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Stagnation Temperature Measurements in the USQ Hypersonic Wind Tunnel

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Abstract

A thermocouple probe with a heated shield has been used to measure stagnation temperature at the nozzle exit of the University of Southern Queensland hypersonic wind tunnel. The thermocouple probe consisted of a welded junction T-type thermocouple mounted within a heated tube with a vent hole downstream of the junction. Pressure transducers within the barrel of the wind tunnel have also been used to obtain the pressure history during the free piston compression process. The pressure measurements have been used to provide a theoretical value for the flow stagnation temperature for direct comparison with the thermocouple measurements. Assuming isentropic compression of the test gas, the flow stagnation temperature would be about 571 K for the current operating condition. After applying a response-time correction for the thermocouple signals, a stagnation temperature value of about 495 K was obtained from the measurements. The measured stagnation temperature of the test gas is somewhat lower than the isentropic value because of heat loss from the test gas to the barrel during the test gas compression and discharge process.

Introduction

Direct measurements of temperature in transient wind tunnels are often difficult to perform due to the impulsive loading of the instrumentation and the short duration test period [2]. However, stagnation temperature is a crucial parameter in most hypersonic flow experiments and therefore stagnation temperature needs to be measured [3].

Various methods have been used to identify stagnation temperature in short duration wind tunnels. Measurements of transient heat flux by using coaxial surface junction thermo-couples have been made. Although this method has several advantages including its fast response and durability, the signal generally has a small amplitude and models for substrate heat conduction and boundary layer heat convection are required to deduce a flow stagnation temperature. It is therefore not a direct measurement of flow temperature. Fast response heat flux gauges can also be used, but these likewise do not provide direct measurement of flow stagnation temperature [6, 7, 10].

Other measurements of stagnation temperature in short duration wind tunnels such as non intrusive measurements [1, 9, 12], also have been performed. However, often these methods are not simple and can therefore be rather expensive.

Facility and Instrumentation

Facility Dimensions and Operation

The free-piston wind tunnel used in the present work was the University of Southern Queensland (USQ) hypersonic wind tunnel (TUSQ). The principal dimensions of the TUSQ facility are presented in table 1.

The TUSQ facility is a short duration hypersonic facility producing useful test flows with a duration of more than 100 ms, so diverse experiments such as hypersonic mixing studies, aerodynamics experiments, hypersonic boundary layer studies, and scramjet start-ability testing can be performed using this facility [4].

Component	Physical Characteristic
Air reservoir	0.350 m^3
Primary valve	Φ = 0.0276 m (1¼'' ball valve)
Barrel	16.0 m, Φ = 0.130 m
Test section	0.830 m, Φ = 0.60 m
Mach 6 Nozzle	1.057 m, Φ^* = 0.0503 m (throat) Φ_{exit} = 0.2159 m (exit dia.)
Piston	0.383 kg (Nylatron)

Table 1. Principal dimensions of the TUSQ facility.

The facility is illustrated schematically in figure 1 and the general arrangement and operation of this facility in different modes is described elsewhere [5].

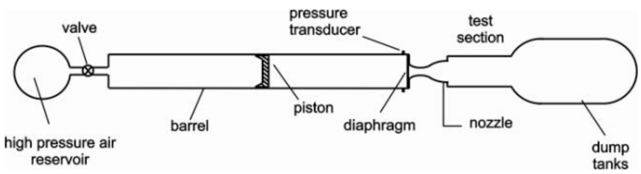

Figure 1. Schematic illustration of the TUSQ facility.

For the present experiments, the initial pressure in the barrel was 94.35 kPa, corresponding to the local atmospheric pressure in Toowoomba on the day of the experiments. The ambient temperature in the laboratory on the day of experiment was 28 ^{o}C. Pressure in the air reservoir was set to 4 MPa (gauge). A 100 µm thick Mylar diaphragm was used at the entrance to the hypersonic nozzle in order to prevent the air in the barrel from draining into the test section before compression by the piston was completed.

A run was initiated by opening the primary valve which separated the high pressure air reservoir and the low pressure test gas in the barrel. The primary valve is a pneumatically driven ball valve installed in the 1¼'' pipe connecting the high pressure air reservoir and the barrel. The valve opening process can be arranged to take about 100 ms. Moderate valve opening times are preferred to fast opening in this application in order to avoid strong compression waves during compression of the test gas. When the diaphragm at the end of the barrel ruptures, the test gas flows into the test section.

Instrumentation

For the present work, the Mach 6 nozzle reservoir pressure history was measured using two piezo-electric transducers located at 130 mm upstream of the end of the barrel. One transducer was PCB model 113A03 (SN14388 with a manufacturer's calibration of -61.89 pC/MPa). This transducer was mounted on the top side of barrel and was operated with a Kistler charge amplifier (SN1340472) giving a sensitivity of 0.5

MPa/V. The other transducer was PCB 113A03 (SN14387 with a manufacturer's calibration of -65.48 pc/MPa). This transducer was mounted on the bottom side of barrel and was operated with a Kistler charge amp (SN1045830) also giving a sensitivity of 0.5 MPa/V.

The stagnation temperature probe used in the present work was a thermocouple probe with a heated shield as illustrated in figure 2. The stagnation temperature probe was positioned on the centre line of the TUSQ nozzle exit. The thermocouple shield was constructed using three different sizes of brass tubes. The outer tube was 42.5 mm long and had a 2.4 mm internal diameter. The inner tube had a 0.8 mm internal diameter with a T-type thermocouple (0.003 mm diameter copper (+) and constantan (-) wires) inserted through its centre. The junction was 1 mm from the inner tube and positioned at 8.0 mm from the probe tip. A 1.0 mm diameter hole acted as a vent and was located at 4.0 mm downstream from the junction.

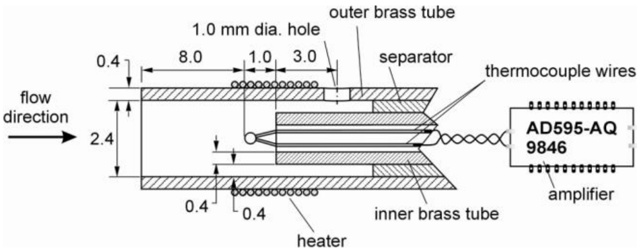

Figure 2. Schematic illustration design and principal dimensions of thermocouple probe (in mm).

An AD595-AQ (9846) chip was used to amplify the thermocouple signal. This chip provides amplification and the cold junction compensation for a type K thermocouple, but can be used directly with type T thermocouple inputs due to the similarity of thermal EMFs in the 0°C to +50°C range. The calibration of the thermocouple and amplifier system was performed using a furnace in order to gain coverage of the full range of temperature operation of the thermocouple in the present application. A K type thermocouple and digital display was used as the temperature reference for the calibration of the T type thermocouple. The two thermocouples were placed close together within the furnace during the calibration process.

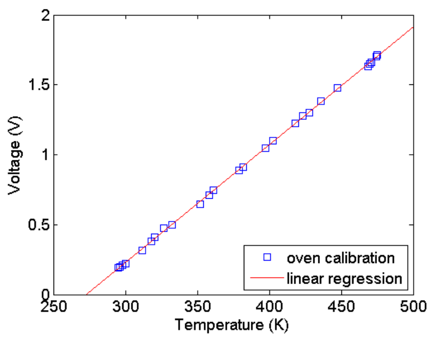

Figure 3. Calibration of thermocouple.

Figure 3 provides the data and the curve fit for the temperature-voltage calibration data. The results of calibration show that 1 Kelvin temperature change produces 8.4 mV after amplification. Although this is somewhat different from the expected sensitivity of a T type thermocouple amplified by the AD595, the calibration appears to reasonable – the results show a linear correlation between temperature and voltage output over this range of temperatures, and the results are repeatable.

A nichrome wire was used as a heater on the external surface of the outer brass tube (see figure 2). By increasing the initial temperature of the probe and thermocouple to a value close to the expected flow stagnation temperature, the magnitude of the response time correction can be reduced, thereby decreasing the uncertainty in the corrected stagnation temperature.

Thermocouple – Correction for Time Constant

Thermocouple temperature measurement errors can arise if the thermocouple response time is not sufficiently fast for the flow dynamics of interest. To correct the temperature measurement by the thermocouple, an approach using differentiation of the recorded thermocouple temperature data can be applied.

The energy equation for a length of bare wire δx inserted through a containing wall into a fluid is written as [11]:

$$\rho c_v \frac{\pi d^2}{4}\delta x\frac{\partial T}{\partial t} = -\frac{\pi d^2}{4}\delta x\frac{\partial q}{\partial x} + h\pi d\,\delta x(T_f - T) \qquad (1)$$

Multiplying equation (1) by $4/\pi\delta\ x\rho cv\ d^2$ and substituting Fourier's law gives:

$$\frac{\partial T}{\partial t} = \kappa\frac{\partial^2 T}{\partial x^2} + \frac{T_f - T}{t_0} \qquad (2)$$

where T_f is the fluid temperature, $t_0 = \rho c_v d/4h$ (which is the time constant), $\kappa = k/\rho c_v$ (which is the thermal diffusivity of the wire), d is the wire diameter, ρ is the density, k is the thermal conductivity, c_v is the constant volume specific heat, and h is heat transfer coefficient.

If the hot junction position is not too close to the wall, it is assumed that the heat flux along the wire is constant (meaning that $\partial^2 T/\partial x^2 = 0$), so equation (2) reduces to:

$$T_f = T + t_0\frac{\mathrm{d}T}{\mathrm{d}t} \qquad (3)$$

Equation (3) indicates that provided a suitable time constant t_0 can be identified, the true temperature of the flow can be estimated from the thermocouple temperature measurement T and the time-derivative of the thermocouple temperature measurement, $\mathrm{d}T/\mathrm{d}t$.

Result and Discussion

Pressure Measurements and Inferred Temperature History

Stagnation pressure of three runs was recorded by pressure transducers and the results are presented in Fig. 4. Once the primary valve opens, the test gas pressure within the barrel rises in an approximately linear manner due to the compression process from the piston. As the pressure reaches about 880 kPa, diaphragm rupture occurs, allowing the test gas to flow into the test section. The diaphragm rupture pressure can be arranged such that the tube pressure is maintained approximately constant during flow discharge into the test section, described as a 'matching condition' in [8]. Oscillations in pressure within the barrel can arise due to a piston mass effect [8]. Piston oscillations can be large if fast primary valve opening is used [11]. Based on the pressure history obtained from the transducers as presented in figure 4, the flow stagnation temperature for each of the three runs as deduced using the isentropic pressure-temperature relationship is presented in table 2. An average stagnation temperature value of about 571 K was obtained.

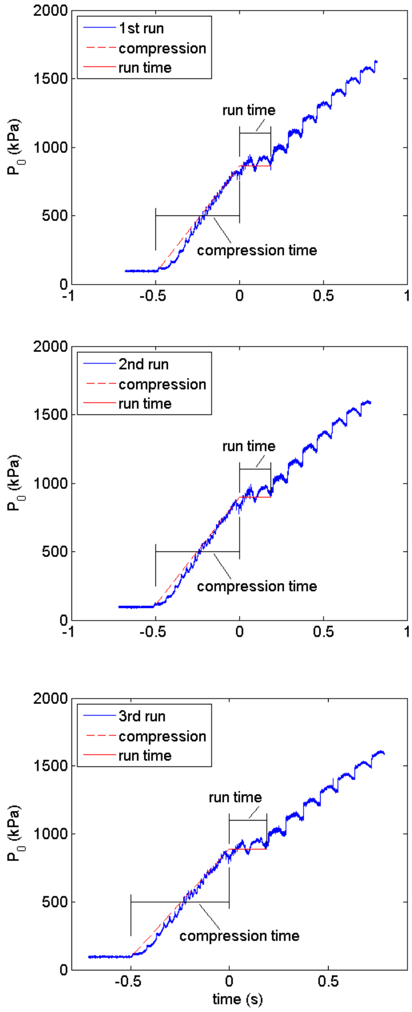

Figure 4. Stagnation pressure measured by the pressure transducer for the 3 runs.

Run	compression time (ms)	run time (ms)	P_0 (kPa)	T_0 (K)
1	490	190	860	566
2	508	188	900	574
3	500	190	890	572

Table 2. Test gas compression time and stagnation properties during the run time based on pressure measurements.

Measured and Corrected Thermocouple Results

Stagnation temperature measurements were obtained for the three different runs as presented in figure 5. Stagnation temperature probe readings for the runs were about 380 K, 450 K, and 500 K respectively towards the end of each run time as shown in Fig. 5. It is clear that the uncorrected temperatures indicated by the thermocouple probe in the first and second runs are not representative of real stagnation temperature of the flow because thermocouple temperature was still rising at the end of the run time. It appears that the thermocouple has a slow response time relative to the short duration of the present tests.

In order to directly measure a thermocouple temperature closer to the stagnation temperature of the flow, a preheating element was

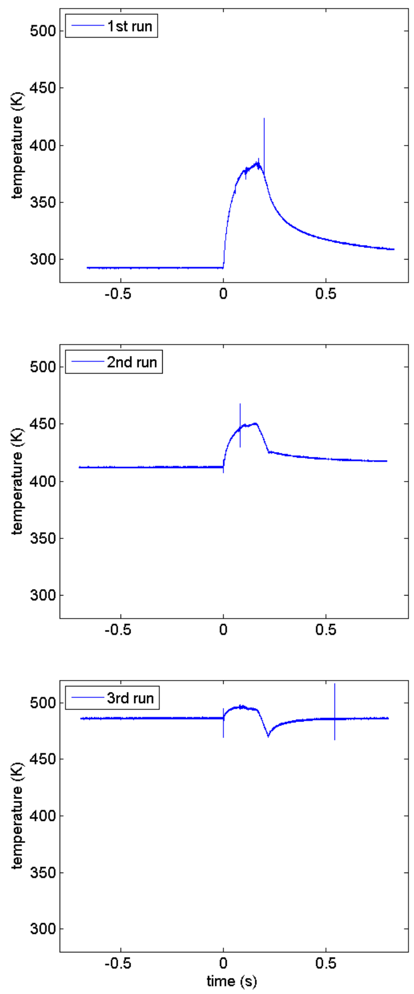

Figure 5. Thermocouple probe temperature measurement for the 3 runs.

used in the present experiments. By increasing the initial temperature of thermocouple towards the flow stagnation temperature, it is expected to minimize error when applying the response time correction in equation (3). Run 1 was performed without any preheating of the probe. For run 2, the heater was supplied with 1.15 A at 8.2 V, giving a power of 9.5 Watts resulting in a probe initial temperature of about 410 K. Prior to the run, the heater was turned off. The maximum temperature obtained in run 2 during the flow period was about 450 K. For run 3, the heater was left on and the initial temperature of thermocouple was about 485 K. The maximum temperature achieved in run 3 during the flow period was about 500 K.

Figure 6 provides a comparison between the measured thermocouple temperatures and the results corrected according to equation (3). The dashed lines indicate the measured (uncorrected) temperatures and corrected temperatures (purporting to be the stagnation temperatures) are represented by the solid line. To make the correction indicated in equation (3), a value for the time constant, t_0 was required. A value of $t_0 = 0.5$ s was used in this work and this value was identified by determining the stagnation temperature as defined in equation (3) for a range of t_0 values. The value of t_0 which minimized the difference between the 3 corrected results during the time period indicated in figure 6 was selected.

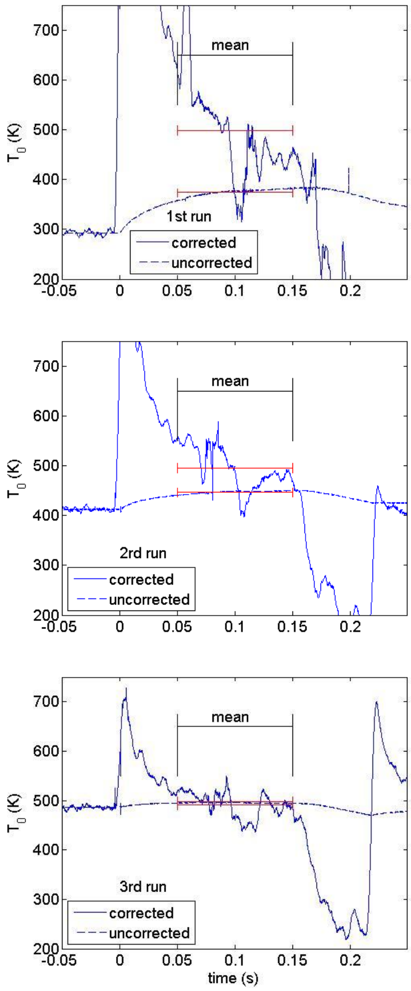

Figure 6. Uncorrected thermocouple temperature (T) and corrected temperature results (T_f) for the 3 runs.

Discussion

A summary of the temperature measurement results are presented in table 3. The results show that uncorrected thermocouple temperatures for each three runs were 374.9, 447.1, and 495 K. These values were obtained as the mean values in the 100 ms time-window indicated in figure 6 and the values give an indication of the maximum temperature achieved by the thermocouple during the test period. After the correction was applied (equation 3) and using the same time-window, the stagnation temperatures for run 1, 2, and 3 were 498.2, 495.3, and 491.7 K respectively.

If the compression process within the barrel was actually isentropic, the stagnation temperature of the test gas would be about 571 K. The stagnation temperatures identified in the present work (values between about 492 and 498 K) are naturally below the isentropic temperature values because of substantial heat loss from the test gas to the barrel during the compression and discharge process.

Based on the average temperature results obtained during the specified time-window, the corrected results for the 3 runs were within about 1%. At least some of the variability in the corrected temperature results can be attributed to the run-to-run variability of the facility. For example, the isentropic temperature values deduced from the pressure measurements differ by more than 1% over the 3 runs, and there is also a similar magnitude of variability in the compression time for each run as presented in table 2.

Run	T (K)	T_f (K)
1	374.4	498.2
2	447.1	495.3
3	495.4	491.7

Table 3. Mean values of the uncorrected thermocouple temperature (T) and the corrected temperature results (T_f) for the 3 runs.

Conclusions

A thermocouple probe with a heated shield has been used for the identification of the stagnation temperature at the exit of a Mach 6 nozzle flow produced by the University of Southern Queensland (TUSQ) hypersonic wind tunnel.

Using a time constant correction for the thermocouple measurements, it was found that the stagnation temperature was around 495 K for the present operating condition. This value is about 75 K lower than the isentropic stagnation temperature deduced from the pressure measurements due to heat loss from the test gas to the barrel.

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