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Comparison of PIV and LDA Measurement Methods Applied to the Gas-Liquid Flow in a Bubble Column

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ABSTRACT

In this work a comparison of multiphase PIV and LDA measurement methods is made. The objective of the work is twofold: to provide measurement results that can be used to validate multiphase CFD simulations and to assess the different acquisition and analysis methods in multiphase measurements. The former is done with the use of a two-camera PIV/LIF method. It is shown that this method gives detailed information about the flow, without prior knowledge of the shape, size or position of the dispersed phase. The latter objective is accomplished by comparing two-camera PIV/LIF measurements with both LDA and single camera PIV measurements. With single camera PIV, it could not be decided which phase really is measured. Accordingly, an algorithm, which can distinguish the tracer particles from the dispersed phase, is needed. The sample period of 300 s for the LDA measurements appeared to be too short to obtain steady time averaged data.

The simultaneous PIV/LIF velocity measurements of the gas and the liquid phase in a bubble column show a core-annulus flow. The slip velocity between the two phases is varying between 0.05 and 0.2 m s⁻¹. The highest velocity fluctuations in the liquid phase are found in the axial direction and are in the order of 0.15 m s⁻¹.

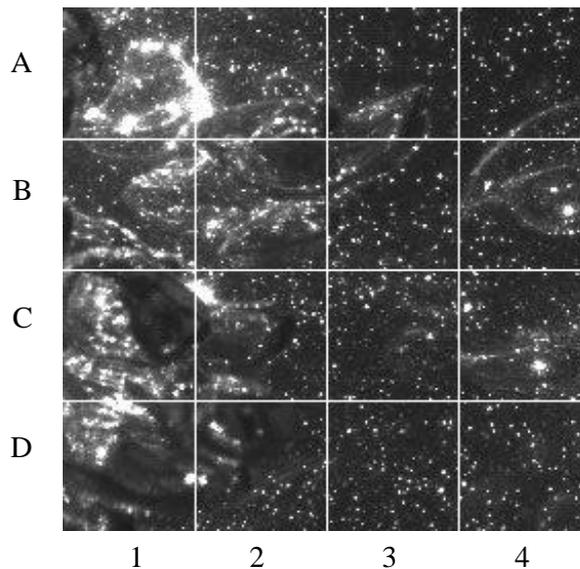
1. INTRODUCTION

Much effort is made to obtain detailed information about the hydrodynamics in chemical reactors. Both Experimental and Computational Fluid Dynamics (EFD and CFD) play an important role in this field. Although there is a general understanding of the way to perform numerical simulations of single phase flows, there is still a lot of discussion on the modelling of multiphase flows (see i.e. Kuipers and van Swaaij (1997) and Jakobsen et al. (1997)). Crucial in the development of CFD for multiphase flows is the availability of detailed and reliable measurement data. The use of laser-based measurement techniques has a lot of potential which can be seen from the number of publications where Particle Tracking Velocimetry (PTV) or Particle Image Velocimetry (PIV) have been used to measure velocities of two individual phases in multiphase flows.

In PIV the continuous phase is seeded with small tracer particles that ideally follow the flow. A laser is used to illuminate the tracer particles in a cross section of the flow. Then two subsequent images with a short exposure time delay are recorded with a digital camera. These images are divided into small interrogation areas. Each interrogation area in the first image is then correlated with the corresponding interrogation area in the second image. In the resulting correlation function a distinct peak can be found. The location of the peak corresponds to the displacement of the particles in the interrogation area. The velocity is determined by dividing the measured displacement by the exposure time delay. The advantage of PTV and PIV are that velocities of two different phases can be determined simultaneously in a whole plane in the flow, without disturbing the flow. One of the major disadvantages of these techniques is the rather low temporal resolution (typically 15 Hz for digital PIV). Laser Doppler Velocimetry (LDA) on the contrary has a very high temporal resolution (typically in the order of 1 kHz). Since LDA is a single point measurement technique, one can only measure the velocity of one particle at a time. Therefore it is not possible to measure the velocities of different phases simultaneously.

There are several implementations of two-phase PIV and two-phase PTV, which will be discussed shortly. This discussion will focus on the use of single-camera systems and the possibilities to apply the implementation to flows in which it is difficult to measure, due to high volume fraction and/or non-sphericity of the dispersed phase.

Fig. 1. Close-up of a PIV recording of the gas liquid flow in a bubble column, showing 16 interrogation areas of 64x64



px².

First of all one should decide whether one should use PTV or PIV for each of the phases. To make this decision, one can use the reasoning in Westerweel (1993) which can be explained as follows. In PTV, the average distance between the particles is much larger than the mean displacement. That means that the displacement of particles can easily be determined, without confusing them with neighbouring particles. In the meanwhile the number of particles per interrogation area (i.e. a small area, in which the velocity is to be determined) is too few to apply PIV. At least four to five particles per interrogation area are needed to determine the velocity with PIV. So, depending on the flow system under consideration one should decide to process the images with PTV or PIV algorithms. In some cases this choice is not obvious, because there can be a wide range of particle concentrations, differing from one interrogation area to another. This is illustrated in Fig. 1. In this figure a close-up of a PIV recording of the gas-liquid flow in a bubble column is shown. It can be seen that in interrogation area D3 there are only tracer particles present, while the entire interrogation area C1 is filled with bubbles. In each area only the velocity of one phase can be determined.

Hassan et al. (1992), Lin et al. (1996) and Reese et al. (1996) all used PTV for both the dispersed and the continuous phase. An important aspect in the processing of the images is the identification of the dispersed phase. Hassan et al. (1992) performed measurements of both the gas and the liquid phase in a system of single bubbles rising in a heavy mineral oil. In order to be able to detect the particle images, the bubbles needed to be overexposed. The bubble images

consisted of overexposed round spots. A threshold function was used to determine the position of the edges of the bubble. Then both the tracer particles and the bubbles were tracked. In order to obtain a velocity field on a regular grid, the PTV data was interpolated. Since the seeding density in PTV is much lower than in PIV, a much lower spatial resolution can be obtained.

In many applications the dispersed phase has a rather low concentration, which enables PTV measurements. The continuous phase on the other hand has a high concentration in most of the interrogation areas, which makes the use of PIV on this phase suitable. This was for example done by

Jakobsen et al. (1996), Oakley et al. (1997), Kiger (1998) and Lindken et al. (1999). Jakobsen et al. (1996) developed PIV/PTV for the application in gas-solid flows. Similar as in the work of Hassan et al. (1992) the dispersed particle phase is expected to scatter much more light than the tracer particles (i.e. the representatives for the gas phase). Therefore the images were scanned for high light intensities. Afterwards, an edge detection technique was used to determine the area occupied by the particle. The principle is simple and works very well for dispersed phases with high intensity. The disadvantage of this method is that it only works if the dispersed phase scatters much more light than the tracer particles and if the surface easily can be detected. The latter is for example not the case when the dispersed phase consists of bubbles. That is, single bubbles are often displayed as two or three spots as also pointed out by Oakley et al. (1997). They used PIV to measure the liquid velocity in a gas-liquid bubbly flow. The velocity of the bubbles was determined by means of PTV. The determination of the bubble positions was done manually. The major disadvantage of this method is that it is very time-consuming. In practice this will only yield a few bubble trajectories. Kiger (1998) studied the liquid-solid two-phase flow in a vertical water channel. He used a scanning PIV technique, which is an extension of the ordinary PIV technique. Since the intensity of the dispersed particles and the tracer particles was in the same order of magnitude, particle detection based on intensity could not be used. However, in this case the scattering pattern of the dispersed particle images was known. This scattering pattern was used as a convolution kernel function to determine the position of the dispersed particles. Similar to the method of Jakobsen et al. (1996), a priori information of the dispersed particle image is needed. In the case of a bubbly flow this technique would only work if the bubbles have a constant size and shape. This is generally not the case.

Gui and Merzkirch (1996) and Gui et al. (1997) used a slightly different approach. They used PIV for the measurement of the velocities of both phases. 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 the one pair the dispersed phase is masked and replaced with the average background intensity. In the other pair the same is done, but then for the continuous phase. The velocities of both phases are determined by a routine that searches for the minimum quadratic difference in intensities between the interrogation areas in two successive frames for different displacements. This is very similar to looking for a maximum in the cross-correlation between interrogation areas in two successive frames, which is generally applied by other researchers. Gui and Merzkirch (1996) and Gui et al. (1997) applied this technique on the liquid-solid flow in a water tank. Gui et al. (1997) also applied this technique successfully to a gas-liquid bubbly flow. According to the images in the paper Gui et al. (1997), the bubbles seem to be considerably overexposed. This means that the bubble images look like big solid white spots, similar to the work of Hassan et al. (1992). At lower light intensities, one could expect that the bubbles would no longer be solid spots. Making a distinction between tracer particles and bubbles based on particle size would then be very difficult.

Delnoij et al. (1999) developed a PIV/PIV method that does not use information of the shape of the dispersed phase. They used the presence of slip velocity between the continuous and the dispersed phase. When the slip velocity is large enough both phases will give a signal when the cross correlation is determined between two subsequent images. The processing program only needs to search for an additional peak in the correlation field. If the flow is buoyancy-driven the sign of the slip-velocity is known a priori and it will be easy to determine which peak belongs to which phase. Both peaks can be distinguished, provided that their distance is large enough so they do not overlap and that there are enough particles present in the interrogation area such that the peak exceeds the noise level. The first can be accomplished by increasing the time delay between the two frames. This is not always possible as was mentioned by Deen et al. (1999), who performed measurement in the impeller region in a stirred tank. They noticed that a relatively long time delay, in order to locate both peaks, could not be used in the impeller region in a stirred tank, because out-of-plane displacement would give problems.

The presence of sufficient tracer particles in the interrogation area is often hard to accomplish as was seen in the discussion of image 1. In order to solve this problem Delnoij et al. (1999) suggested the use of an ensemble average of N subsequent correlation functions:

$$R_{ensemble}(\mathbf{s}) = \sum_{i=1}^N R_i(\mathbf{s}) \quad (1.1)$$

Where $R_i(\mathbf{s})$ is the spatial cross correlation function as described in Westerweel (1993) and Keane and Adrian (1993). This technique can only be used when the timescales of the flow are longer than the timescale of the ensemble. Delnoij et al. (1997) used an ensemble size, N of 15, which corresponds to a period of 1 s. They used the method for the bubbly flow in a bubble column, in which the time scales of the large scale flow structures were longer than 1 s.

In this work, a method will be used which combines Particle Image Velocimetry and Laser Induced Fluorescence (PIV/LIF). This method comprises two cameras and the use of fluorescent tracer particles. Optical filters are used to

obtain images of solely tracer particles with one camera and images of the dispersed phase with the other camera. The subsequent post processing and analysis is similar to single-phase PIV. This system has the large advantage that no prior information of the size or the intensity of the dispersed particles is needed. The disadvantages of the system are the additional cost of the second camera and the doubled data processing. The PIV/LIF method will be compared with single camera PIV and LDA measurements of the liquid velocities. The single camera method is similar to the one used by Delnoij et al. (1999). However, the measurements presented in this work are conducted for a somewhat larger gas hold-up.

2. EXPERIMENTAL PROCEDURE

PIV and LDA measurements were performed on the flow of a bubble plume in a 3-D bubble column which is shown in Fig. 2. The column is filled with distilled water to which 4 g of kitchen salt per litre was added in order to obtain a non-coalescing system. The column has a square cross-section (WxD) of 0.15 x 0.15 m² and a height (L) of 1 m. Air was introduced into the system through a perforated plate. The plate contained 49 holes, with a diameter of 1 mm, which were positioned in the middle of the column at a square pitch of 6.25 mm. In all experiments, the bubble column was operated with an initial liquid level of 0.45 m (L/D=3) and at a superficial gas velocity of 5.0 mm s⁻¹. A PIV/LIF system was used to simultaneously measure the gas and liquid velocities. In the single-camera PIV method both the gas and the liquid phase are recorded with the first camera. In order to verify the single camera method directly the second camera is equipped with a filter in order to measure the velocity of the tracer particles.

The water flow was seeded with fluorescent rhodamin-B particles with a diameter of 50 μm and a density of 1.5*10³ kg m⁻³. The volume fraction of the particles was 10⁻⁴. A pair of 15 Hz New Wave MiniLase pulsed Nd:YAG lasers, with a beam expanding lens was used to create a lightsheet with a depth of 3 mm. Two 30 Hz Kodak Megaplug ES 1.0 cameras were used to record 1008 x 1018 px² images of the flow. The first camera was equipped with an orange bandpass (wavelength of filter in order to detect the fluorescent seeding. The second camera, with a bandpass filter corresponding to the wavelength of the laser light, detected only the gas phase. A Dantec PIV 2100 processor synchronised the laser and the cameras. In the PIV/LIF system 300 image-pairs were recorded during a period of 900 s. This rather long period ensures that a steady time average (i.e. free from wiggles) can be calculated. The period should be long enough, when compared to the 600 s averaging time used by Borchers et al. (1999). Measurements were performed in several planes in the column. In the single-camera PIV experiment, only 50 images were recorded. This may not be enough to reach a steady time average, but will certainly be sufficient to make a qualitative comparison with the PIV/LIF system. An overview of the experimental settings is given in table 1.

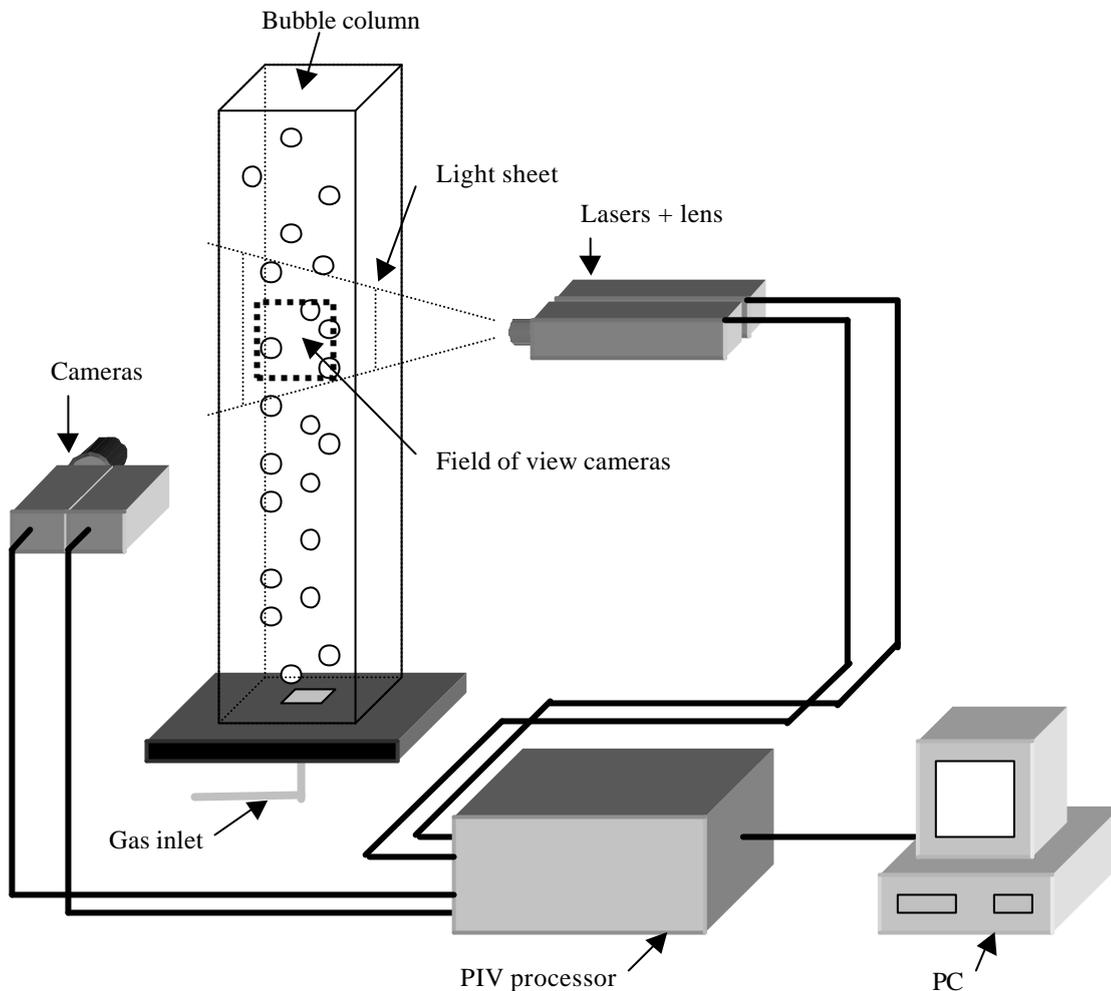
Table 1
Overview of experimental settings.

Measurement setting	PIV/LIF	Single camera PIV
Field of view	0.159 x 0.161 m ²	0.079 x 0.080 m ²
Interrogation areas	64 x 64 px ² = 0.01 x 0.01 m ²	64 x 64 px ² = 0.01 x 0.01 m ²
Exposure time delay	1.0 ms	2.5 ms
Averaging time	900 s	150 s

The interrogation areas had an overlap of 50%. Outliers in the flowfields were detected and removed with two subsequent tests. First a detectability test was performed. In this test the height of the two highest peak in the correlation function are compared. Gas velocity vectors were regarded as outliers when the peak height ratio was less than 1.5. A value of 1.2 was used for the liquid phase. The second test was based on a comparison between the measured vector and the average of the eight surrounding vectors (see Westerweel (1997)). In this test a threshold value of 0.3 was used for both phases.

A Dantec 2D Fiberflow LDA system was used to measure the liquid velocity. In the LDA experiment the water flow was seeded with polystyrene particles with a diameter of 50 μm and a density of 1.03*10³ kg m⁻³. The volume fraction of the particles was 10⁻⁴. A lens with a focal length of 160 mm was mounted on the LDA probe. The experiment was run in back-scatter mode. The axial and the radial velocities were measured with wavelengths of respectively 514.5 nm and 488.0 nm. A frequency shift of 40 MHz was used to remove the directional ambiguity of the velocity. Each point was sampled during 300 s. In that period about 10³ samples were obtained. A preliminary measurement without tracer particles showed that the data rate of the bubbles could be neglected.

Fig. 2. Schematic representation of the experimental PIV set-up.



3. RESULTS

Instantaneous flowfields of both phases, obtained with PIV/LIF is shown in Fig. 3. Most of the outliers are seen to be in the gas flowfield. This is due to the fact that velocities only are measured when there really are bubbles present in the interrogation area. The bubble plume showed large random oscillations, over the entire cross-section of the column.

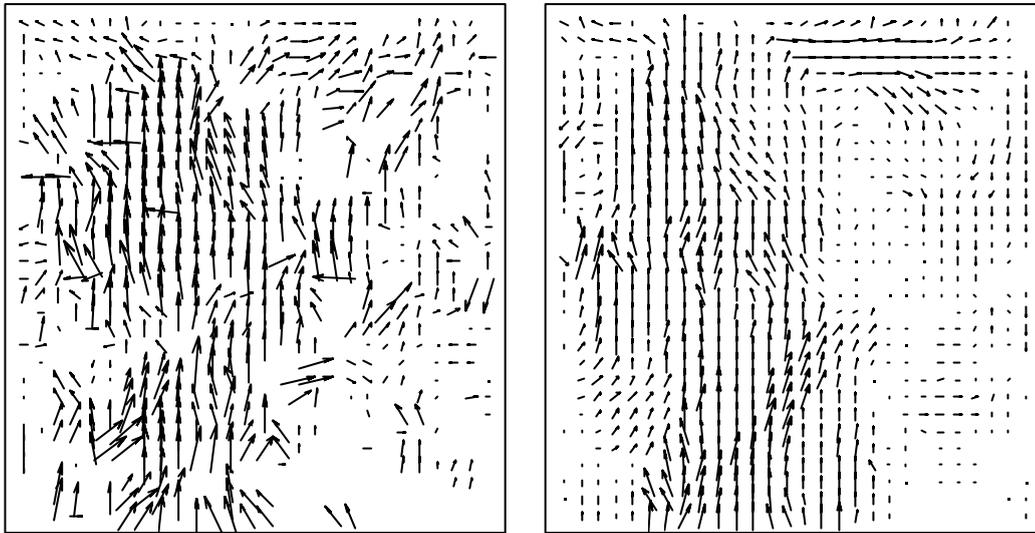


Fig.3. Instantaneous velocity vector plots of the gas (left) and liquid (right) phase. The measurement is made in a centre plane of the column at a height of 0.26-0.41 m.

The time averaged axial velocity profiles at different depths in the column are shown in Figs. 4 and 5. The profiles are approximately parabolic for all depths. The average slip velocity is varying between 0.05 and 0.2 m s^{-1} . Overall this is lower than the slip velocity of a single bubble rising in water (i.e. typically 0.2 m s^{-1}). The downflow of the liquid is seen to take place at the walls and particularly in the corners of the column. In these regions also some downflow of gas can be observed.

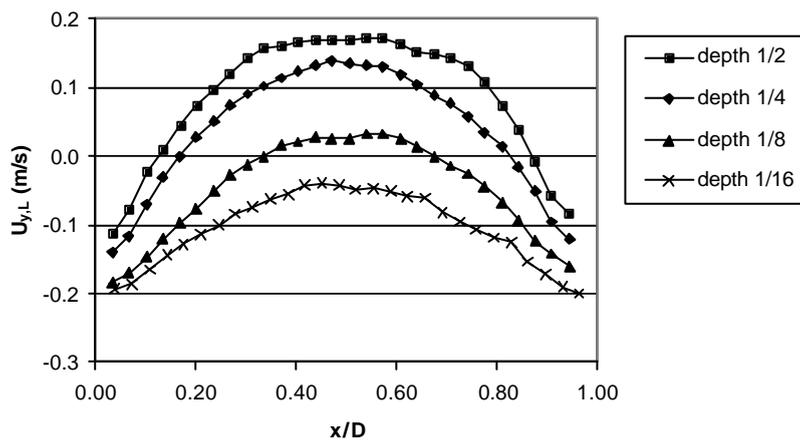


Fig. 4. Time averaged axial liquid velocity for different planes in the column. Measurements at an height of 0.352 m.

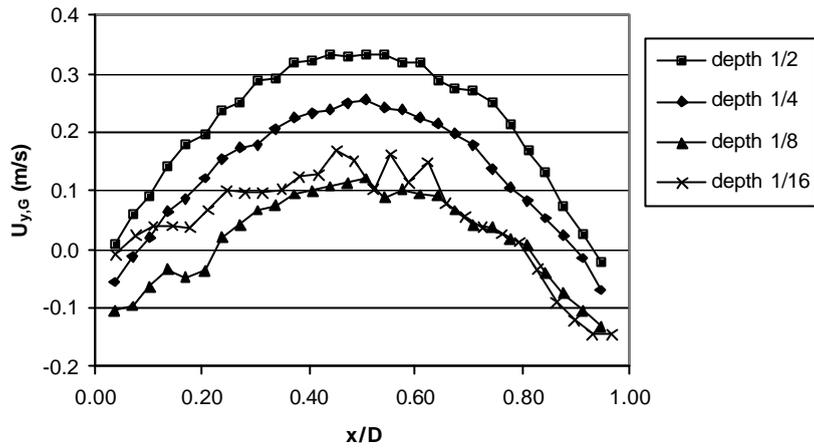


Fig. 5. Time averaged axial gas velocity at different depths in the column. Measurements at an height of 0.352 m.

Figs. 6-9 show the radial and axial velocity fluctuations for both phases. Most of the radial liquid fluctuations take place in the centre of the column. The axial liquid fluctuations show a maximum close to the centre parts of the walls. The fluctuations in the gas velocity show some scatter, especially close to the walls. The average gas-holdup in those areas was probably too low to produce a sufficient amount of samples.

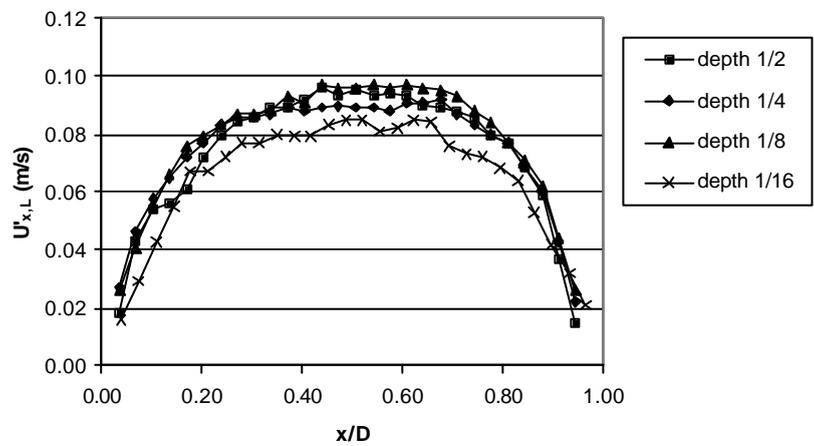


Fig. 6. Time averaged radial liquid velocity fluctuations at different depths in the column. Measurements at an height of 0.352 m.

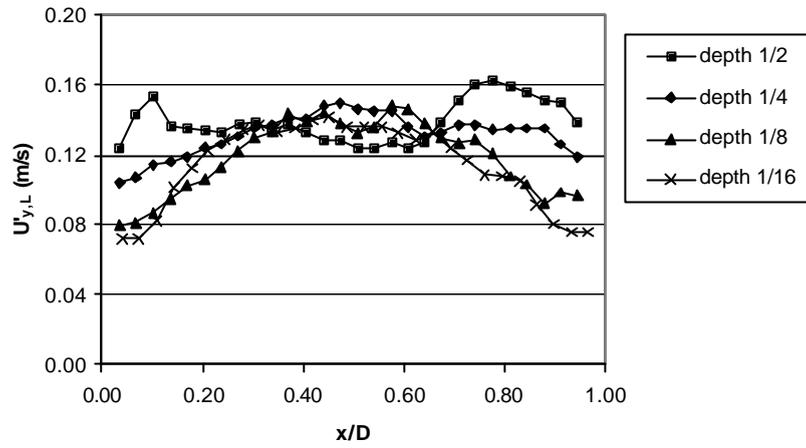


Fig. 7. Time averaged axial liquid velocity for different planes in the column. Measurements at an height of 0.352 m.

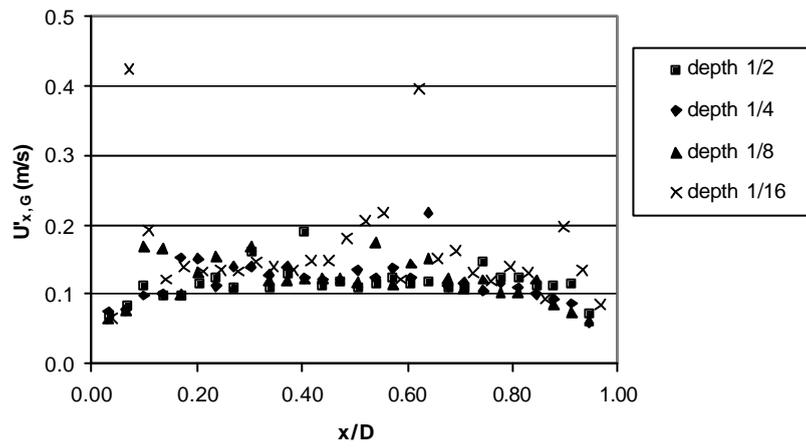


Fig. 8. Time averaged radial gas velocity fluctuations at different depths in the column. Measurements at an height of 0.352 m.

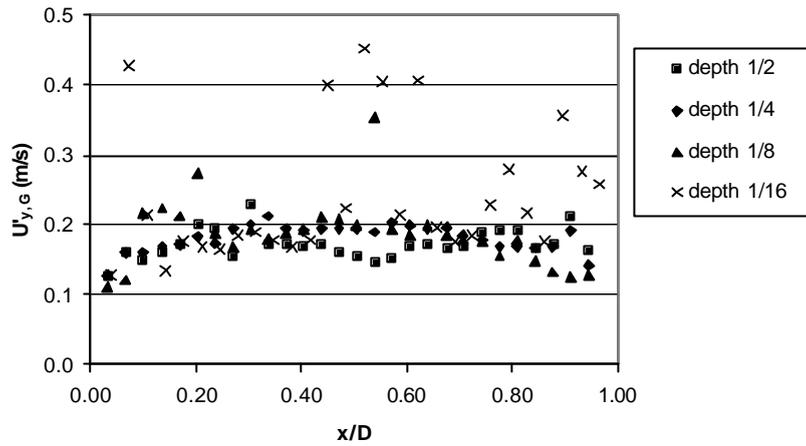


Fig. 9. Time averaged axial gas velocity fluctuations at different depths in the column. Measurements at an height of 0.352 m.

In Figs. 10 and 11, the PIV/LIF data is compared with the LDA data. Although the measured velocity trends agree qualitatively, the PIV/LIF velocity data appears to be much smoother than the LDA data. An explanation may be that the sample period was too short to obtain a steady time average. This idea agrees with the work of Borchers et al. (1999), in which a twice as long averaging period was used. This might also indicate why the measured LDA fluctuations are consistently higher than the PIV/LIF fluctuations. When many points need to be measured the PIV/LIF method has a large advantage over LDA. In every image pair recorded with PIV/LIF, in the order of 10^3 measurement points (i.e. interrogation areas) are acquired. Since every interrogation area contains multiple particles, one can argue that also less images are needed to determine the liquid fluctuations.

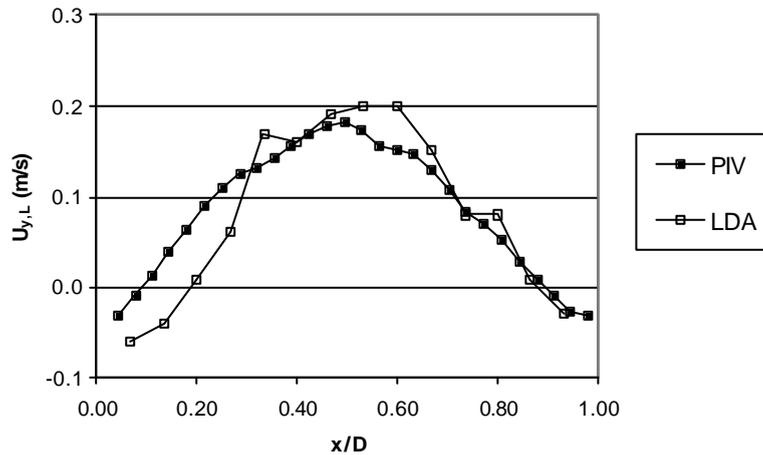


Fig. 10. Time averaged axial liquid velocity for different planes in the column. Measurements at an height of 0.25 m.

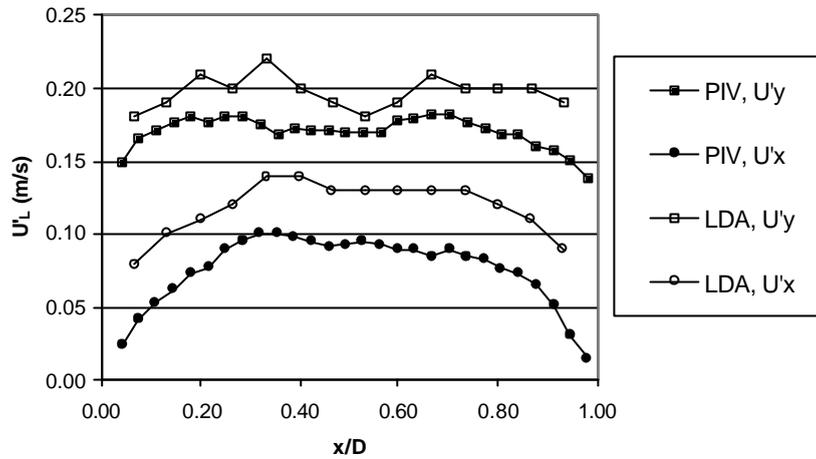


Fig. 11. Time averaged velocity fluctuations at the centre plane in the column. Measurements at an height of 0.25 m.

In Fig. 12 the PIV/LIF of both phases data is compared with single camera PIV data. Similar to the LDA data, the single camera PIV data was obtained with too few samples. The velocities measured with the single camera method are mostly between the gas and the liquid profiles measured with the PIV/LIF method. Apparently, no phase seems to be prevailing. That means that some sort of algorithm is needed in order to distinguish between the tracer particles and the dispersed phase.

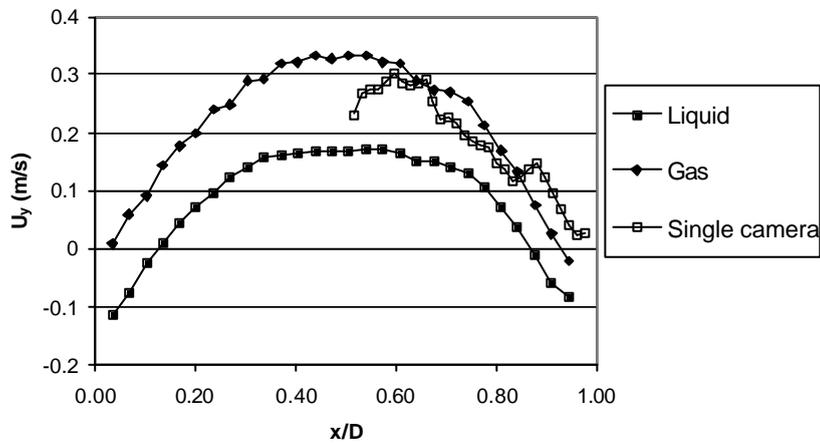


Fig. 12. Time averaged gas and liquid velocity at the centre plane in the column. Measurements at an height of 0.352 m.

4. CONCLUSIONS

In this work a comparison of multiphase PIV and LDA measurement methods was made. The objective of the work was twofold: to provide measurement results that can be used to validate multiphase CFD simulations and to assess the different acquisition and analysis methods in multiphase measurements. The former was done with the use of a two-camera PIV/LIF method. This method was shown to give detailed information about the flow, without prior knowledge of the shape, size or position of the dispersed phase. The latter objective was accomplished by comparing two-camera PIV/LIF measurements with both LDA and single camera PIV measurements. Which phase really was measured with single-camera PIV could not be decided. Accordingly an algorithm, which can distinguish the tracer particles from the dispersed phase, would be needed. The sample period of 300 s for the LDA measurements appeared to be too short to obtain steady time averaged data.

Simultaneous PIV/LIF velocity measurements of both the gas and the liquid phase in a bubble column were presented. The PIV/LIF results showed a core-annulus flow. The slip velocity between the two phases was varying between 0.05 and 0.2 m s⁻¹. The highest velocity fluctuations in the liquid phase were found in the axial direction and were in the order of 0.15 m s⁻¹.

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