Vacuum ultraviolet radiation studies in a plasma torch facility

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For many Earth atmospheric reentry conditions, the vacuum ultraviolet portion of the radiative heating can be significant and information on this region can be important to the development of thermal protection systems. Little experimental data is available in the this spectral region due to the difficulty of measuring a spectral region with such high absorption in air. The 50 kW radio-frequency inductively coupled plasma torch recently installed at the Laboratoire EM2C (Ecole Centrale Paris) has been used to conduct emission spectroscopy measurements in the vacuum ultraviolet region for relevant Earth reentry conditions.

I. Introduction

During the hypervelocity reentry of a spacecraft into Earths atmosphere, a major part of the heating experienced by the spacecraft is due to the equilibrium shock layer radiation. A significant portion of this, estimated to be as much as 60% of the total radiation, is emitted in the vacuum ultraviolet (VUV) region.[1] In order to better size and design the thermal protection system of the spacecraft, the radiation emitted by the shock layer must be accurately predicted. The prediction of the radiative heating relies on a combination of theoretical and numerical studies as well as ground experiments.

Little experimental data is available in the VUV spectral region due to the difficulty of measuring a spectral region with such high absorption in air. However, with such a significant contribution to the radiative transfer at reentry conditions, the gathering of experimental data is highly desirable in order to measure the intensity emitted in the VUV region and allow for further validation of computational radiation models. At NASA Ames, the EAST facility has recently been used in a comprehensive campaign to capture emission spectroscopy data for Earth reentry over a spectral range from the VUV to the IR.[2–7] These measurements were performed at initial pressures ranging from 0.1 to 1.0 Torr and shock velocities ranging from 9 to 11 km/s, with four different spectral ranges measured during each shot. A preliminary analysis of the EAST spectral measurements was conducted in the nonequilibrium post-shock region, comparing the experimental results to computational results obtained with a collisional-radiative model.[8,9] A reasonable agreement was found between the experimental and computational results.

At the University of Queensland, Australia, a method has been developed at the Centre for Hypersonics which permits VUV emission spectral measurements from across and through the surface of a blunt model.[10–13] To date, this is the first study to present through-surface VUV spectral data at high speed superorbital trajectory points. In comparing through-surface and across-surface data, it is possible to calculate a correlation between the VUV radiation observed across a shock layer, as measured in shock tunnel, and the radiation incident on the surface. This correlation will enable shock tunnel data to be more accurately applied in the design of spacecraft heat shields. A secondary study with this system used cylinders of varying lengths to observe the self-absorption of varying lines in air. By changing the length of the cylinder and observing across the surface of the model, it was possible to change the depth of the radiating flowfield, providing information on the self-absorption of spectral lines.

II. Experimental facility

The Laboratoire EM2C at Ecole Centrale Paris has recently acquired a 50 kW radio-frequency (RF) inductively coupled plasma torch previously installed at Stanford University. This facility operates at atmospheric pressure and produces a plasma in Local Thermodynamic Equilibrium (LTE) at the exit of the torch.

The TAFA Model 66 inductively coupled plasma torch is powered by a radio frequency LEPEL Model T-50-3 power supply operating at 4 MHz. This power supply can deliver up to 120kVA of line power to the oscillator plates with a maximum of 12 kV DC and 7.5 A. The plasma torch can operate with a variety of gases (argon, air, methane, nitrogen), which are injected in axial, radial and swirl modes through the manifold located at the bottom of the torch.

Further information on the plasma torch facility can be found in the theses of Laux[14] and Gessman.[15]

III. Optical diagnostics

Spectroscopic imaging of the radiative emission of the flow was achieved using an intensified CCD camera (Princeton Instruments PI-MAX) coupled to the output of an Acton Research Spectra Pro SP2750i. This system is capable of imaging over the wavelength range 150-900 nm.

A spherically-curved mirror of focal length 500 mm was used to collimate the light from the plasma before being focussed by a second spherically-curved mirror (focal length also 500 mm) onto the input slit of the spectrometer. The focussing mirrors were made from a VUV enhanced aluminium material.

Oxygen was removed from the optical train by encapsulating the optical components ahead of the spectrometer in a stainless steel container. This container was flushed with nitrogen gas and evacuated to a pressure of 10^{-2} mbar. A quartz tube was used to extend the evacuated optical path to the edge of the plasma, at a height of 20 mm above the exit of the 7 cm diameter nozzle. A water-cooled copper section was then used to mount a sapphire window of diameter 20 mm against the edge of the plasma. At the end connecting the optical container to the spectrometer, the optical path was sealed using a second sapphire window (diameter 20 mm) which rested against the inlet slit of the spectrometer.

A nitrogen purge was also maintained at a pressure greater than atmospheric within the spectrometer in order to prevent air from leaking into this portion of the optical path.

A schematic of the optical setup can be found in Figure 1.

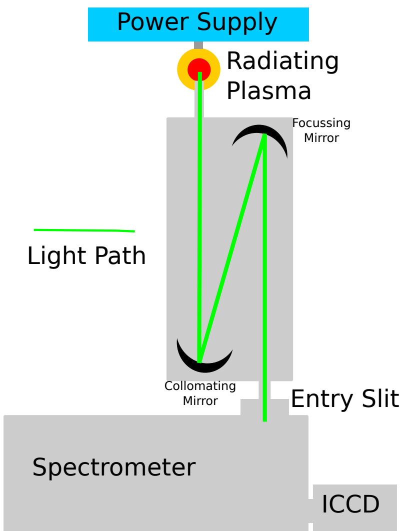

Figure 1: Schematic of the optical diagnostics

IV. Results

IV.A. Experimental measurements

Emission spectroscopy measurements were captured in an air plasma at a height of 20mm from the exit of the 7cm nozzle. Abel-inversion of the line-of-sight measurements were completed for multiple lateral locations ranging from the centre of the plasma to the edge of the nozzle. Further information regarding the method used for the Abel-inversion can be found in the theses of Laux[14] and Gessman.[15]

IV.B. Computational comparison

The air plasma radiation model, Specair,[16] was developed at Stanford university on the basis of the NASA code NEQAIR.[17] The model includes: 33 electronic transitions; 1484 lines of atomic nitrogen from 86.523nm to 54.83 µm; 856 lines of atomic oxygen from 69.753nm to 16.71µm and 1291 lines of atomic carbon from 94.519nm to 12.28µm.

Specair was used to produce a computational spectral comparison to the experimental results.

References

[1]Laux, C. O., Winter, M., Merryfield, J., Smith, A., and Tran, P., "Influence of ablation products on the radiation at the surface of a blunt hypersonic vehicle at 10 km/s," 41st AIAA Thermophysics Conference, San Antonio, Texas, 2009.

[2]Grinstead, J., Wilder, M., Olejniczak, J., Bogdanoff, D., Allen, G., Dang, K., and Forrest, M., "Shock heated air radiation measurements at lunar return conditions," 46th AIAA Aerospace Sciences Meeting and Exhibit , 2008.

[3]Cruden, B., Martinez, R., Grinstead, J., and Olejniczak, J., "Simultaneous vacuum ultraviolet through near infrared absolute radiation measurements with spatio-temporal resolution in an electric arc shock tube," 41st AIAA Thermophysics Conference, 2009.

[4]Brandis, A., Johnston, C., Cruden, B., Prabhu, D., and Bose, D., "Uncertainty Analysis of NEQAIR and HARA Predictions of Air Radiation Measurements Obtained in the EAST Facility," 42nd AIAA Thermophysics Conference, 2011.

[5]Bogdanoff, D., "Shock tube experiments for Earth and Mars entry conditions," Tech. Rep. RTO-EN-AVT-162, NATO Technical Report, 2007.

[6]Grinstead, J., Wilder, M., Reda, D., Cornelison, C., Cruden, B., and Bogdanoff, D., "Shock tube and ballistic range facilities at NASA Ames research center," Tech. Rep. RTO-EN-AVT-186, NATO Technical Report, 2010.

[7]Grinstead, J., Wilder, M., Reda, D., Cruden, B., and Bogdanoff, D., "Advanced spectroscopic and thermal Imaging instrumentation for shock tube and ballistic range facilities," Tech. Rep. RTO-EN-AVT-186, NATO Technical Report, 2010.

[8]Lemal, A., Jacobs, C., Perrin, M.-Y., Laux, C., Brandis, A., Raynaud, E., and Tran, P., "Simulation of shock tube radiation measurements with a collisional-radiative model," 43rd AIAA Thermophysics Conference, 2012.

[9]Jacobs, C., Lemal, A., Perrin, M.-Y., and Laux, C., "Molecular Nonequilibrium Radiation Prediction with a Vibrational Specific Collisional-Radiative Model," 51st AIAA Aerospace Sciences Meeting, 2013.

[10]Sheikh, U., Morgan, R., Zander, F., Eichmann, T., and McIntyre, T., "Vacuum Ultraviolet Emission Spectroscopy System for Superorbital Reentries," 18th AIAA/3AF International Space Planes and Hypersonic Systems and Technologies Conference, 2012.

[11]Sheikh, U., Morgan, R., and McIntyre, T., "Self-Absorption of Vacuum Ultraviolet Radiation in Superorbital Flows," 5th International Workshop on Radiation of High Temperature Gases in Atmospheric Entry, 2012.

[12]Leyland, P., McIntyre, T., Sheikh, U., Eichmann, T., Zander, F., Morgan, R., Loehle, S., Hermann, T., de Fillippis, F., Trifoni, E., and Cillo, G., "VUV Radiation Measurements For Radiation-Abalation Coupling," 5th International Workshop on Radiation of High Temperature Gases in Atmospheric Entry, 2012.

[13]Sheikh, U., Laux, C., Morgan, R., and McIntyre, T., "Through Surface and Across Surface Vacuum Ultraviolet Spectral Measurements in an Expansion Tube," 44th AIAA Thermophysics Conference, 2013.

[14]Laux, C., Optical diagnostics and radiative emission of air plasmas, Ph.D. thesis, Stanford University, 1993.

[15]Gessman, R., An experimental investigation of the effects of chemical and ionizational nonequilibrium in recombining atmospheric pressure air plasmas, Ph.D. thesis, Stanford University, 2000.

[16]Laux, C., "Radiation and nonequilibrium collisional-radiative models," von Karman Institute Lecture Series, Physico-Chemical Modeling of High Enthalpy and Plasma Flows, 2002.

[17]Park, C., "Nonequilibrium Air Radiation (NEQAIR) program: User's manual," Tech. Rep. TM86707, NASA Technical Memorandum, 1985.