

# STUDY OF RADIATIVE HEAT TRANSFER IN TITAN ATMOSPHERIC ENTRY

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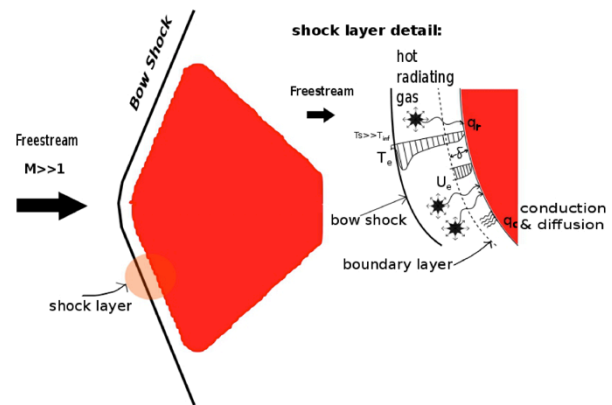
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## Abstract

Preliminary experiments representative of a Titan aerocapture peak heating conditions were conducted in the X2 expansion tunnel. A simulated Titan atmosphere test gas consisting of nitrogen and methane was accelerated to a speed of 6.5km/s. 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.

## 1 General Introduction

Poor understanding and large uncertainties (in excess of 30%) [1] are currently associated with the prediction of radiative heat flux during atmospheric entry. Further development of radiative heating measurement techniques in ground test facilities has the potential for reducing these uncertainties by providing validation cases for CFD codes, and fundamental information needed for radiation modeling. Heat transfer mechanisms for a Titan atmospheric entry are illustrated in Fig. 1. The freestream flow forms a bow shock in front of the capsule, and the shock heated gas transfers heat to the body by convection and radiation.



**Fig. 1** Atmospheric entry heat transfer mechanisms. (adapted from [7] )

Radiative heating accounts for a large percentage of the total heat load for a Titan atmospheric entry. This is caused by the carbon content in Titan’s atmosphere, in the form of methane. Upon atmospheric entry, the methane dissociates in the bow shock layer, and combines with atmospheric nitrogen to form CN. The CN is expected to produce 99% of the radiation in the shock layer. This leads to higher levels of radiation at relatively low entry speeds when compared to earth re-entry because carbon containing species radiate strongly. These processes are currently poorly understood.

Expansion tunnels are an effective technique for simulating hypervelocity atmospheric entry conditions into Titan, and flow over an instrumented cylindrical model is reported here. 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 pressure survey. Radiative heat flux was measured using emission spectroscopy and radiation gauges. Emission spectroscopy provides information

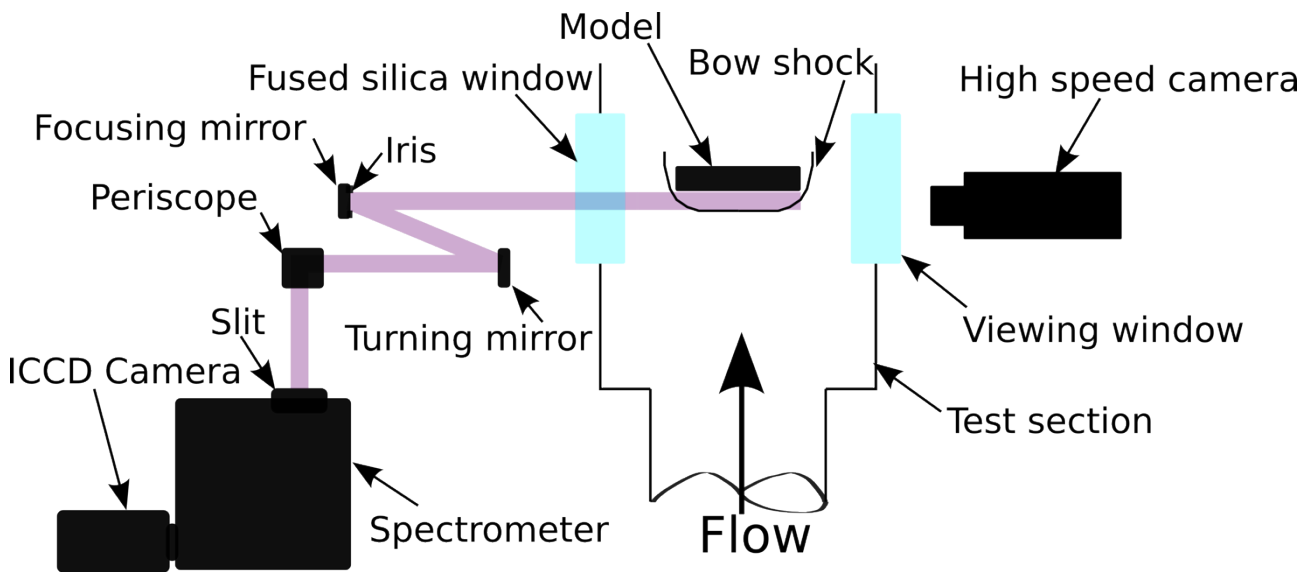
about the radiating species in the shock layer, and the radiation gauges measure the total radiative heat flux on the surface of the cylindrical model. Predicting and measuring the aerothermodynamic heating loads is a critical aspect of the thermal protection system design of an atmospheric entry vehicle.

## 1.1 Measurement Techniques

### 1.1.1 Emission Spectroscopy

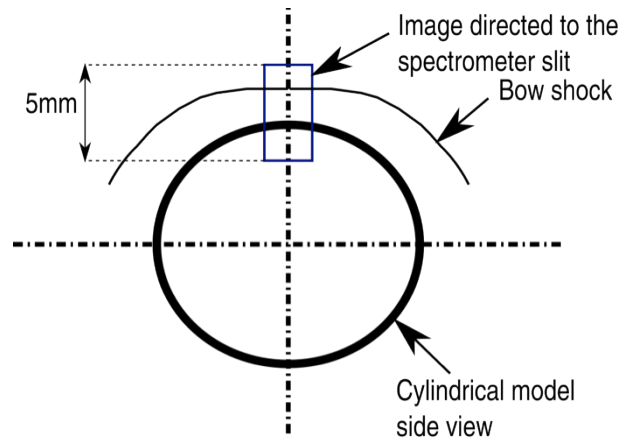
Emission spectroscopy is the technique of measuring the spectrum of radiation emitted by a source [2]. Using a prism or a diffraction grating, the radiation can be separated into different spectral regions and a detector can be used to quantify the radiation at each specific wavelength.

The current study has built on this experience and used an optical setup coupled to a spectrometer to measure the radiation from the shock layer of a Titan simulated atmospheric entry flow around a scaled cylindrical model. The optical arrangement used is illustrated in Fig. 2. The flow enters the test section from the bottom of the image, and creates a bow shock in front of the cylindrical model. A Shimadzu HPV-1 high speed camera, capable of frame rates up to 1MHz, records 100 frames over the test time, using the flow luminosity to illuminate the image. The optics are used to image emitted radiation from the shock layer to the slit of a UV/Visible system comprised of a SpectraPro 2356i 300mm spectrograph and a detector camera PIMAX 1024 SB ICCD.



**Fig. 2** Optical arrangement for emission spectroscopy.

Emission spectroscopy system consists of the optics used to gather the radiation from a specific field of view, a spectrometer that separates the radiation into its component wavelengths, a detector which measures the radiation at each wavelength and a system for controlling and recording the data [2]. Emission spectroscopy was used during several previous experimental campaigns at the Centre for Hypersonics [3, 4, 5, 6].

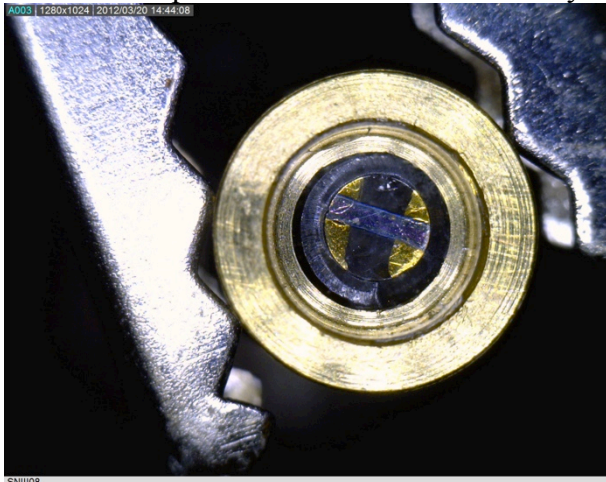


**Fig. 3** The image directed to the slit

The optical arrangement was designed to create a 1:1 magnification image with a depth of field of 80mm and image height of 5mm as shown in Fig. 3. This image enters the slit of the spectrometer.

### 1.1.2 Radiation Gauges

Radiation gauges were developed and tested at the Centre for Hypersonics by Capra [13]. The gauges consisted of a thin film heat gauge sensor mounted behind a viewing window, and were proven to separate convective heating from the measured radiative heating, while transmitting the CN radiation wavelengths which are important for Titan radiation study.



**Fig. 4** A radiation gauge mounted in a brass housing behind a fused silica window.

In the current study an improved version of Capra's radiation gauge was designed, manufactured and tested. The emphasis for the new design was improving the calibration procedure of the gauges, as well as redesigning the optical black coating to maximize the signal measured.

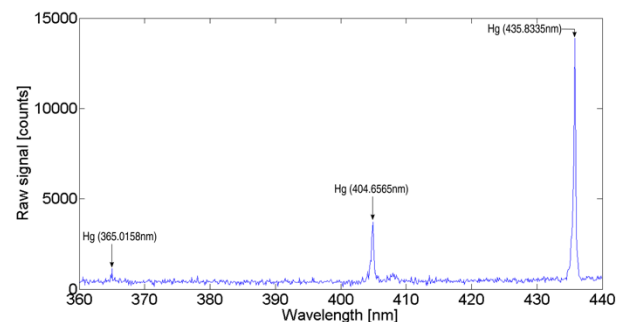
The new radiation gauges, as seen in the microscope image in Fig. 4, consist of a thin film heat gauge that was manufactured out of 2 mm quartz rods cut to 5 mm length pieces. Two gold tabs were hand painted on the quartz substrate to create connections for the nickel sensing element, which was then sputter coated onto the polished quartz face. The exposed nickel strip is approximately 1.0 mm x 0.3 mm x 0.1  $\mu\text{m}$  in size. Insulated wires were soldered to the gold tabs for connections to the external

electronics. The thin film heat gauges were then calibrated, and placed in a brass housing mount that allows the gauge to be mounted behind a fused silica viewing window (4 mm dia. 2 mm thickness).

## 2 Radiation Gauges Calibration

Of special importance is the sensitivity of the gauges in the part of the spectrum dominated by the CN bands (357-418 nm), and a new calibration technique has been set up for this purpose.

Capra [7] performed an indirect calibration of the gauges. Using a welding arc, the gauges were exposed to the same conditions with and without black paint coating and the difference in the measured values were compared with experimental data available for the amount of heat absorbed by black paint application. After achieving good agreement, the theoretical value was used. Capra [7] outlines a method that was not available at the time but is the ideal way to properly calibrate the gauges by generating the three wavelengths of interest (357, 386, 418 nm CN radiation peaks) with known intensities, using a laser.



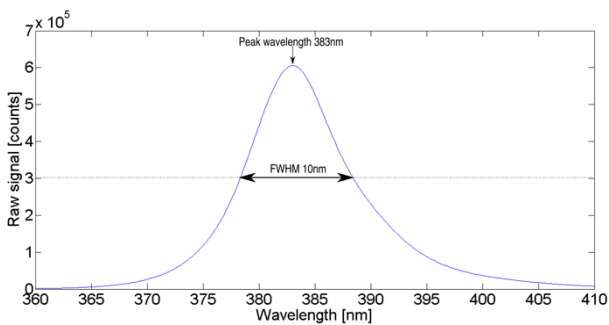
**Fig. 5** Mercury lines from a fluorescent lamp, PMT scan (integration=100ms, power=1000V, slit=10 $\mu\text{m}$ )

The new calibration procedure uses high power narrow wavelength band light emitting diode (LED) instead of a single wavelength laser. Three commercially available LEDs were identified as potentially suitable, covering the wavelength range between 365-404 nm, and a 383 nm peak wavelength LED was used in the preliminary study.

A radiation gauge was connected to an amplifier, and the response to the LED light was recorded by a data acquisition system, allowing the calculation of the heat flux sensed by the gauge. The M385L2 LED with electrical power of 3W and peak wavelength of 385 nm that was originally purchased from Thorlabs was found to give a very small but detectable response by the radiation gauge, when amplified with a gain of 10000. A new 9W LED chip NC4U134A from Nichia was sourced and used instead, generating a good response with amplification between 100-1000 depending on the gauge.

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.

A photomultiplier tube (PMT) coupled to a spectrometer was used to verify the peak wavelength of the 9W LED. A scan of the 9W LED with the PMT is shown in Fig. 6. The x axis represent the wavelength in nm after it was calibrated using a PMT scan of a fluorescent lamp with known mercury lines as shown in Fig. 5. Results indicate the peak wavelength is 383 nm and the full width half maximum (FWHM) is 10 nm.



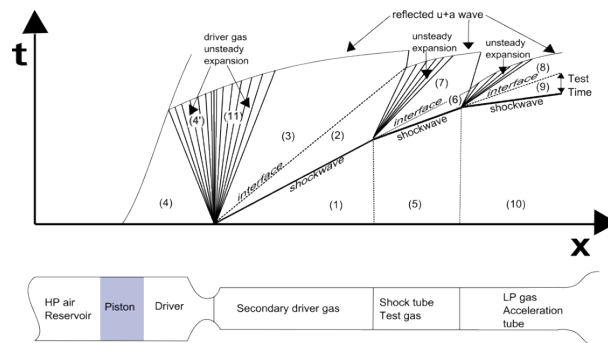
**Fig. 6** 9W LED, PMT scan (integration=100ms, power=300V, slit=10um)

After measuring the heat flux detected by each gauge at a fixed distance of 10 mm away from the LED, a power meter (Thorlabs s302c) is placed in the same location behind a small aperture. The measured power is then converted to heat flux, and compared with the detected heat flux for each gauge, completing the gauge calibration for this spectral region.

### 3 Preliminary Experiments

#### 3.1 Facility

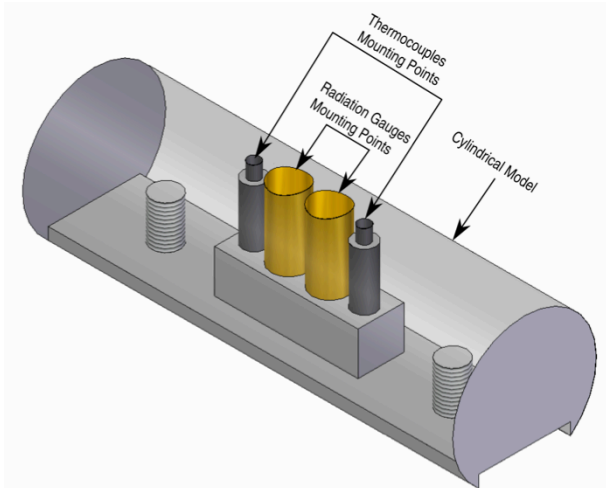
To investigate radiation-flow field coupling in ground test facilities, a subscale model is used. Superorbital entry flows are high total pressure and temperature flows (high enthalpy), typically on the order of GPa and tens of thousands of Kelvin respectively for superorbital entry [8]. Simulating such conditions in ground test facilities is a great challenge best addressed to date by the expansion tube concept [8], first suggested by Resler and Blossom in 1952 [9].



**Fig. 7** Schematic diagram of the X2 facility working in expansion tube mode (adapted from [3])

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. Atmospheric entry studies are performed in the X2 and X3 expansion tube facilities (Fig. ), which are capable of simulating radiating shock layers [10].

A cylindrical model (Fig. and Fig. ) was used for the preliminary experimental campaign. The 25 mm cylinder was 75 mm in length, and was instrumented with two radiation gauges and two thermocouples. Radiative heat flux and total heat flux measurements were made in parallel with emission spectroscopy.



**Fig. 8** CAD illustration of the cylindrical model as it was designed for the next campaign, the thermocouples were relocated and access to the rear has been improved.



**Fig. 9** The cylindrical instrumented model in the X2 test section during the test campaign

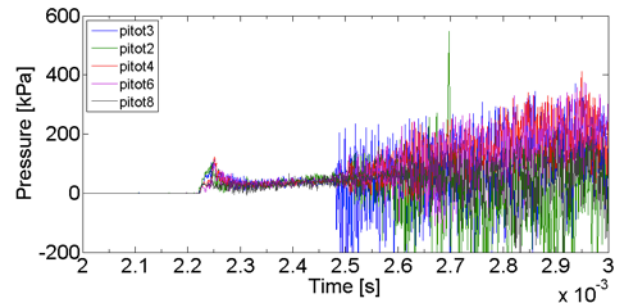
### 3.2 Test Conditions

Two new test conditions were developed. 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 radiation [11]. Table 1 specifies the fill pressure for these conditions for the different tube sections: the reservoir, driver, shock tube and acceleration tube, as they appear in the x-t diagram in Fig. . The test gas mix gas consisted of 95% N<sub>2</sub> and 5% CH<sub>4</sub>, representative of Titan atmosphere.

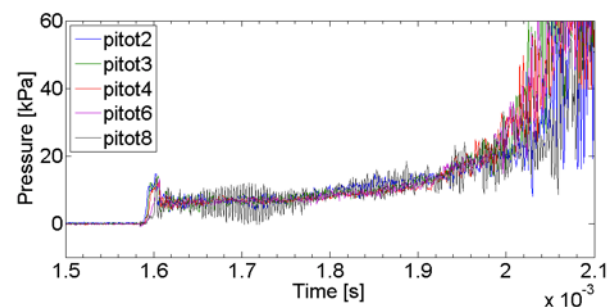
X2 Fill Pressures	Titan 6.5 km/s	Titan 8.5 km/s
Reservoir (air)	6.85 MPa	
Driver (80% He, 20% Ar)	928 mbar	
Shock Tube (95% N <sub>2</sub> , 5% CH <sub>4</sub> )	25.4 kPa	3.2 kPa
Acceleration Tube (air)	68.7 Pa	10 Pa

**Table 1.** X2 Expansion tunnel fill conditions for Titan atmospheric testing.

The conditions were tested in the tunnel using a conical surface impact pressure survey, whereby a pitot rake with vertically aligned cone head caps is used to measure the pressure during a shot. The results for the two conditions are shown in Fig. 1 and Fig. , indicating that the stable test times for the 6.5 km/s and 8.5 km/s conditions are 150 μs and 200 μs respectively. For the hypersonic expansion tunnel, these test times of steady flow are more than sufficient for useful measurements with high speed instrumentation.



**Fig. 10** Conical surface impact pressure survey for 6.5 km/s Titan condition. Shot number x2s1729, 150 μs test time.

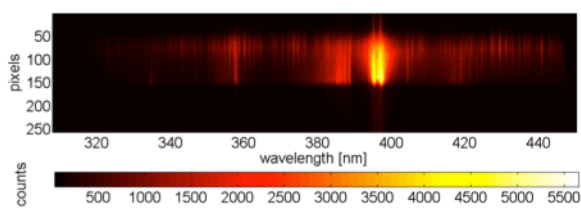


**Fig. 11** Conical surface impact pressure survey for 8.5 km/s Titan condition. Shot number x2s1731, 200 μs test time.

### 3.3 Results

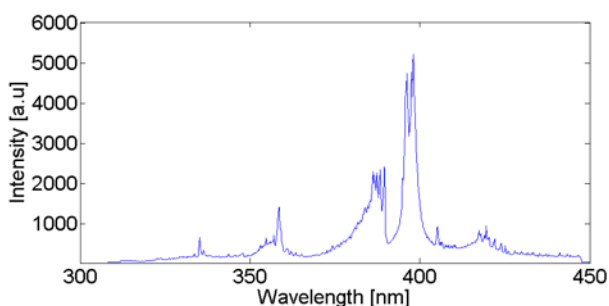
#### 3.3.1 Spectra

Measurements were taken with the spectrometer using the 600 line per mm grating, giving a spectral coverage of 120 nm. The entrance slit, gain and exposure time, were set to 30  $\mu\text{m}$ , 100, and 50  $\mu\text{s}$  respectively. A photodiode was placed outside the test section looking through the side window; its signal triggered the system with a delay of 100  $\mu\text{s}$ .



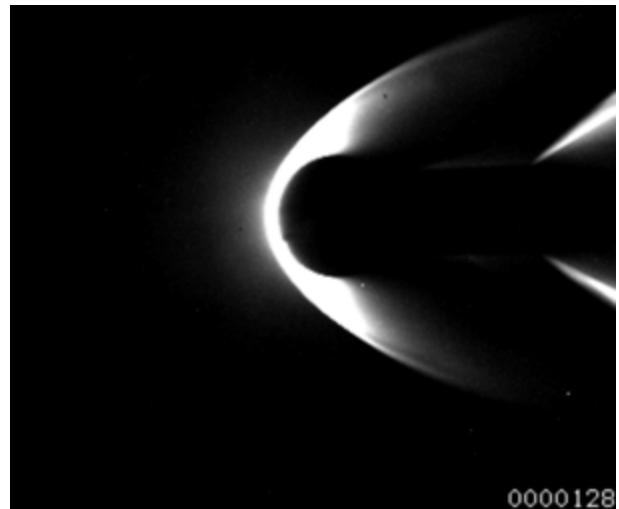
**Fig. 7** Raw spectra from shot number x2s1801, Titan 6.5km/s condition

Raw spectra recorded in the experiments shown in **Fig. 7**, where the horizontal axis represents the wavelength in nm and the vertical axis represents the un-calibrated distance in pixels. The color bar represents the intensity of the signal in raw counts. Looking at the image with the direction of the flow from the bottom to the top, the maximum heating region of the radiating shock layer is encountered immediately behind the shock. Continuing on, the boundary layer can be identified by the extra Fe features that are present, and finally at the top of the image, the model body is found.



**Fig. 13** Raw spectral lines from shot number x2s1801, Titan 6.5km/s condition, integrated at the maximum heating region along the stagnation streamline.

Raw spectral lines from the Titan 6.5 km/s condition are presented in **Fig. 7**, for the maximum heating region along the stagnation streamline (pixels 130-150). The data is yet to be calibrated for spectral irradiance. The most prominent feature of the spectra at 394-396 nm are the aluminum peaks of the aluminum diaphragm used in the test. To the left of the Al peaks, the two CN violet bands are clearly visible with peaks at 358 nm and 385 nm.



**Fig. 8** A frame from the high speed camera video taken during one of the Titan 6.5km/s shots.

A frame from the high speed camera footage taken during the one of the 6.5 km/s condition shots is shown in **Fig. 8**. The frame is taken from the steady test time, and the flow is coming from left to right. The radiating shock layer in front of the cylindrical model is clearly visible, as are the two oblique shocks from the model's mount.

#### 3.3.2 Gauges

Preliminary tests were done in the tunnel to check the radiation gauges response to the new Titan conditions. Two radiation gauges were placed in the model, and connected to the data acquisition system through a thin film heat gauges amplifier. The gauges responded in the experiment well, and the data was then processed to generate the temperature change curve and the heat flux curve as measured by the gauges.

The viewing window in front of the radiation gauge is heavily pitted at the end of each shot, where the damage is done after measurement is made, requiring the window to be replaced between shots. The gauges used to produce the following results were damaged when their windows were replaced, and could not be calibrated. Hence the absolute levels of heat transfer given in Fig. 9 and Fig. 10 and quoted hereafter are lower from the actual values, by 20-90%. This percentage range was calculated using engineering estimates of what the likely absorbance of the sensors in the UV range was, using existing data. The purpose of the LED calibration system developed in this study is to remove the uncertainty of this factor.

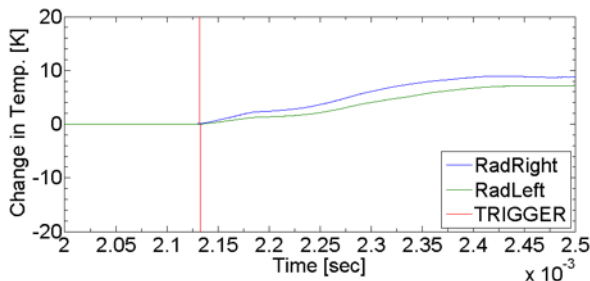


Fig. 9 Preliminary data, shot x2s1786. Temperature change for Titan 6.5 km/s condition, as recorded by the radiation gauges.

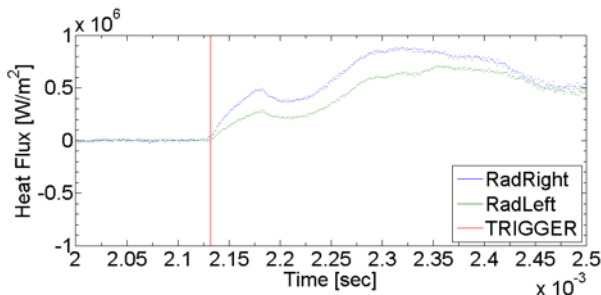


Fig. 10 Preliminary data, shot x2s1786. Heat flux for Titan 6.5 km/s condition, as recorded by the radiation gauges.

In Fig. 9 and Fig. 10 the trigger line represent the photodiode signal, and RadRight and RadLeft represent the two radiation gauges in the model. From previous shots and data collected during the experimental campaign, the test time is estimated to follow the trigger signal after  $125 \mu\text{s} \pm 15 \mu\text{s}$ . Using this data, the heat flux measured during the test time is  $85 \frac{W}{\text{cm}^2}$  and

$62 \frac{W}{\text{cm}^2}$  as detected by the right and left radiation gauges respectively.

#### 4 Conclusion

For fundamental atmospheric entry studies, the spectral distribution of radiation is required, and for engineering purposes, an integrated measurement for the total heat flux is needed. This work addresses both these requirements.

Preliminary results for the measurement of radiative heat transfer to a cylindrical model in expansion tubes using a Titan like atmosphere conditions were introduced. Heat flux measurement techniques using emission spectroscopy and radiation gauges were described, and initial results of preliminary work done were presented. The ongoing work involving the new calibration method for the radiation gauges using a 9W LED light source was introduced. Future work will include producing a final calibration procedure for the radiation gauges, followed by experiments in the X2 expansion tunnel.

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