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Radiation from simulated atmospheric entry into the gas giants

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Abstract

When entering a gas giant, the heat transfer to the surface of the entry vehicle is primarily driven by radiation from the shock layer. It is not currently known how existing techniques used to simulate gas giant entry conditions in ground testing facilities affect this radiating shock layer. This paper proposes a two-step process of testing, where initially ground testing is done comparing radiation between actual gas composition gas giant entry conditions and conditions developed using a substitution, before higher speed substituted gas composition testing is done to allow the radiation from entry into all four gas giants to be simulated. The results of a preliminary test campaign are presented here, where a spectrometer was used to measure H radiation in the Balmer Series, and good comparison was found between comparable actual and substituted gas composition flows.

Introduction

Ever since humankind began to briefly send primitive objects into space in the 1940's, space has captured the hearts and minds of many. To this day, countless experiments and missions have been undertaken to try and further understand our own solar system, and the vast expanse of space surrounding it. Exploration of the gas giants; Jupiter, Saturn, Uranus, and Neptune, has formed part of this effort so far, but there is still a lot more research that can be done. For example, Saturn's moon Titan (that the Huygens probe entered in 2005) is the only moon in our solar system that has its own atmosphere, and Jupiter's 4 Galilean moons are all worthy of exploration: Io has over 400 active volcanoes, and the other 3 moons, Europa, Ganymede, and Callista, are all believed to house oceans of liquid water below their surfaces.

While there are many benefits to be gained in further gas giant research, actually entering the atmosphere of a gas giant is a complex engineering problem, where many design issues must be overcome. Entry speeds of the order of 20-50km/s [1] (compared to 11.2km/s for return to Earth from the moon) result in extremely harsh environments behind the shock layer of crafts entering gas giants. As such, humankind has only ever performed one gas giant entry, the entry of the Galileo probe into the atmosphere of Jupiter on the 7th of December 1995. The probe entered Jupiter at a relative velocity of 47.5km/s, and took less than 100 seconds to decelerate to 1km/s [1]. In this environment, radiative heating accounts for 99% of the total heating load [2], and the H_2 in the flow dissociates very quickly, before collisions with the heavier He atoms start to ionise the H. Due to the much higher electronic excitation level of He (20eV, compared to 10eV for H), any He ionisation is negligible, and the He acts as an inert diluent. As ionisation creates more free electrons, they become the primary driver of further ionisation, and the flow exists as a partially ionised plasma. This entry was the most extreme heating environment ever experienced by a planetary entry probe, as seen in Figure 1.

In planetary entry situations, ablative heat shields are generally required to absorb the surface heating and protect entry vehicles from destruction. This is especially important for gas giant

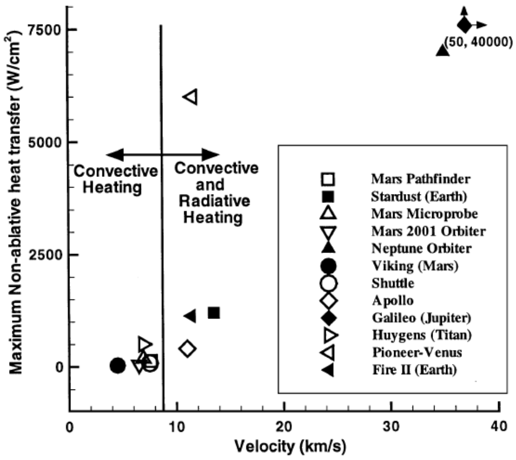

Figure 1: Non-ablative peak heating versus velocity for past and planned planetary entry vehicles [1]. Note the Galileo probe's velocity and maximum heat transfer in the top right hand corner of the plot, and how they're both off the scale.

entry. However, these heat shields comprise a large portion of the weight of the craft, and as such, a compromise is required between safety and mass: Due to the enormous cost required to send any craft into space, the loss of an entry probe due to a non-conservative heat shield design would be catastrophic. However, non-conservative safety factors lower mass, lowering the cost of missions, or allowing for larger payloads. This is motivation for the design of the most efficient heat shields possible.

Due to how little is known about the expected environment when entering a gas giant, conservative safety factors need to be used. So far this has resulted in the design of heat shield that were both bulky and inefficient. The Galileo probe was designed using the best computational aerothermodynamic methods available in the 1970's and early 1980's, but the actual heat shield ablation did not agree well with these predictions [1]. In-flight measurements showed that only half of the heat shield actually ablated during entry [7], and Figure 2 shows that the ablation on the stagnation point and the frustum of the craft differed greatly from what was expected.

The speeds required to simulate actual gas composition gas giant entry are well above the speeds achievable in current impulse facilities. To overcome this issue, Stalker [8] did work that showed that the inert diluent, He, could be replaced by the heavier Ne due to it's similar excitation energy, and the fact that computational work showed that Ne acts almost identically to He for inviscid hypersonic flow, allowing similarity to be reached at speeds of the order of 10km/s. The study also showed that the amount of diluent used for the substitution did not affect the similarity. This is useful because the enthalpy in the flowfield can be increased by adding more diluent to the test gas, creating higher temperatures in the shock layer over the test model, and increasing dissociation and ionisation in the shock layer.

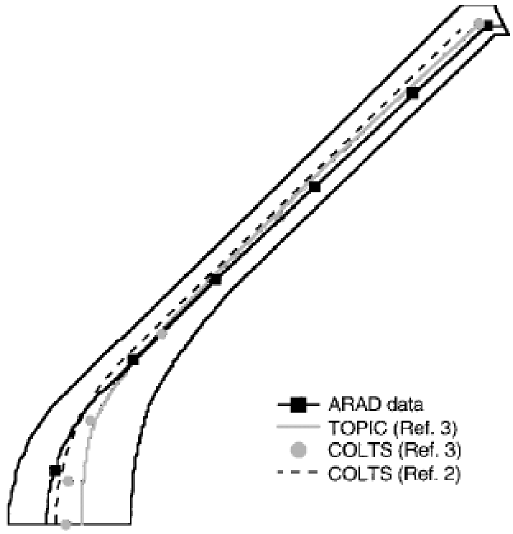

Figure 2: Comparison of the final shape of the Galileo entry probe compared to various theoretical predictions [7]. The solid black line shows the actual surface ablation (with the solid blocks showing where the ablation sensors were located on the heat shield surface), the other 3 lines show results obtained by both NASA and General Electric using two different CFD codes, COLTS and TOPIC.

Previous work in expansion tubes at UQ ([4], [3]) investigated the substitution by measuring shock standoff on blunt bodies with a H_2/Ne test gas, and confirmed the similarity using an analytical ionisation model. Good reproduction of shock standoff was seen between experiment, CFD and analytical results for cylinders and spheres. A test gas utilising 85%Ne diluent (by volume) was used to maximise dissociation and ionisation in the shock layer. However, no radiation measurements were taken.

Due to the high speeds and flow enthalpies experienced during gas giant entry, radiation is the primary driver of heat transfer to the surface of vehicles entering gas giants (see Figure 1), and this makes the study of radiation for gas giant entry flows an important issue. If we want to fully understand what occurs inside the shock layer of a craft entering a gas giant, we need to understand this radiating environment.

An increased understanding of the radiating flow-field inside the shock layer of crafts entering gas giants should allow for lighter but more effective heat shields to be designed, allowing future spacecraft to maximise their scientific payload without compromising cost or safety requirements. As has been mentioned, previous testing has shown good reproduction of shock standoff in the laboratory experiments, but no radiation measurements were taken. This study aims to compare the emission spectra from similar actual gas composition (H_2/He) and substituted gas composition (H_2/Ne) test flows to examine the effect the substitution has on the radiating shock layer. It is hoped that when this is understood, high speed substituted gas composition flows can be used to simulate gas giant entry radiation in expansion tubes.

This paper reports on preliminary testing done at the University of Queensland using the X2 superorbital expansion tube to measure H radiation in the Balmer series using a spectrometer, as well as a proposed test campaign covering both the comparison between H radiation from actual and substituted gas composition conditions, and H radiation from substituted gas composition conditions covering entry into all four gas giants.

Preliminary study

In 2011, as part of an Honours Thesis, a set of pilot tests were conducted in the X2 expansion tube at the University of Queensland to examine the validity of doing further testing to examine the spectra from both actual and substituted gas composition gas giant entry flows. Three separate tests conditions were used, a high speed H_2/He condition, a slower H_2/Ne condition designed to give similarity with the first condition, and a high speed H_2/Ne condition. (Details of the conditions can be found in Table 1.) The conditions were designed using a perfect gas analysis of the X2 expansion tube and then NASA's CEA program [6] was used to match the temperature in the shock layer to design the comparable H_2/He and H_2/Ne conditions. It can be seen in Table 1 that the temperature values for the two comparable conditions are within 15% of each other.

A test gas of 90% H_2/10% He (by volume) was chosen for the H_2/He condition to fall in line with the composition of the actual gas giants (which are 11.5–15% He in H_2 by volume [5]). A 90% H_2/10% Ne (by volume) test gas was chosen for the H_2/Ne conditions to make the real and substituted gas composition flows as comparable as possible.

Preliminary Test Conditions			
	diluent	U (km/s)	T (K)
Test 1	He	12.0±0.25	3699
Test 2	Ne	11.8±0.25	4374
Test 3	Ne	8.16±0.16	3204

Table 1: Test conditions used for the study. Velocities are experimental values measured at the end of the acceleration tube of X2. Temperatures are theoretical post-shock values after an equilibrium shock calculation across the stagnation point of the test model using NASA's CEA program [6].

An intensified CCD camera attached to an imaging spectrograph, capable of imaging across the wavelength range of roughly 400–800nm, was used for spectral imaging. The camera has a 256 pixel spatial resolution, and a 1024 pixel wavelength resolution. The chosen spectrometer settings give a 6.4mm spatial resolution, and a calibration against two known H lines (H–α [656.3nm] and H–δ [410.2nm]) was used to find the actual spectral resolution of the spectrometer (250–750nm).

H was expected to be radiating in the flow field, and the testing was focused on looking at the Balmer series of H lines, the set of discrete lines that radiate when excited H molecules transition from a higher energy state to the n = 2 state. All of the lines lie within the spectral resolution of the chosen spectrometer. The wavelengths that make up the Balmer series can be found tabulated in Table 2.

A basic 1:1 optical system was used to focus radiation from across the shock layer into the spectrometer slit. The test model was a hollow aluminium half cylinder with an outer diameter of 52mm and a width of 10mm. The cylinder was mounted in the tunnel so the flow hit the curved front face. This model has been used for other testing at the University of Queensland, creating the potential for this data to be compared to other similar tests.

An example of the raw spectrometer data can be seen in Figure 3. The x-axis shows the wavelength over the spectral resolution of the spectrometer (250–750nm), the y-axis shows the distance across the spectrometer slit in pixels (corresponding to a total spatial distance of 6.4mm), and the z-axis shows the measured intensity at each point. The two lines shown on the plot indicate the upper and lower bounds of the integration used to produce the worked results in Figure 4, this integration over

Transition	3 > 2	4 > 2	5 > 2	6 > 2	7 > 2	8 > 2	9 > 2	∞ > 2
Name	H-α	H-β	H-γ	H-δ	H-δ	H-ε	H-ζ	H-η
Wavelength (nm)	656.3	486.1	434.1	410.2	397.0	388.9	383.5	364.6

Table 2: Names and wavelengths of the Balmer series for H.

100 spatial pixels corresponds to 2.5mm spatially.

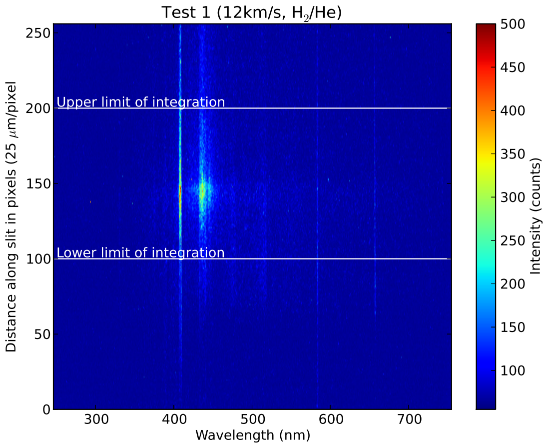

Figure 3: Raw spectrometer data for Test 1. This shows the area integrated over spatially to obtain the data presented in Figure 4.

Figure 4 shows the worked results for the preliminary study. The x-axis once again shows the wavelength, while the y-axis shows the integrated intensity for that wavelength. The top subplot shows the comparison between the comparable H_2/He and H_2/Ne conditions, while the bottom shows the comparison between the low and high speed H_2/Ne conditions.

Some conclusions can be drawn from the data presented in Figure 4. The comparison between the H_2/He and H_2/Ne test conditions shows promise, with the same H lines (H–α, H–γ and H–δ) radiating with similar magnitudes in each test gas, showing that the flows are radiating similarly. The comparison between the two Ne conditions shows evidence of higher energy level transitions (H–ε and H–ζ) for the faster condition, but the spectra also shows evidence of contaminants. Between 430 and 530 nm the well known C_2 Swan band is easily visible, dominating the spectra. This is a contaminant usually caused by the use of mylar diaphragms between different sections in the X2 expansion tube. Mylar contains C. Some experimenters at the University of Queensland use aluminium foil diaphragms instead to remove this issue. The contaminant at 589.6nm is the sodium-D line caused by vacuum grease used in the tube.

This preliminary data is useful as a starting point for further testing, but there is still a lot more work that can be done. Firstly, due to time constraints, no repeat shots were done in this study. This could be improved upon with a more thorough test campaign. The contaminants seen in the results for this study can be mitigated in future testing by using aluminium foil diaphragms. Testing with NASA's CEA program [6] showed that potentially none of the conditions tested had high enough flow enthalpy to cause significant ionisation in the shock layer, and this could be improved with further testing using higher enthalpy flow conditions. Proposed further testing is discussed in the following section.

Further Testing

To conduct a more comprehensive study of the radiation from both actual and substituted gas composition gas giant entry flows, a series of new test conditions have been designed and will be tested in the X2 expansion tube.

Firstly, the amount of inert diluent to be used for each test gas has been increased to 15% (creating test gases that are now 85% H_2/15% He and 85% H_2/15% Ne, by volume) to match the upper limit of diluent concentrations of the actual gas giants (15%He for both Uranus and Neptune [5], by volume) and to slightly increase the flow enthalpies of the test conditions.

A more thorough analysis was used to create two sets of comparable conditions to be tested in the X2 expansion tube, focusing on building expansion tube conditions that gave the same conditions in the shock layer for both actual and substituted gas compositions. The same perfect gas analysis of the X2 expansion tube used for the preliminary study was used as a starting point to design the conditions, and NASA's CEA program [6] was used to perform an equilibrium analysis to find the post-shock conditions at the stagnation point of the test flow over the test model. It was decided that matching temperature and H partial pressure (which is just pressure when both conditions have the same concentration of H) behind the shock wave would create comparable conditions. Two sets of conditions were designed, each set using different driver conditions for the X2 expansion tube. The full set of new conditions can be found in Table 3, and the similarity between the temperature and pressure of each set of conditions should be noted. The temperature error is less than 3% for each set of conditions, and for the level of accuracy used, the pressures are the same. This attention to detail should produce test conditions that are as comparable as possible.

Proposed Test Conditions				
	diluent	U (km/s)	T (K)	p (kPa)
Test 1.1	He	14.1	3660	169.6
Test 1.2	Ne	9.2	3549	169.6
Test 2.1	He	16.3	4040	208.5
Test 2.2	Ne	11.1	3998	208.5
Test 3	Ne	14.8	5290	314.4
Test 4	Ne	16.1	7744	204.1

Table 3: Proposed test conditions conditions for further study. Velocities are theoretical values exiting the nozzle at the end of X2. Temperatures and pressures are theoretical post-shock values after an equilibrium shock calculation across the stagnation point of the test model using NASA's CEA program [6]. Frozen shock calculations from CEA are not shown, but the values were also found to be similar.

The final two test conditions designed (Test 3 and Test 4 in Table 3) are high speed Ne conditions designed to push the limits of what can theoretically be expected to produce a usable test flow in the X2 expansion tube. Initial tests with a pitot rake will be used to examine how steady the test flow is for each of these conditions, and the fastest condition with a steady test flow will be used. These are very high enthalpy conditions (with stagna-

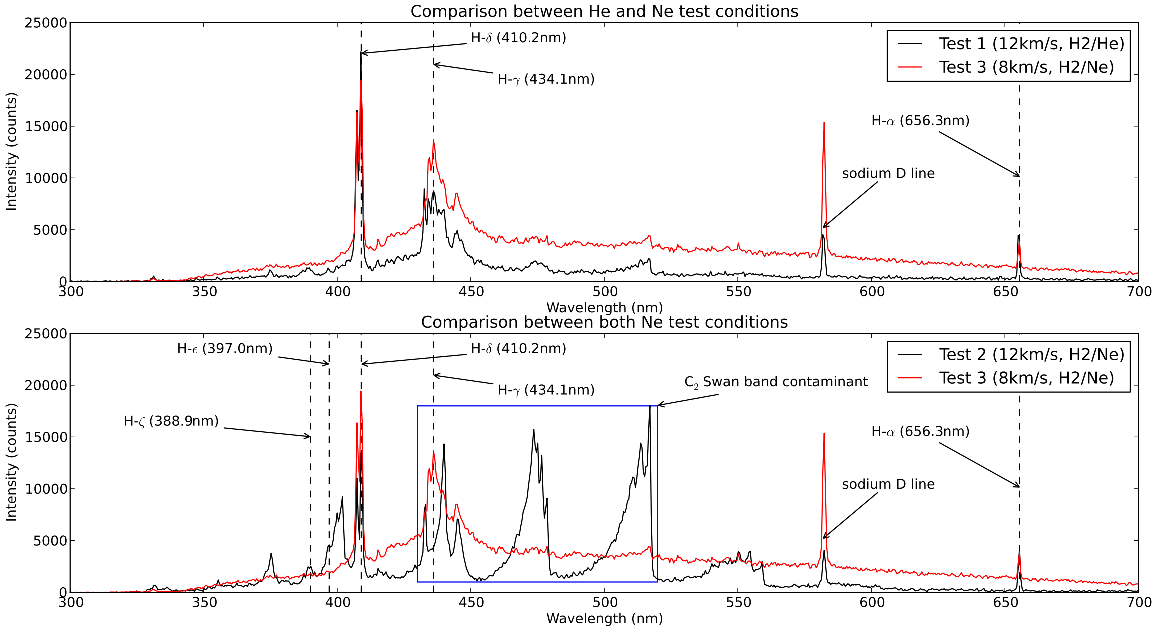

Figure 4: Integrated spectral data from the preliminary test campaign. The top plot shows the comparison between real and substituted gas composition tests, and the bottom plot shows the comparison between low and high speed substituted gas composition tests.

tion enthalpies ranging from 115 to 138 MJ/kg, compared to 70 MJ/kg for the conditions used by Higgins for similar testing in the X2 expansion tube [4]), and these conditions will be useful for simulating gas giant entry.

Another idea that has been considered is using a higher concentration of diluent. Stalker's initial work on the substitution of He for Ne in simulated gas giant entry flows showed that the amount of diluent used did not effect the similarity between He and Ne [8]. Therefore, while an equal diluent concentration between real and substituted gas flows was chosen for the majority of this study, it is not essential, and an easy way to increase the flow enthalpy a lot further is to use more diluent (Higgins used 15% H_2/85% Ne [4]). Initial calculations showed that test conditions with 15%Ne would simulate entry into Uranus and Neptune well (17.2–18.2km/s), while 40%Ne could be used to simulate Saturn entry (28.7km/s) and with 85%Ne Jupiter entry conditions (47.5km/s) could be created behind the shock over the test model.

Conclusions

The results of a preliminary study looking at radiation from the Balmer series in the University of Queensland's X2 expansion tube have been presented, with the results showing promise for the use of H_2/Ne test conditions to simulate the radiation from simulated gas giant entry in expansion tubes. This was followed by a discussion of a larger proposed test campaign that aims to correct any issues in the preliminary study and push further with the research, including faster conditions comparing actual and substituted gas composition gas giant entry flows, higher speed substituted gas giant entry flows, and test conditions simulating entry into all four gas giants.

Based on the success of the initial experiments, we feel justified in extending the work to create precise matched conditions in both H_2/He and H_2/Ne to give full mathematical similarity between both actual and substituted gas composition flows, before moving onward into creating both higher speed and higher enthalpy H_2/Ne flows.

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