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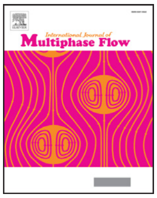

# Large eddy simulation of microbubble transport in a turbulent horizontal channel flow

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ABSTRACT

Liquid-gas multiphase flows occur in many engineering and environmental applications, with the former ranging from the flow of oil and gas in pipelines, of steam and water in nuclear reactors and steam generators, and the evaporation and condensation of refrigerants in refrigeration and air conditioning equipment. In this paper, the dispersion and interaction between microbubbles and turbulence in a horizontal channel flow is investigated using a two-way coupled Eulerian–Lagrangian approach based on large eddy simulation. The microbubbles are considered to be spherical and non-deformable, and are represented by a Lagrangian bubble tracking technique, with the bubbles subject to drag, gravity, buoyancy, shear lift, added mass and pressure gradient forces. Dynamic calibration of a Smagorinsky-type sub-grid scale (SGS) closure is employed to account for the unresolved stresses, whilst a stochastic Markov method is used to describe the effect of the SGS velocity fluctuations on bubble dispersion. Channel flows of water at two shear Reynolds numbers, $Re_\tau = 150$ and 590, and three different bubble diameters, $d_b = 100$, 220 and 330µm, are simulated. The results show acceptable agreement with DNS predictions of single- and two-phase flows, with the low density microbubbles migrating towards the upper channel wall with time under the influence of buoyancy, and segregating in the upper half of the channel, with this effect increasing with bubble diameter. The accumulated bubbles near the upper wall modify the liquid velocity field, with the mean velocity profile becoming asymmetric as a consequence and with slight modification of the turbulent stresses. At higher mean velocity and turbulence levels, the buoyancy effect is reduced due to more effective turbulent dispersion of the microbubbles, leading to reduced bubble migration towards the upper channel wall.

## 1. Introduction

Liquid-gas bubbly flows are frequently encountered in a wide variety of engineering, environmental and industrial applications, including boilers, distillation towers, chemical reactors, oil pipelines and nuclear reactors, amongst many others. The dynamics of bubbly flows are strongly sensitive to the flow regime, bubble size and shape, bubble velocity and void fraction, hence it is imperative to account for these parameters in order to accurately and reliably predict bubbly flow behaviour which is of importance to the operational safety, control and reliability of the type of industrial equipment noted (Hassan, 2014). Dispersed bubbly flows, where gaseous bubbles are present in a continuous liquid flow, and in general most particle-laden two-phase flows, are predicted using either Eulerian–Eulerian or Eulerian Lagrangian approaches, with attendant advantages as well as short comings (Njobuenwu et al., 2013). In this work, the Eulerian–Lagrangian approach is adopted since this method is expedient in terms of the broad motivation of our research which necessitates the accurate tracking of individual bubbles, with their subsequent coalescence due to collisions and break-up due to shear forces monitored. Hence, the subsequent discussion is limited to studies that employed this approach. In the Eulerian–Lagrangian approach, the liquid phase is treated as a continuum in the Eulerian reference frame in which the flow and turbulence are obtained by modelling or simulation, and the dispersed gas phase is treated in a Lagrangian reference frame with the individual bubbles in the system tracked by solving Newton's second law, whilst accounting for the forces acting on the bubbles.

Amongst the different types of bubbly flow, the use of microbubbles injected near a wall into a turbulent flow can generate drag reductions of up to 80%, with reductions of even small amounts being extremely beneficial to pumping and pipeline system efficiency, and skin friction reduction on ships (Apte et al., 2003; Lu et al., 2005). Recently, a series of comprehensive reviews

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of drag reduction by microbubbles was published by a number of researchers (Ceccio, 2010; Murai, 2014; Paik et al., 2016; Pang et al., 2014; Watamura et al., 2013). Bubble size has been found to be a critical factor, with drag reduction only possible when the bubble diameter is less than about 1 mm, and with drag reduction rates generally higher with smaller bubble diameters.

As demonstrated by several studies of bubbly flows, the effect of bubbles and microbubbles on the liquid velocity and turbulence field is extremely complicated and depends on many factors, such as the bubble size and shape, void fraction, gas and liquid velocities, and the flow direction of the liquid (Kitagawa et al., 2005; Wang and Maxey, 1993). Bubbles experience a transverse lift force when moving in a shear or rotational flow, and this plays a decisive role in the lateral distribution of these bubbles in pipes and other industrial flows. In upflow, bubbles move faster than the liquid and, as long as their shape remains close to spherical, they are pushed towards the wall by the lift force. Here, when the bubbles are very close to the wall, the flow of liquid between the bubbles and the wall generates a wall lubrication force that tends to keep the bubbles from contacting the wall (Giusti et al., 2005; Molin et al., 2012). In downflow, the bubbles move slower than the liquid and are pushed towards the centre of the flow and away from the walls (Wang et al., 1987). In addition, when the diameter of a bubble increases beyond a certain value, deformation of the bubble by the inertia of the surrounding liquid can alter the fluid circulation around it, changing the sign of the lift force that consequently pushes the bubble, in upflow conditions, towards the centre of the flow (Ervin and Tryggvason, 1997). Several extensive studies have been carried out on the lift force (Auton, 1987; Auton et al., 1988; Lighthill, 1956) and numerous correlations for this force proposed (Hibiki and Ishii, 2007), among which is the model of Legendre and Magnaudet (1997) that is used in the present work. Nevertheless, the motion of bubbles in turbulent flows and near walls continues to be a topic of considerable interest, as shown by recent studies (de Vries et al., 2002; Jeong and Park, 2015) that considered how the trajectories of bubbles near walls change with bubble size. For relatively low Reynolds numbers, buoyant microbubbles generally rise unsteadily, with repeated interactions between the bubbles occurring (de Vries et al., 2002). This trend is, however, statistically steady and the average motion (averaged over time and space) does not change with time.

But in many practical applications (Wörner, 2012), the Reynolds number is considerably higher and bubbles at high enough Reynolds numbers rise unsteadily, either wobbling as they rise or rising along a spiral path. The direct numerical simulation (DNS) studies of Esmaeeli et al. (1994) found that two-dimensional bubbles in periodic domains start to wobble at much lower rise Reynolds numbers than their three-dimensional counterparts, and that bubbles slow down significantly once they start to wobble. Göz et al. (2002) also observed a chaotic motion for real (three-dimensional) deformable bubbles rising at high enough Reynolds numbers. However, since air bubbles are deformed to a spherical-cap shape only when their diameter is higher than a critical value, such motions might not be observed under normal conditions. From experimental work, Ellingsen and Risso (2001) suggested that the wobbling mode may be a transitionary phase and that wobbly bubbles could eventually rise along spiral paths, if sufficient time were allowed.

Direct numerical simulations of such flows, with homogeneous bubble distributions in fully periodic domains, have been used to obtain results for the bubble rise velocity, velocity fluctuations, and the average relative orientation of bubble pairs (Ferrante and Elghobashi, 2004; Giusti et al., 2005; Mazzitelli et al., 2003; Molin et al., 2012; Pang et al., 2014). Xu et al. (2002) obtained results that increased understanding of turbulent boundary layers laden with microbubbles. Esmaeeli and Tryggvason (1998) used DNS to examine the motion of up to 324 two-dimensional, or 8 three-dimensional, rising bubbles at low Reynolds numbers, similar to those typical of Stokes flows. The results show that a regular bubble array is unstable and that it breaks up in two-bubble interactive systems. At low Reynolds numbers, in agreement with Stokes flow predictions, a freely evolving bubble array rose faster than a regular one, with this trend reversed at higher Reynolds numbers. Due to the rapid increase in the computational resources required to perform such simulations with Reynolds number, however, such studies are mainly limited to low Reynolds number flows. Whilst most of the research on channel flows has been focused on the use of DNS, different authors have employed large eddy simulation (LES) coupled with a Lagrangian bubble tracker to study hydrodynamics, coalescence and break-up in bubbly flows, mainly in square cross-section bubble columns (Delnoij et al., 1997; Deen et al., 2001; van den Hengel et al., 2005; Lau et al., 2014). Instead, in this work, large eddy simulation is used to study the flow of microbubbles in a horizontal channel, with specific consideration of bubble interaction with the turbulent flow, as part of an ongoing development of high accuracy computational fluid dynamic tools of value to the prediction of industrial flows. In LES, filtered forms of the Navier-Stokes equations are solved, with only the large scales of turbulent motion resolved, whereas the sub-grid turbulent scales and their effect on the mean flow are modelled. In liquid-gas flows, the large scale turbulent structures interact with bubbles and are responsible for the macroscopic bubble motion, while small scale turbulent structures only affect small scale bubble fluctuations. Since large energy-containing motions are explicitly captured in LES, and the less energetic small scales are modelled using a sub-grid scale (SGS) model, LES can reasonably reproduce the statistics of bubble-induced velocity fluctuations in the liquid. The LES code is coupled with a Lagrangian bubble tracker and extended to study the dynamics of microbubbles in turbulent channel flows. Given the basis of the predictive methods noted, the overall approach can be expected to properly describe the scales which are responsible for the interactions between the continuous and dispersed phases and, at the same time, to permit subsequent extension to other more complex flows of engineering interest because the overall approach is less-demanding in terms of computational resources than DNS-based methods. The results described are of benefit in improving our understanding of bubbly flows, and hence are relevant to the understanding of more complex industrial flows.

The overall model is applied to the flow of air microbubbles in a horizontal water channel flow. Results are validated against the DNS results of Pang et al. (2014) at a shear Reynolds number, $Re_\tau = 150$ and a microbubble diameter, $d_b = 220\,\mu$m. Additional simulations are made at the higher shear Reynolds number of $Re_\tau = 590$ to study the effect of higher turbulence levels on bubble concentration towards the upper wall promoted by buoyancy, and the modifications induced by the presence of these bubbles in the continuous phase field. Also, two additional bubble sizes ($d_b = 110$ and $330\,\mu$m) are considered at both shear Reynolds numbers to investigate the complex mutual interactions between turbulence, bubble diameter and preferential bubble concentration near the upper wall. The work described forms the basis for further extensions of the overall model to handle more complex phenomena such as bubble deformation, collision, break-up and coalescence, the full implementation of which will allow the model to be deployed to study a wide range of industrially relevant flows. An illustration of how the model can be extended to address bubble coalescence is also included in this work. The paper is structured as follows. Section 2 describes the numerical model, with details of the numerical solution given in Section 3. In Section 4, the results of the simulations are presented and discussed, with concluding remarks in the final section.