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SIMULTANEOUS VELOCITY MEASUREMENT OF PHASES IN A LIQUID-GAS SYSTEM

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Results of velocity measurements of liquid and gas bubbles in a tank with a self-aspirating disk impeller are analysed. Studies were carried out using a fluorescent dye tracer in the measuring system with two cameras (simultaneous phase velocity measurement) and with one camera (sequential measurement of phase velocity). Based on a comparative analysis of the acquired data it was found that when differences in the phase velocities were small the simultaneous velocity measurement gave good results. However, sequential measurement gives greater possibilities for setting the measuring system and if the analysis of instantaneous velocities is not necessary, it seems to be a better solution.

Keywords: fluorescence, self-aspirating impeller, phase velocity, PIV

1. INTRODUCTION

The determination of velocity in a two-phase liquid-gas system is an important processing problem. When liquid is a continuous phase then relative velocity of gas bubbles in the liquid and energy dissipation rate (which may be calculated from velocity fluctuations) affect mass transfer coefficient and bubble size (Alves et al., 2004; Bröder and Sommerfeld, 2002; Garcia-Ochoa and Gomez, 2004; Lau et al., 2014; Linek et al., 2004; Millies and Mewes, 1999; Zhou and Kresta, 1998). On the other hand, when gas is a continuous phase, the velocity of liquid droplets can influence the process of bed humidification (Heim et al., 2004, Heim et al., 2008). However, it is difficult to determine the velocity of both phases. In the case of very small bubbles their population can be divided into two groups and – assuming that the trajectories of small bubbles are the mapping of liquid motion – velocities of the phases can be determined (Deen et al., 2002; Gui et al., 1997; Kiger and Pan, 2000; Stelmach and Kuncewicz, 2011). New possibilities have emerged after the advent of the measurement methods of PIV (Particle Image Velocimetry) (Aubin et al., 2004; Delnoij et al., 2000; Sathe et al., 2010) and PLIF (Planar Laser Induced Fluorescence). A fluorescent dye used in PLIF measurement can be included in trace particles (or liquid droplets) (Lindken and Merzkirch, 2002). Emitting secondary radiation the dye is used to obtain light with two wavelengths in the measuring system, i.e. the wavelengths of laser light and fluorescent dye. This radiation can be separated by optical filters. This allows us to separately analyze the movement of objects which reflect laser radiation and these which emit radiation generated during fluorescence. This measuring system enables a simultaneous measurement of phase velocities but requires the use of two synchronized cameras (Bröder and Sommerfeld, 2000; Chung et al., 2009; Honkanen and Saarenrinne, 2002; Kosiwczuk et al., 2005). Further analysis of this issue leads to a conclusion that in this method a problem may be time intervals between laser pulses, due to which in two frames the shifts of flow tracers are recorded. In the analyzed method such tracers are also gas

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bubbles and if their velocities are much lower than the continuous phase velocities the recorded shifts will be too small to properly determine the velocity of bubbles on this basis.

The aim of the study was to compare liquid and gas velocities obtained by the PIV method during simultaneous and separate measurements of phase velocities. Results should show how the same time interval between laser pulses selected for one phase affects the accuracy of measurement of the second phase velocity during a simultaneous measurement.

2. EXPERIMENTAL

Measurements were conducted in a flat-bottomed glass tank of diameter $T = 292$ mm. The tank was equipped with four standard baffles ($B = 0.1 \cdot T$) and filled with water (20 °C) to height $H = 300$ mm ($H \approx T$). At height $h = 75$ mm over the bottom there was a self-aspirating disk impeller of diameter $D = 125$ mm. The impeller rotated at rotational frequency $N = 6$ s^{-1} (360 min^{-1}) dispersing the gas. The blade tip velocity was equal to $U_{tip} = 2.36$ m/s. The Reynolds number for the mixing process was $Re = 93750$ and the modified Froude number was $Fr' = N^2 \cdot D^2/[g \cdot (H - h)] = 0.255$. In these conditions the gas phase hold-up was $\Phi = 0.4\%$ (Stelmach, 2000). The cylindrical tank was placed in a rectangular tank filled with water. This system of tanks reduced distortions caused by the curvature of the cylindrical tank wall (Stelmach, 2014). Under these conditions Sauter diameter of bubbles is equal to $d_{32} = 1.59$ mm. Bubble size distribution is log-normal with highest number of bubbles in the range from 0.2 to 0.6 mm (Stelmach, 2006; Stelmach, 2007). However, the bubbles flowing out of the orifices are about 5-8 mm in size (Stelmach and Rzyski, 2003).

Velocity measurements were made by the PIV method using a *LaVision* measuring system. A light knife about 1 mm thick cut the tank in a vertical plane symmetrically between the baffles. The light knife was generated by a double-pulse Nd:YAG laser emitting light of a wavelength $\lambda = 532$ nm with the highest frequency of 15 Hz. Tracer particles of size from 1 μm to 20 μm containing the fluorescent dye Rhodamine B were added to water. Under the influence of laser light the dye emits radiation at a wavelength $\lambda = 553$ nm.

Two settings of the measuring system were used:

- In the simultaneous measurement of liquid and gas velocities two *ImagerPro 4M* cameras (2048 px × 2048 px matrix, 14 bit grayscale) were used. Their optical axes were open at an angle of about 16° (Fig. 1a). One camera was equipped with a low-pass filter which cut off radiation with a wavelength greater than $\lambda = 532$ nm. The other camera had a high-pass filter cutting off radiation with a wavelength shorter than $\lambda = 540$ nm. Rays reflected from the interface reached the first camera, while these formed as a result of fluorescence reached the second one. Time interval between laser pulses was $\Delta\tau = 207$ μs and $\Delta\tau = 1500$ μs, respectively. In this measurement two pairs of images were obtained. The interrogation area of both cameras was 60 mm×60 mm. Perspective distortions were corrected on the basis of data acquired during the measuring system calibration.
- During separate (sequential) velocity measurements one *ImagerPro 4M* camera was applied. Its optical axis was perpendicular to the interrogation area (Fig. 1b). During water velocity measurements there was a low-pass filter on the camera lens and displacements of the tracer particles were recorded. In this case time interval between laser pulses was $\Delta\tau = 207$ μs. While measuring the displacement of air bubbles the camera was equipped with a high-pass filter and time interval between laser pulses was $\Delta\tau = 1500$ μs. The interrogation area was about 70 mm×70 mm.

In each case a series of 300 images (quadruple for setting (1) or double for setting (2)) was taken. Then, the images underwent two-pass processing using the *DaVis* 7.2 software. The interrogation area had the final size of 64 px×64 px. A relatively large size of this area was adopted because of the size of gas bubbles. As a result of calculations the field of vectors of averaged axial and radial velocities was obtained. On the basis of velocity components the resultant velocity and angle between the vector of this velocity and level were calculated. For the PIV method it is difficult to estimate the velocity measurement error. Errors can be caused by poor estimation of the time interval $\Delta\tau$ between laser pulses.

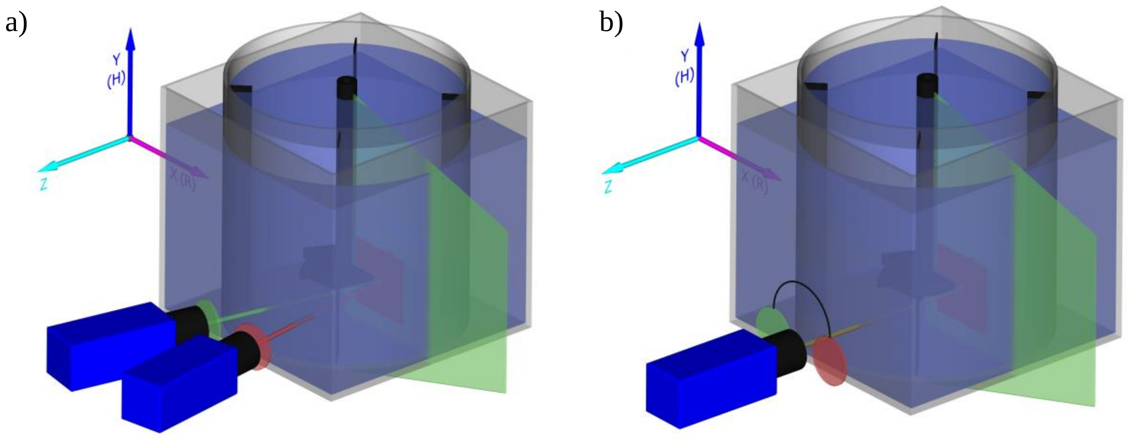

Fig. 1. Setting of the cameras and light knife during measurements, a) two cameras with filters - simultaneous measurement of phase velocity, b) one camera - sequential measurement with filter change

3. RESULTS AND DISCUSSION

3.1. Water velocity

In our earlier studies (Stelmach, 2014) the distribution of dimensionless radial and axial velocities was determined at the height of the impeller in a one-phase system when the impeller did not disperse gas. The reference velocity was the peripheral velocity of the blade tip. Results are shown in Fig. 2. Based on these measurements the required time interval between laser pulses was specified.

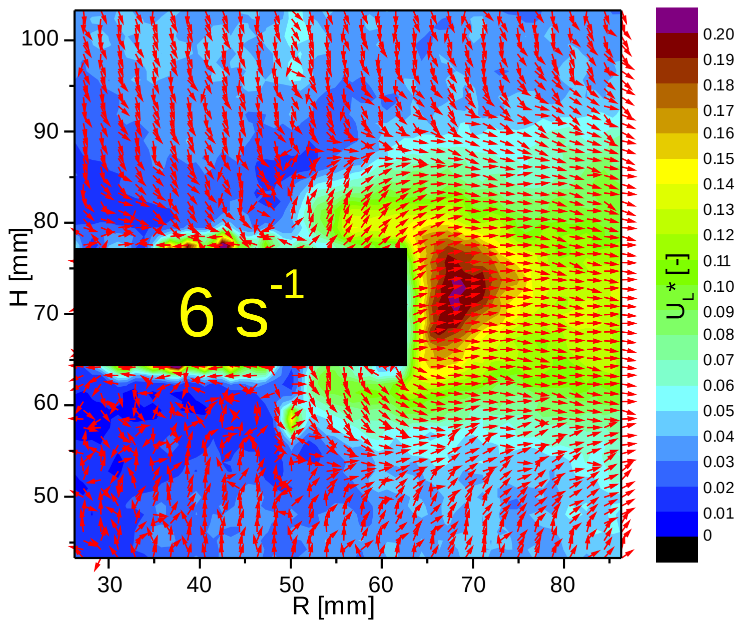

Fig. 2. Dimensionless average water velocities in the one-phase system for $N = 6\ s^{-1}$

Since for process parameters the hold-up of the gas phase and therefore the number of bubbles is small, the results for the one-phase system can be treated as comparative (reference) data for the liquid phase. Figure 3 shows water velocity maps obtained during simultaneous (a) and separate (b) measurements. Due to changes in the equipment setting the interrogation areas in both cases are slightly different.

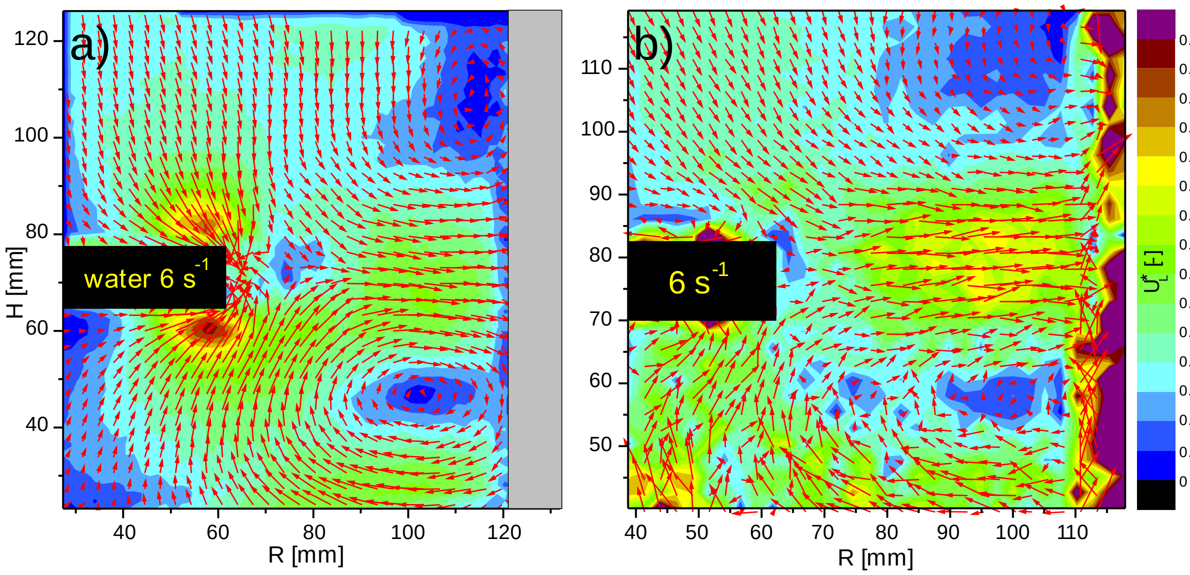

Fig. 3. Dimensionless average water velocities in two phase system in simultaneous (a) and separate (b) velocity measurements for $\Delta\tau = 207$ µs

The analysis of Fig. 3 shows that for these parameters similar water velocity distributions were obtained. The reasons of worse ordering of vectors in Fig. 3b can be as follows:

- different frequency of laser flashes which makes the position of the blade relative to the baffles change. This, as found in the previous studies (Heim and Stelmach, 2011), has an influence on the average velocity field;
- the aging of the fluorescent dye and changes in light emission (tracer particles remained in the liquid for a few days during which the tests were made).

In turn, a comparison of Figs. 2 and 3 leads to a conclusion that gas bubbles leaving the impeller outlets change the flow of liquid at a small distance from the blade tips. In a one-phase system, at a small distance from the blade tip liquid velocities are the highest (about 20% of impeller tip velocity U_{tip}). In the two-phase system in such place slow liquid velocities (only 5% of U_{tip}) are observed because there is the highest concentration of gas bubbles and the interphase surface can strongly diffuse light, leading to a decrease water velocity. By contrast, outside the impeller zone (5 mm above and under impeller plates, 15 mm outside impeller tip) the circulation of liquid in the one- and two-phase system is almost identical and equal to several percent of U_{tip}. Because in the region near the blade tips of the self-aspirating impeller the highest mass transfer coefficients were reported this is a very important problem which requires further in-depth studies at various positions of the blade relative to the baffles. With small gas hold-up in the simultaneous (with gas velocity measurement) and separate liquid velocity measurements almost identical liquid velocity fields were obtained.

During simultaneous velocity measurements of liquid and gas bubbles time interval between laser pulses is constant. If there are significant differences in the velocities of phases the interval determined for one phase can be inappropriate for the second phase which can consequently lead to measuring errors. Since gas bubbles should move more slowly than liquid, the measurements were carried out at time interval between laser pulses being $\Delta\tau = 1500$ µs. Results obtained for this case are shown in Fig. 4.

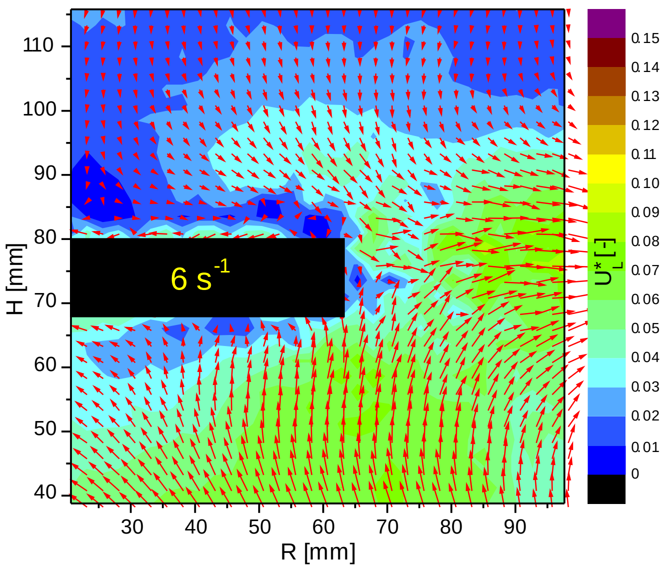

Fig. 4. Dimensionless water velocities in the simultaneous velocity measurement for $\Delta\tau = 1500$ µs

The longer time interval between laser pulses did not affect significantly the image of liquid circulation and velocity. Figure 4 shows that only below the impeller there is a circulation zone in the direction of the tank axis. As such a zone is not observed in the two-phase system, results obtained for $\Delta\tau = 1500$ µs seem to be less reliable in this case. This also confirms the need for a proper selection of time interval between laser pulses. The time interval between laser pulses has an influence on results obtained.

3.2. Air velocities

As mentioned earlier, time interval between laser pulses is associated with the displacement of tracer images in both recorded frames. In the case of the gas phase an additional factor influencing final results is the likelihood of incomplete illumination of gas bubbles by the light knife (Honkanen and Sarenrinne, 2002). This problem is illustrated in Fig. 5.

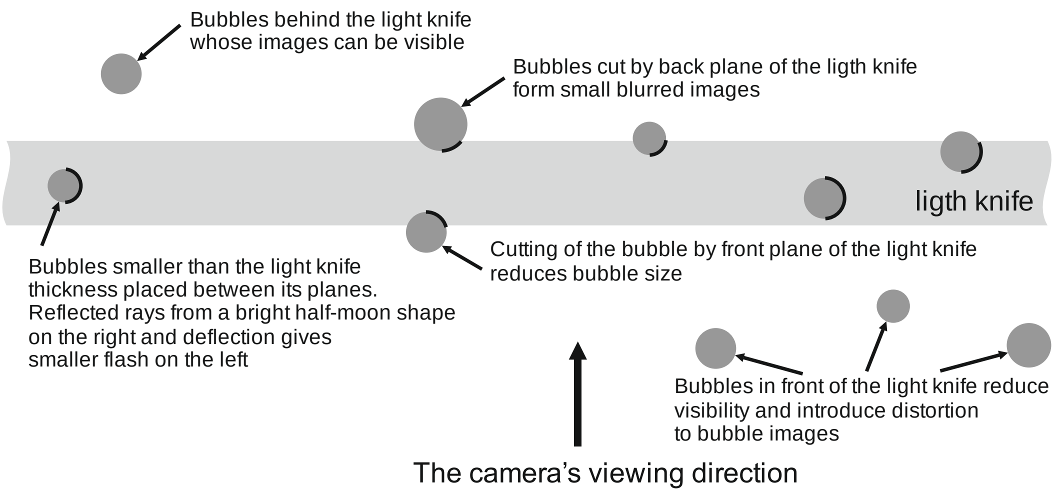

Fig. 5. Lighting of gas bubbles with a light knife

In the two-phase system there is also scattering of light reflected from the surface of bubbles. The scattered light additionally illuminates bubbles located in front of and behind the light knife plane. Therefore the images were binarized to eliminate the effect of background on the measurement. The

ImagerPro 4M cameras differentiate 16,384 levels of brightness. Based on the analysis of images the level of brightness equal to 5,000 was used in binarization. This reduces the number of analyzed objects and it can appear that average velocities determined on the basis of 300 double images will show chaotic velocity vectors, especially in the areas of low concentration of bubbles. This case is illustrated in Fig. 6.

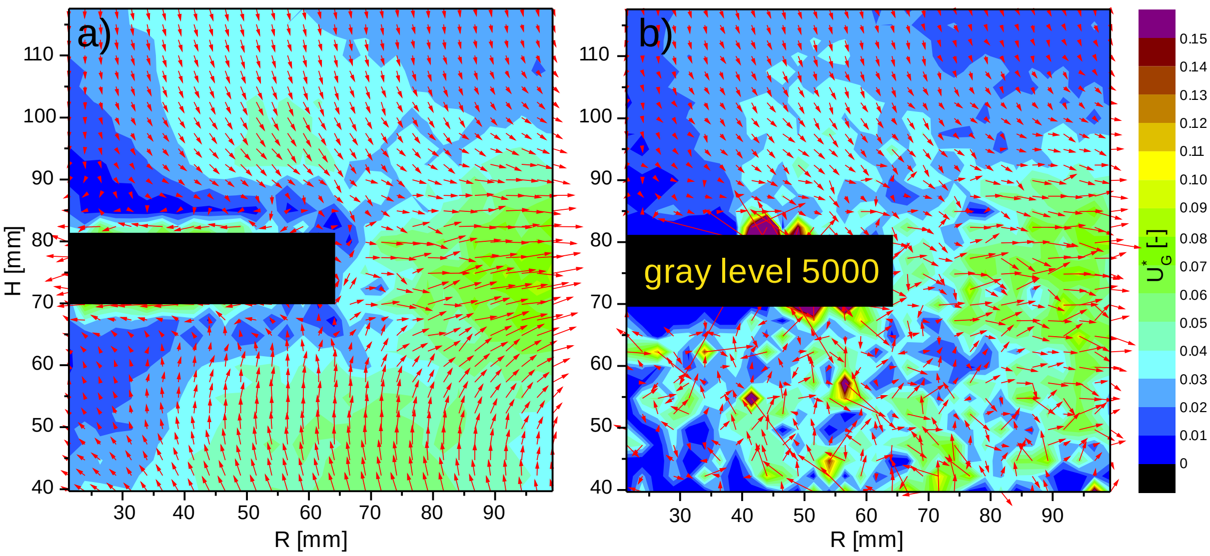

Fig. 6. Comparison of bubble velocity maps obtained on the basis of original (a) and binarized (b) images

In fact, for images subjected to prior binarization below the impeller the average velocity vectors show a large scatter of returns. At the same time, however, a comparison of Figs. 6a and 6b leads to a conclusion that for the assumed level of binarization the velocity differences are very small. This suggests that the impact of the images of bubbles outside the light knife plane is very small.

Bubble velocity maps shown in Fig. 6 were obtained for the time interval between pulses equal to $\Delta\tau = 1500$ µs during the simultaneous velocity measurement. Figure 7 shows the map of bubble velocities for time interval between pulses equal to $\Delta\tau = 207$ µs.

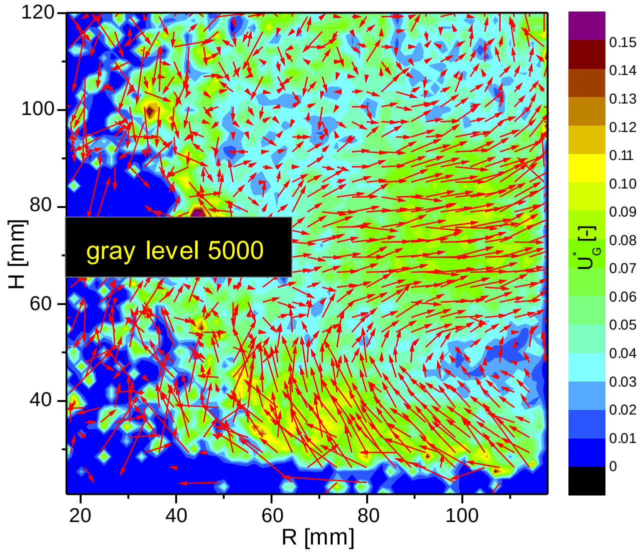

Fig. 7. Gas bubble velocities obtained from binarized images ($\Delta\tau = 207$ µs)

Due to shifting of the fields of camera view in Figs. 6 and 7 there is only a very similar flow of gas bubbles. However, a more accurate comparison of velocities of water and gas bubbles leads to a conclusion that for interval $\Delta\tau = 207$ μs the velocities of bubbles in the stream flowing from the impeller towards the wall are slightly larger than water velocities determined in the same measurement (Fig. 8).

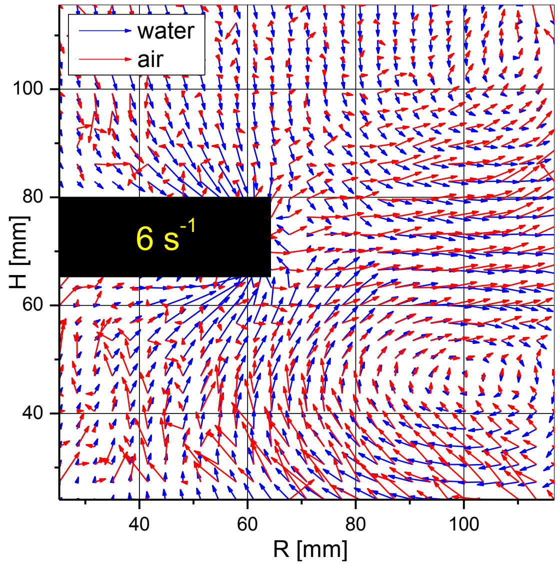

Fig. 8. Comparison of phase velocities for $\Delta\tau = 207$ μs in the simultaneous measurement

In various time intervals during sequential measurements bubble velocities are smaller than water velocity and radial flow from the impeller to the tank wall is observed. However, in this case it seems that interval $\Delta\tau = 1500$ μs assumed for bubble velocity measurement is too big because velocities of the bubble in the radial stream flowing from the impeller to the tank wall are only slightly lower than water velocity.

Determination of a proper interval between laser pulses to measure the velocity of gas bubbles is therefore crucial for the accuracy of results. The importance of this issue comes down to the fact that relative velocities of phases are related to mass transfer rates. Naturally, to obtain correct dependencies it is necessary to carry out similar measurements for peripheral velocity component because the tested type of impeller produces a strong circumferential circulation.

4. CONCLUSIONS

- The use of two cameras and a tracer with fluorescent dye in the PIV system enables a simultaneous measurement of the velocities of liquid and gas bubbles dispersed in it. However, if phase velocities exhibit significant differences, such a measurement can be encumbered with an error difficult to estimate. This error is caused by various shifts of images of the tracer and bubbles in time which elapses between laser pulses. A major problem in this case is such setting of the cameras so that they could cover the same area of the tank.
- In the system with two cameras for simultaneous velocity measurements it is very difficult to obtain the same field in both cameras. In the case of significant non-compliance of these fields it becomes necessary to use interpolation to determine the velocity of one of the phases in the measuring point (in the middle of the area for which the velocity vector is determined).
- Due to differences in the velocity of liquid and gas phases when determining average velocities of the phases, it is more appropriate to measure separately the velocity with one camera. It enables the use of different intervals between laser pulses whose duration is adapted to the phase velocity. Furthermore, for both phases the camera covers the same sector and maintaining the perpendicularity of the optical axis of the camera to the knife light surface correction of the

image distortion is confined to the distortion caused by the curvature of the tank wall. For both phases a different number of frames required to average the velocity can be taken. For the measurement of bubble velocity on the basis of binarized images the assumed sample size is too small.

- A simultaneous recording of images for the liquid and gas phases can be of great importance when studying the flow of liquid around large bubbles.
- The results suggest that there is no need to binarize the images of bubbles. However, studies were carried out for a small gas hold-up. At a greater number of bubbles the bubbles lit by scattered light from the interface can strongly influence the results. It therefore seems appropriate to binarize images for the determined brightness threshold.

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SYMBOLS

B	baffle width, m
D	impeller diameter, m
g	acceleration of gravity, m/s^2
h	impeller level, m
H	liquid height, m
N	rotational frequency, s^{-1}
U	velocity, m/s
T	tank diameter, m

Greek symbols

Φ	gas hold-up
μ	dynamic viscosity, Pa·s
λ	wavelength of light, nm
ρ	density, kg/m^3
$\Delta\tau$	time interval between laser pulses, μs

Dimensionless numbers

$Fr' = N^2 \cdot D^2/[g \cdot (H - h)]$ modified Froude number for mixing process

$Re = N \cdot D^2 \cdot \rho/\eta$ Reynolds number for mixing process

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