Radiation of nonequilibrium plasma flows for reentry applications

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During atmospheric reentry, a capsule enters the atmosphere of a planet (Earth, Mars…) at a velocity that can exceed 10 km/s. The strong shockwave that forms in front of the capsule heats the gas up to temperatures around 10,000K. The high temperature of the gas leads to ionization, molecular dissociation, excitation and intense gas radiation. The study of the radiative and convective heat transfer of such a plasma is critical for the design of the heat shield (or thermal protection system, TPS) of an entry capsule. These heatshields are carbon-based and represent a significant constraint for the mission, particularly in regard to the cost and weight of these materials. The heat flux to the forebody of the capsule has been the primary focus of past research and is now relatively well known. However, predictions for the heat flux to the afterbody surface still suffer from large uncertainties. This is due primarily to two factors. The first is the presence of significant quantities of carbon in the plasma, introduced via the ablative heat shield in the front of the capsule. The carbon sublimates from the forebody heat shield on the capsule and recombines in the flow, forming molecules such as CN and CO, that radiate in the afterbody region. The second phenomenon is the hydrodynamic expansion of the plasma into the afterbody. This expansion rapidly cools the plasma, forces rapid plasma recombination and departure from chemical equilibrium. The result is a nonequilibrium plasma in the afterbody. The prediction of this nonequilibrium and the resulting radiation from such a plasma is not accurately modeled at the moment.

We focus on a seemingly simple experiment to study nitrogen recombination which was previously performed at Stanford University. We used our 50 kW plasma torch to supply a high enthalpy plasma jet. The plasma is then cooled in a water-cooled tube to force the plasma to recombine, resulting in a nonequilibrium plasma at the exit of the tube. We performed Raman and Emission spectroscopy to measure the gas temperature and the plasma radiation. The plasma is found to be highly non-equilibrium which, in turn, leads to much higher radiance values than would otherwise be encountered in an equilibrium plasma. For comparison with experiment, we performed CFD simulations to predict the measured drop in gas temperature. We were unable to find good agreement between simulations and measurements. The results presented are intended as validation test-cases for CFD and kinetics codes used for atmospheric entry.