Analysis of air radiation measurements obtained in the EAST shocktube facility

By A. M. Brandis

1. Motivation and objective

The Vision for Space Exploration has renewed interest in understanding the radiation that is encountered during re-entry into Earth’s atmosphere. In particular, the focus has been to consider conditions that are relevant to the Orion capsule, as part of the Crew Exploration Vehicle (CEV) Aerosciences Project (CAP). Because the radiation is a significant portion of the heat flux, although only for a relatively short time in the trajectory, detailed simulations and experiments have been undertaken to quantify this radiation and the associated uncertainties (Johnston 2008; Bose et al. 2008; Panesi et al. 2009). Previous studies have identified significant differences between the experimental measurements taken in the Electric Arc Shock Tube (EAST) facility at the NASA Ames Research Center (Cruden et al. 2009) and theoretical models (Bose et al. 2008), such as NEQAIR (Whiting et al. 1996)) and HARA (Johnston 2006). Understanding these uncertainties are therefore critical in the design of the thermal protection system (TPS). The present analysis should help provide an insight into the level of fidelity of the theoretical models, and to any previous discrepancies that have already been identified, such as the level of the background continuum (Bose et al. 2008).

2. Results

2.1. Equilibrium condition assumption

A critical aspect of these shock tunnel experiments is whether the shocked flow reaches thermodynamic equilibrium conditions. Owing to the short time-scales and complex flow found in shock tunnels, thermodynamic equilibrium is neither guaranteed nor easily quantifiable. An analysis was undertaken to assess the level of equilibrium that was achieved in the EAST facility. The analysis examined the evolution of the background subtracted ratios of various integrated line intensities at distances behind the shock where equilibrium is thought to exist. The background subtraction comprises of removing all the radiation emitted by the background continuum, leaving the radiation emitted only by atoms and molecules, as represented in Fig. 1. The integration process is represented by Eq. 2.1, where $I_{sf}$ is the integrated value of the spectral feature, $\lambda_c$ is the central wavelength of the integration domain, and $I_{\lambda_{min}}$ is minimum intensity in the specified wavelength domain.

$$I_{sf} = \int_{\lambda_c - k \times FWHM}^{\lambda_c + k \times FWHM} (I_{\lambda} - I_{\lambda_{min}}) \delta \lambda$$

The domain over which each spectral range is integrated is specified by the ratio of the wavelength range/FWHM (full width half max) and is defined as $k$. The integration domain was extended as much as possible to include all the emitted radiation, but it can
be limited by other nearby spectral features. Figure 2(a) shows how the ratio of both the integrated line intensities of 820 nm (predominantly nitrogen, with some oxygen) and 845 nm (oxygen) with 777 nm (oxygen) behind the shock. The experimental values can then be compared with theoretical values. Ratios have been used as an equilibrium indicator, as opposed to an absolute measurement, to remove quantities from the analysis that may be changing with time, i.e., flow density and pressure, or effect of the deceleration of the shock, or uncertainties due to calibration. As Fig. 2(a) shows, the agreement between the EAST data and theory is good and the ratio is fairly constant with respect to distance behind the shock. This indicates that at least partial local equilibrium has been reached, even though the flow is not in full thermo-chemical equilibrium.

3. Analysis of EAST Results

The objective of this section is to present the results of a thorough analysis of the experimental data obtained in the EAST facility. Results of NEQAIR simulations for a post-shock equilibrium state serve as a reference. All of the spectral features observed in the EAST facility, except for contamination species, have been individually analyzed. The benefit of such an analysis, as opposed to comparing the spectrally integrated value, is that individual discrepancies can be identified. Furthermore, spectral features that are known to result from contamination, can be identified and not included in the analysis. It should also be pointed out that the present analysis attempts to remove the background continuum from all calculations and focus purely on the radiance emitted by spectral features. The observed background continuum has yet to be satisfactorily explained, and it is not completely known which mechanism is the source of this radiation and thus can not be included. Due to the large number of shots performed in the EAST facility, there is an excellent basis for a statistical analysis of the data. In this way, the effect of shot-to-shot variation can be seen and an idea of the level of scatter can be assessed.
Furthermore, individual shots can be identified as outliers, and radiance trends can be seen with respect to shock velocity.

In order to develop an accurate assessment of how well NEQAIR simulates measured data, it is not necessary to base this assessment on every single shot in each test campaign. Owing to the variability in the driver, some shots do not reach an adequate plateau region that is designated to be in equilibrium. In some cases, there is no, or very little, test time. Therefore, to better analyze the EAST data, a criterion for classifying each spectral data set was established. Each spectral data set is assigned a value indicating the quality of equilibrium, or plateau, achieved. An example of categories 5 and 3 is shown in Fig. 3. The classification of each shot, on the basis of expert judgement, is as follows:

- **5**: the spectrally integrated radiance shows a long and constant plateau region,
- **4**: the spectrally integrated radiance shows a clear, but shorter constant plateau region,
- **3**: the spectrally integrated radiance shows a reasonably good plateau region, however shows larger noise, a slight slope, or is very short.
- **2**: the spectrally integrated radiance shows no clear plateau region, or significantly slope or noise.
- **1**: hard to determine where the plateau region would be, potentially indicating no test time for the shot, or the spectrally integrated radiance could have been rising steeply the whole time.

3.1. **Cross Section Procedures**

The volumetric radiance is obtained for each camera and shot, and the equilibrium plateau region is taken through inspection of each data set. Volumetric radiance is defined
as the amount of power emitted per unit volume per solid angle (W/cm$^3$.sr). To obtain the volumetric radiance, the calibrated spectral radiance data (W/cm$^2$.µm.sr) from the experiment is normalized by the core flow width and integrated over wavelength. As was outlined above, this equilibrium plateau is more pronounced for some shots compared with others. Various spectral features are then identified in the cross section. The cross section is the profile of the averaged volumetric spectral radiance (W/cm$^3$.µm.sr) in the equilibrium region. For each spectral feature, the minimum value in the wavelength region of interest is subtracted in an attempt to remove the background continuum. The background subtracted spectral feature intensity is then integrated over wavelength.

The advantage of comparing the integrated spectral features rather than the spectra is that differences relating to the spectral resolution can be removed. With these available data the integrated radiance for various spectral features can be plotted for each shot performed on EAST and compared with NEQAIR.

When integrating spectral features care must be taken to avoid the possible errors associated with the integration: first to minimize the errors and second to understand the magnitude of the error. Errors can originate from several different sources. For example, the wavelength range chosen for integration of spectral radiance is not always easily defined. Thus because of different grating settings, the discretization of the wavelength range (pixels), and small misalignments of the grating, the wavelength required for integration of the designated spectral feature can change slightly from a nearby spectral feature does not impinge on the region of interest. It is for reasons such as these that automation of the process is impeded and becomes labor intensive, thereby relying on expert judgement.

To get an accurate integration of the spectral features, the background continuum radiation must be subtracted from the experimental results. Assigning the level of this background is not always straightforward because the mechanisms responsible for the background continuum are not well understood. At present, the integrated spectral regions are chosen such that the minimum value in that region is representative of the continuum. This method is not ideal for a couple of reasons. First, in doing it there is a possibility that part of the line intensity has also been subtracted, and second, the background subtraction is only as precise as the level of noise. The best case would be to subtract the true background continuum, but unfortunately, at present the structure of this continuum is not well understood, so this is not a plausible option and the reason
why the local minimum is used as an estimate of the background continuum. The goal is to select wavelength ranges that would minimize the effect of losing spectral feature radiation to the background subtraction. Thus, a spectral radiance equal to the worst case noise value, as well as any slope in the continuum, is integrated into the volumetric radiance. However, these two factors will offset each other, making it difficult to be any more precise than this. This assumption is quite accurate in certain locations in the VUV and Vis/NIR regions, but less so in the UV/Vis.

3.2. NEQAIR Code

NEQAIR is a line-by-line radiation code that stands for Nonequilibrium Air Radiation. NEQAIR computes spontaneous emission, absorption and stimulated emission from transitions between various energy states of chemical species along a line-of-sight. Individual electronic transitions are considered for atoms and molecules, with the molecular band systems being resolved for each rotational line. For more detail about NEQAIR, refer to published literature (Bose et al. 2009; Whiting et al. 1996). The NEQAIR simulations perform the calculations at a very high spectral resolution which is followed by a convolution (scan) with a slit function. The slit function is a Gaussian function with the FWHM set to the line width of the measured line shapes. The line and band systems used in the radiative heating computation are shown in Table 1. It should be noted that the simulations for modelling the radiation measured on the EAST facility are an idealized approximation of the actual tube-flow phenomena. The NEQAIR simulation is based on an assumption that the flow is in equilibrium, with the post-shock conditions calculated by CEA (chemical equilibrium with applications) (McBride & Gordon 1994). Due to the complex nature of the shock tube environment, there is no guarantee that the EAST flow actually reaches thermodynamic equilibrium. Furthermore, the idea of measuring the level of equilibrium is very difficult, if not impossible, in this situation. Therefore, this approximation could lead to discrepancies between the simulation and measured results. The equilibrium zone is stated to be the region where the integrated radiance reaches a plateau. The equilibrium flow environment is also calculated on the basis of the speed of the shock front at the test section. It therefore does not take into account that the shock is decelerating. This deceleration of the gas is important because the gas in the equilibrium region would have been shocked at different velocities. However, as eluded to earlier, it is possible that there are sections of gas that are in a local equilibrium, but the entire test gas overall is not in equilibrium. In the test section, the shock can be decelerating at approximately 500 m/s² (as an example from 10.1 km/s to 9.92 km/s), which can correspond to a decrease in radiance of approximately 25 - 30% in the Vis/NIR or 35% in VUV region of the spectrometer. Further discrepancies could arise because the calculation was done using a one-dimensional solution, and as such did not include the effect of the boundary layer on the wall of the shock tube. Therefore absorption in the boundary layer is not accounted for in the analysis. A time-accurate two-dimensional/axisymmetric simulation of the facility would be required to address these issues.

3.3. Comparison of EAST and NEQAIR

The comparison of EAST and NEQAIR is not necessarily a trivial task, especially because one must ensure that the comparison is of the same spectral phenomena in the experiment and the simulation. For example, one should not compare the integrated value of a spectral feature from the experiment that includes a large percentage of the background continuum, with a simulated integrated value that accounts only for the spectral
feature intensity. If this were the case, one could get either a false good agreement or false bad agreement. Alternatively, the experimental data could contain contamination that is not included in the simulation. Care must be taken to make sure the same features are compared with integrated intensities. Furthermore, conducting this comparison alongside an appropriately convolved spectral feature analysis is also beneficial. Due to a slightly different optical set up and issues associated with each spectral range, the comparison is broken up into three of the four different cameras used during each EAST experiment. The IR camera has not been analyzed in the present study owing to a recent discovery that there is an issue related to the camera saturating at counts much lower than expected. The following sections present an analysis and comparison of NEQAIR and EAST for the VUV, UV/Vis and Vis/NIR spectral regions. The goal is to assign upper and lower bounds of uncertainty regarding the agreement of the NEQAIR simulations to the EAST experimental results.

3.3.1. VUV Spectra (< ≈ 215 nm)

The VUV spectral region is a difficult region to obtain data due to the absorption of the emitted radiation in this wavelength range by oxygen. The collection optics and spectrometer need to be located in a vacuum environment, and special windows are required to allow the transmission of data for wavelengths shorter than ∼ 190 nm. The EAST experiments are currently the only source of data available for VUV spectra obtained in a shock tube for re-entry relevant conditions. The main spectral features of interest for this comparison in the VUV are the 120 nm and 174 nm nitrogen lines. A comparison of the NEQAIR and EAST data for these lines is presented in Fig. 4. The agreement is reasonably good, within upper and lower error bounds of 0% and -40% for the 149 nm line, and -10% and -30% for the 174 nm line. However, what is interesting about this data set is that the majority of the EAST data are below the NEQAIR prediction, except for a couple of low rated and slow shots. This could indicate either that there is a systematic error in the calibration of the VUV camera or that there is some significant physical process missing from the modeling of this line. For example, there are uncertainties related to the Einstein A coefficients [uncertainties of ≤ 7% and ≤ 10% for the 149 nm and 174 nm respectively (Ralchenko et al. 2010)] or shock-tube flow effects such as absorption in the boundary layer or the deceleration of the shock. Further analysis of this line utilizing two-dimensional/axisymmetric simulations could provide some insight into these issues. A spectral comparison of one shot from EAST and NEQAIR is

Table 1. Line and band systems for radiative heating computations using NEQAIR

<table>
<thead>
<tr>
<th>Species</th>
<th>Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>lines/multiplets between 120 nm and 1.5 µm</td>
</tr>
<tr>
<td>O</td>
<td>lines/multiplets between 120 nm and 1.5 µm</td>
</tr>
<tr>
<td>N⁺, O⁺, e⁻</td>
<td>bound-free and free-free continua</td>
</tr>
<tr>
<td>N₂</td>
<td>1st-positive ($B^3Π_u → A^3Σ_g^+$), 2nd-positive ($C^3Π_u → B^3Π_g$)</td>
</tr>
<tr>
<td>O₂</td>
<td>Schumann-Runge ($B^3Σ_u^- → X^3Σ_g^+$)</td>
</tr>
<tr>
<td>NO</td>
<td>β ($B^2Π → X^2Π$), γ ($A^2Σ^- → X^2Π$), δ ($C^2Π → X^2Π$), ε ($D^2Σ^+ → X^2Π$)</td>
</tr>
<tr>
<td>N₂⁺</td>
<td>1st-negative ($B^2Σ_u^+ → X^2Σ_g^+$)</td>
</tr>
</tbody>
</table>
Analysis of air radiation in EAST

Figure 4. VUV comparisons of NEQAIR simulations and Test Campaign 47 and 50 EAST experiments for the (a) 149 nm nitrogen line (log-scale) and (b) 174 nm nitrogen line (log-scale).

Figure 5. Comparison of NEQAIR and EAST for the 174 nm nitrogen line with the background continuum subtracted at 10.25 km/s.

shown in Fig. 5. This figure shows excellent agreement between the two lines, and also highlights that simply comparing the peaks between experiments and simulations is not always completely valid. As can be seen in the figure, NEQAIR has a greater peak height than that measured on EAST. However, this is compensated by the increased level of energy in the wings of the spectral features measured on EAST. Without doing this, the integrated value of the spectral feature is the best value for comparison.
3.3.2. UV/Vis Spectra (≈ 190 nm – 500 nm)

The UV/Vis region of the spectrometer is one of the more challenging regions to simulate because of the presence of molecular as well as atomic radiation. The modeling of molecular radiation is more difficult due to the existence of the vibrational manifolds and branches of rotational lines. The molecular radiation is a much broader phenomena in terms of wavelength. Therefore, the molecular radiation can be superimposed on the atomic radiation. Furthermore, for many of the conditions observed on EAST, the dissociation limit for some of these processes can be reached. This means that for some of the slower shots, there could be a molecular band radiating, that might not be present in a faster shot because the temperature is much higher, and thus the molecule may have dissociated into its atomic substituents. For example, for the simulation of shot 47 - 43 shown in Fig. 6, it appears that NEQAIR is predicting emitted radiance from an N₂ molecular system between 425 nm and 430 nm. However, this spectral feature is not observed in the EAST experiment. There are two possible causes for this discrepancy, one being that the flow has not reached the equilibrium flow-field as calculated by CEA (McBride & Gordon 1994) and so is in some level of non-equilibrium. The other possible cause is that NEQAIR’s spectroscopic constants are incorrect for this feature.

The analysis of the UV/Vis region of the spectrum is also approached differently from the VUV region because of the superposition of both atomic and molecular emission lines. This means that unlike the VUV region, where single spectral features can be analyzed, the UV/Vis spectral region needs to be analyzed as a whole as it is difficult to separate the various emitting features. Furthermore, the superposition of spectral features and broad band emissions makes the subtraction of the background continuum is more difficult in this region. The comparison of the simulated and experimental radiance integrated over the region of 310 nm to 470 nm is shown in Fig. 7. The results show that NEQAIR and EAST quantitatively agree quite well from 9.7 to 11.5 km/s. Furthermore, the trend of emitted radiance with velocity agrees very well. However, when the lower speeds are analyzed the agreement is not as good, with NEQAIR under-predicting the EAST results. This a common result across all spectral features, with NEQAIR under-predicting the radiation at slower speeds (approximately 8 - 9.5 km/s).

3.3.3. Vis/NIR Spectra (≈ 480 nm – 900 nm)

The Vis/NIR region of the spectrum is typically easier to simulate because the radiation is emitted only from atomic species and the effect of the background continuum subtraction is less significant. Figure 8 indicates that excellent agreement can be seen between NEQAIR and EAST spectra. A comparison of NEQAIR and EAST for the integrated 777 nm oxygen line is shown in Fig. 9. As can be seen, the agreement is very good with upper and lower error bounds of +5% and -35%. Furthermore, as in the VUV, a similar trend can be identified in the Vis/NIR spectral region showing that the NEQAIR solution represents an upper bound to the EAST data.

3.4. Overall NEQAIR Maximum and Minimum Uncertainty Bounds

After the data is collected and analyzed from each camera, the goal is then to determine an overall upper and lower uncertainty bound for the NEQAIR prediction of EAST data. The methodology for this analysis is to assign upper and lower bounds for each spectral region analyzed. The level of the bounds have been assigned to encompass the equilibrium level rated 4 and 5 data, specifically aimed at the shots between 9.5 - 10.5 km/s. This shock speed range was chosen because it is the range with the most shot data as well
Figure 6. Comparison of NEQAIR and EAST for the spectral range of 310 nm to 470 nm with the background continuum subtracted.

Figure 7. UV/Vis comparisons of NEQAIR simulations and Test Campaign 47 and 50 EAST experiments for the spectral range of 310 nm to 470 nm.

as being the most flight relevant. The extent to which the experimental data is over or under predicted by the NEQAIR simulations is then used to determine the overall upper and lower bounds of NEQAIR’s ability to predict the EAST radiance. Once the bounds for each experimental spectral region have been determined, the influence of these uncertainties on the overall uncertainty bounds can be evaluated. This is achieved by weighting each spectral range uncertainty by the amount of radiance emitted in each specific wavelength region. The weighting is evaluated by using the NEQAIR solution
with 10 km/s as the baseline. For each spectral range, the percentage of the emitted radiation in that range compared with the overall radiation emitted is the weighting factor. The weighting factors can then be used as a multiplier for each wavelength range and then summed over all the spectral regions investigated. This process is represented by Eq. 3.1, where $U_{tot}$ is the total uncertainty, $n$ is the number of spectral ranges to be investigated, $I_n$ is the intensity for the $n$th spectral region, $I_{tot}$ is the total intensity, and $U_n$ is the uncertainty for the $n$th spectral region.
### Table 2. Upper and lower bounds for NEQAIR compared to EAST spectral intensities (background continuum subtracted).

<table>
<thead>
<tr>
<th>Wavelength range, nm</th>
<th>NEQAIR radiance @ 10km/s W/cm²sr</th>
<th>Upper uncertainty bound</th>
<th>Scaled uncertainty upper bound</th>
<th>Lower uncertainty bound</th>
<th>Scaled uncertainty lower bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>146 - 153</td>
<td>0.163</td>
<td>0%</td>
<td>0.0%</td>
<td>-40%</td>
<td>-7.2%</td>
</tr>
<tr>
<td>170.7 - 182.2</td>
<td>0.15</td>
<td>-10%</td>
<td>-1.7%</td>
<td>-30%</td>
<td>-5.0%</td>
</tr>
<tr>
<td>310 - 470</td>
<td>0.07</td>
<td>45%</td>
<td>3.5%</td>
<td>-25%</td>
<td>-1.9%</td>
</tr>
<tr>
<td>470 - 500</td>
<td>0.0027</td>
<td>130%</td>
<td>0.4%</td>
<td>0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>507.5 - 556</td>
<td>0.007</td>
<td>125%</td>
<td>1.6%</td>
<td>0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>567 - 648</td>
<td>0.023</td>
<td>70%</td>
<td>1.8%</td>
<td>-3%</td>
<td>-0.1%</td>
</tr>
<tr>
<td>664 - 704</td>
<td>0.013</td>
<td>68%</td>
<td>1.0%</td>
<td>0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>735 - 755</td>
<td>0.061</td>
<td>-10%</td>
<td>-0.7%</td>
<td>-36%</td>
<td>-2.4%</td>
</tr>
<tr>
<td>767.5 - 786.5</td>
<td>0.08</td>
<td>5%</td>
<td>0.4%</td>
<td>-35%</td>
<td>-3.1%</td>
</tr>
<tr>
<td>804 - 834</td>
<td>0.145</td>
<td>7%</td>
<td>1.1%</td>
<td>-36%</td>
<td>-5.8%</td>
</tr>
<tr>
<td>850 - 885</td>
<td>0.19</td>
<td>10%</td>
<td>2.1%</td>
<td>-33%</td>
<td>-6.9%</td>
</tr>
<tr>
<td>Sum:</td>
<td>0.9047</td>
<td>8.9%</td>
<td>-32.4%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ U_{tot} = \sum_{i=1}^{n} \frac{I_n}{I_{tot}} \times U_n \quad I_{tot} = \sum_{i=1}^{n} I_n \quad (3.1) \]

The results of the analysis is shown, Table 2, show, for each spectral range analyzed, the upper and lower bounds of uncertainty scaled by the relative contribution of radiance emitted by that range to the total radiance. These scaled upper and lower uncertainties are then summed and give the upper uncertainty bound to be +8.9% and the lower uncertainty bound to be -32.4%. This indicates that NEQAIR generally provides more of an upper bound prediction of the EAST radiance emitted by atomic and molecular species. It should also be pointed out that these uncertainty bounds do not include any uncertainty related to the background continuum. Displaying the data in this way also provides a means to compare other current or future simulations and experiments.

### 4. Future Plans

Future efforts aimed at constructing and implementing a two-dimensional/axisymmetric simulation of the EAST flow should prove to be highly beneficial. The present analysis has also shown the importance of analyzing both CFD and experimental results together. In particular, the benefits obtained by expanding the experimental scope to include off-nominal design conditions would provide a comprehensive data-set to better validate the simulations. There is scope for the optimization of the EAST buffer design to provide even higher speeds. Furthermore, the focus of the buffer testing thus far has been directed toward Earth entries. Future testing could also provide high speed entry data for other atmospheres, such as Mars, Venus, and Titan. For future testing in the IR region of the spectrometer, modifications of the optical arrangement could reduce the amount of light entering the spectrometer and provide more robust IR data.
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