論 文 の 内 容 の 要 旨

論文題目　A numerical framework for simulations of gas-solid-liquid flows with complex geometries
（複雑壁面境界内の固気液三相流問題の数値解析）

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The work in this thesis is dedicated to the numerical modeling of complex multiphase flows, specifically the gas-liquid flows and gas-solid-liquid flows interacting with general geometries. Those flows involving free surface, granular particles and complicated boundaries are widely encountered in chemical engineering including various mixing and grinding processes, e.g. agitation tank, wet beads or ball mill, and twin screw kneader (TSK). There is an urgent need for accurate, robust and efficient computational fluid dynamics (CFD) techniques that can assist engineers in designing and optimizing their operational conditions for those industrial problems.

From an engineering point of view, key factors affecting the process performance and product quality comprise the design of stirring paddles, rotation speed, fluid filling ratio and solid load of particles; for their counterparts in the numerical perspective, the considerations of boundary shape and movement, interfacial flow motion, solid behavior and fluid-particle interaction could be important. In these respects, numerical models that are able to provide integrated solutions have not been soundly established by past studies.

Therefore, the objective of the present study is to develop a numerical framework capable for predicting the macroscopic behaviors of two- and three-phase flows within complex geometries to facilitate their practical analysis. The current numerical framework provides systematic approaches to three types of flow problems with pragmatic relevance: (a) modeling of gas-liquid flows in complex geometries, (b) macroscopic large-scale modeling of gas-solid-liquid flows in complex geometries, and (c) microscopic direct numerical simulation (DNS) of gas-solid-liquid

flows with full resolution of fluid-particle interactions. In our attempts to treat these problems of diverse complexities and scales, new computational technologies have been proposed and their validity has been tested thoroughly.

The first part of our main matter describes a computational method namely the VOF-IB method for the three-dimensional simulations of two-phase flows in general geometries. This method adopts a volume-of-fluid (VOF) approach to capture and advance the fluid interface, and it integrates the fluid solver with the immersed-boundary (IB) modeling of arbitrary-shaped walls and moving bodies. The shape and movement of general geometries are efficiently represented by an auxiliary signed distance function (SDF) field with local coordinate transformation. The VOF-IB method is a versatile two-phase solver allowing for a wide range of flow conditions as well as topological changes of the free surface. The simplicity and efficiency of its numerical algorithm are remarkable for real applications in comparison with existing CFD models.

In the second part, an Eulerian-Lagrangian model, specifically the DEM-VOF method, is proposed to perform three-dimensional simulations of gas-solid-liquid flows, for which the fluid motion is solved by using the preceding computational techniques and the distinct particle phase is tracked by the discrete element method (DEM). The fluid-particle coupling is achieved by the volume-averaging approach wherein an empirical closure is employed for the description of interphase momentum transfer. In particular, the combination of the SDF representation and the IB method tackles the modeling of complex geometries that are in simultaneous interaction with the three-phase flow. A variety of model verification and validation tests are performed to show the capability of the DEM-VOF method to simulate macroscopic three-phase behaviors such as free surface deformation, water displacement, and configuration of solid beds. Results are also presented for its successful application to a laboratory TSK system.

The last development in this thesis is undertaken for the DNS method for the microscopic modeling of gas-solid-liquid flows. The discretization of the coupled system is accomplished by an improved IB method accounting for increased accuracy and generalized fluid actions. The VOF-based interface calculation is enhanced by the level set (LS) model to treat surface tension and contact angles on solid surface. Unlike the macroscopic model for large-scale simulations needing closure equations for unresolved terms, the DNS-based method can fully resolve the gas-solid-liquid interactions inclusive of both the fluid-particle hydrodynamic force and the particle-interface capillary force dominant in a typical three-phase flow system. Hence the DNS method is conceptualized as a supportive tool to validate and develop useful correlations for the large-scale simulations. Such an example is shown in this part to establish a preliminary link between the two levels of numerical modeling.