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Influence of the lift force in direct numerical simulation of upward/downward turbulent channel flow laden with surfactant contaminated microbubbles

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Abstract

In this work, we employ direct numerical simulation of turbulence one-way coupled to Lagrangian tracking to investigate microbubble distribution in upward and downward channel flow. We consider a closed channel flow at $Re_\tau = 150$ and a dispersion of microbubbles characterized by a diameter of 220 μm. Bubbles are assumed contaminated by surfactants (i.e., no-slip condition at bubble surface) and are subject to drag, gravity, pressure gradient forces, Basset history force and aerodynamic lift.

Our results confirm previous findings and show that microbubble dispersion in the wall region is dominated by the action of gravity combined with the lift force. Specifically, in upward flow, bubble rising velocity in the wall region generates a lift force which pushes bubbles to the wall. In downward flow, bubble rising velocity against the fluid generates a lift force which prevents microbubbles from reaching the viscous sublayer.

In the wall region, we observe bubble preferential segregation in high-speed regions in the downflow case, and non-preferential distribution in the upflow case. This phenomenon is related to the effect of the lift force. Compared to experiments, the current lift force model produces larger consequences, this effect being overemphasized in the upflow case in which a large number of bubbles is segregated near the wall. In this case, the resulting bubble wall-peak of concentration outranges experimental results.

These results, so deeply related to the lift force, underline the crucial role of current understanding of the fluid forces acting on bubbles and help to formulate questions about available force models, bubble–bubble interactions and two-way coupling which can be crucial for accurate predictions in the region very near the wall.

Keywords: Bubble; Dispersion; Fluid mechanics; Multiphase flow; Simulation; Turbulence

1. Introduction

The dispersion of microbubbles in turbulent boundary layers has relevance in a number of engineering and environmental applications ranging from bubble columns, gas–liquid reactors, fluidized beds to the transfer mechanisms which couple ocean and atmosphere. In all these applications, the presence of microbubbles, which reportedly are non-uniformly distributed, may significantly change transfer rates. The overall liquid–bubble interface controls gas–liquid transfer, but complex bubble motions also have an influence on overall heat, momentum and mass transfer, playing a crucial role in many industrial and environmental processes. A fashionable application due to current energy awareness is turbulent drag reduction by microbubble injection, recently examined by Madavan et al. (1984), Pal et al. (1988) and Xu et al. (2002) and strictly connected to the change of momentum transfer rate due to microbubbles.

Detailed numerical simulations are an useful tool to improve the current understanding of the local and

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instantaneous interactions between bubbles and turbulence and are thus fundamental to predict the overall system evolution. Yet, to the best of our knowledge, there are only few direct numerical simulation (DNS) studies on microbubble behavior in turbulent flows. Among them, Mazzitelli et al. (2003a,b), who studied the behavior of microbubbles in isotropic turbulence, put in evidence the importance of the lift force both for microbubble dispersion and for turbulence modification induced by bubbles. Important results were also obtained for turbulent boundary layers laden with microbubbles (Xu et al., 2002; Ferrante and Elghobashi, 2004). Ferrante and Elghobashi (2004), performed a DNS of a horizontal spatially developing turbulent boundary layer two-way coupled to Lagrangian tracking of pointsize bubbles to investigate on drag reduction by microbubbles. They found that the main effect of microbubbles is to displace away from the wall the quasi-streamwise longitudinal vortical structures which populate the near-wall region (Brooke and Hanratty, 1993; Schoppa and Hussain, 1997), thus reducing the high-shear zones and increasing the low-shear zones.

Bubble behavior in fully developed turbulent boundary layer in duct flow or pipe flow was studied in experimental works. In particular, the works by Serizawa et al. (1975), Hibiki et al. (2004), Kashinsky and Randin (1999) and Beyerlein et al. (1985) led to the conclusion that bubbles injected in a vertical pipe tend to migrate toward the walls in the case of upward flow whereas they tend to concentrate at the core of the pipe in the case of downward flow.

Felton and Loth (2001, 2002) studied experimentally the dispersion of single bubbles in a spatially developing upward turbulent boundary layer. They investigated the specific bubble diameter range of $d_p \in [0.37\text{–}1.2]$ mm, to ensure observing spherical, non-deformable bubbles. They again observed the existence of bubble preferential location which peaks at the wall, this effect being stronger for larger bubbles. A further exploration of this diameter-modulated behavior of microbubble was conducted by Tomiyama et al. (2002) who studied bubble motion in a upward shear flow driven by a moving wall for a wide range of bubble diameters. They observed that, due to shape deformation, larger bubbles (i.e., d_p larger than about 5 mm) move away from the wall, whereas smaller bubbles move towards the wall (in agreement with previous results). They also observed that bubble lateral migration decreased for very small bubbles ($d_p < 0.4$ mm). In connection to the influence of the wall, Takemura and Magnaudet (2003) recently underlined that current lift force model may be inadequate to compute the transverse migration bubble velocity specifically in the wall region: wall effects may be thus crucial in limiting wall-peak accumulation of bubbles.

In previous papers (Marchioli and Soldati, 2002; Marchioli et al., 2003), we characterized the interactions between inertial microparticles and wall turbulence structures, identifying the mechanisms that control the macroscopic non-uniform particle distribution in the wall region of a boundary layer: particle concentration increases in the wall region due to synchronicity between particle transfer and wall turbulence regeneration cycle at the wall. It may be argued that the turbulence structures control bubble transport as well. Yet, due to the very low inertia of the bubbles, we expect preferential bubble concentration to arise from mechanisms which are different from those leading to particle preferential concentration (Maxey, 1987). In the case of microparticles, segregation in boundary layer is due to the large influence of inertia on particle motion in the viscous sublayer, the lift force adding just a quantitative correction to particle behavior. In the case of microbubbles, the aerodynamic lift force is expected to have a dominant effect.

The mechanisms which drive bubbles to the wall in upward flow and away from the wall in downward flow are connected to the driving action of the quasi-streamwise vortices in the wall layer combined to the action of gravity and lift force. Quasi-streamwise vortices have streamwise axis and populate the wall region in the range $z^+ \in [8\text{–}50]$, where they generate jets of outer fluid towards the wall and jets of wall fluid towards the outer region (Schoppa and Hussain, 1997). Both in upward and downward case, bubbles are driven through the last stretch to the wall by the quasi-streamwise vortices. In downward flow, the action of gravity and lift generates a resulting force which pushes bubbles *towards* the inner region of the quasi-streamwise vortices which in turn drive again bubbles away from the wall. In upward flow, gravity and lift combine to push bubbles *away* from the vortex, from which bubbles are thus disengaged. At the same time, they are pushed in a region very near the wall where jet flows directed away from the wall are much less energetic and frequent.

This work focuses precisely on the effect of the lift force on bubble behavior in the wall-region of vertical turbulent channel flow. In particular, we will examine the influence of turbulence on particle distribution in the wall region and we will quantify the role of the forces acting on bubbles and inducing their preferential distribution.

To this object, we ran numerical simulations of upward and downward turbulent channel flow. For each case the trajectories of $O(10^5)$ bubbles were tracked (under one-way coupling assumption) with and without the inclusion of the lift force term in the equation of motion. Our simulations mimic the physics of a dilute swarm of very small microbubbles moving in upward or downward vertical channel flow added with surfactants. Due to the presence of the surfactants, no-slip condition is imposed on bubble surface. Since bubble density is negligible compared to that of the fluid, the bubbles can be considered as *massless spheres* (Ferrante and Elghobashi, 2004), and the effect of bubble internal circulation can be neglected. Due to the small diameters we perform Lagrangian tracking under the pointsize approximation of rigid spherical bubbles.