

THE OXFORD HIGH DENSITY TUNNEL

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ABSTRACT

This paper summarises the design, operation and installation of the High Density Tunnel at The University of Oxford. Developed in the early 1960's, the facility has been used in various operating modes throughout its life. Acquired from Qinetiq in 2012, the facility has been refurbished and is currently undergoing installation at The University of Oxford as a cold hypersonic aerodynamic facility. The facility will be operated as either a Ludwieg tube or a Light Isentropic Compression Heating (LICH) tunnel and will be capable of generating flows with test times up to 70 ms and cores larger than 200 mm. This paper describes the infrastructure, operation and associated instrumentation for the facility and the current progress in commissioning.

1. INTRODUCTION & HISTORY

The High Density Tunnel (HDT) was originally developed at the RAE in the United Kingdom in the 1960's. Constructed from 6 inch gun barrels, the facility was initially operated as a cold hydrogen driven shock tube and tunnel. The facility had a driver working pressure up to 1000 bar and a driven tube working pressure up to 400 bar. Eventually the operation was extended to include a reflected shock tunnel mode, which brought about shortening of the driven tube. It was operated in this mode until the mid 1980's when the facility was again converted, this time into a Ludwieg Tube with the ability to add light piston compression heating [LICH, 1]. In the early 1990's, external electrical heating and a fast acting plug valve were added to the facility to further increase the capabilities. Most recently the HDT has been used by Qinetiq in support of the HyShot [2] and SHyFE hypersonic flight experiments [2].

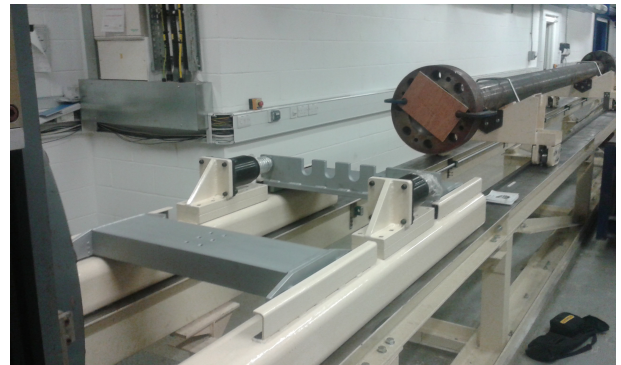
The Oxford High Density Tunnel was acquired from Qinetiq in 2012 to widen the portfolio of hypersonic ground-test facilities within the Osney Thermo-Fluids Laboratory at the University of Oxford. The HDT adds to the existing Oxford Low Density Tunnel and the new multi-mode T6 Stalker Tunnel [3] which is also under development. Capable of generating relatively long duration flows at high Reynolds number, the Oxford HDT will be suitable for

both steady and unsteady aerothermodynamic testing of hypersonic configurations.

Section 2 of the paper briefly describes the HDT, its operation and includes some preliminary numerical results. Section 3 summarises the supporting infrastructure while Section 4 describes the available instrumentation. The paper concludes in Section 5 with an outlook to future work.



(a) View looking downstream



(b) View looking upstream. The plug and gate valves and nozzle have yet to be installed.

Figure 1. Photographs of the installed HDT

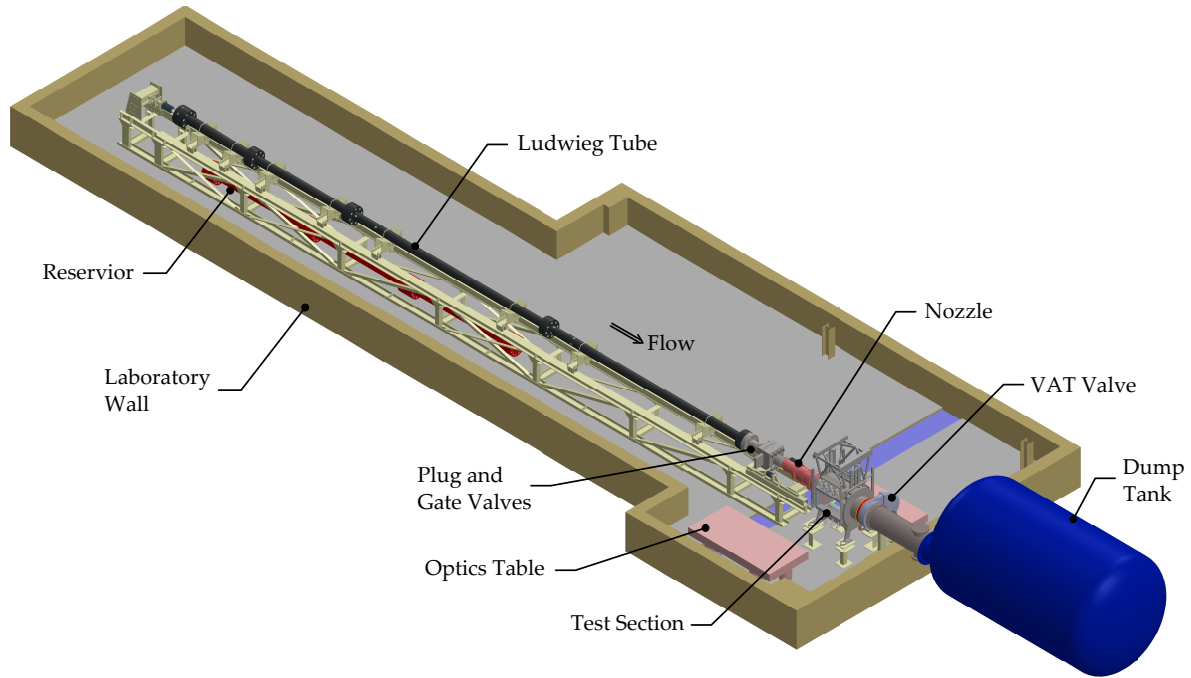


Figure 2. Schematic of The University of Oxford High Density Tunnel showing its placement in the laboratory.

2. FACILITY DESCRIPTION & OPERATION

Photographs provided in Figure 1 show the current state of the installation of the HDT at the University of Oxford. A corresponding schematic of the facility is given in Figure 2. The HDT features a 17.4 m long steel Ludwig Tube with internal diameter 152.4 mm. This tube is formed from four shorter, flanged sections which are bolted together. The Ludwig Tube is attached to a contoured converging/diverging nozzle via a fast-acting plug valve assembly that was designed by Jones et al. [1]. The facility nozzle exhausts into a test section and then into a 28 m³ vacuum tank that is external to the building. When operated in LICH mode, the previous driver tubes act as the reservoir for the facility. This reservoir is 6.5 m in length with internal diameter of 152.4 mm and, as shown in Figure 2, is mounted beneath the Ludwig Tube. The reservoir is attached via fast acting piloted solenoid valves and flexible hosing to the upstream end of the Ludwig Tube. For all components upstream of the facility nozzle the maximum pressure rating has been reduced to 275 bar. This pressure rating is at a temperature of 300 °C for the Ludwig Tube components and at ambient temperature for the reservoir components.

The Oxford HDT can be operated in two different modes, either as a simple Ludwig Tube or as a LICH tunnel [4]. In each mode, external electrical heating of the test gas may be used to increase the total temperature. The aim is to keep the test gas just above liquefaction at the nozzle exit, thus resulting in a high Reynolds number, albeit cold, test flow. The Ludwig Tube concept was developed in 1955 by Hubert Ludwig to produce high

Reynolds number, transonic or supersonic flows at low operating costs [5]. By allowing a high-pressure source of test gas contained in a long reservoir to expand transiently into a test section through a supersonic or hypersonic nozzle these facilities can ideally produce clean flow with minimal perturbations. The use of a long reservoir delays the return of reflected expansion waves that disrupt the test flow. Operation at hypersonic Mach numbers requires active heating of the test gas before expansion to avoid condensation and liquefaction. The maximum temperature the Oxford HDT can reach through electric heating is 573 K. One-dimensional simulations of the HDT were performed by Neely et al. [6] to determine the potential run times in the facility under standard Ludwig Tube operation (Figure 3). Ideally, run times of ≈ 80 ms could be achieved at a Mach number of 6, for the maximum stagnation conditions of 275 bar and 573 K.

In Ludwig Tube mode the achievable maximum Mach number is limited to approximately $M = 6$. Testing at higher Mach numbers requires higher total temperatures which may be achieved through the inclusion of a light piston compression stroke in the process, i.e. a LICH tunnel [4]. A drawback of this mode of operation is that further flow disturbances can be introduced through a mismatch of temperature across the piston, additional finite expansion waves and the rolling up of vortices in front of the piston.

Figure 3 plots the variation in achievable unit Reynolds number with gas total temperature for each facility nozzle. The corresponding model wall to flow total temperature ratios are also indicated. It can be seen that LICH mode allows for a wide range of wall to gas total temperatures

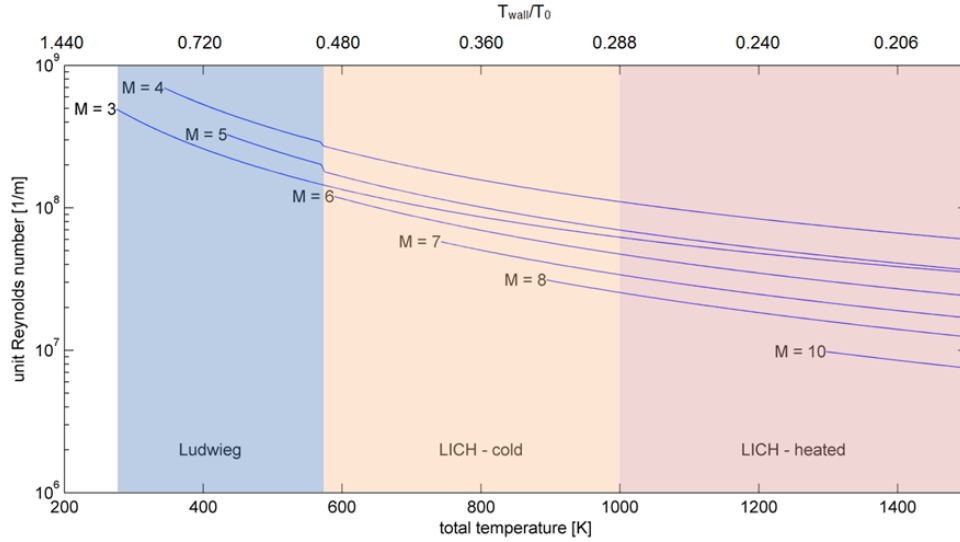


Figure 3. Maximum unit Reynolds number achievable for each nozzle at a given total temperature. Low Mach number test conditions are limited by keeping test section below atmospheric pressures, even with nozzle unstart.

Table 1. Safe operating limits of the HDT. Maximum pressures can be increased provided the facility nozzle remains started and the test section pressure remains sub-atmospheric.

Property	Mach 3	Mach 4	Mach 5	Mach 6	Mach 7
Operation Mode	Ludwig		Ludwig/LICH		LICH
Max. Total Pressure (bar)	30	95	100	90	90
Min. Total Temperature (K)	288	360	454	580	750
Max. unit Reynolds number ($10^6/\text{m}$)	493	694	326	120	58

to be examined, albeit at a cost of unit Reynolds number and test time. Although the facility has an overall pressure limit of 275 bar, currently the test section must be kept sub-atmospheric throughout the test duration. This limits the allowable pressure for the Mach 3 and 4 nozzles. Furthermore, for larger experimental models, the permissible operating conditions are restricted to ensure that even if the facility nozzle unstarts the pressure within the test section remains sub-atmospheric. Finally, when operated in LICH mode the achievable pressure is limited by the volume of the reservoir. The overall performance of the facility with these limitations is presented in Table 1.

2.1. Fast Acting Plug Valve

A bespoke fast acting plug valve was designed by Jones et al. [1], to allow for quicker and cleaner operation of the facility. Jones et al. used a similar design on light piston tunnels for turbine facilities, like the Oxford Turbine Research Facility (OTRF). Shown in Figure 4, the valve is an upstream facing plug valve. The valve is operated by venting a high pressure reservoir of air from behind the plug, allowing for the test gas to push the plug open and pass through radial cut-outs. To re-seal the plug valve, high pressure gas is injected behind the piston. Several coarse steel meshes are placed downstream of the valve to mitigate the wake formed behind the plug valve.

Initial 3D numerical simulations of an open plug valve are presented in Figure 5 in the form of Mach number contours. The simulations were undertaken to assess the influence of the wake formed behind the plug valve on the facility nozzle exit flow without the presence of the coarse steel meshes that are currently present. Due to the asymmetric supports of the plug valve, a 120° sector was simulated with the plug fixed in its fully open position (steady state). The commercial solver ANSYS CFX¹ was used; the inlet flow was taken to be at 95 bar and 400 K, corresponding to a Mach 6 test condition (Figure 3). Flow was assumed turbulent throughout the computational domain and was modelled using the Spalart-Allmaras [7] model. Different simulations were completed with either an adiabatic or isothermal wall boundary condition. Although the results presented in Figure 5 show strong non-uniformities in the flow behind the plug valve body, as shown in Figure 5 these are damped by the exit of the facility nozzle, resulting in a relatively uniform (to within 2 % of the mean) flow over a core of ≈ 120 mm for each flow property. Figure 5 also shows little difference between the 2D and 3D simulations. Development of a transient 3D simulation of the facility is an area of ongoing research.

3. SUPPORTING INFRASTRUCTURE

In addition to the basic facility, there are a number of secondary systems and infrastructure that are required for

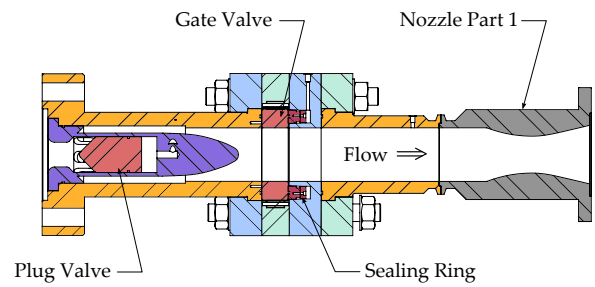


Figure 4. Schematic of fast-acting plug valve developed by Jones et al. [1]

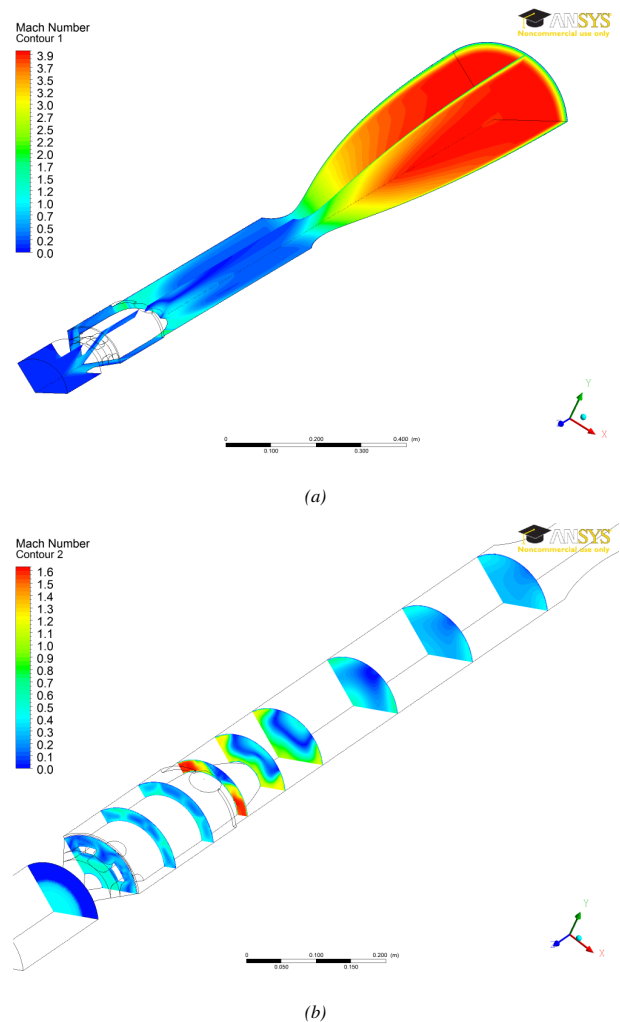


Figure 5. Mach number contours behind the plug valve housing computed using CFX (steady state). Flow is from bottom left to top right.

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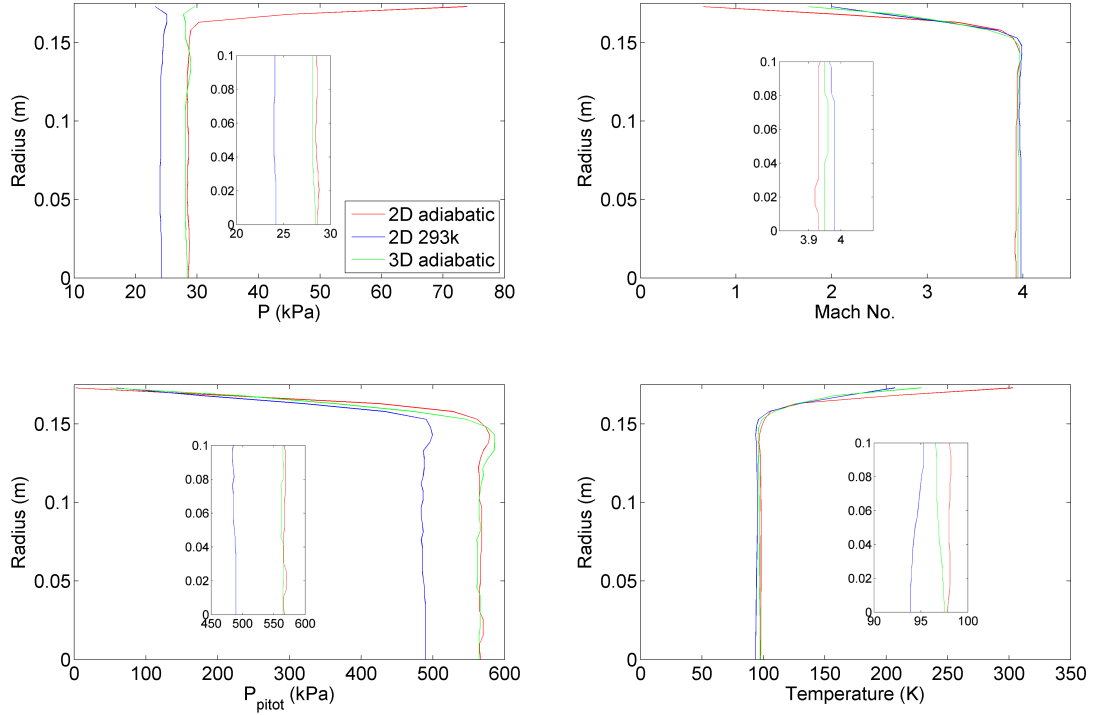


Figure 6. Radial profiles of pressure, temperature, Mach number and Pitot pressure at the exit of the Mach 6 facility nozzle.

the facility operation. This section gives a brief overview of these systems. High pressure air for both the HDT and T6 Stalker Tunnel [3] is supplied by a Gardner Denver 54371A compressor (350 bar, 145 m³/h) that is fitted with a dryer and which is connected 3000 l volume bottle bank. Heating of the facility is provided by an Eltherm[®] bespoke system that is based on a set of mineral insulated heating cables. Gas heat up time is estimated to be on the order of a few minutes once the facility is filled, with excess heat removed from the laboratory by an environmental fan system. The lightweight piston, that is yet to be designed, is expected to have mass ≈ 150 g. Return of the piston to the initial position is achieved via a low differential pressure (i.e. gas return).

The facility instrumentation consists of GEMS pressure transducers, which are used to monitor the fill pressures; Inficon capacitance diaphragm gauges, which monitor the test section pressure and are used for calibration; three Kulite[®] XTEH-7L-190-3000A 210 bar spaced along the length of the Ludwig Tube, and two Kistler 601H transducers which are located just upstream of the nozzle throat.

The previous HDT test section is being used. This has a diameter of 760 mm, is 939 mm in length and features large windows (778 \times 423 mm) for optical access. The test section is fitted with a traverse mechanism developed by Quadratic Ltd that allows automatic re-orientation of an experimental model over a range $\pm 20^\circ$ angle-of-attack and

$\pm 5^\circ$ angle-of-yaw. Five contoured nozzles covering the range Mach 3 to 7 have been designed by Gas Dynamics Ltd. Finally, the test flow exhausts into an existing mild steel dump tank, 28 m³ in volume. During a test the recoil forces are transferred into the frame via a single ACE model A3x5EU-R-199 shock absorber (Figure 2).

4. INSTRUMENTATION & DATA ACQUISITION

The instrumentation available for experimental models consists of PCB[®] model 132 and Kulite[®] XTEL-140 high speed pressure transducers and in-house thin film heat transfer gauges (HTA3 and HTA4). Data is recorded using National Instruments PXIe-8135 controller with several PXIe-6368 (2 MHz/channel) and PXIe-6363 (2 MHz aggregate) cards. A free-flight DAQ featuring 6 channels recorded at 20 kHz (with signal conditioning) is also under development. For high speed Schlieren and Shadowgraph the laboratory has two high speed cameras, a Specialised Imaging Kirana (5 MHz for 250 frames) and a Photron Mini UX-100 (1 MHz with reduced capture window for 3 s). A 1 MHz LED light source has also been developed. Finally, for laser diagnostics the laboratory has a Continuum Powerlite ND-YAG laser, a low noise Oxixium DPSS 532 nm laser and a Laser Quantum DPSS 671 nm laser. These lasers will be used for PLIF, LIGS [8] and FLDI [9] respectively.

5. SUMMARY & OUTLOOK

This paper has presented a brief overview of the design, installation and operation of the HDT at The University of Oxford. This facility will be a relatively long duration cold flow facility, capable of generating high unit Reynolds number hypersonic flows over a range of wall to total temperature ratios. It will be suitable for both steady and unsteady aerodynamic testing at hypersonic velocities up to approximately Mach 8. Installation of the facility is well underway with initial commissioning expected to begin from mid-2015.

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