The Hong Kong University of Science and Technology

Department of Mathematics

PhD THESIS EXAMINATION

Gas-Kinetic Theory-Based Methods for Nonequilibrium Flow Simulations: Acceleration Strategies and Applications in Aerospace and Microflows

By

Mr. Wenpei LONG

ABSTRACT

Nonequilibrium flows are frequently encountered in aerospace engineering and micro-electromechanical systems (MEMS), where traditional computational fluid dynamics methods based on continuum assumptions fail to capture rarefied gas physics. Kinetic methods like the direct simulation Monte Carlo (DSMC) are accurate but prohibitively expensive near continuum regimes. In this thesis, a series of gas-kinetic theory-based methods are presented and extended to multi scale nonequilibrium hypersonic and microflows.

The practical limits of the gas-kinetic scheme (GKS) with kinetic Maxwell boundary conditions are first established with validation against NS slip solvers, DSMC, and experiment. GKS outperforms NS slip and matches references up to 80 km, beyond which truly multiscale schemes become necessary. To address this, two methods are developed under the direct modeling framework. The unified gas-kinetic wave-particle (UGKWP) method adopts a wave-particle decomposition to efficiently resolve the nonequilibrium distribution function via stochastic particles, enabling three-dimensional re-entry and jet-shock simulations on a single workstation. The implicit adaptive unified gas-kinetic scheme (IAUGKS) couples implicit iteration and velocity space adaptation, achieving 700-fold acceleration with over half memory saving relative to the original UGKS. Free of statistical noise, the implicit UGKS captures subtle microflow phenomena with over two orders of magnitude core-hour savings over DSMC. The framework further extends to multi-species flows under the Andries–Aoki–Perthame (AAP) model with Shakhov Prandtl-number correction, yielding four orders of magnitude speedup over explicit treatment.

Together, these methods provide a framework for efficiently and accurately solving multiscale problems spanning from low-speed microflows to hypersonic aero dynamics, with promising potential for aerospace vehicle design, MEMS systems, and semiconductor manufacturing applications.

Date : 30 July 2026, Thursday

Time : 10:00 am

Venue : Room 4502 (near Lifts 25/26)

***Thesis Examination Committee*:**

Chairman	**:**	**Prof. Hongkai WU, CHEM/HKUST**
Thesis Supervisor	**:**	**Prof. Kun XU, MATH/HKUST**
Member	**:**	**Prof. Tiezheng QIAN, MATH/HKUST**
Member	**:**	**Prof. Zhichao PENG, MATH/HKUST**
Member	**:**	**Prof. Zhigang LI, MAE/HKUST**
External Examiner	**:**	**Prof. Kailiang WU, Department of Mathematics/ Southern University of Science and Technology**

(Open to all faculty and students)

The student's thesis is now being displayed on the reception counter in the General Administration Office (Room 3461).