Direct Numerical Simulation of Particle Mixing in Dispersed Gas-Liquid-Solid Flows using a Combined Volume Of Fluid and Discrete Particle Approach

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Introduction

Dispersed gas-liquid-solid flows are frequently encountered in a variety of industrial processes involving a.o. coating, granulation, drying and synthesis of fuels (Fischer Tropsch) and base chemicals. The dynamics of these flows is dictated by the motion of the individual phases and the complex mutual interactions and as a direct consequence thereof CFD-based modelling of these systems has proven notoriously difficult. In literature both the Eulerian and Lagrangian method have been adopted to study multiphase flows. Although these computational methods are in principle well-suited to simulate the large-scale flow behaviour problems arise related to the representation of the interactions between the individual phases (closure problem).

In this paper a novel simulation approach will be presented for dispersed gas-liquid-solid three phase flows accounting for i) all important mutual interactions between the phases ii) all relevant forces acting on the phases iii) the three-dimensional nature of the flow. In view of its fundamental nature, it is an important complementary tool in developing closure equations for the Eulerian approach.

Computational model

Our model is based on a combined Volume Of Fluid (VOF) and Discrete Particle (DP) approach applied for respectively dispersed gas bubbles and solid particles present in the continuous liquid phase. The VOF method constitutes a powerful and efficient Direct Numerical Simulation (DNS) technique for complex free surface problems. Our VOF implementation is based on a piecewise linear interface representation (PLIC-VOF) for two-material flows embedding a three-dimensional version of the CSF model for the computation of the surface tension force. In our model relatively high values for the density and viscosity ratio (typically one hundred) can be used without an adverse effect on the stability and the required computational effort. Traditionally systems with a high density and viscosity ratio have proven difficult to simulate as reported by Scardovelli and Zaleski (1999).

In DP individual particles are tracked taking into account i) all relevant external forces (gravity, pressure, drag, lift and virtual mass forces) acting on the particles and ii) collisions between particles and confining walls. Finally, two-way coupling, which becomes important at high solids volume fraction, is also taken into account. In this study the hard sphere DP model, originally developed by Hoomans et al. (1996) for gas-solid systems, has been extended to account for all additional forces acting on particles suspended in a viscous liquid and has been combined with the VOF model presented recently by van Sint Annaland et al. (2005).
Results

In this paper the physical foundation of the combined VOF-DP model will be presented together with illustrative computational results highlighting the capabilities of this hybrid model to study in detail bubble-induced particle mixing in three-phase systems. Specifically the effect of gas bubbles (rising in isolation or in a swarm) on particle mixing and bubble-wake-induced particle transport will be quantified focusing on the effect of the particle physical properties such as density and size. Below a typical result is presented, showing the co-axial rise and coalescence of two gas bubbles rising through a suspension of $10^5$ particles in an initially quiescent viscous Newtonian liquid. Through the Lagrangian treatment of the particles the bubble-induced particle mixing can be quantified and studied in great detail.

Figure 1: Co-axial rise and coalescence of two gas bubbles (initial diameter 0.01 m) rising through a suspension of $10^5$ particles (diameter 200 $\mu m$, density 3000 kg/m$^3$) in a quiescent viscous liquid (viscosity 0.0467 kg/(m.s); density 1000 kg/m$^3$) using a 80x80x160 computational grid.