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Abstract 122

DSMC-CFD Consistency in the Continuum/Transition Overlap Region for a Deployable Mars Capsule

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Atmospheric re-entry is a critical phase for any space mission. To accurately model the flowfield around a vehicle during re-entry, it is essential to identify the flow regimes encountered along the trajectory. The re-entry of a hypersonic vehicle begins in an extremely rarefied environment, where the particle number density is low and the mean free path is large. As a result, the Knudsen number (Kn), defined as the ratio of the mean free path (λ) to a characteristic length (D), exceeds the limit of 10, corresponding to the Free Molecular Flow (FMF) regime. Under these conditions, the classical governing equations of fluid dynamics, i.e., the Navier–Stokes (N-S) equations, fail to capture the physics because the continuum hypothesis breaks down. Therefore, a different approach is required: the Direct Simulation Monte Carlo (DSMC) method, which is based on the Boltzmann equation. DSMC analyses can be extended to the transition regime ($0.01<Kn<10$), where the particle density increases and the mean free path decreases, driving the Knudsen number toward the continuum limit ($Kn \approx 0.01$).

In the overlap between the transition and continuum regimes, DSMC can still be applied. However, as the number of simulated particles increases, the computational cost grows dramatically. Although the underlying physics allows DSMC analyses to extend into the continuum regime, the associated computational cost makes its use in the fully continuum regime prohibitive. Conversely, continuum Computational Fluid Dynamics (CFD) solvers based on the Navier-Stokes equations perform well when the continuum hypothesis holds, but their validity becomes questionable as the flow approaches the transition regime. To extend the validity of N-S based methods, slip boundary conditions are implemented [1]. These conditions allow N-S-based methods to capture the flow physics more accurately for Knudsen numbers slightly above 0.01. Consequently, an overlap region exists in which both DSMC and continuum CFD solvers are applicable, and consistency between the two approaches must be ensured.

The DSMC simulations in this work are performed using the SPARTA code [2], with a Variable Hard Sphere (VHS) collision model and a Total Collision Energy (TCE) chemistry model following the reactions described by Park et al. [3]. The CFD simulations are carried out using the commercial solver STAR-CCM+ and include chemical reactions consistent with the DSMC setup, transport properties from Gupta et al. [4], and thermodynamic properties based on NASA polynomials. The 2D analyses consider a deployable capsule in the Mars atmosphere, building upon the results of Portis et al. [5].

This work aims to improve the consistency between DSMC and continuum CFD by tailoring the CFD model so that transport properties and chemical kinetics are aligned with those used in the DSMC simulations.

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