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Two-way coupling simulations of a bubble swarm in a vertical turbulent channel flow

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Object of this work is to study the behavior of a microbubble swarm in a vertical turbulent channel flow. A two-way coupling approach on a upward/downward flow under an imposed pressure gradient is considered. The presence of bubbles is seen to increase/decrease the driving pressure gradient, respectively in upward/downward flow, thus yielding to an increase/decrease of the wall shear and of the shear Reynold number. For the considered bubble average volume fraction ($\alpha = 10^{-4}$), the corresponding shear Reynolds numbers are about $Re_{\mathrm{t},2U} = 174$ for the upflow case and $Re_{\mathrm{t},2D} = 121$ for the downflow case in agreement with a simplified force balance on the entire domain. Deviations from simple models are attributed to non uniform bubble distribution - and hence the body force distribution on the fluid - in the domain. The non uniform distribution is investigated carefully examining statistics of the flow variables. A detailed account of the reasons for bubble preferential distribution is supported in the contest of the dynamics of turbulence wall structures.

1. Introduction

Bubbly flows play an important role in a wide variety of areas, ranging from biomedical field, environmental phenomena, industrial applications to chemical processes. In all these applications the presence of microbubbles which are non-uniformly distributed, may significantly change transfer rate: the overall liquid-bubble interface controls gas-liquid transfer, but complex bubble motion also have an influence on overall heat, momentum and mass transfer, playing a crucial role in many industrial and environmental processes. Due to their importance, bubbly flows have been extensively analyzed and several studies, mainly experimental, are available in the literature. However, the complete understanding of the dynamics of bubbly flows is still a challenging task, due to the large number of factors affecting the interactions between the bubbles and the surrounding fluid. Detailed numerical simulations are an useful tool to improve the current understanding of the local and instantaneous interactions between bubbles and turbulence. Yet, to the best of our knowledge, there are only few numerical studies on microbubble behavior in turbulent flows. Giusti et al. (2005)

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underlined the importance of the lift force effect on bubble behavior with a numerical simulations of a swarm of microbubbles dispersed in a turbulent vertical close channel flow. Mazzitelli et al. (2003a), simulated the behavior of microbubbles in isotropic turbulence and the turbulence modification induced by microbubbles (Mazzitelli et al., 2003b). Xu et al. (2002) and Ferrante and Elghobashi (2004) investigated microbubble power to reduce the skin friction drag in horizontal turbulent boundary layers.
In this work, a direct numerical simulation of turbulence is coupled to the Lagrangian tracking to study the behavior of 220*μm* and 110*μm* bubbles in a vertical turbulent channel flow. The two-way coupling approaches and both upward and downward flows are considered with the same external imposed pressure gradient. In the coupled cases, the presence of bubbles increase/decrease the driving pressure gradient, respectively in upward/downward flow, thus yielding to an increase/decrease of the wall shear stress and of the shear Reynold number. The interactions between bubble and the near-wall turbulence structures is also investigated and a preferential bubble segregation in high-speed/low-speed zones is observed for the upflow/downflow cases respectively.

2. Computational Methodology

Air bubbles (ρ_p = 1.3 kg/m^3, ν_p = 1.57 10^{-6} m^2/s) are dispersed in a fully-developed turbulent flow of water (ρ_p = 10^3 kg/m^3, ν_p = 10^{-6} m^2/s) driven by an imposed streamwise pressure gradient dp/dx . The flow is bounded by two infinite flat parallel walls with origin of the coordinate system located at the channel centerline and the *x*, *y*, and *z* axes pointing in the streamwise, spanwise and wall normal direction respectively. Periodic boundary conditions are imposed on the fluid velocity field both in *x* and *y*; no slip boundary condition are enforced at the walls. Two flow configurations were considered: downflow, where the pressure gradient acts in the same direction as gravity, and upflow, where the pressure gradient acts in opposite direction.
Since the pressure gradient is the same for all simulations, we can compute the shear velocity as $u_{\tau} = \sqrt{\frac{dp}{dx}\frac{h}{\rho}}$, where *h* is the channel half-width. All variables are normalized using $r_t\rho$ and ν: dimensionless variables (in wall units) are characterized by the superscript "+".
The dimensions of the computational domain are 1885x942x300 wall units in x*,* y and z, discretized using 128x128x129 grid points. The streamwise and spamwise grid spacings are $\Delta x^+ \sim 15$, $\Delta y^+ \sim 7.5$. The wall-normal spacing, Δz^+, ranges from 0.045 at the walls to 3.682 in the center of the channel: this grid resolution is sufficient to describe the significant length scales in the flow.

2.1 Flow Field

The flow field was calculated by integrating mass and momentum balance equations which in dimensionless form read as:

$$\frac{\partial u_i}{\partial x_i} = 0, \qquad (1)$$

And

$$\frac{\partial u_i}{\partial t} = -u_j \frac{\partial u_i}{\partial x_j} + \frac{1}{Re_\tau} \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial p}{\partial x_i} + \delta_{1,i} + f_{2W,i} \tag{2}$$

where u_i is the ith component of the velocity vector, $\delta_{1,i}$ is the mean equivalent (i.e. including the effect of gravity) pressure gradient, f_{2W} is the force per unit volume exerted on the fluid by the bubbles and $Re_\tau = hu_\tau/\nu$ is the shear Reynolds number. Eqs. 1 and 2 were solved directly using a pseudo-spectral method similar to that used by Kim et al. (1987) to solve the turbulent, closed channel flow problem and by Lam and Banerjee (1992) to solve the turbulent, open-channel flow problem. The pseudo-spectral method is based on transforming the field variables into wave-number space, using Fourier representations for the periodic streamwise and spanwise directions and a Chebyshev representation for the wall-normal (nonhomogeneous) direction. A two level, explicit, Adams-Bashforth scheme for the non linear terms $u_j \partial u_i / \partial x_j$, and an implicit Crank-Nicolson method for the viscous terms, were employed for time advancement. Details of the method have been published previously (Lam and Banerjee, 1992).

2.2 Bubble dynamics

A Lagrangian method is used to compute the trajectory of microbubbles (bubble's diameters: dp = 220 10^{-6} m (d^+ =1.65) and dp = 110 10^{-6} m (d^+ =0.825)) under the pointsize approximation. The equation, in vector form, used to calculate the time evolution of bubble velocity, $\mathbf{v}_p = d\mathbf{x}_p / dt$, is:

$$\begin{aligned} \frac{d\mathbf{v}_p}{dt} = & \left(1 - \frac{\rho}{\rho_p}\right)\mathbf{g} + \frac{(\mathbf{u} - \mathbf{v}_p)}{\tau_p}\left(1 + 0.15 Re_p^{0.687}\right) C_W \\ & + \frac{\rho}{\rho_p}\frac{D\mathbf{u}}{Dt} + C_L \frac{\rho}{\rho_p}\left[(\mathbf{u} - \mathbf{v}_p) \times \omega\right] + f_{LW}\mathbf{e}_z + \\ & + \frac{9\nu}{d_p \rho_p \sqrt{\pi \nu}} \int_0^t \left(\frac{d\mathbf{u}}{dt} - \frac{d\mathbf{v}_p}{dt}\right) \frac{d\tau}{(t-\tau)^{0.5}} \\ & + \frac{\rho}{2\rho_p}\left(\frac{D\mathbf{u}}{Dt} - \frac{d\mathbf{v}_p}{dt}\right) \end{aligned} \tag{3}$$

where, $\mathbf{x}_p$ and $\mathbf{v}_p$ are the bubble instantaneous position and velocity, $\mathbf{u}$ and ω are fluid velocity and vorticity (calculated at bubble position), d_p and ρ_p are bubble diameter and density and g is gravitational acceleration.

Right hand side terms in Eq. 3 represent the forces per unit of mass acting on a bubble and describe the effect of gravity, drag, pressure gradient, aerodynamic lift, time-history Basset and added mass force respectively.

3. Results and Discussion

The main effect of bubbles in the two-way coupling simulation is to increase the liquid flow rate in the upflow and to decrease it in the downflow, as a consequence of the buoyancy force acting on bubbles. Significant flow rate variations were observed, even for the low void fraction value considered ($\alpha = 10^{-4}$) due to the low Reynolds number (Re_τ = 150), i.e. to the low externally imposed pressure gradient of the present simulations.
The two-way induced flow rate variations are related to variations of the wall shear. In the upflow case, the wall shear is expected to increase proportionally with the void fraction. This is in agreement with the trend shown, in the low void fraction range, from the experiments of Liu (1997). Similarly, in the downflow case, a wall shear decrease, proportional to the void fraction, is expected. The wall shear values resulting from present two-way coupled simulations are in agreement with the attended theoretical values (figure not presented).
For the fluid velocity turbulent intensity, the bubble two-way coupling effect is to increase the velocity fluctuations in the upflow and to decrease them in the downflow. Since these results are also affected by the change of the flow rate and, then, of the bulk Reynolds number, a new non-dimensional set of variables has been defined to compare the statistics from present two-way coupled flows with the results expected for mono-phase flows at "equivalent" shear Reynolds number. Starting from the theoretical values of the wall shear values, the statistics of the two-way upward flow and of the two-way downward flow have been shown as a function of variables made non-dimensional with respect to the shear velocity of a mono-phase flow at $Re_{\tau,UP}$ = 174 and $Re_{\tau,DW}$ = 121, respectively (figure 1). With these new non-dimensional variables, it can observe that the fluid turbulent fluctuations are lower with respect to the one-way flow at Re_τ = 150, both in the upflow and in the downflow cases. In particular, for the downflow case, we can't say whether this turbulent reduction is an effect of bubble modification of the fluid turbulent structures or is simply due to the decrease of the "equivalent" shear Reynolds number (see Moser et al., 1999). To achieve further information, we should compare the results of the present two-way downflow simulation with the statistics of a one-way coupling flow at a wall-shear Reynolds number equal to 121,1. On the other hand, for the two-way upflow case, the observed reduction of the fluid turbulent intensity, being in contrast with the expected increase related to the increase of the "equivalent" shear Reynolds number, suggests the existence of an interaction between bubbles and the fluid turbulent structures. The effect of this interaction is a decrease of the fluid velocity fluctuations. This result seems to be in agreement with Serizawa et al. (2004).

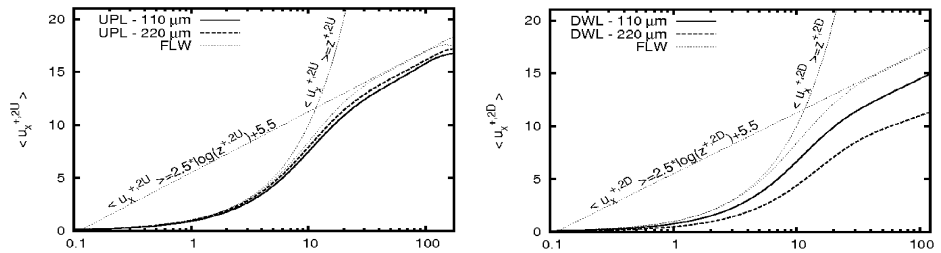

Figure 1: Streamwise component of fluid average velocity for the pure fluid (FWL) and the two-way coupling simulations, with variables made non-dimensional with respect to the shear velocities $u_{\tau,2U}$ and $u_{\tau,2D}$ respectively for upflow (UPL) and downflow (DWL) for two different bubble's diameters.

In Fig. 2 the time evolution of bubbles distribution is shown for the two bubble's diameters: 110 μm and 220 μm. Bubbles tend to migrate towards the wall in the upflow and away from the wall in downflow case. These results are in agreement with several experimental observations in bubbly turbulent flows in vertical ducts (Tomiyama et al., 2002; Ogasawara et al., 2004; Hibiki et al., 2004).

A qualitative comparison between the two simulations for different diameters can be made considering the shape of bubble concentration profiles and compating them with the one-way coupling case showed in Giusti et al. 2005. In one-way coupling case a saddle has been observed at a wall distance of about $z^+ = 1.5$. Even if it is not clear the mechanism responsible for such behavior, it seems related to the combined action of the lift force and of the interaction between the bubbles with turbulence structures capable to push the bubbles towards or away from the wall. Such a saddle is not observed in two-way coupling case, thus suggesting a possible modification of the turbulence structure induced by the bubbles. For the downflow case, as soon as the simulation starts, bubbles are swept away from the near-wall region (Giusti et al., 2005), and almost no bubble ($c = c_0 < 1$) can be found in the viscous sublayer ($z^+ < 5$); then a steady state of bubble distribution is achieved with an almost constant profile in the central region of the channel ($z+ > 10$) for both diameters. In the two-way coupling case a similar bubble concentration profiles has been observed.

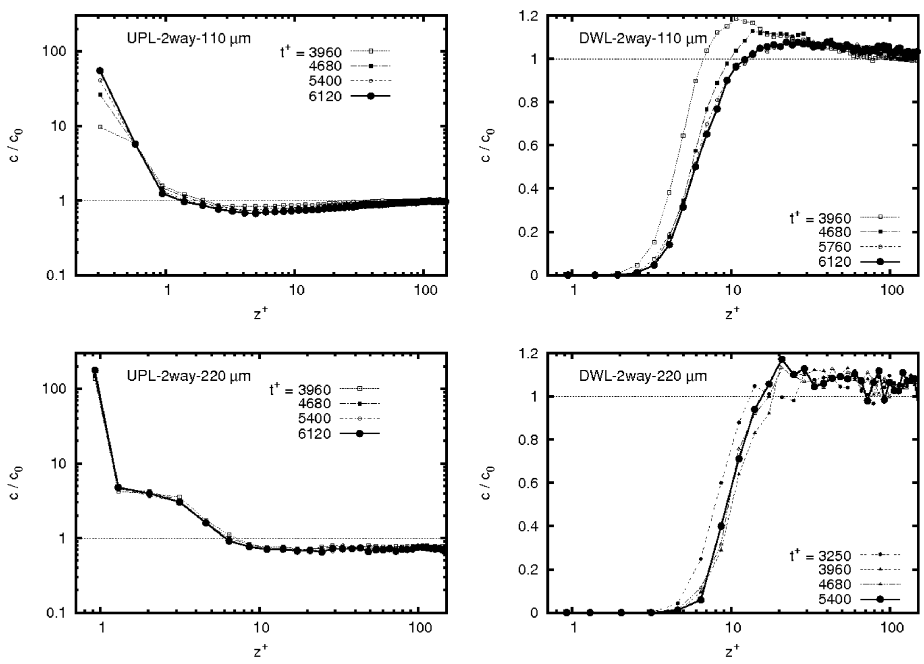

Figure 2: Time evolution of microbubbles concentration profile for the upflow (UPL) and downflow (DWL) cases for two different bubble's diameters.

From a quantitative point of view, in the two-way coupled simulations, the region with almost no bubbles ($c{=}c_0 < 1$) is enlarged ($z^+ < 7$) for the 220 μm bubbles, instead for the 110 μm bubbles it is comparable with the one-way coupling simulation. Also the distance from the wall ($z^+ > 20$) at which the concentration profile starts to be almost constant value has increased for the bigger bubble diameter. Again, bubble distribution seems to achieve a steady state, since profiles referred to different instants are almost superimposed.
As a possible future development, the inclusion of a bubble bubble interaction model as well as of a two-way coupling

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