

Commissioning Ludwig Mode with Isentropic Compression Heating for the Oxford High Density Tunnel

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A new mode of operation, Ludwig mode with Isentropic Compression Heating (LICH), has been commissioned for the Oxford High Density Tunnel (HDT). LICH mode can extend the total temperature range of Ludwig tunnels by including a piston stroke in the shot sequence, compressing the test gas and heating it above the level achievable by electrically pre-heating Ludwig tubes alone. A numerical model for HDT has been developed for rapid assessment of conditions, aiding in the design of a lightweight piston. Initial testing has been carried out, producing 600 K Mach 7 flow and proving the capability of LICH mode in HDT. An assessment has been carried out of the overall performance of HDT operating in LICH mode at Mach 7. Condition maps have been generated using the numerical model, validated from experimental data. Finally, the freestream noise is compared to various other facilities which produce similar flow conditions.

Nomenclature

A	=	area, m^2	<i>Subscripts</i>	
a	=	speed of sound, m s^{-1}	1	= condition in the reservoir
F	=	friction, N	2	= condition in the barrel (driver gas)
M	=	Mach number	3	= condition in the barrel (test gas)
m	=	mass, kg	4	= condition in the nozzle plenum
Nu	=	Nusselt number	5	= condition in the test section
p	=	pressure, Pa	D	= barrel diameter
Pr	=	Prandtl number	f	= fill/initial condition
R	=	gas constant, $\text{J kg}^{-1} \text{K}^{-1}$	o	= condition at plug valve opening
Re	=	Reynolds number	P	= relating to the piston
T	=	temperature, K		
x	=	displacement, m		
γ	=	ratio of specific heat capacities		
ρ	=	density, kg m^{-3}		
τ_d	=	plug valve opening time, s		
τ_m	=	piston mass time constant, s		

I. Introduction

WIND tunnels using isentropic piston strokes have been used since the early 1970s, with several key improvements being incorporated in developments since then. The addition of a piston stroke to isentropically heat test gas for wind tunnels was first investigated by Jones et al. [1] after employing a similar technique for producing engine-realistic flows in gas turbine cascades. A trial facility was built which produced steady, high temperature, supersonic ($M > 1.8$) flows. Oldfield et al. [2] then incorporated this into the Oxford University Gun Tunnel, producing similar but more steady stagnation conditions than the gun tunnel was capable of. Following this success, a dedicated LICH tunnel was built at Southampton University [3] which added electric heaters to the barrel to preheat the test gas, allowing even greater total temperatures to be achieved. All of the tunnels up to this point used a diaphragm to release the test gas

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into the test section when the tube pressure reached a certain threshold. At Syracuse University [4, 5] a LICH tunnel was developed which used a fast acting ball valve instead. This increased the opening time, extending the length of the rarefaction wave which propagates along the barrel. This had the result of decreasing the magnitude of reflected waves from the piston and producing steadier flow. Currently, the TUSQ facility at the University of Southern Queensland uses a light piston to heat test gas in a Ludwig tube and can produce Mach 6 flows with total temperatures above 500 K [6].

LICH mode has been implemented in the Oxford High Density Tunnel (HDT) to address the need for higher total temperatures, allowing for a greater range of wall to total temperature ratios and unit Reynolds numbers to be tested. Higher temperatures also allow higher Mach number nozzles to be used while avoiding liquefaction of the test gas as it expands through the nozzle.

This paper presents a description of HDT, how LICH mode operation is achieved, and a simple numerical model of the tunnel. Sample experimental data is then presented, followed by performance maps calculated using the validated numerical model.

II. LICH Mode Operation in the High Density Tunnel

Shown schematically in Figure 1, the HDT consists of a 152.4 mm diameter x 17.4 m long, electrically heated barrel (2 & 3) capped, on the downstream end, by a pneumatically operated fast-acting plug valve. A contoured nozzle sits downstream of the plug valve via an intermediate plenum (4). Nozzles exist for Mach numbers of 4, 5, 6, and 7 which can be interchanged as necessary. The Mach 7 nozzle was used for all shot data presented in this work. All nozzles have a 0.351 m exit diameter and exit into a free jet test section (5). The test section leads to a dump tank of 28 m³. For further details on the construction and operation of HDT, see McGilvray [7] & Wylie [8].

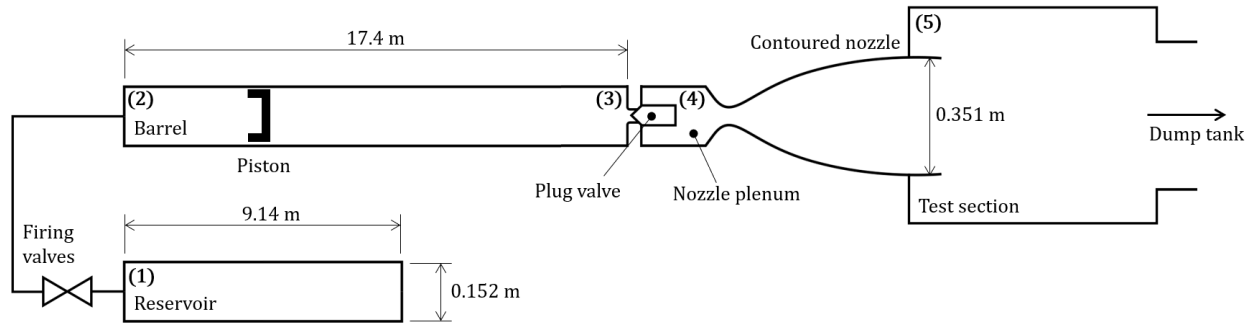


Fig. 1 Schematic of HDT showing key infrastructure

Additional infrastructure for LICH mode includes the piston and the piston reservoir (1). In HDT, the piston is driven using an external reservoir of high pressure gas, which consists of a 152 mm bore, 9.14 m long tube situated below the barrel. Unlike the barrel, the reservoir is unheated and remains at ambient temperature, which is advantageous for maintaining the temperature of the piston during the stroke. The reservoir is connected to the barrel via 2 Hale Hamilton MV22 pilot-operated solenoid valves and 2 Douglas-Chero 2500 manually operated globe valves. The Hale Hamilton valves are fast-acting so are used to initiate the piston stroke, while the Douglas-Chero valves are used to adjust the mass flow rate and enable tuning of the piston motion. The maximum effective diameter of the barrel feed pipework is 17.7 mm. The globe valves were set to an effective diameter of 11 mm for shots presented in this paper.

The piston was designed to minimise mass while maintaining enough strength to both survive an impact with the end of the barrel and withstand a significant pressure differential during barrel filling and venting. Shown in Figure 2, two different pistons were designed - a “low” temperature piston suitable for use with the barrel cold and a “high” temperature piston, suitable for use with the barrel heated to 500 K.

The low temperature piston was designed primarily as a test piston for the initial stages of commissioning and is a fairly simple single-piece design. It is constructed from oil impregnated nylon which is self-lubricating, ensuring a smooth piston stroke, but limits it to be used while the barrel is unheated. The piston has a free-running sliding fit with the barrel while maintaining a low level of leakage with the three channels in the outer face acting as a rudimentary labyrinth seal. The mass of the low temperature piston was 0.28 kg.

The high temperature piston was designed to be able to run with the barrel pre-heated and consists of an anodised aluminium body and two brass rings, which are shrink fit onto the body, to provide the sliding contact between the

piston and the barrel. The piston has a loose fit with the barrel at room temperature and, due to the different rates of thermal expansion of the aluminium piston body and the steel barrel, a close sliding fit at the design point of 500 K. The high temperature piston has a mass of 0.68 kg.



Fig. 2 Left: oil-filled nylon low temperature piston. Right: anodised aluminium high temperature piston.

In addition to the reservoir, piston and firing valves, further modifications to the HDT pipework were required to ensure safe operation. During filling and venting of the barrel, the presence of the piston results in relatively small, trapped volumes of gas. These could result in large differential pressures on the piston, risking damage so were vented through the addition of a balance line.

A. Ludwig Mode Operation

Before discussing LICH mode operation, it is worthwhile revisiting the fundamentals of Ludwig mode operation. A Ludwig tunnel consists of a high pressure reservoir which is isolated from a converging/diverging nozzle, typically via a diaphragm or a fast-acting valve. A shot occurs when the test gas is allowed to pass through the nozzle into the test section. A feature of HDT, which is not typical of Ludwig tunnels, is a plenum located between the plug valve and the nozzle throat (region 4 in Figure 1). The flow stagnates in the plenum, causing two effects: firstly, a large unsteady temperature spike occurs during flow initialisation; secondly, the additional flow path and surface area causes total temperature losses. Additionally, the freestream noise levels (in terms of $\text{RMS}(\overline{p_{\text{pitot}}}) / \overline{p_{\text{pitot}}}$) have been measured to be lower than other Ludwig tunnels which is postulated to be due to the presence of the nozzle plenum.

As the plug valve opens, rarefaction waves begin to travel upstream through the test gas in the barrel. These waves are reflected once they reach the upstream end of the barrel and travel back to the nozzle plenum. During the time between the rarefaction wave leaving and returning to the plug valve, the supply pressure to the nozzle plenum remains constant. During a shot, this process occurs multiple times, leading to a series of steady flow periods of subsequently lower and lower pressures of between 30-70 ms in length depending on fill conditions. The strength of the pressure drop between reflected waves depends on the speed at which the plug valve opens and as presented by Hillyer [9], can be altered to extend the steady test time.

B. LICH Mode Operation

To operate in LICH mode, a light piston is placed inside the barrel which separates the test gas in volume 3 from the driver gas in volume 2 (see Figure 1). The shot firing sequence includes a piston stroke to compress and heat the test gas. The piston can operate inside the already pre-heated barrel, meaning that the temperature of the test gas can exceed that which is possible in Ludwig mode. Compared with gun tunnels, which operate in a similar way [10], the piston in a LICH tunnel moves relatively slowly - the piston stroke can take several seconds. This is to ensure the test gas is compressed isentropically and avoids the production of compression waves, resulting in a prolonged steady test time and a uniform temperature distribution in the test gas.

The following paragraphs detail some of the key differences in operation between Ludwig mode and LICH mode:

Tunnel Setup

In LICH mode, there are four independent inputs that may be adjusted to alter the test condition achieved. They affect the resulting nozzle supply conditions in the following ways:

- $p_{3,o}$ - the barrel pressure at which the plug valve is set to open. The nozzle supply pressure, p_4 , is purely a function of $p_{3,o}$.
- $p_{3,f}$ - the initial barrel fill pressure. The compression of the test gas is set by the ratio of initial to final barrel pressure, $p_{3,o}/p_{3,f}$. Greater compression ratios lead to higher nozzle supply temperatures, T_4 . The compression ratio also influences the total test time available - see *Test Time* below.
- $T_{3,f}$ - the initial barrel fill temperature. The temperature of the test gas at the beginning of the piston stroke dictates the final temperature after compression. A given T_4 is achievable using multiple combinations of $p_{3,o}/p_{3,f}$ and $T_{3,f}$, the implications of which are discussed further in Section V.B.
- $p_{1,f}$ - the initial reservoir fill pressure. This gives control over the piston stroke, with larger pressures leading to faster strokes. Additionally, the reservoir pressure affects the rate of change of p_4 during a shot - see *Matched Conditions* below.

Fill conditions are all set prior to the shot and a threshold for $p_{3,o}$ is input into the programmable logic controller (PLC) which controls HDT. A GEMS 3100 Series pressure sensor monitors the barrel pressure during the piston stroke and once the preset threshold is measured, the PLC performs an automated sequence to actuate the valves that allow the plug valve to open and initiate the shot.

Test Time

The test time in LICH mode can be defined by either the total flow time or the duration of the steady flow periods caused by rarefaction waves. The total flow time, defined as the time taken for the test gas to exit the facility nozzle, is a function of two variables: compression ratio and nozzle throat area. The compression ratio determines the piston displacement when the plug valve is opened, with higher compression ratios corresponding to greater displacements from the initial position and resulting in a shorter total flow time. Nozzles with a smaller throat have a lower mass flow rate for given supply conditions which results in a longer test time. In the case of HDT, for which the nozzle exit diameters are constant across the range of nozzles, this means that higher Mach number nozzles in HDT have a longer test time in LICH mode compared with lower Mach number nozzles.

Piston Mass

An ideal piston for LICH mode acts purely as a barrier between the driver gas and the test gas and is massless. In reality, the mass and consequent momentum of the piston result in bulk oscillation of the piston when subject to a rapid differential pressure. This happens at two occasions during a piston stroke: firstly, at beginning of the piston stroke when the firing valves connecting the reservoir to the barrel are opened; secondly, when the plug valve is opened to begin the shot. In the first case, the piston oscillations have little effect on performance. However, in the second case, the piston oscillations are transferred to the test gas and lead to oscillations in stagnation pressure, typically at a higher frequency than rarefaction wave transmission.

Another effect of the piston having mass is that the rarefaction waves created at the beginning of a shot are partially reflected by the piston. Acoustic analysis carried out by Oldfield et al [2] and later by Magari & LaGraff [5] show that this effect is dependent on the ratio of the plug valve opening time, τ_d , to the time constant associated with the piston mass, τ_m , given by Equation 1.

$$\tau_m = \frac{m_P}{2A_P \rho_{3,o} a_{3,o}} \quad (1)$$

Where m_P and A_P are the piston mass and cross-sectional area and $\rho_{3,o}$ and $a_{3,o}$ are the density and speed of sound of the barrel test gas at plug valve opening. Results from the analysis showed that the reflected waves are only significant if the piston mass time constant is of a similar magnitude to the plug valve opening time. At values of $\tau_d/\tau_m \gg 1$ the strength of reflected rarefaction waves diminished greatly, being negligible at $\tau_d/\tau_m = 10$. The high temperature piston (right in Figure 2) has a mass of 0.68 kg, resulting in τ_d/τ_m values of between $\sim 10 - 80$ depending on the tunnel conditions chosen.

Matched Conditions

After the plug valve opens, mass is lost from barrel. The flow is said to be matched if the mass flow rate from the reservoir to the barrel is equal to that from the barrel to the nozzle. This means that the test gas barrel pressure is constantly being replenished during the shot from further piston compression, leading to a steady barrel pressure and consequently constant nozzle supply pressure during the shot. If the mass flow rate from the reservoir is greater than that through the nozzle, the pressure will rise during a shot, and if it is lower, the pressure will fall during a shot.

Achieving a matched condition in HDT is made difficult due to a relatively high mass flow rate through the nozzle. In order to match this using the current tunnel setup, the reservoir pressure must be $\sim 6 - 8.5$ times the nozzle supply pressure at plug valve opening, depending on tunnel conditions. A high reservoir pressure causes a fast piston stroke, which is undesirable in LICH mode. A method, proposed by Jones et al [1], to achieve both a slow piston stroke and matched conditions is to perform the piston stroke with a small reservoir flow area and increase it once the shot begins. This would be achievable in HDT by operating the two reservoir firing valves independently but has currently not been explored.

III. Numerical Modelling

A numerical model has been developed which uses a system of ordinary differential equations (ODEs) to describe the mass flow of gas between regions of the tunnel, the temperature of gas in each region, and the dynamics of the piston. The model was originally created by Buttsworth [11] for modelling TUSQ at the University of South Queensland, and is described in detail in Reference [11]. As part of an initial investigation of the implementation of LICH mode in HDT, McGrath [12] updated the model to reflect the geometry and plug valve operation of HDT. Key updates to the current version of the model, used in this work, are presented in the following paragraphs.

HDT Geometry

The majority of geometry updates were made by McGrath [12] with the exception of the nozzle plenum (region4). This was included, which involved an additional set of mass flow and heat transfer equations being added into the system of ODEs.

Piston Heat Transfer

Heat transfer to the piston was modelled to aid in piston design. The correlation shown in Equation 2, from Taylor [14], describes heat transfer to pistons in internal combustion engines and, in the absence of a more specific model, is taken to be valid for this work.

$$Nu_P = 10.4 \cdot Re_P^{3/4} \quad (2)$$

Re_P refers to the Reynolds number based on the piston velocity and the piston diameter. For implementation into the ODE model, the correlation was used to calculate heat transfer to the front and the rear faces of the piston using gas properties from volumes 2 and 3, with the overall heat transfer being the sum of that to the front and rear faces. The piston was assumed to be thermally thin, having a uniform internal temperature distribution at all times.

Heat Transfer Scale Factors

Heat transfer between gas and the barrel walls can be approximated as that of a gas flowing through a cylinder in steady state, given by the commonly named Dittus-Boelter equation [13] shown in Equation 3.

$$Nu_D = 0.023 \cdot Re_D^{4/5} \cdot Pr^n \quad (3)$$

Where $n = 0.4$ for gas heating and $n = 0.3$ for gas cooling. This approximation does not fully capture the transient nature of the flow in the vicinity of the piston, in particular a vortex ring which is generated by the boundary layer being “scooped” off the barrel walls as the piston moves [1]. Additionally, some parts of the tunnel (such as the plug valve) have more complex geometries, leading to higher levels of heat flux. These heat transfer effects are modelled by including heat flux augmentation factors for certain gas volumes - this approach gives reasonable results with sufficient tuning to experimental data. Scale factors were applied to the heat transfer coefficients calculated from Equation 3.

Piston Friction Model

A new friction model for the piston which is proportional to the piston velocity was implemented for use in the equation of motion for the piston. The friction model is given by Equation 4 and produced accurate piston stroke dynamics.

$$F = 10 \cdot \dot{x}_P \quad (4)$$

Implementation

The system of ODEs was solved using the `ode15s` function within MATLAB. This particular solver was chosen due to its efficiency with stiff differential equations which helped during periods of rapid variation (e.g. just after the plug valve opens or at piston impact). Outputs of the model are (referring to Figure 1 for subscripts): x_P , \dot{x}_P , m_1 , m_4 , m_5 , T_1 , T_2 , T_3 , T_4 , and T_P . Pressures in each volume are calculated from the mass and temperature solutions using ideal gas assumptions. The model is terminated when the piston impacts the end of the barrel and the total simulated time is typically between 1 and 10 seconds, depending on initial conditions. Table 1 presents the range of initial conditions investigated in this work.

Table 1 ODE model initial conditions

Variable	Units	Range
$p_{3,o}$	bar	8 – 50
$p_{3,f}$	bar	$1 - 0.95 \cdot p_{3,o}$
$p_{1,f}$	bar	$1.1 \cdot p_{3,o} - 200$
$T_{3,f}$	K	300 – 550

A. Model Validation

Prior to LICH mode shots being undertaken in HDT, the ODE model was validated using data from both a Ludwig mode shot and an unheated LICH shot. For the Ludwig mode validation case the ODE model was simplified by setting the piston velocity to 0 and removing gas volumes 1 and 2 (the reservoir and the barrel upstream of the piston).

Figure 3 shows the results from the model compared with Ludwig mode shot data. The ODE model does not calculate any acoustic effects so does not follow the more transient changes in pressure and temperature caused by rarefaction waves being reflected in the barrel. However, the overall trends in both pressure and temperature are captured with reasonable accuracy.

Figure 4 shows the barrel pressure and the nozzle supply pressure for a cold LICH shot compared with results from the ODE model. Once again, the model follows the overall trend: a steady pressure rise during the piston stroke followed by a sudden drop when the plug valve opens at $t = 0$. It is still unable to capture the shorter duration transients in pressure. The sudden change in barrel pressure in the shot data at $t = -1.5$ is an aberration caused by the piston passing over the barrel pressure sensor.

These validation cases were used to tune the effective diameter of the reservoir to barrel contraction, the heat flux augmentation factors in different parts of the tunnel, and plug valve opening times.

B. Model Predictions

Typical results from the ODE solver are presented in Figure 5 for the initial conditions given in Table 2. This tunnel setup is referred to as Condition A and is the condition chosen for experimental testing. Plots of pressure, temperature, and piston dynamics are shown. The legend in the pressure plot (top) also applies to the temperature plot. The time axis has been adjusted such that $t = 0$ corresponds to the first rise in the nozzle supply pressure. This enables consistent comparison with Ludwig mode shots and experimental data.

During the piston stroke, the reservoir pressure, p_1 , decreases while both barrel pressures, p_2 and p_3 , increase simultaneously. At the beginning of the shot, at $t = 0$, the nozzle plenum pressure, p_4 , increases to a level slightly lower than p_3 . p_4 is seen to decrease, along with p_2 and p_3 while the plug valve is open. This indicates that the condition is not matched as if it were, p_4 would stay constant.

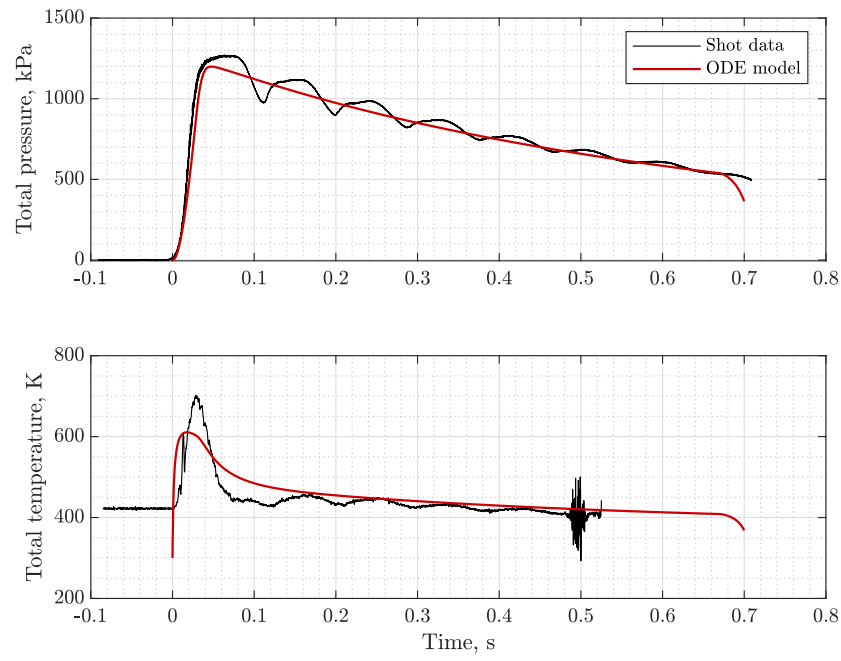


Fig. 3 Ludwig mode shot freestream total pressure and temperature compared with results from the ODE model.

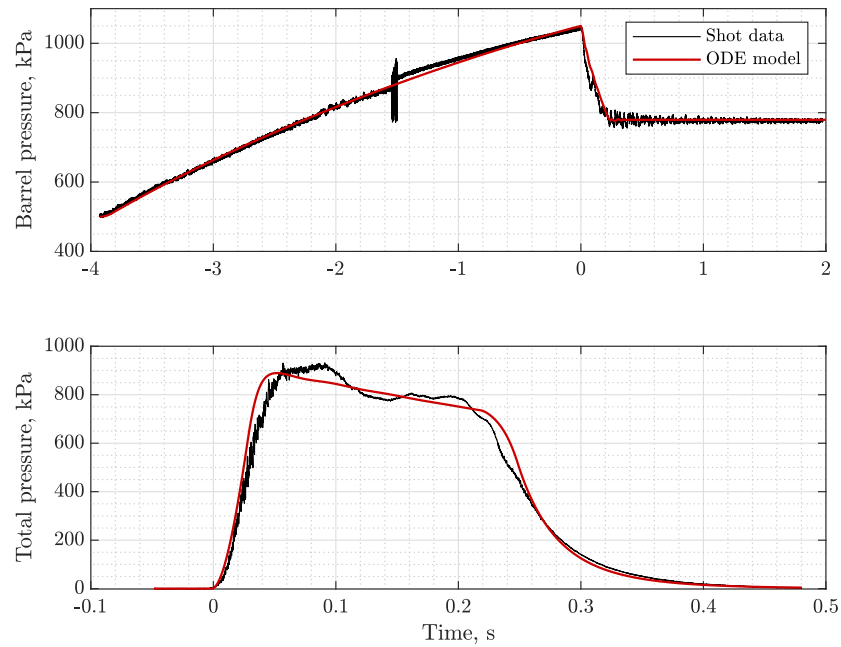


Fig. 4 Barrel pressure and freestream total pressure for a cold LICH mode shot compared with ODE model results.

Table 2 Tunnel setup for Condition A

Variable	Units	Value
$p_{3,o}$	bar	9.5
$p_{3,f}$	bar	1.5
$p_{1,f}$	bar	25
$T_{3,f}$	K	500

The difference in temperature between the upstream, T_2 , and downstream, T_3 , barrel gas is consistently large due to the flow of cold reservoir gas into the barrel behind the piston. One benefit of a cold driver is that the reservoir gas acts to cool the piston which has a temperature of just over 500 K at the end of the stroke. Thermal energy is lost from the test gas when it flow past the plug valve, resulting in the nozzle supply temperature, T_4 , being significantly lower than the temperature of the test gas in the barrel, T_3 . There is also a more pronounced drop in T_4 over the test time compared with the p_4 . This is partly due to the presence of the spike in temperature as the gas first enters the nozzle plenum (seen more clearly in Figure 3) and partly due to large rates of heat transfer in the nozzle plenum.

The piston begins the stroke with a rapid acceleration after which the velocity gradually falls to a very low level at the end of the stroke. When the plug valve opens, the piston accelerates again and large oscillations occur which are strongly attenuated. The piston is predicted to impact at a velocity of 12.5 m/s. Although the magnitude of the oscillations is large, the velocity remains positive, and the piston continues travelling downstream.

IV. Experimental Setup

Experiments were conducted in the HDT with a heated barrel to prove the operation of LICH mode and to characterise the freestream conditions produced by LICH mode. A series of commissioning shots were undertaken with increasingly larger compression ratios over the range $p_{3,o}/p_{3,f} = 1.25 - 6.33$. Taking this staged approach enabled risk to the facility infrastructure to be appropriately managed. The initial conditions for the largest compression ratio tested are provided in Table 2. Only results from this condition will be presented here.

The commissioning tests were also used to evaluate the new, LICH-specific infrastructure, control system logic and high-temperature piston design. This was mostly successful with the infrastructure and logic performing as expected, however during the highest-compression ratio testing, the piston impacted the downstream end of the facility, damaging the piston but not the facility barrel. The impact was not intentional and a consequence of lack of fine control on the closing time of the plug valve, which may be mitigated in future by the addition of a buffer to catch the piston. Further work is required to enable consistent operation of the LICH mode in HDT, however the results presented in the next section prove the capability.

A. Freestream Characterisation

Stagnation pressure measurements were taken using a Kulite XCQ-080-70BARA piezo-resistive pressure sensor, amplified using a Fylde FE-H379-TA transducer amplifier which applied a low pass filter with a cutoff frequency of 30 kHz to the signal. The sensor has a measurement uncertainty of 0.5 % of the full scale output of 70 bar.

Measurements of the freestream were taken using a pitot probe and an aspirated thermocouple. Pitot pressure was measured using a Kulite XCQ-093-100A piezo-resistive pressure sensor which was also amplified using a Fylde FE-H379-TA amplifier with the same 30 kHz low pass filter applied. The sensor has an associated measurement uncertainty of 0.5 % of the full scale output of 100 psi (~ 700 kPa).

The aspirated thermocouple consists of a pre-heated 0.076 mm (3 thou) diameter K-type thermocouple suspended across a hollow cylinder through which the post-shock freestream can flow (hence “aspirated”). The flow over the thermocouple is approximated as a cylinder in cross-flow of which the diameter is known. Effective cylinder length and heat transfer coefficients were calculated using an optimisation process which attempts to fit data from three differently heated thermocouples to a derived total temperature trace. Data at three initial thermocouple temperatures typically requires three identical shots to be carried out in succession. Hermann et al [15] describe this process in more detail and give an overall uncertainty of ± 15 K for the resultant total temperature.

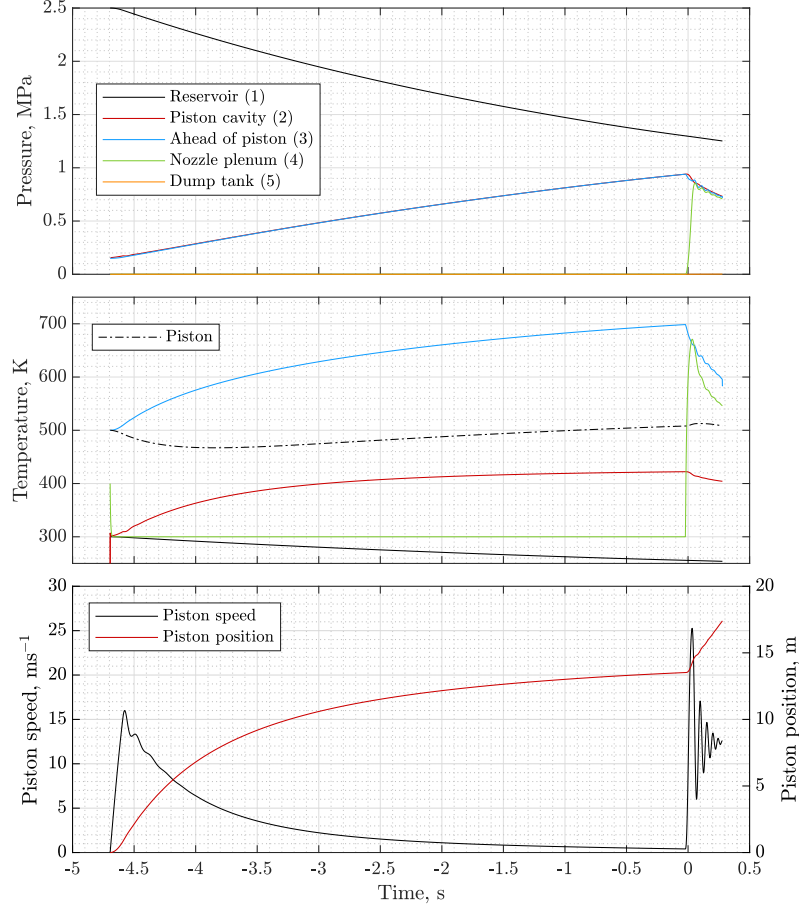


Fig. 5 Results from the ODE model for Condition A. Pressure, temperature and mass for all tunnel sections and piston dynamics plotted against time.

V. Results

Presented in this section are shot data compared with solutions from the ODE model and predicted tunnel performance maps calculated using the ODE model.

A. Shot Data

Figure 6 presents experimental freestream data from a shot at Condition A compared with results from the ODE model. Freestream quantities presented are total pressure (top), total temperature (middle) and unit Reynolds number (bottom). The pressure and temperature from the ODE model are p_4 and T_4 in Figure 5 respectively. The viscosity for Re_{unit} was calculated using Keyes' relation [16].

The three peaks in the experimental pressure trace are caused by the rarefaction waves in the barrel. These flow periods are much less pronounced than those of the Ludwig mode pressure trace in Figure 3. This is primarily due to a much longer plug valve opening time for the LICH shots (~ 80 ms rather than ~ 30 ms) which has the effect of spreading out the rarefaction waves. The cause of the difference in plug valve opening speeds is purely that the LICH mode shot was operating at a significantly lower barrel pressure than the Ludwig mode shot. The effect of piston oscillations and reflected rarefaction waves is not apparent in the experimental pressure. In contrast, the pressure oscillations in the ODE data are caused solely by piston oscillations. Although the acoustic effects aren't modelled, the overall downwards trend

in pressure is captured by the ODE model.

At $t = 0.25$ s, the shot ends when the piston impacts the end of the barrel. The pressure abruptly falls as the nozzle plenum empties. The ODE model currently overpredicts the test time by ~ 30 ms which is likely due to a slight mismatch in the barrel temperatures between the shot data and ODE model. The temperature of the test gas in the barrel during the piston stroke is not experimentally measured so this was difficult to tune in the model. A difference in barrel temperature would lead to a difference in mass flow rate during the shot, and therefore a difference in test time.

The stagnation temperature trace is also different to what is usually seen in Ludwig mode (see Figure 3 for a typical shot). The initial unsteady peak in total temperature does not appear in the LICH mode shot data. Instead, the temperature is reasonably steady for the entire duration of the shot. In this case, the ODE model overpredicts the initial temperature rise but falls more quickly towards the end of the shot, indicating that the heat transfer scaling in the barrel and the nozzle plenum may need further tuning.

Re_{unit} is derived from the pressure and temperature data and approximately follows the pressure history in shape. The dependency of viscosity on temperature results in the downward trends of both the pressure and temperature somewhat cancelling out in the calculation of Re_{unit} .

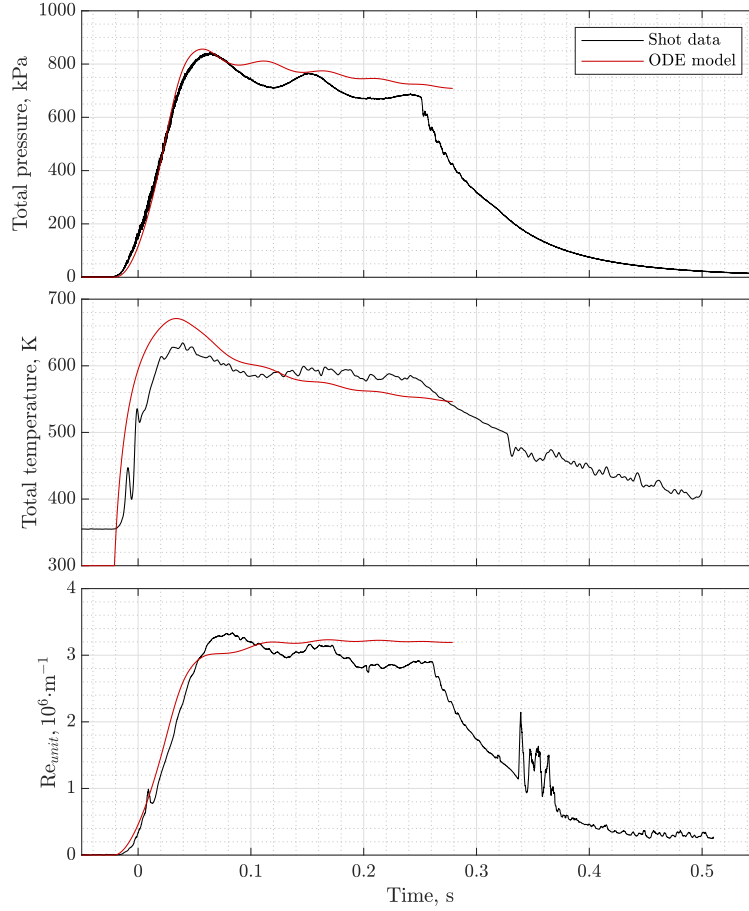


Fig. 6 Freestream total pressure, temperature, and Re_{unit} of a shot compared with results from the ODE model, both at Condition A.

B. Performance Maps

The current operational range of HDT in LICH mode at Mach 7 was examined by running cases with the tuned ODE model spanning the range of inputs in Table 1. Figures 7-10 show maps of various tunnel conditions plotted against initial tunnel conditions, with the location of Condition A being indicated by a black cross. The maps are intended to be used as guides for tunnel operation.

Figure 7 shows a map of the mean total temperature during a shot plotted as a function of $T_{3,f}$ and $p_{3,o}/p_{3,f}$. The mean is taken from the end of the initial rise until piston impact- referring to Figure 6, this is the mean of the total temperature between $t = 0.04$ s and the end of the shot at $t = 0.28$ s. As discussed earlier, T_4 is a function of both $T_{3,f}$ and $p_{3,o}/p_{3,f}$. This is seen here, with the highest available temperatures of just under 1100 K being produced at $T_{3,f} = 550$ and $p_{3,o}/p_{3,f} = 50$. The isotherms lie on approximately diagonal lines, showing that there are multiple combinations of initial conditions which are able to produce a given T_4 . From an operational perspective, lower compression ratios are more desirable due to the associated decreased risk to infrastructure. Additionally, lower compression ratios produce longer test times (see below in Figure 10). Condition A lies at the lower end of possible compression ratios (with $p_{3,o}/p_{3,f} = 6.33$) but produces a total temperature of ~ 600 K due to a higher $T_{3,f}$. Ludwig mode operates on the y-axis of this map, with an effective compression ratio of 1. This shows the capability of LICH mode, with even small compression ratios producing greater temperatures than possible in Ludwig mode.

Figure 8 shows a map of the piston temperature at the beginning of a shot and uses the same axes as Figure 7. Both maps look largely the same, with large T_P and large T_4 being produced by the same mechanisms. It is interesting to note that the piston temperature never rises by more than ~ 150 K at even the highest compression ratios. This is attributed to the cold reservoir gas cooling the piston from the rear. This is advantageous as it allows the use of lightweight materials, such as aluminium, to be used in the construction of the piston.

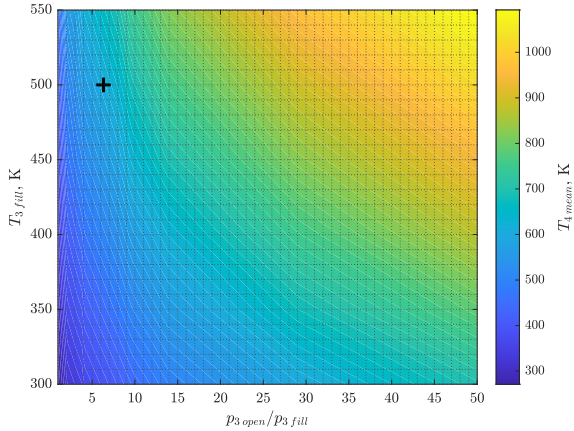


Fig. 7 Map of mean total temperature for the full range of barrel fill temperatures and pressure ratios.

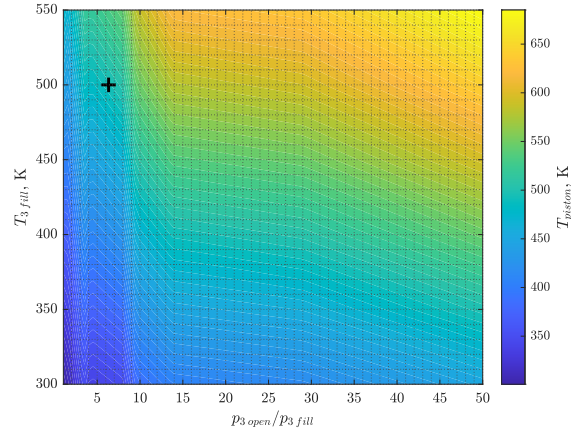


Fig. 8 Map of final piston temperature for the full range of barrel fill temperatures and pressure ratios.

A map of Re_{unit} plotted as a function of $T_{4,mean}$ and $p_{3,o}$ is shown in Figure 9. To use this map for estimating conditions, first $T_{4,mean}$ must be read from Figure 7. High Re_{unit} are generated from high pressures and low temperatures while low Re_{unit} are generated from low pressures and high temperatures. A white dashed line shows the approximate upper temperature limit of Ludwig mode. LICH mode allows for lower Re_{unit} to be achieved than is possible in Ludwig mode - the area in the upper left corner, containing Condition A, produces lower Re_{unit} than anything below the white line.

The final performance map is given in Figure 10 and shows total shot duration as a function of $T_{3,f}$ and $p_{3,o}/p_{3,f}$. The x-axis is plotted on a log scale as most of the variation in shot duration occurs at low compression ratios. Shot duration is primarily a function of compression ratio, with only a small dependency on $T_{3,f}$. At very low compression ratios, the piston does not move very far before the shot begins, leading to long shot durations of several seconds. However, for useful LICH conditions which produce higher total temperature flows, $p_{3,o}/p_{3,f}$ must be greater than ~ 5 . In this regime, shot lengths are below 1 s, with that for Condition A being predicted at 0.28 s. For the highest total temperatures possible using LICH mode, shot durations are well below 0.1 s. However, this is still comparable to the duration of the steady flow periods produced in Ludwig mode.

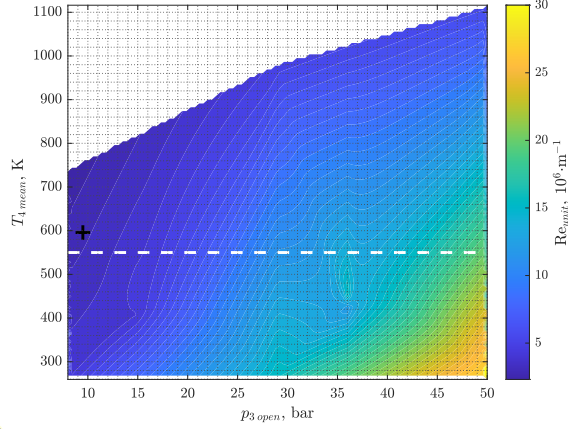


Fig. 9 Map of Re_{unit} for the full range of mean total temperatures and plug valve opening pressures.

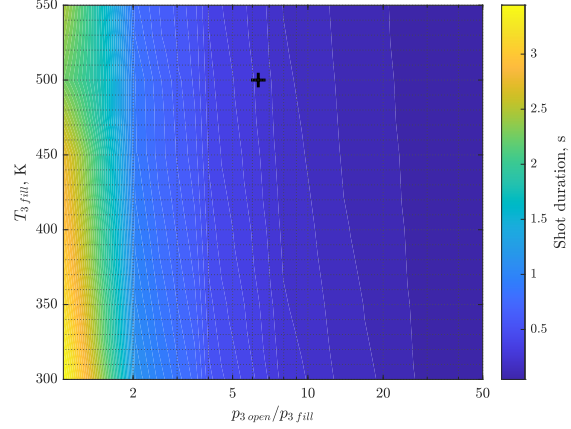


Fig. 10 Map of total shot duration for the full range of barrel fill temperatures and pressure ratios.

C. Freestream Noise

The freestream noise experienced during LICH mode is expected to be greater than during Ludwig mode due to the piston interacting with and reflecting rarefaction waves in the barrel, leading to significant pressure oscillations. There are multiple methods used in the literature to quantify the freestream noise of wind tunnels. One such method, proposed by Laderman [17], uses a normalised noise defined by Equation 5.

$$\text{Normalised noise} = \frac{RMS(p)/\bar{p}}{\gamma M^2/2} \quad (5)$$

The pressure can be any measured pressure - pitot pressure was used in this case. The Kulite sensor used for this measurement has a maximum bandwidth of 20 kHz. This does not give a full picture of all the noise present in the facility but does allow for quick qualitative comparisons between different modes of operation or different facilities. A more complete nozzle survey test campaign with an appropriately instrumented rake is planned for the future. However, due to the relatively low frequency effects that the piston causes, much of the differences in noise levels between Ludwig mode and LICH mode are thought to be measurable using the current setup.

Figure 11, adapted from Birch et al [18], shows the normalised noise evaluated for a number of facilities similar to HDT along with some HDT data. The x-axis is the freestream Reynolds number based on nozzle exit diameter. Several Ludwig mode shots for a range of Re_D at Mach 6 and 7 are displayed, along with two LICH shots at Condition A. For LICH mode shots, pitot pressures were taken across the entire test time: from the end of the initial pressure rise to the piston impact. For Ludwig mode shots, pressures were taken from the second steady flow period (e.g. $\sim 0.13 - 0.15$ s in Figure 3). Pitot pressure signals were filtered using a bandpass filter with cutoff frequencies of 1 and 20 kHz. The bandpass function in Matlab was used, with a steepness factor of 0.98.

The noise level for Ludwig mode shots is self-consistent, with a trend of higher Re_D conditions leading to lower levels of normalised noise. Although the Re_D of the LICH mode condition is below the limit of operation for Ludwig mode, the LICH mode data points appear to fall on the same line. This suggests that there is no significant increase in freestream noise levels at frequencies below 20 kHz when operating in LICH mode. It is encouraging, however, to see that noise levels in LICH mode are very comparable to other facilities.

VI. Conclusion

This paper has described the successful implementation of LICH mode of operation in the HDT. New tunnel infrastructure has been proven and a design for a piston has been assessed, showing a need for some improvement. A LICH condition, which provides increased total temperature flow in HDT, has been tested and characterised. Experimental data has been collected which was used to validate a simple numerical ODE model to simulate the key processes which happen during a shot. The ODE model was used to generate performance maps for estimating flow conditions in LICH mode operation at Mach 7. An increase in operating range compared to Ludwig mode has been shown. Experimental

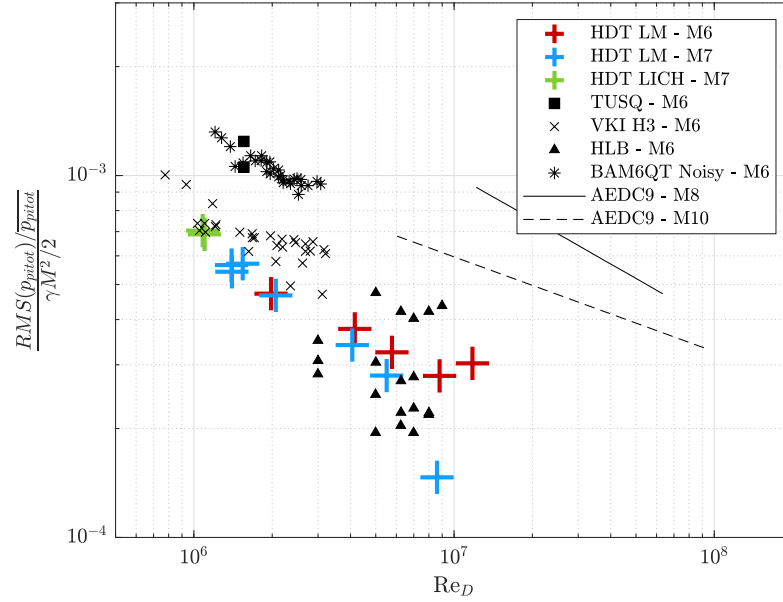


Fig. 11 HDT freestream noise compared with other similar facilities: TUSQ [18], VKI H3 [19], HLB [20], BAM6QT [21], and AEDC Tunnel No. 9 [22]. Reproduced from Birch et al [18].

data was also used to assess levels of freestream noise, which was found to be comparable to operation in Ludwig mode.

For future work, a clearer understanding of the acoustic effects which have a large influence on various aspects of LICH operation would be valuable. Simulations using tools such as L1d would give an insight into these effects. For HDT to operate in LICH mode more regularly, the piston design will need to be re-assessed to ensure greater survivability. Finally, LICH mode will be most effective if matched conditions are able to be used. The implementation of additional logic to control the reservoir firing valves would make this more easily achievable while maintaining tunnel performance.

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