

## Comparison between DSMC and CFD for hypersonic planetary entry simulations

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Hypersonic planetary entry flows span a wide range of Knudsen numbers between rarefied and continuum flows. While computational fluid dynamics (CFD) techniques cannot provide an accurate solution for flows in the rarefied regime, the direct simulation Monte Carlo (DSMC) method is capable of providing accurate solutions for flows in both the rarefied and continuum regimes but becomes prohibitively expensive as the Knudsen number decreases. For the purpose of thermal protection systems (TPS) design and post-flight reconstruction, various selected points along an entry trajectory are often solved using hypersonic solvers. The quantities of interest that are obtained from the exercise are generally surface quantities, such as pressure, heat flux and enthalpy. Then, material response solvers are used to either design the heat shield to an optimal thickness based on a choice of material, or to provide in-depth heating profiles through the material at various select locations, and compare with flight instrumentation such as the ones that flew on NASA's two most recent Mars missions, MSL and Mars2020. While most of the heating is generally experienced during the continuum part of the entry, the heating within the rarefied regime is significant for some atmospheres, and hence the flow solutions need to be computed using the DSMC method. Ensuring consistency between hypersonic CFD and the DSMC is crucial so that reliable surface quantities can be passed to material response solvers.

Studies were performed to compare the two methods at select locations, for both non-reacting argon flows as well reacting  $\text{CO}_2/\text{N}_2$  flows. Preliminary conclusions show that, for non-reacting flows, the agreement between the two methods for surface heating is excellent (within expected uncertainties) for a freestream Knudsen number of 0.0006, and gets progressively worse as the Knudsen number increases to 0.06. Continuum breakdown analyses were performed and showed that, in general, the Gradient Length Local Knudsen number ( $\text{Kn}_{\text{GLL}}$ ) from Boyd [1] and associated criteria ( $\text{Kn}_{\text{GLL}} > 0.05$ ) can be accurately used to predict zones of breakdown in the flow, and associated errors for surface quantities. Furthermore, when studying reacting flow, our studies showed that while flow quantities are highly dependent on relaxation parameters and chemistry rates, it is possible to obtain a good agreement for surface heating, as long as the continuum breakdown is minimal (see Fig. 1). Finally, we studied the impact of the grid refinement on the surface quantities in DSMC.

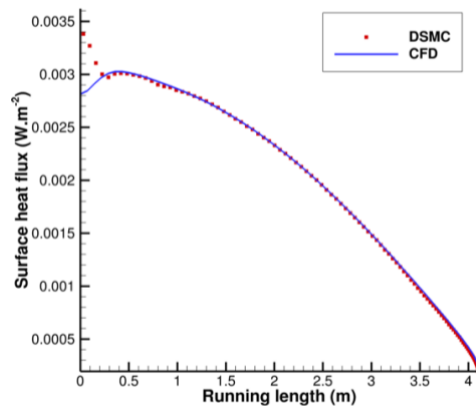


Figure 1. Surface heat flux comparisons between DSMC and CFD for a reacting ( $\text{CO}_2/\text{N}_2$  mixture) 2D axisymmetric sphere case, with  $\text{Kn}_{\text{freestream}} = 0.02$ , using a re-radiating equilibrium surface boundary condition.

- [1] I. D. Boyd, "Predicting breakdown of the continuum equations under rarefied flow conditions," *Rarefied Gas Dynamics: 23rd International Symposium, AIP Conference Proceedings*, **663**, 899, AIP (2003).

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