DSMC and Beyond: Modeling Nonequilibrium Flow in Aerospace Applications

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This short course presents a comprehensive overview of recent developments in nonequilibrium flow modeling, centered around the Direct Simulation Monte Carlo (DSMC) method and its integration with broader kinetic and multiphysics approaches. The course covers kinetic modeling efforts that include the development and implementation of Fokker–Planck and BGK models, as well as their integration with DSMC in hybrid frameworks for addressing multiscale nonequilibrium transport. Recent advances in gas–surface interaction modeling are also discussed, including the incorporation of chemical energy accommodation (CEA), the AO adsorption adaptive α (AAA), and a radiative equilibrium boundary condition within the finite-rate surface chemistry (FRSC) framework. In addition, a new scattering kernel, the corrugated CLL model, has been developed as a physically grounded extension of the conventional Maxwell and CLL models. The course further explores plasma–flow coupling using particle-in-cell (PIC) and hybrid PIC–DSMC methods for simulating the plumes of electric propulsion devices, including Hall, ion, and electrospray thrusters. Extensions of DSMC to multiphase flow regimes involving solid–gas mixtures are also introduced, particularly in the context of solid rocket exhaust plumes.

Application domains include a wide range of aerospace problems such as hypersonic reentry, drag prediction and system-level analysis in Very-Low-Earth-Orbit (VLEO) including atmosphere-breathing electric propulsion (ABEP), plume–surface interactions for various electric propulsion systems, and solid rocket plumes. Most of the models and simulation strategies presented in this course have been implemented within the modular open-source DSMC code SPARTA, which serves as the primary development and demonstration platform. The course is intended for both new and experienced users, offering physically grounded modeling strategies and practical implementation insights for complex nonequilibrium flow environments.