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Effect of velocity fluctuations on the rise of buoyant bubbles

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ABSTRACT

The rise and shape oscillations of bubbles in a homogeneous, isotropic turbulent flow are studied numerically and compared to bubbles rising in quiescent liquid. The disturbances are generated by applying a pseudo-spectral forcing method on a fully periodic domain where a body force is randomly distributed in Fourier space at small wave-numbers. This produces velocity fluctuations at large length scales while the smallest length scales evolve naturally as a solution of the Navier–Stokes equations. Simulations of various cases considering a less deformable bubble ($Eo = 1$) and a more deformable bubble ($Eo = 4$) were carried out. The simulations were performed for clean bubbles without a surface tension gradient. The forcing parameters were chosen such that the bubble size is about equal and half the integral length scale. The mean rise Reynolds number ranged from 58 to 94, the ratio of the isotropic liquid velocity fluctuation to the bubble rise velocity varied from 0.01 to 0.12 and Stokes numbers ranging from 0.3 to 13.2, depending on the characteristic time scales of the liquid flow, were computed. The results for bubbles rising in a liquid with imposed velocity fluctuations revealed a reduction of the bubble rise velocity of up to 38% and an increase of the bubble velocity fluctuations, mainly caused by an increase of the lateral bubble motion. While minor changes in the average deformation for less deformable bubbles were found, the ellipticity of deformable bubbles increased up to 9.8%. The fluctuations of the orientation angle, as well as the angle of motion, were also increased. The characteristic frequencies of path oscillation and the frequencies of the shape and orientation angle were determined. Besides the amplification of dominant frequencies it was found that the frequency range expanded to lower and higher frequencies for simulations with forced velocity fluctuations.

1. Introduction

Bubbly multiphase flows play a critical role in many industrial processes, including the production of synthetic fuel, as well as in determining the transfer of gases between the atmosphere and the oceans. Although the behavior of bubbles has been studied extensively, both experimentally and numerically, the main focus has been on quiescent, laminar or shear flows whereby studies of turbulent flows are restricted to modest Reynolds-numbers. Since industrial and natural flows are usually turbulent, it is necessary to investigate the influence of turbulence on the rising characteristics of bubbles, including the path and shape oscillation, for a detailed modeling of bubbly multiphase flows.

Bubble motion in turbulent flows. As bubbles rise due to buoyancy through vortical structures in turbulent flows, the bubbles modify the existing turbulence. Their motion also stirs up the liquid and causes velocity fluctuations which differ from those existing in single-phase flows [1–3]. These disturbances are often referred to as pseudo-turbulence in order to distinguish them from turbulence caused by the unsteady vortical motion in single phase flows. The bubble motion itself is also strongly affected by the ambient vortical structure. Thus we are faced with a highly complex and coupled system where sorting out the role played by each process is a formidable task.

One of the main difficulties in examining how bubbles and turbulent flows affect each other is setting up the problem. Researchers have used essentially three different approaches: (i) Relying on the motion of the bubbles to generate the turbulence; (ii) injecting bubbles into already turbulent flows and examining the flow as the turbulence decays; (iii) or generating the turbulence using an external force. The first two are the simplest but are applicable only to relatively special cases.

(i) The first approach was used, for example, in the numerical studies of homogeneous bubbly flows by Esmaeeli and co-workers [4–10]. They showed, using simulations of a few hundred bubbles in a periodic domain at low rise Reynolds

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numbers $\mathcal{O}(1)$ that the bubble interaction lead to an increase of the bubble rise velocity compared to a single bubble in a periodic domain (regular array of bubbles). This effect is reversed at moderate rise Reynolds numbers $\mathcal{O}(10\ldots30)$ with the tendency to a further decrease of the rise velocity if the bubbles start to wobble. Bunner and Tryggvason [7,8] examined three-dimensional bubbly flows of up to 216 nearly spherical bubbles at rise Reynolds numbers $\mathcal{O}(12\ldots30)$. It was found that only 12 bubbles were necessary to estimate the average rise velocity of the bubbles but the fluctuation velocities and Reynolds stress in the liquid increased with increasing the number of bubbles. Further, both the bubbles and liquid velocity fluctuations showed a strong anisotropy and that declined significantly when the void fraction was increased. Bunner and Tryggvason [9] performed simulations including 27 deformable bubbles and compared the results with results for less deformable bubbles, at $\mathcal{O}(30)$ Reynolds numbers. The study demonstrated that the deformable bubbles induced large-scale flow structures and the formation of vertical streams which resulted in larger bubble rise velocities. As a consequence of the stronger bubble wake and the interactions with the bubble stream, or plume, the velocity fluctuations of the bubbles and the liquid increased. The kinetic energy spectra revealed the production of scales larger than the bubble size implying an inverse energy cascade. The formation of bubble streams was explained by changes in the lift-force. While the lift-force of deformable bubbles drives them into the wake of other bubbles and therewith leads to an upward moving stream of bubbles, it is vice versa for spherical bubbles with the result that spherical bubbles remain nearly uniformly distributed. In addition to these studies of pseudo-turbulent two-phase flow simulations, an extension to non-isothermal flows with phase change reported by Bois et al. [11] for deformable bubbles ($Re_b \approx 50$) should be mentioned also.

(ii) For bubbles in decaying turbulence, most research has focused on how the turbulence is modulated by the presence of dispersed particles or bubbles. Lucci et al. [12] give three reasons why the turbulence modulation should be examined in decaying turbulence. First, it is not really possible to discriminate the modulation by dispersed particles from the large fluctuations of kinetic energy due to forcing. Second, although the turbulent kinetic energy is statistically stationary, for example after forcing at all wave-numbers in physical space, the energy spectrum decreases with time at large wave-numbers (small length scales) while it increases at small wave-numbers (large length scales). This contradicts the modulation effect of the particles. Third, it is difficult to separate the natural reduction of kinetic energy at small wave-numbers by the dispersed particles from the artificial amount of energy at small wave-numbers due to forcing. Recently, Balachandar and Eaton [13] reviewed studies of turbulent dispersed multiphase flow, focusing on the preferential concentration of the dispersed phase and the turbulence modulation of the carrier-phase caused by dispersed particles or bubbles. The tendency of particles heavier than the fluid to concentrate in regions of high-strain, where vortex rings form a convergence zone, is well accepted and it is known that particles lighter than fluids tend to accumulate in the vortex core. However no consistent picture can be drawn for bubbly flows in general [13]. The mechanisms of turbulence modulation and whether particles or bubbles attenuate or augment the turbulence are still insufficiently known and remain a challenge for future research [13]. Other researchers have focused on the interaction of bubbles with spatially decaying turbulence. For instance, Toutant et al. [14] reported such a study for deformable bubbles ($Re_b \approx 26$) to extract information of subgrid contributions for two-phase large eddy simulations.

(iii) For the third case a distinction must be drawn between naturally forced turbulence caused for example by wall bounded domains and synthetic forced turbulence. Naturally forced turbulence includes numerical simulations of bubbly flows in turbulent channels by Lu and Tryggvason [15–17] for example, who found that the void fraction distribution has a relatively simple structure in turbulent bubbly upward and downward flows. Other computational studies of the interaction of bubbles with turbulence in channels include [18–20], who examined bubble induced frictional drag reduction. These will be not discussed here. For a more complete compilation and discussion of computational studies of homogeneous bubbly flows and bubbly flows in channels see, for example, [21,22]. In channel flows the turbulence is generally inhomogeneous, but if the fluid is stirred continuously a statistically stationary homogeneous flow can be achieved. Furthermore, continuously generating turbulence using synthetic forcing has the charm that different length scales of the liquid motion can be investigated at different turbulence levels, even at moderate Reynolds numbers. Moreover, synthetic forcing allows us to get a statistical picture of the interactions between a bubble and the velocity fluctuations of the liquid flow at steady state. However, it is difficult to implement since the force has to be selected in such a way that it does not introduce any artificial or unphysical motion. How to implement the force has been the subject of many papers, but mostly for either single-phase flows [23–40], flows where the dispersed phase is modeled as point-particles/bubbles [41–51], or by solid particles and rigid bubbles of finite size [52–56]. For the simulations of buoyant bubbles in homogeneous isotropic turbulence conducted by Maxey and co-workers [42,43,47–51] the point-particle approximation was used. For this approximation to be valid, it is necessary that the bubble diameter is much smaller than the Kolmogorov length scale (smallest turbulence length scale). Thus, the particle relaxation time is also much smaller than the turbulence time scale, resulting in relatively weak interaction between the bubbles and the turbulence [55]. Simulations using the point-particle-approximation all show a preferential concentration of bubbles in vortices, resulting in a significant reduction of the average bubble rise velocity. In contrast to that, Wang and Maxey [41] obtained from direct numerical simulations (DNS) with heavy point-particles suspended in a turbulent flow an increase of the settling velocity up to 50% due to a preferential sweeping in downward moving fluid, since settling particles approach vortical structures usually from above. Further, they found a strong accumulation of particles on the periphery of vortices caused by inertial bias. These effects are strongest for particles with a particle response time and a terminal velocity comparable to the Kolmogorov scales of turbulence. The fluid velocity seen by a particle is not necessarily zero in a flow with zero mean, that means the effective drag is higher or lower, compared to the standard drag [13]. Two counteracting mechanisms are known to affect the settling velocity of particles [52]. The first mechanism, which decreases the settling velocity by increasing turbulence intensity, results from a higher drag because of the nonlinear drag dependence as well as loitering and vortex trapping [13,57]. The second mechanism, which increases the settling velocity results from preferential trajectories (particles try to take the fastest lane, see [41] Fig. 13) and two-way coupling effects [13,52]. These opposing