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Fluid dynamics of single bubbles in different continuous phases measured with two high-speed cameras carried on a real-time controlled linear guidance

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Abstract

Being able to accurately describe gas/liquid flows on different time and length scales is still a challenging task. The hydrodynamic description alone is a complex challenge. Adding the prediction of mass transfer and reaction in the systems, the inaccuracy of the calculations increase. The Priority Program (SPP 1740) deals with reactive gas / liquid flows in which the chemical reaction takes place in the liquid phase to gain a better understanding in these systems. This subproject reduces the complexity by first analyzing single bubbles instead of a swarm of bubbles. This is done in an especially for this tasks developed single bubble rising cell. A bubble is created at the bottom of a column of liquid and the free-rising bubble is tracked with two high-speed cameras from two sides with an angle of 90 degrees. In order to realize a high-resolution recording of the bubbles, the two cameras are carried on a linear guidance system following the bubble. This has been accomplished with a real-time control of the motor for the guidance system.

1 Introduction

The design of reactors with a gaseous phase dispersed in a liquid one, (e.g. bubble columns) is in most cases based on rather roughly estimated parameters. The Priority Program SPP 1740 "Influence of local transport processes on chemical reactions in bubbly flows" of the German Research Foundation (DFG) was set up to get a deeper insight in such systems. The interdisciplinary program allows a close cooperation between chemists, process engineers and mathematicians for both experimental work and simulation, e.g., using CFD. Aim of the SPP 1740 is to develop a fundamental understanding of the interactions in gas/liquid-reactions, especially concerning fluid dynamics, mass transfer, reaction rate and their influence on yield and selectivity. In this subproject, the complexity of the two-phase flow prevailing in a bubble column is reduced by the observation of single-bubbles. This allows highly detailed and reproducible experiments.

2 Experimental setup

To carry out the measurements with a high degree of accuracy, an experimental test cell has been developed, which enables the measurement of fluid dynamics, also considering the size and shape of bubbles with high temporal resolution. The system is shown schematically in Figure 1. On the left side the test cell is shown schematically. The main part of the system is a 2 meter long glass tube (1) with a maximum filling volume of 10 liters. This tube stands on a stainless steel plate through which a glass capillary is inserted (2). Single bubbles can be generated at this capillary. The glass capillary is shaped like a straight-cut tube with different diameters or like a trumpet with a smooth opening. The glass capillary is connected tube to a T-piece with a PTFE tube. The T-piece is further connected to a car injector valve with a gas source (3) and a Hamilton syringe pump (4). The bubbles can be produced in different ways. An amount of gas can be injected with millisecond accuracy into the liquid filled T-piece by opening the car injection valve. The gas in the T-piece can be flushed out by pumping further liquid with the syringe pump until the gas leaves the glass capillary. The generated bubble size can be varied almost arbitrarily. This method is similar to that developed by Ohl (2001) with two valves. The volume for flushing can either be sucked out of the system beforehand with the syringe or removed from a separate container. Another option is to work without the syringe pump. The tube and the capillary are filled with gas and the valve lets a specific amount of gas pass when the car injection valve opens.

The glass tube is covered with an octagonal acrylic glass jacket (5). This serves on the one hand as heating jacked to temper the system and on the other hand to reduce the optical distortions of the round glass tube.

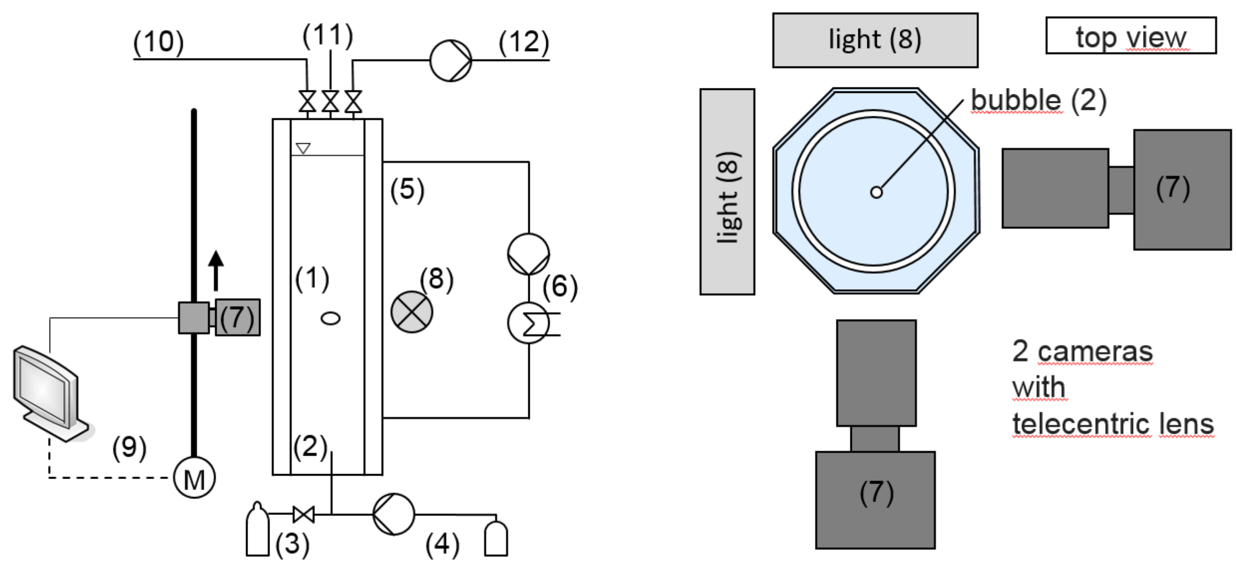


Figure 1: Experimental setup rising bubble test cell: schematic sketch (left), single bubbles rise in a temperature-controlled glass tube (h = 2m) observed with high-speed cameras; Cross section of the system (right)

The bubble is observed during ascent by two high-speed cameras (7) mounted 90° apart on a slide (Vieworks VC-4MC-M180E0-CM). In addition to the two cameras, the slide also has two LED panels (8) attached, which allow sufficient lighting of the bubble. The cameras have telecentric lenses (Sill TZM 2298) and capture images at a resolution of 1400 x 1696 Px² at 200 fps.

The speed of the motor (9) for the slide is controlled in real time by the position of the bubble in the picture. The start time can be triggered either via the injection valve or via an image evaluation on the capillary. The possible movement distance of the carriage is approx. 1800 mm.

Thus, the trajectory of a bubble in a volume of 33 x 33 x 1800 mm³ can be measured in three-dimensional space. In addition to the path, the size and shape of the bubble can be traced. The volume of the bubble is reconstructed by row-wise measurement of the bubble width in both views (w_1 and w_2) and therefore determining the ellipsoidal area at one height. With the height of a pixel h_{Px}, a volume element can be calculated. This is done for the entire bubble:

$$V_B = \sum \pi \, w_{1,i} \, w_{2,i} \, h_{Px} \qquad , \tag{1}$$

like Timmermann (2016) did for a view from one side.

The programming of the entire setup was realized in LABVIEW. For the motor control a cRIO system (cRIO-9024 from National Instrument) is used.

The continuous phase to be measured comes in contact only with parts of glass, PTFE, PCTFE and stainless steel, which not only allows aqueous solutions to be tested, but also organic solvents, e.g. Methanol or dichloromethane. It is possible to work under a protective atmosphere (10-12), as is usually necessary for measurements with chemical reaction, Merker (2017).

3 Results

One system often measured in the literature is water with gas bubbles, Clift (1978). Figure 2 left and center shows the two views of the two cameras of a 2mm bubble in water. Thus, with a series of images the three-dimensional trajectory of the bubble can be reconstructed. It is possible to analyze the oscillation frequency and the movement pattern in the xy plane. The bubble volume and both the rising velocity and the 3D velocity along the trajectory are measured.
A comparison with the literature, e.g., with Clift (1978) shows good agreement for non-contaminated systems.

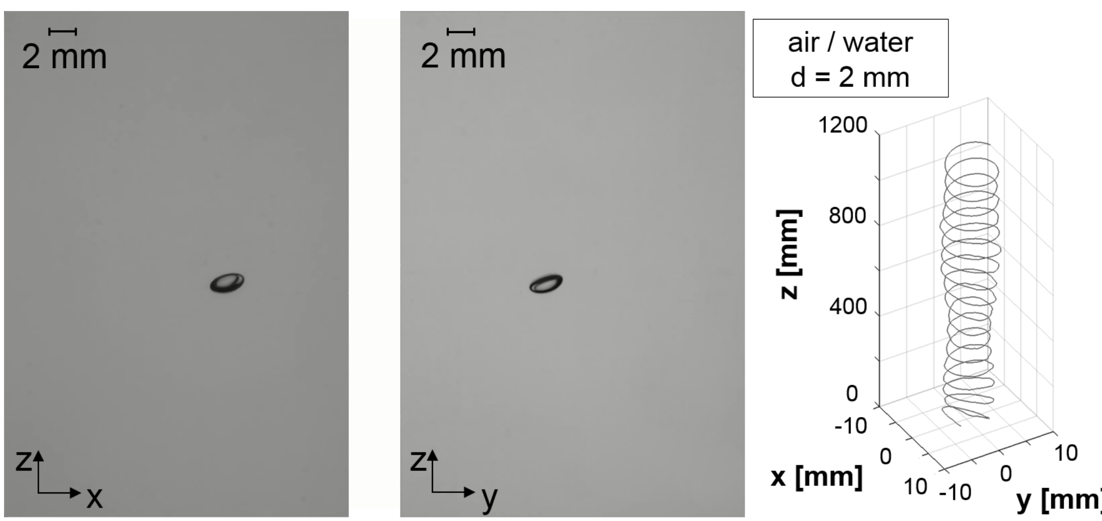
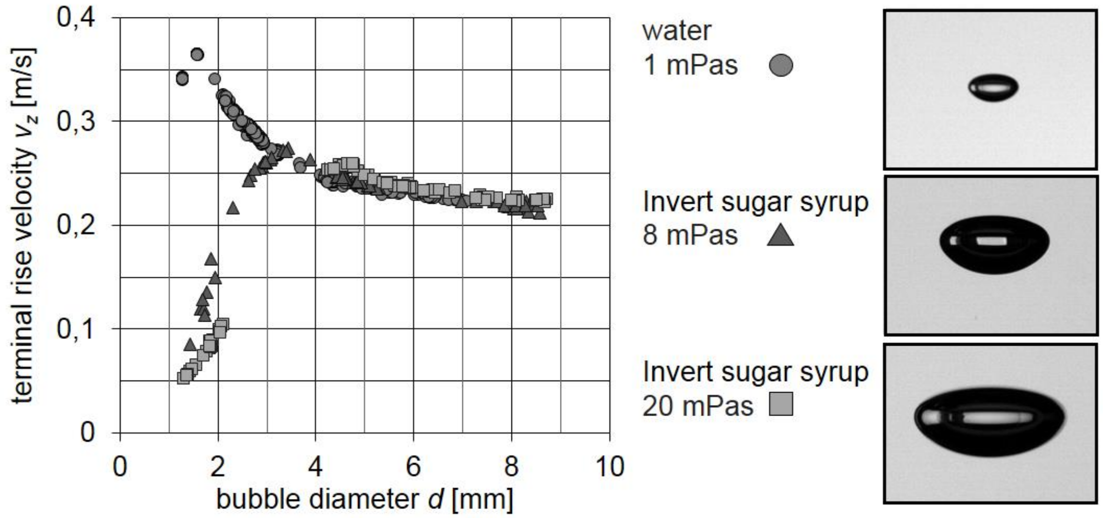


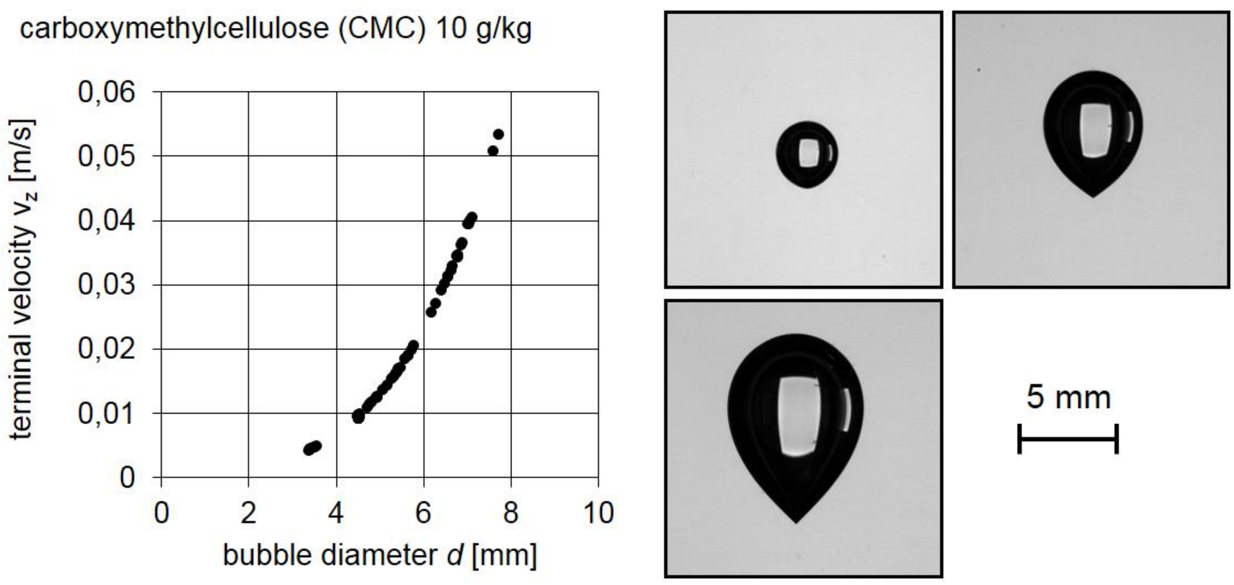
Figure 2: Two views on a bubble in water from different sides (left and middle); Reconstructed 3D bubble trajectory (right).

In addition to water, other Newtonian fluids were also investigated. Different concentrations of invert sugar syrup were used. In Figure 3, on the left, the terminal rising velocity depending on the bubble diameter are shown for water and two types of syrups with viscosities of 1, 8 and 20 mPas respectively. It can be seen that the terminal rising velocity decreases with increasing sugar concentration and the bubble diameters increase. To get an idea of how the shape and size of the bubbles changes, the bubbles with the highest terminal rising velocity of the three different systems are shown on the right.
A comparison with shape regimes for bubbles according to Grace (1973) shows an apt description of the Eötvös Number and Morton number.



Figute 3: Terminal rise velocities of bubbles Newtonian liquids (left); shapes and sizes of bubble with the maximum terminal velocity in each liquid (right)

In addition to Newtonian media, shear thinning and viscoelastic fluids were also investigated. Carboxymethylcellulose (CMC) was chosen at a concentration of 10 g / kg of water. Rising velocities were measured as a function of bubble size, as shown in Figure 4, left, and the shape of the bubbles analyzed. It can be seen in Figure 4 on the right that the shape differs significantly from the shape of bubbles in Newtonian media. CFD simulations to predict the fluid dynamics and shape of bubbles in non-Newtonian media were conducted and will be published elsewhere.



Figute 4: Terminal rise velocities (left) of carboxymethylcellulose (CMC) and the shapes of different bubble sizes (right)

4 Conclusion

A setup was built to investigate the fluid dynamics and the mass transfer on single bubble basis, if necessary with a chemical reaction. This can be done with high spatial and temporal resolution. As a result, reliable data for the three-dimensional fluid dynamics of single bubbles are experimentally accessible and can be used, e.g., to validate CFD simulations. The rising test cell is not limited to aqueous continuous phases, inorganic solvents can also be measured. This enables the study of a broad spectrum of substance systems.

Acknowledgements

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