The Hong Kong University of Science and Technology

Department of Mathematics

PhD THESIS EXAMINATION

The Development of Gas-Kinetic Theory Based Methods for Nonequilibrium Flow Simulations

By

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ABSTRACT

Nonequilibrium flows are encountered in diverse engineering applications with great influence on heat and mass transfer, whereas the experimental reaches are environmentally demanding and costly, hence the importance of developing numerical methods. Nonequilibrium physics can be caused by the free transport of gas molecules or physical and chemical transformation. Its accurate description requires additional degrees of freedom as macroscopic information is insufficient to fully characterize them. Therefore, the gas-kinetic theory under mesoscopic description should be employed. The unified gas-kinetic scheme (UGKS) and unified gas-kinetic wave-particle (UGKWP) method are two typical numerical methods constructed by gas-kinetic theory. Introducing degrees of freedom through deterministic discrete velocity space or stochastic particles, these methods record the evolution of the gas distribution function, and thus preserve the nonequilibrium physics of flow fields. The fluxes construction of both methods are based on the integral solution of the kinetic model, coupling particle collisions and free transport, and thus releasing the restriction on time step and mesh size imposed by the splitting methods. With these, the UGKS and UGKWP method have capability of multiscale simulations for all flow regimes. In this study, the methods are further developed in aspects of application, acceleration, and extension. The UGKWP method is applied to nonequilibrium flow simulations in near space, extended to vibrational nonequilibrium, and accelerated by adaptive wave-particle decomposition. For the UGKS, with an adaptive velocity space decomposition, the vibrational nonequilibrium with heat flux corrections is extended, an implicit acceleration is developed, and finally extended to chemical nonequilibrium. All the research in this study has been validated from classical one-dimensional cases to complex three-dimensional geometries. Overall, the study demonstrates the tremendous potential of gas-kinetic theory based numerical methods for nonequilibrium flow simulations.

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