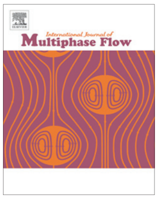
International Journal of Multiphase Flow 75 (2015) 174–193

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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



Direct Numerical Simulations of spherical bubbles in vertical turbulent channel flow

C. Santarelli *, J. Fröhlich

Institute of Fluid Mechanics, Technische Universität Dresden, 01062 Dresden, Germany

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form 6 March 2015
Accepted 11 May 2015
Available online 27 May 2015

Keywords:
Direct Numerical Simulations
Bubbly flow
Spherical bubbles
Turbulent channel flow
Pair correlation function

ABSTRACT

The paper presents results of Direct Numerical Simulations of bubbles rising in a vertical channel flow configuration for a dilute and for a denser swarm. The bubbles, considered as spherical objects, are simulated by means of an Immersed Boundary Method and the channel dimensions are chosen in order to address large-scale flow features. The interaction between the bubbles and the fluid phase is investigated with instantaneous flow visualizations and a detailed statistical analysis for both phases addressing single-point statistics, two-point correlation functions and pair correlation functions. Elongated flow structures in the streamwise direction induced by the bubbles are found in both cases but are somewhat larger and present a higher turbulence level in the denser swarm. For the chosen parameter range turbulence enhancement due to the bubbles is observed. The small-scale interaction of bubbles is investigated yielding different results for the two cases: in the dilute swarm, the aspiration mechanism of a trailing bubble yields a preferential vertical alignment while in the denser swarm, a pressure-related mechanism dominates due to the smaller bubble distance yielding a preferential horizontal alignment. The results reported here provide detailed and reference data for model development and validation.

1. Introduction

Two-phase flows and in particular bubbly flows are an essential part of many industrial applications, occurring in nuclear power generation, chemical industry, in food-processing industry and many other installations. As soon as a flow contains a second phase, complex phenomena regarding the interaction of the two phases take place and in general need to be accounted for. One of the most fascinating aspects is the mutual interaction between the bubbles and the surrounding fluid turbulence in a configuration as simple as a vertical bubble-laden pipe flow: the bubbles modify the turbulence and thus the behavior of the fluid which, in turn, influences the behavior of the bubbles themselves, resulting in a phenomenon of substantial complexity still not fully understood. Due to its relevance, this topic has been investigated repeatedly over the last decades and several approaches have been employed to address such phenomena (Clift et al., 2005; Crowe, 2005; Michaelides, 2006). In view of the large body of work, the following literature review addresses only papers very closely related to the present study.

The first studies of bubbly flows were experimental investigations, and among the fundamental contributions the work of Serizawa et al. (1975,) has to be mentioned. These authors investigated upward-directed bubbly flows in a vertical pipe and focused on the disperse regime and the slug flow regime. For the first one, they observed peaks of the radial void fraction distribution at the walls. Later on, Wang et al. (1987) extended these studies also to downward-directed bubbly, for which a peak of the void fraction in the center region was observed. In their experiments, the presence of bubbles could both enhance or diminish the liquid turbulence, depending on the flow rate and the global void fraction. Since then, many more experimental studies have been conducted for the investigation of different aspects of this type of flow. Takagi and Ogasawara (2008), for example, performed experiments of upward bubbly flow in a plane channel geometry and studied the influence of surfactants on the dynamics of the bubbles. They observed that half-contaminated bubbles experience a lift force, induced by the mean flow gradient, that pushes them toward the walls where they form horizontal clusters, while fully-contaminated bubbles do not experience the same lift force. Martinez Mercado et al. (2010) devoted their study to the so-called pseudo-turbulence, that is when bubbles rise in an otherwise quiescent fluid and turbulence is generated only by the bubbles. In their work bubble–bubble interaction was investigated and the influence of the bubbles on the fluid energy spectra was

---

* Corresponding author.
E-mail addresses: claudio.santarelli@tu-dresden.de (C. Santarelli), jochen.froehlich@tu-dresden.de (J. Fröhlich).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2015.05.007
0301-9322/

addressed. A slope of -3.2 of the double-logarithmic energy spectrum of the velocity fluctuation was observed which is in close agreement with (Mendez-Diaz et al., 2013) for a similar configuration. In a previous work Mendez-Diaz et al. (2012) collected several experimental results to develop a criterion of void fraction distribution as a function of the bubble Reynolds number and of Weber number.

At the same time, numerical investigations were carried out by other researchers in a strong relationship with experiments. The first computations of bubbly flows were based on models for the description of the mean quantities of the flow, in what now is commonly referred to as two-fluid models. Among the first approaches, the one proposed by Sato et al. (1981) should be mentioned. This model is based on the assumption that the fluid turbulence can be decomposed in two contributions, one related to the fluid itself by means of a mean shear and one related to the presence of bubbles. This assumption is still one of the most widely employed for modeling bubbly flows (Lopez de Bertodano et al., 1994; Troshko and Hassan, 2001; Krepper et al., 2005). Such models are based on correlations that were developed from experimental results, either derived from the analysis of the dynamics of a single bubble or from the investigation of bubble swarms. During the last years, increasing computer resources have allowed performing more accurate simulations, where the bubble dynamics and the coupling between the two phases do not rely on models but are resolved by the numerical method. These computational approaches, mainly referred to as two-phase Direct Numerical Simulations (DNS), have proven to be a trustworthy tool to gain deep understanding of the complex phenomena involved. Furthermore, DNS of bubbly flows can be used to deduce closure relations for two-fluid models as described, for example, by Deen et al. (2004).

To simulate a large number of bubbles, mostly two configurations have been investigated in the literature: A triply periodic domain and channel flow. The first configuration is used to investigate the behavior of bubble swarms in an unbounded infinite domain. This design was employed, among others, by Bunner and Tryggvason (2002,) for nearly spherical bubbles and later by the same authors for deformable bubbles, focusing on bubble–bubble interaction and on the spectrum of the velocity fluctuations (Bunner and Tryggvason, 2003). Their analysis was later extended to bubbles at higher Reynolds number in (Esmaeeli and Tryggvason, 2005). Roghair et al. (2011) performed simulations of bubble swarms in the periodic domain to investigate the drag of the bubbles in monodisperse swarms and to compare it to the drag experienced by a single bubble. They derived a correlation for the bubble drag coefficient as a function of the void fraction and in a later work expanded the analysis to bidisperse swarms (Roghair et al., 2013). Although valuable information can be obtain from these simulations, results are influenced by the periodicity constraint and by the dimension of the domain, which is not able to capture the large-scale flow features that can have a strong influence on the small-scales behavior. An example of such an influence is given in (Roghair et al., 2011), where the numerical results regarding the bubble pair alignment were compared with the experimental works of Martinez Mercado et al. (2010). Poor agreement because of the “lack of large-scale flow circulations due to the limited size of the computational domain and absence of walls in the domain” was observed (Roghair et al., 2011).

The second geometrical configuration employed for the analysis of bubble swarms is channel flow, where the two-phase flow is confined between two vertical walls and is periodic in the streamwise and spanwise direction. The advantages of this setup are a larger resemblance to real industrial situations and, as in the case of the periodic domain, the possibility to collect statistics over time and over the two periodic directions. Additionally, the presence of the walls increases the complexity of the flow, due to the presence of a mean shear flow of the fluid velocity and due to the interaction between bubbles and wall turbulence. Examples of studies regarding the interaction between bubbles and walls are the work of Takemura and Magnaudet (2003), who performed experiments for bubbles rising along a vertical wall, and the work of Tran-Cong et al. (2008), who studied the influence of a turbulent boundary layer on the dynamics of small bubbles. Regarding the simulation of bubble swarms in vertical channels, fundamental contributions were provided by Tryggvason and his research team. Lu et al. (2006) investigated bubble swarms in laminar channel flow, both for upward and downward flow configurations. For the upward case, they found that bubbles tend to rise in the wall region while, for the downward flows, that bubbles tend to rise in the center region, both features in good agreement with experimental observations (Serizawa et al., 1975; Wang et al., 1987). Lu and Tryggvason (2008) performed simulations of nearly spherical and of deformable bubbles in a turbulent vertical channel flow and observed a different behavior of the two bubble classes. While nearly spherical bubbles tend toward the walls as in the laminar case, the deformable ones prevalently rise in the channel center. This was also observed in experiments conducted by Tomiyama et al. (2002), concerned with the rise of single bubbles in flow with constant shear rate. The different behavior was hypothesized to be due to the effect of the slanted wake generated by the deformable bubble, which causes the change of sign of the lift force. A more detailed investigation was later provided by Adoua et al. (2009) by means of DNS of the flow around an oblate ellipsoid with a body-fitted mesh. Two different processes for the genesis of the lift force were observed, one related to the shear flow and the other related to the vorticity generation at the phase boundary. The latter effect was found dominant for ellipsoidal bodies determining the sign of the lift force.

The influence of deformability on the dynamics of bubble swarms was further addressed by Dabiri et al. (2013) who confirmed the aforementioned behavior of bubbles with different deformations. Lu and Tryggvason (2013) extended their previous studies and simulated a bubble swarm where the background fluid turbulence was increased with respect to the earlier study (Lu and Tryggvason, 2008). Tanaka (2011) performed similar computations of a swarm of nearly spherical bubbles, focusing on the heat transfer mechanism between the two-phase mixture and the walls. In the same configuration, Bolotnov et al. (2011) investigated a swarm of nearly spherical bubbles and observed that bubbles tend to rise in the wall region and to increase the production of turbulence. Yamamoto and Kunugi (2011) analyzed the behavior of four bubbles at somewhat larger bubble Reynolds number, around 120. They noted that two of the bubbles stayed mainly in the center region and that one bubble rose in the near-wall region, possibly captured by the low-pressure zone of high-speed streaks, and no information was given on the fourth bubble.

Bubbles have proven to modify not only small-scale flow features but also the large scales. Such an influence was described in the pioneering work of Lance and Bataille (1991) for upward bubbly flow in grid-generated turbulence and afterward by Panidis and Papailiou (2000). A similar feature was observed by Uhlmann (2008) and Garcia-Villalba et al. (2012) for the sedimentation of heavy particles in channel flow, where the presence of elongated structures is due to an intrinsic instability of the flow triggered by the presence of the particles. Many of the DNS of bubbly flow mentioned here were performed in small channel geometries due to limited computer resources and therefore large-scale flow features could not be addressed. As a result, a clear separation of flow scales was not possible: small scales influence the large ones and vice versa. Several authors state that neglecting the large scales flow features can have a substantial influence on the results (Tanaka, 2011; Roghair et al., 2011; Dabiri et al., 2013). One of the