Heat and Mass Transfer

M. Sommerfeld

Bubbly Flows

Analysis, Modelling and Calculation

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Martin Sommerfeld (Ed.)

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With 194 Figures

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Series Editors
Prof. Dr.-Ing. Dieter Mewes
Universität Hannover
Institut für Verfahrenstechnik
Callinstr. 36
30167 Hannover, Germany

Prof. em. Dr.-Ing. E.h. Franz Mayinger
Technische Universität München
Lehrstuhl für Thermodynamik
Boltzmannstr. 15
85748 Garching, Germany

Editor
Prof. Dr.-Ing. Martin Sommerfeld
Universität Halle-Wittenberg
Fachbereich Ingenieurwissenschaften
Institut für Verfahrenstechnik
06099 Halle (Saale), Germany

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Heat and Mass Transfer

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Preface

The priority research „Analysis, Modelling and Numerical Calculations of Multiphase Flows“ was running for 6 years (from 1996 to 2002) and financially supported by the Deutsche Forschungsgemeinschaft (DFG). The main objective of the research programme was to provide a better understanding of the physical basis for multiphase gas-liquid flows as they are found in numerous chemical and biochemical reactors. The research comprised steady and unsteady multiphase flows in three frequently found reactor configurations, namely bubble columns without interiors, loop reactors, and aerated stirred vessels. For this purpose, new and improved measurement techniques should be developed. From the resulting knowledge and data, new and refined models for describing the underlying physical processes should result, which can be used for the establishment and improvement of analytic as well as numerical methods for predicting multiphase reactors. Thereby, the development, lay-out and scale-up of such processes should be possible on a more reliable basis.

For achieving this objective three research areas were defined:

- development and improvement of experimental techniques which allow accurate measurements in steady and unsteady multiphase flows
- elaboration of new modelling approaches in order to describe the basic transport processes for mass, momentum, and heat in bubbly flows
- development of analytical and numerical methods supplemented by the new modelling strategies in order to support optimisation and lay-out of technical multiphase processes.

In order to enhance cooperation within the priority research five working groups were established:

- bubble driven flows as for example in bubble columns and loop reactors
- three-phase flows (i.e. gas-liquid-solid flows)
- aerated stirred vessels
- experimental techniques
- modelling and numerical calculations

More details about the individual projects and their achievements can be found at www-mvt.iw.uni-halle.de. This homepage will be maintained for some period.

Within the priority research in total 22 projects were supported with durations between 2 and 6 years. This corresponds in total to about 105 man-years of scientists. The entire financial support through the DFG was about 6.9 million Euro. The scientific outcome of the research programme was published in about 60 journal papers and 100 conference contributions.

The final colloquium of the priority research was held in Freyburg (Unstrut) from 23. – 25. September 2002. During the colloquium most of the participants presented the main achievements of their research effort. In addition other research groups working in similar fields were invited to present recent research.

The financial support of the final colloquium by BASF Ludwigshafen is gratefully acknowledged.

Prof. Dr.-Ing. M. Sommerfeld
Dr.-Ing. B. Giernoth

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Oliver Borchers, Gerhart Eigenberger

Institut für Chemische Verfahrenstechnik, Böblinger Straße 72, D-70199 Stuttgart, email: egb@icvt.uni-stuttgart.de

Abstract:
Various flow configurations in a flat bubble column reactor were investigated with optical measurement techniques such as Laser Doppler Anemometry (LDA) and a newly developed image processing method based on Particle Tracking Velocimetry (PTV). Using the new two-phase PTV, bubble and liquid phase velocity with high resolution in time (up to 2,000 Hz data rate) and space (video imager resolution down to 4 μm per pixel) were examined simultaneously at a local gas hold-up up to 12%. The detailed experimental data was used for validation of numerical modeling and simulations of the hydrodynamics in two-phase flow as described in the contribution of Sokolichin and Eigenberger. Good agreement could be stated for bubble flow with local gas volume fractions up to 5% regarding both time averaged velocities as well as turbulence data.

Keywords:
Bubble column, two-phase bubble flow, particle tracking velocimetry, laser Doppler anemometry

1 Introduction

Numerical modeling and simulations of bubble column reactors require the combined calculation of flow structures, mass transfer and reaction. The main difficulty lies in the proper modeling of the complex hydrodynamics of gas-liquid bubble flow. Therefore, many contributions have focused on this topic, e. g. Delnoij et al. [1], Lain et al. [2], Sokolichin and Eigenberger [3].

Any improvement of hydrodynamics modeling and simulation requires a detailed comparison and validation with experimental results. Recently, good agreement could be stated for several bubble flow configurations (Borchers et al. [4]), but many important questions remain unsolved. They comprise the question of bubble swarm velocity and its relation to single bubble velocities (Schlüter and Räbiger [5]), the question of bubble-bubble interactions via coalescence and redispersion and two-phase and bubble-induced turbulence. Mathematical models for the bubble-induced turbulence are often derived in analogy to the single-phase k-ε-model with additional bubble-induced source terms for the turbulent kinetic energy k and the turbulent energy dissipation ε (e. g. Kataoka and Serizawa [6]). While established measurement techniques such as LDA and PIV allow for a direct determination of the turbulent kinetic energy k, the turbulent energy dissipation ε is subject of estimation.

Examination of single-phase turbulence and slip velocity requires experimental methods, which record the velocity of both phases simultaneously and with high resolution in time and space. Measuring the turbulent kinetic energy and the dispersion coefficient allows for validation of the parameters chosen for modeling bubble-induced turbulence. For this purpose, non-intrusive measurement techniques like Laser Doppler Anemometry and digital image processing methods are discussed. A new versatile method based upon Particle Tracking Velocimetry has been developed and will be presented in this contribution.

Experiments with the new measurement technique were carried out in two flat bubble columns with rectangular cross-section. This type of apparatus has several advantages in comparison to the more common cylindrical reactors. The depths of 4 and 8 cm, respectively, enables measurements in bubbly flow at high gas volume fractions up to 12 %. Furthermore, no refraction correction at the walls is necessary as in cylindrical columns. The flat columns can be modeled more easily with a rectangular space grid and boundary conditions are easier to implement.

2 Experimental

2.1 Gas-liquid reactor facility

The experimental studies were performed in flat bubble column reactors with rectangular cross-sections, see Fig. 1. For measurements of the hydrodynamics, the columns were filled with water and aerated with air by frit spargers and hole plate spargers leading to bubble diameters in the range of 3 to 5 mm. Glass and plexiglass plates on the front and back side allow for use of optical, non-intrusive techniques such as LDA and image processing. Due to the rectangular cross-section, no correction to the refraction index is needed. Mounting fixed internals in the 2 meter column allowed for a loop reactor configuration with forced circulation flow. By variation of water level, gas flow rate, sparger type and position, various flow configurations were realized.

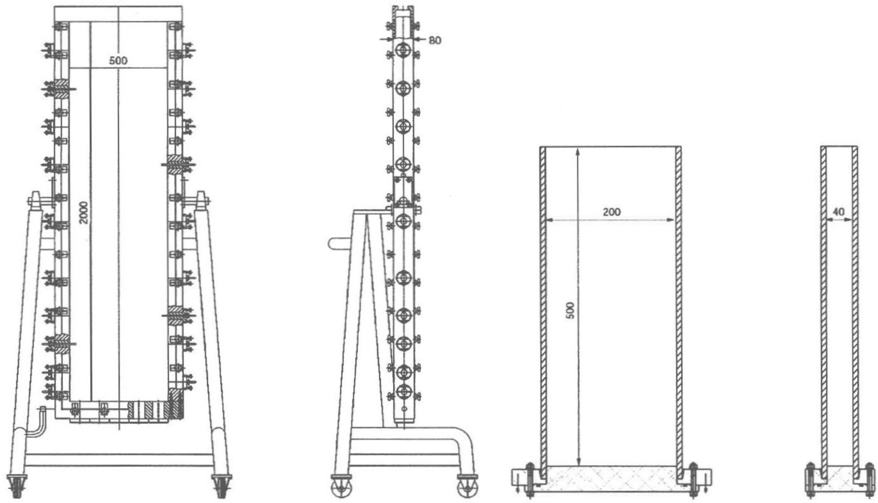

Fig. 1. Flat bubble column reactors with rectangular cross-section, dimensions in mm

2.2 Laser Doppler Anemometer

LDA measurements of the liquid velocity were performed with a DANTEC two-component system which operated in backward scattering mode. Laser light was provided by a 300 mW argon ion laser. Two laser wavelengths of 514.5 nm and 488 nm were used in order to measure two velocity components simultaneously. For detection of the liquid phase, hollow glass sphere particles with 10μm diameter having almost no slip and the same density as water were added to the flow. In both columns, measurements were taken in the mid plane between the front and the back plate at regular grid points 10 or 20 mm apart.

Bubble velocity measurements with LDA by use of special electronics or in combination with Phase Doppler Anemometry (PDA) was topic of several studies (e. g. Martin et al. [7], Brankowic et al. [8]). However, these were focused on single bubble experiments or bubbles with diameters less than 1 mm. Recent contributions have shown that LDA velocity measurements of the gaseous phase are not reliable in realistic bubbly flow (Groen et al. [9]). Hence, LDA was used for liquid velocity measurements only. Tracer particles were added in high concentrations so that few incidences of bubble signals could be neglected in relation to tracer signals as reported by Borchers et al. [4].

LDA provides time dependent data at single points, from which information on high and low-frequency flow fluctuations can be obtained. Hence, flow maps and velocity profiles for quantitative validation of numerical simulations are reliable only with long time averaged data while dynamic flow behavior was analyzed at single points. Calculating time weighted averages, the biasing error was minimized.

2.3 Image processing: two-phase PTV

The image processing procedure consisted of three major steps. Firstly, image sequences were recorded using a Weinberger high-speed video camera. Images with 512 x 512 pixels resolution were captured at up to 1000 Hz frame rate and at 2000 Hz with half of the maximum resolution. After storing the sequences on CD ROM, they were processed with image processing C-algorithms which are described in detail by Borchers [10].

In the gray scale images, bubbles and tracer particles were detected and stored in binary images as objects with label 1 (white in Fig. 2) while the background was set to 0 (black). After this time consuming segmentation step, bubbles and tracer particles were discriminated by their different sizes. The third step consisted of tracking the detected objects over successive images. Velocities were calculated from the displacement of corresponding bubbles and particles.

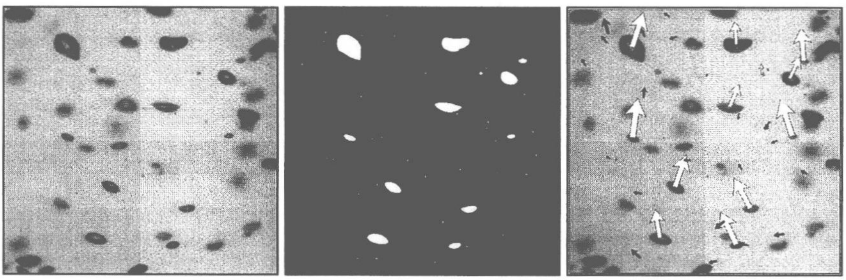

Fig. 2. Gray scale image of bubbly flow with added tracer particles (left), detected objects in the binary image (middle) and instantaneous velocity vectors (right).

3 Flow configurations

Various flow structures were established by changing the aeration and/or the internals of the bubble column reactor sketched in Fig. 1 (left). Fig. 3a shows the influence of water level for local aeration in central position and a gas flow rate of 1 l/min. In case the ratio of height to width (H/W) equals 1, the flow has an essentially stationary character in which one circulation cell spreads over the full width of the bubble column. As H/W increases slightly over 1.5, an unsteady flow structure develops with two staggered rows of vortices moving downwards in a periodic way. The bubble swarm distribution is shown for aspect ratios of 2, 3 and 3.8 at different times. Increasing gas flow rate, the periodic flow structure becomes more and more irregular until the fluctuations are completely chaotic. The time dependent behavior of the oscillating bubble swarm with liquid vortices moving downwards is depicted in Fig. 4 for a H/W ratio of 2.

Using two frit spargers for aeration, two separated bubble swarms oscillate irregularly but correlated to each other as shown in Fig. 3b. This flow configuration is extremely susceptible to changes of the experimental conditions.

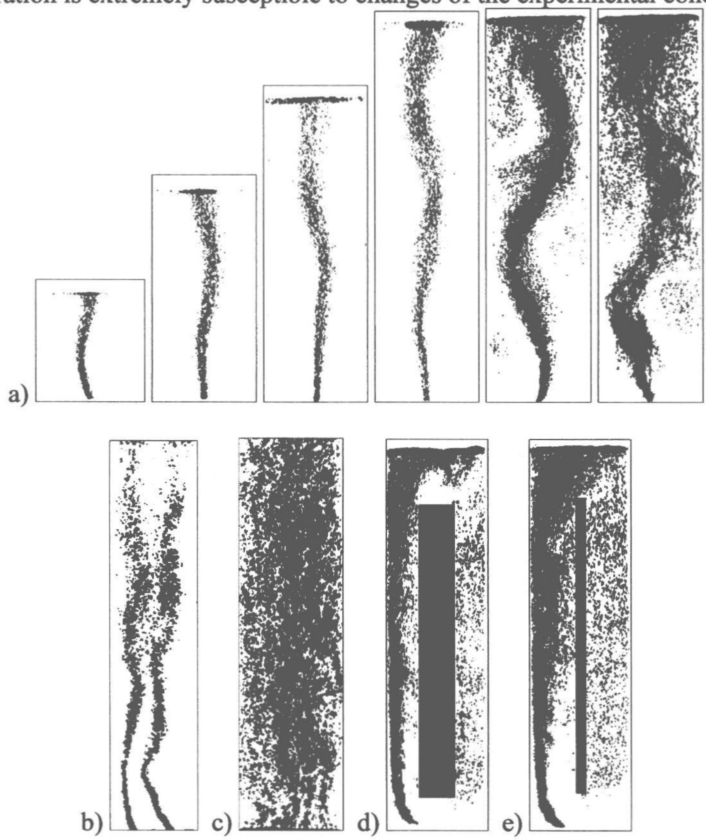

Fig. 3. Bubble column configurations with different water level and gas flow rate (a), with two correlated bubble swarms, with homogeneous aeration (c) and loop reactor configurations with flexible reactor internals (d and e)

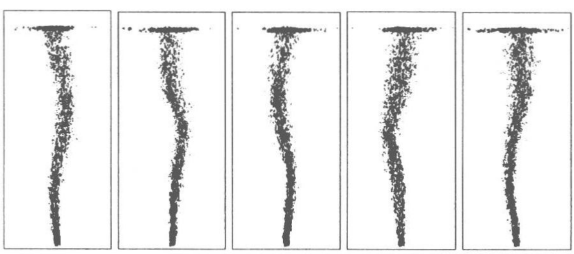

Fig. 4. Bubble column configuration with oscillating bubble swarm

A plate sparger with one single line of 0.3 mm holes generated a homogeneously aerated bubble column configuration (Fig. 3 c). Mounting of different internals in combination with local aeration forced clock-wise circulation of the liquid flow leading to loop reactor configurations (Fig. 3 d and e).

4 Results and discussion

4.1 Reproducibility and accuracy of flow investigations

Although the mean flow structure in a bubble column is described to be either steady-state or periodic, it is still turbulent and has therefore an essentially chaotic character on a smaller scale. Hence, the measuring time interval for mean values must be chosen long enough in order to get reproducible results. Fig. 5 shows the cumulated time averaged liquid velocity as function of the length of the averaging time for two different experiments at the same position and with identical conditions. The measuring time has to be chosen long enough so that periodic and high frequency fluctuations do not influence the mean value. However, it can be clearly seen that the flow has a substantially transient character even on the long time scale.

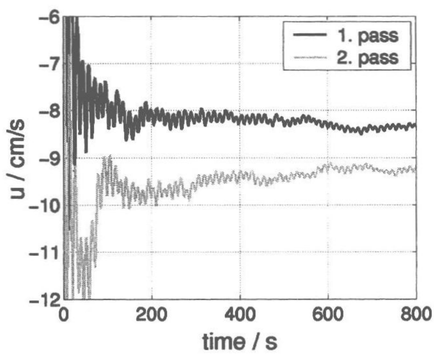

Fig. 5. Long time LDA measurements in a periodic flow under identical conditions: accumulated average of the liquid velocity

4.2 Validation with LDA: example

LDA measurements and validation of the corresponding simulations were performed for the flow configurations of Fig. 3 under various conditions. Here, the configuration sketched in Fig. 3a with an aspect ratio of 2 shall be presented exemplarily.

Quantitative comparison of LDA measured and calculated liquid velocity data is shown in Fig. 6. Since dynamic measurements with LDA are restricted to single points, only the time-averaged velocity patterns can be compared with respective simulation results. Due to this long time averaging the oscillations caused by moving vortices result in a symmetrical flow structure. The long-time averaged liquid velocity flow map shows two liquid vortices on both sides of the bubble swarm. A similar flow structure was obtained in the simulations. Also one-dimensional velocity profiles at different heights show good agreement of experiments and simulations. Differences occur only in the region directly above the aeration where the flow has a very turbulent, chaotic structure.

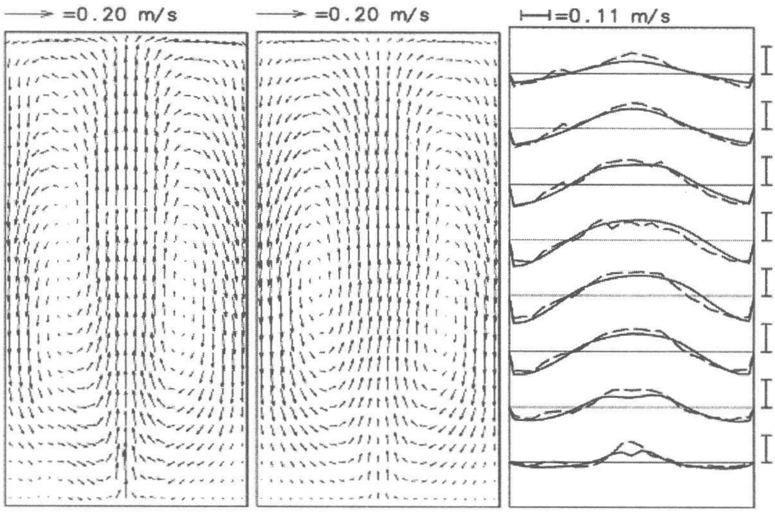

Fig. 6. Long time averaged liquid velocity profiles for the flat bubble column reactor with 100 cm water level and 1 l/min gas flow rate as in Fig. 4 – LDA measurements (left) and simulations (middle). Comparison of measured (---) and calculated (—) vertical velocity component.

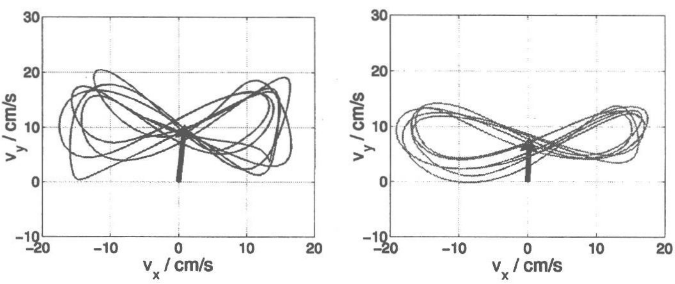

Fig. 7. Trajectories of FFT-filtered liquid velocities: experimental data (left) and simulations (right) in the column center.

The presented quantitative results are based on time averaged velocity data. This analysis neglects the dynamics of the strongly transient flow which is the main reason for lateral mixing. The flow dynamics consist of a low-frequency part due to the bubble swarm's periodic motion and a superimposed turbulent high-frequency part. In the following, dynamics concerning the low-frequency periodic liquid motion are analyzed.

The LDA system provides time-dependent, two-dimensional liquid velocities at single measurement points. In Fig. 7 a comparison of measurements and simulations will be presented for the central point of the regarded flow configuration.

Phase trajectories enable the simultaneous visualization of the two-dimensional change in velocity with the time. To get such a phase trajectory, the time dependent trace of the velocity vector is plotted. In case of periodic motion, the phase trajectories remain close together following a common curve. In case of chaotic motion the trace will randomly cover a larger area of the velocity plane.

Experimental and simulation data were low-pass filtered to get the low-frequency motion, the trajectories of which are drawn in Fig. 7 for a time of 200 sec. The center of mass of subsequent curves equals the time averaged velocity at the measuring point, indicated by the black arrow. In the column center, liquid vortices pass on both sides so that the trajectory resembles a horizontal 8.

4.3 Validation of two-phase PTV

For validation of the newly developed tow-phase PTV technique, the bubble column configuration shown in Fig. 3b was measured with LDA and PTV. The measured time averaged, two-dimensional vertical velocities and standard deviations of both phases are shown for the whole width at 121 cm height in central depth position. Liquid velocities are measured with PTV and LDA, bubble velocities with PTV only (Fig. 8).

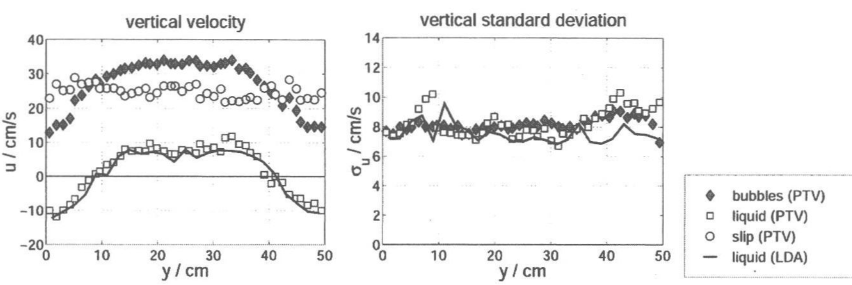

Fig. 8. Vertical liquid velocity and standard deviation in bubble column configuration (3b) at 121 cm height