Chemical Engineering Science 185 (2018) 26–49

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Modulation of turbulent flow field in an oscillating grid system owing to single bubble rise

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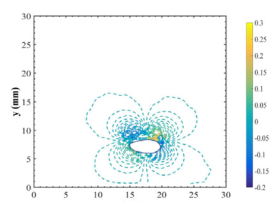
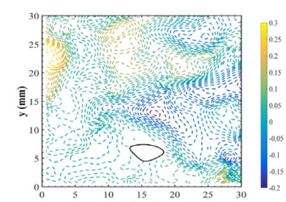
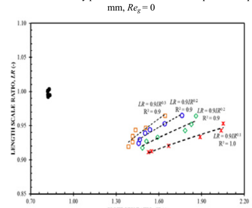
HIGHLIGHTS

- Systematic experiments were conducted to investigate the turbulence modulation.
- Deviation from single-phase isotropic ratio was noted in presence of bubble.
- Single phase turbulence length scales decreased due to the presence of bubble.
- Inertial subrange slope less steep than −5/3 was found in presence of bubble.
- Rise of energy was found in the inertial subrange due to single bubble train.

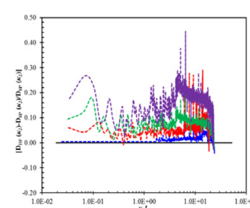
GRAPHICAL ABSTRACT


Instantaneous horizontal velocity profile around the bubble in quiescent liquid, D_b = 3.40 mm, Re_g = 0


Instantaneous horizontal velocity profile around the bubble; D_b = 3.40 mm, Re_g = 10800



Ratio of horizontal to vertical integral length scale as a function of *IR*



Dissipative spectrum, Re_g = 10800 (—— Single–phase, - - D_b = 2.70 mm, - - D_b = 2.93 mm, - - D_b = 3.40 mm, - - D_b = 3.52 mm)

ARTICLE INFO

Article history:
Received 16 November 2017
Received in revised form 19 March 2018
Accepted 23 March 2018
Available online 27 March 2018

Keywords:
Bubble dynamics
Turbulence modulation
Energy spectra
Length scales
Dissipative spectra
Dispersed phase

ABSTRACT

Modulation of turbulent flow in an oscillating grid system due to controlled release of a bubble train was experimentally investigated using particle image velocimetry (PIV) technique wherein flow field modulation was reported in single bubble resolved manner. The bubble diameter was varied in the range ~2.70 to 3.52 mm (~26 to 34 times the single-phase Kolmogorov scale, and ~1.05 to 1.35 times the single-phase integral length scale). The two-dimensional (2D) instantaneous velocity fields were obtained for both single–phase and bubble train cases at grid Reynolds numbers (Re_g) ranging from 1080 to 10,800. The modulation of single-phase turbulence due to bubble was analysed based on the turbulence intensity, isotropy ratio (*IR*), length scales, specific energy dissipation rates and energy spectra. The single-phase turbulence fluctuating velocity increased ~5–76% in the inertial subrange region in the presence of bubbles. Presence of bubbles also led to enhancement in the flow field isotropy ratio due to upward acting buoyancy force. It was noted that at high Re_g (6480–10800), the *IR* value of the flow was found to be more dependent on the grid Reynolds number compared with bubble diameter. The integral length scale of the single-phase flow decreased following a power law dependency over the Re_g. It was found that the specific energy dissipation rate of single–phase flow increased with an increase in bubble diameter. The energy spectra exhibited a slope less steep than −5/3 which indicates the additional turbulence

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https://doi.org/10.1016/j.ces.2018.03.039

production by the bubbles in the inertial subrange region. Energy transfer augmentation from large scale to small scale due to bubble was explianed by the dissipative spectrum which showed reduction of the energy in the small scale and an enhancement of the energy in both large scale and inertial subrange.

1. Introduction

Multiphase flow systems comprising two phase, i.e. gas-liquid mixtures with gas as the dispersed phase in the form of bubbles are commonly encountered in the chemical and allied process industries in numerous applications ranging from physical separation (distillation), heat exchange with phase change (thermal power generation boiler, distillation column reboiler) and chemical reactions (multiphase reactors for fermentation, polymerisation, hydrogenation) to obtain desired products. In practice, such multiphase systems are inherently unstable due to the interactions in form of momentum exchange between the continuous (primary) and the dispersed (secondary) phase and creates turbulence which is also referred to as so-called bubble generated turbulence or pseudo-turbulence (Martínez Mercado et al., 2010; Sathe et al., 2013). Exchange of kinetic energy through momentum transfer between the phases creates turbulent flow structures of different length and time scales which contribute towards the improved transport processes.

The characterisation of turbulence in bubbly flows is of utmost practical and theoretical interest. In last decade, many researchers have reported the characteristics of two-phase bubble-induced turbulence in different experimental geometries e.g., pipe flow (Michiyoshi and Serizawa, 1986; Wang et al., 1990), bubble column (Cui and Fan, 2004; Mudde and Saito, 2001; Riboux et al., 2010; Sathe et al., 2013) and grid turbulence (Lance and Bataille, 1991; Luther et al., 2005). The experimental studies on bubble-induced turbulence can be classified into three categories: (1) vortex structures of single zigzagging bubbles, (2) measurements of velocity fluctuations in vertical water tunnels at very low gas hold-ups, and (3) experimental studies on turbulent energy spectra in bubble column, pipe or grid turbulence flow. It is noted that although bubbly flow turbulence is dealt in a number of previous studies, there have been very few studies (Nagami and Saito, 2014; Rensen et al., 2005; Van den Berg et al., 2006) that actually provide quantitative flow information on the modulation of primary phase turbulence in the presence of bubbles. A review of related studies emphasising the effect of bubbles on the turbulence properties of different systems is summarised in Table 1 which depicts four prime aspects of turbulence quantification namely turbulence intensity, length scales, energy dissipation and inertial subrange slope of the energy spectrum.

The role of the dispersed phase (bubbles, drops or particles) on modulation of turbulence intensity has been a much-debated topic over the last 50 years, specifically on the context whether the second phase acts as turbulence promoter or dampener (Joshi et al., 2017). Bubbles can enhance or suppress liquid phase turbulence intensity, depending on bubble size, volume fraction and gas flow rate (Lance and Bataille, 1991; Serizawa et al., 1975; Shawkat et al., 2008; Theofanous and Sullivan, 1982; Veldhuis et al., 2008) (see, Table 1). Several studies have reported the influence of volume fraction on turbulence intensity (Lance and Bataille, 1991; Michiyoshi and Serizawa, 1986; Shawkat et al., 2008). Also, the modulation of turbulence intensity was found to be dependent on the bubble size. Gore and Crowe (1989) suggested that the turbulence intensity is dependent on the scale ratio of particle/bubble diameter and integral length scale (large eddy size), D/L_x, where D denotes the particle/bubble diameter and L_x is the integral length scale. Their study showed that turbulence intensity decreases when $D/L_x < 0.1$ while larger values of D/L_x cause an increase in turbulence intensity. The bubble Reynolds number (Re_b) might also play a key role in turbulence modulation in bubble-induced turbulence, as the particle Reynolds number (Re_p) does in particle-laden flow (Joshi et al., 2017). For particle-laden flow, Hetsroni (1989) showed that a particle Reynolds number, Re_p, (based on relative velocity and particle size) larger than 400 tends to enhance turbulence intensity, while particles with lower Reynolds numbers suppress turbulence intensity. It is, however, worth pointing out that such inclusive and quantitative analysis is not currently available for the gas-liquid system and needs to be addressed in future studies (Joshi et al., 2017).

Departures from the Kolmogorov spectral slope $-5/3$ in the inertial subrange due to the presence of bubbles have drawn a lot of attention in the last two decades. Unlike single–phase flow turbulence where energy transfer occurs from larger to smaller eddies following an energy cascade, the origin of the energy spectrum in the presence of bubbles is different. In this case, energy is introduced by the bubbles into the flow, and the observed length scales vary from the size of the bubble (or even smaller) to size of the flow chamber (Joshi et al., 2017). Contribution to turbulence generation in the presence of bubbles can be quantified from the slope of the energy spectrum in the inertial subrange which is reported to be steeper ($-8/3$) than the corresponding slope in single–phase system ($-5/3$) (Lance and Bataille, 1991; Michiyoshi and Serizawa, 1986; Wang et al., 1990) (see, Table 1). Conversely, Rensen et al. (2005), Van den Berg et al. (2006) and Mazzitelli et al. (2003) reported a slope slightly less than $-5/3$ for grid turbulence. The classical $-5/3$ scaling law for both pipe flow turbulence and bubble column was reported by Mudde et al. (1997), Mudde and Saito (2001) and Cui and Fan (2004). Riboux et al. (2010) found a slope of -3 for bubbles smaller than the integral length scale while for bubbles larger than the integral length scale, they obtained a slope of $-5/3$. For bubble-induced turbulence in bubble columns, Martínez Mercado et al. (2010) and Mendez-Diaz et al. (2013) found spectral slopes of -3.18 and -3, respectively. Recently, Sathe et al. (2013) reported Kolmogorov's slope ($-5/3$) in the inertial subrange, followed by slopes of -3 in higher wavenumbers until the dissipation range. The difference in the inertial subrange slopes in bubble-induced turbulence occur for three main reasons: (1) change in length scale in the presence of bubbles; (2) change in the bubble rise velocity by the bubble-induced turbulence which alters the rate of turbulence generation of each bubble and (3) turbulence generation and energy dissipation in the inertial subrange of the energy spectrum due to the presence of bubble (Sathe et al., 2013). However, there is no consensus on a single value for the spectral slope, and very few studies take account the change of length scales and specific energy dissipation rate due to the presence of a bubble and require further systematic investigation.

The available literature indicates that although some general understanding is available about bubble-induced turbulence, a large area pertaining to quantification of turbulence modulation in the presence of a single bubble rise remains largely unexplored and requires systematic investigation (Joshi et al., 2017). A critical requirement for the characterisation of turbulence in such system is the measurement of single (carrier) phase velocity in the vicinity of the bubbles (Balachandar and Eaton, 2010). In practice, however,