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Sharp interface Cartesian grid method II: A technique for simulating droplet interactions with surfaces of arbitrary shape

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Abstract

A fixed-grid, sharp interface method is developed to simulate droplet impact and spreading on surfaces of arbitrary shape. A finite-difference technique is used to discretize the incompressible Navier–Stokes equations on a Cartesian grid. To compute flow around embedded solid boundaries, a previously developed sharp interface method for solid immersed boundaries is used. The ghost fluid method (GFM) is used for fluid–fluid interfaces. The model accounts for the effects of discontinuities such as density and viscosity jumps and singular sources such as surface tension in both bubble and droplet simulations. With a level-set representation of the propagating interface, large deformations of the boundary can be handled easily. The model successfully captures the essential features of interactions between fluid–fluid and solid–fluid phases during impact and spreading. Moving contact lines are modeled with contact angle hysteresis and contact line motion on non-planar surfaces is computed. Experimental observations and other simulation results are used to validate the calculations.

Keywords: Multiphase flow; Sharp interface method; Cartesian grid; Level-sets; Droplet impact

1. Introduction

In Part I [18] an easily implemented three-dimensional sharp interface treatment was developed for solid–fluid boundaries immersed in flows. The method relied on a framework that meshes well with the sharp-interface ghost fluid method (GFM) [4,12,16] for fluid–fluid boundaries. In this paper, the sharp-interface treatment of the solid–fluid boundaries is combined with the GFM to simulate interactions between

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droplets and solid surfaces. The challenge here is to treat all interfaces sharply while allowing for large interface deformations, including fragmentation, and to handle moving contact line dynamics. Treatment of contact line conditions is fairly challenging with the level-set method when compared to say the VOF method [2] or Lagrangian finite element methods [5]. In the VOF approach the contact angle can be imposed by reconstructing the partial volume in the fluid–fluid interface cell that lies adjacent to the solid surface such that the reconstructed surface (typically a plane) assumes the specified contact angle with respect to the solid surface [2]. In the Lagrangian moving mesh approach the mesh node that lies on the solid surface can be moved to apply the desired angle [5]. For junctions between multiple fluid phases several techniques [26,32] have been investigated in the level-set framework. For solid–fluid–fluid tri-junctions, Sussman [27] has presented a technique for applying contact angles. An alternative approach based on a local level-set reconstruction was outlined by Noble et al. [20]. This second approach has been modified and advanced in the present work; it was found to be more suitable for situations such as droplet impact, where the contact angle evolves from the pre-impact to the spreading and equilibrium resting situations. Additionally, the method is designed to enable simulations of droplet spreading on arbitrarily shaped solid surfaces.

2. Methods for simulation of droplet impact

Harlow and Shannon [9] were the first to simulate droplet impact on a solid surface. A ''marker-and-cell'' (MAC) finite-difference method was used to solve the NS equations. To simplify the problem, viscosity and surface tension were neglected so that a physically accurate representation was obtained only for the very initial inertia-dominated stages after impact. Later workers [30] improved the MAC model of Harlow and Shannon to include surface tension and viscosity effects.

The volume-of-fluid (VOF) method has been used frequently in studying droplet-wall interactions. Trapaga and coworkers [28,29] applied a commercial code FLOW-3D, using VOF tracking, to study isothermal impingement of liquid droplets in a thermal spray process. Liu et al. [17] used a VOF-based code, RIPPLE [14] to study the impact of a molten metal droplet and its subsequent solidification. Pasandideh-Fard et al. [22] have shown that the values of contact angle can significantly influence model predictions in combined experimental and numerical studies of droplet impact. The VOF method has also been applied to simulate droplet spreading by Renardy et al. [24] for droplets in prior contact with a wall.

Lagrangian finite-element methods were used by Fukai et al. [5–7] to model droplet impact normal to a flat plate. Like most previous researchers, experimentally measured contact angles were used as inputs to their previous numerical model. With the inclusion of contact angle dynamics, their model reproduced experimental data, not only in the spreading phase but also during recoil and oscillation. Baer et al. [1] used a simple but computationally tractable linear variation between contact line velocity and contact angle in their 3D simulations. They successfully captured contact angle hysteresis and critical contact angles.

The level-set method was used in combination with a curvilinear grid finite-volume approach by Zheng and Zhang [33] to study droplet spreading and solidification. However, they did not compare their predictions of droplet shapes during impact with experimental or numerical results. Recently the phase field method, has also been applied to simulations of wetting and spreading of droplets on surfaces [11].

Three-dimensional simulations of droplet impact have only been possible in recent years. Bussmann et al. [2] demonstrated a three-dimensional, finite difference, fixed-grid Eulerian model using VOF tracking. Droplet impact and spreading on surfaces of arbitrary shape has also received limited theoretical treatment in the literature [23]. Droplet impact on an inclined plane and on a step was simulated in [2]. Although their model for the variation of contact angle with velocity was simplified, the 3D model yielded good predictions of gross fluid deformation during droplet impact onto an incline and onto an edge.

In the following sections a sharp-interface method is described for the simulation of droplet/ bubble interactions with arbitrary solid interfaces. The method relies on level-set representations of all interfaces