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Thermal-fluid-structural analysis of the Oxford High Density Tunnel

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Abstract

Modelling of the operation of the Oxford High Density Tunnel (HDT) was performed to establish the level and duration of test gas heating required in the facility and the thermal structural implications of this heating. 1-D gas dynamic simulations of the transient flow conditions in the facility were performed for a range of starting pressures and tunnel configurations demonstrating potential test times of 80ms at M6 and unit Re = 1.45e8m^{-1}. Gas-state analysis was used to establish the liquefaction limits for the oxygen and nitrogen components of the air test gas at the outlet of the nozzle to quantify the heater requirements (power and duration) for the facility. The HDT is required to contain high-temperature and high-pressure test gas safely for extended periods to ensure uniform heating and transient FEM simulations showed that the structural and thermal-structural loads on the facility during its heat up and operation were well within the static limits of the facility. FEM was also used to perform transient simulations of the heat loss from the test gas during the experimental runs. CFD simulations of the buoyant mixing were performed to establish the duration of preheating of the test gas required in the facility to ensure gas temperature uniformity prior to operation of the tunnel. This was found to be of the order of minutes.

Introduction

The Oxford High Density Tunnel (HDT) was acquired from Qinetiq in 2012 to widen the portfolio of hypersonic ground-test facilities at the Osney Thermo-Fluids Laboratory at the University of Oxford, adding to the existing Oxford Low Density Tunnel and Oxford Gun Tunnel. The Oxford HDT, operated in heated Ludwieg tube mode, will enable the Osney Lab to produce relatively long duration flows at high Reynolds number for both steady and unsteady aerothermodynamic testing of hypersonic configurations.

The HDT originated at RAE/DRA/DERA in the UK and since the early 1960s has seen operation as a shock tube, a shock tunnel and then both as an unheated and heated high-pressure Ludwieg tube and also as a Ludwieg tube Isentropic Compression Heated (LICH) tunnel [6]. It had most recently been used by Qinetiq to support the HyShot [2] and SHyFE hypersonic flight experiments. The current facility has an 18m long steel Ludwieg Tube made up of a number of flanged sections (ID 152mm) bolted together and attached to a hypersonic nozzle via a fast-acting plug valve assembly.

Ludwieg Tube Operation

Hubert Ludwieg, developed the Ludwieg tube concept in 1955 to produce high Reynolds number, transonic or supersonic flows at low operating costs [7]. Ideally these facilities can produce clean flow with minimal perturbations by allowing a high-pressure source of test gas contained in a long reservoir to expand transiently out into the test section through a supersonic or hypersonic nozzle. The use of a long reservoir delays the return of reflected expansion waves to disrupt the test flow. Operation at hypersonic Mach numbers requires active heating of the test gas before expansion to avoid condensation and liquefaction. This heating is usually achieved by either heating the tunnel itself [4,8] or by operation in LICH mode [1,6] through the use of a light piston to compress and heat the gas in the tube although the later can induce additional flow disturbances.

One-dimensional simulations of the HDT operation were performed using Jacob's L1D code [5], from the University of Queensland, to determine the potential run times in the facility under standard Ludwieg tube operation (figure 1, 2). Ideally, run times of ~80ms could be achieved at a Mach number of 6 and a unit Reynolds number of 1.45e8m^{-1} for the maximum stagnation conditions of P_o = 27.6MPa and T_o = 673K.

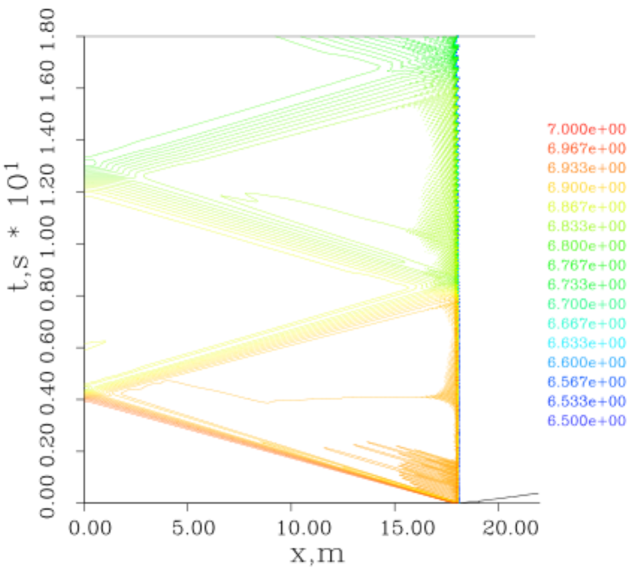

Figure 1. Example x-t diagram of flow in the HDT for fill pressure of 90 bar and preheat of 500K showing the passage of the expansion wave through the Ludwieg tube. (Contours show log(P)).

The influence on the flow of the plug valve constriction and the nozzle supply plenum downstream was also investigated and they were found to have a noticeable starting time with the potential to shorten the steady test flow delivered by the nozzle (figure 3). These 1D calculations are however inconclusive and will require further detailed investigation using full axisymmetric CFD.

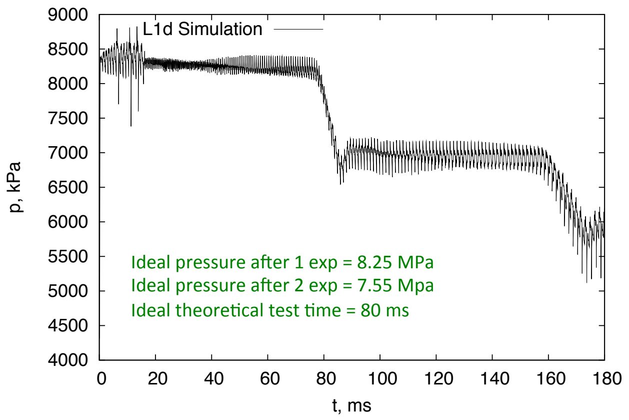

Figure 2. L1D calculation of the nozzle supply static pressure for a fill pressure of 90bar and preheat of 500K showing the pressure steps resulting from the passage of the expansion wave.

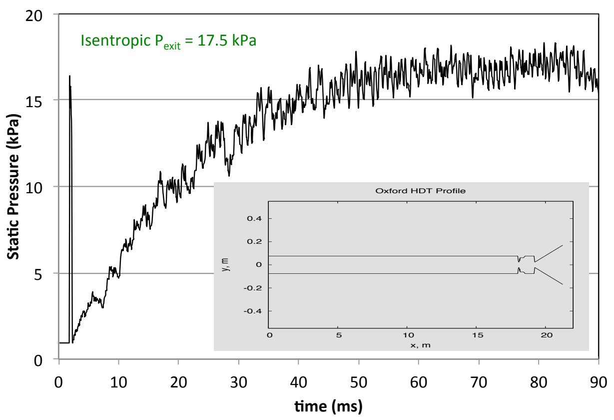

Figure 3. L1D calculation of the pressure history at exit of the HDT nozzle with incorporation of the plug valve and plenum geometry for a fill pressure of 276bar and preheat of 500K.

Test Gas Preheat

Irrespective of the heating strategy, it is necessary to determine the test gas stagnation temperature required to avoid liquefaction in the nozzle exit. An equilibrium calculator was used to establish the liquefaction limits for the N_2 and O_2 components of the air test gas at a range of fill pressures (figure 4).

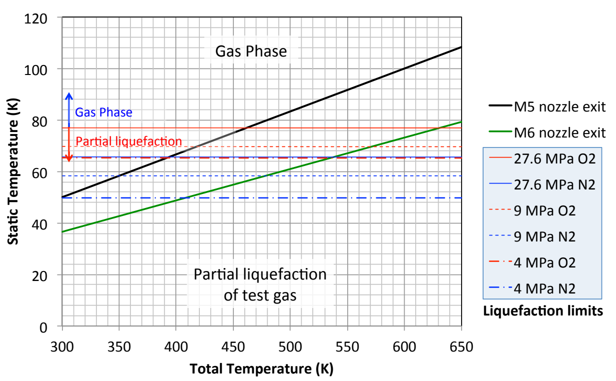

Figure 4. Plot of the static temperature at the exit of M5 and M6 nozzles, assuming isentropic expansion, as a function of the preheat temperature, superimposed on the liquefaction thresholds for N_2 and O_2 at a range of charge pressures.

Increasing the charge pressure and thus the initial test gas density will raise the liquefaction temperature and thus require greater pre-heat to avoid it. For a 27.8MPa charge of O_2, the test gas must be preheated to 630K to avoid liquefaction while a 40bar charge of N_2 only requires the test gas to be preheated to 420K.

Sizing the Heater

The Ludwieg tube section of the HDT had previously been heated using trace heater wires, spirally wound around the tube (though not the flanges) and then wrapped with an insulating blanket. The existing heater was removed due to deterioration and required replacement. This original heater had been operated up to 500K but based on the analysis above would not be sufficient for the higher density air conditions to be run in the facility at M6.

The heater must be sized with consideration of three primary requirements, the maximum test gas temperature, the heat-up time and the cost. These must be balanced to achieve acceptable performance by selecting the maximum driving temperature of the heater and the heater power, which govern the rate of heating. Likely operation will involve a morning heat up and then maintenance of the tube temperature throughout the day's testing by using insulation to minimise heat loss from the pressurised and heated test gas in the tube (figure 5).

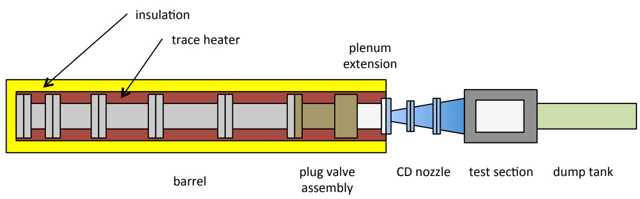

Figure 5. Schematic layout of the HDT showing the heated and insulated Ludwieg tube supplying the hypersonic nozzle.

Transient thermal FEM simulations were performed to examine the heat-up times for various combinations of heater power, layout and driving temperature. It was found that configurations of external contact heaters could be designed which reduced the thermal nonuniformity in the HDT structure to within ~10°C (figure 6)

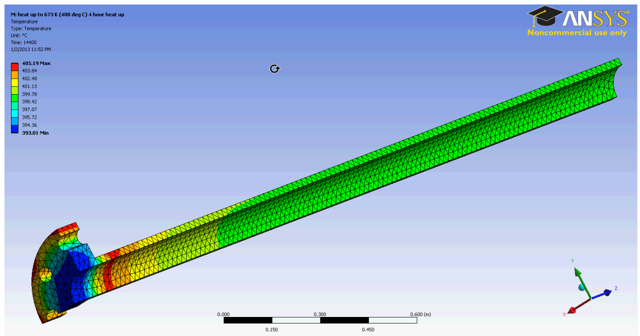

Figure 6. Temperature distribution in a section of the HDT Ludwieg tube for preheat to 673K for 3 hours using 13.9kW/m^2 on the flange, 8.3kW/m^2 near the flange and 3.6kW/m^2 on the tube (T= 393–405°C).

Thermal-Structural Loads on the HDT

The superposition of high temperatures and high pressures requires careful consideration of the stresses induced in the facility. Transient thermal-structural FEM simulations were performed to examine the resulting worst-case stressing in the HDT (figure 7). The large thermal mass of the flanges requires dedicated heaters to ensure temperature uniformity for practical heat-up times.

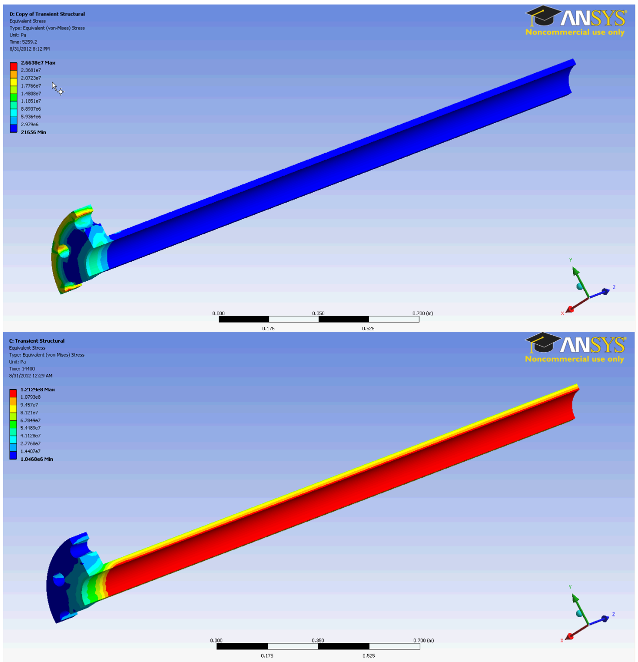

Figure 7. Transient thermal-structural simulation of stress distribution in a section of the HDT for preheat of 500K comparing the cases of (a) no internal pressure (Stress=0.2–27MPa) and (b) for a fill pressure of 276bar (Stress=1–120MPa).

Transient Heat Up of the Test Gas

A uniform state is required in the test gas in the HDT before running the facility. It is hence necessary to determine the time taken for the test gas to reach thermal uniformity when heated.

There are three potential modes of heating during the operation of the tube.

1. Heating the tube with the cold gas charge present.
2. Topping up the charge in the heated tube after a run.
3. Charging the preheated tube with test gas.

Case 1 represents the start condition at the beginning of the day and will be dominated by the thermal mass of the tube and the sizing/power of the heater unit, as described in the previous section.

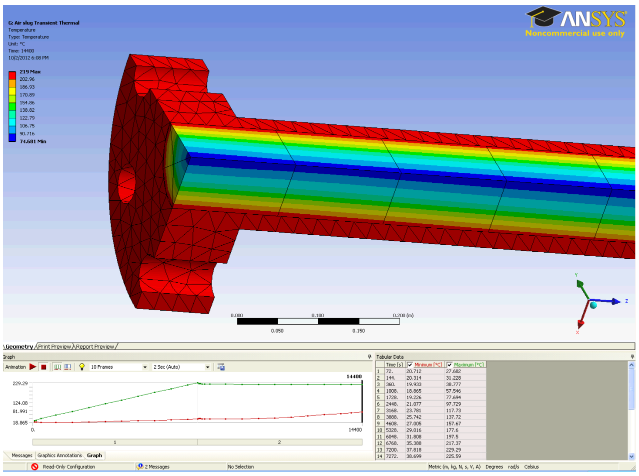

Figure 8. Temperature distribution through the stagnant test gas within the HDT, for 2 hours of active heating to ~500K and 2 further hours of conductive heat spread with no heat addition or loss (T=75–219°C).

Case 2 will be the most common usage scenario during a run campaign while Case 3 represents another start scenario. To estimate the nominal worst-case test gas heat-up time, calculations were performed of heating a pressurised slug of air at ambient temperature in contact with an isothermal wall.

Initial transient FEM calculations demonstrated that heating of stagnant gas in the HDT (figure 8), in which heat is transferred only via conduction gave unrealistic gas heat up times of the order of hours (figure 9) as it did not account for mixing of the gas via buoyant convection.

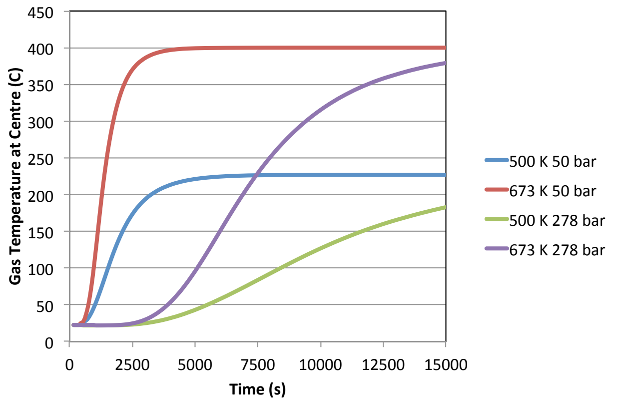

Figure 9. Heat-up times deduced from the history of the central gas temperature at the centre of the slug, from FEM conduction analysis with no account of buoyant mixing.

Buoyant Mixing of the Test Gas

To establish more realistic heat-up times that accounted for the natural convection in the heated tube a transient 2-D CFD simulation was performed in which a pressurised slug of air was exposed to an isothermal wall at the tube preheat temperature.

Solutions were established to be both mesh and time step independent [3]. A standard mesh of 21726 elements was then employed. Simulations were run for the 4 cases set out in table 1. The air in contact with the wall quickly heats up and starts to buoyantly rise, inducing a region of higher velocity flow close to the wall (figure 10) with the cooler air in the centre of the tube sinking to take up its place.

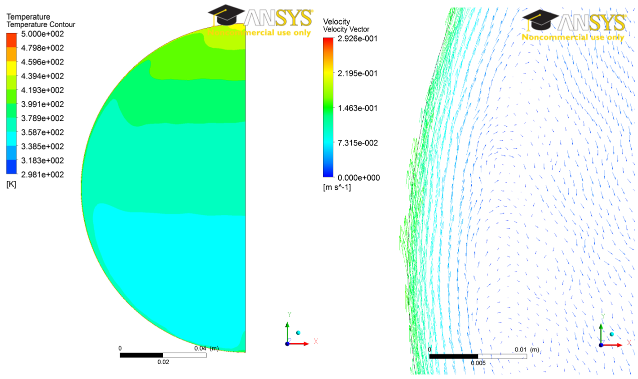

Figure 10. Distribution of (a) temperature (T=298–500K) and (b) flow velocity (V=0–0.3m/s) in the tube during preheating [3].

This flow field then gradually quiesces as the heat convectively spreads through the gas and the temperature approaches uniformity. Figure 11 and figure 12 illustrate the evolution of the temperature distribution during the heat up. It can be seen that for these conditions (preheat of 500K and a fill pressure of 50bar), nominal thermal uniformity of the test gas is reached within approximately 80-100s.

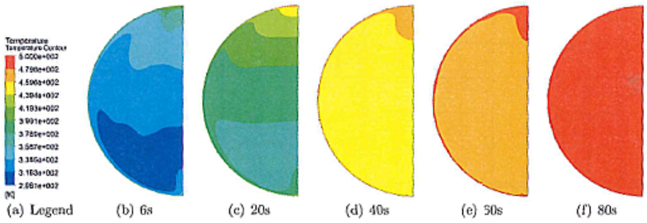

Figure 11. Evolving temperature distributions during the test gas heat up for preheat of 500K and a fill pressure of 50bar (T=298–500K). [3]

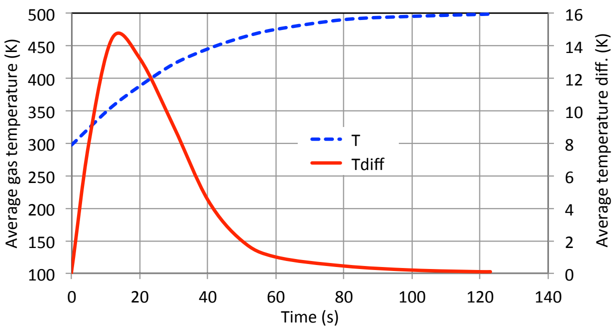

Figure 12. Plot of histories of (a) average gas temperature and (b) maximum temperature variation in the test gas for preheat of 500K and a fill pressure of 50bar.

Table 1 summarises the heat-up times for the four combinations of wall temperature and fill pressure considered. It can be seen that the combination of lower fill pressure and higher wall temperature induces the fastest heat up due to the lower thermal mass of the gas and the higher driving temperature difference. This is consistent with the trend observed for the pure conduction case illustrated in figure 9 but occurs in 1 to 2 orders of magnitude shorter time, emphasising the significance of the buoyant mixing.

Property	Case 1	Case 2	Case 3	Case 4
Wall Temp (K)	500	673	500	673
Fill Pressure (bar)	50	50	278	278
1% heat up time (s)	120.3	93.4	156.8	126.4
Time constant	30.9	25.7	41.8	34.6

Table 1. Heat up times predicted by transient CFD simulation.

This heat-up period of ~2 minutes is also orders of magnitude quicker than the initial heat up time of the tube structure. Since the buoyant convective mixing occurs in a relatively short period this allows refilling of the heated tube between runs while avoiding the long delay of the initial preheat of the tube.

While these simulations were performed using in isothermal wall condition rather than employing more accurate conjugate heat transfer, which would account for non-uniform evolving wall temperatures, it is not expected that the result would be noticeably different. This is due to the relatively small thermal mass of the test gas compared to the structural mass of the tube and the orders higher conductivity of the steel walls than the gas, which would smooth out any temperature non-uniformity.

Non-Ideal Heat Loss

The outflow of the heated test gas through the plug valve assembly during operation of the HDT will result in heat loss to the wetted surfaces. This must be minimised by active heating of these components to maintain uniform stagnation temperatures.

A brief study of the effectiveness of conductive and radiative heat transfer was examined for external wall heating of the plug. Large temperature gradients remained in the plug even after a significant heating time (figure 13). This issue will require further examination using a more accurate CHT approach to quantify the cooling effect on the exiting gas.

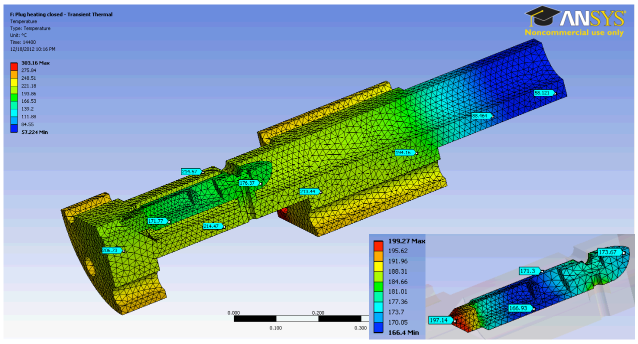

Figure 13. Temperature distribution in the plug valve assembly for a 3-hour, 500K wall preheat (T=57–303°C, T=166–199°C).

Conclusions

This paper has outlined the fluid thermal structural considerations for the operation of the Oxford High Density Tunnel. Successful operation of the HDT at the highest fill pressure of 27.6MPa requires preheating of the test gas to at least 460K for M5 and 630K for M6 to avoid liquefaction. These combinations of pressure and temperature result in structural loads well within the static strength of the facility. Fluid heat-up times are of the order of minutes, aided by buoyant mixing.

Acknowledgments

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