Experimental study of a recombining plasma

Background: Understanding the complex plasma flow surrounding a reentering space vehicle is necessary to design reliable and cost-effective vehicles for space exploration but remains a difficult challenge. A spacecraft can enter a planet's atmosphere well within the hypersonic flight envelope at velocities between 10 - 15 km/s [1]. The strong shockwave that forms about the vehicle intensely heats, via strong compression, the air flowing around the spacecraft (Figure 1). The high gas temperature leads to several complex phenomena: ionization, molecular dissociation, chemical reactions and strong gas radiation. Thermal protection systems (TPS) are designed to protect the spacecraft from this strong aerodynamic heating which is due to a combination of convective and radiative heat transfer.

One outstanding problem pertains to the radiative heat flux directed towards the surface, particularly in the afterbody region of the capsule. The strong hydrodynamic expansion from the forebody into the afterbody results in rapid cooling of the plasma, leading to a departure from equilibrium [2, 3]. Non-equilibrium phenomena therefore play an important role in the afterbody flow and the heat flux to the capsule surface, particularly the radiative heat flux. For example, comparisons between simulations and measurements performed using radiometers on the back shell of the FIRE II mission showed a disagreement of up to 100% on some regions in the afterbody [4]. It is important to work towards reducing these uncertainties because they result either in cost increases or, due to increases in the TPS thickness and weight to satisfy safety margins, a reduction in the useful payload which can be brought along for the mission. Both factors can critically determine whether a particular mission is possible.

To reduce this uncertainty for the afterbody heat flux, it is necessary to understand the dynamics of a recombining plasma which occur during the expansion from the forebody into the afterbody. This includes both the chemical kinetics of the recombining plasma and the impact of these kinetics on hydrodynamics.

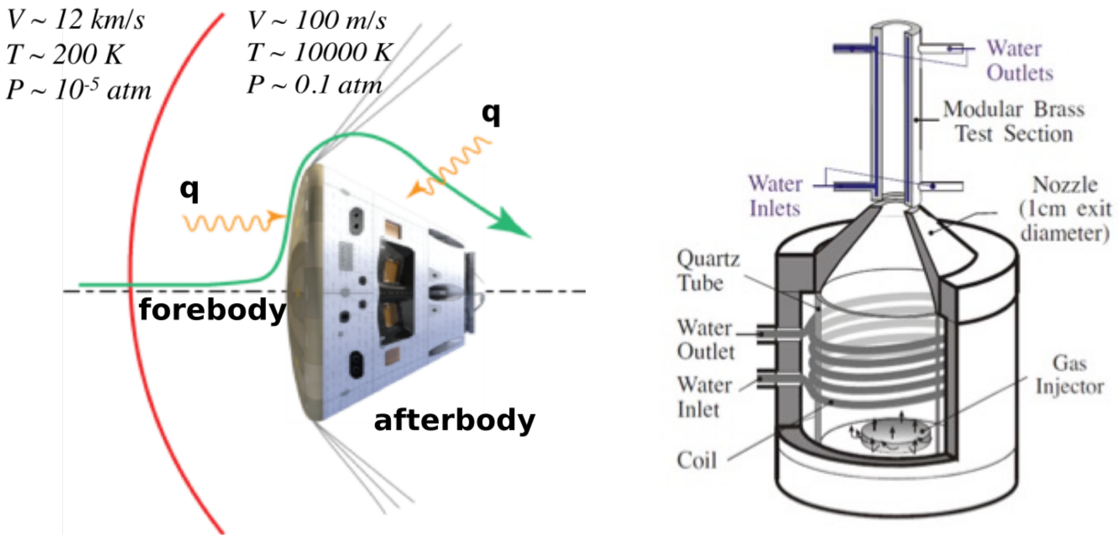

Figure 1: (*left*) Canonical atmospheric entry situation with numbers taken from the 1999 NASA Stardust mission. '**q**' denotes the heat flux, convective plus radiative, to the capsule surface. (*right*) Plasma torch facility with water-cooled tube mounted at the exit. The water-cooled tube is designed to rapidly cool the plasma, providing an analogue to the rapid cooling that occurs during the expansion from forebody to afterbody.

Goal of this thesis: This thesis will be built upon previous work looking at recombining plasmas in nitrogen, air and carbon dioxide for Earth, Mars and Venus entry applications. The previous work, performed by Laux and coauthors [5-12], has made use of an atmospheric pressure plasma torch. This 50-kW radiofrequency plasma torch facility produces an equilibrium plasma at 7000 K, which is close to conditions seen in the forebody during atmospheric entry. In order to model the hydrodynamic expansion and subsequent rapid cooling of the gas as it passes into the afterbody, a water-cooled tube is mounted at the exit of the plasma torch facility (Figure 1). Rapid gas-cooling occurs as the plasma transits the water-cooled tube, reproducing certain recombination phenomena that occur during atmospheric entry. Optical diagnostics may then be used to study the plasma dynamics and properties during recombination. This work has been done using N_2 , CO_2 and air mixtures and led to an enhanced understanding of recombination processes in these plasmas.

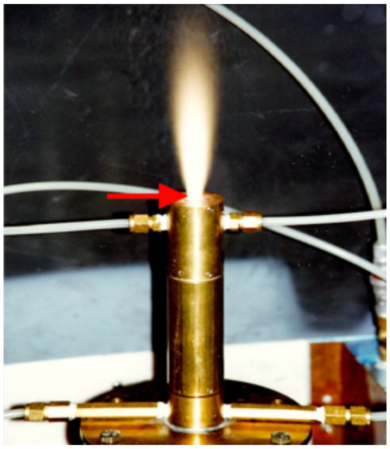

Figure 2: A brass water-cooled tube is mounted at the torch exit to rapidly cool the plasma as it transits the tube. The tubes visible in the image supply the water for cooling. Directly at the tube exit (red arrow) the recombining plasma can be in strong chemical non-equilibrium depending upon the operating conditions.

The goal of this thesis is to study the dynamics of a recombining plasma in CH_4, CH_4/N_2, CO_2 and CO_2/air mixtures. The CH_4 and CH_4/N_2 mixtures are relevant for missions to Titan, whose atmosphere is composed of nitrogen and methane. CO_2 is relevant for missions to Mars, whose atmosphere is primarily composed of CO_2. The CO_2/Air mixture is relevant for Earth entry applications and permits the study of chemical kinetics linked to ablative species via the inclusion of carbon in the mixture. In all cases, we are interested in studying plasma recombination dynamics that will be important for the design of thermal protection systems for manned missions to Mars where weight and cost considerations are critical [13]. Studying the relevant recombination dynamics will require measuring the properties of the recombining plasma using various optical techniques. The gas temperature is a primary parameter of interest, as is the identification of any departure from equilibrium. The thesis would be primarily experimental in nature and would supply experimental measurements for comparison with model predictions.

Experimental Methods: The experiments will be performed using the 50-kW plasma torch facility at CentraleSupélec. The plasma team has expertise in various optical and laser-based measurement techniques: quantitative emission spectroscopy (OES), Rayleigh/Raman spectroscopy, Thompson scattering, laser-induced fluorescence (LIF), mid-IR absorption spectroscopy and others. A portion of the measurements in this thesis will be done using OES. CH_4 and CO_2 emit strongly at infrared wavelengths and thus the study will focus on this region of the spectrum. The infrared region of the spectrum is of particular interest because it yields information on ground state CO_2 concentrations. Other species derived from these molecules emit in the visible and ultraviolet spectral regions. Emission spectra in these wavelength regions yield information on excited state distributions. Measured spectra may be compared with theoretical spectra to determine parameters such as temperature or species concentration. The student will use numerical tools to analyse experimental results. Other measurements will be made using laser diagnostics. Two laser diagnostics of particular interest are Thompson scattering for electron density measurements and Coherent anti-Stokes Raman Scattering (CARS) for vibrational/rotational molecular distribution measurements. Finally, the lab has expertise in modeling of recombining plasmas and the student will design their experiments in coordination with experts in numerical modeling to ensure that the measurements made contribute to arriving at a better understanding of the recombining plasmas dynamics.

Contacts:

Directeur de thèse :

Sean McGuire, Maître de Conférences, CentraleSupélec, sean.mc-guire@centralesupelec.fr

Codirecteur de thèse :

Christophe Laux, Professeur CentraleSupélec, christophe.laux@centralesupelec.fr

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