is followed down the tube by the interface between the test gas and the expanded driver gas (states 2 and 3). When the primary shock reaches the secondary diaphragm the diaphragm ruptures and a shock propagates through the gas in the acceleration tube changing it from state 10 to state 20. Behind this acceleration gas comes the test gas, which has been further accelerated to state 5 through an unsteady expansion centred on the original location of the secondary diaphragm. It is this gas at state 5 that is used as the test slug for experiments. The test period is terminated by the arrival of the unsteady expansion.

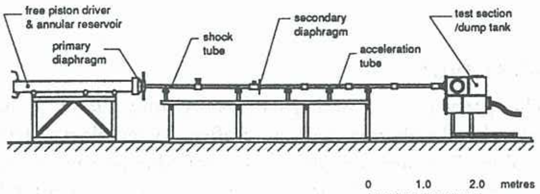

**Figure 1** Schematic of X1 expansion tube (Neely et al., 1991)

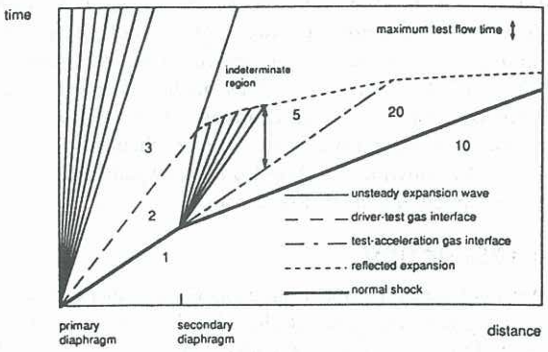

**Figure 2** Wave diagram for an expansion tube.

While it is possible to produce very high flow speeds with expansion tubes, the test time is limited to the order of tens or hundreds of microseconds.

The proposed modification to the expansion tube to produce rarefied hypervelocity flow is to run a tube with low initial filling pressures for the test gas and acceleration gas and then to expand further the flow at exit of the expansion tube into the dump tank. This final expansion is proposed to be a steady expansion either with a nozzle attached to the end of the tube or without a nozzle, by allowing the test gas to expand into the dump tank as a free jet (see Fig. 3). It may be possible to design a contoured nozzle to produce a uniform flow with negligible streamwise and spanwise gradients in quantities. The free jet expansion (which is sometimes used in lower speed rarefied gas testing, e.g. Gusev, 1994) would be expected to produce a flow with streamwise gradients and some divergence but may be useful for testing if these gradients and divergence are small for the scale of model being tested. The success of such modifications will be gauged by the quality of flow uniformity around the location proposed for a test model and the duration for which such a flow can be sustained.

## EXPERIMENTAL METHOD

Pilot experiments to determine the suitability of an expansion tube for producing rarefied flows have been performed in the X1 expansion tube of the Centre for Hypersonics at The University of Queensland. This facility is described in Neely et al. (1991). In order to investigate the use of a nozzle to expand the flow from the conditions at exit of the constant area acceleration tube (38 mm diameter) a conical nozzle was attached at the exit of the tube (Fig. 3a). This nozzle was 271.5 mm long and had a half-angle of $8^{o}$ giving an exit diameter of 114 mm. It may be possible to make a contoured nozzle to produce a more uniform outflow than will be obtained with the conical nozzle but this simple geometry is a good starting point for the present study. Argon was used as the test gas in order to simplify the gas chemistry models required in the computations.

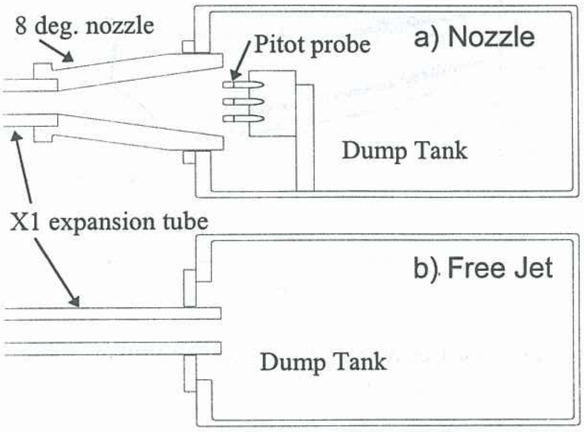

**Figure 3** Methods for producing rarefied hypervelocity flow with an expansion tube. (a) nozzle. (b) free jet.

Three Pitot probes were arranged at the exit of the nozzle as shown in Fig. 3a. The spacing between probes was 28 mm and allowance was made for movement of the probes between tests so that a higher spatial resolution could be obtained from repeat shots of the tunnel. PCB piezoelectric pressure transducers were located in the tips of the probes.

## NUMERICAL METHOD

Calculations of the flow in the expansion tube were performed with an axisymmetric Navier-Stokes code based on a finite-volume formulation and upwinding techniques (Jacobs, 1994). The code is capable of simulating the flow from rupture of the primary diaphragm through to expansion into the dump tank. In the present simulations the calculations start at the end of the shock tube and the inflow conditions were the pressure and speed of the gas at state 2 (see Fig. 2).

This code has been developed and tested for continuum flows and its performance in regions where the breakdown parameter, $P_D$, exceeds the critical value is unknown. One proposal for dealing with this is to run this code up to the point where the continuum assumption is no longer valid and then to perform further calculations with a DSMC code.

## RESULTS

The test conditions for the experiments are shown in Table 1. Pitot pressure profiles measured at the exit plane of the conical nozzle are shown in Fig. 4. These data are taken as an average over the 60 μs of test flow. This figure represents a compilation of data obtained from 11 shots of the tunnel. It can be seen that there is up to 40% scatter in some of the results. The data show a general trend of symmetry in the distribution about the centre-line with peaks in Pitot pressure towards the centre-line and at the extremities of the of the nozzle. Across the central 50 mm of the nozzle exit the Pitot pressure varies by ± 30%. This variation is larger than would be acceptable for testing. Some further testing of shot-to-shot repeatability is required and a nozzle other than conical may be necessary.

**Table 1** Average test conditions for experiments

| | |
|---|---|
| **Fill pressures** | |
| Reservoir pressure (Air) (MPa) | 3.9 |
| compression tube (Helium) (kPa) | 130 |
| shock tube (Argon), $P_1$ (kPa) | 2 |
| acceleration tube (Air), $P_{10}$, (Pa) | 24 |
| **Test flow** (gas state 5) | |
| flow speed (m/s) | 8600 |
| pressure (kPa) | 16 |
| temperature (K) | 7000 |
| density (kg/m$^3$) | 0.011 |
| Reynolds number per m (m$^{-1}$) | 320000 |
| Mach number | 5.5 |

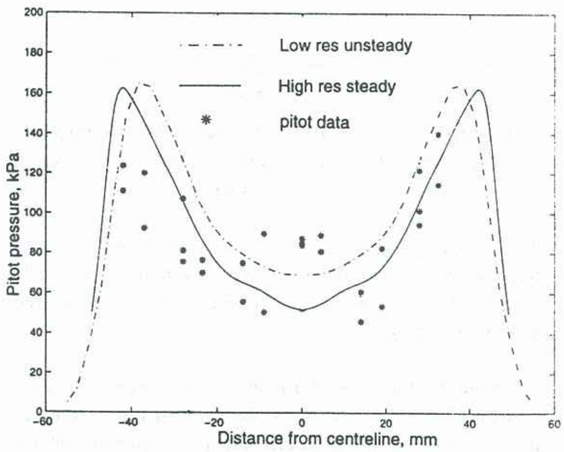

**Figure 4** Pitot pressure profiles at exit of the conical nozzle.

Shown also in Fig. 4 are results from the CFD simulation. Two calculations are shown. The first (chained line) is a simulation of the acceleration tube, nozzle and dump tank with inflow conditions to the acceleration tube taken from the measured shock speed and pressure in the shock tube. Due to resource restrictions only a course mesh (40 cells across the tube and nozzle) could be used. The second (solid line) is a higher resolution calculation of only the nozzle (140 cells across the nozzle). The inflow conditions to the nozzle were taken as the average conditions from the coarse mesh calculation during the steady test time and were held constant during the period of calculation. This second calculation was made to better resolve the viscous effects in the nozzle. In each case results are shown for the Pitot pressure calculated 36 μs after the test gas reaches the nozzle inlet.

The computed results show a similar overall trend to the experimental data but without a peak on the centreline of the nozzle. The levels of both computations and the experiments are similar and the computations indicate that over a central core of 50 mm diameter where the Pitot pressure varies by ± 30%.

For a model of characteristic size 25 mm in the nozzle exit flow, contours of the rarefaction parameter, $P_D$ (of eq. 1), and contours of Pitot pressure are shown in Fig. 5. It can be seen that $P_D$ is well above the continuum-flow limit at the nozzle exit, indicating that the flow is in the transitional regime.

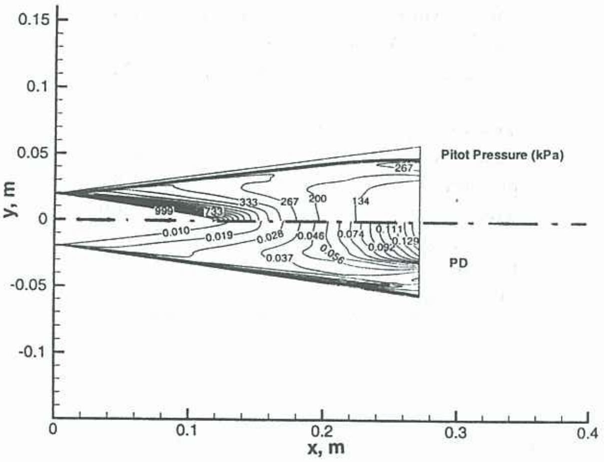

**Figure 5** Contours of Pitot pressure and rarefaction parameter, $P_D$, for nozzle flow (high resolution calculation).

The other possible method for producing a rarefied hypervelocity flow using an expansion tube is to allow the flow from the end of the acceleration to expand freely into the dump tank.

A calculation has been made of this geometry with a constant inflow to the dump tank from the acceleration tube. Contours of the rarefaction parameter and of Pitot pressure from this calculation are shown in Fig. 6. The calculations indicate that, as expected for hypersonic flow, the flow speed varies little as the gas expands into the dump tank. They also show that a flow which spans the transitional regime between continuum and rarefied is produced. At given locations from the tube exit regions of quite uniform Pitot pressure profiles are obtained. However a variation in Pitot pressure in the streamwise direction cannot be avoided and this may be an issue for large models.

## CONCLUSION

Preliminary experiments and computations aimed at investigation of the use of an expansion tube for producing a rarefied hypervelocity flow have been made. A conical nozzle attached to the end of the acceleration tube produced a non-continuum core flow of 50 mm diameter in which the Pitot pressure variation was ± 30%. The level of Pitot pressure and the distribution measured were similar to computations made with a Navier-Stokes code. The code also indicates that a more uniform flow may be produced by allowing the gas from the expansion tube to expand freely into a large dump tank. Further tests are required to check this experimentally. Also computations with a DSMC code are required to verify the validity of using the Navier-Stokes code at the present conditions.

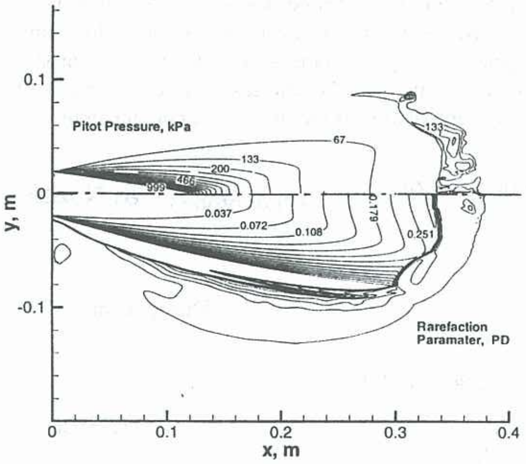

**Figure 6** Contours of Pitot pressure and $P_D$ for free-jet expansion into the dump tank.

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