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Direct Numerical Simulation of Bubble-Particle Interaction by Combination of Immersed-Boundary and Volume-of-Fluid Methods

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ABSTRACT

In this paper, we report an improvement for numerical simulation of gas-liquid-solid three-phase flows[1]. In our simulation, flow around each particle and flow in both sides of gas-liquid boundary can be directly captured. Then the method is applied to a flow including multiple bubbles and particles.

Momentum exchange between the fluid and solid phases is treated by our original immersed boundary method (IBM) of body-force type[2, 3], which has enabled direct numerical simulation of interaction between a fluid and rigid spherical particles of a total number of $O(10^3)$. In the present study, the interface of two immiscible fluids (gas and liquid) is captured by the volume of fluid (VOF) approach[4]. The interface is reconstructed by mixed Youngs-centered method and advected by split Lagrangian explicit scheme[5]. In this approach, a volume-averaged velocity field (of the existing phases) is governed by the Navier-Stokes equation of motion and the equation of continuity. The equations are temporally integrated by fractional procedures based on Adams-Bashforth method with a specially designed interaction force of body force type[2, 3], irrespective of the substances (gas, liquid or solid) occupying each cell. The treatment for moving interface established in our IBM for fluid-solid system can be coupled consistently with VOF method to deal with gas-liquid-solid three-phase flows. Poisson equation for pressure is solved by BiCGSTAB method to allow high density ratio of liquid to gas.

In our IBM, time-advancement of the solid phase is completed by integrating the fluid forces over the domain including particle volume. This procedure considerably simplifies the inter-phase momentum exchange, as the momentum exchange is done through the fixed Cartesian grid shared by both Eulerian and moving Lagrangian frames, rather than a coupling of the phases by cross-interpolation of physical properties between the two references. Also, the use of the same body force for the phases in a cell guarantees no leakage in the momentum exchange between the phases.

To validate present method, the problem about lifting a circular cylinder from water is simulated. It is represented that the cylinder is detached from the surface and water droplets drip down from the water film(Figure1). The result is in good agreement with theoretical result without breakup of the freesurface[6].

Further applicability of the present method is demonstrated in a 3-D flow field under the effect of gravity. In the present work, a total of 10^2 monosized spherical particles are tracked allowing six degrees of freedom (translation and rotation) for each particle. Figure2 shows a snapshot of a part of three-phase flow field, in which velocity vectors of liquid flow are shown in a cross section. The deformation of bubbles due to the interaction with solid particles through liquid flow is efficiently captured. In this study, it has been showed that the present method allows to solve solid-multiple fluids interaction over independent of the form of fluid interface (bubble, droplet, freesurface) with high accuracy.

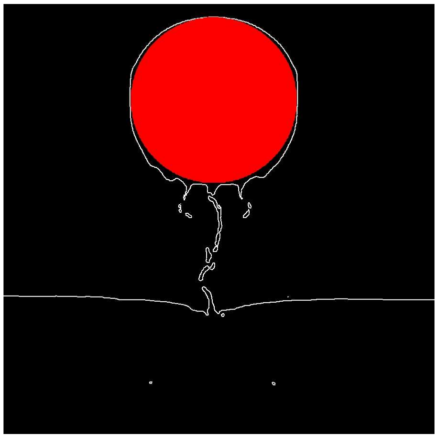

Figure1 : Computational result of breakup of the water surface due to lifting a circular cylinder.

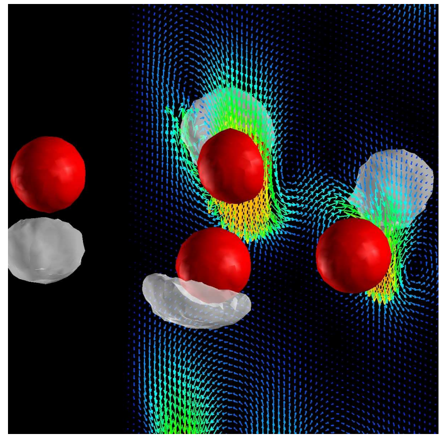

Figure2 : Close-up image of bubbles-particles interactions and surrounding liquid field.

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