International Journal of Heat and Fluid Flow 70 (2018) 152–159

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

A numerical study of the phase distribution in oscillatory bubbly flows

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ARTICLE INFO

Keywords:
DNS
Oscillation
Bubbly flow
Cluster

ABSTRACT

The evolution of the distribution of several bubbles in a channel subjected to periodic oscillations is examined using direct numerical simulations. The flow is initially quiescent and the bubbles are randomly distributed in the domain, which is bounded by walls parallel to the direction of oscillations, and periodic in the perpendicular direction. The results show that the oscillations lead to clustering of the bubbles, generally spanning the channel cross-section. The dependency of the rate at which the bubbles clusters, the inter-cluster distances and the void fraction distribution, on the frequency and amplitude of oscillations, as well as the fluid properties, are examined.

1. Introduction

Gas-liquid two-phase flows are found in equipment used in, for example, the chemical and power industry. Understanding their behavior is essential for safety and efficiency-driven design of processes, and many studies have been devoted to such flows (Wang et al., 1987; Liu, 1993; Nakoryakov et al., 1996; Liu, 1997; Kashinsky and Randin, 1999; So et al., 2002; Guet et al., 2004; Matos et al., 2004; Mendez-Diaz et al., 2012; Descamps et al., 2008). A description of an early experimental investigation of the velocity and void fraction distribution in bubbly flows in vertical pipes can be found in Serizawa et al. (1975), and other experimental investigations of bubbly flows include (Kobayashi et al., 1970; Song et al., 2001; Lu and Tryggvason, 2007), where other aspects, including the effect of void fraction and bubble sizes, has been documented. Dabiri et al. (2013) examined bubbly flow in up flow with Front Tracking (Tryggvason et al., 2001) Direct Numerical Simulation (DNS) method, and found that above a critical value of the Eötvös (*Eo*) number the deformation of the bubbles has minor impact on the flow rate, while below the critical *Eo* number the flow rate is nearly constant. Only in a transition region, between the low flow rate, for low *Eo*, and the high flow rate at high *Eo*, does the flow rate depend strongly on the bubble deformation. Experimental studies show that bubble size has significant impact on the bubble distribution. Liu (1993), for example, found that small bubbles (diameter < 5 mm) gather at the wall but bigger bubbles (diameter > 6 mm) stay away from the wall. Mercado et al. (2010), using three-dimensional particle tracking velocimetry (PTV) and phase-sensitive constant temperature anemometry, investigated bubble clustering, the mean bubble rise velocity, and bubble velocities distributions, in pseudo-turbulence flow, and found that the bubble velocity probability density functions (PDFs) had a non-Gaussian form. They also saw both vertical and horizontal clusters.

Here, we examine the response of bubbly flows to periodic oscillations. The study is motivated by an interest in the response of multiphase systems, such as heat exchangers and power plants on-board ocean-going vessels, to unsteady accelerations. Wind forcing and earthquakes may also lead to periodic accelerations, although in the latter case the duration is likely to be short. As a ship rolls in response to ocean waves we expect pressure oscillations that may impact the flow rate as well as the void fraction distribution. Significant changes in the void fraction are likely to make predictions based on results for non-oscillating systems unreliable and unfavorable void fraction distribution can affect heat transfer, enhance thermal fatigue and even cause burnout in boiling systems. This is likely to be a particular concern for narrow parallel board heat exchangers, where the walls are weaker and more sensitive to changes in loading in oscillatory flow. Oscillation flow is also sometimes used to enhance mass transfer in bubble columns, as discussed by Buchanan et al. (1962), Baird and Garstang (1972) and Krishna and Ellenberger (2002), for example. Roig et al. (2012) experimentally studied bubbly flow in a thin gap, Hele-Shaw like flow (Bouche et al., 2012), and found that although the bubbles are confined by the gap, the bubbles can move freely in the two directions parallel to the walls. Spicka et al. (2001) compared two-dimensional CFD simulation results on slug flow and bubbly flow with experimental data, which verified the two-dimensional simulation assumption. Bouche et al. (2012) experimentally examined bubble rise velocity, path and the dispersion of the gas phase in a homogeneous swarm of

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https://doi.org/10.1016/j.ijheatfluidflow.2018.02.004
Received 7 June 2017; Received in revised form 25 December 2017; Accepted 8 February 2018
0142-727X/

bubbles confined within a thin gap. They found that the bubbles rise along oscillatory paths while keeping a constant shape, and that the bubble dispersion coefficient increased almost linearly with the volume fraction.

One type of oscillatory bubbly flow is called Cavitation Resonance, first described by Li et al. (2008) in 1983, where under certain flow conditions a particular component of pressure change would be significantly magnified, when studying Venturi tube. Further work on this phenomena has been done by Li's team and other researchers (Li, 2000). Chen et al. (2008) used a DNS front-tracking method to simulate the propagation of the pressure oscillation. In their work, a sudden pressure jump was applied at the top boundary of the simulation domain to study the volume change of the compressible bubbles. It was found that the bubbles' volume oscillate but the frequency is independent of the excitation.

We note, however, that the bubbles do not need to be compressible to have significant effect on the structure of the flow, as shown here. Gao is best known for early studies on the heat transfer at ocean condition. Her experimental study has focused mainly on rolling platforms (Gao et al., 1999). Recently, her team further simplified the ocean condition experimental setup by forcing the flow by changing the pump's turning speed (Zhou et al., 2012), giving a sinusoidal driven force. They found that the phase difference between the flow rate and the pressure drop is related to the frequency of oscillation.

2. Problem formulation and computational setup

To simplify the problem, we consider the flow in a straight rectangular channel with periodic boundaries in the stream wise (Y) direction, see Fig. 1. No slip boundary condition is used for the side walls. The fluid velocity is initially zero but a cyclic pressure gradient sets up the oscillating flow. Thus, we write the pressure as sum of the imposed oscillations and a perturbation pressure to enforce incompressibility in the usual way:

$$\nabla p = \nabla p' + \mathbf{j} C \sin(\omega t). \quad (1)$$

Here ω is the frequency of the pressure oscillations, $\mathbf{j}$ is a unit vector in the Y direction, and C is the amplitude. We ignore gravity and do not allow the bubbles to coalescence. Several bubbles are initially placed randomly in the domain, but a finite minimum distance is imposed between every two bubbles in the channel. We examine how their locations change with time. For all the two-dimensional simulations described here we take the domain width and length to be 2×2 in computational units, and use 256×256 grid points to resolve the domain.

The dynamics of the fluid is governed by the Navier–Stokes equations, which can be written as

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \nabla\cdot\mathbf{uu}\right) = -\nabla p + \nabla\cdot\mu(\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathrm{T}}) + \mathbf{f}_s. \quad (2)$$

Here, u is the velocity, p is the pressure, ρ and μ are the discontinuous density and viscosity fields, and f_s stands for the surface force. This equation applies to the whole flow field, including both the liquid and the gas. Here we also assume that the flow is incompressible so that

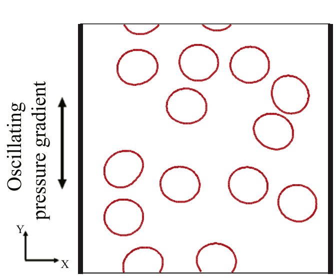

Fig. 1. 2D simulation domain set.

$$\nabla\cdot\mathbf{u} = 0. \quad (3)$$

The governing equations are solved using a finite-volume/front-tracking method, originally developed by Unverdi and Tryggvason (1992), and then improved and verified by Tryggvason et al. (2001). The Navier–-Stokes equations are solved by an explicit second order discretization on a staggered grid and the interface between the gas and the liquid is explicitly tracked by connected marker points. This method has been used for direct numerical simulations of a wide range of multiphase flows and is described in detail in, for example, Tryggvason et al. (2001).

The dynamics is governed by three nondimensional numbers, in addition to the ratios of the density and the viscosity of the gas and the liquid, which we assume to be sufficiently small as to have a small effect on the dynamics. If we use the diameter of the bubbles, D, the density of the liquid and the frequency of the pressure oscillations to nondimensionalize other variables, three nondimensional numbers are obtained, the *Reynolds, Weber* and *Euler* number defined by:

$$Re = \frac{\rho_l D^2 \omega}{\mu_l}; \qquad We = \frac{\rho_l D^3 \omega^2}{\sigma}; \qquad Eu = \frac{C}{\rho_l D \omega^2}. \quad (4)$$

Here, σ is the surface tension coefficient and ρ_l and μ_l are the density and viscosity of liquid. In the limit of small We we expect the bubbles to be spherical (cylindrical in two-dimensional flow) and the evolution to be independent of We and in the limit of high Re we expect the evolution to be independent of Re. For small Eu, where the pressure fluctuations are so fast that the flow does not have time to respond, we also expect the pressure fluctuations to have little effect. When presenting the results we nondimensionalize velocity by $\tilde{\mathbf{u}} = \frac{\mathbf{u}}{D\omega}$ and time by $\tilde{t} = t\omega$.

We note that here we use relatively modest density and viscosity ratios, thus considering light drops or gas bubbles in very high pressure systems. We do, however, believe that the results should apply, at least approximately, to gas bubbles in liquid, and therefore refer to the light drops as bubbles. We have not, at the present time, studied exactly how different the results are from true gas bubbles at atmospheric pressure.

3. Results

Several simulations have been carried out for two-dimensional channels. In most of the simulations, we place 29 bubbles, with diameter 0.2, randomly in a square domain and follow their evolution for different nondimensional forcing frequencies and amplitudes. In Fig. 2 we show the bubbles at three different times (nondimensional time 3.98, 20.73 and 460.56) for one particular case where $Re = 21$, $We = 0.44$, $Eu = 2.76$, a density ratio of 10 and a viscosity ratio of 5. In addition to the bubbles, the instantaneous vorticity (left half of each frame) and streamlines (right half) are also shown. At the earliest time the bubbles are still randomly distributed and close to their initial locations, but as time evolves, horizontal clusters appear that eventually span the width of the channel.

The average liquid velocity is plotted in Fig. 3(a). In the left part of the Figure we show the first few cycles and in the right part we show the average velocity after many cycles, when the motion has reached an approximately steady oscillation state. The average slip velocity between the bubbles and the liquid is shown in Fig. 3(b), for the first few cycles on the left and after a long time on the right, in the same way as in Fig. 3(a). The slip velocities were computed as the averaged gas velocity minus the averaged liquid velocity. It is immediately clear that the amplitude of the slip velocity is smaller at a late time compared to the initial time, indicating that the bubbles follow the liquid more closely than at the beginning.

The most noticeable change in the flow with time is that the bubbles line up across the channel, forming horizontal clusters. Indeed, this is likely to be the main reason for the reduction in the slip velocity between the bubbles and the liquid, seen in Fig. 3(b). There are several ways to quantify the clustering, but here we use the approach described