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Upgrade of the X3 Super-orbital Expansion Tube

A. G. Dann[*], R. G. Morgan, D. E. Gildfind, P. A. Jacobs, M. McGilvray[*] and F. Zander

Centre for Hypersonics
The University of Queensland, Brisbane, Queensland 4072, Australia

Abstract

Expansion tubes are important facilities for the study of high enthalpy hypersonic flows which avoid the non-equilibrium chemical and thermal effects associated with the flow stagnation intrinsic to reflected shock tunnels. X3 is one of the largest free-piston super-orbital expansion tube in the world with an overall length of approximately 69 m and is capable of generating re-entry speed flows equivalent to those experienced during a hyperbolic re-entry trajectory. It was originally built with a two-stage free-piston driver to achieve the high compression ratio of a large diameter compression tube without the high construction costs of designing the large diameter tube to be strong enough to resist peak driver pressure loads. However, this arrangement proved difficult in operation. This paper describes the upgrades to X3, in respect to its physical layout. The facility has been recommissioned to incorporate a single-piston driver, a steady expansion nozzle and a new test section. Major changes have been made to the free-piston driver with a re-designed piston and launcher and a new end cap tube which is 200 mm thick to contain driver pressures up to 80 MPa. The re-designed piston introduces an area change at the primary diaphragm, ensuring that the maximum increase in total pressure and temperature can be gained as the driver gas undergoes unsteady expansion from sonic to supersonic conditions. The compression process steadily increases up to Mach 1 at the throat then gains of up to an order of magnitude in total temperature and pressure can be realised as the unsteady expansion process takes over. The area change will also increase test times; with a throat at the primary diaphragm, the piston mechanics can be more readily tuned to minimise reflection of waves off the piston which would otherwise reduce the test time. A new Mach 10 steady expansion nozzle has been developed which has increased the core flow and the test time for appropriate conditions. The dump tank has been replaced with a larger tank and test section giving a larger volume with greater potential for instrumentation.

Introduction

The concept of replacing the steady expansion of a shock tunnel with an unsteady expansion was first investigated by Resler and Bloxsom [14] in 1952. By adding to the total enthalpy of the test gas using an unsteady expansion rather than with a shock it was claimed that higher flow velocities, and high Mach number and Reynolds number flows could be generated. The flow was not stagnated and this in turn would mean less dissociation and ionisation. The disadvantages were a much shorter test time and development of large boundary layers in the resulting test flow. Hertzberg et al [6] were the first to apply the unsteady expansion concept by modifying a shock tunnel but Trimpi [19] in 1962 performed a more detailed theoretical study and was the first to coin the term ‘expansion tube’. NASA investigated the use of expansion tubes in the 1960’s and 70’s and highlighted a number of discrepancies between theory and experiment [7]. In particular there were problems with flow attenuation, secondary diaphragm rupture, flow turbulence, interface mixing, boundary layer thickness, thermal non-equilibrium and test time. After many investigations the expansion tube at NASA Langley was deactivated since only one usable condition for each test gas was obtainable for model testing.

Expansion tube research began at The University of Queensland in 1987 when Paull et al [13] converted the small shock tunnel, TQ, to an expansion tube by directly connecting the driver to the shock tube. This facility, reconfigured by Morgan [11, 9] and renamed X1, used multiple diaphragm sections to create the compound driver and to generate super-orbital capabilities. Investigations by Paull and Stalker [12] into test gas disturbances and research at GASL [18] finally determined that by using blends of nitrogen, argon and helium as the driver gas the perturbations could be reduced and many more conditions could be achieved. The successful driver gas blends sufficiently increased the speed of sound over the driver/test gas interface which was shown to limit the penetration of driver gas noise into the test gas.

Currently, the largest expansion tube in the world is the Lens-XX at the Calspan-University of Buffalo Research Center (CUBRC) in New York State, USA [4]. It has the capacity to measure heat transfer in flows ranging from 3-8.4 km/s at enthalpies from 5-36 MJ/kg.

In 1995, the X2 free-piston driven expansion tube was commissioned at The University of Queensland [3]. The two-piston configuration was chosen to reduce the cost of the high pressure primary driver section, which increases greatly with diameter. This decision was taken in the knowledge that it would give reduced performance and increased complexity in order to build the largest driven tube diameter possible with the funds available at the time. It was the prototype for a larger expansion tube, X3, which was subsequently commissioned in 2001. The original full facility layout is shown in Fig. 1 which illustrates the smaller diameter secondary stage of the compression tube. At this time only two diaphragm stations were possible with this configuration (primary steel and secondary mylar).

X3 proved to be difficult to operate in a two-stage configuration and this experience contributed to the conversion of X2 to a single-stage piston with a contoured exit nozzle [15] which commenced in 2002. A lightweight piston was used to develop tuned driver operation [17] in 2010 which further improved X2 and opened up a larger envelope of operating conditions [5]. In 2004 funds became available to convert X3 to a single-stage piston offering greater capabilities which the X2 facility had demonstrated. The initial funding through the Queensland Government Smart State Research Facilities Fund supported design and construction of the single-stage piston, a larger compression tube and new nozzle. Subsequent funding through SCRAMSPACE (funded by the Australian Space Research Program) has seen the addition of a new test section, instrumentation, data acquisition and other ancillary systems.

The development of X3 is on-going, however, this paper covers the original configuration of X3, the single-stage piston, the filament-wound nozzle and the test section additions.

[*]A. G. Dann and M. McGilvray presently at Department of Engineering Science, University of Oxford, Oxford, OX2 0ES, UK

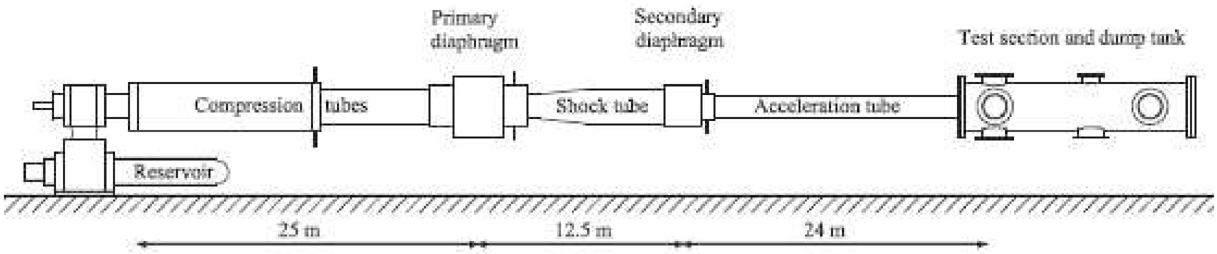

Figure 1: Schematic of the original X3 superorbital expansion tube (not to scale) [16]

Original Configuration

The original X3 piston configuration incorporated a lightweight outer piston and a heavy inner piston. These pistons were driven as one by a high pressure air reservoir until the outer piston was stopped by impacting on a buffer. This resulted in the heavy piston further compressing the driver gas by traveling down the secondary compression tube until it caused primary diaphragm rupture. In this configuration there was no area change from the secondary compression tube to the driven tube. Also, the kinetic energy of the outer piston was lost in the impact and could not be transferred into the driver gas. The primary diaphragm rupture pressures were limited to approximately half the design rupture limit by the outer piston impact speed. Attempts to increase this speed by using a hydraulic damper were not successful due to mechanical failure. The cost advantages of the two-stage piston become apparent because it allowed the large diameter compression tube to have a smaller wall thickness since the maximum operating pressure at this stage of compression was relatively low. The second stage of the compression where pressures were driven much higher, was contained in a tube of the same inner diameter as the acceleration or shock tube, hence reducing cost further.

Re-Design Details

The re-designed X3 expansion tube is shown in the schematic in Fig. 2 without the steady expansion nozzle fitted. It now has only one piston and therefore only one compression tube but the new rearrangement has created additional flexibility with the addition of an extra diaphragm station. The final compression tube is the largest addition in the upgrade, weighing just over 5 tonne.

A schematic of the piston arrangement is shown in Fig. 3 which illustrates the single large diameter piston with interchangeable weights to adjust the piston mass. When tuned correctly, the piston will now come to rest with minimal impact on a nylon rod buffer thus ensuring that the maximum amount of energy is transferred to the driver gas. A new primary diaphragm station has been designed with a new capstan nut, end cap and pressure plate.

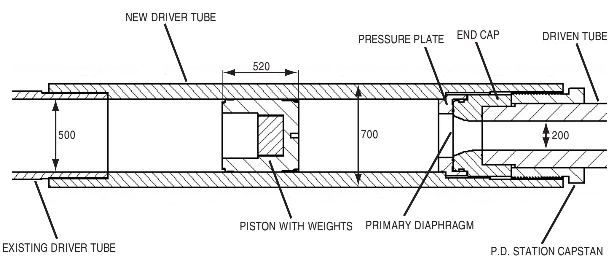

Figure 3: Schematic of the recommissioned X3 superorbital expansion tube piston assembly

Figure 4 illustrates the major features of the X3 single-stage piston. The piston body was constructed from aluminum and has a diameter of 498 mm and a length of 520 mm. A chevron seal attached to the front of the piston creates the seal to the compression tube inner diameter of 500 mm. Low friction wear rings, front and back, allow the piston to slide within the compression tube. The front plate is flat and the inner part of the piston is hollow with attachment points to add more mass to the piston if required.

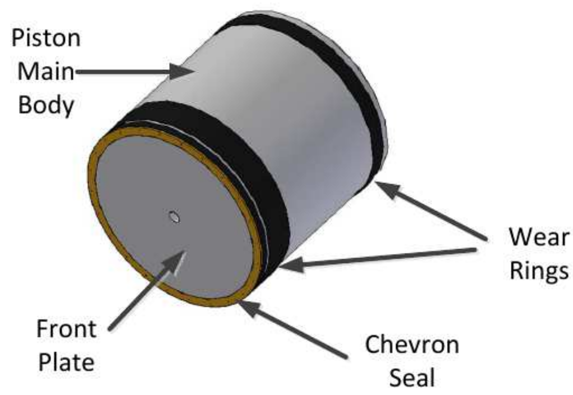

Figure 4: X3 single-stage piston components

The addition of a steady expansion nozzle to the end of the acceleration tube (thus operating in expansion tunnel mode) has three main benefits: increased test core flow diameter; slight increase in test time from use of gas in the unsteady expansion fan; and avoidance of viscous corruption of test flow for low enthalpy true flight scramjet conditions. This comes at the cost of density-length capability and a reduction in the total pressure/total enthalpy multiplication achieved through the test gas unsteady expansion for a targeted test flow Mach number. However, with a high performance driver like that implemented on X3, these losses in capability can be easily overcome for most conditions.

The Mach 10 steady expansion nozzle (Fig. 5) was manufactured by Teakle Composites. It consisted of three main components: steel attachment components for connection to the acceleration tube, a filament-wound nozzle and a sliding seal. The steel components for attachment to the acceleration tube consisted of two parts. A carbon-steel nozzle section allowed attachment to the existing acceleration tube which in turn threaded on to a carbon steel collar and fiber-attachment point. The glass fiber was wound directly on to the collar to provide a mechanical lock and pressure seal. The filament-wound nozzle was made from a glass fiber and an epoxy resin with a minimum thickness of 5 mm to maintain structural integrity and prevent through-gassing. It was wound on to a high density polyurethane mandrel which had been machined to the required

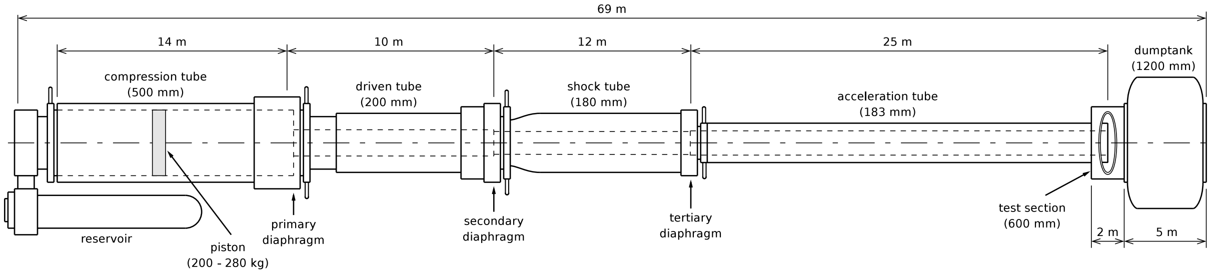

Figure 2: Schematic of the recommissioned X3 superorbital expansion tube (not to scale) [10]

contoured profile. To create the constant diameter sliding seal, an additional winding was made at the nozzle end and finished with a gel coating. The nozzle has a total length of 2.5 m and increases the flow exit diameter to 440 mm from the existing acceleration tube exit diameter of 183 mm.

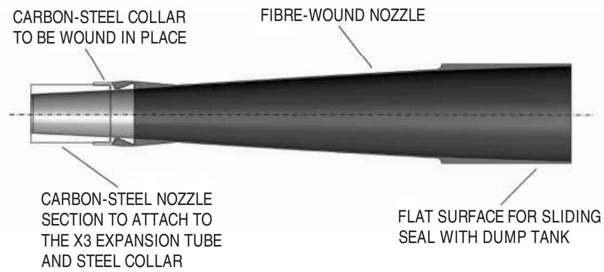

Figure 5: Sketch of the X3 steady expansion nozzle [2]

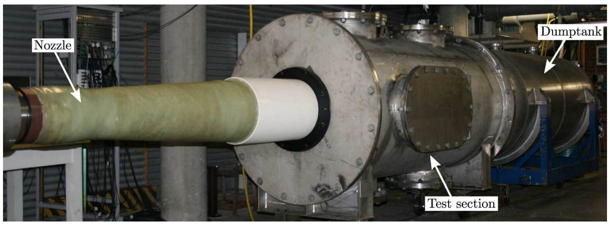

Figure 6: X3 nozzle, test section and dump tank [5]

A photo showing the assembled Mach 10 nozzle, test section and dump tank is shown in Fig. 6. The test section provides increased space for large scale models and multiple viewing and data ports. The standard diameter of the test section is approximately 1200 mm with a length of approximately 2500 mm and was constructed from 304 stainless steel. Together with the dumptank, the effective test section/dumptank volume is over 6.2 m^3.

The interior of the test section is shown in Fig. 7. A pitot rake is mounted in the test section to allow measurement of nozzle exit pitot pressures at radial spacings of 20 mm. The pitot probe tips are a new design consisting of a 15° cone tip. Following recent experimental testing of high total pressure scramjet conditions in X2, it was found that the bow shock associated with normal pitot measurements led to erosive heating damage. The cone probe was thus developed to provide a partial impact pressure measurement. The static pressure on the cone surface is measured with these probes and while this is not a Mach number independent measurement, sensitivity to Mach number reduces for Mach$>>$5. If the Mach number of the flow is approximately known, this cone pressure can be relatively easily correlated to actual pitot pressure or an equivalent metric in CFD. Large optical viewing ports were constructed in the test section and one of these is visible on the left in Fig. 7 although it is not fitted with an optical window at this stage.

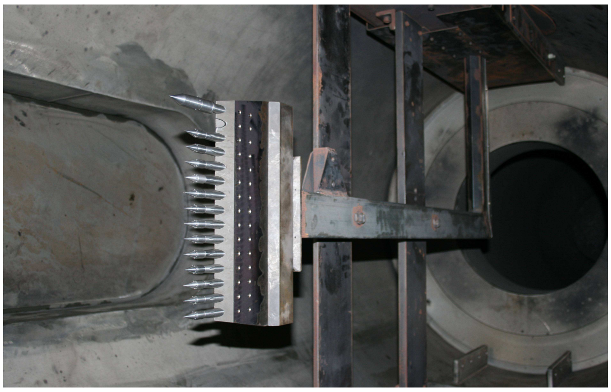

Figure 7: Internal view of X3 test section with pitot rack installed [5]

The re-designed facility has produced test flows of up to 1 ms duration at Mach 10 using a piston of mass 200 kg. The new driver is more reliable, with more repeatable test flows and the new test section permits greater flexibility to install more complex experimental models. Current commissioning experiments are focused on optimising the operation of the 200 kg piston and are aimed to achieve ‘tuned’ performance using a high percentage of argon in the driver gas. These conditions will be very suitable for lower enthalpy scramjet test flows at Mach 10 with

$p_o \approx$100-200 MPa. To achieve the performance necessary for super-orbital conditions, and also for scramjet flows at the upper limit of foreseeable scramjet combustion, lighter driver gas mixtures will be required. Up to 100% helium will be needed and a lighter piston will be required to achieve tuned operation. Design is currently underway for an $\approx$100 kg metallic piston which will be commissioned in late 2012.

Using a family of larger nozzles going up the Mach 14, vehicle re-entry simulations will be carried out on larger models, including a full sized replica of the Hayabusa asteroid return capsule. This will enable direct laboratory simulation of radiating flows for the first time in a shock layer without the need for scaling.

Scramjet combustion was tested in X2 by McGilvray [8] and achieved scramjet combustion in an expansion tube for the first time. While the McGilvray tests were constrained by the relatively small size of X2, new tests in X3 as part of the SCRAMSPACE project, will conduct a series of scramjet combustion experiments which are planned to overlap with the existing measurements made on the Centre for Hypersonics reflected shock tunnel, T4 at Mach 10, and using the same model. The tests will then be repeated at higher total pressures and Mach numbers to investigate the Mach 10 to Mach 14 operating envelope which is an essential precursor to developing a scramjet assisted access to space vehicle.

Conclusion

The X3 upgrade is an on-going project to improve the existing expansion tube capabilities at the Centre for Hypersonics at The University of Queensland. The previous two-stage piston arrangement has been replaced with a more reliable, higher performance single-stage piston. Other additions such as the filament-wound nozzle and larger test section have widened the envelope of test conditions, instrumentation and test capabilities to allow the generation of hypervelocity flows suitable for high total pressure scramjet testing and high total temperature re-entry vehicle testing.

Acknowledgments

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