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Direct numerical simulation of a hydrodynamic interaction between settling particles and rising microbubbles

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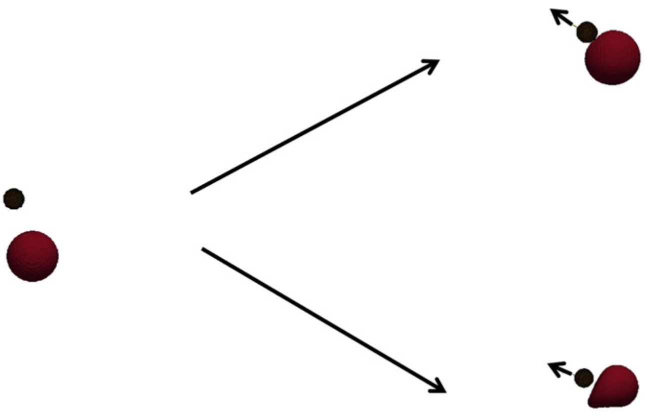
HIGHLIGHTS

- A single multiphase DNS framework for particle–bubble interactions in a liquid.
- Simultaneous handling of both deformable and non-deformable objects in a fluid.
- Validated against a series of well-established results from the literature.
- Influence on attachment from initial separation, particle density & bubble shape.

GRAPHICAL ABSTRACT



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ABSTRACT

We present in this paper a framework for Direct Numerical Simulation (DNS) of flows involving non-deformable (solid particles and spherical bubbles) and deformable (bubbles and droplets) moving objects suspended in a fluid (liquid or gas). The simulation framework is based on solving a shared set of momentum equations for the phases involved. Special care is taken to adapt the method for simulating solid particles in a flow. We first validate the framework with a series of well-established results from the literature. Then, we demonstrate its capabilities by investigating the influence of relevant parameters (e.g. the shape of the bubble, particle density and the separation distance) on the behaviour and the interaction of deformable and non-deformable objects in the flow. The suggested framework successfully reproduces both the particle–bubble attachment when the initial horizontal distance between their centres is small, and that the particle passes the bubble without attaching when this distance is large. Furthermore, we show that the probability of a successful attachment decreases if the bubble Eötvös and Morton numbers are substantially larger than unity. Finally, we demonstrate the capability of the proposed method to handle flow situations that involve a simultaneous presence of both multiple solid particles and multiple deformable objects.

1. Introduction

Multiphase flows with a simultaneous presence of both non-deformable (solid particles and spherical bubbles) and deformable objects (bubbles and droplets) suspended in a liquid or gas are

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ubiquitous in a great number of industrial processes. The interaction between such objects characterizes, for example, the collection of solid particles in flotation or describes changes in overall fluid rheology and dynamics in the oil and gas industry. Typically, models in those applications depend extensively on empirical constants and are regularly limited to a particular process of interest. To overcome this difficulty, it is clear that there is a need for studies that describe the interaction between bubbles and particles from first principles and in great detail. An example of the latter type of study is to perform direct numerical simulations (DNS) in order to get a full resolution of the behaviour of single or of a group of bubbles and solid particles in a carrying fluid. To be precise, under the term "multiphase DNS" we denote numerical simulations of multiphase flows where one fully resolves the temporal and spatial scales relevant to the fluid dynamics. In other words, when conducting DNS of multiphase flows, one computes the time-dependent flow field for a system that is sufficiently small so that it can be fully resolved, but large enough so that relevant scale interactions are captured (Tryggvason et al. [1]). With such techniques, the Navier–Stokes equations are solved directly together with a method for taking the presence of immersed objects into account. Some of the most common multiphase DNS methods include Volume of Fluid (VOF), front tracking, the immersed boundary method and smoothed particle hydrodynamics (SPH) (see e.g. Hirt and Nichols [2], Tryggvason et al. [3], Peskin [4] and Monaghan and Kocharyan [5]). This work also deals with DNS, and we apply it to the interaction of bubbles and solid particles suspended in a carrying fluid.

From a modelling point of view, the interaction between bubbles and particles (and the possible creation of agglomerates as a desired outcome in e.g. flotation) can be studied from two perspectives: a hydrodynamical one and a physicochemical one. In practice, the process comprises several phases: it starts with the approach of a bubble to a particle and then continues with thinning of the intervening liquid between the two in order to form a film at a critical thickness. Afterwards, the liquid film ruptures, that leads to collision and the subsequent attachment of a particle to a bubble [6]. In flotation, solid particles are typically below 100 μm, whereas bubbles are somewhat above that size (often termed "microbubbles"). The aim is that particles get attached to bubbles and that they then rise together through a suspension. Finally, the created agglomerates are skimmed from the surface of the suspension [6]. Froth flotation, ion flotation, foam fractionation, waste water treatment, and foam separation of proteins are only several examples of such processes in which millions of tons of material are treated annually [7]. Comprehensive computational fluid dynamics (CFD) models of, for example, mineral flotation have been presented by Koh and Schwarz [8–10]. These models are based on an Eulerian–Eulerian approach in which the phases (one termed the pulp phase, representing the liquid–solid phase, and the gas phase) are understood as interpenetrating continua. Those studies resulted in relevant information on both the interaction between bubbles and solid particles, and on the overall behaviour in a flotation cell. However, since the size of the formed aggregates in mineral flotation is not significantly different from that of the bubbles, detailed information about the hydrodynamics of the formation and flow of aggregates may not be needed. In the current work, the intention is to study these hydrodynamics to obtain information needed in other flotation techniques, where bubbles and particles are of similar size (e.g. waste water treatment).

Successful attachment of particles to bubbles depends on a number of parameters, such as the separation distance, bubble and particle size, particle density, hydrophobic or hydrophilic properties of the particle surface, concentration of surfactants, as well as the forces between the bubble and the particle [11]. The separation distance is understood as the initial horizontal distance between centres of gravity of a bubble and a particle, when the process of interaction has not yet commenced. As for the forces, they can be generally divided into surface and hydrodynamic forces. The surface forces are van der Waals and electrostatic forces. They become significant when the distance between bubble surface and particle surface is very low, typically 100 nm [7,11]. On the other hand, the hydrodynamic repulsion force, gravity, and buoyancy belong to the hydrodynamic forces.

Various DNS techniques have been used in the literature for investigating the behaviour of isolated bubbles and the interaction between bubbles and solid particles. Dijkhuizen et al. [12] employed the front tracking technique and studied the drag force on single bubbles rising in a liquid. The authors obtained drag closures valid for both spherical and deformed bubbles. Deen et al. [13] used a combined front tracking and immersed boundary method to examine a flow with a simultaneous presence of bubbles and solid particles. The immersed boundary part of the procedure was used for modelling the behaviour of a solid particle in a fluid. The study showed potential of such a method to investigate flows in which significant topological changes in the interface are present. Another interesting technique for studying in detail the problems involving interfacial dynamics is to use smoothed particle hydrodynamics (SPH). Recently, Shadloo et al. [14] demonstrated the potential of SPH when they looked at the Rayleigh–Taylor instability problem in an incompressible viscous two-phase immiscible fluid and when effect of the surface tension is manifested.

In this paper, we also limit ourselves to hydrodynamic forces. We propose a multiphase DNS method capable of resolving both the motion and the interaction of solid particles and bubbles in a single framework. The method is based on solving a shared set of mass and momentum balance equations on a single Eulerian mesh for all the phases involved. A suitable framework in this case is the Volume of Fluid (VOF) multiphase model. For applications involving fluid-like particles, VOF is considered appropriate [15], since it is relatively straightforward to implement and computationally efficient as it avoids explicit computation of the hydrodynamic force and torque on the particles [16]. Special effort, however, needs to be invested in adapting the method for simulating solid particles. Apparent particle viscosity and a velocity field correction algorithm are used for that purpose (see Section 2.1). The suggested procedure guarantees that the no-slip boundary condition is applied at the surface of moving solid particles and that the interface separating the fluids (i.e. the phases involved) is tracked accurately. In the present work we examine a particular situation when a solid particle is settling in a carrying liquid and when it interacts with a rising microbubble. Apart from varying a number of physical properties, our main interest is in investigating how a solid particle will hydrodynamically interact with a non-deforming (i.e. spherical) and a deforming bubble respectively. Note that here we are primarily interested in fully resolving the motion of such objects. Therefore, phenomena such as the existence of the gradient of surfactant concentration on the bubble surface (known as the Marangoni effect) are not included in the modelling procedure. The definitive goal is to determine how variation in the listed parameters affects the probability of collision and formation of agglomerates.

2. Proposed simulation framework

We consider here a three-phase flow problem: water as the surrounding fluid, an air bubble as the gas phase, and a solid particle as the solid phase. The VOF method was originally proposed by Hirt and Nichols [2] for simulation of gas–liquid and liquid–liquid systems. As indicated above, using VOF for simulating solid particles requires some additional considerations and assumptions that will be discussed after introducing the governing equations.