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Title
Exponential Differencing BGK Method for Multiscale Flow Simulation

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Abstract
When a gas flow is rarefied up to a point where the continuum assumption no longer holds, the Navier-Stokes (NS) equations fail to describe it accurately. The common numerical tool used to simulate such flows with a high Knudsen number is the Discrete Simulation Monte-Carlo (DSMC) [1]. This method, widely developed in recent years, becomes however computationally costly in transition regimes, and conducting coupled NS-DSMC simulations is particularly challenging due to the inherent differences between the two approaches. A multiscale method would thus greatly improve the efficiency and accuracy of simulations in cases where the Knudsen number varies by several orders of magnitude, such as atmospheric re-entry flows or nozzle expansions.
The Bhatnagar-Gross-Krook (BGK) model [2] offers this possibility, since it is an approximation of the Boltzmann equation that remains valid for non-equilibrium flows while allowing for numerical solvers with less strict resolution requirements as DSMC. This model can be developed into gas kinetic schemes by fully discretizing it in phase space and using a wide range of partial differential equation solvers, leading to a variety of discrete velocity methods (DVM) [3][4]. Although significant progress has been made on DVM, with many solvers offering different stability and convergence properties, the accurate discretization of the velocity space remains problematic for three-dimensional cases when the distribution function is far remote from equilibrium (e.g., shocks, high Mach number flows).
Another type of BGK methods, based on stochastic simulation particles similarly as DSMC, has therefore recently come to the fore as an efficient way to handle such flows [5]. However, the operator splitting approach it implies usually limits such stochastic particle BGK methods to explicit schemes with first order accuracy, thus requiring fine spatiotemporal resolutions.
We present here a multiscale method based on an exponential differencing of the BGK operator (EDBGK), with second order accuracy and asymptotic preserving behavior towards both continuum and free-molecular limits. The mathematical structure of our scheme allowed for an implementation, in the open-source code PICLas [6], as both a discrete velocity and a particle-based method [7] sharing the aforementioned properties. This double approach makes then possible a coupling in either velocity or physical space, using each method where they perform the best. Our EDBGK scheme is validated on several test cases and its performance compared to preexisting gas kinetic solvers.

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