Experimental and Numerical Investigation of Air Radiation in Superorbital Expanding Flow

Han Wei ¹  Richard G. Morgan ¹  Timothy J. McIntyre¹
Aaron M. Brandis ²  Christopher O. Johnston ³

¹Centre for Hypersonics, the University of Queensland

²AMA at NASA Ames Research Center

³NASA Langley Research Center

9th June 2017
1 Introduction

2 Experimental Campaign

3 Numerical Simulation

4 Results and Analysis
   - Flow Establishment
   - VUV Spectra

5 Conclusions
1 Introduction

2 Experimental Campaign

3 Numerical Simulation

4 Results and Analysis
   - Flow Establishment
   - VUV Spectra

5 Conclusions
Afterbody TPS

Afterbody Heatshield:
- Cocooning the bulk of the vehicle surface
- Bearing large design uncertainty up to 300%[1]

Afterbody Radiative Heating:
- May be important for Superorbital re-entry: Mars return
- Found to be significant with state-of-the-art simulations[2]
- No discernible data recorded by afterbody radiometers of Fire II and Apollo 4

Wright et al.\cite{3} achieved excellent agreement with Fire II forebody convective heating data, but the afterbody experimental data were a factor of two higher than the noncatalytic predictions.

Johnston and Brandis\cite{4} re-examined the FIRE II afterbody measurements and questioned the analysis of the radiometer data. Major sources of model uncertainties for afterbody radiation were identified: the rate coefficient for the three-body electron-ion recombination reaction, the escape factors on collisional-radiative modelling, and the impact of forebody ablation.


Johnston and Panesi\textsuperscript{[5]}: treating nitrogen atoms of different grouped electronic levels as individual species in the flow field model, coupling radiative transition rates to the species continuity equations, adopting a ray-tracing approach in radiation transport calculation and developing a nonequilibrium model for NO

Lopez et al.\textsuperscript{[6]} improved the non-Boltzmann modelling of nitrogen by adopting a state-to-state description of grouped electronic states.


West et al.\[7\] performed sensitivity analysis and uncertainty quantification of afterbody radiation for Stardust at peak afterbody radiative heating conditions. Four variables were found to contribute to nearly 95% of the uncertainty: the electronic-impact excitation rate for N between levels 2 and 5 and the rates of three chemical reactions that affect the number densities of N, N\(^+\), O and O\(^+\).

Validation data of afterbody radiation is in high demand, particularly in the VUV wavelength range.

1 Introduction

2 Experimental Campaign

3 Numerical Simulation

4 Results and Analysis
   - Flow Establishment
   - VUV Spectra

5 Conclusions
X2 Expansion Tunnel

Test Model:

- 54° wedge: 25mm tall and 100 mm wide

Flow Conditions:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Velocity (m/s)</th>
<th>Static Pressure (Pa)</th>
<th>Static Temperature (K)</th>
<th>Stagnation Enthalpy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9714±0.6%</td>
<td>1308±8.8%</td>
<td>2609±1.1%</td>
<td>50.7±0.9%</td>
</tr>
<tr>
<td>2</td>
<td>10899±0.3%</td>
<td>1523±6.8%</td>
<td>2713±1.0%</td>
<td>63.4±0.7%</td>
</tr>
<tr>
<td>3</td>
<td>11837±1.0%</td>
<td>843±10%</td>
<td>2892±0.8%</td>
<td>75.4±2.0%</td>
</tr>
</tbody>
</table>
The Spectral Measurements

Attached Shock Wave

MgF₂ window

VUV Measurement across Model Width

VUV Measurement through Model Surface

21

54°
Through-Wedge Measurement

Han Wei
- Filtered high speed imaging with a bandpass filter coupled to Shimadzu HPV-1 1MHz high speed camera (left)
- VUV emission spectroscopy system (right)
Outline

1 Introduction

2 Experimental Campaign

3 Numerical Simulation

4 Results and Analysis
   ■ Flow Establishment
   ■ VUV Spectra

5 Conclusions
Numerical Simulation

- Flow Solver: Eilmer3\textsuperscript{[8]}
- Grid Generator: GridPro
- Radiation Modelling: NEQAIR V14\textsuperscript{[9]}
- Chemical Species: 11 species air including N, N\textsuperscript{+}, NO, NO\textsuperscript{+}, N\textsubscript{2}, N\textsubscript{2}\textsuperscript{+}, O, O\textsuperscript{+}, O\textsubscript{2}, O\textsubscript{2}\textsuperscript{+} and e\textsuperscript{−}
- Thermo-chemical model: Park’s two temperature model and associated reaction rates\textsuperscript{[10]} with rate controlling temperature defined as $T_d = T_{tr}^{0.7} T_{ve}^{0.3}$


Grid topology and boundary conditions
1. Introduction

2. Experimental Campaign

3. Numerical Simulation

4. Results and Analysis
   - Flow Establishment
   - VUV Spectra

5. Conclusions
1 Introduction

2 Experimental Campaign

3 Numerical Simulation

4 Results and Analysis
   - Flow Establishment
   - VUV Spectra

5 Conclusions
Flow Establishment

High speed video through Thorlabs FBH780-10 bandpass filter at 0.5 MHz
Synchronisation of under-model probe pressure, trigger signals and camera outputs
Extracted pixel counts at 3.25mm above wedge top for Shot x2s3022 with Condition 3
1. Introduction

2. Experimental Campaign

3. Numerical Simulation

4. Results and Analysis
   - Flow Establishment
   - VUV Spectra

5. Conclusions
Raw spectral image for Shot x2s3022 with Condition 3
Calibrated Spectra

Calibrated spectral image for Shot x2s3022 with Condition 3

Condition-3: x2s3022

Radiance of 149.3nm N line

Spatially Averaged Spectrum

Spectral Radiance (W/(m²·sr·nm)) \times 10^5

Wavelength (nm)

Post-Shock Distance (mm)
Radiator Identification

Shock layer radiators for Shot x2s3026 with Condition 1

![Spectral Radiance graph showing peaks at various wavelengths with annotations for Al⁺ and Fe⁺]
Expansion fan radiators for Shot x2s3026 with Condition 1
Radiator Identification

Shock layer radiators for Shot x2s3028 with Condition 2
Expansion fan radiators for Shot x2s3028 with Condition 2
Radiator Identification

Shock layer radiators for Shot x2s3022 with Condition 3
Expansion fan radiators for Shot x2s3022 with Condition 3
The level of contamination increases with flow enthalpy.

The expansion fan spectra tend to be packed with more distinguishable features of contaminants.

C and Al$^+$ can be stronger relative to N lines in the expansion fan for certain conditions.
Through-wedge spectrum of Shot x2s3056 with Condition 1

Condition-1: x2s3056

Radiance of 149.3nm N line

Spatially Averaged Spectrum

Spectral Radiance (W/(m\(^2\)·sr·nm)) ×10\(^3\)
Through-wedge spectrum of Shot x2s3059 with Condition 2

Condition-2: x2s3059

Radiance of 149.3nm N line

Spatially Averaged Spectrum

Spectral Radiance (W/(m²·sr·nm)) ×10⁴
Through-wedge spectrum of Shot x2s3060 with Condition 3

Condition-3: x2s3060

Radiance of 149.3nm N line

Spatially Averaged Spectrum

Spectral Radiance (W/(m²·sr·nm)) ×10⁵

Figure: Through-Wedge Spectra
Radiance profiles of the 149 nm N line at 3.25, 5.75 and 8.25 mm above the top of the wedge compared between experiments and NEQAIR simulations for Condition 1.
Radiance profiles of the 174 nm N line at 3.25, 5.75 and 8.25 mm above the top of the wedge compared between experiments and NEQAIR simulations for Condition 1.
Experiment and NEQAIR results of the 149 nm N line, as well as selected flow variables along the line of sight at 8.25 mm above the top of the wedge for Condition 1.
Experiment and NEQAIR results of the 149 nm N line, as well as selected flow variables along the line of sight at 8.25 mm above the top of the wedge for Condition 1.
Density and selected species mass fraction distributions along the line of sight at 8.25 mm above the top of the wedge for Condition 1
Radiance profiles of the 149 nm N line at 3.25, 5.75 and 8.25 mm above the top of the wedge compared between experiments and NEQAIR simulations for Condition 2.
Experiment and NEQAIR results of the 149 nm N line, as well as selected flow variables along the line of sight at 8.25 mm above the top of the wedge for Condition 2.
Density and selected species mass fraction distributions along the line of sight at 8.25 mm above the top of the wedge for Condition 2
Radiance profiles of the 149 nm N line at 3.25, 5.75 and 8.25 mm above the top of the wedge compared between experiments and NEQAIR simulations for Condition 3.
Experiment and NEQAIR results of the 149 nm N line, as well as selected flow variables along the line of sight at 8.25 mm above the top of the wedge for Condition 3.
Density and selected species mass fraction distributions along the line of sight at 8.25 mm above the top of the wedge for Condition 3
Radiance profiles of the 777 nm oxygen triplet at 3.25, 5.75 and 8.25 mm above the top of the wedge compared between experiments and NEQAIR simulations for Condition 2.
Density and selected species mass fraction distributions along the line of sight at 8.25 mm above the top of the wedge for Condition 2.
Radiance profiles of the 777 nm oxygen triplet at 3.25, 5.75 and 8.25 mm above the top of the wedge compared between experiments and NEQAIR simulations for Condition 3.
Filtered Images vs Simulations

Density and selected species mass fraction distributions along the line of sight at 8.25 mm above the top of the wedge for Condition 3
1. Introduction

2. Experimental Campaign

3. Numerical Simulation

4. Results and Analysis
   - Flow Establishment
   - VUV Spectra

5. Conclusions
Conclusions

- The spatial profiles of 149 and 174nm N radiance are in general of larger spans than those predicted by NEQAIR.
- For Conditions 2 and 3, the peak radiance levels are significantly underestimated. Large departures of predicted radiance values from experiment appear to occur at the start of the expansion fan where the electron-ion recombination process commences.
- NEQAIR results agree well with the filtered images of 777nm oxygen triplet in the compression region and at the start of the expansion fan for Condition 2. For Condition 3, radiance in the compression region and at the start of the expansion fan are underpredicted by as much as 40%, but the afterbody radiance is overpredicted by up to 100%.
Many Thanks
Any Questions?

Figure: Long exposure image of CO$_2$ flow over the wedge.