

Development of Particle and Mesh-Particle Hybrid Methods for Multi-Phase Flow Simulations

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(多相流シミュレーションのための粒子法及び格子-粒子ハイブリッド法の開発)

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論 文 内 容 の 要 旨

For design and safety of nuclear reactors, we have to analyze complex thermal-hydraulic problems, and many phenomena in them include multi-phase flows with large deformation of phase interfaces. Up to now, the vast majority of computational fluid dynamic (CFD) studies performed to address this issue have been based on Eulerian approaches. However, conventional Eulerian mesh methods revealed their limitation in representing essential characteristics of multi-phase flows, namely interface phenomenon between two different phases. As fully Lagrangian methods, particle-based methods can implicitly track the phase interface. In addition, there is no numerical diffusion arising on interfaces since no convection term is required to solve governing equations in the particle methods. However, they would cause unphysical numerical oscillations in pressure and need large calculation resources to perform simulations, compared with mesh-method calculations on a similar scale. On the other hand, a hybrid Eulerian-Lagrangian method, where the advection of fluid phase is handled in a Lagrangian manner, while fluid velocity and pressure information is constructed on a fixed Eulerian grid, makes use of advantages in both approaches. Therefore, in the present study, advanced CFD methods widely applicable to multi-phase flow simulations were developed based on particle and mesh-particle hybrid methods.

In this study, first the finite volume particle (FVP) method was extended to multi-phase flow simulations especially to cope with a numerical instability problem attributed to large difference in phase properties. A computational framework for simulations of multi-phase flows with solid-rich phases was also developed by introducing solid-phase interaction models. Subsequently, a particle-mesh hybrid method was developed for efficient and accurate simulations of multi-phase flows. This mesh-particle hybrid method was also extended to calculate heat transfer with phase change and compressible flows. The present thesis is divided into six chapters.

Chapter 1 introduces the background and objective of the present study. Overviews of CFD methods for multi-phase flow simulations are described.

Chapter 2 describes fundamental models and methods for particle-based simulations including the FVP method, governing equations and their solution algorithm, and treatment of boundary conditions. The FVP method was extended to multi-phase flow simulations by couplings the distinct element method (DEM) to calculate interactions among solid particles. In multi-phase flow simulations, serious numerical instability could be caused by large change in density and viscosity on the interface between gas and liquid phases. To

eliminate this problem, a new two-step pressure solution algorithm, which solves the Navier-Stokes equations of gas and liquid phases separately, was implemented into the FVP method. An interface sharpness model was also introduced to capture the interface by numerical particles clearly.

In Chapter 3, validation of the developed FVP method is presented based on fundamental two-phase and three-phase flow simulations. Simulations of a single bubble rising in a stagnant liquid show good agreement with a conventional shape regime map in both terminal bubble shape and velocity even for density and viscosity ratios of 1,000 between two phases. Both the two-step algorithm and the interface sharpness model contribute to improve the numerical stability of the FVP method successfully. A newly performed experiment of a single bubble rising in a solid particle-liquid mixture was simulated to investigate applicability of an apparent viscosity model and an empirical drag force model to represent solid particle-fluid interactions as well as DEM to gas-liquid-solid three-phase flow simulations. The calculation considering effective viscosity of the mixture reproduced reasonable change in bubble shape and rise velocity. The results demonstrate that the present computational framework of particle-based method is useful for simulations of multi-phase flow behaviors in solid particle-fluid mixtures.

Chapter 4 describes fundamental models of the developed mesh-particle hybrid method, which couples the constrained interpolated profile/multi-moment finite volume method (CIP/MM FVM) and the FVP method. In this hybrid method, the main part of flows is solved by CIP/MM FVM, while the interface between two phases is captured by the FVP method. Numerical particles in the FVP method are distributed only on the surface of liquid to capture the interface between liquid and gas phases, and they are used to determine fluid density of each mesh grid. Physical models to calculate heat transfer between phases and compressible flows using this hybrid method is also described. The developed hybrid method enables accurate interface tracking without impairing numerical efficiency.

In Chapter 5, the developed hybrid method was validated by simulating several conventional benchmark problems. The simulation of water column collapse resulted in accurate agreement with measured movement of a column with large interface deformation. The hybrid method reproduced experimental data on shape change patterns of a single bubble rising in liquid and droplet breakup induced by a velocity difference appropriately. For heat transfer calculations, the simulations of a 1D Stefan problem and horizontal film boiling indicate that the present hybrid method is applicable to two-phase flow calculations with phase change occurring at moving interface. In addition, the simulation of bubble compression behavior presents that the developed hybrid method was successfully extended to calculate mixed compressible and incompressible flows simultaneously. In these benchmark simulations, the present hybrid method required less than one-tenth the computation time of the particle method calculations. The present validation comprehensively demonstrates that the developed hybrid method is potentially useful to simulate gas-liquid two-phase flows under various thermal-hydraulic conditions efficiently.

Chapter 6 draws a conclusion of this thesis. For future extensive works, several directions were also suggested.