Anwendung einer endoskopischen Messtechnik in Blasenströmungen – Vergleich mit herkömmlichen PIV-Messungen

Application of the endoscopic PIV measurement technique in bubbly flows – comparison with state-of-the-art PIV measurements

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Abstract

Multiphase Flows are of high interest in many industrial processes. Although much research has been carried out for a considerable amount of time especially on bubble columns, there still remain several crucial parameters which cannot be modelled in a satisfying way, such as turbulence structure (especially bubble induced turbulence), bubble size distribution as well as concentration fields and mass transfer coefficients.
The measurement of velocity fields – and by this, the measurement of velocity fluctuations – within bubbly flows by standard PIV is challenging. With higher gas holdup the bubbles induce a shadowing of the laser light sheet. As a consequence, no or only fragmentary information about the flow field can be obtained. (Schlüter 2011)
An interesting approach to avoid this disadvantage is to no longer conduct the measurements from outside the bubbly flow, but from the inside, using an endoscopic measurement technique (Schlüter et al. 2006). Generally speaking, the endoscopic measurement technique enables the measurement of fluid velocity, flow structure, bubble velocity and bubble size distribution (Richter et al. 2012). It can be applied either in a laser-pulsed or in an LED-pulsed mode for illumination.
In this work, the mode of operation of the endoscopic measurement technique is illustrated, and it is applied and validated by comparing the fluid velocity data obtained with state-of-the-art PIV technique. This is done in a flow channel (base 10 cm x 10 cm, length 450 mm), as this geometry allows comparability of both techniques: No refractive index adaption is needed and measurements can be conducted at several axial positions.

Introduction

Multiphase reactors are frequently used in chemical and biochemical industry. For many applications, bubble columns are a good choice as their main advantage is the simple construction without any installations except from a gas distributor, which makes this reactor type an attractive solution for processes run at high temperature, pressure or with aggressive chemicals, for example hydrogenation or oxidation. Besides the constructive point of view, bubble columns are used in processes like exothermal chemical reactions, absorption or stripping, which all need a large interfacial area for heat and mass transfer. This large

interfacial area is produced by the disperse phase by means of gas bubbles that pass through the continuous phase (liquid).
Although much research has been done especially on bubble columns and several empirical correlations have been developed (Deckwer und Schumpe 1985), (Deckwer 1977), (Akita und Yoshida 1974), (Shah et al. 1982), there are still some parameters which cannot be described and modelled yet in a satisfying way. These are turbulence structure, bubble size distribution, concentration fields and mass transfer coefficients. In this work, an endoscopic measurement technique is introduced by which detailed information about the flow structure within the bubbly flow of multiphase reactors can be obtained. Knowledge about the flow structure or, more precisely, turbulence structure and its connection with heat, momentum and mass transfer allows improved design of reactors and processes and thus reduction of costs, energy consumption and resources.

State of knowledge
Flow regimes of two-phase flows with gas as dispersed phase and liquid as continuous phase shift in dependency of gas velocity and diameter of the vessel. The regime of bubbly flow is characterized by almost uniformly sized bubbles with equal radial distribution. As a rule of thumb, bubbly flow occurs if the superficial gas velocity is less than 0.05 m/s. (Shah et al. 1982)
The accessibility of bubbly flows for optical measurements depends on several parameters. One may consider the flow channel with a rectangular cross section. The area which is visible for a camera that is positioned directly in front of the channel is now called optical accessibility (shaded area in Figure 1). The optical accessibility principally drops with increase of three influencing parameters: bubble size (monodisperse bubbles are supposed) d_p, gas hold-up ε_g, and the distance L between the channel wall and the area on which the camera is focused on.

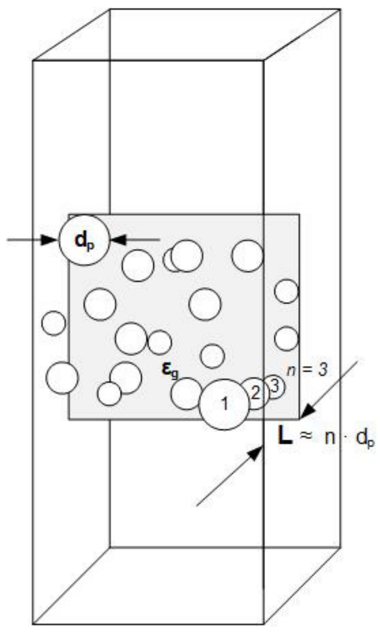


Figure 1: Influencing parameters on optical accessibility in bubbly flows.

L can be approximated as an integer factor of the bubble size and thus, it represents the layers of bubbles which are located in front of the focused area. In Figure 1, three bubble layers are outlined.
Bubble size and gas hold-up cannot be influenced, since this changes the flow situation of the bubbly flow. But by coupling the camera into an endoscope, the parameter *L* can be diminished and thereby, the optical accessibility can be enlarged.

For investigation of fluid mechanical processes, the standard Particle Image Velocimetry (PIV) is a widely established technique (Adrian 1991). Hereby, tracer particles, which are assumed to follow the flow with negligible inertia, are added to the liquid phase. The particles are illuminated by a thin laser light sheet. The laser stimulates a fluorescent dye on the tracer particle surface so that due to spontaneous emission the particles emit light of a certain wave length that is recorded by a camera twice within a short time interval. As the time delay is known, displacement of the particles within this time interval and thus, velocity can be obtained. (Raffel et al. 2007)
At higher gas holdup the standard PIV measurements become challenging because the bubbles induce a shadowing of the laser light sheet with the consequence that no or only fragmentary information about the flow field can be obtained. Therefore the laser and/or the camera are implemented in an endoscope to directly transfer the laser and camera view into the bubbly flow.

Endoscopes are thin optical instruments which are used to visually inspect the inside of organisms or technical apparatuses through natural or artificial openings. The main and best known field of application is medicine, but also in technology, endoscopes are used, for example in automotive engineering or for quality control of pipelines in pharmaceutical or food industry. (Katalog Industrieendoskope der Karl Storz GmbH & Co. KG, Tuttlingen)

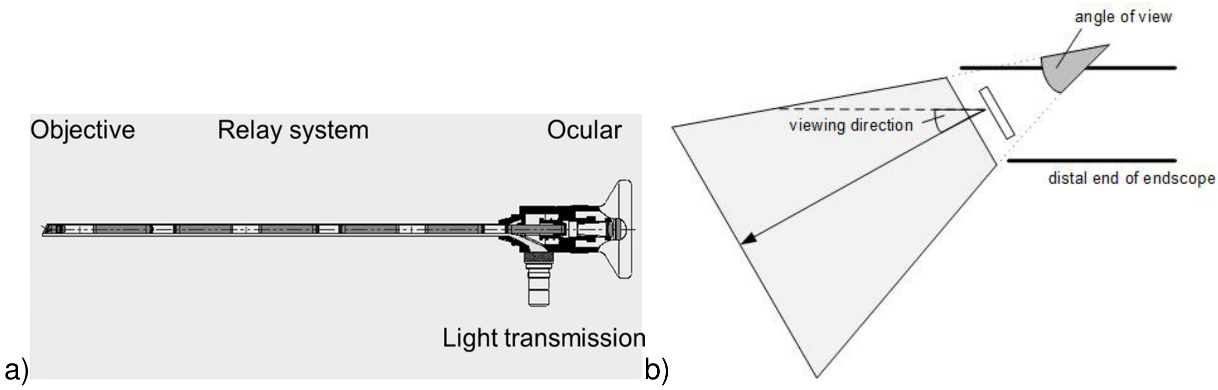


Figure 2: a) Setup of a rigid endoscope as used in this work, image credits: Karl Storz GmbH & Co. KG b) optical features of rigid endoscopes

Three types of endoscopes are distinguished: Flexible endoscopes, video endoscopes and rigid endoscopes. In flexible endoscopes, the images are transferred by a bundle of optical fibers from the object lens to the ocular. Video endoscopes are based on the same functional principle as flexible endoscopes, but a CCD chip is fixed at the distal (ocular) end (chip-on-the-tip (Vogel 2011)). In this work, rigid endoscopes, also known as borescopes, are used since their resolution is much higher. The optical system, which basically differs from that of flexible endoscopes, is composed of an objective, a relay system and an ocular (see Figure 2a). The objective produces a real image onto the first intermediate level. There, it is transmitted in several steps by the relay system of rod lenses onto the last intermediate level. The ocular then produces a virtual image, which can now be imaged onto a film plane by a camera objective. (Katalog Industrieendoskope der Karl Storz GmbH & Co. KG, Tuttlingen; Reling 1988)
The light transmission for the illumination of the test site is not needed for this experimental setup since the illumination is carried out by the laser.
Rigid endoscopes are available with different angles of view and different fields of view (see Figure 2b). The endoscope used in this work has a viewing direction of 0° and a viewing field angle of 67°.

To date, there are only few papers which deal with EPIV. The fields of application which the research aims for are combustion engineering (Dierksheide et al. 2002),(Rottier et al. 2010; Gindele and Spicher 1998) and turbomachinery (Kegalj und Schiffer 2009). There is one paper dealing with pipe flow (Xiong and Merzkirch 1999). Except from Dierksheide et al. (Dierksheide et al. 2002) and Kegalj and Schiffer (Kegalj and Schiffer 2009), so far no publication reports about using an endoscope for the laser light sheet besides the camera endoscope, which has been done in this work. Although an endoscopic technique is an invasive technique, the advantage is that the measurements can be conducted locally in the area of interest. Its applicability at high gas hold-ups is a substantial argument to aim for an implementation in real processes.

To implement the endoscopic measurement technique, two big challenges have to be accepted. The first difficulty is to guide a laser beam of high power - as it is required to resolve flow fields in detail - through the optics. The lens material may be destroyed when the laser beam with high energy density passes the endoscope.
Secondly, monochromatic aberrations have to be taken into account. Due to the wave-particle duality of light, calculation of light propagation is not trivial. The Gaussian optics is a possibility to solve this problem: Light is thought as a beam, whose power is concentrated within a small cylinder that surrounds the beam axis, and wave nature of light is taken into account, since the Gaussian beam is a solution of the Helmholtz equation and thus, the intensity distribution over the beam cross section is a Gaussian function (Saleh, B. E. A. and Teich 2007). The Gaussian optics only takes into account beams with a small parallel shift to the principal axis or a small angle from the principal axis. Therefore in the equations of Gaussian optics the sinus of the angle is approximated by the angle itself with the first element of the Taylor series of sinus according to

$$sin\varphi \approx \varphi \qquad (1).$$

If beams are further away from the principal axis, the approximation in equation (1) is no longer satisfying. Including also the second element of Taylor series of sinus yields an enhanced approximation with

$$sin\varphi \approx \varphi - \frac{\varphi^3}{3!} \qquad (2).$$

From the deviations between (1) and (2), third order aberrations result. The following aberrations have to be taken into account. For further information, see (Hecht 2009), chapter 6.3.

- *Field of curvature*: A nearly even optical image of an object vertical to the principal axis is only obtained close to the principal axis. This kind of aberration is known as Petzval field of curvature. In this setup, the lenses within the endoscope project the image of a planar object onto a spherical surface, but the camera sensor surface is plane. Therefore, the image that can be seen is a projection which is not uniformly sharp. For EPIV, this means that the particles on which the camera is focused on are not lying in the planar laser light sheet but on a spherical area.
- *Astigmtism:* An object which is not on the principal axis, is imaged blurred since the light beam hits the lens asymmetrically. This aberration is known as astigmatism. Rottier et al. (Rottier et al. 2010), who investigated high-temperature furnaces by using EPIV, do not see a large problem in this geometric distortion as they find the result even without correction during image processing sufficient to deduce a velocity field.
- *Barrel distortion:* The most important occurring aberration is barrel distortion, which yields incorrect correlations of the particle displacement and thus defective vectors. As a consequence of the fact that different parts of the lens have different focal lengths and magnifications, distortion occurs. In this case, barrel distortion (straight lines at the edge of the image field appear barrel-shaped), colloquially called fish eye, can be observed as a result of the wide-angle lenses of the endoscopic optical arrangement, which has to be taken into account. Dierksheide et al. (Dierksheide et al. 2002) corrected it via software during digital image processing. Xiong and Merzkirch (Xiong and Merzkirch 1999) avoided optical distortion by using an endoscope with total viewing angle of 80° (see Figure 2b) with an effective viewing angle of only 40°, which is the central part of the visual field. Gindele and Spicher (Gindele and Spicher 1998) present two different calibration methods to compensate radial symmetric distortion, applied to either the raw image or to the vector plots. Therefore, target images as used in PIV (pattern of equidistant dots or a mesh) are recorded as shown in Figure 3. After applying and comparing both methods, the authors conclude that both techniques produce the same correct vectors. In this work, barrel distortion is also corrected via software (PivView2C, PivTec GmbH).

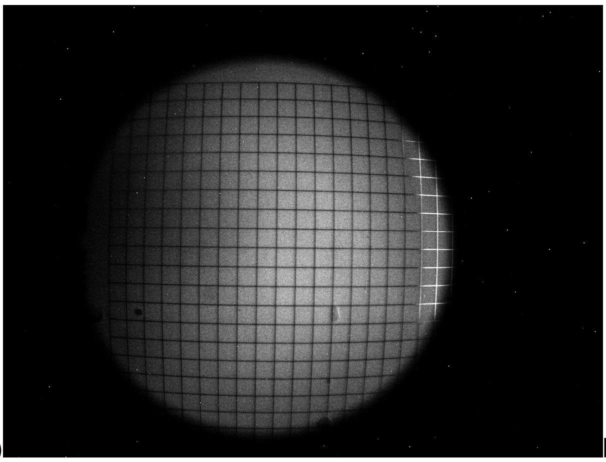
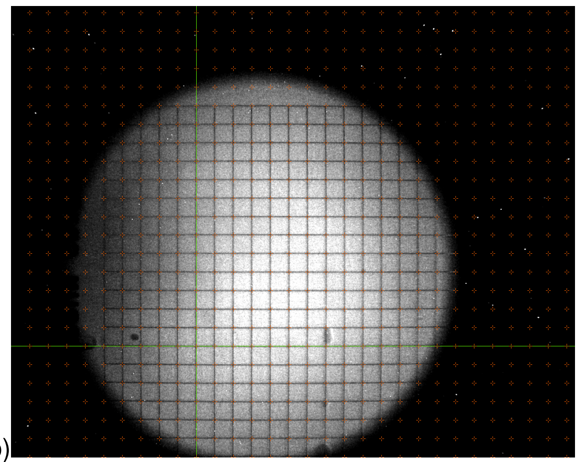
a)  b) 

Figure 3: Target image before (a)) and after (b)) rectification.

The laser light sheet can be realized either from outside or also endoscopic by an endoscopic light sheet optics with a cylindrical lens within an endoscope. The latter is advantageous if the reactor wall is not transparent, for applications within closed casings or at high gas hold-up to avoid shadows of the bubbles within the light sheet. The disadvantage is a comparative broad light sheet and the limited laser energy per pulse which can be lead through the lenses within the endoscope without damaging them.

Experimental Setup

Measurements are conducted in a flow channel made from acrylic glass which was designed for these investigations (see Figure 4). The base of the channel has the area 10 cm x 10 cm, the length of the channel is 45 cm. These dimensions have been chosen as the square shape allows uncomplicated PIV measurements without refractive index adaption so that comparability of PIV and EPIV measurements is ensured. At four axial positions, ports for a laser endoscope as well as the camera endoscope are located. The measurements are conducted at the same axial position respectively; dependent on the conditions (EPIV/ PIV), the ports are used or the channel is turned and the recordings are done through the plane wall. Gas bubbles (air, saturated with water) are brought into the channel from the bottom by a gas distributor. It is made from Teflon and has 30 holes with 1mm in diameter. The holes are arranged as corners of equilateral triangles.

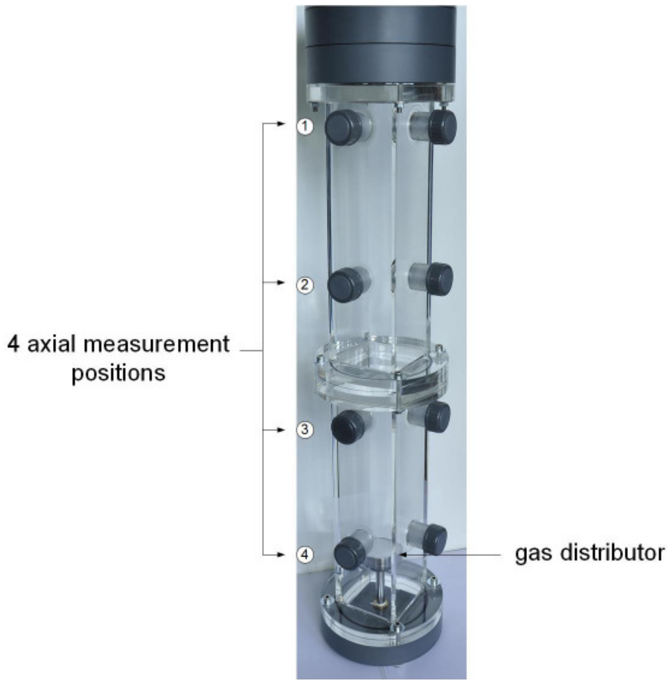


Figure 4: Flow channel for PIV and EPIV measurements.

At the beginning of the experiments, the flow channel is filled with demineralised water. Polystyrol particles (3.16 µm in diameter) with a Rhodamine B as fluorescent dye (MicroParticles GmbH, Berlin) are added to the liquid. Then a constant superficial gas velocity of air (u_0=0.26, 0.8 cms^{-1}) in the range of bubbly flow is adjusted by a coriolis mass flow controller (Bronkhorst Cori-Flow), so that the bubbles rise through the static liquid.

State-of-the-art PIV:

A high speed Yttrium Lithium Fluoride laser (Darwin-Duo 527-100M) and a high speed camera (PCO dimax) with exposure time of 40 µs are synchronized both at frequency 2kHz. Per measurement, approximately 15000 images are taken. Images are processed via software PivView, PivTec GmbH. For the adjustment and calibration, the laser light sheet is oriented towards the edge of a target, where with fluorescent dye impregnated paper is fixed (see Figure 5). After adjustment of the light sheet, the camera is focused on the target and target images are taken.

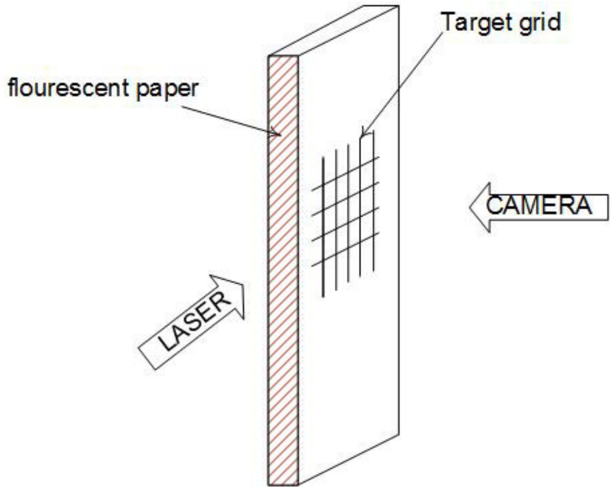


Figure 5: Sketch of the target construction used for adjustment of camera and laser light sheet.

EPIV:

The high speed laser and high speed camera with exposure times of 300 µs are synchronized both at frequency 2 kHz and coupled within the laser endoscope (endoscopic light sheet optics, diameter 12 mm, Intelligent Laser Applications GmbH, Jülich) and the camera endoscope (Storz Hopkins Borescope, 88370 AX. diameter 8mm, length 300mm, viewing direction 0°, viewing field angle 67°). Target images are taken as described above; but a smaller target is used since the area which is pictured by the camera is much smaller (diameter approximately 1 cm).

Results and Discussion

At low superficial gas velocities (0,26 cm/s, see Figure 6 a), b)), the state-of-the-art PIV yields acceptable results. In Figure 6 a), a bubble and beside it, its shadow can be seen (laser light comes from left hand side). For a first qualitative observation, bubble and shadow are masked during image processing manually, so that these areas are not taken into account for calculation of the velocity field. In the future, a more sophisticated method to mask bubbles automatically will be used that is described e.g. by Lindken (Lindken 2003).

Below the bubble the turbulent structure induced by the bubble can be identified and a region with high velocities can be observed.

At three times higher superficial gas velocity (u_0=0.8 cms^{-1}, see Figure 6 c), d)), most of the image consists of shadows created by the bubbles within the laser light sheet. Also bubbles which are to the left of the image section of the camera evoke shadows, which follow that the image taken at this moment is not analyzable any more. The velocity vector field in Figure 6 d) indeed shows regions of higher and lower velocity, but because of the high percentage of shadows, and thus, of masks, meaningful statements cannot be obtained at higher gas hold-ups. An approach to solve this problem is to conduct EPIV measurements, which means that the light sheet is spanned from within the bubbly flow and the camera endoscope is very close to the light sheet. This leads to a smaller image section and to the possibility to have a close look at the wake of a bubble which is within the light sheet without the disturbance of other bubbles.

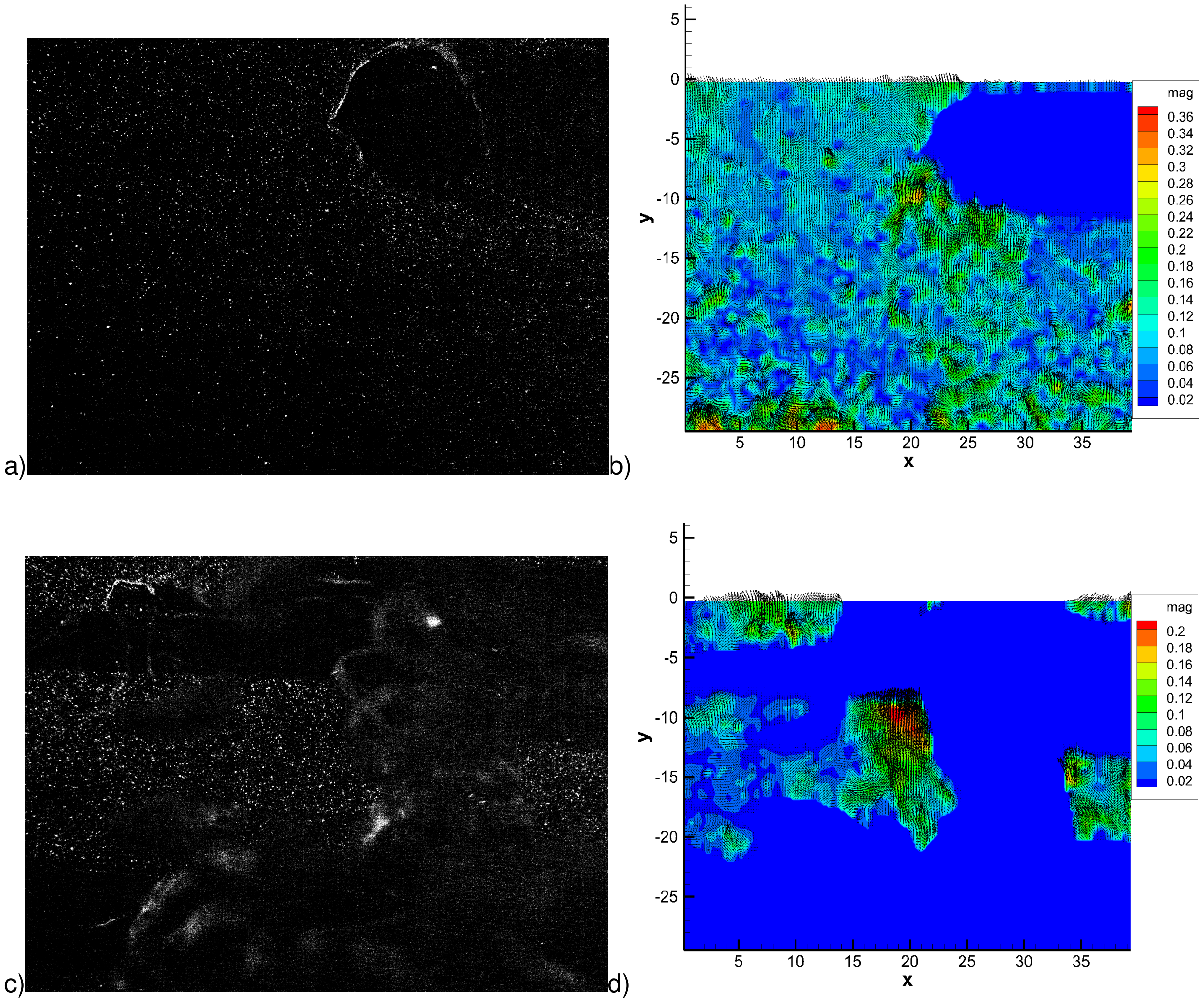


Figure 6: State-of-the-art PIV measurements at different superficial gas velocities: a), b): 0,26 cm/s, c), d): 0,8 cm/s. Left: raw image, right: velocity field, m/s.

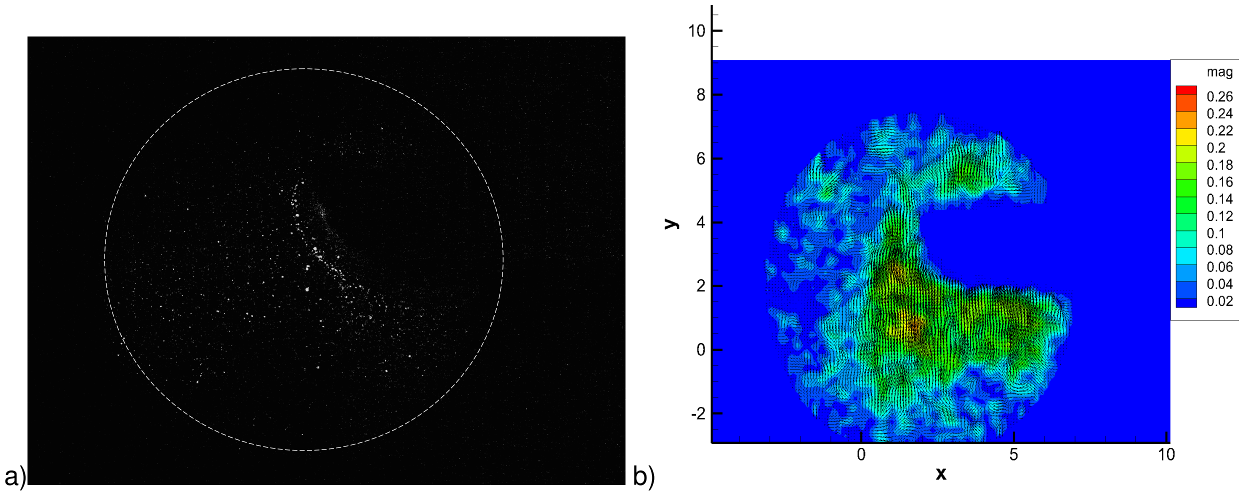


Figure 7: EPIV measurement. a) raw image, b) velocity field, m/s.

Figure 7 shows the results of the EPIV measurements. The barrel distortion has been corrected successfully via software as shown in Figure 2 and the bubble shadow has been masked here as described above. The turbulence structure as well as the bubble wake is clearly visible and the velocities are of the same magnitude. Furthermore with the endoscopic PIV nearly the whole flow field in the vicinity of the bubble becomes observable whereas with the standard PIV only fragments of the flow structure can be obtained.

Outlook

The results show that the endoscopic measurement technique is applicable in bubbly flows. The disadvantage of the state-of-the-art PIV is the high percentage of shadows so that the surroundings of a bubble cannot be investigated closely. EPIV can be a good choice in this case, albeit the experimental setup is more challenging in this case. In this work, the experimental setup and first qualitative results are shown. Further research is necessary to go more into detail and to find out whether it has to be taken into account that EPIV is an invasive technique. In the presentation more quantitative data as well as further images and high speed movies will be provided.

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