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Modeling of radiating flows in the atmospheres of the gas giants

R.G.Morgan,
Centre for Hypersonics,
The University of Queensland, Brisbane, Australia 4072

Abstract

This paper investigates the possibility of recreating the radiating flow field characteristic of the shock layers involved from hyperbolic entry into the atmospheres of the Gas Giants**,** *Jupiter, Neptune, Saturn, Uranus*. A series of experiments are proposed whereby the Helium content of the atmospheres is replaced by Neon, creating a similarity between flight and laboratory simulation and enabling emission spectrometry to be performed from the highly radiating shock layer.

Introduction

The design of thermal protection systems (TPS) is a critical issue for hypervelocity flight. The issue first arose in the 1950's when sustained supersonic flight became viable. Early solutions are illustrated by the well known pioneering vehicles the SR71 'Blackbird' and the Concorde. These vehicles incorporated 'hot structures' to balance aerodynamic heat loads, using radiative cooling within the thermal limits of titanium and aluminium respectively at Mach numbers up to 3.2. As flight speed increases, so too does the associated heat input, and more advanced techniques are needed to maintain structural viability. The X15 rocket plane used a combination of inconel and titanium hot structures at speeds up to Mach 7 to survive short durations of hypersonic flight.

In parallel with these developments, exploration of space required structures to survive speeds of up to 8 km/sec for reentry from low earth orbit, and 11.2 km/sec for return from the moon, and up to 47km/sec for Jupiter entry. These designs were based on sacrificial ablative heat shields, where aerodynamic heating drives ablative products into the 'shock layer' of heated gas which surrounds the windward surfaces of hypersonic vehicles. This protects the structure of the space craft using the latent heat of the volatiles, through the insulating effect of the vapourised products surrounding the craft, and by radiative cooling from the carbon 'char' which is left behind after vapourisation. In addition, the layer of ablated products surrounding the vehicle can act as an a block to prevent radiation generated in the shock layer reaching the surface. This last mechanism is especially important for the high speed flows involved with the Gas Giants.

Entry into the atmospheres of the gas giants presents an extreme challenge to TPS, as the speeds reach values up to 47 km/sec, and shock layer temperatures greatly exceed those of the Sun's surface. The atmosphere consists primarily of H2 in He. The H2 dissociates very quickly after the shock, and ionisation of the H atoms occurs initially through heavy particle collisions. When sufficient electrons are released, they become the primary cause for further ionisation, through a two step process of excitation to the first excited state, followed by ionisation on subsequent collisions. The ionisation energy of the Helium is such that not much of it ionises, and its primary role is to initialize the ionisation of the H atoms. These speeds exceed those that can be attained in facilities for reproducing aerodynamic flows. However, the primary non equilibrium process of interest is the ionisation of Hydrogen atoms in the shock layer, and it has been shown (Stalker [21], Inger [7]) that by substituting Ne for the Helium found in the atmospheres of all the gas giants, a similarity can be obtained with flight at speeds of the order of 10km/sec, because the heavier Ne atoms reach the same temperature as the helium atoms would do at the higher speeds. The Ne atoms also have a high ionisation energy, so they play the appropriate role of non reacting collision partners. Previous work in expansion tubes has investigated this effect through measurements of shock standoff on blunt bodies, and has confirmed the similarity by use of an analytical model based on Dahmkohler numbers for the ionisation process.

This paper discusses the effect the substitution has on the radiation from the shock layer, which is the dominant form of heat transfer for entry into the atmospheres of the Gas Giants. It has been shown that good reproduction of the macroscopic flight parameter of shock stand off was achieved in the laboratory experiments. However, the complexity of the radiating gas mechanisms has not been considered yet, and this is required before a useful analysis of simulated reentry heating measurements can be performed. The study is a precursor to proposed experiments using emission spectrometry in the superorbital expansion tubes X2 and X3, Morgan [15]. For the entry of the Galileo probe into Jupiter in 1995, significant differences were noted between the predicted and measured amounts of surface heat transfer and the associated heat shield erosion, though no direct radiation measurements were made. The capsule survived the entry as good conservative design factors had been used. However, the heat shield design was not optimal, involving higher heat shield mass and significant risk of failure at critical structural points. The objective of this work is that improved understanding of the radiating shock layer will enable more advanced reentry capsules to be designed, with minimised mass and increased reliability.

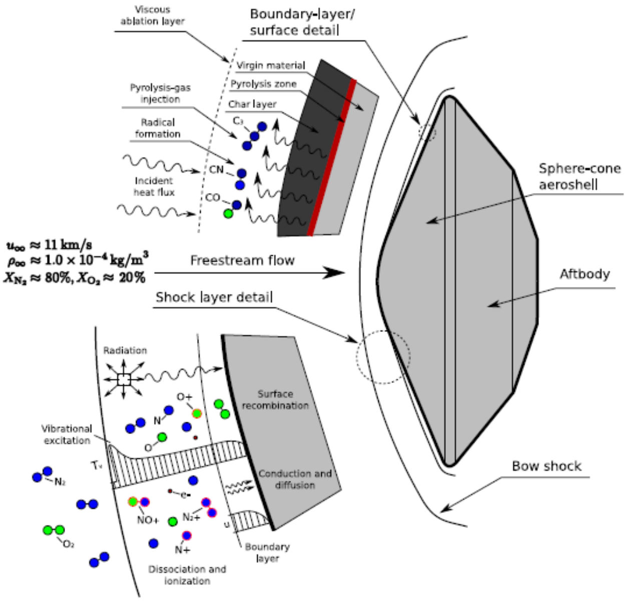

Figure 1 Radiating and ablating shock layer Potter 2009

Gas Giants (Jupiter, Neptune, Saturn, Uranus)

For the purposes of this study, we want to investigate the effects of the Gas Giant atmospheres on the ablation process. Jupiter entry is a classic case of radiation driven heat transfer, with radiation contributing over 95% of the total surface heating, so we will need to understand the radiating environment, and specifically to know what effects the Ne-He substitution will have. Another interesting feature of Jupiter entry is that the cloud of ablating products acts as an energy absorbing layer between the shock layer and the surface. To investigate this phenomena, surface mounted instrumentation will be required, so we can measure the heat transfer to the model with and without ablative products. For this set of experiments, we will artificially inject a flow of simulated products into the shock layer, and measure the subsequent surface heat transfer through total radiation probes (Capra [1]), and spectrometers fed by fibre optics embedded in the surface.

The shock heating of the gas processed by the bow shock of a blunt body at hypervelocity speeds occurs over a distance of several mean free paths, and leaves the gas in a state of chemical and thermal non equilibrium. In the subsequent relaxation region, non equilibrium radiation takes place which will have an effect on the total heating to the flight vehicle, to an extent which is determined by the length and density scales involved, and the kinetic properties of the specific species present. The classical wind tunnel technique of studying flight phenomena on small scaled models starts to break down when applied to radiating flows. Provided flight total enthalpy is matched, maintaining the binary scaling parameter in a scaled model may be done by conserving the product of density and a characteristic length scale with flight (commonly referred to as ‘rho-L scaling’), which conserves Reynolds number and viscous effects, and matches binary chemical processes, such as dissociation. The convective heat transfer is also scaled correctly, and the heat removed from the streamtubes (per unit mass of streamtube flow) will be the same in the scaled and unscaled cases.

However, when the radiation field associated with these two flows is considered, the mathematical similarity breaks down. When the point-to-point transfer of radiation through an optically thin flow is considered, similarity is conserved, because transmission is attenuated in proportion to the exponential of the mass traversed along the line of sight, which scales as the (constant) rho-L product. But when the total amount of heat removed from the streamtubes by radiation is considered, that scales in proportion to the volume of gas times a density (ie rho-L^3), whereas the mass flux into the shock layer scales with the sectional area (i.e. rho-L^2). Therefore the amount of heat removed by radiation per unit mass scales in proportion to the absolute length scale. This means that when small scaled models of flight vehicles are tested in the laboratory, not enough heat is removed from the stream tubes by radiation (by an amount equal to the scale factor), and true mathematical similarity is not maintained between tunnel and flight. The significance of this discrepancy will depend on how strong the coupling is between the radiation flux and the aerodynamic flow field. If the total amount of radiated energy is so high that the local thermodynamic condition of the flow is significantly altered (i.e. it is cooled down), then macroscopic changes to the flow field will occur, and the tunnel will not produce a direct simulation of flight. If the cooling produces only minor changes in condition (i.e. weak coupling), then the aerothermodynamic flow field is adequately reproduced in the tunnel, and direct simulation of flight will be achieved. The radiant surface heating component can be very significant, ranging from about 20% of the total for sections of the Apollo return trajectory, 70% for a Titan hard shell aerocapture flight and 95% for a Titan ballute entry, (Cauchon [2], Park [17]). The last two numbers are based on unvalidated CFD models, and significant variations on these values are given by different researchers. For Titan entry, the main radiating species is CN (cyanogen), the concentration of which can be an order of magnitude above local equilibrium levels in the relaxation zone. The CN is present due to the small quantities of CH4 in the predominantly N2 atmosphere. In addition to the chemical non equilibrium, the population levels of the excited CN states appear to follow a non Boltzmann distribution, indicating a fundamental flaw in current modelling procedures, (Gnoffo [5]).

To address these issues, more physical data is needed relating to the radiation spectra in the relaxation zone. Whilst there is some flight data available from the FIRE series of flights, (Cauchon [2]), flight testing in general is not a viable means of obtaining the comprehensive data involved. To investigate radiation-flow field coupling, the whole flow field surrounding a body has to be simulated, and because spacecraft dimensions are typically in the range of metres, small scale models have to be tested. This requires facilities with very high total pressures and temperatures (typically GPa and 10’s of thousands of K respectively for superorbital entry). Expansion tubes are the most capable facilities currently available for such study, and this report describes the X1, X2 and X3 family of expansion tubes at The University of Queensland. Experiments performed therein involve coupled radiating flows, but they are not direct simulations of flight conditions, as mentioned above. The coupling of the radiation with the flow will be different, and it is unknown what effect doing the experiments at the higher density required for scaled tests will have on the radiation process. However, the measurements provide useful data for comparison with numerical simulations.

The zones of non equilibrium radiation are typically of small extent physically, and are located near the bow shock, figure 1. It is necessary to categorise the appropriate length scales for various missions in order to identify suitable facilities. For the FIRE missions, the shock standoff distance was of the order of 50 mm, with the non equilibrium zone extending approximately 20 mm behind the shock. For a CEV type lunar return vehicle standoffs of the order of 500 mm are expected, and a Titan hardshell aerocapture capsule would experience standoffs of the order of 200mm. For a ‘worst case’ example, an upper atmosphere Titan ballute vehicle would experience shock standoff’s of the order of 1 m, with the non equilibrium radiation region extending about 300mm. Typically, therefore, the extent of the non equilibrium radiation zone will only be in the range of cm’s to 10’s of cm, at real flight conditions. This opens up the possibility of doing non reflected shock tunnel (NRT) tests at real flight conditions, but recreating only the flow in the non equilibrium region, just behind the bow shock. The UQ expansion tubes have been designed with dual-mode configurations, so that they can also do NRT experiments. With the high performance free piston drivers, and the provision for a shock heated intermediate driver tube, they have been used to drive shock at speeds up to 15 km/sec.

By using the Neon-Helium substitution mentioned above, the non equilibrium state of the gas chemical composition should be accurately recreated in the shock tube, in regard to the primary radiating species of H and H^+, as demonstrated by Higgins [6]. As neither the Neon nor the Helium will experience significant ionisation, and neither are radiation absorbers, the nature of the radiating field would be expected to be similar. However, the thermodynamic state of the gas will be somewhat dependent on the collisions between the noble gas atoms and the participating radiators. This effect, if significant will change the population levels of the excited states, consequently the associated radiation intensity and spectra.

In previous experiments, the radiating shock layer has been observed through qualitative luminosity photographs, Figure 2, (Lourel [13]), and qualitatively by McIntyre [14] and Eichmann [3] to measure ionisation and electron concentration levels, Figure 3. To evaluate the radiating flows field, further experiments are required give quantitative measurements of the associated spectra.

Conslusions

Experiments performed in expansion tubes have been shown to reproduce the primary aerothermodynamic effects associated with non equilibrium shock layers created on entry to the atmospheres of the Gas Giants. The opportunity now exists to use this capability for the study of the radiative heat transfer created, which drives the design of heat shields for planetary exploration.

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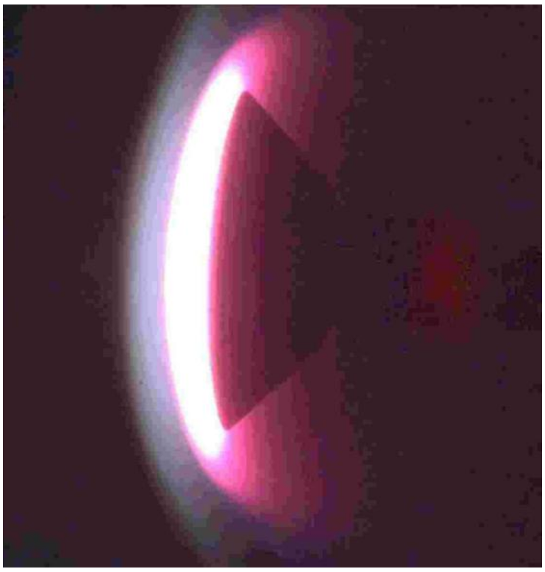

Figure 2 Radiation from shock layer Lourel [13]

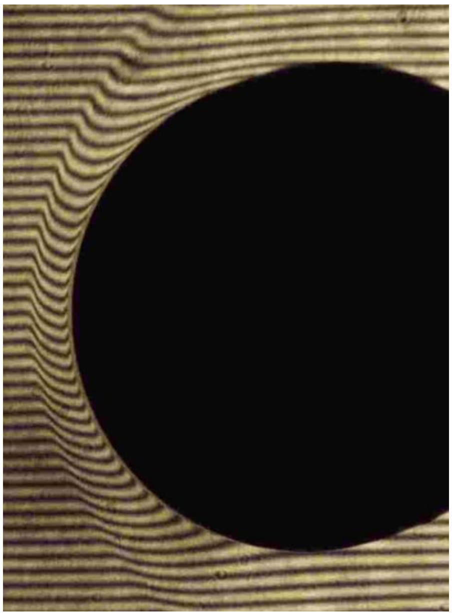

Figure 3 Interferogram used to compute electron concentrations. McIntyre [14] and Eichmann [3]

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