An 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 holdup 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 high local gas hold up (~10%) with wide variation of bubble sizes (0.1-15 mm). A 2D discrete wavelet transform (DWT) was performed on the liquid velocity field 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 bubble 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 for 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 insight into the turbulent 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 holdup, 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 this data, reportedly at fair time resolution (Alley and Elkins, 2007). However MRV is a difficult technique and the cost of the equipment required 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. The versatility of the technique allows the usage of the same hardware for different resolutions of the flow field, varying 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 mainly differ in the phase discrimination algorithms employed to isolate gas and liquid phase regions, and also in the ways by which gas velocity is estimated. Schemes of different arrangements for phase discrimination are depicted in Fig. 1. Over the past 15 years, there have been significant developments within the the bubbly flow PIV technique. A brief review is given below.

Chen and Fan (1992) reported a PIV system with continuous 4W Ar ion laser applied on a refractive index matched three phase fluidized bed. The phase discrimination was achieved by sorting each identified particle into the respective class by means of its size. Phase velocities were calculated using particle tracking. However, the number of velocity vectors obtained in the field of view was too less and the liquid velocity in the vicinity of the bubble was not detectable.

Delnoij et al. (2000) proposed ensemble correlation PIV for bubbly flow based on the single-frame double-exposure technique along with image shifting to overcome directional ambiguity. About 10-15 images were ensemble averaged prior to PIV processing in order to identify the two correlation peaks for bubbles and liquid. This criterion limits the use of technique to study only time averaged flow fields. Also, this method requires a considerable velocity difference between the phases, which may not exist in for small bubbles.

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A rather sophisticated image size discrimination called masking technique was implemented by Lindken and Merzkirch (1999). The phase discrimination was based upon the size of the detected particles based on the grayscale values. This technique requires the identification of the bubble images and, for determining their velocity based on tracking, the localization of the bubble image centers. This method can only be successfully used if the bubble concentration is very small, to the order of less than 1 %. Therefore, it was only applied to analyze the flow field induced by a group of bubbles (Lindken et al. 1999).

A big hurdle in the application of standard PIV to bubbly flows is the strong scattering of the penetrating laser light sheet on the surface of the bubbles at higher gas hold-up. Many
investigators used fluorescing tracer particles to overcome this difficulty. The tracer particles emit fluorescing light at a different, higher wavelength and the phase separation is then achieved by using two cameras fitted with appropriate filters. One camera only captures the green laser light, while another records the orange light emitted by fluorescing tracer particles. Such a method was used for studies on a flow induced by single or very few bubbles till now.

Deen et al. (2000) applied the Laser Induced Fluorescence (LIF)-PIV technique to the analysis of the hydrodynamics in a locally aerated square bubble column. The velocity measurements for both phases were compared with results obtained by a single-camera ensemble-averaged PIV technique and Laser Doppler Anemometry (LDA). The results revealed clearly that a proper discrimination between the phases is not possible with the single-camera technique. The mean liquid velocity obtained by LDA agreed reasonably well with the LIF-PIV results, but the fluctuating velocities showed considerable differences.

Bröder and Sommerfeld (2002) extend this method to the simultaneous measurements of the velocity field of both phases in a laboratory scale, cylindrical bubble column operated at a relatively high void fraction. The cameras used for viewing bubble and seeding particles were kept at special angle with respect to the laser sheet in order to achieve maximum difference in the intensity of reflected and fluorescent light. However, the technique employed can give valid bubble velocity only in case of spherical or slightly ellipsoidal bubbles with smooth interface, which generate a unique reflection spot per bubble. Thus, the velocity measurements reported were only for small bubbles with diameter of 0.5 mm and 1.8 mm.

In another study, Bröder and Sommerfeld (2003) report PIV measurement based on shadow imaging in a rectangular airlift reactor. Instead of double pulsing laser sheet, double pulsing LED backlight was used to generate the particle and bubble shadow images. The discrimination between particles and bubbles was achieved by the size difference between the seeding particles and the bubbles (150 µm vs. few mm). Out of focus bubbles were identified with image processing and were removed from the image. However, this method cannot provide the liquid velocity information near the bubbles, since the shadow of particles gets mixed with the shadow of the bubbles.

The above mentioned methods work well for small bubbles. Large bubbles pose two fold problems. Firstly, their interface is wavy, making a number of reflecting spots around their surface. Also, the generation of mask from transverse laser sheet illumination is difficult because of the refraction and reflection near the interface (Diaz and Riethmuller, 1998), which causes ambiguity about the bubble contour.

A common method in dispersed two-phase flows is shadowgraphy. A shadow image of the gas bubbles is recorded on the CCD camera and the velocity distribution of the gas bubbles is evaluated with a particle tracking velocimetry (PTV) algorithm. The velocity of the liquid cannot be determined using the shadowgraphy technique. Therefore this technique is combined with a PIV measurement. Tokuhiro et al. (1998) used two cameras facing each other for combined PIV and shadowgraphy measurements on a single bubble. They used the bubble contours to delete PIV velocity information at the area of the gas bubble with a post processing procedure. Lindken and Merzkirch (1999b) used two cameras under a 30° angle for PIV and Shadowgraphy measurements. The bubble velocity was measured with 3D PTV. The 3D bubble velocity was measured very inaccurately because of the weak signal from the gas bubble in the PIV measurement. With this set-up they were able to determine the position of the bubbles relative to the 2D-PIV measurement plane.

The technique employed in current work is extension of the work reported by Tokuhiro et al. (1998) and by Lindken and Merzkirch (2002). Dichroic mirror has been used to split the shadow and PIV image. A digital mask generated from shadow image is applied to particle image in order to achieve reliable liquid velocity measurement. In addition, the liquid velocity data is subjected to wavelet transform to quantify the flow structures.
2. Measurement technique

2.1 Principle

Fig. 2 shows the schematic of the image acquisition with the combined PIV/LIF with fluorescent tracer particles and shadow imaging of the gas bubbles. A dual head Nd:YAG laser illuminates a 2D light sheet in the multiphase flow at 532 nm wavelength. Fluorescent tracer particles in the flow reflect part of the light and they emit light at a wavelength of 555–585 nm with an emission peak at 566 nm. Thus, reflected light contains 532 nm laser light along with the longer wavelength fluorescent light. The light with wavelength longer than 540 nm passes through the dichroic mirror. The use of dichroic mirror allows the recording of the shadow image and particle images without introducing skewness in either image.

The reflected light at 532 nm is almost blocked by this assembly to a great extent, while most of the fluorescent light passes to the CCD. An optical long wave pass filter with a steep transmission edge at 570 nm±5 nm is fitted on camera lens to further arrest the green laser light. The laser intensity needs to be adjusted to minimize the intensity of leakage light from the filter. Bubbles are still detected by CCD chip in the long wave pass filtered image. However, the part of image containing reflections is completely blocked when mask generated from the shadow image is applied.

A double-pulsed high-power light emitting diode (LED) array illuminates the bubbly flow for the recording of the gas bubbles. The blue LED array emits light at 470 nm. The flow is back-illuminated and the gas bubbles produce a shadow. The shadow image with light of wavelength 470 nm is reflected by the dichroic mirror, and passes the optical low pass filter, and the shadow image is recorded on the detector of the camera.

![Diagram of experimental setup for simultaneous PIV and shadowgraphy measurements using twin Nd:Yag laser with double pulsed Blue LED array for backlighting with two cameras and a dichoric mirror as image splitter](image_url)

**Fig. 2** Experimental setup for simultaneous PIV and shadowgraphy measurements using twin Nd:Yag laser with double pulsed Blue LED array for backlighting with two cameras and a dichoric mirror as image splitter.

Both the sets of information from the tracers and from the bubbles are recorded by two different cameras. Blue illumination has been used to achieve high intensity backlighting, which allows high speed camera recording to obtain bubble trajectories. Even after choosing such a wide difference in the wavelengths of backlight and fluorescence from seeding, the backlight intensity has to be carefully adjusted in order to get least interference in the images used for PIV processing.
2.2 The measurement system

The experiments were performed with a modified commercial PIV system, consisting of a New wave dual head Nd:YAG laser with up to 120 mJ per pulse and two TSI Powerview 4MP cameras with 2,048×2,048 pixels and 12-bit resolution. A TSI synchronizer was used to control the PIV system. Additionally the pulsed LED array has been integrated in the PIV measurement set-up as shown in Fig. 2. The pulsed LED array consists of 144 high-power diodes with a small emission angle. A diffuser plate has been used in front of the LED array. The LEDs are operated in pulsed mode (19 Volts for less than 1 ms). This increases the light emission and the moving bubbles do not cause blurring of the image.

An in-house developed timing card fires the LED array in synchronization with laser pulses. The timing sequence for Shadowgraphy+PIV measurements used in current work is similar to that used by Lindken and Merzkirch, 2002. Fig. 3 shows the timing diagram for synchronization between the High speed camera, PIV camera, laser and LED array. This combination has been used to record the bubble trajectories with liquid velocity field. PIV exposure is 800 μs. Within 1 μs, the data is removed from the light sensitive part of the pixels. At the beginning of the first recording, an 8 ns laser pulse illuminates the flow. Simultaneously the pulsed LED array is triggered and the LEDs emit light for about 80 μs. The information from the laser light and the information of the LED illumination are recorded on the first frame of the same CCD chip. After a time interval dt=1000 μs, the laser and the LED array are triggered again, and the information is recorded in the second frame of the PIV/Shadowgraphy recording.

LED illumination circuit was designed following the recommendations of Lindken and Merzkirch (2002). The resultant short pulse duration allows the use of LED for illumination of fast moving objects (up to few m/s) without blur. Slight discrepancy in the background intensity between the two frames is taken care of by the dynamic histogram based threshold in the image processing algorithm. For recording with high speed camera, the LEDs were kept on for 20 ms, during which the high speed camera recorded 5 images at 250 Hz. This frame rate is sufficient to capture the relatively smooth trajectory of bubble needed to deduce the bubble velocity and acceleration.

3. Data Processing

3.1 Image processing

The shadow images were processed by the image processing routines programmed in MATLAB R2007a. The flow chart for image processing is shown in Fig. 4. The grayscale images from the high speed camera are read, and corrected with first order perspective correction to obtain perfect overlap between PIV and High speed camera image. This is verified by comparing the images captured by a calibration target in the focal plane of the square tank used for the experiments. After this, the images are binarized to black and white using an optimum threshold.
value. This threshold is calculated on the basis of intensity histogram of the grayscale image, and has to be optimized in the case of non-uniform background illumination. However, artifacts such as a dark border on either side of the image remain, and they are removed before image registration to detect bubbles. After binarization, the ‘holes’ in the bubble image, primarily caused by the curvature of the bubble, are removed by morphological image processing, which involves subsequent dilation and erosion of image. After ‘filling’ the holes, the image registration detects bubbles as isolated regions of the image with the type of pixel connectivity specified. Every region is labeled for different properties like equivalent area in pixel squared units, and location of the centroid. The detected bubble image is used as a digital mask to blank the PIV images in these regions.

Finally, the centroid locations exported from the image processing routine are processed to track the particles by an open source code available from Daniel Blair and Eric Dufresne. The routine searches for particles with similar location from the location array provided. This was tested on dummy images before being applied to ‘Rough’ images caused by bubbles. The routine works satisfactorily even with more than 100 bubbles present in the image. However, care must be taken while capturing the images by adjusting the $\Delta t$, limiting bubble movement to less than half the bubble diameter. Additional check tracked bubbles having identical area was implemented in the particle tracking code. The tracking code returns the trajectory as array of centroid locations. Then, a 4th degree polynomial is fitted to this trajectory which is used to evaluate the first and second derivative of the bubble trajectory. This yields the bubble velocity and acceleration respectively.

3.2 PIV processing

The digital PIV recordings were evaluated using the deformation processing method with TSI Insight 3G software. Since bubbles and water move with different velocities it is necessary to separate the signals from the two phases in the PIV recordings. The bubble image derived from the shadowgraph using the methodology described in section 3.1 was used as the digital mask. The flow velocity of water was obtained from the masked tracer particle image, while that of the bubbles was obtained from particle tracking applied to the bubble image pairs obtain from shadow images. The deformation PIV processing requires significantly more computational time than Nyquist grid. However, it is effective in resolving the small scale velocity fluctuations and velocity gradients caused by passage of the bubbles, and allows for very small interrogation spot size of 16x16 pixels, giving output of 128x128 vectors corresponding to the spatial resolution of 0.52 mm over a field of view of 66x66 mm. This allows for detailed data processing of the PIV velocity field to obtain the information on the length scale of eddies using spatial filtering based on 2D Discrete Wavelet Transform.

3.3 Discrete wavelet transform (DWT) based frequency and wavenumber spectrum

The DWT separates the information content in the data from a fine scale to a coarser scale systematically, by isolating the fine scale variability in terms of wavelet coefficients representing the details from the corresponding coarser scale coefficients depicting the smoothness. This procedure can be repeated iteratively over smooth scales to obtain scalewise detailed decomposition in a multiresolution framework. In the current work, the excellent filtering capabilities of wavelet transform are employed to obtain bubble slip velocity and wavenumber spectrum of liquid velocity field, which gives information about different length scales of turbulence present in the flow.

2D DWT can be applied over the 2D snapshot data as:

$$W_{i,j}^{a,b}(x) = \int u_i(x) \psi^{a,b}(x) dx$$

where,

$$\psi^{a,b}(x) = 2^{a/2} \psi(2^a (x - b);$$

The 2D wavelet functions $\psi^{a,b}(x)$ are chosen to be orthogonal to their dyadic dilations by
2^{-a}$ and their translations by discrete steps $2^{-b}$, for $b = 1, \ldots, 2^a$, it allows a multiresolution analysis in wavelet scales $a = J, -1, -2, 1, 0$ that can be carried out in the 2D domain. Here, $J$ refers to the number of scales in the directions of $x$ and depends upon the data resolution. The wavelet coefficients obtained from (2) are convolved with scaled wavelet function in order to obtain the scalewise reconstruction.

This scalewise decomposition is used to separate the velocity field into two parts: spatial velocity variation with length scale larger than mean bubble size, and the spatial velocity variation with length scale smaller than mean bubble size. The reconstructed velocity fields obtained for larger scale are summed together to yield a ‘smoothened’ velocity field, which is ultimately used to calculate the slip velocity. In another part, the scalewise reconstruction of velocity field is used to calculate the vorticity. This vorticity field is used to identify the eddies of different size by thresholding criteria, which is primarily based on conservation of energy. The eddy sizes are determined by the same MATLAB routine which isolates bubbles from binarized shadow images. The scalewise reconstruction is masked with the thresholded vorticity matrix, and the resultant matrix is used to get the velocity magnitudes inside each isolated ‘structure’, thus making it possible to calculate its energy.

![Figure 5](image-url)

**Figure 5:** (a) PIV/PTV velocity field obtained using methodology in current work; Red vectors: bubble velocity, black vectors: liquid velocity (b) Velocity field with liquid plume pushing bubbles down (c) Liquid velocity field showing large scale structures (d) Liquid velocity field showing small scale structures (e) Shadow bubble image obtained by flashed LED backlight (f) Gas hold-up contour at $H/D=1$ obtained by averaging 500 images

### 4. Results and Discussion

For the results reported in the current work, the air sparging rate was 68 cc/s, and the corresponding gas hold-up was 3.5 %. The superficial velocity is 22 mm/s, and column operated in transition regime. The liquid velocity was observed to fluctuate significantly. This causes the bubble rise behavior to be significantly different from that of the single bubble rising in quiescent liquid. The wide range of bubble diameters was observed, which indicates the onset of heterogeneity.

Fig. 5 (a) and (b) show the sample velocity field obtained by the current methodology. The contours in the background represent liquid velocity magnitude, with bubbles shown in deep red.
The liquid velocity is shown with black vectors. All the velocity vectors are not shown, in order that the clarity of graphics may not be compromised. The bubble velocities are represented by red vectors originating from bubble centroids. In general, bubbles seem to follow the motion of liquid. A plume region with high liquid velocity magnitude can be observed in the left part of Fig. 5(a) and (b). From the sequence of recorded images, this plume was found to oscillate at the frequency of about 0.3 Hz along the width of the column. Larger bubbles rise in the vicinity of this plume. This type of turbulent, time varying liquid flow causes the wake structure of the bubbles to be significantly different than those rising in quiescent pool of liquid.

Fig. 5(e) shows a sample shadow bubble image. Bubbles of size range varying from 0.3 mm to 15 mm are clearly visible. Also, it can be observed the bubbles are neither strictly spherical nor ellipsoidal. Small bubbles of size less than 3 mm have nearly ellipsoidal shape. Larger bubbles are highly irregular in shape, and they consist of the major volume fraction of the gas inside column. Thus, the interfacial area of these bubbles is significantly higher than that estimated using the spherical, ellipsoidal or spherical cap approximation of shape. With the current methodology, it was not possible to reconstruct the instantaneous 3D geometry of each individual bubble in order to obtain its exact interfacial area. Much more sophisticated technique like holographic/Tomographic Schlieren imaging or chemical methods of measuring interfacial area should be used to throw some light on exact interfacial area characteristics of these bubbles. This is extremely important in order to model their mass transfer behavior.

Fig. 5(c) and 5(d) show the velocity field filtered using two-dimensional discrete wavelet transform. The field was decomposed into 7 scales. Fig. 6 shows the vorticity contours calculated using scale wise reconstruction of the velocity field. The location of eddies of different size are clearly visible from this scalogram. Scales 5-7 were added to generate the vector field showing small scale structures, while scales 1-4 were added to generate the vector field showing large scale structures. This separation was used to determine the slip velocities of bubbles in terms of ‘local’ liquid velocity. The liquid circulation is a combined effect of lateral movement of bubbles caused by either random motion (turbulent dispersion) or the lift force or the bubble coalescence in the region of higher velocity and gas hold-up. This is sustained by formation of the gas hold-up profile along the radial dimension, generating the driving force for liquid circulation. The mechanism of how these instabilities supplement each other is not yet well known, but their combined ultimate
effect in terms of liquid circulation velocity and gas hold-up profiles is well understood, and few empirical correlations are also available to predict these values.

Fig. 5(f) depicts the gas hold-up field generated by averaging 500 bubble images together. The shadow images were binarized by image processing program written in MATLAB. The pixels inside the bubbles were assigned the value of 1, while the background was assigned the value 0. After averaging sufficient images, the hold-up contour was obtained as shown in Fig. 5(f). Although, the increase in number of images smoothen the contours, 500 images gave a fair picture of hold-up profile. Thus, the hold-up profile, just above the sparger, is significantly flat in central region with very low gas hold-up near the wall. The area averaged hold-up was confirmed with the overall hold-up value within an experimental error of 10%.

In the current work, the velocity of structures having sizes larger than the largest bubble has been used as an estimate of local liquid velocity surrounding the bubble. This velocity field was interpolated to the bubble centroid location, and the liquid velocity was subtracted from bubble rise velocity to obtain the bubble slip velocity. Fig. 7 shows the results obtained from ensemble of bubbles detected in 3 images, for the purpose of illustration. Lines 1, 2 and 3 represent the single bubble slip velocity obtained using data reported by Clift et al. (1978) for distilled water, contaminated water and the correlation proposed by Nguyen (1998), respectively. As it can be clearly observed, most of the bubbles have higher or lower slip velocity than corresponding rise of individual bubble of same diameter. This difference in slip velocity was attributed to the change in flow field around the bubbles. Since the rising plume keeps on oscillating, some bubbles rise synergistically with the upward motion of liquid in plume. These bubbles were observed to be pulled in the wake of other bubbles rising in the chain. While, many encountered a downflow of the liquid (Fig. 5 b), and experienced effectively higher drag force, corresponding to higher slip velocity. However, in order to have clear understanding of the phenomena, detailed analysis of the data collected in current work is necessary.

Fig. 8 shows another feature of the current work. The velocity and acceleration measurements have been performed on single spherical cap bubble rising in a square tank of 200×200 mm cross section, generated with a special bubble generator. Fig. 8 (a) shows the raw bubble image from a sequence of 5 images used to calculate the trajectory of the bubble. Fig. 10(b)
shows the pseudo color image of the detected bubble contour, the bubble trajectory, bubble velocity and acceleration directions along with the liquid velocity field plotted using MATLAB routine. It can be observed that the bubble velocity and acceleration direction are quite different, and the lateral acceleration is significant. The spherical cap bubble was 52 mm in diameter, and corresponding Reynolds number is ~24000. The rise velocity of the bubble (0.48 m/s) was confirmed with that reported in literature (Clift et al. 1978). These results are shown to demonstrate the measurement capability of the developed measurement technique. However, significant effort is required to apply the acceleration measurement on bubbles in swarms, in order to discern the mechanism of enhanced/reduced interface forces caused by interaction between bubbles in a swarm.

![Image](image.png)

**Fig. 9** Wavenumber spectrum obtained by data processing of the scale wise reconstruction of velocity field using DWT.

- Individual eddy energy.
- Smoothed spectrum

Fig. 9 shows the wavenumber spectrum obtained using the data processing of DWT scalogram. The spectrum shows several peaks in the small wavenumber (larger length scale) region. The red line in the Fig. is the smoothed spectrum. The Kolmogorov length scale was estimated to be ~50 µm corresponding to averaged energy dissipation rate, corresponding to the wavenumber of 62000. Thus, the current spectrum was not resolved up to the dissipation regime. However, information regarding the large scale eddies is useful to understand parameters like mixing time. The line corresponding the the −5/3 law was also superimposed over the spectrum. Thus, it can be seen that the current method is able to resolve the wavenumber spectrum up to the inertial subrange. It should be noted that the spatial resolution of current PIV measurement was 520 mm, which was about 100 times the Kolmogorov length scale, and was well within the inertial subrange. Thus, the spectrum obtained from current methodology can be used to model the finer scale turbulence, and improve the understanding of transport phenomena like mass and heat transfer.

The major shortcoming of the current technique is its inability to measure the 3-D profile of bubbles and the location of the bubbles in the direction normal to the PIV measurement plane. This implies that the bubble might not be cutting the measurement plane at its equatorial plane, represented by its boundary in the shadow image. This problem has been addressed in the current work by only using the filtered liquid velocity field, comprising only of the spatial variations larger than bubble diameter. This ensured that there was little change in the liquid velocity magnitude over the distance of the order of half the bubble diameter, thus allowing sensible estimation of slip
velocity. However, smaller bubble may be significantly off the plane, experiencing completely different velocity field than represented by the PIV measurement plane at its projected location. Thus, the slip velocity plot shows higher scatter for small bubble diameter. However, due care has been taken to choose the narrow dimension of the column and the macro lens with narrow depth of focus, which ensured that bubbles used for the calculations were not too far from the measurement plane. Thus, the reliability of the measurement for the present case of narrow rectangular column has been confirmed. However, these limitations have to be addressed with more sophisticated capture and processing tools, in order to have valuable information which will be helpful to improve the existing knowledge of bubble motion in flow conditions similar to real life process equipment.

5. Conclusion

A proposed PIV/LIF + Shadowgraphy setup has been successfully demonstrated with measurements in a narrow rectangular bubble column, and for a single spherical cap bubble rising in a stagnant pool of water. The bubble shape, size, velocity and acceleration can be measured along with the liquid velocity, right up to bubble interface. The results clearly show the turbulent flow structures in the bubble swarms. The slip velocity of bubbles rising in swarms is measured and compared with that of the single bubbles rising in stagnant liquid. The results clearly mark the effect of flow disturbances on the rise characteristics of bubbles. The flow information obtained from these measurements has been subjected to rigorous data processing using 2D DWT, and relevant details like length scales and energies of the individual eddies have been extracted. However, the wealth of information obtained using current measurement and data processing technique still needs to be explored for understanding the role of turbulent structures to improve the transport phenomena in gas-liquid dispersions.

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Notations

\[ a = \text{scaling parameter, m} \]
\[ b = \text{translation parameter, 1/m} \]
\[ d_B = \text{bubble diameter, mm} \]
\[ E = \text{spectral Energy Density, m}^2/\text{s} \]
\[ n = \text{Number of data points corresponding to b} \]
\[ u = \text{instantaneous velocity, m/s} \]
\[ V_S = \text{Slip velocity, m/s} \]
\[ W_{a,b} = \text{wavelet coefficient in DWT} \]
\[ x = \text{spatial location} \]
\[ C_I = \text{Scaling constant for Kolmogorv’s -5/3^{rd} law} \]

Greek letters

\[ \psi = \text{mother wavelet function} \]
\[ \kappa = \text{wavenumber, 1/m} \]

References


