Studies of Bubbly Channel Flows by Direct Numerical Simulations

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ABSTRACT

Recent DNS studies of buoyant bubbly flows in vertical channels are discussed. Simulations of nearly spherical bubbly flows in vertical channels show that the bubbles move towards the wall for upflow and away from the wall for downflow in such a way that the core is in hydrostatic equilibrium. For downflow the wall layer is free of bubbles but for upflow there is an excess of bubbles in the wall layer. The liquid velocity in the core is uniform. For laminar downflow the velocity in the wall layer can be computed analytically and for turbulent flow the velocity is given (almost) by the law of the wall. For upflow the velocity is strongly influenced by the presence of the bubbles. Results from several simulations, fully resolving the flow around each bubble, are used to discuss the effect of void fraction and bubble size for turbulent downflow.

INTRODUCTION

Bubbly flows in vertical pipes and channels are encountered in a wide variety of industrial systems. The best-known early study of such flows is by Serizawa, Kataoka and Michiyoshi [1,2] who examined experimentally the void fraction distribution and the velocity profile in turbulent air-water bubbly flows. Other experiments have been done by Wang, Lee, Jones and Lahey [3], Liu and Bankoff [4], Liu [5], Kashinsky and Randin [6], So, Morikita, Takagi, and Matsumoto [7], and Guet, Ooms, Oliemans, and Mudde [8], for example. The results show that for nearly spherical bubbles the void fraction distribution and the velocity profile in the core of the channel are relatively uniform and that a void fraction peak is generally found near the wall for upflow but not for downflow. Sufficiently deformable bubbles, on the other hand, show exactly the opposite behavior and migrate to the center of the channel in upflow and toward the walls in downflow. A number of authors have also developed two-fluid models of bubbly flows in vertical channels. General descriptions of the two-fluid model can be found in [9,10], for example. Numerical studies, using the two-fluid model can be found in Lopez De Bertodano, Lahey, and Jones [11,12], Kuo, Pan, and Chieng [13], and Guet, Ooms and Oliemans [14], and others. The model results generally reproduce the experimental results reasonably well.

While the flow is likely to be turbulent in most cases of practical interest, laminar flow is an important limiting case that can be used to explore aspects of multiphase flow modelling that do not depend on the specifics of the turbulence. This was recognized by Antal, Lahey and Flaherty [15] who developed a two-fluid model for such flows and compared the model predictions with experimental predictions. The agreement between the model and the experiments was good, although for upflow there is a need to introduce a wall repulsion force to keep the centre of the bubbles at least a radius away from the walls and the authors observed some dependency on the exact value of the lift coefficient used. Other studies of laminar flow include the experimental investigation by Song, Luo, Yang, and Wang [16] who studied flows with both uniform and nonuniform distribution of bubble sizes and Lou, Pan, and Yang [17] who examined the motion of light particles. Both studies were done for upflow and both found wall peaking.

NUMERICAL METHOD

In the simulations discussed here, the flow is taken to be incompressible and the governing equations are solved by a second-order accurate projection method on a fixed and staggered grid. The original method has been described in detail [18,19] and additional validation tests are described in [20]. For the simulations presented here we started with a fully parallel code written in Fortran 90/95 for the simulations presented by Bunner and Tryggvason [21]. Three major changes have been made for simulations of bubbles in a turbulent channel flow. First, the code is changed to accommodate non-uniform grids in the wall-normal direction. As the Reynolds number is increased, the resolution requirement increases, particularly near the wall. Non-uniform grids, clustered in the near wall region, are frequently used in simulations of wall boundary flows. Secondly, the demand on the advection solver also increases as the Reynolds number increases and we have implemented a third-order upwind scheme (QUICK) instead of the centred difference scheme used by Bunner and Tryggvason [21] to allow us to accurately deal with such systems. Centred difference schemes often lead to unphysical oscillatory behaviour or disastrous non-convergence in regions where advection strongly dominates diffusion. And thirdly, a nonconservative form of the governing equations is used in the new code. The original code used a conservative form of the governing equations, and it is found to cause increasing irregularities in the velocities near the front for high Reynolds number flows. The new code was tested extensively by comparing it with the original code (which has been thoroughly validated) and by grid refinement studies. It has already been successfully used in our simulations of bubble-induced drag reduction (Lu, Fernandez, and Tryggvason [22]).

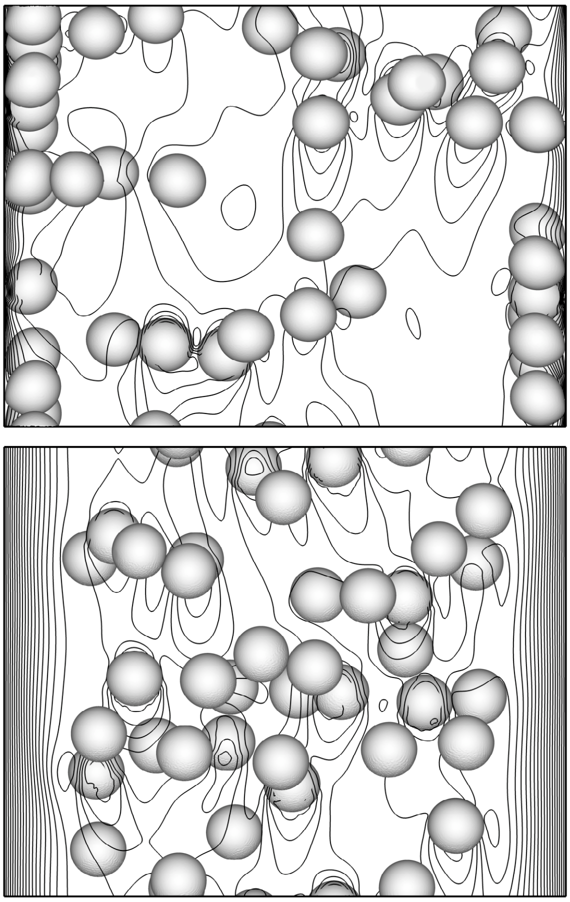

***Figure 1**. The bubble distribution at one time for upflow (top) and downflow (bottom). Isocontours of the vertical velocity are also shown for a plane going through the center of the channel.*

LAMINAR BUBBLY CHANNEL FLOWS

In this section we review briefly recent results for the motion of several nearly spherical bubbles in laminar flow in a vertical channel, both for upflow and downflow, where all flow scales are fully resolved. The simulations showed that in both cases the flow consists of two well-defined regions: A thin wall-layer and a homogeneous core, occupying most of the channel. The formation of these regions is due to lift induced lateral motion of the bubbles. For a nearly spherical bubble rising due to buoyancy in a vertical shear, it is well known that the lift force pushes the bubble toward the side where the liquid is moving faster with respect to the bubble. Thus, in upflow a bubble near the wall is pushed toward the wall and in downflow the bubble is pushed away from the wall. The weight of the bubble/liquid mixture and the imposed pressure gradient must be balanced by a shear stress due to a velocity gradient. For upflow the mixture, on the average, must be sufficiently light so the imposed pressure gradient can push it upward. As bubbles are removed from the core, its average density increases until the weight is balanced exactly by the pressure gradient. The shear is then zero and the migration of the bubbles to the wall stops. For downflow the opposite happens. Bubbles move into the core and make it more buoyant, until its weight is balanced by the pressure gradient and further lateral migration is stopped. Thus, in both cases

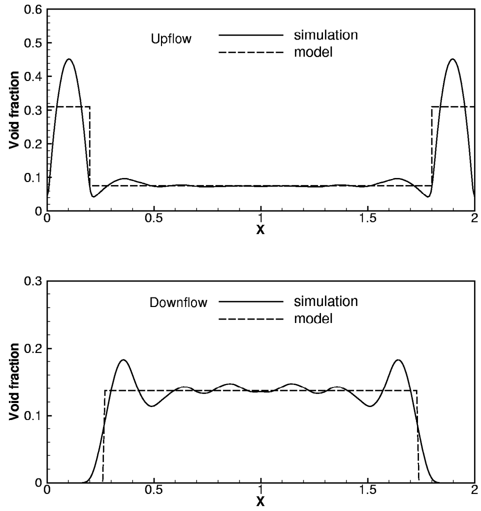

***Figure 2.** The average void fraction profiles across the channel for upflow (top frame) and downflow (bottom frame). The dashed line is the results of a simple analytical model.*

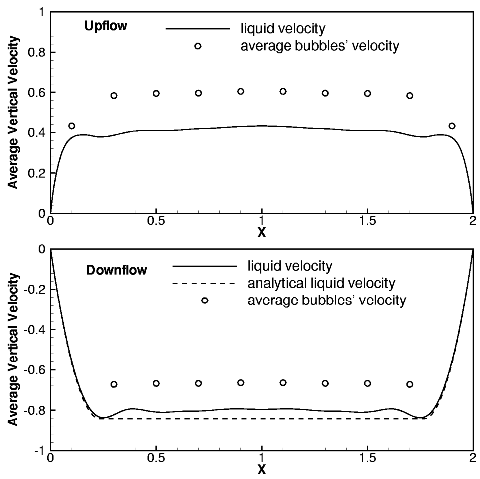

***Figure 3.** The average liquid velocity across the channel for upflow (top frame) and downflow (bottom frame). The open circles are the average bubble velocities. For the downflow, the dashed line shows the predictions of a simple analytical model.*

the core is in hydrostatic equilibrium and it is only in the wall-layer where there is a non-zero velocity gradient. For upflow where the weight of the mixture in the core is increased by pushing bubbles to the wall, the bubble rich mixture in the wall-layer is driven upward by the imposed pressure gradient. For downflow, on the other hand, bubbles must be drawn away from the wall to decrease the weight of the mixture in the core and the dense bubble-free wall-layer is driven downward by its weight and the imposed pressure gradient. This distribution is stable in the sense that if too many bubbles end up in the wall layer for upflow, the core slows down with respect to the wall layer, thus generating shear that will drive the bubbles out of the wall-layer. Similar if too many bubbles end up in the core for downflow, its velocity is reduced and bubbles are driven back to the wall. Figure 1 shows the bubble distribution and the vertical velocity at one time for both upflow and downflow. The average void

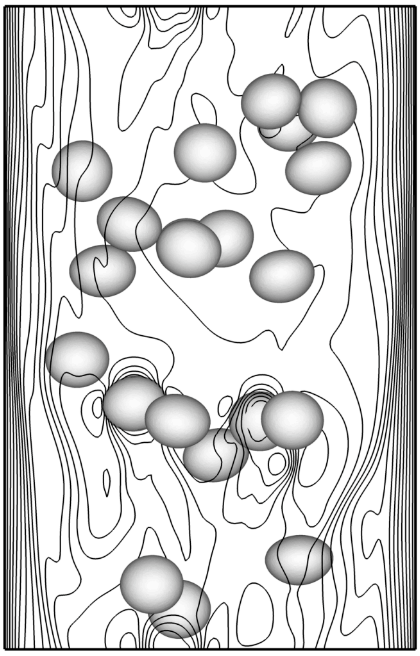

Figure 4. *One frame from a simulation of turbulent bubbly downflow in a channel. The bubble distribution and iso-contours of the vertical velocity in the middle plane of the channel are shown.*

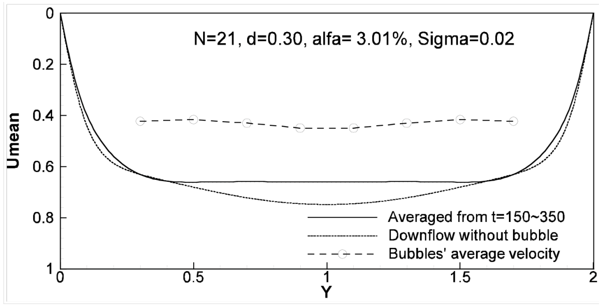

Figure 5. *The average vertical liquid velocity profile across the turbulent channel for one case. The solid lines is the simulated result, averaged over 200 time units. The dashed lines is the simulated result of the single phase downward flow. The dashed line represent the average bubble velocities in 10 equal sized bins across the channel.*

fraction is easily predicted given the considerations explained above and in figure 2 the average void fraction profile across the channel is plotted along with the model predictions. Obviously the agreement is excellent (the shape of the void fraction profile in the wall layer for upflow is different from the average, but the exact shape can be obtained also by assuming that the bubbles are nearly spherical).

For downflow, where the wall-layer is bubble free, the velocity profile is easily found by integrating the Navier-Stokes equations for steady laminar parallel flow and the flow rate can be predicted analytically, with a fair degree of accuracy. For upflow, on the other hand, the presence of the bubbles makes the situation more complex and the velocity profile is not as easily found. Figure 3 shows the average velocity profile across the channel for upflow and downflow. For downflow the model predictions are also included. Since the velocity increase across the wall-layer determines the liquid velocity in the core of the channel, it is critical for predicting the total flow rate. For the most part the bubbles in the wall layer interact only weakly with the bubbles in the core layer and as a first approximation it seems that they can be neglected, as long as the fluid is in hydrostatic equilibrium and the shear there is zero.

While the basic structure of bubbly flow in a channel has been observed experimentally before, we have not found the simple picture outlined above described in the literature. Experimentally the flow is generally made more complex by variables not completely under the control of the investigator (such as the distribution of bubble sizes, contamination, and so on). We therefore believe that these results are a powerful demonstration of the potential for scientific discovery through computations. Although the elegance of the final result is the simplicity of the flow structure, we note that the computations were far from trivial. In addition to computational issues such as accuracy and resolution, considerable effort was necessary to ensure that the flow had reached an approximately steady state. For more details of our study of laminar bubbly flows, see [23].

TURBULENT CHANNEL FLOWS

Simulations of bubbly flows in turbulent channels, although not nearly as complete yet as for laminar channels, suggest that the simplifications seen for laminar flow carry over, at least to some extend, to turbulent flows. We have started by looking at bubbles in a turbulent downflow in some detail. For the downflow case we expect the lift force to drive nearly spherical bubbles away from the walls, as for the laminar flow case. The velocity in the bubble free wall layer should therefore be given by the standard law of the wall. The main complication is if that if the wall layer is too thin, the presence of the bubbles may prevent the growth of turbulence structures near the wall and if the wall-layer is too thick, the core may meander in an unsteady way. Results obtained so far suggest that even for a very thin wall-layer (less than fifty wall units thick) the turbulence is sustained but that for thick wall layers the boundaries may vary in time due to meandering of the bubbly core. One frame from a simulation of bubbles in a turbulent downflow is shown in figure 4. The average void fraction profile and the average liquid velocity is shown in figure 5, where we also plot the average velocity in the absence of bubbles. For turbulent flow the velocity in the middle of the channel is relatively uniform in the absence of bubbles and since the main effect of adding the bubbles is to make the velocity there completely uniform, adding the bubbles causes surprisingly little change in the velocity. The main increase in velocity takes place in the bubble free wall layer where the velocity profile remains nearly the same and while the turbulent velocity profile without bubbles is not completely flat as it is after adding the bubbles, the differences are small. Since the flow in the core of the channel is uniform, the turbulent Reynolds stresses there are zero and in the buffer layer these are reduced. The slow growth of the velocity in the buffer layer and the wall region is also cut short at the outer edge of the wall layer and replaced by the uniform velocity characterizing the bubbly core. We are currently extending these results by examining additional cases. We do believe, for example, that the bubble size will have relatively little effect on the velocity profile, although the rise velocity of smaller bubbles will certainly be smaller than for larger bubbles at the same void fraction.

CONCLUSION

While the basic structure of bubbly flows in a vertical channel has been observed experimentally before, the computational studies discussed here have allowed us to explore the dynamics in detail in a very well-controlled and characterized situation. Results for both laminar and turbulent flows show that the structure of the flow is determined by the lift on the bubbles. At steady state the flow in the center of channel is in hydrostatic equilibrium for both upflow and downflow (as also found by Azpitarte and Buscaglia [24], and the dynamics is well described by results for homogeneous flows. The wall region is, however, very different for up-and downflow. For downflow, where there are no bubbles near the wall, the flow is particularly simple. In upflows, when the wall layer contains a large number of bubbles, the dynamics depends sensitively on both the number of bubbles and their deformability. Further studies of bubbly wall layers are in progress.

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