SHOCK TUBE MEASUREMENTS OF RADIATIVE HEATING FOR TITAN AND NITROGEN

Aaron Brandis(1), Brett Cruden(1), Chris Johnston(2)

(1) AMA Inc at NASA Ames Research Center, Moffett Field, CA, USA, E-mail:aaron.m.brandis@nasa.gov
(2) NASA Langley Research Center, Hampton, VA, 23681, USA

ABSTRACT

Detailed spectrally and spatially resolved radiance has been measured in the Electric Arc Shock Tube at NASA Ames Research Center for conditions relevant to Titan entry, with varying atmospheric composition, free-stream density (equivalently, altitude) and shock velocity. The test campaign measured radiation at velocities from 4.7 km/s to 8 km/s and free-stream pressures of 0.1, 0.28 and 0.47 Torr with a variety of compositions. Radiances measured in this work are substantially larger compared to that reported both in past EAST test campaigns and in other shock tube facilities. Depending on the metric used for comparison, the discrepancy can be as high as an order of magnitude. Due to the difference with previously reported data, a substantial effort was undertaken to provide confidence in the new results. The present work provides a new benchmark set of data to replace those published in previous studies. The effect of gas impurities identified in previous shock tube studies was also examined by testing in pure N_2 and deliberate addition of air to the CH_4/N_2 mixtures. Furthermore, a test campaign in pure N_2 was also conducted with the aim of providing data for improving fundamental understanding of high enthalpy flows containing N_2, such as high-speed entries into Earth or Titan. These experiments cover conditions from approximately 6 km/s to 11 km/s at an initial pressure of 0.2 Torr. It is the intention of this paper to motivate code comparisons benchmarked against this data set.

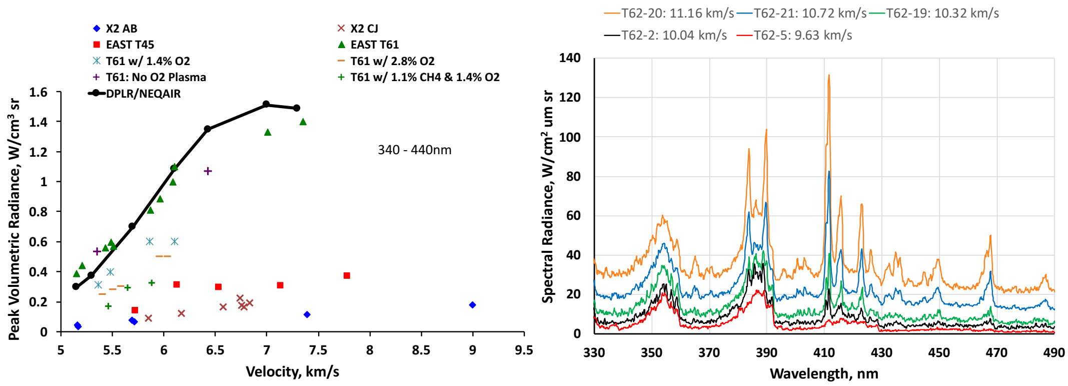
1. INTRODUCTION

The non-equilibrium radiation from the CN molecule is of particular interest to radiative heating during Titan entry. Two previous test campaigns (Tests 43 and 45 conducted from 2003 to 2005 [1]) in the Electric Arc Shock Tube (EAST) and two test campaigns in the X2 shock tube [2,3] reported results inconsistent with simulations. Furthermore, Test 43 has been shown to be inconsistent with Test 45 and X2 data [2]. It was reported that the suspect results (EAST Test 43) were potentially due to issues with the radiance calibration and carbon contamination [2]. Even though these results have been shown to be potentially questionable, they are still frequently used as benchmark data for development of simulation models for Titan entry [5-7]. Since test campaigns 43 and 45, the EAST facility has undergone substantial upgrades, improving both the data quality and the quantity obtained [4]. With updates to calibration techniques, and improved cleaning of the shock tube reducing carbon contamination [4], additional tests were conducted to update the previously reported experiments. Due to the limited data available sets and the poor level of agreement between previously reported data with either Boltzmann, standard QSS approaches or Collisional-Radiative (CR) models [1,8,9], developing a model to accurately simulate non-equilibrium CN radiation for N_2/CH_4 mixtures has proven to be difficult.

Over the last decade, the focus of EAST testing has generally been to provide data directly relevant to planetary entry conditions by using velocities, densities and atmospheric composition as close as possible to flight [1,4], as in the case of Titan testing. In contrast, the goal of the pure nitrogen test campaign reported here is to provide more fundamental data, over a range of conditions, that can be used to inform model development to advance the state-of-the-art for future mission design. By focusing on pure nitrogen, this test series aims to provide detailed information for a reduced system that isolates nitrogen specific mechanisms. In doing so, the relevant chemistry is greatly simplified as the number of collision partners is reduced and the complexity of various mechanisms, such as excitation, energy exchange and dissociation, is minimized. This allows for simpler analysis to infer or extract fundamental chemistry results from the experiment when testing in pure nitrogen as compared to air. The data presented in this paper can be used to validate models relevant to vibrational relaxation, non-equilibrium state population models and partner specific dissociation. This is an area of research with substantial fundamental calculation and simulation efforts in recent years [10], though validation data has been lacking. This dataset thus provides the capability to validate the range of physics and chemistry models for N_2.

2. RESULTS

More detail will be provided in the final paper. For the abstract an example result is presented for Titan (Figure 1a) and for Nitrogen (Figure 1b). Figure 1a shows a comparison of the new EAST data with data previously reported from EAST and X2, as well as simulations from DPLR/NEQAIR. The new EAST data is significantly larger in radiance. The plot also shows an attempt to deliberately add an air leak as an impurity into the Titan gas to offer a potential reason for the discrepancy. Figure 1b shows equilibrium spectral radiance measured in EAST in the UV/Vis spectral range for velocities from 9.6 to 11.2 km/s at 0.2 Torr. More detail on both test campaigns will be provided in the final version of the paper.



(a) (b)

Figure 1. (a) Comparison of X2 & EAST Titan data with DPLR/NEQAIR. (b) Equilibrium EAST spectra for N_2

3. REFERENCES

1. Bose, D., Wright, M. J., Bogdanoff, D. W., Raiche, G. A., and Allen, G. A., "Modeling and Experimental Assessment of CN Radiation Behind a Strong Shock Wave," Journal of Thermophysics and Heat Transfer , Vol. 20, No. 2, 2006, pp. 220–230.
2. Brandis, A., Morgan, R., McIntyre, T., and Jacobs, P., "Nonequilibrium Radiation Intensity Measurements in Simulated Titan Atmospheres," Journal of Thermophysics and Heat Transfer , Vol. 24, No. 2, 2009, pp. 291–300
3. Jacobs, C., McIntyre, T., Morgan, R., Brandis, A., and Laux, C., "Radiative Heat Transfer Measurements in Low-Density Titan Atmospheres," Journal of Thermophysics and Heat Transfer , Vol. 29, No. 4, 2015, pp. 835–844
4. Cruden, B., Martinez, R., Grinstead, J., and Olejniczak, J., "Simultaneous Vacuum-Ultraviolet Through Near-IR Absolute Radiation Measurement with Spatiotemporal Resolution in An Electric Arc Shock Tube," 41st AIAA Thermophysics Conference , San Antonio, Texas, 2009, AIAA-2009-4240.
5. Joiner, N., Beck, J., Capitelli, M., Fertig, M., Herdrich, G., Laricchiuta, A., Liebhart, H., Lino da Silva, M., Marraffa, L.,Nguyen-Bui, N., Reynier, P., and Tran, P., "Validation of Aerothermal Chemistry Models for Re-entry Applications: Theoretical and Computational Synthesis," Proceedings of the 8th European Symposium on Aerothermodynamics for Space Vehicles , 2015.
6. Palmer, G., Prabhu, D., Brandis, A., and McIntyre, T., "Numerical Simulation of Radiation Measurements taken in the X2 Facility for Mars and Titan Gas Mixtures," 42nd AIAA Thermophysics Conference , Honolulu, 2011. AIAA 2011-3768.
7. Vargas, J., Lino da Silva, M., and Lopez, B., "Improvement of state-resolved kinetic models applied to N2– CH4 hypersonic entry flows," 7th International Workshop on Radiation of High Temperature Gases in Atmospheric Entry , Stuttgart, Germany, 2016
8. Wright, M., Olejniczak, J., Walpot, L., Raynaud, E., Magin, T., Caillault, L., and Hollis, B. R., "A code calibration study for Huygens entry aeroheating," 44th AIAA Aerospace Sciences Meeting and Exhibit , Reno, Nevada, 2006, AIAA-2006-382.
9. Brandis, A., Laux, C., Magin, T., McIntyre, T., and Morgan, R., "Comparison of Titan Entry Radiation Shock-Tube Data with Collisional-Radiative Models," Journal of Thermophysics and Heat Transfer , Vol. 28, No. 1, 2014, pp. 32–38.
10. Sahai, A., Lopez, B., Johnston, C. O., and Panesi, M., "Adaptive coarse graining method for energy transfer and dissociation kinetics of polyatomic species," The Journal of Chemical Physics , Vol. 147, No. 5, 2017, pp. 054107