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Radiation measurements in a simulated non-terrestrial atmosphere

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Abstract

A high-speed wind tunnel has been used to experimentally simulate the flow experienced by a capsule entering a planetary atmosphere. High speed photography showed that a steady test time of approximately 50 μs existed in the facility. Holographic interferometry has been performed to measure the two-dimensional density distribution around a cylinder in the flow. A peak density ratio (density normalised by the free-stream density) of about 14 was observed. Emission spectroscopy allowed the characterisation of the conditions along the stagnation streamline in front of the capsule model. The results showed a temperature that varied between 8,500 K and 11,000 K in this region.

Introduction

Aerocapture is a manoeuvre used to transfer a spacecraft from a hyperbolic trajectory to an elliptical trajectory around an astronomical body with an atmosphere, without the use of propellant. The incoming spacecraft makes a single pass deep into the atmosphere where drag rapidly decelerates it into a captured orbit. This is opposed to alternative techniques which require multiple passes through the atmosphere and/or propellant before reaching a stable orbit. The aerocapture technique can reduce the mass of an interplanetary spacecraft by half compared to alternative techniques, allowing for a smaller cheaper vehicle or one outfitted with a larger scientific payload. The design of an aerocapture aeroshell requires reliable estimates of the total heat transfer to the vehicle's surface. At the conditions encountered during an aerocapture manoeuvre, a large component of the heat transfer to the vehicle will be radiative rather than convective in nature. Present estimates arrived at by computational methods vary greatly and necessitate the inclusion of a very large safety margin (over 100%) in the design of the thermal protection system [6].

Current experimental research of high-speed or super-orbital flow at the University of Queensland is performed using the X-series impulse facilities. These tunnels can generate high speed gas flows simulating capsule entry into planetary atmospheres. Previous studies have looked at entry into the Earth, Martian, Titan and gas giant atmospheres. In general, gas conditions and surface heat flux measurements have been examined but few studies have addressed the radiative nature of the flow. To investigate radiation, two approaches are possible. With the test facility configured in the non-reflected shock tube mode, the conditions behind the bow shock on a hypersonic vehicle are directly simulated. These conditions are achieved behind the inital shock wave as it propagates through the gas initially placed in the test section. Free-stream densities and shock velocities are directly recreated so that levels of radiation in the test facility match those in flight. The alternative approach uses a test model in the facility and operating conditions are adjusted to preserve ρ-l or binary scaling where ρ is the density and l is a length scale such as the diameter of the vehicle. This ensures that non-equilibrium chemical processes such as ionisation and dissociation proceed to the same level of completion along the stagnation streamline in the test flow as for the flight vehicle. A drawback of this approach is that radiative processes do not scale correctly and the ratio of radiative to convective heat flux to a vehicle is much lower than in flight conditions. However, this configuration allows the implementation of other measurement techniques to obtain important data about the conditions in the flow field.

In the current work, the flow facility was operated taking the latter approach to generate conditions that simulate entry into a planetary atmosphere using binary scaling. A carbon dioxide/nitrogen test gas mixture was used to approximate the atmosphere of Mars. The test gas undergoes a series of chemical reactions in the high temperature bow shock generated in front of the capsule. One species that is formed in this region is CN which is known to be a strong radiator [6] and hence is of great interest when studying radiative heat flux. Several optical techniques were used to study and measure conditions in the flow.

Experimental Facilities

Measurements were performed in the X2 super-orbital expansion tube using three optical imaging techniques. High speed photography was used to study the steady test time of the flow. Holographic interferometry has been used to visualise the shock shape and to determine the overall density distributions in the shock layer. Spectroscopic methods have been employed to detect CN along the stagnation streamline and to infer the flow temperature. The following sections describe the various aspects of the experimental approach.

Test gas	96%CO_2 + 4%N_2
Total enthalpy (MJ/kg)	25
Velocity (km/s)	6.4
Mach number	12
Density (kg/m^3)	0.0018
Temperature (K)	880

Table 1: Calculated free-stream conditions.

The X2 super-orbital expansion tube

Flow was generated using the X2 super-orbital expansion tube [5] shown in figure 1. To achieve the test section conditions, a piston was used to compress a helium/argon driver gas mixture to burst a steel diaphragm. The resultant shock wave compressed and heated the test gas which burst a second, thinner diaphragm. The test gas then underwent an unsteady expansion accelerating to the free-stream conditions observed in the test section. Steady flow was expected to last for around 50 - 100 μs. The calculated operating conditions are given in table 1. These values were determined from shock velocity measurements in the shock and accelerator tubes, and from the initial

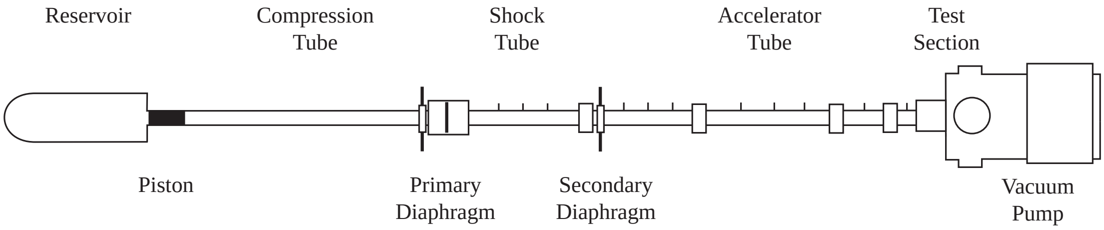

Figure 1: A schematic diagram of the X2 super-orbital expansion tube.

pressures in each section. All measurements were carried out using a cylindrical test model that had a 25 mm diameter and was 100 mm in length. Previous studies [2] have shown that flow around such a body is quasi-two-dimensional, at least for the shock stand-off and density distribution.

High speed photography

High speed photography was implemented to identify the period when steady conditions were established in front of the cylinder. A Shimadzu HPV-1 high speed camera was used to image the natural luminosity present in the flow. The region between the shock wave and the cylinder is at high temperature and species present in the flow give strong radiation, particularly in the blue region of the spectrum. The camera was placed adjacent to the test section and recorded images in tandem with the spectroscopic measurements. The layout for these tests is shown in figure 2(a).

The camera began recording before arrival of the incident shock wave in the test section and was set to take 100 frames at 2 μs intervals spanning the test time. After recording, the shock stand-off along the stagnation streamline was measured by an automated process and plotted as a function of time.

Holographic Interferometry

The flow around the cylinder was imaged using holographic interferometry as shown in figure 2(b). The laser and optics were mounted on stable optical tables placed either side of the test section of the facility. Dust is a significant problem in this environment and the equipment was protected by large covers placed on top of the tables. To record an image, the 532 nm output from an injection-seeded pulsed Nd:YAG laser was used to illuminate the test section of the facility. The laser was triggered by a pressure transducer or photodiode mounted upstream in the expansion tube which detected the arrival of the initial shock wave generated from diaphragm rupture. The trigger time was controlled by a programmable timing system which ensured that the laser pulse occurred during the steady test time of the facility. Holographic images of the model were recorded on a single holographic plate for both no-flow and with-flow conditions. The holographic plate was later used to reconstruct the two recorded images which were then overlapped yielding interference fringes. Further details can be found in [4].

The interferograms were post processed using an interactive analysis package developed by Bishop [1]. Fast-Fourier techniques were used to remove noise followed by an unwrapping routine which extracts the phase shift imparted on the light as it passes through the test flow. This phase shift is dependent on the density of the flow and the results can be used for comparison with numerical simulations either as phase or density.

Emission Spectroscopy

The characteristics of the radiation present in the hot test gas were measured using emission spectroscopy. A gated, intensified CCD camera (Princeton Instruments) was connected to a 300 mm focal length grating spectrometer (Acton Research) and placed adjacent to the test section as shown in figure 2(a). The flow along the stagnation streamline was imaged onto the entrance slit of the spectrometer via a 90^o beam rotator yielding an image on the camera that had one spatial dimension (along the flow) and one spectral dimension. A 1200 lines per millimetre grating was used allowing a spectrum that was about 140 nm wide to be recorded. The camera was triggered as for the interferometry measurements and delayed to record an image in the test time.

In the analysis, the region between the shock and the body was divided into bins each about 0.1 mm wide. For every bin, the spectrum was determined by averaging across the section of the flow covered by the bin. For the current work, no attempt was made to calibrate the absolute intensity of the measurements. Instead, the relative intensities of the CN molecular bands were compared with simulations using the LIFBASE program [3]. In determining a simulated spectrum, the flow was presumed to be in chemical and thermal equilibrium and the temperature was varied to obtain the best fit between the simulation and the measurement.

Results and Discussion

High speed photography

A sample of the images taken with the high speed camera is given in figure 3. The upper series of ten images show single frames extracted at steps of 10 μs during the recording. The second of these shows a small luminous region around the body just after the arrival of the incident shock wave. At this early stage, the flow is made up purely of the accelerator gas. A further 10 μs later, a near maximum shock stand-off is established before the flow settles to a near steady state at around 25 μs after arrival. The lower part of figure 3 shows the time history of the shock stand-off over the duration of the test. Based on these measurements, the steady test time seems to start about 30 μs after the arrival of the incident shock. An approximately constant shock stand-off distance (within the level of fluctuation) is observed for about another 50 μs. Beyond this the stand-off slowly decreases. This is consistent with static pressure measurements (not shown) which show a pressure increase at about 80 μs after the arrival of the incident shock indicating a test time of about 50 μs.

Holographic Interferometry

An interferogram of the flow over the cylinder was taken using

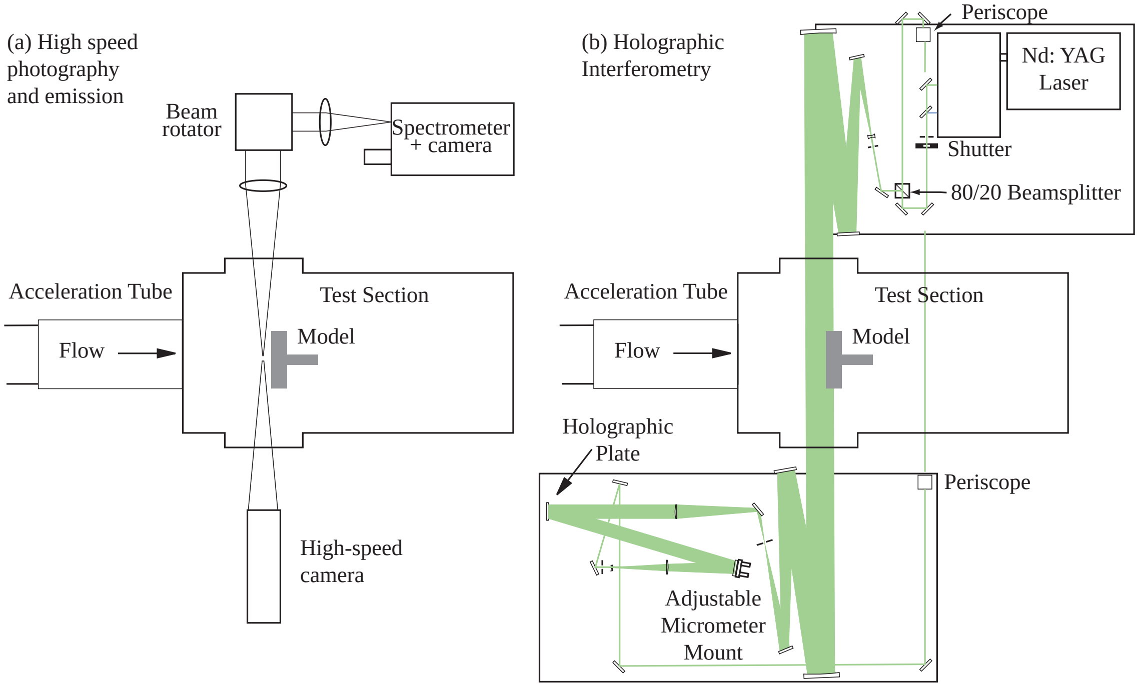

Figure 2: The optical arrangement for (a) high speed photography and emission spectroscopy, and (b) holographic interferometry.

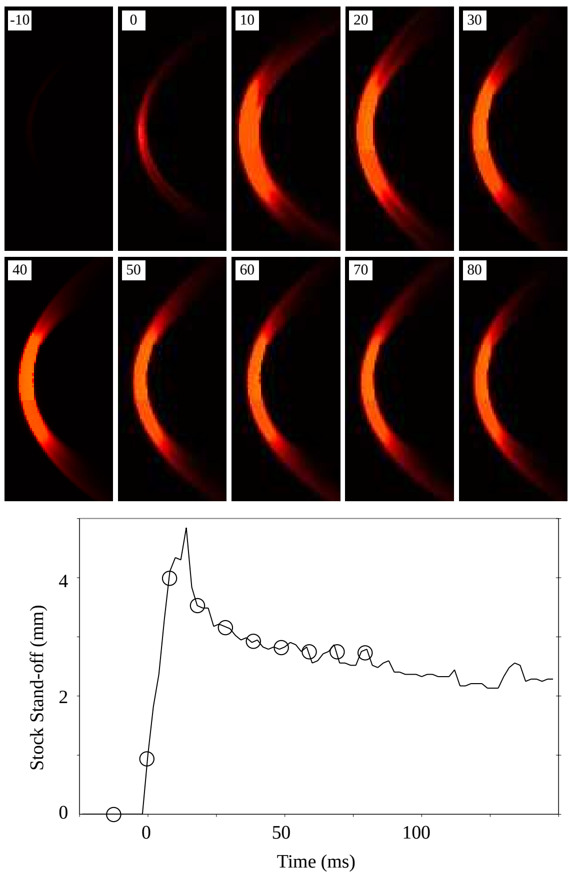

Figure 3: High speed imaging results. Upper - images with indicated delays in microseconds. Lower - the time history of the stand-off. Circles show image times.

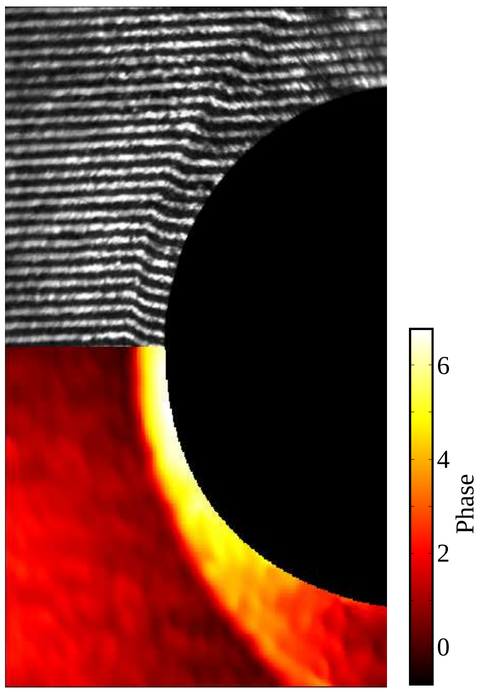

Figure 4: Holographic interferometry results. The upper half of the image shows a raw interferogram of flow over the cylinder. The lower half shows the phase shift imparted on the light by the flow obtained from processing the interferogram.

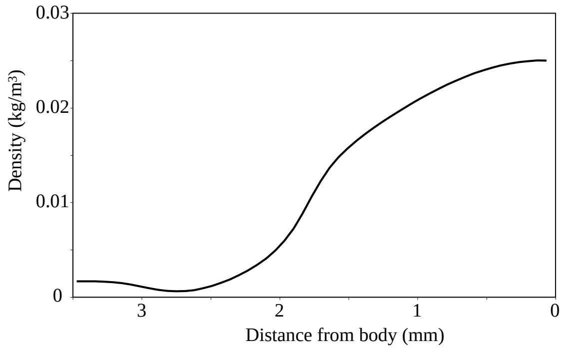

Figure 5: The density along the stagnation streamline obtained from the holographic interferometry measurements.

holographic interferometry. The results of this measurement are shown in figure 4. The upper half of the image shows the raw interferogram. Due to some window damage and a poor laser beam profile, the quality of the image is less than ideal. However, by using Fourier transform techniques, it is possible to eliminate the noise and obtain the phase shift, ϕ, that the light undergoes due to the flow. This is shown in the lower half of the image. The phase shift is directly related to the density, ρ, via the equation

$$\rho = \rho_0 + \frac{\phi}{2\pi} \frac{\lambda}{Gl} \tag{1}$$

where ρ_0 is the free-stream density, λ is the wavelength of the light used (here 532 nm), G is the Gladstone-Dale constant and l is the path length that the light travels (here the width of the cylinder, 100 mm). In a mixture of gases, the Gladstone-Dale constant must be determined by combining the Gladstone-Dale constants for individual species based on their relative densities. Hence a knowledge of the species distribution is required to obtain an absolute density. In comparing the results with numerical simulations it is thus best to calculate the phase from the simulation (in which species concentrations are calculated) rather than comparing the density. However, a density estimate can be made by assuming that, behind the shock front, the gas is mostly a mixture of carbon monoxide and oxygen atoms allowing the Gladstone-Dale coefficient to be determined. Equation (1) can then be evaluated to give the density as $\rho = 1.8 \times 10^{-3} + 3.7 \times 10^{-3}\phi$. A plot of the density along the stagnation streamline obtained in this manner is shown in figure 5. A peak density ratio (density normalised by the free-stream density) of about 14 is reached near the body.

Emission Spectroscopy

The results of the emission spectroscopy are shown in figure 6. Figures 6(a) and 6(b) show the spectrum that was obtained from the emission along the stagnation line in front of the cylinder. In the two-dimensional image (figure 6b), the spatial dimension is the vertical axis and flow is from top to bottom. The horizontal axis shows the wavelength in the violet/blue region. The spectral lines at around 390 nm and 415 nm result from transitions in the CN molecule referred to as CN violet. The bands at 390 nm are from no change in the vibrational quantum number (ie 0-0, 1-1, 2-2, ... bands) while the 415 nm bands have an increase in quantum number of 1 (ie 0-1, 1-2, 2-3, ... bands). Other lines result from impurities in the test gas such as iron.

The region between the shock wave and the body was divided into about 15 horizontal slices effectively representing 15 measurement points along the stagnation streamline. In each region,

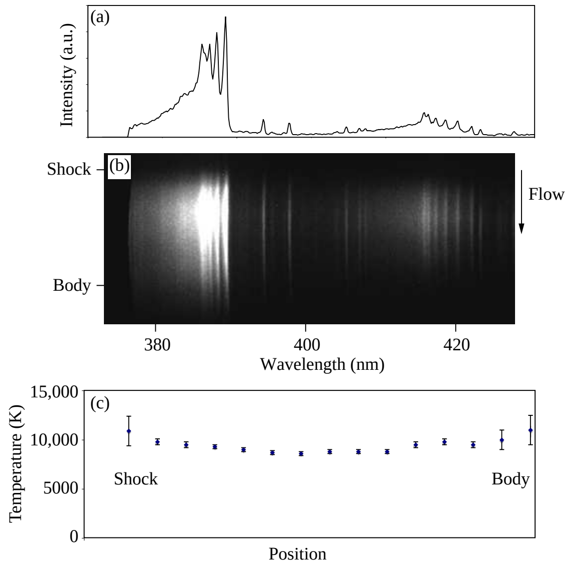

Figure 6: Emission spectroscopy results. (a) A single spectrum; (b) Spatially and spectrally resolved image; (c) temperature distribution between the shock and the body.

the emission intensity was averaged along the spatial (vertical) direction to obtain an emission spectrum, an example of which is shown in figure 6(a). The LIFBASE program [3] was used to fit spectra to the 390 nm band of the emission for each of these regions using the temperature of the flow as the free variable. In this process, it was assumed that thermal equilibrium is established and that translational, rotational and vibrational temperatures are all equal. This is not a good assumption directly behind the shock front where high levels of thermal non-equilibrium are present, characterised by a significantly higher translational/rotational temperature than the vibrational temperature. The temperature distribution obtained is shown in figure 6(c). It shows an initial temperature behind the shock front of just over 10,000 K. The temperature then slowly decreases most likely due to an energy loss from radiative processes. There follows a slight increase as the flow approaches the body and kinetic energy is converted back to thermal energy.

Conclusions

Experiments have been performed to characterise the flow over a blunt body in a hypersonic flow simulation capsule entry into the Martian atmosphere. The flow establishment was studied using high speed photography from which the test time could be determined. Holographic interferometry allowed a measurement of the flow density. The temperature along the stagnation streamline was obtained using emission spectroscopy. Comparison with numerical simulations are planned to allow a better understanding of the flow.

Acknowledgements

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