RADIATION-ABLATION COUPLING FOR CAPSULE REENTRY HEATING VIA SIMULATION and EXPANSION TUBE INVESTIGATIONS

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Abstract
A capsule entering a planetary atmosphere at hypersonic speeds experiences high levels of radiative heating. Furthermore, coupling between the ablation products from the surface of the vehicle and the high temperature gas can have a major effect on the head load experienced by the vehicle. This paper discusses a collaborative project aimed at better characterising the flow processes involved. A ground-based expansion tube facility is described in which radiation-ablation coupling is achieved through the use of a pre-heated model placed in a high temperature flow. In parallel, simulation techniques are being developed to model the complex chemical processes occurring in the flow.

1. Introduction

Capsule return missions are amongst the oldest space transportation missions dating from before the Luna exploration era, through to more recent ones of planetary exploration of Mars, Titan, Jupiter and Venus, where capsules are used for atmospheric entries and for the return part of the mission. The design of the Thermal Protection System (TPS) of the capsule, and in particular the forebody, is driven by the estimation of these heat loads. There are several philosophies for these designs, and one of the main categories is to use an ablative material for part of the forebody heatshield. Such designs are obligatory for hyperbolic returns, such as certain lunar return trajectories or small experimental capsules such as the recent Stardust (2006) or Hayabusa (2010) missions. The heating rates associated with these missions was so high that the exposed surface temperatures required could not be sustained continuously by any suitable existing materials, and surface erosion forms an integral part of the thermal protection mechanisms involved. However, the ablation and pyrolysing processes ejects new species into the reacting boundary layer, some of which are highly radiative, , which can enhance or block the radiation heat flux.
In the case of Earth return the main flight data of such missions are from the Apollo era, with the FIRE II experiments and the Apollo missions. Recently small size return capsule missions have been performed – Stardust and Hayabusa – with hypervelocity superorbital re-entry trajectories, rendering data from external flight path observation.

Capsule return missions are amongst the oldest space transportation missions dating from the Lunar exploration and subsequent return to Earth through to more recent explorations of Mars, Titan, Jupiter and Venus. One of the main features of the atmospheric entry is the extreme surface heating of the body which consists of contributions from convective and diffusive aerothermodynamic heating and from radiative heating. The design of the Thermal Protection System (TPS) of the capsule, and in particular the forebody, is highly dependent on an understanding of these heat loads. The importance of this analysis cannot be underestimated - these missions generally attempt to retrieve important scientific data or, in the case of ISS or Lunar missions, involve the return of humans to Earth.

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There are several competing philosophies for the design of the TPS. One option is to use an ablative material as the heat shield on the surface of the forebody. Such a design is thought to be obligatory for hypervelocity return given the extreme heat loads experienced. Capsules from certain lunar return trajectories and experimental small capsules such as the recent Stardust (2006) and Hayabusa (2010) missions have been equipped with heat shields made of composite materials such as carbon phenolic PICA-like or TWCP (Tape Wrapped Carbon Phenolic material. The ablating material removes heat from the body, however the ablation and pyrolysing processes eject new species into the reacting boundary layer, including highly radiative ones, which can enhance or block further radiation from impinging on the surface.

Reproducing such trajectories and, in particular, the peak heating conditions (radiative and convective) in ground facilities is a challenging task. A high temperature flow of gas with sufficient density can generally only be created for a short period and hence such facilities are impulsive in nature with short test times. The operating conditions for the facilities are aimed to be relevant to actual missions (past, present and future) ranging from Apollo-type to sample return from Mars or Moon to small capsule missions such as Stardust, Hayabusa and ESA's recent prospective project Phoebus. Continuously running facilities such as plasma wind tunnels (PWTs) can achieve the time dependant heat loads experienced in such missions but cannot reproduce simultaneously the flight conditions of pressure, density and enthalpy.

One type of facility that is capable of generating the flow conditions experienced during atmospheric entry is the super-orbital expansion tube. Flight conditions are created in the test section of the facility matching flow speeds, pressures, enthalpies and convective fluxes, but only for short test times of the order of 50-500 microseconds. This implies that the temperature of the surface of a model placed within the oncoming flow in the expansion tube does not reach a significant temperature as compared to flight, where the surface heats up progressively along the trajectory path reaching values of over 3000 K. However, this drawback of short testing times can be circumvented by the use of in-situ pre-heating by an electrical arc within the material [1], as long as the electrical conductivity of the material is compatible, [2]. This is the case, at least for carbon composites such as RCC and also carbon phenolics. Important information about the mechanisms involved in the ablation can be obtained by placing probes within the sample, and by the use of non-intrusive high-speed imaging and spectroscopy.

Testing of this type can be used to measure the level of radiative heat transfer from the hot radiating plasma to the surface the model. At high entry speeds this heating mechanism represents a significant contribution to the overall heat load. For a non-ablating surface, modelling of the flow chemistry can be used to infer heat flux levels. The presence of ablation significantly complicates the situation. Heat shield made from modern lightweight carbon phenolics inject highly radiating species such as CN into the hot boundary layer as well as other reacting species such as C3, C2, CO, CH, CH2, CH3, H20 and the radicals of C2H. Carbon derivatives such as CO2, CO, CN, C and C3 are mostly important for surface ablation of carbonaceous materials, whereas H, H2, CO, HCN, C2H and C3H are important for pyrolysis in the case of quasi steady-state ablation. CH3, CH4, C2H2, C2H6, H2O, H2, CO2 and CO are significant species for lower wall temperatures, especially for highly porous materials (with short time residence of gases in the material).

The ablative products interact with the radiating species of the flow field, creating new radiating species and, in particular, the emission of products such as C3, C2, HCN, CN, CH2 and CH3 in the boundary layer enhance the radiative heat flux associated with such products and modify the transport and diffusion fluxes. Radiation blockage or a radiation enhancement can occur depending on whether the ablation and pyrolysis products are strongly absorbing or emitting. The whole procedure leads to a complex radiation-ablation coupling.

Flight data on hypervelocity entry into planetary atmospheres is extremely limited, especially with ablative coupling. In the case of Earth return, the main flight data still in use are from the Apollo era, including the FIRE II experiments and the Apollo missions themselves. The FIRE II experiment of the 60s was unique in the prediction-validation of heat flux levels and serves as a standard validation test case for International Workshops such as the ESA-CNES RHTW, Radiation Working Group and Ablation Working Group. For Apollo 4, an Avcoat5026-39G material was used which was a silica fibre/epoxy resin/phenolic microballons/silica microballons, containing also Al2O3, CaO and B2O3, and hence rendered ablative products similar to modern ablative materials. In such material the carbon deposition by pyrolysis of gases is important. Available data about this kind of material is limited and hence detailed calculation of pyrolysis and permeation of gases is difficult. [4].

Recently, small size return capsule missions have been performed. Both the Stardust and the Hayabusa missions involved super-orbital re-entry trajectories with peak values at trajectory points corresponding to altitudes of 50-58 km, rendering data from external flight path observations. It should be noted that radiative heat fluxes were approximately 10% of the total heat flux for these small sized capsules, whereas radiative fluxes are estimated to be over 40% of the total heating for certain trajectory points of FIRE II. Nevertheless, detailed measurements were made to evaluate the radiation over a large spectral range. Theoretical modelling of the missions agreed well with measurements but indicated that there was a significant contribution to the radiation from the vacuum ultraviolet (VUV) region of the spectrum which was outside the measurement capability of both the ground- and flight-testing teams.

ESA is presently conducting a project to attempt to evaluate the VUV contribution in these conditions [5]. Ground-based facilities including the super-orbital expansion tubes are being used to generate the flight conditions with observations using VUV detection systems. In parallel, numerical modelling is being conducted to compare with the measurements. This paper discusses progress in this project including the evaluation of radiation and radiation-ablating coupling in expansion tubes, and the corresponding modelling issues related to hypervelocity return of capsules equipped with PICA-like materials.

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