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Advanced PIV/LIF and shadowgraphy system to visualize flow structure in two-phase bubbly flows

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ABSTRACT

Particle image velocimetry (PIV) is a promising technique to measure dispersed phase size, dispersed phase hold-up and velocity of both the phases. The current work reports measurement of the shape, size, velocity and acceleration of bubbles using shadowgraphy, and liquid velocity measurement obtained using PIV/LIF with fluorescent tracer particles. Measurements were performed in a narrow rectangular column at moderate gas hold-up ($\sim$5%) with wide variation of bubble sizes (0.1–15 mm). The liquid velocity field was subjected to 2D discrete wavelet transform (DWT) to visualize the flow structures in the bubbly flow. Further, the slip velocity of individual bubbles was obtained from the DWT filtered liquid velocity field. The results are compared with the slip velocity correlations reported in literature for single bubbles rising in quiescent water. The comparison shows the difference in slip velocity of single bubbles and bubbles rising in swarm. The scale wise decomposition obtained from DWT was also used to quantify the liquid velocity field in terms of wavenumber spectrum. The velocity and acceleration measurements are demonstrated on a single spherical cap bubble rising in quiescent water. The measurements show the potential of the 2D acceleration measurement to facilitate the estimation of unsteady drag on bubbles.

1. Introduction

Bubbly flows are encountered in many industrial equipment. Gas–liquid contactors including bubble column reactors, plate columns for distillation and absorption of gases, fermentors, stirred tank reactors with gas dispersing impellers, boilers and evaporators are typical examples where gas–liquid dispersions are encountered. The flow behavior in such equipment is complex. The complexity is aggravated by the limited amount of information that conventional measurement techniques provide with respect to such a system. There is a large difference between the physical properties of gas and liquid which causes strong discontinuities within the flow field in most of the physical variables used to sense the flow. For instance, hot film anemometry (HFA) is hampered by the large thermal conductivity difference between gas and liquid while all optical techniques including laser doppler velocimetry (LDV), particle image velocimetry (PIV) and phase doppler analyzer (PDA) are restricted to very low gas hold-ups because of the large refractive index gradient. Thus, most of the velocimetry instruments capable of giving insights into the turbulence aspects of the flow do not work well with gas–liquid flows and hence understanding and modeling of these flows is difficult.

In order to model the bubbly flow with good physical consideration, dispersed phase hold-up, dispersed phase size and velocity of both the phases should be known over the entire flow domain. Also, the time variance of the flow field should be known. Recently developed techniques like magnetic resonance velocimetry (MRV) can provide all these data, at fair time resolution (Alley and Elkins, 2007). However MRV is a difficult technique and the cost of the equipment is high. In this context, particle image velocimetry (PIV) is a more promising technique. However special image acquisition and processing strategies are required in order to get all the desired parameters listed above. Because of the versatility of the technique the same hardware can be used for different resolutions of the flow field, from few hundred microns to few centimeters. This has attracted several workers to characterize bubbly flows using PIV.

The major difference in the two phase and single phase PIV is the requirement of phase discrimination. The reported studies in the literature manly differ in the algorithms employed to isolate gas and liquid phase regions, and the estimation of the gas velocity. Schemes of different arrangements for phase discrimination are depicted in Fig. 1. Over the last 15 years, the bubbly flow

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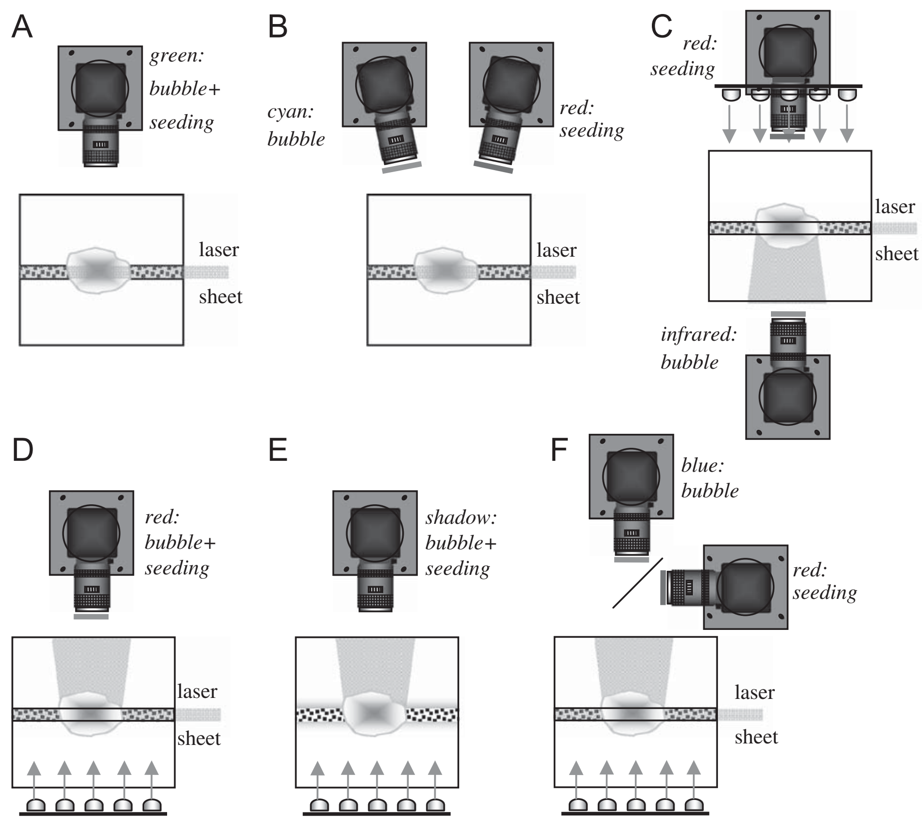

Fig. 1. Different camera arrangements used in previous bubbly PIV work: (A) single camera: Delnoij et al. (2000); (B) two cameras with filter, looking from an angle: Bröder and Sommerfeld (2002); (C) two cameras looking form opposite side: Tokuhiro et al. (1998); (D) single camera with filter: Lindken and Merzkirch (2002); (E) single shadowgraphy camera (no laser): Bröder and Sommerfeld (2003) and (F) two cameras with filters and a dichroic mirror: current work.

PIV technique has developed significantly. A brief overview of the PIV and shadowgraphy methodologies is reported in Table 1.

The initial studies on PIV in bubbly flows relied upon the size difference between the bubbles and the seeding particles in PIV images. The works of Chen and Fan (1992), Gui et al. (1997), Lindken et al. (1999) and Bröder and Sommerfeld (2003) employed this method of phase discrimination. The bubbles thus detected were isolated using the 'mask' image. The mask image is the image marking the areas in composite image where the desired phase is present. The bubble mask was obtained by setting the pixels in the detected bubble regions to 1, while setting the rest to 0. When the raw PIV image is multiplied with the desired mask, only the desired phase remains in the image. The masked images are then subjected to PIV/PTV processing using suitable algorithms including classic cross correlation or the minimum quardratic difference (MQD) algorithm. However, the bubbles being very larger than seeding particles reflect a much larger amount of light and hence detection of seeding particles in the vicinity of bubbles is very difficult in case of large bubbles. Also, the determination of bubble shape is very difficult when the flares due to intense laser reflection are present. Hence, these studies reported velocity field with very low resolution. In a marked variation, Bröder and Sommerfeld (2003) reported a complete shadow PIV with no use of laser illumination at all. They used pulsed LED backlight along with larger seeding particles (100 μm) which were detectable in shadow image. The planer velocity measurement was ensured by using a narrow depth of focus lens and an image processing program which rejected the out of focus bubbles and seeding particles. The bubbles were separated from particles based on their larger size. However the out of focus bubbles present a significant change in background intensity and interfere with the edge detection of the in-focus bubbles. Because of this interference, the method can be used only for sparse dispersions of small bubbles in narrow columns.

An alternative for phase discrimination by image processing or optical separation was proposed in the form of ensemble correlation algorithm (Delnoij et al., 2000). The method relies on the fact that bubbles rise faster than surrounding liquid by a certain value, which corresponds to the slip velocity between two phases. Thus, when the cross correlation functions of several images are ensembled together, two correlation peaks are observed. The peak corresponding to larger displacement was attributed to bubbles and the other was attributed to liquid. About 10–15 correlation planes needed to be ensemble averaged in order to identify the two correlation peaks for bubbles and liquid. This criterion limits the use of technique to study the time averaged flow fields. Also, this method requires a considerable velocity difference between the phases, which may not exist in for small bubbles. In spite of the simplicity of measurement offered, the method has limited applicability in the sense that it does not allow the instantaneous slip velocity measurement at any location in the column.

To reduce the interference of the flaring caused by laser light reflection, the use of fluorescent seeding particles and corresponding interference filters on cameras has been an effective method (Delnoij et al., 2000; Bröder and Sommerfeld, 2002). The scattered light from the bubbles has the wavelength of the illuminating laser while the tracer particles emit fluorescing light at a different, higher wavelength. The phase separation is then achieved by using two cameras fitted with appropriate filters. One camera only captures the green laser light, while the other records the orange light emitted by fluorescent tracer particles. Such a method was used for studies on a flow induced by single or very few bubbles. An advantage of this method is that an obstruction of