18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

Study of Radiative Heat Transfer in Titan Atmospheric Entry

Hadas Porat[1], Richard G. Morgan[1] and Timothy J. McIntyre[2]

[1]School of Mechanical and Mining Engineering
The University of Queensland, Queensland 4072, Australia

[2]School of Mathematics and Physics
The University of Queensland, Queensland 4072, Australia

Abstract

The heating of the hypersonic flow forming in front of a capsule during a Titan entry is dominated by radiation due to the carbon content in the atmosphere (CH_4). This leads to higher levels of radiation at relatively low entry speeds when compared to earth re-entry because C species radiate so strongly. Predicting and measuring the aero heat loads is a critical aspect of the thermal protection system design of an atmospheric entry vehicle.

Preliminary experiments in the X2 expansion tunnel used a simulated Titan atmosphere consisting of nitrogen and methane with shock speed of 6.5km/s representative of a Titan aerocapture peak heating condition. Measurements were conducted using emission spectroscopy and specially developed radiation gauges. Emission spectroscopy results successfully detected the main spectral contributors to the radiation in Titan entry, and the radiation gauges detected the radiative heat flux on the surface of the cylinder. Hence the ability of the radiation gauges to detect and measure the radiative heat flux in these conditions was demonstrated. A calibration procedure was developed, aiming to determine the amount of radiation detected per gauge in the UV band. The experiments provide benchmark data to help understand and analyse these flows.

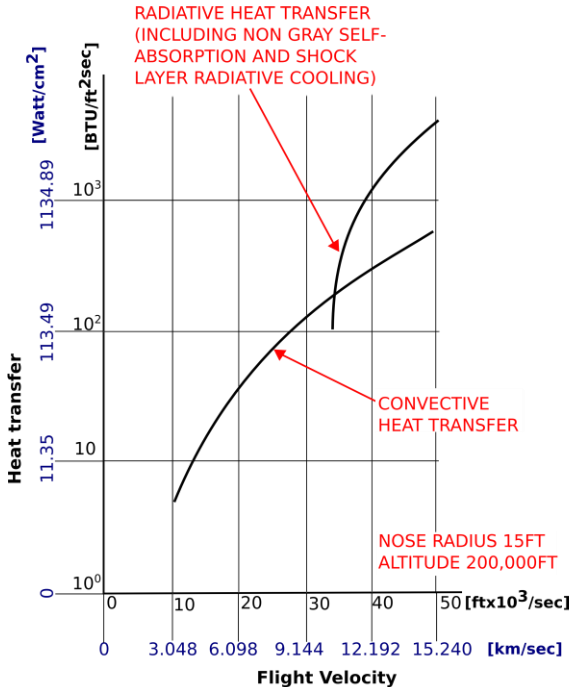

Figure 1. Comparison of radiative and convective stagnation point heat transfer in Earth atmospheric entry a function of flight velocity (adapted from [1])

Introduction

The prediction of the heating that a spacecraft will experience at atmospheric entry is very important, as it determines the design of the thermal protection system (TPS). For an efficient TPS design, it is critical to determine the heating that the vehicle will experience accurately, so that no excess weight is carried to space at great cost and for no reason. Unfortunately the current designs of TPS are not ideal, as the radiative portion of the heat transfer is not well understood and large safety factors are in use.

When a spacecraft enters an atmosphere, the freestream flow forms a bow shock ahead of the forebody, and the shock heated gas transfers heat to the body by convection and radiation. While convection can be predicted well, radiative heating predictions still have uncertainties larger than 30% when using state of the art models [2]. Radiative heating becomes more significant at high entry velocities (figure 1), but for atmospheric entry into Titan (a moon of Saturn) it is responsible for a large portion of the heat load at relatively low entry speeds when compared with earth entry. This is caused by the carbon content in Titan's atmosphere, in the form of methane. The methane dissociates in the bow shock layer (figure 2) and combines with atmospheric nitrogen to form CN. The CN is expected to produce 99% of the radiation in the shock layer. These processes are currently poorly understood, and are not exclusive to Titan atmospheric entry. The CN is a strong radiator that dominates the radiative heating into the atmosphere of Mars as well.

Expansion tunnels are an effective technique to produce hypervelocity entry flows typical of Titan atmospheric entry, enabling the study of radiative heat transfer. New conditions for peak heat transfer at the stagnation point of a cylindrical model with an entry velocity of 6.5km/s have been developed and validated with a pitot survey. Preliminary measurements of heat transfer were made using radiation gauges and emission spectroscopy, in an effort to demonstrate their applicability.

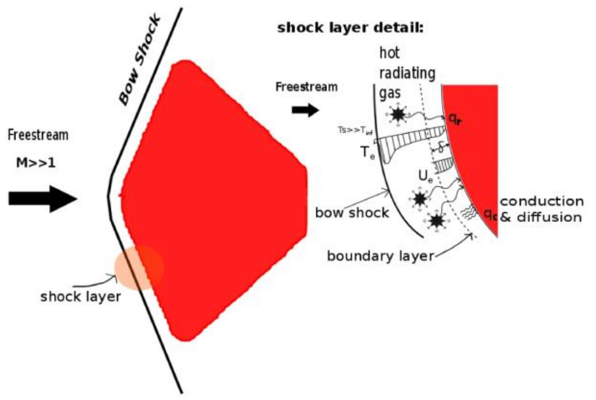

Figure 2. Atmospheric entry heat transfer mechanisms (adapted from [3])

Facility

The University of Queensland's Centre for Hypersonics has a series of impulse facilities that are used for research of atmospheric entry flows and scramjet development. The X2 and X3 expansion tube facilities are capable of simulating atmospheric entry conditions, for different atmospheres. Wave propagation in a superorbital expansion tube is illustrated by the x-t diagram in Figure 3.

High-pressure air in the reservoir initially accelerates the piston down the tube, which in turn compresses the driver gas. The driver gas is comprised of a light gas such as helium, and is simultaneously heated during the compression. Compressive heating of the light driver gas achieves a high driver gas sound speed, which is the key to achieving a high Mach number shock in the driven tube. The strong shock wave propagates through the tunnel following the main diaphragm rupture. A series of unsteady expansions adding energy to the flow follows, from the primary diaphragm to the test section. The test gas is processed by an unsteady expansion after the burst of the secondary diaphragm. This process generates high enthalpy test flows suitable for aerodynamic testing. Typical available test time is in the order of tens to several hundred microseconds, and fast response measurement equipment is used to record data during this time (represented on the x-t diagram by region 5, Figure 3).

Superorbital entry flows are high total pressure and temperature flows (high enthalpy), typically on the order of GPa and tens of thousands of kelvin respectively for superorbital entry [4]. When simulating entry flows the test gas is a representative atmospheric mixture for the celestial body of interest. For example, for Titan flows as discussed hereafter, the test gas is a mixture of 95% Nitrogen and 5% Methane.

A 25 mm dia. cylindrical model of 75 mm length was used for the preliminary experimental campaign. It was instrumented with two radiation gauges and two thermocouples. Radiative heat flux and total heat flux measurements were made in parallel with emission spectroscopy.

Test Conditions

Two new Titan atmospheric entry test conditions were developed, with freestream velocities of 6.5 km/s and 8.5 km/s. The first condition simulates peak radiation for Titan entry at the stagnation point, using a test flow with a freestream velocity of 6.5 km/s. The second condition, having an 8.5 km/s freestream velocity, represents the case where almost all the heat transfer is believed to be from CN dissociation [5].

The conditions were tested in X2, and the freestream cone head pressure was measured. This was done by using a rake with vertically aligned 15º cone head caps to measure the static pressure on the cone surface during a shot. The test times for the two conditions were measured as 150 µs and 200 µs for the 6.5 km/s and 8.5 km/s respectively.

Flow Property	5% CH_4 / 95% N_2	
	Measured	CEA
U_1[km/s]	3.376	-
U_2[km/s]	-	2.965
p_{s_5}[kPa]		31.224
p_{s_∞}[kPa]	-	2.136
p_{c_∞}[kPa]	26.642	27.496
T_∞[K]	-	864.21
a_∞[m/s]	-	607.5
ρ_∞[g/m^3]	-	7.763
M_∞		11.09
γ_∞		1.341
R_∞[J/kg·K]		318.398
h_∞[MJ/kg]		1.7101
S_∞[MJ/kg·K]		9.697
H_0[MJ/kg]		23.358
U_5[km/s]	6.58	
U_e[km/s]		6.835

Table 1. Flow properties for Titan 6.5 km/s condition

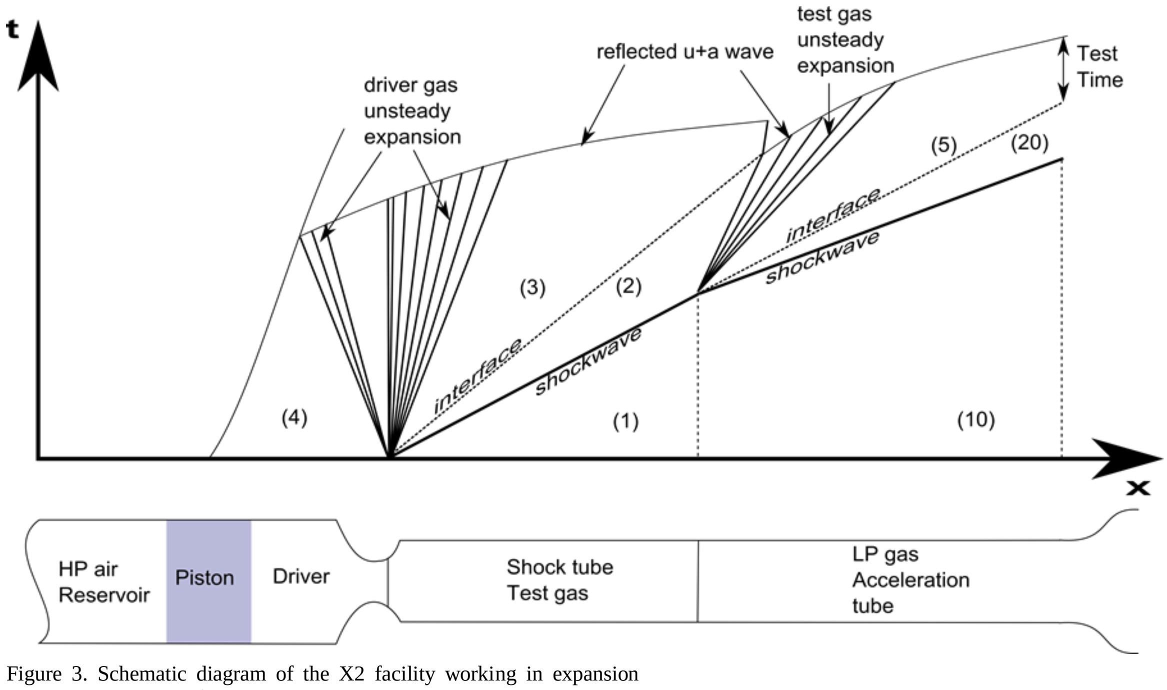

Figure 3. Schematic diagram of the X2 facility working in expansion tunnel mode (adapted from [4])

Table 1 and 2 present flow properties for the two conditions where:

U_1, U_2, p_{s_5} are the primary shock speed, processed shock speed, static pressure of the test gas;

$p_{s_\infty}, p_{c_\infty}, T_\infty, a_\infty, \rho_\infty, M_\infty, \gamma_\infty, R_\infty, h_\infty, S_\infty$ are the free stream: static pressure, cone head pressure, temperature sound speed, density, Mach number, heat capacity ratio, gas constant, specific enthalpy and entropy;

H_0, U_5, U_e are the enthalpy, test shock speed and the equivalent flight speed .

The tables indicate what was calculated using NASA's Chemical Equilibrium with Application models (CEA) and what was measured during the shots.

Flow Property	5% CH_4 / 95% N_2	
	Measured	CEA
U_1[km/s]	4.1	-
U_2[km/s]	-	3.668
p_{s_5}[kPa]		2.346
p_{s_∞}[Pa]	-	580.314
p_{c_∞}[kPa]	6.675	6.809
T_∞[K]	-	1583.14
a_∞[m/s]	-	822
ρ_∞[g/m^3]	-	1.151
M_∞		8
γ_∞		1.290
R_∞[J/kg·K]		318.434
h_∞[MJ/kg]		2.444
S_∞[MJ/kg·K]		10.913
H_0[MJ/kg]		39.596
U_5[km/s]	8.62	
U_e[km/s]		8.899

Table 2. Flow properties for Titan 8.5 km/s condition.

Experimental Measurements

Emission spectroscopy measurements were taken during the 6.5 km/s Titan conditions. The optical arrangement as it was setup in X2 is illustrated in Figure 4. A 1MHz high speed camera Shimadzu HPV-1 was used to record 100 frames over the test time. The optical arrangement was designed to image the emitted radiation from the shock layer onto the slit of a UV/Visible system compromised of a SpectraPro 2356i 300mm spectrograph and a detector camera PIMAX 1024 SB ICCD.

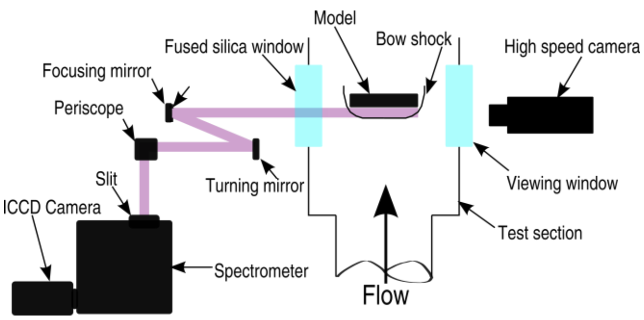

Figure 4. The optical arrangement for emission spectroscopy in X2 (not to scale)

Raw spectra as recorded in the experiments is shown in Figure 5. The orientation of the spectra corresponds to a flow coming from the bottom of the image. The most prominent feature of the spectra is the two CN violet bands, clearly visible with peaks at 358 nm and 385 nm. The maximum heating along the stagnation streamline, corresponds to pixels 130-150. Integrated raw spectral lines from this region are shown in Figure 6. The data is yet to be calibrated for spectral irradiance. The additional (Fe) features in the shock layer reveal the boundary layer before the model face. The two peaks at 394-396nm correspond to the aluminium diaphragm used in the test.

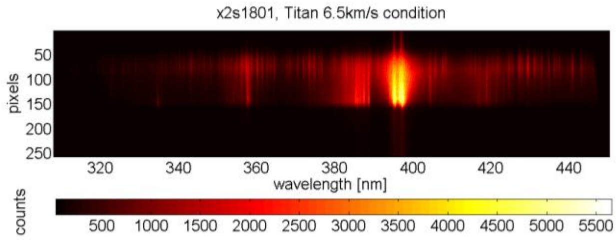

Figure 5. Raw spectra from shot number x2s1801, Titan 6.5km/s condition

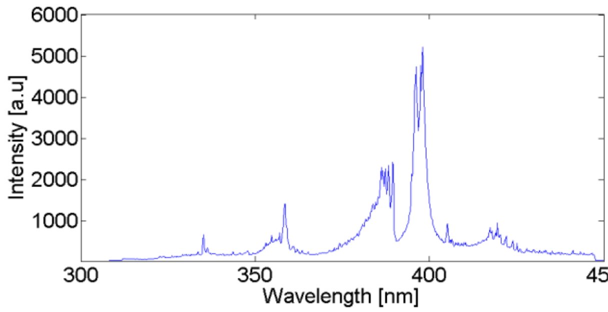

Figure 6. Raw spectral lines from shot number x2s1801, Titan 6.5km/s condition integrated at the maximum heating region along the stagnation streamline.

Radiation Gauges

Radiation gauges were developed and tested at the Centre for Hypersonics [6], using thin film heat gauges mounted behind a viewing window, where the window separates the convective heating from the radiative heating. A development of a calibration procedure for the radiation gauges is reported hereafter. The radiation gauges were intended to be used in a Titan atmospheric entry conditions, and so the radiation was expected to be dominated by CN violet. The new calibration technique was intended for this wavelength.

Preliminary experiments in X2 with the new Titan conditions confirmed that the radiation gauges are sensitive enough to respond to this level of radiation at the short test time. These tests were conducted using two uncalibrated gauges, mounted on a cylindrical model. Uncalibrated results from the radiation gauges for a 6.5 km/s Titan condition are presented in Figure 7.

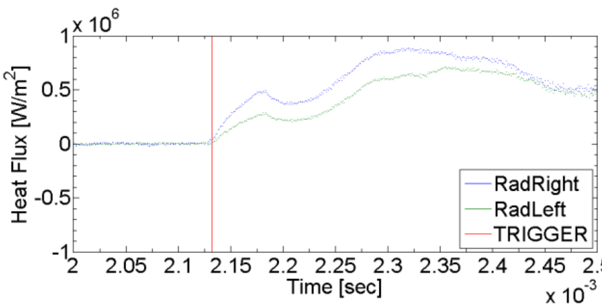

Figure 7. Un-calibrated radiation gauges, heat flux during Titan 6.5 km/s condition, shot x2s1786

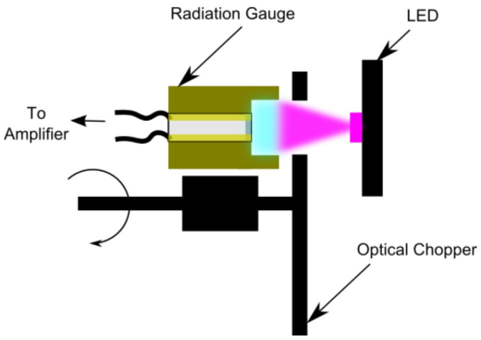

Figure 8. Radiation gauges calibration setup I (not to scale)

A high power narrow wavelength band light emitting diode (LED) was chosen as the calibration source. Three commercially available LEDs where identified as potentially suitable, covering the wavelength range between 365-404nm, and a 383 nm peak wavelength LED was used in the preliminary study. A 9W LED chip NC4U134A from Nichia was sourced, and a photomultiplier tube (PMT) was used to verify the peak wavelength of the 9W LED.

All the gauges were coated with an antireflection coating that can vary from one gauge to another and the aim of the calibration is to account for these differences by calibrating each gauge independently for radiative heating band of 380-390nm. The calibration procedure developed compromises of two stages. At the first stage illustrated by Figure 8, a radiation gauge is connected to an amplifier, and the response to the LED light is recorded by a data acquisition system. An optical chopper was designed to expose the calibration source for short periods of time. The radiation gauges tested produced good response to the LED, with amplification between 100-2000 depending on the gauge. The data gathered is then used to calculate the heat flux sensed by the gauge, and is then compared to the heat flux that was measured by the power meter.

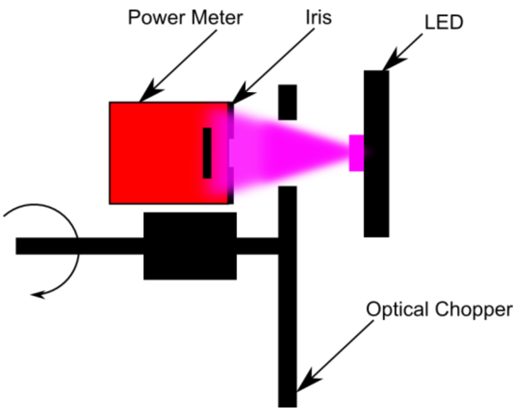

Figure 9. Radiation gauges calibration setup II (not to scale)

After measuring the heat flux detected by each gauge at a fixed distance away from the LED, the second stage utilises a power meter (Thorlabs s302c), placed in the same location behind a small aperture (Figure 9). The measured power is then converted to heat flux, and compared with the detected heat flux per gauge, completing the gauge calibration for the waveband. To date, only preliminary analysis of such data was conducted, and further development of the calibration method may be necessary to ensure each radiation gauge can be calibrated easily.

Conclusion

The study of radiative heat transfer for atmospheric entry is required for the future development of better and more effective spacecraft thermal protection systems. Ground based experiments in expansion tunnels provide a complex but effective research tool for the study of hypervelocity radiation. Radiative measurements in expansion tunnels can provide a detailed view and understanding of the chemical processes in the flow and aid the prediction of the thermal radiation. Emission spectroscopy can be used to investigate the distribution of radiating species in the shock layer, and radiation gauges can be used to measure the total radiative heat transfer.

Preliminary results from emission spectroscopy for a 6.5 km/s Titan atmospheric entry were presented. The spectra was dominated by the CN violet as expected.

The successful use of radiation gauges in Titan entry conditions was reported. Radiative heat flux calibration for the radiation gauges using a 9W LED light source was introduced.

The next campaign for the two Titan atmospheric conditions will aim to use calibrated radiation gauges.

Acknowledgments

The authors would like to thank: Brian Loughrey and Franz De Beurs from the workshop team for their advice and work on models and facilities; Barry Allsop for his work on the amplifiers and advice for all electronic components; our colleagues for their advice, support and operation of the tunnel: Reader Peter Jacobs, Fabian Zander, Troy Eichmann, Dr. Bianca Capra, David Gildfind, Umar Sheikh, Dr. Carolyn Jacobs, Dylan Wise and Chris James. Thanks are also extended to NICHIA Company Japan for supplying a sample LED. Funding through the ARC Discovery Grant program is gratefully acknowledged.

References

[1] J. D. Anderson, "An Engineering Survey of Radiating Shock Layers," AIAA JOURNAL, vol. 7, 1969

[2] P. A. Gnoffo, C. O. Johnston, and B. Kleb, Challenges to Computational Aerothermodynamic Simulation and Validation for Planetary Entry Vehicle Analysis, NASA Langley Research Center Hampton, Virginia, 2010.

[3] B. R. Capra, Aerothermodynamic Simulation of Subscale Models of the FIRE II and Titan Explorer Vehicles in Expansion Tubes, PhD thesis, Division of Mechanical Engineering, School of Engineering, The University of Queensland, 2006.

[4] R. G. Morgan, T. J. McIntyre, D. R. Buttsworth, P. A. Jacobs, D. F. Potter, A. M. Brandis, R. J. Gollan, C. M. Jacobs, B. R. Capra, M. McGilvray, and T. Eichmann, Impulse Facilities for the Simulation of Hypersonic Radiating Flows, *38th Fluid Dynamics Conference and Exhibit*, Seattle, Washington, U.S.A. , 2008.

[5] M. J. Wright, J. Olejniczak, D. Bose, and T. Gokcen, A Summary of Radiation Prediction Capabilities for Titan Aerocapture Applications, NASA Ames Research Center Moffett Field, CA, 2004.

[6] B. R. Capra, R. G. Morgan, Radiative and Total Heat Transfer Measurements to a Titan Explorer Model, *AIAA Journal of Spacecraft and Rockets*, issue 49, vol 1. Jan-Feb, 2012.