Effects of thermochemical non-equilibrium in the boundary layer of an ablative thermal protection system: a state-to-state approach

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Abstract: The aim of this work is to investigate the effects of thermochemical non-equilibrium in the shock layer and boundary layer of hypersonic flows past blunt bodies entering planetary atmospheres. Ablative thermal protection systems change the mixture composition of the boundary layer with significant impact on the surface heat flux. In this context, a vibrationally resolved state-to-state approach is employed in order to understand the effect of non-equilibrium of the molecular energy level population on the surface heat flux.
Keywords: Ablation, Hypersonic Flows, Thermochemical Non-Equilibrium, State to State Kinetics.

1 Introduction

In recent years, the interest in space exploration has raised significantly due to a new impetus from the private sector. Among many complex problems related to space exploration, one of the greatest challenge is the tremendous heat load on the vehicle during its entry into a planetary atmosphere. Designing a suitable Thermal Protection System (TPS) can have a huge impact on the success and cost of space missions. Ablative TPSs dissipate energy through material decomposition and mass loss; obviously, this may cause some modification of the boundary layer gas composition, which in turn can affect the surface heat load by blocking the radiation coming from the shock layer. In this context, an intriguing phenomenom recently observed in the Plasmatron wind tunnel at the von Karman Institute for Fluid Dynamics (VKI) is the non-equilibrium population of the energy levels of the cyanogen molecule (CN) [1]. Spectroscopic measurements on both graphite and carbon bonded carbon fiber material suggest that the rotational and vibrational temperatures strongly depart from a Maxwell-Boltzmann equilibrium population close to the ablating surface. Non-dissociated nitrogen in the boundary layer can play a significant role in the vibrational excitation of the CN molecule. A state-to-state (StS) approach will help us to identify the cause of this non-equilibrium effect and its impact on the surface heat flux, either through increased radiation or exothermic surface reactions. At present, an effective vibrationally resolved StS approach for N_2, O_2 and CO molecules has been implemented in a multi-GPU solver of the Navier-Stokes equations [2]. In the present work, we will simulate air or oxygen hypersonic flows past simple blunt bodies made of graphite (e.g., spheres or cylinders) to examine if molecules are characterized by non-Boltzmann distributions and eventually assess such non-equilibrium effect on the surface heat flux.

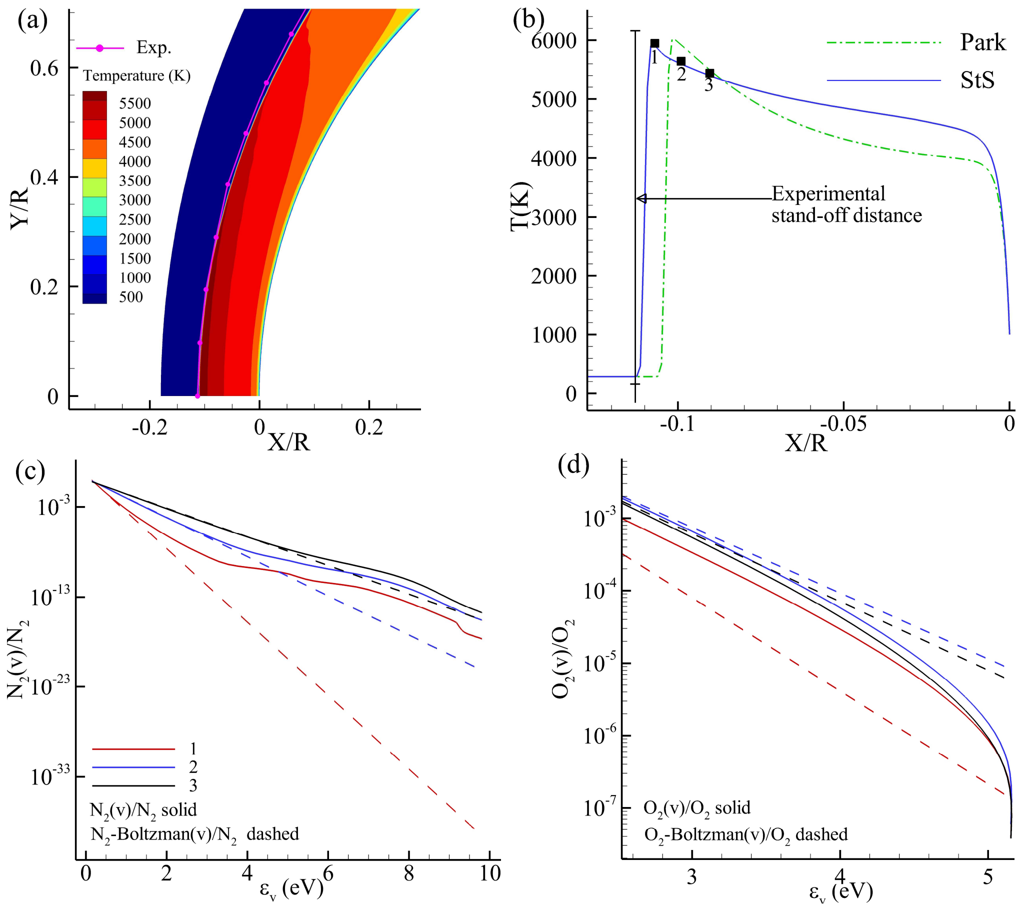

Figure 1: (a) StS temperature contour plot around a sphere and comparison with experimental shock position, (b) temperature profile along the stagnation line, comparison of experimental data with StS and Park's model results, (c) N_2 and (d) O_2 vibrational distribution functions, evaluated along the stagnation line at probes 1, 2, and 3 (see Fig. 1 (b)), compared to Boltzmann distributions at T=Tv (extracted from levels v=0 and v=1) (dashed lines).

2 Preliminary results

Previous results, obtained with a five species air mixture (N_2, O_2, NO, N, O), including StS of N_2 and O_2, have shown that, downstream of a strong bow shock, non-Boltzmann distributions affect reaction rates and, consequently, temperature profiles and stand-off distance (see Fig. 1) [2]. Specifically, O_2 high energy levels are underpopulated (Fig. 1 (d)) thus reducing the dissociation rate. In the present work, the StS model will be extended by including CO plasma chemistry and CO vibrational kinetics [3], whereas mass and energy balance at wall will be computed by using the VKI Mutation++ library [4]. This approach will be employed to investigate the effects of non-equilibrium in the boundary layer. Results will provide information regarding temperature, pressure, species mass fractions, vibrational distribution of molecules and surface heat flux.

References

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