Research News

Two-Phase PIV in Bubbly Flows: Status and Trends

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1 Introduction

In the chemical process industry there is a vast interest in the behaviour of multiphase flows within chemical reactors. Computational Fluid Dynamics (CFD) is a state of the art tool that is being used to simulate this flow behaviour. While there is a lot of dispute about the formulation and closure of the fluid dynamical equations, there is a clear need for experimental validation of CFD. Particle Image Velocimetry (PIV) is a measurement technique that has received a lot of attention for this purpose in the last decade. PIV is an optical and thus non-intrusive measurement technique that gives instantaneous 2D velocity data for a whole plane in a 3D flow field. There are many different implementations of PIV for two-phase flows, which have been reviewed extensively by Brücker [1] and Deen *et al.* [2]. In this paper we will focus on recent developments in PIV for dispersed two-phase flows in particular for bubbly flows.

2 Basic Principles of Two-Phase PIV

A schematic overview of an experimental PIV set-up is shown in Fig. 1. In PIV the flow is seeded with small tracer particles that follow the flow. A cross section of the flow is illuminated with the use of a laser light sheet. A CCD camera is used to record images of the particles in the illuminated plane. Two subsequent images of the flow, separated by a short time delay, Δt, are divided into small interrogation areas. The volume-averaged displacement, $\mathbf{s}(\mathbf{x}, t)$, of the particle images between the interrogation area in the first image and the interrogation area in the second image is determined by means of a cross-correlation analysis. When the interrogation areas contain a sufficient number of particle images the cross-correlation consists of a dominant correlation peak embedded in a background of noise peaks. The location of the tall peak, referred to as the displacement-correlation peak, corresponds to the particle-image displacement. The velocity within the interrogation area, $\mathbf{v}(\mathbf{x}, t)$ is then easily determined by dividing the measured displacement by image magnification M and the time delay:

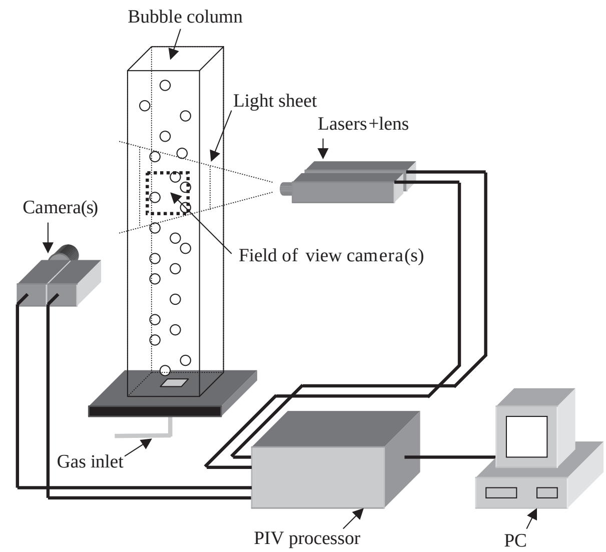

Figure 1. Schematic representation of an experimental PIV setup.

$$\mathbf{v}(\mathbf{x}, t) = \frac{\mathbf{s}(\mathbf{x}, t)}{M \Delta t} \quad (1)$$

provided that Δt is sufficiently small. Further details on the interrogation of PIV images are given by Adrian [3] and Keane & Adrian [4]. The visibility of the displacement-correlation peak does not only depend on the number of particle images in the interrogation area, but also on the magnitude of the in-plane and out-of-plane displacements and the variation of the displacement over the interrogation area. Under less favourable circumstances the height of the displacement-correlation peak is reduced, and drops below the level of the tallest noise peak. This results in a spurious measurement of the displacement. The probability that the interrogation yields the location of the displacement-correlation peak, i.e. the probability that the displacement-correlation peak is the tallest peak in the correlation domain, is referred to as the *valid detection probability*, Γ.

The presence of the dispersed phase introduces problems to the PIV method, which are not present in single-phase flows. Some of these problems are illustrated in Fig. 2. In the area

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marked with "A", the bubble concentration, $N_{i,B}$ is rather low and the image looks very much like a PIV image of a single-phase flow. In that case, the number of correct measurements of the liquid phase (i.e. the valid detection probability) will be high, as illustrated in Fig. 3. In another part of Fig. 2, marked with "B", the bubble concentration is rather high, in fact most of the image of that region is filled with bubbles, so there is little space left for the tracer particles. This results in a low valid detection probability, as is shown in Fig. 3.

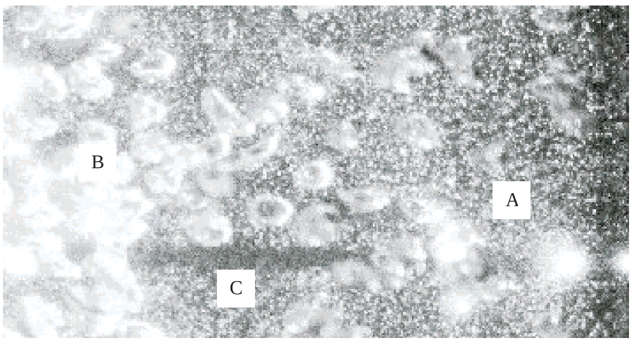

Figure 2. Example PIV measurement in a bubbly flow at a gas volume fraction of about 1 %. From Deen *et al.* [14].

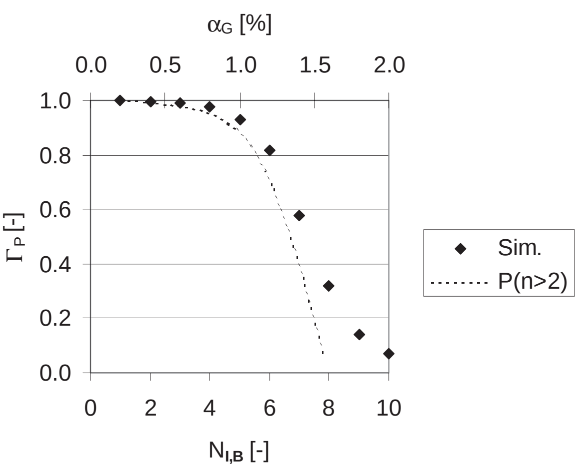

Figure 3. Effect of the bubble source density, $N_{i,B}$ on the valid detection probability of the liquid phase. P (n > 2) represents the probability to find at least two tracer particles in the measurement volume, from Deen *et al.* [14].

Another problem present in PIV measurements of dispersed two-phase flows is that the dispersed phase can introduce shadows, as is shown in Fig. 2 at marker "C". These shadows can, together with bubbles in front of the light plane, reduce the amount of information present in the PIV images. Finally, the deformation of bubbles during the time delay between the two recordings of the flow may deteriorate the precision of the measurement.

Some of the problems introduced above can be overcome with the use of ensemble correlation, which will be presented in the next section. The PIV measurement technique is nevertheless limited to low volume fractions of the dispersed phase, typically 1–4 %.

3 Available Methods

The PIV images contain a mixture of information from both phases. Several methods are available to distinguish and separate the information of the phases present in the flow. Some of these methods are discussed below. First the idea of ensemble correlation will be explained.

As explained earlier the displacement is determined through correlation analysis. In ensemble correlation the correlation functions of subsequent recordings of the flow are added up, as demonstrated in Fig. 4a. Provided that the flow characteristics do not change over short time scales the displacement peaks will be in the same position and they will therefore add up. The random noise peaks generally do not coincide, and therefore the effect of adding the correlation planes will enhance the visibility of the displacement-correlation peak, enabling an easier detection of the displacement peak. The effectiveness of this method was also shown by Meinhart *et al.* [5], who examined the accuracy of three different methods to obtain time averaged velocity fields. They found that the ensemble averaging of the correlation function was superior to either averaging velocity fields or averaging images.

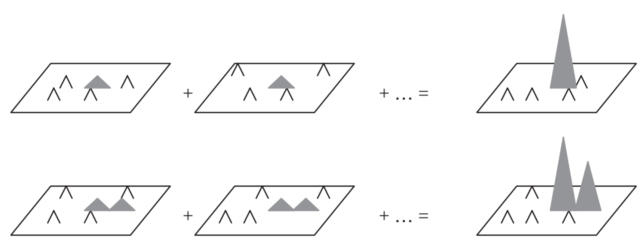

Figure 4. Principle of ensemble correlation for a: single phase flows and b: two-phase flows.

In the case of a two-phase flow with significant slip between the phases, two different displacement peaks will be present in the correlation plane. When ensemble correlation is applied, the two highest peaks in the correlation plane represent the velocities of both phases, as is shown in Fig. 4b. Delnoij *et al.* [6] used ensemble correlation to increase the signal to noise ratio (SNR) of the dispersed phase. They then applied the algorithm to the flow of a bubble plume in a flat bubble column and they have also applied ensemble correlation PIV to the flow of a bubble plume rising in a 3D bubble column [7]. Fig. 5 shows an example result of Delnoij et al. (1999) [7] for the correlation ensemble averaged flow fields of both the gas and the liquid phase in a bubble plume.

In certain two-phase flows, a short exposure time delay is needed, so the ensemble correlation algorithm can not be used. For example: Deen and Hjertager [8] performed measurements in a stirred tank. In order to limit the out-of-plane loss of particle image pairs the exposure time delay needed to be small. This resulted in a relative displacement between the phases of ~ 1 pixel. For such a small relative displacement, the two displacement peaks would overlap and

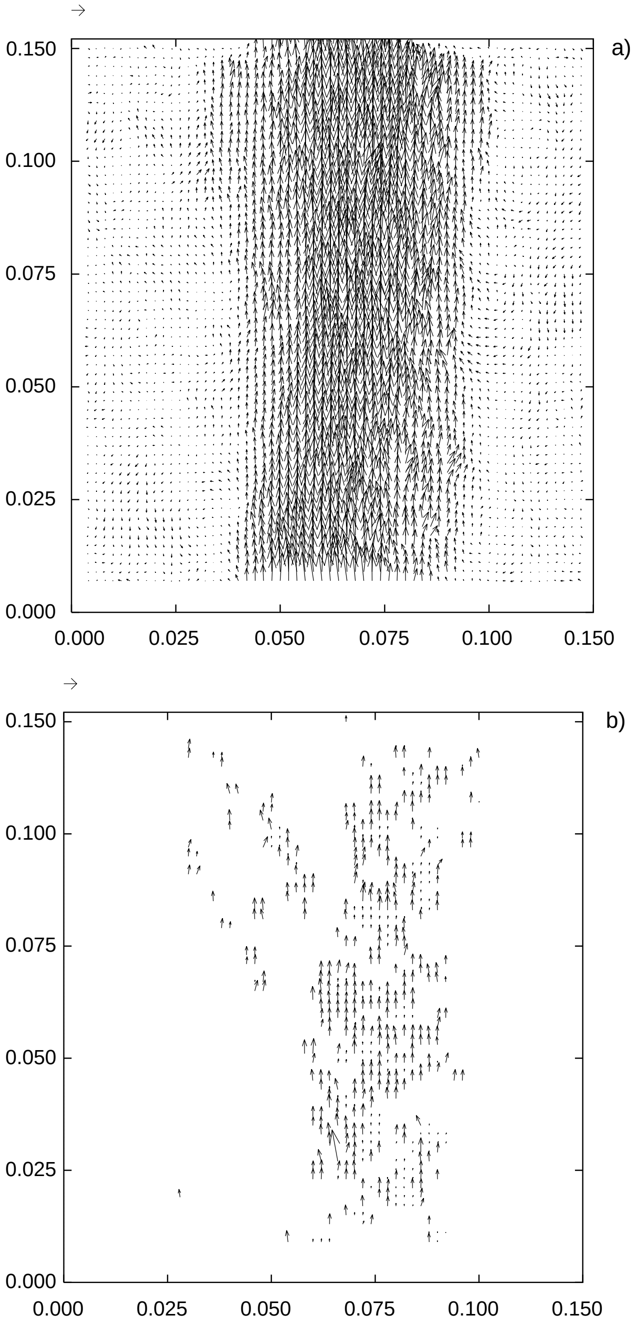

Figure 5. Ensemble correlation averaged flow fields in a vertical cross section in a bubble column at a gas fraction of about 0.1 %; a: liquid velocity; b: gas velocity. The ensemble size is 15 images. The field of view is 0.15 × 0.15 m^2. The reference vectors are 0.60 m/s. [7].

it would no longer be possible to discriminate between the two phases by means of the ensemble correlation algorithm.

Gui and Merzkirch [9] and Gui *et al.* [10] used a slightly different approach. The detection of the dispersed particles is based on particle size. When the dispersed phase has been detected, two new image pairs are generated. In one pair the dispersed phase is masked and replaced with the average background intensity. In the other pair the same is done for the continuous phase. They applied this algorithm to the liquid-solid flow in a water tank, and to a gas-liquid bubbly flow. According to the images in the paper by Gui *et al.* [10], the bubbles appear to be considerably overexposed. This means that the bubble images look like big solid white spots. At lower light intensities however, one could expect that the bubbles would no longer be solid spots therefore making a distinction between tracer particles and bubbles based on particle size more difficult.

Grota and Strauß [11] developed a technique which can be considered as the combination of the ensemble correlation algorithm of Delnoij *et al.* [6] and the masking algorithm of Gui and Merzkirch [9]. They applied it to determine the velocity fields of both phases in a dilute particle-laden gas flow. In their case the hold-up of the particulate phase was very low, so ensemble correlation was applied to increase the SNR. High accuracy in the measurements of mean velocities was obtained, even in the case of large velocity fluctuations [11].

Khalitov and Longmire [12] used criteria based on both size and brightness of the dispersed phase to discriminate between the phases. This algorithm works well for particle-laden flows, with spherical particles of a known size range. However, this method will probably not work very well for bubbly flows, because usually the bubbles can not be distinguished as single entities.

Kiger and Pan [13] and Deen *et al.* [14] used a median filter to separate the phases into two images. Kiger and Pan [13] showed that the median filter does not alter the measurement results for the continuous phase. The filtering procedure is very effective in flows were the dispersed phase consists of solid particles. However bubbles can have complex shapes and scattering patterns. The effect of the median filter is demonstrated in Fig. 6. The top row of images in Fig. 6 consists of synthetic PIV images. It is seen that the tracer particles can effectively be removed from the image, resulting in an image of the bubbles only. When the bubble image is subtracted from the original image, one obtains an image of the tracer particles. For PIV images from an actual measure-

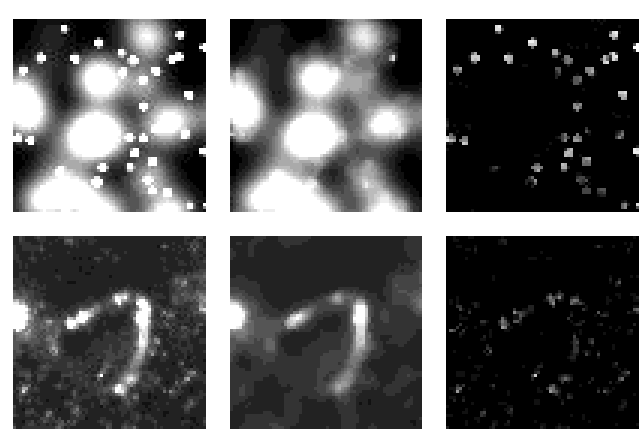

Figure 6. Demonstration of the effect of the median filter. From left to right: original image, median filtered image and the original image minus the median filtered image. Top row: synthetic PIV images; bottom row: real experiment images. All the images are 64 × 64 px^2 and have a gas volume fraction of about 1 %. A filter width of 5 pixels was used, from Deen *et al.* [14].

ment in two-phase bubbly flow the median filter is not fully effective, because the bubbles are not single entities, as can be seen in the bottom row of images in Fig. 6. The accuracy of the median filter is reduced by the fact that the edges of the bubbles are still present in the bottom image. This is an artefact of the filter, which may cause problems when the signal of the tracer particles is weak. A possible solution to this problem is the use of masking [9]. Note that masking would only work if the bubbles are single entities, as for example is the case in the work of Gui et al. [9] Deen *et al.* [14] did not use this technique, because in their case there were no apparent criteria for separating the particle-images from the bubble-images.

Deen *et al.* [2] used yet another PIV system. They used a two-camera system and fluorescent tracer particles. By mounting optical filters on the cameras, the images of tracer particles and the bubbles are separated optically. An ordinary single phase cross correlation algorithm is used to determine the velocities of both phases. This algorithm seems to be more robust than the ensemble correlation algorithm. However, the optical filters and the extra camera will make the experimental set-up more complicated and expensive. Deen *et al.* [2] were able to apply this algorithm on the flow in a square cross-sectioned bubble column with a gas fraction of up to 4%. Examples of their work are shown in Figs. 7 and 8. These figures clearly show that PIV in multiphase flows can reveal important quantitative information on the prevailing flow phenomena. For example, in Fig. 8 it can be seen that the slip velocity decreases by a factor 3 when the superficial gas velocity (viz., volume fraction) increases by a factor of 3.

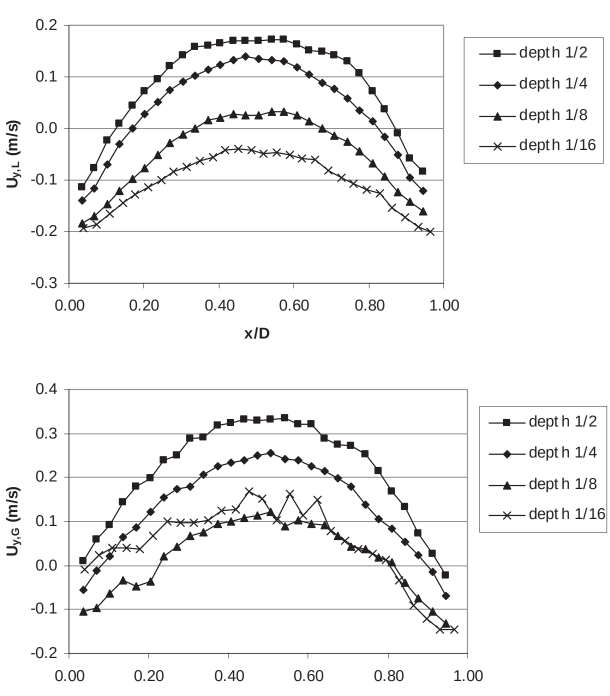

Figure 7. Time averaged axial velocity profiles for different depths in the column for a: the liquid phase and b: the gas phase. Measurements at an height of z/H = 0.78 [2].

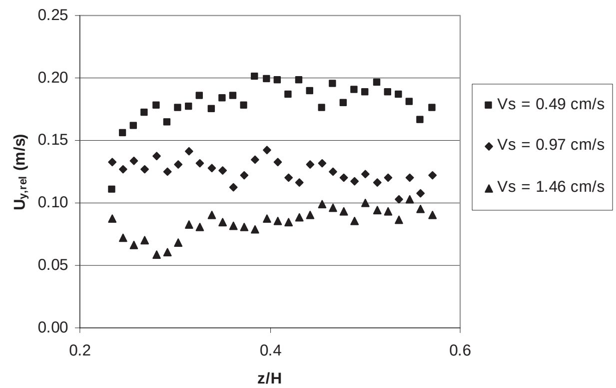

Figure 8. Slip velocity as a function of height in the bubble column and superficial gas velocity. Data from Deen *et al.* [2].

4 Discussion and Conclusions

In this work we have discussed recent developments in the area of two-phase PIV of bubbly flows. Several problems occur due to the presence of the dispersed phase, especially at high gas fractions. These are, shadows of the bubbles and the bubbles them selves block a lot of the area available for tracer particles. It then becomes very difficult to measure the velocity of the continuous phase. For future measurements we suggest one of the following two options. The first option is the ensemble correlation algorithm. This algorithm can help us in analysing bubbly flows, provided that the flow is pseudo-stationary during the period of ensemble averaging. When the ensemble correlation algorithm is combined with an algorithm to detect the dispersed phase (for example a median filter) and a masking technique, the measurement technique can be pushed towards a gas-holdup of about 4 %. When there are no problems with optical access and if the time scale of the flow is very short we suggest two-camera PIV. This second option has a lot of potential. We have seen that this technique is very effective in the discrimination between the phases.

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References

[1] Brücker, C., PIV in Two-Phase Flows, von Karman Institute for Fluid Dynamics, Lecture Series 2000-01.
[2] Deen, N. G.; Hjertager, B. H; Solberg, T, Comparison of PIV and LDA Measurement Methods Applied to the Gas-Liquid Flow in a Bubble Column, *10th Int. Symp. on Appl. of Laser Techniques to Fluid Mech.*, Lisbon, Portugal, 2000.
[3] Adrian, R. J., Particle-imaging Techniques for Experimental Fluid Mechanics, *Annu. Rev. Fluid Mech. 22* (1991) pp. 261–304.

[4] Keane, R. D.; Adrian, R. J., Optimization of Particle Image Velocimeters: I. Double Pusled Systems, *Meas. Sci. Technol. 1* (1990) p. 1202.
[5] Meinhart, C. D.; Werely, S. T.; Santiago, J. G., A PIV Algorithm for Estimating Time-averaged Velocity Fields, *J. Fluids Eng. 122* (2000) pp. 285–289.
[6] Delnoij, E.; Kuipers, J. A. M.; van Swaaij, W. P. M.; Westerweel, J., Measurement of Gas-Liquid Two-Phase Flow in Bubble Columns Using Ensemble Correlation PIV, *Chem. Eng. Sci. 55* (2000) pp. 3385–3395.
[7] Delnoij, E.; Westerweel, J.; Deen, N. G.; Kuipers, J. A . M.; van Swaaij, W. P. M., Ensemble Correlation PIV Applied to Bubble Plumes Rising in a Bubble Column, *Chem. Eng. Sci. 54* (1999) pp. 5159–5171.
[8] Deen, N. G.; Hjertager, B. H., Multiphase Particle Image Velocimetry Measurements in an Aerated Stirred Tank, presentated at *Annual Meeting AIChE*, Dallas, USA, 1999.
[9] Gui, L.; Merzkirch, W., Phase-Separation of PIV Measurements in Two-Phase Flow by Applying a Digital Mask Technique, *ERCOFTAC Bulletin 30* (1996) pp. 45–48.
[10] Gui, L.; Lindken, R.; Merzkirch, W., Phase-separated PIV Measurements of the Flow around Systems of Bubbles Rising in Water, *ASME FEDSM'97*, (1997).
[11] Grota, B.; Strauß, K., DPIV in a Particle-laden Gas Flow – The Influence of the Particle Fluctuation Velocities on the Accuracy of Several Cross-Correlation-Based Analysis Methods, presented *at EUROMECH 4*, Eindhoven, The Netherlands, 2000.
[12] Khalitov, D. A.; Longmire, E. K., Simultaneous Two-Phase PIV by Two-Parameter Phase Discrimination, submitted to *Exp. Fluids* (2000).
[13] Kiger, K. T.; Pan, C., PIV Technique for the Simultaneous Measurement of Dilute Two-Phase Flows, *J. Fluids Eng. 122* (2000) pp. 811–818.
[14] Deen, N. G.; Westerweel, J.; Delnoij, E., Upper Limit of the Gas Fraction in PIV Measurements in Dispersed Gas-Liquid Flows, submitted for presentation at the 5th Int. Conf. on Gas-Liquid and Gas-Liquid-Solid Reactor Eng., Melbourne, Australia, 2001.

