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Flow visualizations around a bubble detaching from a particle in turbulent flows

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ABSTRACT

The thrust of this paper concerns flow visualizations around a bubble–particle aggregate in oscillating grid turbulence where no net flux is presented. The influences of a turbulent liquid's motion on the detachment of a bubble from a particle are explored. The methods of analysing the two dimensional velocity fields are compared, including: Reynolds' decomposition, Galilean decomposition, Gaussian filtering and discrete wavelet transform (DWT). The decomposed velocities that are extracted using the different methods on a snapshot of a velocity field series are illustrated and compared. In terms of the flow structure visualizations, the DWT proved to be advantageous over the other methods for the reasons that no a priori cut-off frequency needed to be defined and the flow structures could be decomposed, scale to scale. The DWT was a sufficient method to decompose the velocity fields and to achieve flow structure visualizations, which is conducive to understanding the mechanisms of bubble–particle detachment in a turbulent field. This method was extended to analyse the instantaneous velocity fields around a bubble detaching from a stainless steel particle and the influences of eddies on the detachment. Under the same operating conditions, different detachment modes were identified from the instantaneous velocity fields around the detaching bubble in the oscillating-grid turbulence, including:

- the sliding of a bubble resulting from the shearing force in the turbulent flow field;
- the stretching of a bubble resulting from the pulling force in the turbulent flow field;
- the entrainment of a bubble into an eddy, so that the bubble followed the movement of the eddy.

1. Introduction

The detachment of particles leading to a low flotation recovery is a limitation for coarse particle flotation, and the decline in recovery is related to the hydrodynamic conditions in the flotation cells (Jameson, 2012). The hydrodynamics of turbulent flows are characterised by flow structures with wide ranges of lengths and time scales (Joshi et al., 2009). Hence, a proper understanding of the flow structures can improve the understanding of the mechanisms of bubble–particle detachment in turbulent fields. Once the mechanisms of bubble–particle detachment in turbulent fields are well understood, measures can be introduced to decrease the bubble–particle detachment in order to increase particle recovery.

The characteristics of the hydrodynamics are reflected in eddies as a turbulence composed of a series of eddies of different dimensions. Eddy identification in a velocity field is normally accomplished by identifying a region of eddy core denoted by the vorticity (Jiménez et al., 1993). In a complex flow, where eddies are embedded in a strong shear, it is difficult to use vorticity maps to identify eddies (Adrian et al., 2000). The methods of extracting information on an eddy from the velocity fields are constituted by Reynolds averaging, Galilean transformation and filtering. However, the best method for a particular situation depends on the specific investigation objectives.

Reynolds decomposition is generally used in analysing and interpreting velocity fields to understand the kinematics, dynamics and scales of the turbulences. Nevertheless, Reynolds decomposition is not always the correct choice for visualizing the turbulence's mechanics (Adrian et al., 2000). Based on the use of different filters, the velocity fields are separated based on the scale of the fluid's motions. The eddy structure identification methods were compared utilising the same data base (Bonnet et al., 1998). Good quantitative and qualitative agreements were observed, although these were accompanied by noted differences. Coherent structure identification from the wavelet analysis was carried out to analyse the particle image velocimetry (PIV) data (Camussi, 2002). Deshpande et al. (2008) applied a multiresolution wavelet trans-

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form to study the evolution of the structures and their interactions. For the identification and physical characterisation of coherent structures, the wavelet-based method was shown to analyse some aspects which were partially missed by the other identification methodologies.

Exploring flow fields around a bubble detaching from a particle has strong implications for understanding bubble–particle detachment in turbulent fields. The flotation recovery rate plummets for coarse particles as the bubble–particle detachment becomes obvious in turbulent flow fields. However, the nature of the hydrodynamics' influence on this process remains mysterious (Jameson, 2010). The dynamics of the interactions between the fluid structures and the bubble–particle aggregates is almost impossible to visualize in a real flotation system as the phases are in constant motion, and these change with time and position. It is advisable to test a single particle–bubble aggregate system in an ideal turbulence field in order to surrender deeper insights into the influences of the hydrodynamics on the stability of bubble–particle aggregates. As isotropic stationary turbulence is the simplest turbulence, with unique characteristics, it is widely used in the theoretical treatment of turbulent flows (Hinze, 1975). However, the instantaneous velocities in oscillating-grid turbulences have been scarcely discussed. An instantaneous velocity vector map and large eddies were visually shown to determine the integral length scales of turbulences by Eidelman et al. (2002). Wang et al. (2014) studied the detachment of bubbles anchored to a vertical cylindrical surface in a oscillating-grid turbulence. The energy dissipation rate around the detaching bubble was calculated from the instantaneous velocity fields. The results showed the energy dissipation rate to be higher around a detaching bubble than a non-detaching bubble, and to be higher in the vicinity of the bubble.

With the purpose of exploring the influences of turbulence on the bubble–particle detachment process, flow visualizations were carried out for a flow field where a bubble–particle aggregate was positioned in the centre of a tank. The turbulent liquid motion was supplied by a pair of oscillating grids moving inwards and outwards simultaneously. This process was accomplished using a particle image velocimetry (PIV) system, accompanied by a laser induced fluorescence (LIF) technique, in order to measure the instantaneous velocity fields in the vicinities of the bubble–particle aggregates.

2. Experimental setup and measurement techniques

In tune with these aims, the experimental methodology adopted in this work consisted of two main components:

1. The measurement of the liquid velocity flow fields in the centre of the tank using the PIV for a region of interest (ROI) of 10×10 mm and 30×30 mm.
2. The measurement of the instantaneous velocity fields around a bubble–particle aggregate using a technique which combined both the PIV and the LIF.

The liquid used was Milli-Q water and atmospheric air was used to generate the bubbles. A stainless steel particle with a diameter of 3 mm was used. The details of each experiment are described below.

2.1. Oscillating-grid turbulence generator

A schematic view of the turbulence generator is shown in Fig. 1. The oscillating-grid apparatus described by Doroodchi et al. (2008) and Wang et al. (2014) was used to produce a stationary and near isotropic turbulent flow field. Only a brief introduction will be presented here. The device consisted of a rectangular Perspex tank with a pair of vertically orientated grids moving horizontally in and out together. By setting the two grids at their extent, so that the two grids could move inward and outward simultaneously, the jets and the wakes merged together at the centre of the tank. The two grids were connected by connecting rods and linear bearings to variable speed stepper motors, which were mounted on separate benches to avoid any vibrations being transmitted to the water inside the tank. Each stepper motor was fitted with an eccentric cam which allowed variations of both the stroke amplitude and the mean separation distance between the two grids. The advantage of utilising a stepper motor is that the two grids can be synchronized to move inwards and outwards simultaneously by setting the initial positions of grids.

We were able to accurately control the turbulence intensity by changing the oscillation frequency, *F*, the stroke amplitude, *SA*, and the mean separation distance, *SD*, between the two grids. In this study, the stroke length was fixed at 50 mm, while the mean separation distance between the grids was set at 70 mm. A stationary and nearly isotropic homogeneous turbulent flow field was generated in the region between the two grids.

2.2. Bubble generator

The method of generating bubble–particle aggregate described by Wang et al. (2015) was used. A schematic representation of the bubble generation system is shown in Fig. 2. A syringe was inserted from the bottom of the tank and a bent needle was arranged on the top of the syringe. A stainless steel particle with a diameter of 3 mm was tightly fitted onto the needle tip. The capillary system was used to generate a bubble on the particle with a syringe pump. As the bubble grew larger than a critical size, where the buoyancy force was larger than the capillary force, the bubble would slide to the top of the particle. The bubbles generated using this method had a reproducible diameter of approximately 2.5 mm. A distinct advantage of this bubble generator was that a bubble at the top of the sphere is sealed, ensuring that the bubble volume does not change by an exchange of gas with the capillary tube. The bubble was tethered to the particle, forming a bubble–particle aggregate which was employed to study the detachment of a bubble from a particle in turbulent fields.

The experimental procedure for the detached bubble experiments involved operating the micro syringe pump to generate a bubble at the top of the particle. At this stage, the grids were not operating and the liquid was quiescent. The grids were set in motion and the oscillation frequency was increased, remaining at 4 Hz. The PIV was applied to capture the velocity fields around the bubble–particle aggregate, and the cases where the bubble detached were analysed to interpret the functions of the turbulent liquid's motion on the bubble–particle detachment.

2.3. Instantaneous velocity measurement system (PIV+LIF)

The instantaneous velocity measured in the x–y plane around the bubble was performed using a particle image velocimetry (PIV) with a laser induced fluorescence (LIF), as shown in Fig. 3. The system was comprised of: (1) A Litron LDY 300 laser capable of generating 30 mJ/pulse energy with 532 nm wavelength at 1000 Hz; (2) Optics used to produce a 2-D light sheet out of the laser beam; and (3) A Dantec SpeedSense camera with 1600×1600 pixels and an 8-bit resolution.

The camera, laser and image capture software were synchronized through a Dantec hub in double frame mode. The time gap between two frames was modulated by changing the capturing frequency in such a way that the seeding particles' movements in the image pairs were conspicuous enough to calculate trustworthy