

# Assessment of Flow Structures in Bubble Columns by X-ray Based Particle Tracking Velocimetry

A. Seeger, K. Affeld, U. Kertzscher, L. Goubergrits, and E. Wellnhofer

**Abstract** For the investigation of flow structures in bubble columns it is necessary to measure the local liquid velocity. Common optical methods fail in a bubble flow with a large void fraction. The cause is the different refraction index of liquid phase and gaseous phase, which leads to reflection and dispersion. The new X-ray based Particle Tracking Velocimetry (PTV) - called "XPTV" - presented here permits to obtain the liquid velocity three-dimensionally, touch-free and for any large void fraction. The problem of light reflection and light refraction on phase boundaries is solved by the use of X-rays instead of light. X-rays penetrate a gas/liquid flow in straight lines. The method can also be applied to opaque liquids, where optical methods fail.

## 1 Introduction

Bubble columns are liquid filled cylinders, which are aerated - usually from the bottom. They are widely used in biotechnology and chemical engineering, i. e. for the yeast production and waste water treatment. Despite their widespread application, the flow in those apparatuses are not yet understood. One reason for that is a lack of measurement methods with which the liquid flow can be investigated. There are various methods available to measure local liquid velocity in a bubble column, and the present knowledge of bubble flow has been achieved by application of the methods shown in table 1 (Chen et al. (1994); Deckwer (1988); Groen et al (1996); Franz et al 1984; Mudde (1997a,b); Pauli (1991); Reese et al. (1995); Rehm and Reed (1993); Delnoij et al. (2000); Chen et al. (1999)).

	Methods for small void fraction (void fraction < 1 %) - optical methods	Methods for larger void fractions
<b>Point measurement methods</b>	<ul style="list-style-type: none"> <li>• Laser Doppler Velocimetry (LDV)</li> </ul>	<ul style="list-style-type: none"> <li>• Prandl- or Prestontube</li> <li>• Hot-Film-Velocimetry (HFV)</li> <li>• Computer Aided Radioactive Particle Tracking (CARPT)</li> <li>• Electrodiffusion method</li> </ul>
<b>Two- or three-dimensional methods</b>	<ul style="list-style-type: none"> <li>• Particle-Image-Velocimetry (PIV)</li> <li>• Laser Induced Fluorescence (LIF) based PIV</li> <li>• Particle Tracking Velocimetry (PTV)</li> </ul>	

**Table 1** Available methods for the measurements of the velocity of the liquid phase in a bubble column

All optical methods like Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV), Laser Induced Fluorescence (LIF) based PIV, and (optical) Particle Tracking Velocimetry (PTV) face the problem that its application is limited to a flow with few bubbles and a small void fraction. The reason for this is the reflection and dispersion on phase boundaries. Figure 1 shows a bubble flow with a void fraction of 2.7 % and 5.4 %. In the depth of about 5 cm a grid (1cm grid distance) is fixed. Obviously it is difficult to recognize the grid even at small void fractions. This problem gets even larger, if the bubbles are smaller. Hence, optical methods are inapplicable for bubble columns with high void fraction.

Other methods such as the electrodiffusion method, the Hot Film Velocimetry (HFV), the Prandl- and the Prestontube can be applied in bubble columns with a high void fraction. However, these are intrusive methods, which disturb the flow. Moreover, they are single point methods and therefore flow structures are difficult to obtain. The only non-intrusive method which works independently from the void fraction is the Computer Aided Radioactive Particle Tracking (CARPT, Chen et al. (1999)). It is a single point method, too.

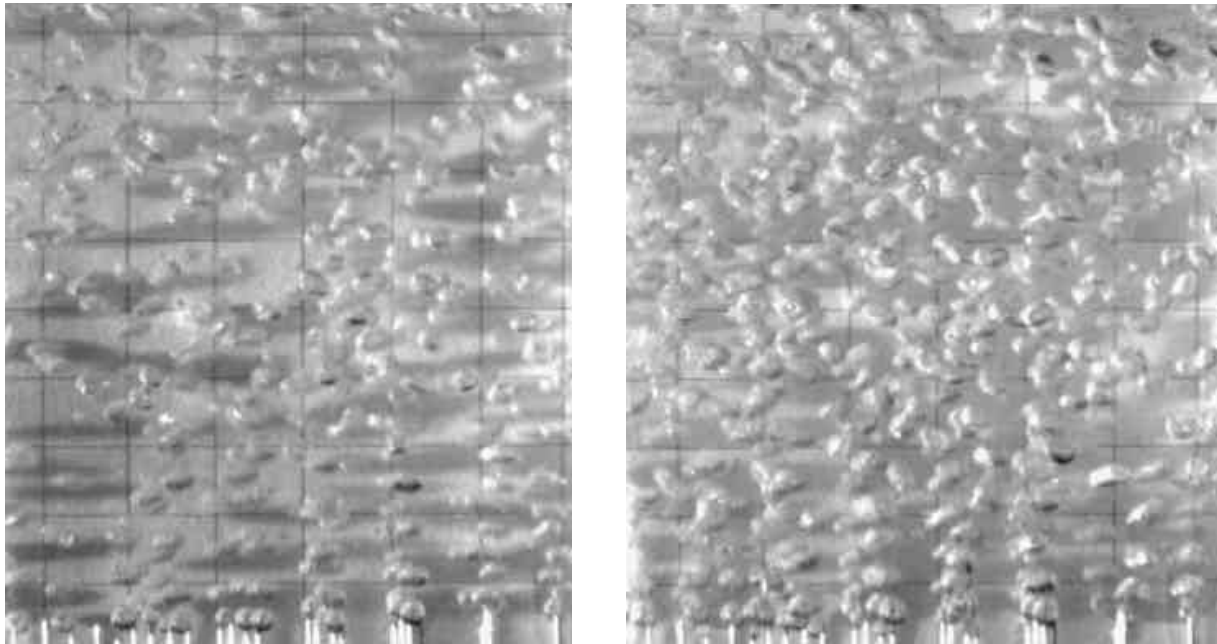
In this work a new non-intrusive method is presented, which works independently from void fraction and is a multi-point method. It allows the assessment of three-dimensional three-component vector fields.

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**Fig 1** Bubble flow in front of a grid. The grid is fixed in a water depth of 5 cm. On the left-hand image the void fraction is about 2.7 %. On the right hand image the void fraction is about 5.4 %. In both cases the grid is difficult to realize. This shows that it is difficult to obtain good flow measurement results by optical methods.

## 2 Method

### Idea

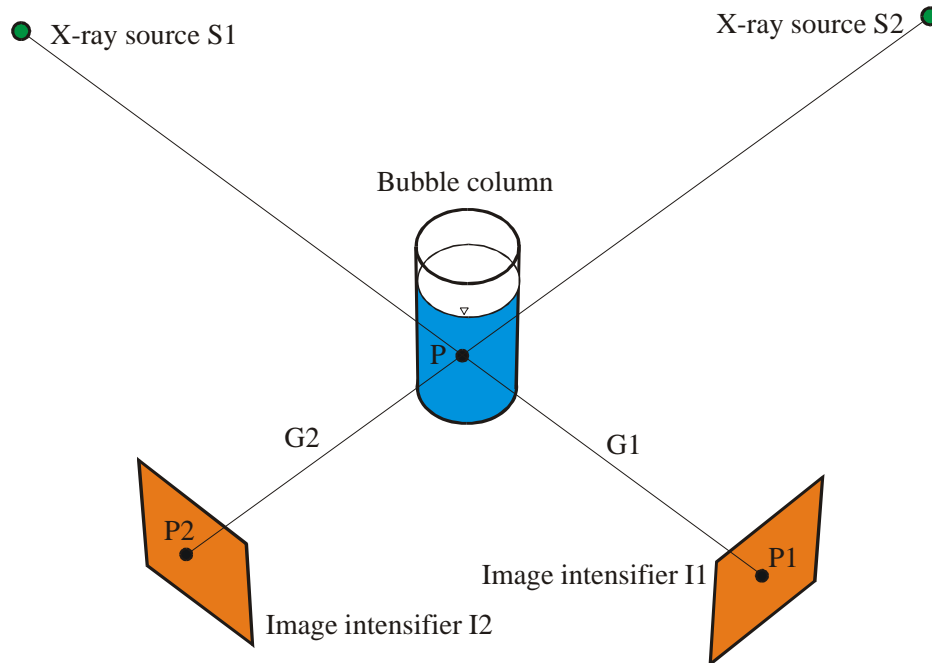
The new method is an X-ray based Particle Tracking Velocimetry – called XPTV. The liquid in question is seeded with X-ray absorbing particles. These particles have the same density as the liquid. It is assumed that the particles are representing the liquid velocity. Therefore, by the knowledge of the particle motion, the liquid motion is assessed.

X-rays penetrate a gas-liquid interface in straight lines. Thus the above-described problems of the observation using visible light - refraction and reflection – do not appear. In addition, this method does not disturb the flow like probe methods.

A typical experimental set-up is shown in figure 2. Two X-ray-sources S1 and S2 generate X-rays, which are directed through the bubble column onto the image intensifiers. The image intensifiers convert X-rays into visible light and intensifies it. Digital cameras behind the image intensifier take the images. An X-ray absorbing particle, represented by point P, is mapped on the two image intensifiers I1 and I2 generating the points P1 and P2. The point P is reconstructed from P1 and P2. By taking image series, motion of a particle can be observed. The velocity of the particle can be obtained by its displacement and the time difference between the images. By the observation of many particles a vector field can be calculated. The method resembles 3D optical PTV.

### Device

A medical X-ray device (Philips Integris BH 3000) is used for the investigations. It is clinically used for the visualization of flow in human coronary blood vessels and heart ventricles. This device was provided by the German Heart Center in Berlin. Two X-ray sources generate X-rays, which are directed through the bubble column onto the image intensifiers. The input screen of the image intensifier has a size of 23 cm x 23 cm. Image intensifiers, CCD-chips, and frame grabbers transform the X-ray intensities into digital 8 bit grayscale images, which are stored onto CD. The images have a resolution of 512x512 pixels. An X-ray flash is generated and an image is taken every 20 ms alternating on each X-ray system, thus 25 image pairs per second are taken. An image serie of up to 1000 images (500 image pairs) can be acquired. The investigated volume has a size of about 12 cm x 12 cm x 12 cm.



**Fig. 2** Experimental set-up. Two sources generate X-rays, which are directed through the bubble column onto the image intensifiers. A point P is mapped onto the two image intensifiers I1 and I2 generating the points P1 and P2. The point P can be reconstructed from P1 and P2. By observing the motion of the particle, its velocity can be obtained by its displacement and the time difference. G1 and G2 are the straight lines between the points P1 and P2 on the image intensifiers and the X-ray sources S1 and S2. X-rays penetrate a gas/liquid flow in straight lines.

### Particles

Particle Tracking Velocimetry (PTV) is based on the observation of particles, which move with the liquid in question. In this case the particles have to have the same density as water and in addition, have to absorb x-rays. Particles were manufactured according to this requirement. They have a cubic shape with the dimensions of  $2 \times 2 \times 2$  mm<sup>3</sup>. The cubic shape was chosen due to fabrication reasons. The particles are made of polyurethane foam with an cylindrical insert of a lead alloy with length of 2 mm and a diameter of 0.5 mm. The alloy absorbs x-rays, while the foam makes the cubes buoyant. The particles are large compared to particles used for optical PTV. However, despite their size it is possible to assess flow structures accurately by the use of these particles, because they are small in comparison with typical flow structures in our flow system. Moreover, most of the experiments are performed in glycerin, which is highly viscous. Often the particle relaxation time is taken as a typical measure to quantify the quality of a particle. This measure says how the particle reacts after a sudden flow velocity change (Raffel et al (1998)). In this case the particle relaxation time of the particle in glycerin is about 0.01 ms.

### Particle recognition and 3D-reconstruction

All algorithms like particle recognition, particle tracking, 3D-reconstruction, distortion correction and isocenter correction, are implemented in MATLAB®, the Mathworks Inc. They are described more in detail in Seeger et al (2001).

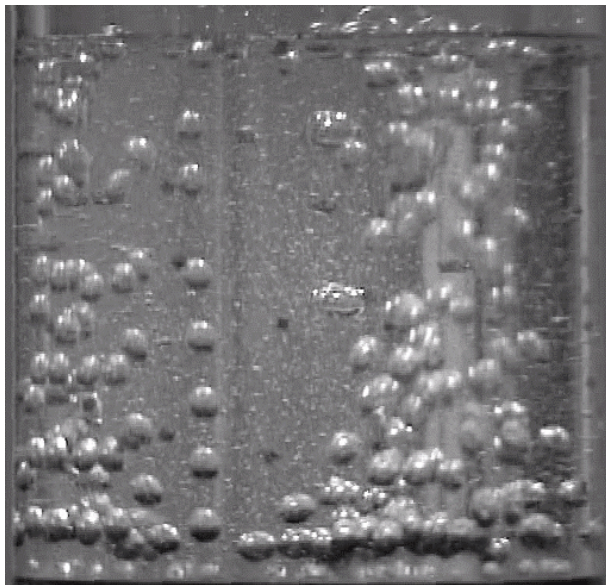
## 3

### Results

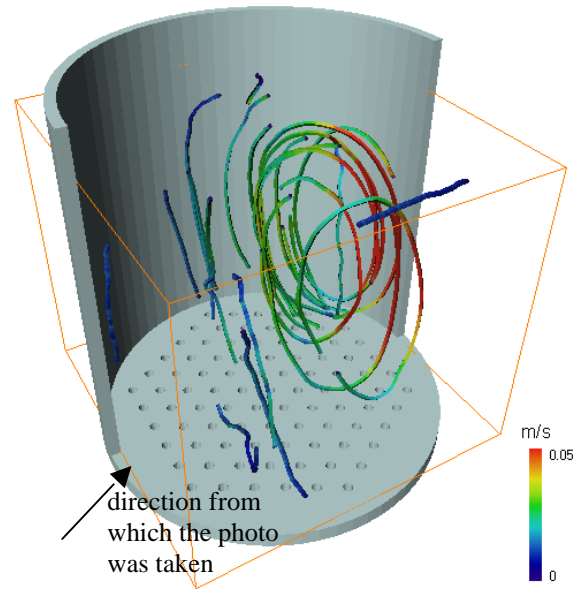
The method was validated in a bubble column with a rectangular cross section (size:  $450 \times 200 \times 40$  mm<sup>3</sup> (height x width x depth)). The void fraction was that small ( $\ll 1$  %), that optical flow measurement methods could be applied. Water was used as liquid and air as gas. LDV (Laser Doppler Velocimetry) and optical PTV (Particle Tracking Velocimetry) was used to investigate the flow by Borchers and Eigenberger (2000). The experimental set-up is described in this publication in more detail. Since the flow is 2D due to the small depth of the bubble column, the experimental set-up differs from the normal one. Only one x-ray source and one image intensifier are needed. The investigated area of our system has a size of about  $150 \times 150 \times 40$  mm<sup>3</sup> due to system limitations. The experimental set-up is shown in figure 3. The liquid velocity was measured by optical Particle Tracking Velocimetry (PTV), Laser Doppler Velocimetry (LDV), and the new X-ray based Particle Tracking Velocimetry. Figure 4 shows that the X-ray based Particle Tracking Velocimetry results are in very good agreement with the common Particle Tracking Velocimetry and Laser Doppler Velocimetry. Obviously, despite the comparable large size of the particle it is possible to assess the velocity fluctuation.



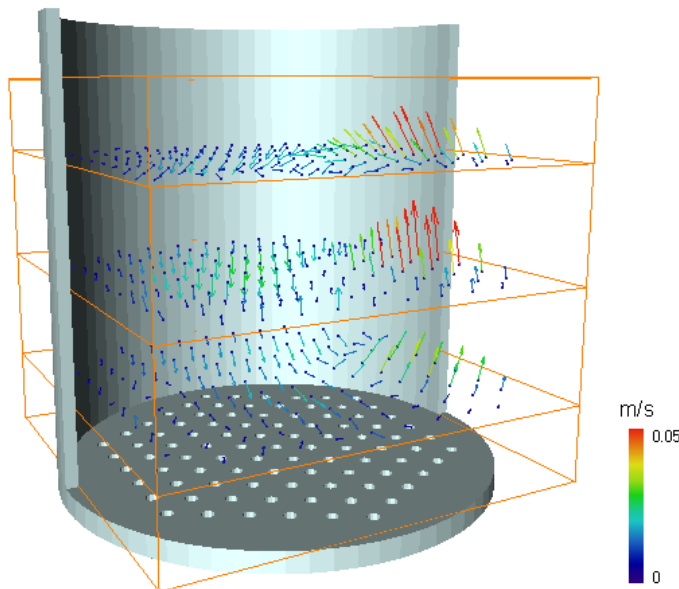
The method was also applied to a cylindrical bubble columns with a void fraction of up to 10.5 %. The bubble column is shown in figure 5. Results of two different measurement conditions are shown in figure 6 and 7. The cylindrical bubble column has an inner diameter of 104 mm and a filling height of 100 mm. 91 injection needles having an inner diameter of 0.34 mm are used as gas disperger. The use of the needles makes the gas distribution more uniform. A disc is mounted at the tip of the needles to prevent a flow between them (see figure 5). Glycerin with a viscosity of 850 mm<sup>2</sup>/s was used as liquid.



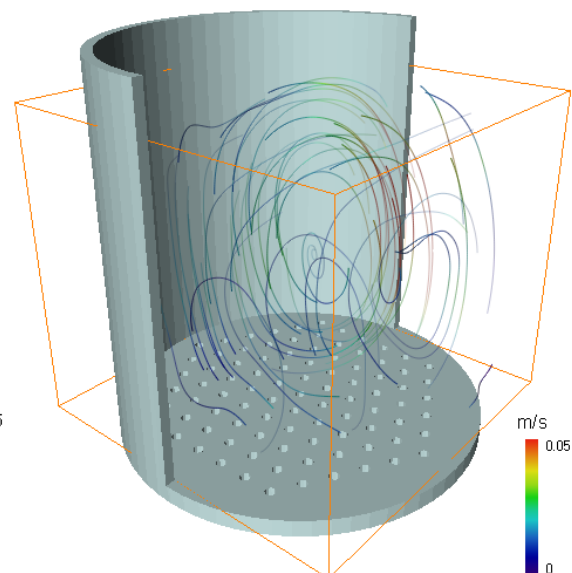
**Fig. 6a** Photo of the flow. The direction from which the photo was taken is shown in figure 6b. The superficial gas velocity was set to 1 mm/s. The void fraction was about 1.5 %. The bubbles are rising on two sides and dragging liquid in their wake.



**Fig. 6b** Some of the trajectories which are obtained by XPTV. The orange bounding box describes the investigated area.



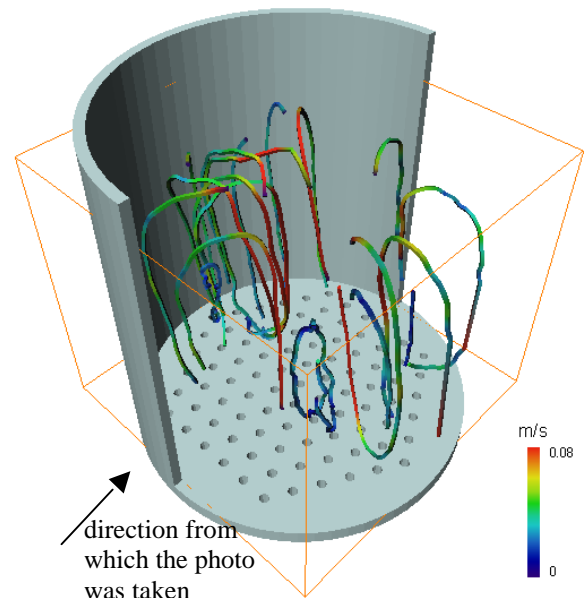
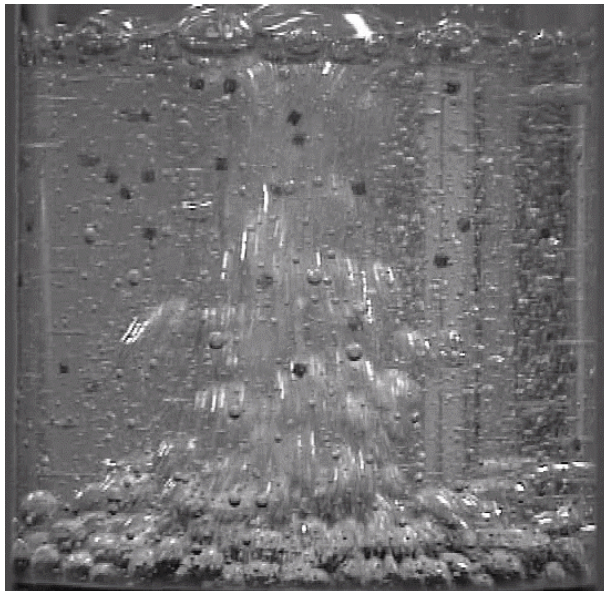
**Fig. 6c** Vector field. The vector field is calculated from the trajectories. It is averaged over 19 seconds recording time. The color of the vectors indicate the absolute value of the velocity. The orange bounding box describes the investigated area.



**Fig. 6d** Streamlines calculated from the vector field. The color of the vectors indicate the absolute value of the velocity.

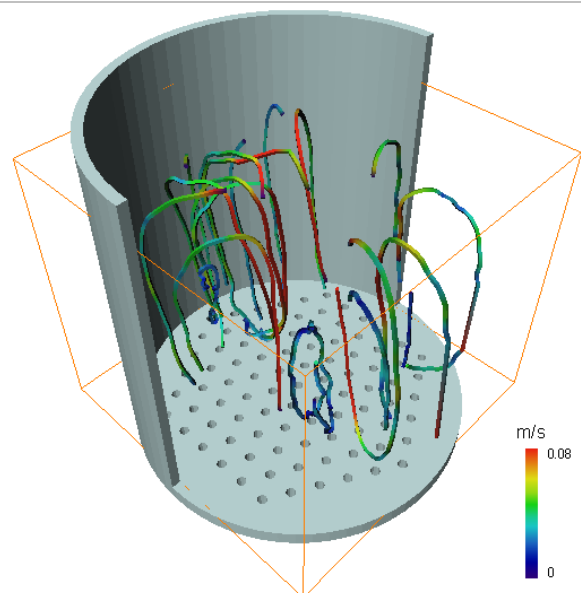
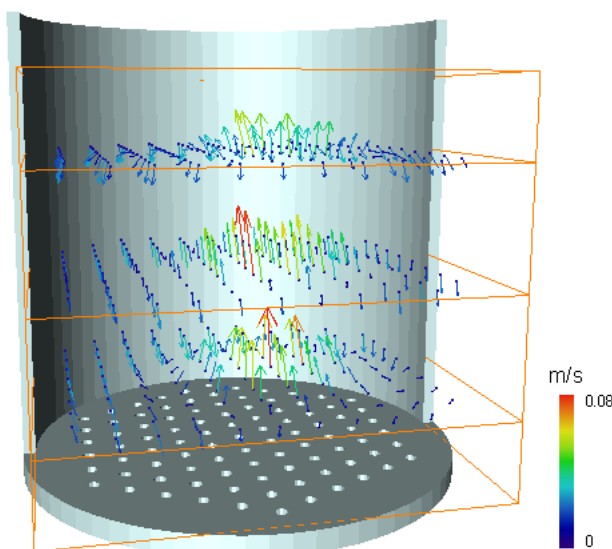
The superficial gas velocity was set in one case to 1 mm/s (figure 6) and in the other case to 3 mm/s (figure 7) resulting in a void fraction of 1.5 % in the first and 3 % in the second case. These two conditions were chosen, because the flow is so-called homogeneous (more specific: homogeneous flow regime or bubbly flow) in the first case and so-called heterogeneous (more specific: heterogeneous flow regime, churn-turbulent flow) in the second one. The visualization of the results was performed with AMIRA (Indeed - Visual Concepts GmbH, Berlin).

The shown vector fields are the mean values of 460 image pairs having about 10000 3D-velocity vectors in both cases. Since 25 images were taken per second, the recording time was about 19 s. The void fraction is in real bubble columns much higher. Results of a bubble column with a higher void fraction is shown in Seeger et al (2001).



**Fig. 7a** Photo of the flow. The direction from which the photo was taken is shown in figure 7b. The superficial gas velocity was set to 3 mm/s. The void fraction was about 3 %. The bubbles are rising in the middle and coalesce. They drag liquid in their wake.

**Fig. 7b** Some of the trajectories which are obtained by XPTV. The orange bounding box describes the investigated area.



**Fig. 7c** Vector field. The vector field is calculated from the trajectories. It is averaged over 19 seconds recording time. The color of the vectors indicate the absolute value of the velocity. The orange bounding box describes the investigated area.

**Fig. 7d** Streamlines calculated from the vector field. The color of the vectors indicate the absolute value of the velocity.

## 4

### Discussion

In conclusion, XPTV was validated successfully in a bubble column with a rectangular cross section and a bubble column with a large void fraction. The method is suitable to assess the three-dimensional velocity of the liquid phase of a bubble column independently from the void fraction. The main advantages of this technique are:

- No reflection and refraction problems arise at phase boundaries - application of the method is not limited by a large void fraction or opaque fluids.
- The liquid velocity is measured at many points in the volume simultaneously.
- 3D-velocity components are measured
- It is a non-intrusive technique - the flow is not disturbed by probes.
- The method is also applicable to opaque liquids and areas with no optical access.

The disadvantages of this method are:

- Low image frequency
- Large particles
- Hazard by X-rays

These three problems can be solved. The use of modern X-ray sources, cameras and image intensifiers allows measurement frequencies of up to 150 Hz. The particles are large due to the facts that the image resolution is low and that the used medical system works with an auto contrast system. The contrast between particle and surrounding fluid is therefore bad on the image. The hazard by X-rays can be prevented by the use of special investigation rooms.

## 5

### References

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