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Heated Barrel Mode for a Hypersonic Ludwieg Tube with Free-Piston Compression: Preliminary Performance

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Abstract

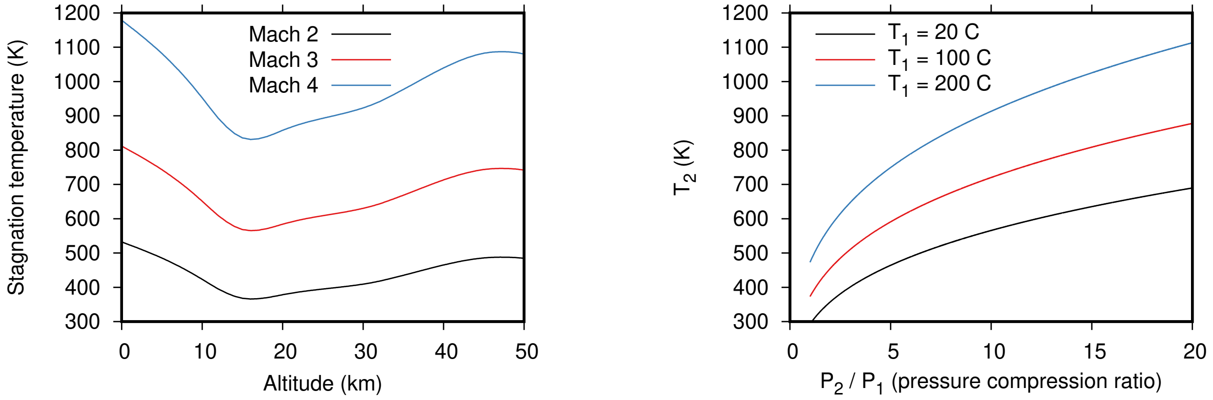
The upgrade of the University of Southern Queensland's hypersonic facility to enable access to higher flow enthalpy conditions– potentially up to true Mach 4 conditions– is presented. To produce higher flow enthalpy conditions, the test gas is heated in its pre-compressed state in the barrel. Early experimental results from the commissioning phase of this upgrade show that the uniform barrel heating mode produces conditions that can be well predicted by existing models. Further commissioning of a non-uniform initial gas temperature distribution to compensate for heat losses from the test gas during compression and nozzle discharge shows potential, however further development of design tools or augmentation of the pre-heated gas state is required.

1 Introduction

The University of Southern Queensland's hypersonic wind tunnel facility (TUSQ) produces flows of gas for test durations of hundreds of milliseconds. These relatively long flow durations are used for the fundamental study of: hypersonic mixing, aerodynamics, aeroelasticity, boundary layers and heat transfer; and the analysis of applications including flight vehicles and related geometries. In TUSQ, the test gas is directly heated via free piston compression in a barrel and through the use of the free piston, longer test flow durations can be achieved relative to a standard Ludwieg tube of the same dimensions. To enable investigations where it is important to match the true flight enthalpy, such as combustion research at high supersonic flight conditions, higher stagnation temperatures than can be achieved with an unheated barrel are required. The stagnation temperature that is required for flow enthalpy matching is shown in Figure 1a for Mach 2, 3 and 4.

An increased flow stagnation temperature can be achieved by: (1) increasing the compression ratio; (2) preheating the barrel; or (3) a combination or (1) and (2). For a given stagnation temperature, an increased pressure compression ratio results an increase of $\frac{T_0}{T_{wall}}$, therefore increasing the rate of heat loss from the test gas and possibly resulting in temperature non-uniformities in the expanded supersonic test gas. Through barrel preheating, $\frac{T_0}{T_{wall}}$ can be reduced and stagnation temperatures matching Mach 4 flight conditions can theoretically be achieved using a pressure compression ratio of approximately 10 (see Figure 1b). Additionally, the known reduction of barrel temperature with time can be potentially compensated for using a non-uniform barrel preheat as implemented in the decommissioned University of Southampton facility (East and Qasrawi, 1978).

This work presents the design of the TUSQ barrel heating system and experimentally measured flow stagnation temperatures for the cases of a uniformly and non-uniformly preheated barrel. In the non-uniform preheating mode of operation, significant differences from the projected performance were identified which, through the use of computational simulations, was traced to buoyancy effects in the preheated gas which significantly affected the post-compression stagnation temperature. These buoyancy effects were not identified by East and Qasrawi (1978) when using a non-uniformly heated barrel of similar $\frac{L}{d}$ to TUSQ (115 and 123 respectively) and pressure compression ratio of 7.



(a) Stagnation temperature required to match true flight enthalpy conditions.

(b) Compressed gas temperature as a function of preheat and pressure compression ratio for $\gamma = 1.4$.

Figure 1. Stagnation temperature requirements for flow enthalpy matching and the facility condition required to achieve this temperature demonstrating the value of an elevated initial temperature T_1.

2 Facility and Instrumentation Description

2.1 Facility Overview

The University of Southern Queensland's Ludwieg tube with free piston compression heating (TUSQ, Figure 2) is used to generate quasi-steady cold flows of hypersonic air for hundreds of milliseconds (Buttsworth, 2010). Prior to firing, the facility is comprised of three discrete volumes of gas: (1) the 350 L high pressure air reservoir; (2) the air in the Ludwieg tube (or barrel); and (3) the low pressure (1 kPa) region within the nozzle, test section and dump tanks. A light piston, 85 g for the present work, is positioned in the barrel immediately downstream of the primary valve and a light diaphragm separates the barrel and nozzle inlet.

Typically, the test gas initially residing in the barrel is at the local atmospheric pressure and ambient temperature (approximately 94 kPa and 24 °C respectively in Toowoomba), but in the present work the gas in the barrel is raised to an elevated temperature prior to piston compression. A run is initiated by opening the primary valve which causes the piston to be driven along the barrel by the flow of high pressure air from the reservoir, compressing the test gas. The pressure in the barrel is measured by a PCB113A03 piezoelectric pressure transducer ($0 - 500$ kHz) positioned 225 mm upstream of the nozzle entrance. Compression continues until the pressure ruptures the diaphragm which then allows gas to leave the barrel and accelerate through the nozzle. In this work the Mach 7 nozzle was used, which has a nozzle exit diameter of 217.5 mm.

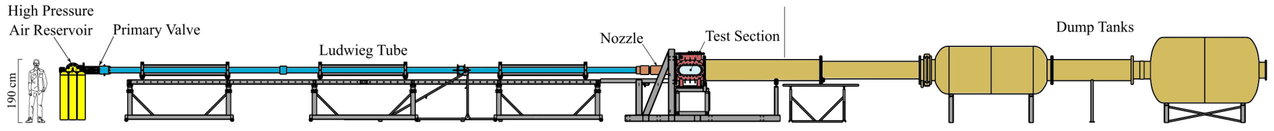


Figure 2. General arrangement of TUSQ.

2.2 Facility Heating System

To increase the enthalpy of the flow produced by TUSQ, the barrel section was fitted with a heating system such that the gas initially residing in the barrel could be heated. This barrel heating system uses ten individually controllable resistance wire heating sections beneath a layer of thermal insulation, with the temperature of the outer barrel surface measured at the ten locations using PT100 sensors shown in Table 1. The output of these PT100 sensors is connected to the heating system control system to provide feedback to the control system. Following preliminary system testing, additional heating capability at the barrel nuts (where the individual barrel segments are connected) was installed. This additional heating capability was added via hot-air blowers which direct hot air beneath the insulation layer and over the outer surface of the barrel nuts.

Sensor number	0	1	2	3	4	5	6	7	8	9
Axial location (m)	0	1.43	3.93	5.23	6.63	9.18	10.54	11.93	14.41	15.82
T, Run 1200 (°C)	105	105	105	105	105	105	105	105	105	105
T, Run 1202 (°C)	105	105	110	117	128	139	145	149	159	168

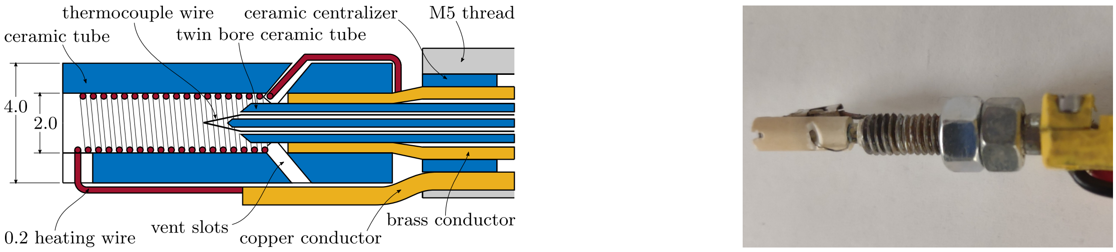
Table 1. Barrel heater station information and set points for the runs presented herein. Axial location is relative to the upstream end of the barrel.

The ability of the TUSQ barrel pre-heating system to achieve the required temperature distributions along the barrel was confirmed using a carriage holding an exposed junction thermocouple within the tube bore. The carriage was slowly traversed along the length of the barrel to measure the gas temperature distribution. In the case of a target temperature distribution that was uniform, offsets in the barrel temperature set points were defined through measurement of the difference between the gas temperature within the bore of the tube and adjacent set point values for the barrel wall. These offsets were then applied to the set points in order to improve the actual uniformity of the gas temperature distribution. The resulting temperature distributions within the test gas initially residing in the barrel were found to be uniform to within about ± 2 °C relative to the target uniform gas temperature of 100 °C.

Heating of the barrel walls to 180 °C takes approximately one day. Once at operating temperature, the time to recover to this operating temperature following a run is negligible compared to other operations required to configure a subsequent run.

2.3 Thermocouple Design

Three thermocouples based off the design presented by East and Qasrawi (1978) were manufactured for this work. These thermocouples utilise a null point operating method, where the thermocouple rapidly reaches the flow stagnation temperature, for the measurement of the stagnation temperature at three locations on the Mach 7 nozzle exit plane. The temperature-measuring element of the thermocouple construction was a 0.025 mm diameter K-type buttweld junction (Omega CHAL-001) as shown in Figure 3. The thermocouple junction was exposed to the flow and held in a custom probe consisting of a two-hole ceramic tube, 2.38 mm diameter brass tube and an M5 connection for interfacing with an existing rake. The probe included a heater element which allowed raising the thermocouple temperature to approximately the flow stagnation temperature prior to flow arriving at the thermocouple.



(a) Schematic representation.

(b) Photograph as manufactured.

Figure 3. Details of the thermocouple used in the present work.

3 Results

3.1 Uniform Barrel Heating

To investigate the performance of the TUSQ barrel heating system in a uniform preheating mode, the barrel walls were heated to 105 °C to preheat the pre-compressed gas. During this heating process the barrel pressure was regulated to 94 kPa and a valve connecting the regulator to the barrel was closed shortly after the desired barrel temperature was achieved. Per regular facility operation, a piston compression process was used to further heat the test gas and a diaphragm designed to maintain a pressure compression ratio of approximately 10, which was realised as approximately 11 during the experiments detailed herein.

Three thermocouples were positioned at the exit plane of the Mach 7 nozzle at $r = 30, 50$ and 70 mm vertically below the nozzle centreline. These thermocouples were preheated to approximately the flow stagnation temperature predicted using isentropic compression such that the wire temperature during the flow will closely match the flow stagnation temperature.

Flow measurements and a comparison to simulation tools for Run 1200 are presented in Figure 4. The barrel pressure trace demonstrates that a 'matched' flow condition (nominally constant pressure) was achieved. Hypersonic flow begins at $t = 0$ s and terminates at $t = 367$ ms as indicated by the termination of the temperature lines. Because a matched flow condition means that the pressure compression ratio is constant during a run, the effects of barrel preheating can be investigated without the complexities of a time-varying compression ratio.

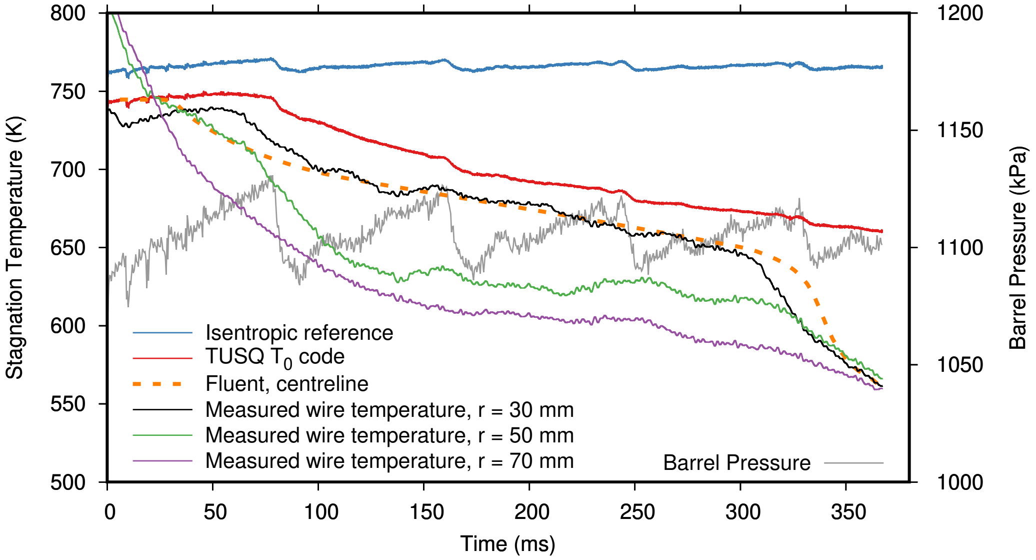


Figure 4. Facility flow characteristics for Run 1200 demonstrating a matched pressure condition and strong agreement between the experimentally measured and simulated stagnation temperature.

To investigate the measured wire temperature, two simulation tools were used to predict the flow stagnation temperature: (1) an in-house code (Widodo and Buttsworth, 2013; Birch et al., 2020) which was updated to include the effects of hot barrel walls on the test gas; and (2) ANSYS Fluent which modelled the preheat and piston compression processes. Both of these simulation tools modelled only the piston compression process up until the instant of diaphragm rupture, with the axial temperature distribution within the compressed gas slug related to the flow time assuming a constant piston velocity during nozzle flow. The ANSYS Fluent simulation (see Section 4) required a specified piston trajectory. An in-house code (Widodo and Buttsworth, 2013; Birch et al., 2020), which is based on uniform state uniform flow principles in four zones of the facility and the dynamics of a finite piston mass, was used to determine the time-resolved flow stagnation temperature from an input initial facility condition and measured or predicted barrel pressure trace. This stagnation temperature simulation determines the estimated piston trajectory; and this predicted piston trajectory was used for the Fluent simulation.

The measured wire temperature at $r = 30\,\mathrm{mm}$ closely matches the results of the simulation tools at the barrel centreline for and takes the general form of previously published measured flow stagnation temperature results without barrel preheating (Widodo and Buttsworth, 2013). For measurements using preheat wire temperature significantly different from the flow stagnation temperature, reached the centreline temperature after approximately 20 ms of flow. Therefore, the wire temperature presented in Figure 4 can be treated as the flow stagnation temperature for $t \gtrsim 20\,\mathrm{ms}$ to a reasonable degree of accuracy, confirming the null operating mode for the thermocouple.

For positions further from the nozzle centreline ($r = 50\,\mathrm{mm}$ and $r = 70\,\mathrm{mm}$), the wire preheat temperature was significantly above the maximum temperature possible when using an isentropic compression assumption. For these data, the wire temperature for $t < 25\,\mathrm{ms}$ does not accurately represent the flow stagnation temperature. Thereafter significant temperature non-uniformity in the radial direction is apparent. The spatial distribution of flow stagnation temperature has been investigated for the Mach 6 nozzle, which has the same physical exit diameter as the Mach 7 nozzle, with the stagnation temperature of found to be $530\,\mathrm{K} \pm 6\%$ for $r < 80\,\mathrm{mm}$ at $t = 100\,\mathrm{ms}$ (Widodo and Buttsworth, 2013). The present work does not attempt to quantitatively state the spatial variation of stagnation temperature, however these variations are qualitatively may be as large as 10% for $r < 70\,\mathrm{mm}$. This non-uniformity is due to radial temperature gradients in the barrel which are driven by the ratio of gas temperature to wall temperature. Should a higher compression ratio have been preferred to preheating the barrel wall, it is reasonable to conclude that the radial nonconformity in the hypersonic test flow would have been higher due to an increased gas to wall temperature ratio ($\frac{T_0}{T_{wall}}$).

For the first 65 ms of flow time, the flow stagnation temperature is slightly below the isentropic prediction which is consistent with previously published results for an unheated barrel (Birch et al., 2020). During this period of flow, both simulation tools have strong agreement with each other and the $r = 30\,\mathrm{mm}$ measurement, however the Fluent simulation does under-predict the duration of these near-isentropic compression temperature results.

From 65 ms to 310 ms, both simulation tools follow the same trend and agree well with the $r = 30\,\mathrm{mm}$ experimental data. For $t > 310\,\mathrm{ms}$, rapid cooling due to the cold vortices which exist ahead of the piston result in a rapid drop of stagnation temperature. These cold vortices result in significant mixing of the test gas in the barrel, This mixing results in a more uniform distribution of stagnation temperature in the hypersonic flow. The Fluent simulation predicts the effects of the vortices well, while the TUSQ code does not attempt to model these effects due to the reduced flow quality of this final flow period.

Comparing similar r/R for the barrel region and experimental measurements, the Fluent simulation under-predicted the measured temperature at $r = 30\,\mathrm{mm}$ by no more than than 2%. For $r = 50\,\mathrm{mm}$ and $r = 70\,\mathrm{mm}$, Fluent over-predicted the experimental measurements by a maximum of 4% and 5% respectively. Thus, the spatial distribution of stagnation temperature in the hypersonic flow can be approximated to a reasonable degree of accuracy from spatial distributions in the barrel from the Fluent simulation. Improved results may be achieved with an improved mesh resolution and/or coupling to a nozzle flow simulation. However this may become prohibitively computationally expensive for the purpose of these simulations– the present work requires approximately 9 h to solve using 120 cores and 480 GB of RAM.

3.2 Gradient Barrel Heating

A uniform barrel wall temperature and thus gas temperature distribution is known to result in temporal variations in the stagnation temperature in the hypersonic flow because of the heat transfer from the test gas to the relatively cold walls of the barrel during the piston compression stroke (East and Qasrawi, 1978). For the elevated uniform barrel wall temperature operation described in Section 3.1 the same characteristic stagnation temperature changes were measured. To minimise these temporal changes to flow stagnation temperature, a now decommissioned facility at the University of Southampton (East and Qasrawi, 1978) designed and implemented a non-uniform axial temperature distribution in the barrel temperature to compensate for the heat transfer from the test gas during the compression and flow discharge process. From a single point wire temperature measurement at the nozzle throat, East and Qasrawi (1978) reported that, for a compression ratio of seven, a flow stagnation temperature of 605 K could be maintained to within 2 % for approximately 240 ms, which was the time at which the cold vortices propagating ahead of the piston arrived at the nozzle supply region. For their 12.5 m long barrel, East and Qasrawi (1978) implemented a wall temperature that was 95 °C at the nozzle entrance and 120 °C at the start of the barrel, but did not explicitly state the temperature profile between these two points.

The TUSQ barrel preheating system can produce temperature gradients for the barrel wall and thus also for the test gas. Therefore, compensation for heat loss from the test gas during the compression stroke using the methodology of East and Qasrawi (1978) should be possible. Therefore, an initial temperature profile for the barrel was designed for TUSQ assuming that the gas within the barrel reaches the same one-dimensional temperature profile. This first barrel temperature profile was tested in Run 1202 with the measured thermocouple temperature at a position 30 mm directly below the centreline of the nozzle exit presented in Figure 5.

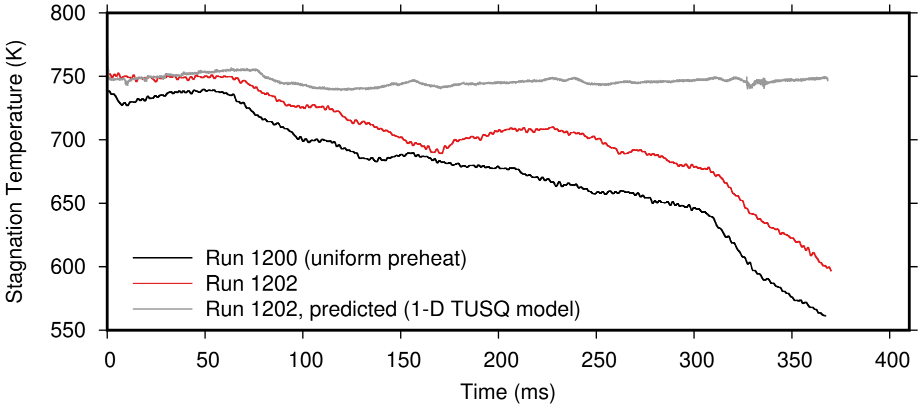


Figure 5. Thermocouple temperature at 30 mm below the nozzle exit centreline for runs of different barrel preheat values and distributions. Wall temperature set points are shown in Table 1.

For Run 1202 a matched barrel pressure condition was achieved, so the effects of the barrel gradient preheat can be compared with the uniform preheat for Run 1200. For the first 150 ms of flow, the measured thermocouple temperature for Run 1202 appears offset from the Run 1200 measurements which suggests that there was minimal effect of the barrel wall temperature gradient during this period of flow. At $t \approx 160$ ms, unlike for Run 1200, the thermocouple temperature increased for Run 1202 suggesting that there were some effects from the barrel heating gradient.

The TUSQ 1-D barrel compression model was updated from an initial uniform gas and wall temperature model to allow for an initial 1-D initial gas temperature gradient. The Run 1202 data was processed using the updated TUSQ barrel compression code which revealed poor simulation performance for $t > 65$ ms which is when the heat transfer from the test gas becomes significant. The reasons for the discrepancy between the 1-D model and experimental results are investigated in Section 4.

4 Investigation of Performance in Gradient Heating Mode

During barrel preheat commissioning, the gas temperature in a hot barrel was measured by slowly traversing a carriage holding an exposed junction thermocouple at the centreline of the tube bore and showed that the gas temperature was close to the expected barrel wall temperature along the barrel length. Because these measurements were conducted at the centreline there was no information available in the non-axial direction. ANSYS Fluent was used to: (A) model the compression process for a uniform preheat of 105 °C to investigate Run 1200; and (B) investigate the temperature distribution in the pre-compressed gas within the barrel for the case of a linear barrel wall gradient from 180 °C at the start of the barrel ($x = 0\,\mathrm{m}$) diaphragm to 90 °C at the diaphragm ($x = 16\,\mathrm{m}$). A general schematic of the simulation geometry is presented as Figure 6.

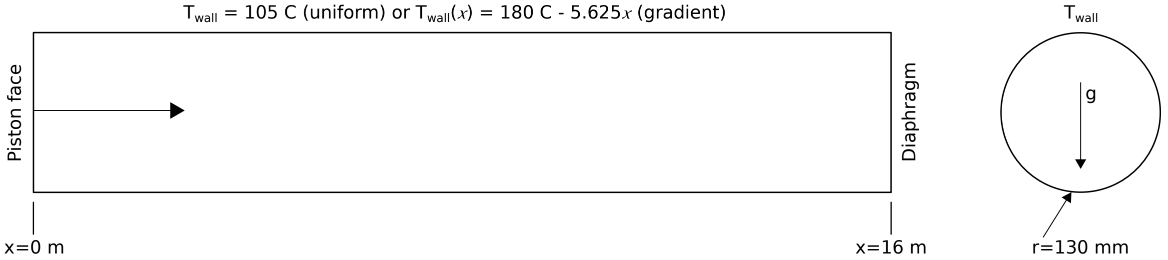


Figure 6. Geometry setup for the Fluent piston compression simulation.

For both case (A) and case (B) the simulation process was:

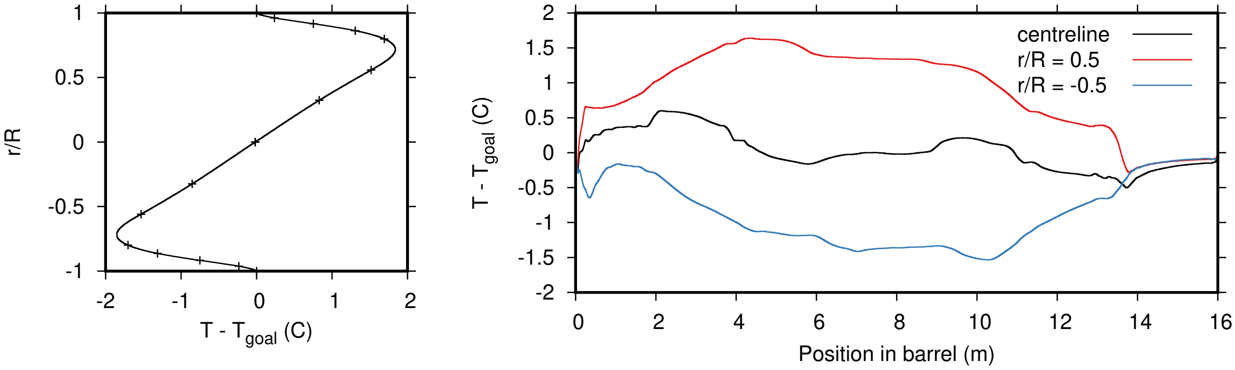
1. Establish the temperature gradients with the diaphragm modelled as a pressure outlet at 105 °C (case 1) and at 90 °C (case 2) so that the pressure in the barrel remained at 94 kPa.
2. Change the diaphragm to a constant temperature wall and wait for a steady solution.
3. Drive the piston along the barrel as a moving wall with the piston trajectory from the TUSQ in-house piston compression code.

The Fluent simulations were completed using the 3ddp pressure-based solver with the energy model and the SST k-omega turbulence model using ideal air as the fluid. For the piston compression simulation ($t = 1.161\,\mathrm{s}$), dynamic mesh with layering was used with a time step of 40 µs.

As presented in Figure 4, the simulation closely matched the experimentally measured temperature for case (A). The agreement of the Fluent simulation at the centreline (Figure 4) and at to within 2% and 5% at $r = 30\,\mathrm{mm}$ and $r = 70\,\mathrm{mm}$ respectively indicates that the mesh (pre-compression: 908684 cells, max aspect ratio 3.93, min orthogonal quality 0.56; at-rupture: 148120 cells, max aspect ratio 3.93, min orthogonal quality 0.56) was of sufficient resolution and quality for the purposes of this work. Therefore only case (B) is discussed further here. The same mesh and piston trajectory was used in both case (A) and case (B)

For case (B), the Fluent simulations revealed significant temperature gradients within the barrel in the vertical direction. For the input desired axial temperature gradient of 5.6 °C m^{-1}, the temperature gradient was significantly higher in the vertical direction– for the case at $x = 8\,\mathrm{m}$ (Figure 7a) the vertical temperature gradient reached 32.7 °C m^{-1}. Whilst the centreline temperature remained very close to the target value, significant non-uniformities in the vertical direction were found as shown in Figure 7b. These temperature effects are due to buoyancy and natural convection and also induce axial velocity gradients of up to $0.5\,\mathrm{m\,s^{-1}}$ in the barrel. The identified 3-dimensional effects in the preheated test gas are likely the cause of the poor performance of the 1-D piston compression model shown in Figure 5.

Following a simulation piston compression process, the Fluent simulation predicts significant temperature non-uniformities in the vertical direction as shown in Figure 8b. The non-uniformities are more significant than the case of uniform preheating (Figure 8a), including for regions with off-scale temperatures. Note that the target of this simulation was not to identify an appropriate preheat temperature profile, but to investigate the effects of the initial 3-dimensional gas temperature distribution in the barrel. Non-uniformities in the gas temperature at the nozzle supply region (the diaphragm station)

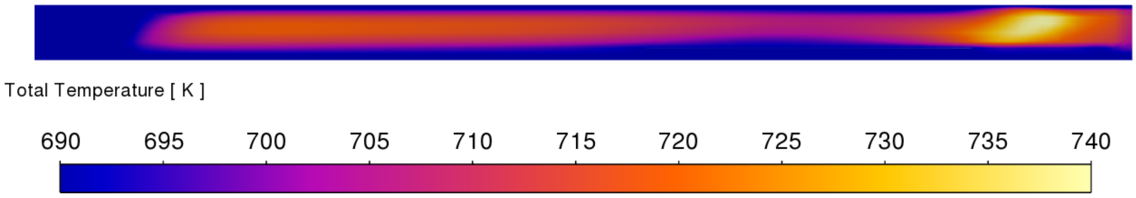


(a) Temperature distribution at $x = 8\,\text{m}$.   **(b)** Difference between actual and setpoint temperature on midplane.

Figure 7. Pre-compression temperature distribution from Fluent simulation on a vertical plane passing through the barrel centreline for a gradient preheat of $180\,°\text{C} - 5.625\,°\text{C}\,\text{m}^{-1} \times x$.

will result in a non-axisymmetric temperature profile for the hypersonic test flow. As presented in a partner paper (Grybko et al., 2022), efforts are underway to overcome the effects of natural convection such that a 1-dimensional temperature distribution in the barrel can be achieved.

(a) Case (A), uniform preheat of 105 °C.



(b) Case (B), gradient preheat of $180\,°\text{C} - 5.625\,°\text{C}\,\text{m}^{-1} \times x$.

Figure 8. Temperature distribution (Fluent) at the instant of diaphragm rupture on a vertical plane passing through the barrel axis. The piston face is on the left of the images and the diaphragm station on the right. The axial length of the zone at diaphragm rupture is 2.58 m.

5 Conclusions

The commissioning of a preheated barrel and test gas mode for the TUSQ facility has begun. For a configuration with a uniformly preheated barrel and thus a uniformly preheated test gas prior to the compression process, flow stagnation measurements made using a null operating method thermocouple indicate that current simulation methodologies can be used to accurately model the flow stagnation temperature at $r = 30\,\text{mm}$. In this uniform preheat mode the time-resolved stagnation temperature profile at $r = 30\,\text{mm}$ exhibits the same characteristics as previously published research for an ambient temperature barrel.

The TUSQ barrel was operated with a temperature gradient to compensate for the heat loss during compression with the goal of achieving an approximately constant flow stagnation temperature for the first 80% of the flow time. Initial experiments in this mode of operation showed that existing 1-dimensional tools were inadequate for designing an appropriate temperature gradient for the barrel. Nonetheless, a short iterative approach demonstrated that it was feasible to compensate for heat loss during the compression stroke.

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