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A hybrid particle-mesh method for viscous, incompressible, multiphase flows

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Abstract

A hybrid method to simulate unsteady multiphase flows in which a sharp interface separates incompressible fluids of different density and viscosity is described. One phase is represented by moving particles and the other phase is defined on stationary mesh. The flow field is discretized by a conservative finite volume approximation on the stationary mesh, and the interface is automatically captured by the distribution of particles moving through the stationary mesh. The effects of surface tension and wall adhesion are evaluated by the continuum surface force model. The different phases are treated as one fluid with variable material properties. Advection of fluid properties such as density and viscosity is done by following the motion of the particles. The method simplifies the calculation of interface interaction, enables accurate modeling of two- and three-dimensional multiphase flows and does not impose any modeling restrictions on the dynamic evolutions of fluid interfaces having surface tension. Several two-dimensional numerical simulations are given to illustrate the efficiency of the hybrid method.

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Keywords: Multiphase flow; Hybrid method; Particle method; Mesh method; Interface tracking; Finite volume method; Surface tension; Wall adhesion; Contact angle

1. Introduction

Accurate simulation of multiphase flows with a sharp interface has considerable difficulty in numerical methods. Problems with a moving interface are important in many technological applications in which

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moving interfaces play a dominant role. Capillarity phenomena, wetting effect, deformation of droplet or bubble, motion of boundaries between immiscible fluids are some of well-known examples in engineering and science. In order to describe quantitatively such problems, the understanding of physical processes taking place on the interfaces is necessary. In particular, successful simulation of the moving interfaces depends on the numerical method in which the corresponding interfaces can be captured effectively.

The most popular approach to compute multiphase flows is to capture the front directly on a regular, stationary mesh. For example, marker-and-cell (MAC) [1] method uses marker particles to identify each fluid. The volume-of-fluid (VOF) [2] method uses a marker function to identify the interface. The main difficulty in using these methods is the maintenance of a sharp boundary between two phases and the computation of surface tension. Further developments to the methods that capture fluid interfaces on a fixed grid include the CIP [3] method and the phase field method [4], etc.

Adaptive (moving) grid methods alter the computational grid so that the interface always coincides with one of the grid lines. The interface is then a well-defined, continuous curve. The information regarding the location and curvature of the interface is readily available. The review of techniques for the construction of boundary conforming coordinates is referred to [5]. The main advantage of this approach is that it is possible to maintain sharp resolution of the interface, while the main disadvantage is the difficulty in adjusting the grids to follow the highly deformed interfaces.

The front tracking is another method where the interface itself is descried by additional computational elements, and the fixed grid is kept unchanged. The major difficulty of direct front tracking is the question of how the interface grid interacts with the stationary grid, and vice versa. It is also necessary to restructure the interface grid dynamically as the calculations proceed. Computational points must be added in regions where the interface grid points become scattered, and eliminated from regions of concentration. Another problem in front tracking results from the interaction of a front with another front. Double interfaces have to be merged into one interface or eliminated. A merging algorithm is usually used. A development to this method made by Tryggvason et al. [6] is a hybrid between front capturing and front tracking technique. A stationary regular grid is used for the fluid flow, but the interface is tracked by a separated grid of lower dimension. However, unlike front tracking methods where each phase is treated separately, all phases are treated together by solving a single set of governing equations for the whole field. The explicit tracking of the interface reduces errors associated with the surface tension computations, and its flexibility makes it applicable to problems where complex interface physics must be accounted for. The specific difficulties with front tracking are discussed by Glimm et al. [7] and two computational algorithms to handle changes in the interface topology for dynamic interface tracking in three dimensions have been described [8].

From the point of view of numerical algorithms, the methods mentioned above are classified as Eulerian method. Lagrangian method is another category, which is suited for moving boundary problems because it permits interfaces to be specifically delineated and precisely followed and it allows interface boundary conditions to be easily applied [5]. The two main problems of the Lagrangian methods are mesh tangling and numerical inaccuracy due to highly irregular meshes. Particle method is another Lagrangian description of flows in which particles are explicitly associated with different materials and thus the interfaces can be easily followed. The well-known example is the particle-in-cell (PIC) [9] algorithm. The basic idea of PIC is to divide the region of interest into regular Eulerian cells for purposes of computing field variables such as pressure and fluid velocity, and to simulate the material transport from cell to cell in a Lagrangian fashion in the form of discrete simulation particles. The attractive features of the method are no mass diffusion and the ability of treating large distortions of fluids, large slippages, and colliding interfaces. The problems consist of a large numerical diffusion caused by transferring the momentum from the grid to the particle and back, numerical noise caused by the use a finite numerical of fluid particles, and limited spatial resolution because of a fixed uniform Eulerian grid being used.