

X-ray Based Velocimetry Measurements in Multi-Phase Flows - an Alternative to Optical Methods?

by

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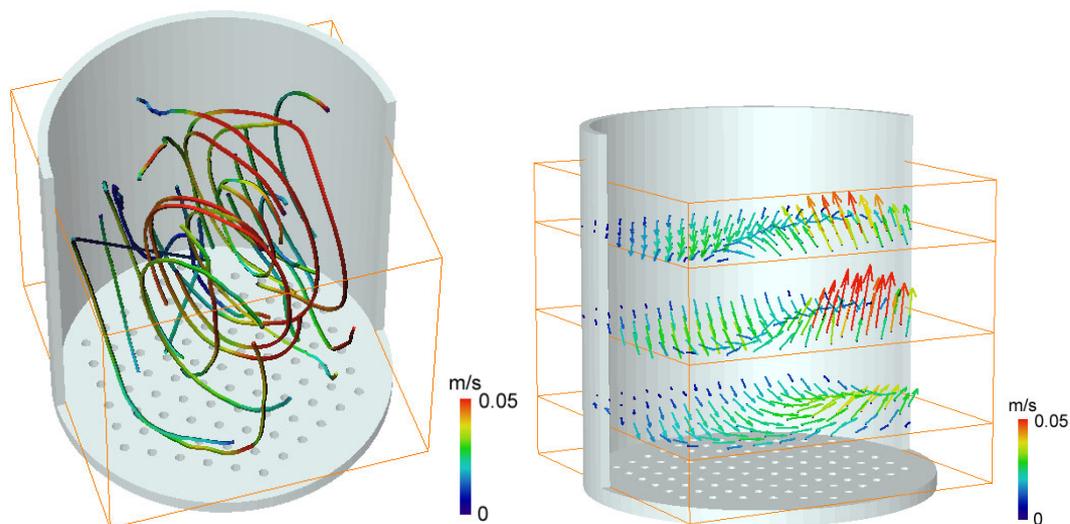
ABSTRACT

Bubble columns are aerated liquid filled vertical tubes, which are widely used in biotechnology and chemical engineering. Despite their widespread use, the fluid mechanics in these apparatuses are not yet understood. Therefore, the investigation of the fluid mechanics is necessary. This investigation with optical methods is yet difficult and, for high void fractions, impossible due to the fact that reflection and refraction of light occur on the gas-liquid boundaries. These effects do not occur applying X-rays instead of light. These rays penetrate a multi-phase flow in straight lines.

The use of X-rays is not new. The medical application of X-ray angiography is a good example. However, X-rays were also applied to multiphase flows. They are used to measure the local time-averaged void fraction in bubble columns by X-ray tomography, to determine the overall void fraction dynamically, and to visualize the flow by an injection of an X-ray absorbing liquid into a bubble column.

We developed a new velocimetry method based on X-rays. 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 measured. The particle motion is observed from two direction using X-rays to allow a three-dimensional particle tracking. Velocity fields are calculated from the trajectories. One example is shown below: The superficial gas velocity was set to 1 mm/s. The void fraction was about 5 %.

The method proved to be suitable to measure the velocity of the liquid phase of a bubble column. The method is a 3-dimensional, 3-component method. The main advantages, compared to optical methods, is that no reflection and refraction problems arise at phase boundaries. Therefore, the application of the method is not limited by a large void fraction or opaque fluids. Like optical methods, the technique is non-intrusive. The time for the acquirement of a 3-dimensional velocity field is small (less than 20 sec).



Particle trajectories (left) and velocity field (right).

INTRODUCTION

Bubble columns are liquid filled vertical tubes, which are aerated - usually from the bottom. They are widely used in biotechnology and chemical engineering, i. e. for the Fischer-Tropsch-Synthesis (production of hydrocarbons, Sie & Krishna, 1999). The void fraction in industrial bubble columns ranges from about 1 % to about 40 %. Despite their widespread application, the flow in those apparatuses is not yet understood (Ranade & Utikar, 1999). In order to improve the performance of bubble columns, the velocity distribution of the different phases and the gas hold-up is essentially to be known. To do this, computational fluid dynamics (CFD) is used more frequently to model the flow within bubble columns. However, the experimental validation of the results of these simulations is still needed to be done due to closure forms used in the description of phase interaction terms and the complexity of the system. This experimental validation is yet difficult due to a lack of adequate measurement techniques (Dudukovic, Larachi & Mills, 1999).

There are various methods available to measure the liquid velocity. However, all optical methods based on visible light (Laser Doppler Velocimetry, Particle Image Velocimetry, Particle Tracking Velocimetry) face the problem of reflection and refraction of light on the gas-liquid boundaries. Therefore, these methods can only be applied when no bubbles obscure the path of light. That means that these methods are only applicable for a small void fraction. Larue de Tournemine, Roig, & Suzanne (2001) say that the maximal void fraction in bubble columns at which optical methods can be applied is 5 %. This value depends on the bubble size distribution and the length of the optical path.

Methods, which work independently from void fraction are the Electrodiffusion Method (Guder, 1997), the Computer Aided Radioactive Particle Tracking (Chen et al., 1999), and the Hot Film Velocimetry (Larue de Tournemine, Roig, & Suzanne, 2001). However, these methods are single point methods and their application is very time consuming.

The only multi-point measurement method, which works independently from the void fraction is X-ray based Particle Tracking Velocimetry (XPTV, Seeger et al., 2001). X-rays penetrate a multi-phase flow in straight lines. The method is a 3D-3C (three-dimensional / three component) method and allows to obtain a mean velocity field of the investigated area within 20 seconds. The method and new results of this method are presented in this paper and compared to methods using visible light such as laser light.

The use of X-rays in flow measurement techniques is not new. The application of X-ray angiography in medicine is one example. It is a commonly used technique to visualize the flow in coronary vessels, where an optical access is impossible (Webster, 1988). An X-ray absorbing liquid is injected into the coronary vessels to be visualized and the motion of the liquid is recorded. The cardiologist can therefore detect and locate a stenosis. Other applications in multi-phase flows are the measurement of the local time-averaged void fraction in bubble columns by X-ray tomography (Mewes & Schmitz, 1999), the determination of the overall void fraction dynamically (Beinhauer, 1971), and the flow visualization by an injection of an X-ray absorbing liquid into a bubble column (Seeger et al., 2002).

METHOD

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 measured.

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 1. 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 intensify 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.

Technical details of the method can be found in Seeger et al. 2001.

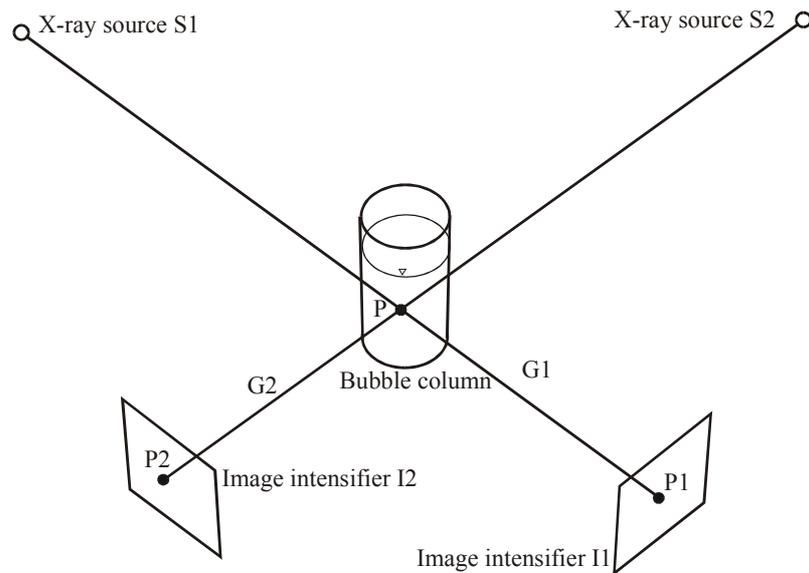


Fig. 1. Experimental set-up.

RESULTS

The method was applied to a cylindrical bubble column with a large void fraction. The cylindrical bubble column had an inner diameter of 104 mm and a filling height of 100 mm. 91 injection needles with an inner diameter of 0.34 mm were used as gas disperser. The use of the needles made the gas distribution more uniform than the use of a perforated plate. A disc was mounted at the tip of the needles to prevent a flow between them. Glycerine with a viscosity of $850 \text{ mm}^2/\text{s}$ was used as liquid. A medical X-ray device (Philips Integris BH 3000) is used for the investigations. It took 25 image pairs per second.

The measurements in the cylindrical bubble column were taken under different condition. One example is shown here. The superficial gas velocity was set to 1 mm/s. The void fraction was about 5 %. The left-hand image of figure 2 shows a photo of the flow. The right-hand image of figure 2 shows the bubble column with a paper grid in the middle of the bubble column. The grid can hardly be seen, which shows that optical methods could probably not be applied in this case.

Particle trajectories were obtained by the algorithm. Some of them are shown in figure 3 (left-hand side). A velocity field was calculated from the trajectories, which is shown in figure 3 (right-hand side). It is a mean values of 470 image pairs. Since 25 images were taken per second, the recording time was about 18.6 s.

To figure out, if the velocity field was changing during the measurement, a velocity field was calculated for the first 235 images (image series 1) and the last 235 images (image series 2) separately. To do this, the trajectories were calculated separately, too. 8941 velocity vectors in the trajectories were found in image series 1 and 8193 velocity vectors in the trajectories were found in image series 2. Again, velocity fields were calculated and they resembled. The mean velocity in image series 1 was 24,4 mm/s and in image series 2 24,9 mm/s. The mean standard deviation in the investigated area was 22,8 mm/s and 21,3 mm/s respectively.

The visualization was performed with AMIRA (Indeed - Visual Concepts GmbH, Berlin), a software package for the visualization of three-dimensional data.

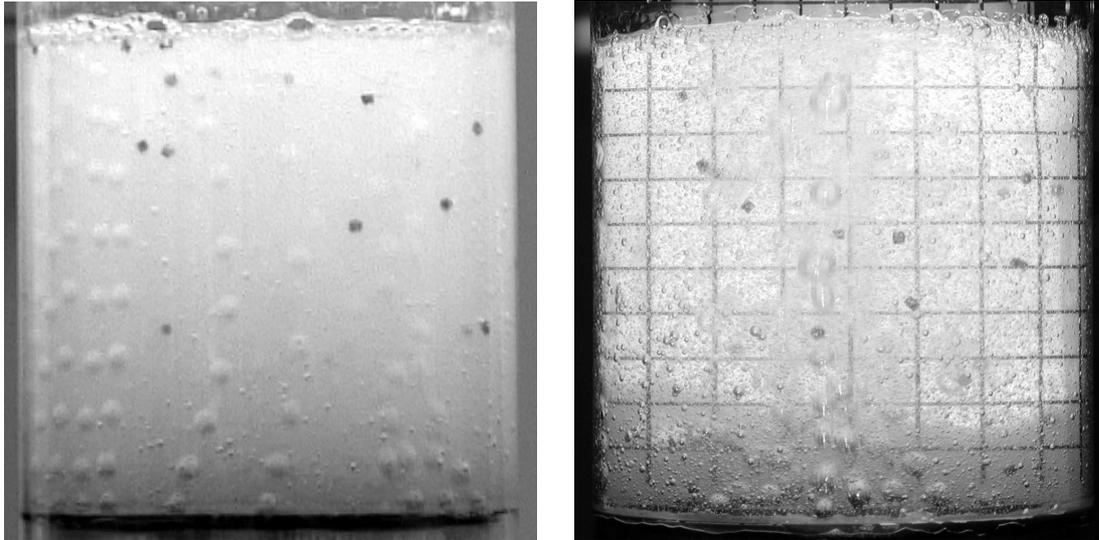


Fig. 2. Photo of the flow (left-hand side) and paper grid in the middle of the bubble column (right-hand side).

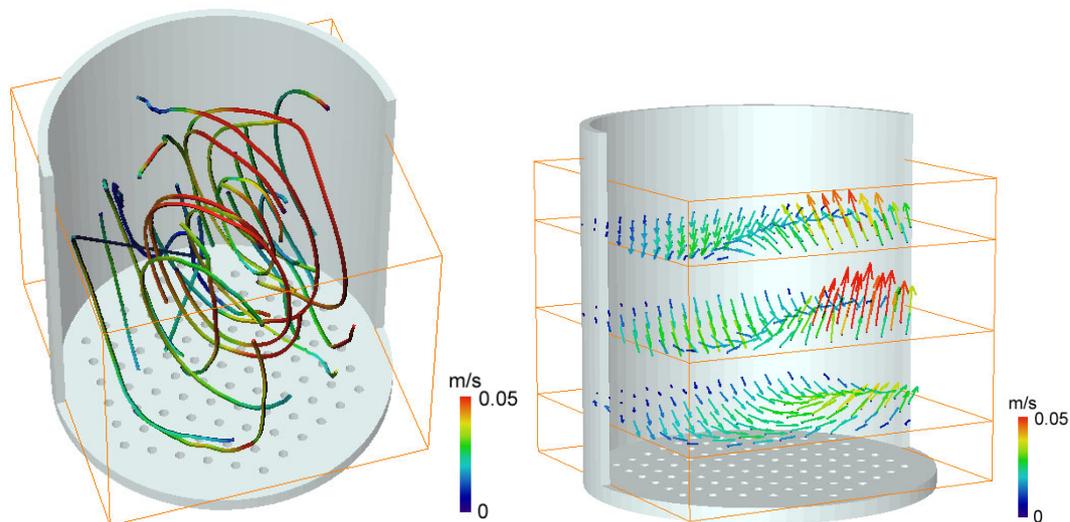


Fig. 3. Trajectories and velocity field

CONCLUSIONS

XPTV was applied to a cylindrical bubble column with a high void fraction. The method proved to be suitable to measure the velocity of the liquid phase in a bubble column. The method is a 3-dimensional, 3-component method. The main advantages, compared to optical methods, is that no reflection and refraction problems arise at phase boundaries. Therefore, the application of the method is not limited by a large void fraction or opaque fluids. Like optical methods, the technique is non-intrusive. The time for the acquisition of a 3-dimensional velocity field is small (less than 20 sec).

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