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UV and VUV emission measurements in an ICP torch facility

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Abstract

We present UV/VUV emission measurements of both CO_2/Ar and Air plasmas at conditions relevant for the study atmospheric entry. The plasmas are found to be in equilibrium at a temperature of approximately 6500 K and a pressure of 1 atm. A system was designed in order to make measurements without being subject to oxygen absorption. The measured emission is compared with theoretical predictions made using the SPECAIR radiation code. For the range of wavelengths examined, SPECAIR works very well at predicting the measured emission.

1. Introduction

Past studies have indicated that the radiative heat flux becomes very significant at high earth entry speeds, even dominant for Mars return conditions.[1-4] Johnston et al. provide simulated values of convective and radiative heat fluxes for a Mars return case for various configurations.[1] For a 1 m radius sphere entering at 15 km/s, the stagnation point heat fluxes are estimated to be approximately 2000 W/cm^2 for the radiative flux and less than 500 W/cm^2 for the convective heat flux. Tauber and Sutton [3] and Brandis and Johnston [4] provide simplified correlations for calculating radiative fluxes that can be compared with convective heating correlations provided by Brandis and Johnston or Sutton and Graves.[5] Generally speaking, the radiative heat flux becomes more significant at high entry velocities and for large capsule sizes, such as would be used in a manned mission.

The VUV region of the spectrum contributes a substantial portion of the total radiative heat flux for many conditions of interest.[6] Laux et al. study a lunar return condition and find that the VUV can contribute upwards of 60% of the total radiative heat flux.[7] Furthermore, these estimates are based on emission models that are difficult to validate in the VUV due to a lack of data that is difficult to obtain. Our current work is pursuing two goals. First, our goal is to experimentally measure equilibrium emission in the VUV for conditions relevant for atmospheric entry using a VUV spectroscopy setup. Second, we will then compare with SPECAIR predictions as part of an effort to assess the performance of this radiative model and update it if necessary.[8, 9] Our focus is on gas mixtures relevant for Mars and Earth entries.

2. Experimental Setup

The plasma torch facility used to produce the plasma at the inlet of the water-cooled test-section is a TAFA Model 66 inductively coupled plasma (ICP) torch powered by a 120 kVA radio frequency LEPEL Model T-50-3 power supply. The power supply operates at 4 MHz and can supply a maximum of 12 kV DC and 7.5 A to the oscillator plates. Details of the plasma torch facility are provided in previous publications: see Refs. [10] and [11]. The plasma at the exit of the torch is at atmospheric pressure. Figure 1 shows a schematic of the facility. Calibrated flow meters are used to control the mass flow rate of each gas through the system. For the experiments presented here, a 5-cm diameter exit nozzle was used. To simulate the radiative environment for Mars entry, we use a mixture of CO_2 (0.35 g/s) and Ar (3.79 g/s). The argon emission does not significantly interfere with the VUV emission from the CO 4th positive band of interest. This emission is nonetheless modeled in SPECAIR. The argon is necessary as the torch cannot be operated using pure CO_2. To simulate the radiative environment for Earth entry, we inject air (2.57 g/s) directly into the torch.

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The plasma is known to be at atmospheric pressure. To determine the temperature, the absolute intensity of atomic lines in the visible and near IR are used. For these measurements a visible spectrometer (Acton SpectraPro 500i) and imaging setup is used. A filter is installed in the optical path to suppress higher order interferences within the spectrometer. The imaging system makes use of parabolic mirrors and a periscope to image the spectrometer slit across the jet profile. Intensity measurements are Abel-inverted to provide spatially resolved intensity measurements. The procedure for these emission-based temperature measurements is documented in several references.[8, 10] The analysis relies upon the assumption of thermochemical equilibrium - an assumption that has been previously verified using this plasma torch facility with air injection.[8] For the air mixture, the oxygen 777 nm triplet is used as a measure of temperature. For the CO_2/Ar mixture, this line is also used as well, in addition to a Carbon line (833 nm) and Argon line (764 nm). These are found to yield the same temperature profile, to within 100 K. Figure 2 shows the results.

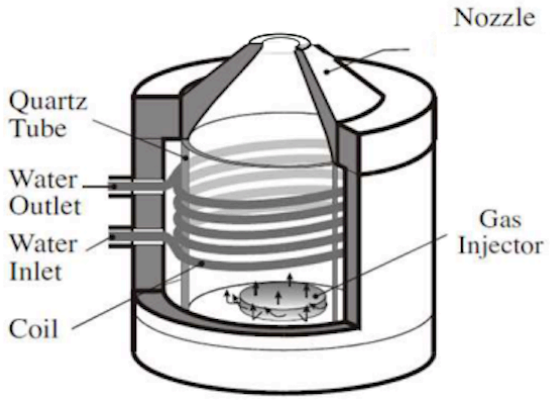

Figure 1: Plasma torch head and nozzle assembly. The gas injectors include radial, swirl and axial injectors.

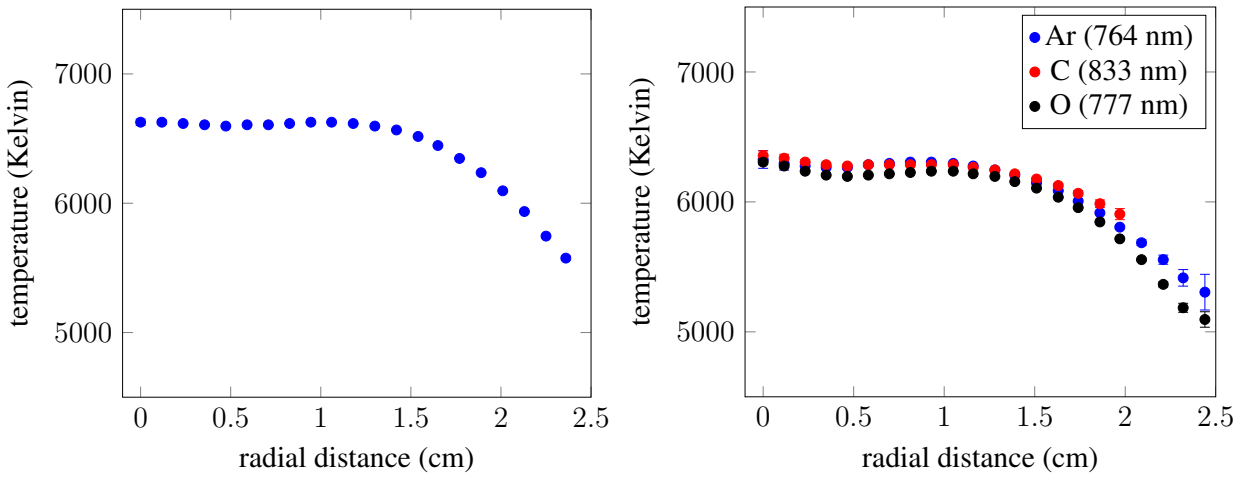

Figure 2: (left) Air plasma composition as a function of plasma jet radius. (right) CO_2/Ar plasma composition as a function of plasma jet radius.

The VUV system used for this work involves components from previous measurements done using a nitrogen purged VUV spectrometer.[12] Measurements were obtained down to 170 nm, but oxygen absorption was affecting the measurements below a wavelength of about 180 nm, making it somewhat difficult to compare with radiative model predictions. We have upgraded this spectrometer to a McPherson vacuum spectrometer capable of making measurements down to 120 nm. Figure 3 shows a diagram of the experimental setup. An imaging box is attached to the spectrometer with two mirrors for imaging the spectrometer slit onto the plasma. The mirrors are Acton optics mirrors with a #1200 coating for 120 nm reflection. The slit function for the measurements reported here has a FWHM of about 0.10 nm. An adapting tube protrudes from this imaging box and terminates at the plasma boundary to avoid

oxygen absorption. Given the high temperature of the plasma, this tube is specially designed to withstand the thermal heat flux that results.[13] The final piece in contact with the plasma is a water-cooled copper piece. Teflon and PEEK plastics are used to manufacture the portion of tube separating this copper adaptor from the imaging box. These plastics were chosen for electrical isolation given that the plasma is at a 10 kV potential. For calibration, an argon discharge is used that supplies a well-known intensity in the UV/VUV spectral regions and that is traceable to NIST standards.[14] Note that the VUV system supplies measurements only along a single line-of-sight. For the results presented here, the system was aligned so as to look directly across the central portion of the plasma.

Once a calibrated UV/VUV emission spectrum is obtained, the radiation code SPECAIR was used to calculate a theoretical spectrum for comparison. This involved solving the radiative transport equation along the system line-of-sight using the measured temperature profile. The details of the radiative models used for the air calculation can be found in Ref. [8]. For the CO_2/Ar mixture, the primary radiator in the UV/VUV is the CO 4^{th} positive band. The radiative model in SPECAIR is based upon the electronic transition moment function of Kirby and Cooper [15] and Spielfiedel [16]. These two separate publications give virtually the same model of the electronic transition moment function and thus we don't distinguish between them. Figure 4 shows the plasma composition as a function of plasma jet radius used for the calculations. The plasma composition was calculated using NASA CEA given the measured temperature profile and gas injection composition. For the CO_2/Ar mixture, Ar, CO, C and O are the dominant species present. For the air mixture, N, O and N_2 are the dominant species present.

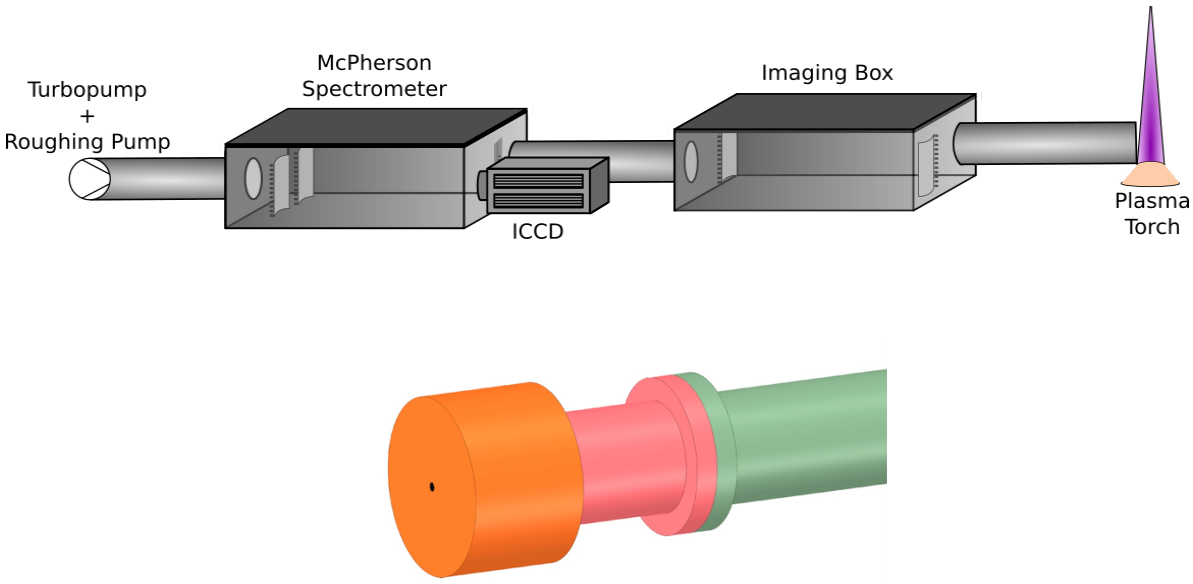

Figure 3: (*top*) VUV setup used for emission measurements in the UV/VUV showing the location of the vacuum pumps, imaging box and final tube that adapts the system to the plasma torch. (*bottom*) Detail of the adapting tube. The portion in green is under vacuum and mounts to the imaging box. A MgF2 window separates the green and red portions of the tube in the image. The final piece in contact with the plasma is highlighted orange and is water-cooled copper. The portions in red and orange are under a high purity argon purge.

3. Results

The air test case has been extensively studied and verified to be in equilibrium. To verify that the CO_2/Ar mixture was indeed in equilibrium, we measured temperature based upon three atomic features from three difference species. As an additional check, we measured the C_2 emission around 500 nm and compared with SPECAIR predictions based upon the measured temperature profile. We obtained very good agreement, and this gives us confidence in the equilibrium assumption.

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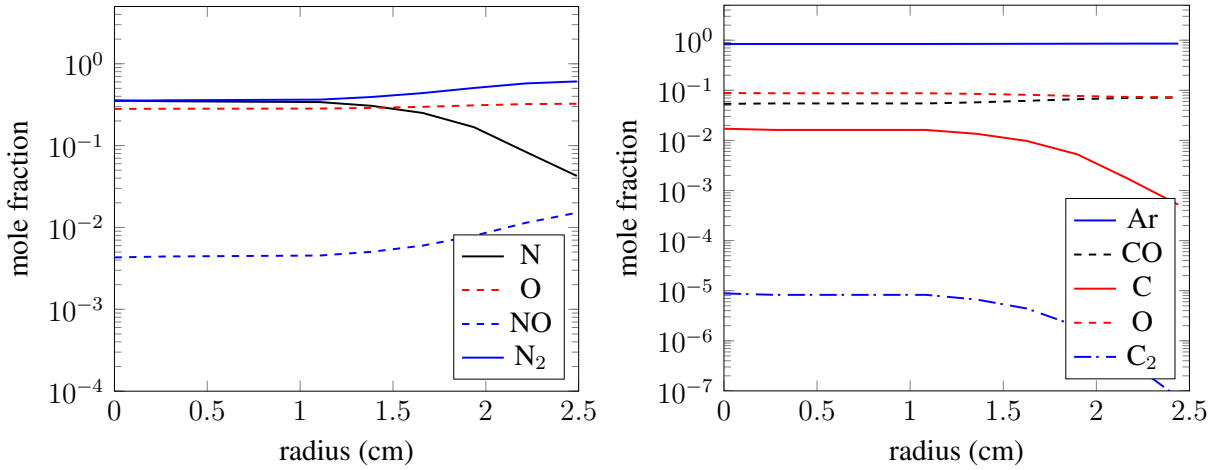

Figure 4: (left) Air plasma composition as a function of plasma jet radius. (right) CO_2/Ar plasma composition as a function of plasma jet radius.

Figure 5 shows a measured UV/VUV spectrum obtained using the CO_2/Ar mixture and the corresponding comparison with SPECAIR. SPECAIR captures well the CO 4th positive bands, giving us confidence in the measurements and SPECAIR model predictions. The disagreement that begins to appear above 215 nm is believed to be due to air entrainment in the plasma jet. Air entrainment leads to the production of additional species, such as NO, that can strongly radiate and interfere with the emission to a small degree. Because the CO 4th positive signal becomes quite small at these higher wavelengths above 215 nm, it becomes comparatively easy for any interference to become significant. Our goal is to extend these measurements down to 150 nm to obtain a better comparison with theoretical calculations.

Figure 6 shows the measured UV/VUV spectrum obtained using an air mixture and the corresponding comparison with SPECAIR. NO is the primary molecular emitter responsible for the observed emission. The good agreement for these wavelengths is expected as the SPECAIR model has already been validated down to about 195 nm.[8] The good agreement validates the measurement approach. A small disagreement begins to appear around 190 nm. As with the CO_2/Ar measurements, our goal is to extend these measurements down to lower wavelengths. For this particular test case, this will permit us to see if this discrepancy that appears around 190 nm persists and is significant.

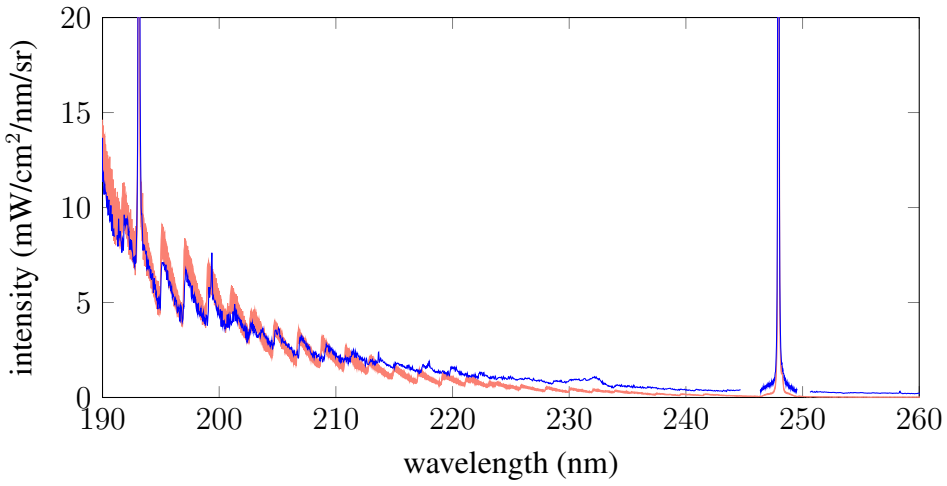

Figure 5: Comparison between measured (blue) and calculated (salmon) spectra. The calculated spectra is actually a shaded region corresponding to the maximum and minimum intensities that can be anticipated given the uncertainty in the temperature measurements.

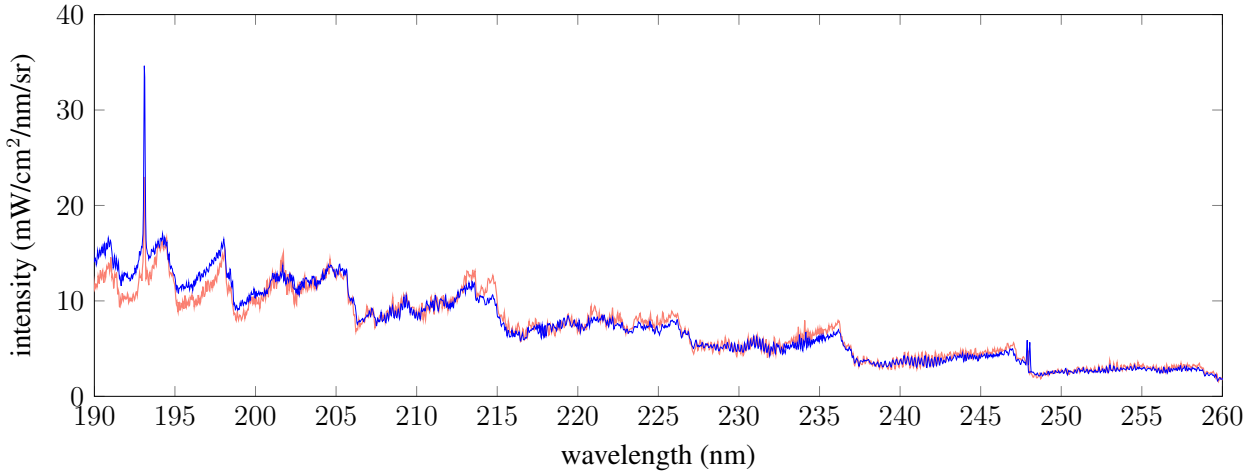

Figure 6: Comparison between measured (blue) and calculated (salmon) spectra.

4. Summary

We present preliminary measurements of air and CO 4th positive emission that extend down into the VUV region of the spectrum. For the test cases presented here, SPECAIR accurately predicts the molecular emission for these two test cases. Our goal now is to extend these measurements down to lower wavelengths in order to further test the model performance. For the air case, in particular, a discrepancy begins to occur around 190 nm that may potentially grow larger at wavelengths deeper in the VUV region of the spectrum.

As an additional goal, we would also like to verify that the atomic emission is correctly predicted in the VUV. The atomic features are predicted to be heavily optically thick. The amplitude of these features, therefore, is not only dependent upon the Einstein coefficient of the transition. The predicted amplitude is also dependent on the line-broadening model used due to the fact that this determines the extent to which the line is affected by self-absorption. Furthermore, atomic lines account for a large portion of the radiative heat flux at high entry velocities due to the high temperature and high level of dissociation behind the shock wave. Being able to compare measured emission with SPECAIR predictions will allow us to validate or refine the line-broadening models used for these features.

Acknowledgments

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