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Analysis of the homogeneous turbulence structure in uniformly sheared bubbly flow

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HIGHLIGHTS

- Separation of "shear induced turbulence" and "bubble induced turbulence" contributions in bubbly flow.
- Assess the modelling of the transport equation of the "shear induced turbulence"
- Numerical simulations of the uniformly sheared flow over an isolated sphere are carried out.
- Agreement of results with reduction of second order turbulence closures in bubbly flow.
- Description of the modification of turbulence structure by the bubbles presence.

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ABSTRACT

Separating "shear induced turbulence" and "bubble induced turbulence" contributions in gas-liquid bubbly flows is still experimentally difficult to characterize. Numerical simulations were investigated in order to isolate the turbulence produced by the mean velocity gradient of the continuous phase which comprises the turbulence generated in bubbles wakes, from the pseudo-turbulence induced by the bubbles' displacements. Simulations of the uniformly sheared flow over an isolated sphere are carried out to superimpose the homogeneous turbulence with constant shear at equilibrium conditions with the turbulence produced in the bubble wake. The analyses of the turbulence statistics computed on a control volume whose size is set based on void fractions, for different shear rates, are carried out in order to assess the modelling of the transport equation of the "shear induced turbulence". Simulation results show that for low void fractions, the hypothesis of turbulence equilibrium in the bubble wake is verified in a wide range of shear rate. Numerical results are in satisfactory agreement with the formulations resulting from the reduction of second order turbulence closures in bubbly flow. These formulations are based on a dimensionless number expressed in terms of two time scales which characterizes the bubbles' effects on turbulence structure in sheared flow.

1. Introduction

Several analytical, experimental and numerical studies were carried out to develop turbulence closure in gas-liquid bubbly flows. The bubbles induce turbulent fluctuations that enhance the global liquid turbulence level and alter the mechanisms of turbulence (Alméras et al., 2015; Fujiwara et al., 2004; Lance et al., 1991; Shawkat et al., 2008; Zhou et al., 2006).

Several experiments show important changes in the structure of two-phase bubbly flows, particularly at high void fraction. The experimental data indicate that the presence of the bubbles, even with low presence rate, significantly alters the turbulence structure of the liquid in different ways: in two-phase flows with low turbulent intensities (Ex: weakly sheared flows) the presence of bubbles induced a significant increase in turbulence compared with equivalent single-phase case (Lance and Bataille, 1991; Lance et al., 1991). However, in turbulent flows characterized by high turbulent intensities (Ex: highly sheared flows), the effect of bubbles presence is more complex: Experimental observations obtained in vertical pipe (Liu and Bankoff, 1993; Serizawa et al., 1992) show an increase of the turbulent fluctuations in low shear zones (in the central core near the pipe axis), while in zones close to the walls, where the production by shear of turbulence is important, the effect of bubbles is more complex and can even produce, in certain conditions, a reduction of the turbulent intensity in comparison with the equivalent single-phase case.

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More recently, Shawkat et al. (2008) studied the bubble and liquid turbulence characteristics of bubbly flow in a large diameter vertical pipe. They observed in general, an increase in the turbulence intensities at low liquid superficial velocities. Turbulence suppression is, however, observed at relatively high liquid superficial velocities close to the wall for low void fractions. Lelouvetel et al. (2011, 2014) investigated the mechanisms determining the turbulent kinetic energy modification induced by the bubbles in pipes for both upflow and downflow configurations. Keeping the Reynolds number and the bubble diameter constant among the two experiments, their analysis shows that the energy transfer from large to small scales is decreased in upward flows and is increased in downward flows. The turbulent flow receives energy from bubbles in upward flow (positive relative velocity), suggesting that pseudo-turbulence and bubble wakes affect the large eddies of the flow, while in downward flow (negative relative velocity), the flow transfers more energy to the bubbles.

The experiments in bubbly flow with constant shear carried out by Lance et al. (1991) are very interesting since they allow overcoming difficulties related to the distribution of bubbles (homogeneous void fraction) to focus the analysis on the effects of bubbles on turbulence structure in the continuous phase. These experiments showed that the bubbles, in their random movements, induce a supplementary screeching of the turbulent eddies that leads to an increase of the isotropy of the turbulence and a decrease of the turbulent shear stress.

Experiments on turbulent bubbly flows were accompanied by first and second order turbulence modelling that attempt to describe the mechanisms involved in the modification of the turbulence structure in bubbly flow (Bannari et al., 2008; Chahed et al., 2003; Hosokawa et al., 2010; Laborde-Boutet et al., 2009; Law et al., 2008; Liu and Hinrichsen, 2014; Liu et al., 2015; Lopez de Bertodano et al., 1994; Mohajerani et al., 2012; Rafique and Duduković, 2006; Sato et al., 1981; Selma et al., 2010; Soccol et al., 2015; Troshko and Hassan, 2001; Yamoah et al., 2015). First order turbulence models and particularly k–ε models are widely applied in simulating bubbly turbulent flows (Borchers et al., 1999; Selma et al., 2010). Ekambara and Dhotre (2010) assessed the performance and applicability of the standard k–ε, RNG k–ε and k–ω models. Laborde-Boutet et al. (2009) investigated three formulations of the k–ε model (standard, RNG, realizable) combined with three different modalities to account for gas-phase effects (Dispersed, Dispersed + Bubble Induced Turbulence, Per-Phase). Liu and Hinrichsen (2014) implemented k–ε model and Reynolds stress model with bubble-induced turbulence models to account for the liquid phase turbulence.

In general, the approach adopted in developing two-equation turbulence models consists in introducing source terms in the transport equations of the turbulent kinetic energy and its dissipation rate (Politano et al., 2003; Rzehak and Krepper, 2013a,b,c; Rzehak and Kriebitzsch, 2015; Wang and Yao, 2016). In the k-equation, the source term (i.e. interfacial transfer term) is an inner product of the interfacial forces. Since the drag force is the predominant interfacial force, the interfacial transfer term in the k-equation is interpreted as a function of the drag force and relative velocity; which means that the additional turbulent kinetic energy source comes from the energy lost by the bubbles in the wakes due to drag. The additional turbulent dissipation source represents the destruction of bubble-induced turbulence by dividing the k-source term by a characteristic time scale. Rzehak and Krepper (2013a,b,c) introduced the time scale $d_B/\sqrt{k_L}$, and Troshko and Hassan (2001) have used the bubble time scale d_B/u_{rel}.

Different proposals have been made for the form of these additional source terms to k–ε turbulence model, but no generally accepted practice has emerged from these investigations so far. First order turbulence models are structurally unable to represent the bubbles' effects on the mechanisms involved in the modification of turbulence structure in bubbly flow. Only models resulting from second order closures are able to represent the bubbles' effects on the redistribution mechanisms (Chahed et al., 2003; Colombo and Fairweather, 2015; Laborde-Boutet et al., 2009; Lance et al., 1991).

More complete models with first and second order turbulence closure introduce separate transport equations to describe the bubble induced turbulence. The second order closure turbulence modelling proposed by Chahed et al. (2003) is based on the decomposition of the Reynolds stress tensor of the continuous phase into two independent parts: a turbulent part produced by the gradient of the mean velocity, which also contains the turbulence generated in the bubbles wakes, and an irrotationnal pseudo-turbulent part induced by the bubbles' displacements and controlled by the added mass effects. Each part is predetermined by a transport equation. In the transport equations of the turbulent part, it is assumed that the interfacial production of the turbulent energy and its dissipation rate are balanced in the bubbles wakes. In these transport equations the redistribution and diffusion terms were modified to take into account the interfacial effects. In this regard, these terms were modelled using two timescales that characterize the turbulent effect and the effect associated to the bubbles' motions. The reduction of the second order turbulence closure provides an expression of the turbulent viscosity that is able to account for the observed phenomena in turbulent bubbly flows (Bellakhel et al., 2004).

More recently, Guan et al. (2015) developed a dual-scale turbulence model where the liquid phase turbulence is split into shear-induced and bubble-induced turbulence. Single-phase standard k–ε model is used to compute "shear-induced turbulence" and another transport equation is added to model "bubble-induced turbulence". As for the new transport equation, the production term is equal to the interfacial energy loss due to drag, and the dissipation term is modelled through introducing a characteristic length scale for the "bubble-induced turbulence" which is the bubble diameter. To compute turbulent viscosity, a linear superposition of shear-induced and bubble-induced viscosity is selected, similar to the turbulent viscosity formulation proposed by Sato et al. (1981).

Introducing separate transport equations for the bubble-induced turbulent kinetic energy represents a real progress towards more accurate closure of turbulence in gas-liquid bubbly flows; however, the development of such models requires suitable databases for validation (Rzehak and Krepper, 2013a). Some experiments have sought to provide data on the "bubble induced turbulence" by analysing homogeneous turbulence produced by the bubbles rising in still liquid (Garnier et al., 2002), or by reproducing the "bubble induced turbulence" by means of a flow through a random array of fixed spheres (Amoura, 2008). Nevertheless, even in homogeneous turbulence produced exclusively by the bubbles, the turbulent fluctuations produced in the bubble wake involve shear at the scale of the bubble. One of the main difficulties to analyse bubbly flow experimental data, consists in how to separate "bubble induced turbulence" and "shear induced turbulence" parts. It follows that the investigation of the coupling between the turbulence produced by the mean shear of the continuous phase and by the shear at the bubble wake is, on the experimental level, a complex task.

Since it is experimentally difficult to isolate the "shear induced turbulence" from the "bubble induced turbulence" in sheared bubbly flows, we propose to carry out numerical simulations in order to explore the superposition of an homogeneous turbulence with constant shear at equilibrium conditions and a turbulence produced in a bubble wake. The RANS calculation of an uniformly sheared flow on a sphere aims at keeping only the "shear induced