Comparison between CFD and DSMC Analysis for a Deployable Mars Entry Vehicle

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During planetary atmospheric entry, hypersonic vehicles experience different flow regimes due to the progressive decrease in gas density —and the corresponding increase in molecular mean free path—with altitude. In the continuum regime ($Kn<0.01$) the gas behaves as a continuous medium, and the Navier-Stokes (NS) equations are applicable. As the vehicle descends from space, it first traverses the transition regime ($0.01<Kn<10$), where non-continuous effects become significant and the assumptions of continuum fluid mechanics begin to break down. In the transition regime, the Direct Simulation Monte Carlo (DSMC) method becomes necessary to accurately model gas/surface interactions and non-equilibrium phenomena. While DSMC is well-suited for rarefied conditions, it becomes computationally inefficient in the continuum regime, where NS solvers are more appropriate. Consequently, efforts to extend the applicability of continuum-based methods into the lower transition regime are of ongoing interest in entry modelling.

This work focuses on the Space Manufacturing in Situ (SMS) spacecraft, an entry capsule equipped with a deployable, flexible Thermal Protection System (TPS) [1], based on the IRENE (Italian Re-Entry NacElle) technology. The mission involves atmospheric entry into the Martian atmosphere, with particular attention devoted to the transition regime encountered at higher altitudes along the entry trajectory. Direct Simulation Monte Carlo (DSMC) analyses are performed in this regime using the SPARTA code [2]. To reduce computational cost, the applicability of the NS equations is extended into the transition regime. For this purpose, the commercial CFD code STAR-CCM+ is employed to model both the continuum regime and its extension into the lower transition regime. However, the traditional CFD approach—solving the NS equations with no-slip boundary conditions—becomes increasingly inaccurate in the transition regime, where discrepancies with DSMC results grow. The physical validity of the NS equations can be extended by implementing velocity slip and temperature jump boundary conditions, which better capture the molecular behavior within the Knudsen layer [3]. CFD analyses of the SMS geometry revealed regions within the flowfield where the continuum hypothesis breaks down, indicating a transition toward rarefied behavior. This breakdown is evaluated using the gradient-length local Knudsen number (Kn_{GLL}), a parameter tailored to characterize non-equilibrium effects in compressible hypersonic flows [4-5]. For such complex flowfields—induced by the deployable, umbrella-like shape of the TPS—comparisons between CFD and DSMC become particularly valuable. The strong expansion region caused by the TPS geometry lead to a flowfield that naturally divides into two regions: one governed by continuum behaviour and the other by the rarefied gas dynamics. DSMC simulations are carried out in the latter, using data from the CFD solutions in the continuum region as boundary inputs.

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