Atmospheric entry plasma models consistent from kinetic- to hydrodynamic scale

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Transport phenomena in plasmas are characterized by strong nonequilibrium conditions resulting from distinct time scales for excitation and relaxation of the translational and internal energy modes of the gas particles, as well as for the influence of the electromagnetic field and chemical reactions. Many engineering models are based on experimental data and often contain ad-hoc terms that are only valid for some dedicated applications, whereas models derived more rigorously from kinetic theory can be based on assumptions that are too strong to describe complex physico-chemical phenomena. Our objectives are to enrich mathematical models by incorporating more physics in a rigorous way and to identify the mathematical structure of the equations derived. We show three examples. First, we use the moment method of Grad to derive macroscopic conservation equations for multicomponent plasmas for small and moderate Knudsen numbers, accounting for the electromagnetic field influence and thermal nonequilibrium between light electrons and heavy atoms and ions. In the low Knudsen number limit, the equations derived are fully consistent with those obtained by means of the perturbative Chapman-Enskog method. In particular, we retrieve the Kolesnikov effect coupling electrons and heavy particles, in the case of the Boltzmann moment systems. Then, we present a spectral-Lagrangian method for the Boltzmann equation for a multi-energy level gas. Internal energy levels are treated as separate species and inelastic collisions (leading to internal energy excitation and relaxation) are accounted for. The formulation developed can also be used for the case of a gas mixture made of monatomic gases without internal energy (where only elastic collisions occur). The advantage of the spectral-Lagrangian method lies in the generality of the algorithm in use for the evaluation of the elastic and inelastic collision operators, as well as the conservation of mass, momentum and energy during collisions. Computational results are compared with those obtained by means of the DSMC method. Finally, we derive a wall boundary condition for catalytic recombination and implement it in a DSMC code. The implementation is tested by comparing the numerical results with an analytical solution developed for a diffusion problem in a binary mixture. Next, the effect of catalysis is studied for a state-specific bin model for internal energy exchange and molecular dissociation.