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Radiative Comparison Between High and Low Density Hypersonic Argon

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Abstract

This paper reports on the analysis of hypersonic argon flows generated in the expansion tube X2 located at the University of Queensland (UQ). A two dimensional wedge model was used for these experiments with the goal of measuring the radiation over the surface of the model and in the expansion region. Radiation was measured in front of the shock, between the shock and expansion fan and for some of the region after the expansion fan. Measurements of the excitation temperature of the argon gas have been made and reported twice previously for each density condition. In this paper, focus is placed on the region in front of the shock. Significant electronic energy level populations were detected in the freestream flow of both the low and high density experiments. It is found that this precursor radiation is likely caused by radiation emitted from the hot argon above the wedge model, radiating upstream and exciting the incoming free-stream argon and then re-radiating before reaching the shock layer. Ionisation was measured in both low and high density experiments. The low density experiments were found to have a higher amount of ionisation, and percentage ionisation before the shock layer.

Keywords: *Hypersonics, Argon, Radiation, Spectroscopy, Free-stream*

Nomenclature

Latin

T – Excitation temperature (K)
k – Boltzmann constant $(J\,K^{-1})$
g – Energy level degeneracy
n – Number density $(\text{atoms}\,m^{-3})$
B – Free-free emission $\left(W\,m^{-3}\,m^{-1}\,\text{steradian}^{-1}\right)$

Subscripts

i – Argon ions
e – electrons

1. Introduction

For a spacecraft to descend through a planetary atmosphere and onto the surface, it must first decelerate. This causes extreme heat-loads in the gas which then may be transferred to the spacecraft. Fundamental understanding of the hot flow-field and how this interacts with the object creating the flow-field is essential.

Studies of how to navigate this problem have been performed, generally focusing on the stagnation regions usually around the front surface of the vehicle[1, 2, 3]. Thermal loads around the rear of the vehicle, and the interaction between radiating gas and the external flow-field have been less studied.

This paper follows on from two previous papers that investigated argon flows[4, 5]. A hypersonic facility was used to generate high speed argon flows over a wedge model. Energy levels of excited argon atoms were measured through the shock over the model and into the expansion fan. Excitation temperatures were determined from these measurements by assuming a Boltzmann distribution. The level of equilibrium could be measured by considering how well each energy level matched the Boltzmann distribution.

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2. Experiments

To investigate the radiation experienced during atmospheric entry, realistic hypersonic enthalpies and speeds are required. Such flows can be generated in the X2 expansion tube facility located at The University of Queensland. X2 uses a free-driven piston for generating hypersonic enthalpies for testing flight case experiments or fundamental physics[6]. A diagram of the tunnel is shown in figure 1. X2 uses a reservoir to drive a piston through the compression tube (ct) compressing the driver gas. This ruptures the primary diaphragm (pd) sending a shock into the shock tube (st1) which heats and compresses the test gas. When the shock reaches the weak secondary diaphragm (sd) the shock moves into the low pressure acceleration tube (st2 and at) and expands towards the nozzle (n) which expands the flow further into the test section (ts).

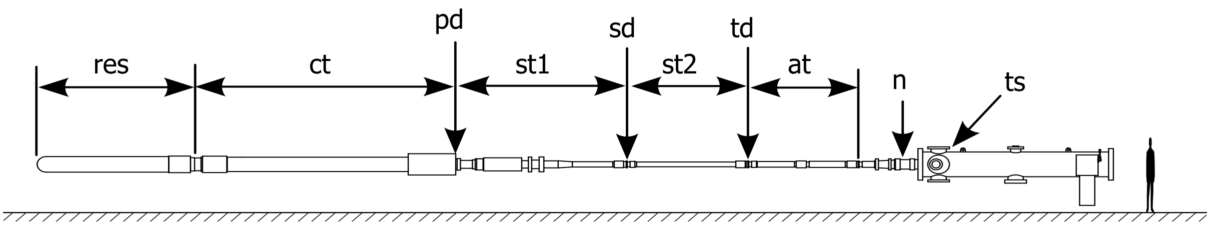

Fig 1. Schematic of the X2 expansion tunnel, adapted from [6].

Two conditions have been tested, a high and low density argon condition. These conditions were designed to be as similar as possible whilst significantly differing in density. Both conditions for free-stream and post-shock over a 35° wedge properties are shown in table 1.

Table 1. Predicted properties pre[7] and post shock

	Low density Free-stream	**Low density Post-shock**	**High density Free-stream**	**High density Post-shock**
Velocity $(m\,s^{-1})$	5795 ± 60	2020 ± 218	5880 ± 55	6880 ± 385
Pressure (Pa)	92 ± 29	50700 ± 17100	2110 ± 380	540000 ± 106000
Temperature (K)	194 ± 27	24100 ± 5200	293 ± 21	17600 ± 1970
Density $(kg\,m^{-3})$	(2.25 ± 0.43)x10^{-3}	(9.68 ± 1.85)x10^{-3}	(34.5 ± 3.90)x10^{-3}	(147 ± 16.6)x10^{-3}

2.1. Model

It is desired to generate a strong shock followed by an expansion fan. As more emphasis is placed on measuring the radiation of the hot argon produced by a shock and then expanded through an expansion fan, a simplified geometry is required. Hypersonic phenomena were generated using a two dimensional wedge model as shown in figure 2. The wedge is 100mm by 100mm by 25mm tall, with a 35° nose angle.

The reference location used in these experiments is the top shoulder of the wedge model. Zero is defined at the top shoulder, positive is defined in the direction of flow. Experiments are done with no angle of attack, and with the wedge placed as close to the nozzle exit as the optical field of view would allow.

2.2. Optics

Measurements of the argon gas radiation were done via emission spectroscopy. For each experiment, two spectrometer systems were aimed and focused to a region above the wedge model. Each optical system consisted of a camera coupled to a spectrometer, with optical mirrors used to redirect and focus the light onto the spectrometer slit entrance. Both high density and low density argon tests used a liquid nitrogen cooled camera, the IRC800HS, coupled to a Acton SP2500i Czerny-Turner spectrometer. This camera and spectrometer were used to measure radiation wavelengths in excess of 790nm up to

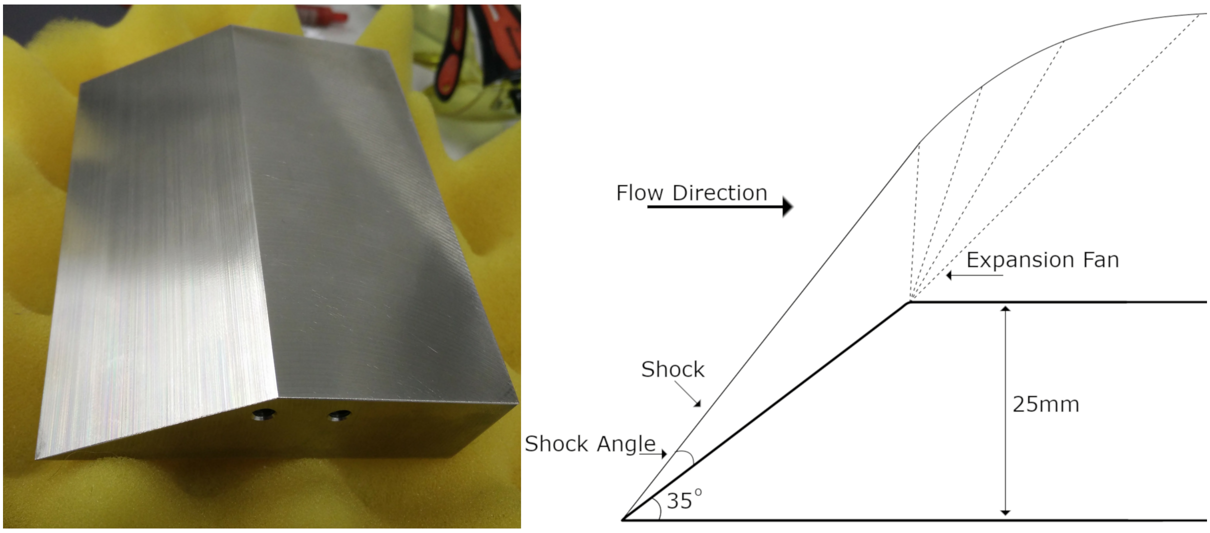

Fig 2. Wedge model with a 35° nose angle.

4300nm. For the low density campaign, a Princeton Instruments PI-MAX Intensified CCD camera was coupled to a Acton SP2300i Czerny-Turner spectrometer to measure radiation wavelengths between 650nm and 800nm. For the high density campaign, a Andor iStar DH340T camera was coupled to the SP2300i spectrometer to measure radiation wavelengths from 300nm to 800nm. Both systems were calibrated in wavelength using argon and krypton pencil lamps, and calibrated for focusing using a knife edge.

Each spectrometer was capable of imaging a one-dimensional line of sight. During both high and low density campaigns, three heights above the model were imaged as horizontal lines; 0.75mm, 3.25mm, 5.75mm. An additional location was imaged in the high density campaign, viewing a horizontal region 3.25mm below the model top surface, showing flow hitting the surface of the model.

3. Results and Analysis

Initial results from each of the experimental campaigns have been discussed in previous papers[8, 5]. Using the Boltzmann distribution, and accounting for some optical thickness, excitation temperatures could be determined along the line of sight of the spectrometer.

Figures 3 and 4 show the results from the low density campaign and from the high density campaign. For clarity, the shock and expansion fan regions, as detected by the high speed camera, are shown as solid and dashed lines respectively. Flow is from top to bottom. As can be seen in both images, the spectral lines of argon extend far into the free-stream flow before the shock. In both campaigns, strong radiation from argon was found in the free stream. Radiation before the shock may have been caused by the bright post-shock argon, emitting radiation into the free-stream which was absorbed by the free-stream gas and re-emitted. Such an effect has been seen in other facilities[9] and could lead to ionization ahead of the shock layer[10].

A similar effect was observed when measuring the flow around the side of the wedge. During the high density campaign, some spectral images were taken below the wedge shoulder (see figure 5). This was done to examine the flow in front of the wedge. The field of view for this height included the free-stream, shock layer, and post shock up to the wedge surface. Beyond this, the observed radiation is emitted by gas that has flowed to the side of the model. Flow in this region is mostly free-stream flow that has not interacted with the model. In this region many spectral lines could still be seen and a temperature could be estimated. The region had a similar radiation profile as that far upstream from

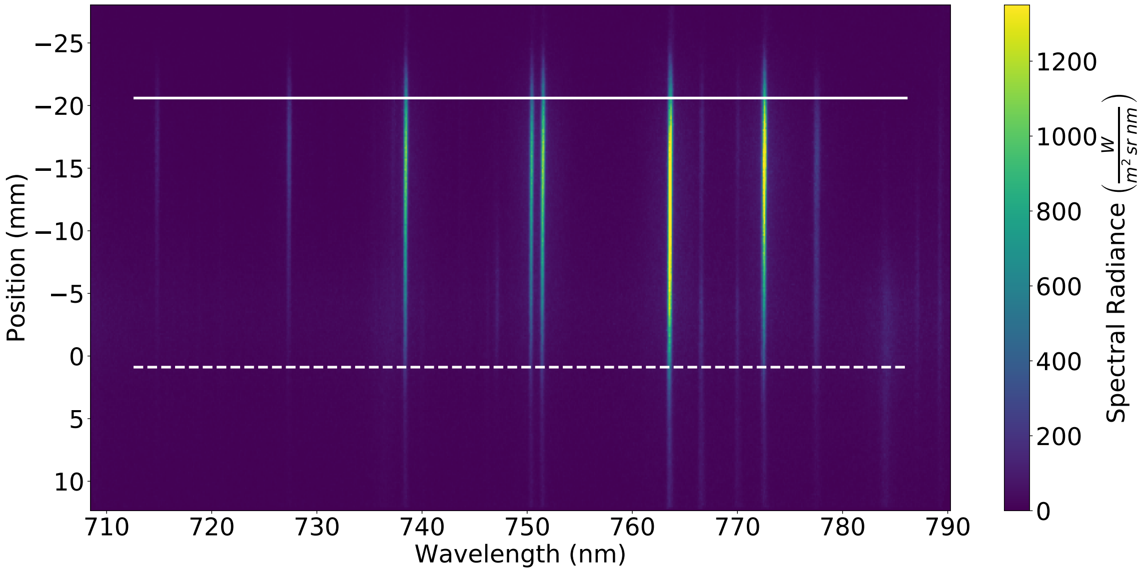

Fig 3. Visible spectrometer images from low density argon. White lines drawn to show the shock (solid) and expansion (dashed) fan locations.

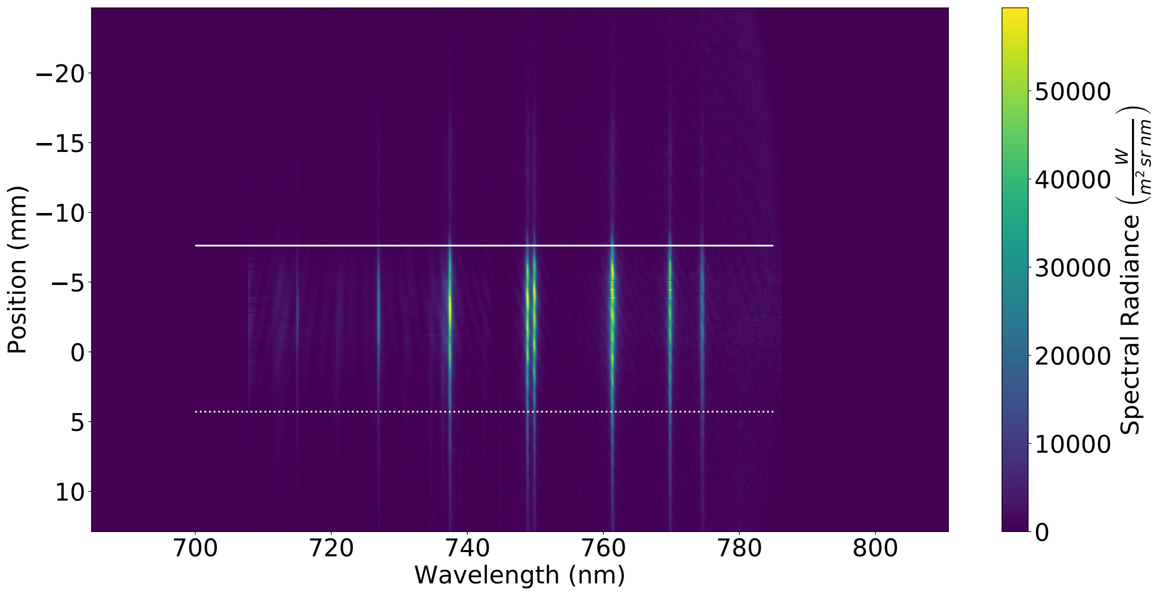

Fig 4. Visible spectrometer images from high density argon. White lines drawn to show the shock (solid) and expansion (dashed) fan locations.

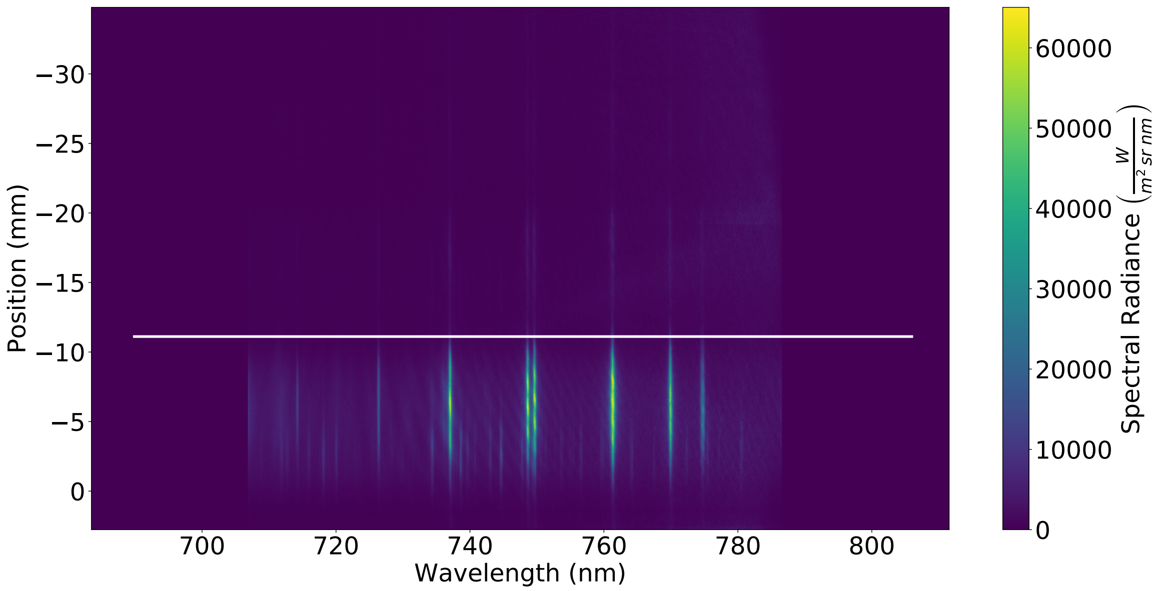

Fig 5. Visible spectrometer image from high density argon, 3.25mm below the wedge surface. White line shows shock (solid) wave as detected by high speed camera. Position set to zero for wedge surface. Flow is from negative to positive position.

the shock. Figure 6 shows the spectrum taken 27mm ahead of the shock in the free-stream compared with a similar spectrum 4mm past the surface of the wedge model from gas passing to the side of the model. The excitation temperature of the gas, as determined by the Boltzmann fit, in the flow 27mm before the shock in the free-stream flow to the flow 4mm after the wedge model are the same, with similar error.

If the hot post shock gas can excite the incoming freestream flow, then it would likely be having an effect on all the surrounding argon gas. The expansion fan region of the flow may have it's electronic states preserved at significantly higher populations than would normally occur. This would increase the non-equilibrium between the electronic temperature and the translational temperature.

The expansion region of the flow was examined in both sets of experiments, and it was expected that the flow temperature may have been frozen. If the argon is exciting and maintaining the electronic energy level populations, then the electronic temperature may not be in thermal equilibrium. This effect would also occur in hypersonic flight with any gas species bright enough to radiate strongly.

In the low density experiments, there was less relative argon excitation before the shock. The radiation detected in the freestream was around 100 times weaker than that detected in the peak radiation of the post-shock argon. Figure 7 shows the radiation detected before the shock in the low density experiments. A calculated profile for the argon radiation is also shown. It can be seen that the signal of the argon radiation is still strong ahead of the shock layer.

In the high density experiments there was a greater relative argon excitation before the shock. The radiation detected was only 10 times lower than the peak argon radiation. Figure 8 shows the radiation detected before the shock in the high density experiments. A calculated profile is shown in black, with the profiles base shifted upward to match the measurements. This signal is about as strong as the peak post-shock radiation detected in the low density campaign. The offset from zero spectral radiance also suggests a boradband radiator is present in the flow ahead of the shock layer.

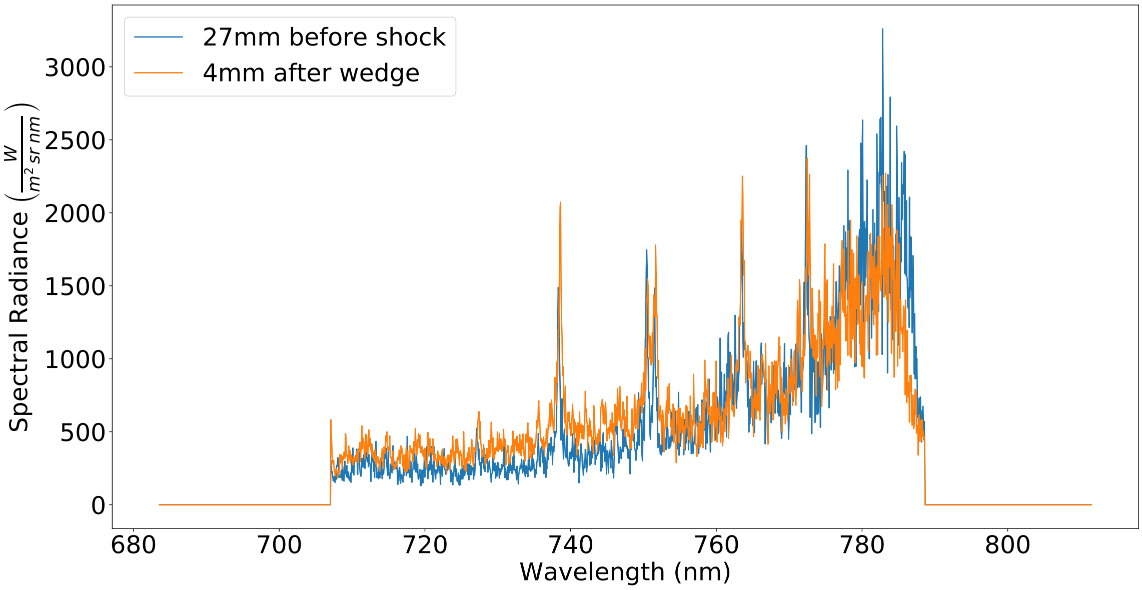

Fig 6. Spectral results before and after the wedge.

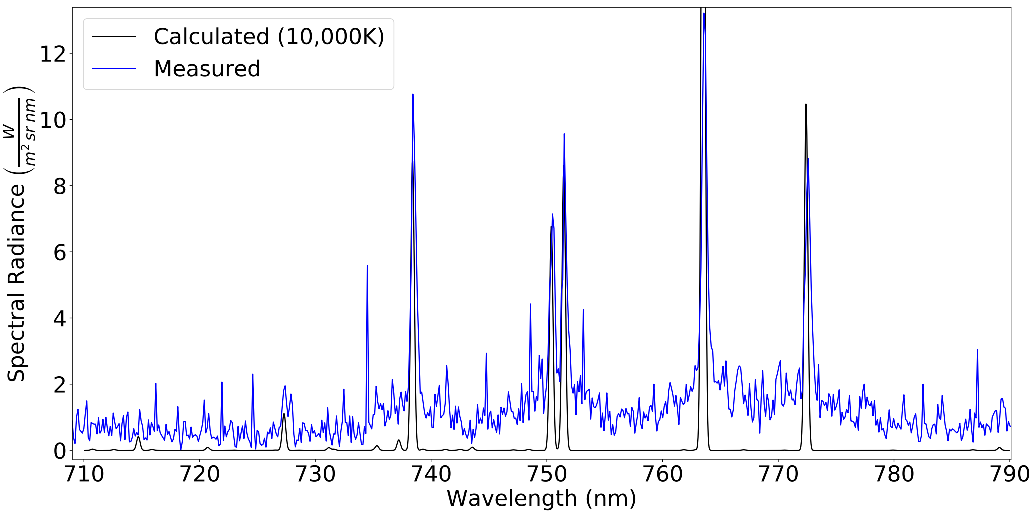

Fig 7. Freestream flow 7mm before the shock, 3.15mm above the wedge in low density argon.

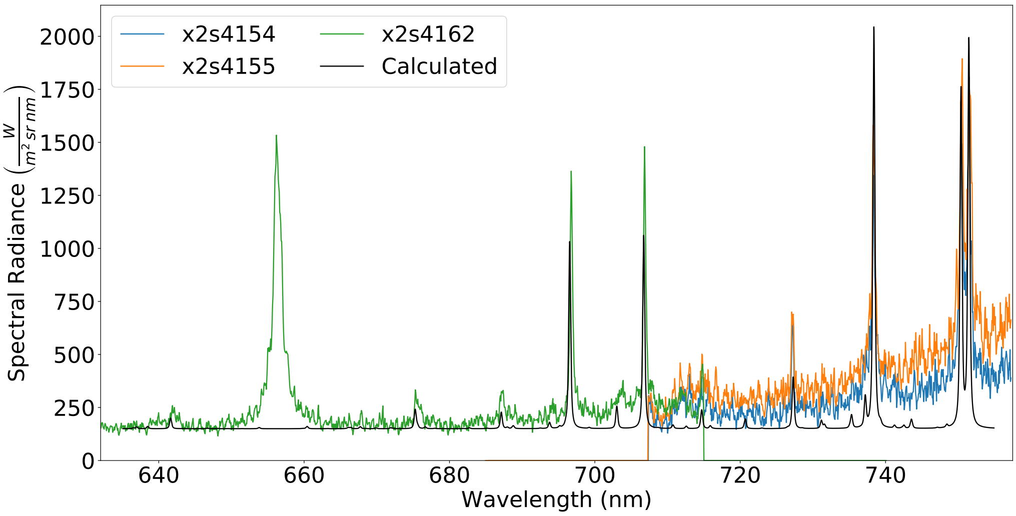

Fig 8. Freestream flow 15mm before the shock, 3.15mm above the wedge in high density argon.

Both low and high density experiments had a offset to the spectral radiance in the post-shock measurements. This indicates that in both experiments, a continuum radiator was detected. Assuming that there was argon ionisation which led to an electron cloud, the electrons could be generating a continuum signal through Bremsstrahlung radiation. The radiation from the free-free interactions of the electrons can be found using the Kramers-Unsöld expression[11]:

$$B = \frac{16\pi e^6}{3\sqrt{3me^2}} \frac{\text{Z}^2}{\lambda^2 \left(2\pi mkT\right)^{1/2}} n_i n_e \exp\left(-hc/\lambda kT\right) \tag{1}$$

where e is the elementary charge, m is the mass of the electron, n_i is the number density of the ions, n_e is the number density of the electrons and Z is the effective coulombic charge of the species doing the scattering. For this it is assumed that the electrons in the flow for both low and high density experiments are primarily generated by the ionisation of argon, and that the amount of electrons is not depleted by the metallic surroundings of the hypersonic facility. This would cause the number density of the electrons to equal the number density of ionised argon. The Z^2 value for temperatures between 8100-10800K, is $Z^2 = 2.4\text{x}10^{-2}$. This was experimentally determined by Taylor and Caledonia[11]. The electronic temperature of the argon in the low density and high density experiments were both around 10,000K, within the range determined.

The electron number density was determined for both the low density and high density experiments. It was also found that in both low and high density experiments, a significant amount of ionisation occurred in the freestream before the shock layer. For the low density experiments the ionisation was between 4%-25% of the total argon in the freestream, then it was between 23-43% immediately post-shock and rose to around 70-80% just before the expansion fan. As the ionisation levels were rising, the signal from the argon was decreasing. Figure 9 shows the peak spectral line measurements from a low density argon experiment, the black line is the total intensity measured on the spectrometer (scaled down to fit) and the red line shows the calculated electron number density. The vertical lines show the position of the shock and the expansion fan as determined by the high speed camera. This figure and the low density experiments are more thoroughly discussed in [4]. For the high density condition, the ionisation was found to be consistent in the post-shock region at around 40%, and consistent in the freestream at around 5%.

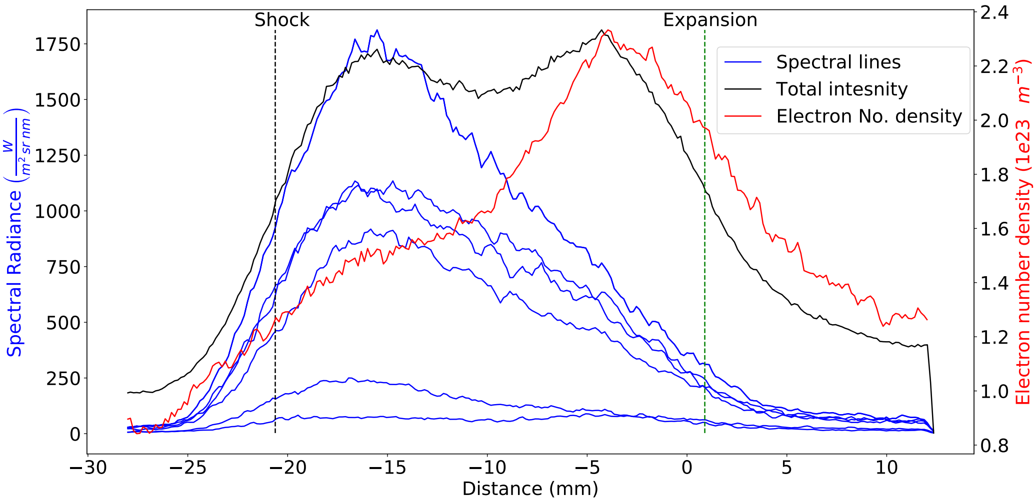

Fig 9. Spectral line intensities above the wedge.

Radiation was detected in both campaigns occurring before the shock layer, up to the edge of the spectrometers field of view. To rule out optical blurring, focusing images were taken in each campaign measuring the optical blur around a knife edge. This was done at the focus centre above the model, and at both ends of the model. After ruling out blur, radiation due to the condition having high excitation of the gas exiting the nozzle must be ruled out. Experiments were conducted without the model, imaging the flow after the shock passes the region where the spectrometers were imaging. Free-stream measurements were conducted at multiple wavelengths with $\approx$ 1250 times the sensitivity of the previous measurements. As nothing was detected, it is concluded that the incoming flow was not the cause of the pre-shock radiation.

4. Conclusion

Two experimental campaigns in a hypersonic argon flow were compared. The effect of the strong post-shock radiation on the surrounding argon flow was shown. Measurements of the freestream and of the expansion region of the flow shows significant electronic energy level populations. High electronic energy level populations in the freestream are not commonly modelled in numerical simulations of hypersonic experiments.

A level of ionisation was detected in both low and high density argon experiments. For both there was found to be ionization in the freestream flow, significantly before the shock layer. The low density experiments had significantly more ionisation than the high density experiments. This may be due to the higher density experiments reaching an equilibrium faster due to the increased pressure and number density increasing the collisional interactions.

The expansion region of the flow may be also susceptible to the radiation of the post shock region. Depending on the penetration depth of the radiation from the post-shock gas, incoming flow upstream of the nozzle may also be influenced, changing the expected electronic energy levels and the ionization of the incoming freestream flow.

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