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LUTZ BÖHM, MATTHIAS KRAUME*,

HYDRODYNAMIC INVESTIGATION OF SINGLE BUBBLES

HYDRODYNAMICZNE BADANIE POJEDYNCZYCH PĘCHERZYKÓW

Abstract

The presented work shows the results of fundamental fluid dynamical investigations of the rise of single bubbles in a rectangular channel with a channel depth in the range of the equivalent bubble diameter. A fully automatized experimental rig was built so that for each parameter combination, (parameters: channel depth, the bubble size and the liquid velocity) at least 1000 single bubble rises were realized. The Electrodiffusion Method (EDM) was used to measure the shear stress on the wall. The maximum shear stress and the range of shear stress fluctuations are analyzed. Additionally fundamental investigations of the bubble behavior were performed with Particle Image Velocimetry (PIV). A comparison to CFD results from literature is done.

Keywords: bubble, Electrodiffusion Method, Particle Image Velocimetry, shear stress

Streszczenie

Artykuł niniejszy prezentuje wyniki podstawowych badań nad dynamiką płynów przy wzroście pojedynczych pęcherzyków w kanale prostokątnym z głębokością kanału w zakresie równoważnej średnicy pęcherzyka. W pełni zautomatyzowany sprzęt doświadczalny zbudowano w taki sposób, by dla każdej kombinacji parametrów (parametry: głębokość kanału, wielkość pęcherzyka i prędkość cieczy) powstało co najmniej tysiąc pojedynczych pęcherzyków. Do pomiaru naprężenia stycznego na ściance zastosowano metodę elektrodyfuzyjna (EDM). Przeanalizowano maksymalne naprężenie styczne i zakres jego wahań. Dodatkowo przeprowadzono podstawowe badania nad zachowaniem pęcherzyków z pomiarem prędkości obrazu cząsteczki (PIV). Porównano też znane z literatury wyniki CFD.

Słowa kluczowe: pęcherzyk, metoda elektrodyfuzyjna, pomiar prędkości obrazu cząsteczki, naprężenie styczne

* Lutz Böhm, Prof. PhD. Eng. Matthias Kraume, Chair of Chemical and Process Engineering, TU Berlin.

1. Introduction

Gassing is an operational tool widely used in process engineering. Its function is reaching from e.g. mass transport between the phases to enhancement of heat and mass transfer in the liquid phase and – the motivation for this project – the generation of shear forces on surfaces which are e.g. used in Membrane Bioreactors (MBR) and heat exchangers to clean the surfaces from deposition layers. Especially in MBRs often flat sheet membranes are used. In this case two plane membrane plates are glued together at the edges to form a cushion. Several of such cushions are arranged in modules. Using the static head a high pressure on the outside of the cushions or, alternatively, a low pressure on the inside of the cushions is used to get an outside-in filtration. During filtration a fouling layer builds up between the cushions. This space between the cushions has a rectangular shape and is aerated to generate flows and therefore shear forces which are responsible for the cleaning of the membranes. The system is often also constructed in a way that the air lift loop effect can be used to generate additional liquid flows. This makes the system with its multiphase flow in multiple rectangular channels fairly complex.

The rather academic single bubble approach is chosen here to be able to determine the influence of specific parameters on the bubble rise. Bubble swarms are such complicated systems that altering one parameter will most likely have several effects on the behavior of the entire swarm. Starting from the 'simplified' system with single bubbles the complexity can be increased in the future and a deeper understanding of more complex systems can be gained.

In this project two measurement techniques are used to investigate the hydrodynamics of the rise of single bubbles.

The measurement technique that will be mainly discussed is the Electrodiffusion Method (EDM). This technique is known for mass transfer and hydrodynamic investigations for more than 50 years [1, 2]. Especially in membrane research it was used several times to determine the shear stresses that are induced by the aeration of such systems. Ducom et al. [3, 4] applied the technique to a flat sheet system. They used a rather small test cell with a height of only 147 mm and a fixed depth of 5 mm. The tests are done with single bubbles and bubble swarms. Due to the low height, general and repeatable conclusions cannot be gained from the experiments. They only give relative values and do not apply the transient correction (discussed in chapter 2.2) to the data. For the test cell that they used they found out that the shear stress is not evenly distributed over the flat sheet. Gaucher et al. [5–8] investigated a system of comparable size to Ducom et al. with a depth of 1–5 mm. This is a channel depth that is rather small for MBRs as such channels would clog almost instantly. They varied several parameters such as channel depth, liquid distributor types and viscosity of the liquid. As they did simultaneous filtration tests they found out that fluctuating shear stress has a positive effect on the cleaning process. Finally Zhang et al. [9] applied the measurement technique to a test rig that had a height of 1000 mm and a depth of 20 mm. The depth is rather wide in comparison to real membrane systems [10]. They varied the air flow rate, bubble size and the bubble frequency and found a strong influence of these parameters on the occurring shear stress.

Additionally results from measurements with Particle Image Velocimetry (PIV) will be presented. Only Gaucher et al. [11] applied PIV to a flat sheet system which was described above. They used the technique to support their EDM findings. But as they used the same system the shortcomings are accordingly.

Although numerous investigations about single bubble and bubble swarm behavior are apparent in the literature as shown above, to the knowledge of the author, no fundamental investigation can be found for single bubbles rising in rectangular channels with a channel height that ensures steady conditions, a channel depth of 3–10 mm and an equivalent bubble diameter in the same range which both is the case in flat sheet membrane modules.

2. Materials and Methods

2.1. Apparatus

The three parameters channel depth (3–7 mm), bubble size (3–9 mm) and superimposed liquid velocity (0–20 cm/s) were chosen to be varied in this investigation. Different rectangular acrylic glass channels with variable depth were constructed. The width is 160 mm and the height is between 1000–1500 mm. At the bottom of the channel the needle of a 50 ml Hamilton Gastight syringe can be inserted into the channel through a septum. The syringe is

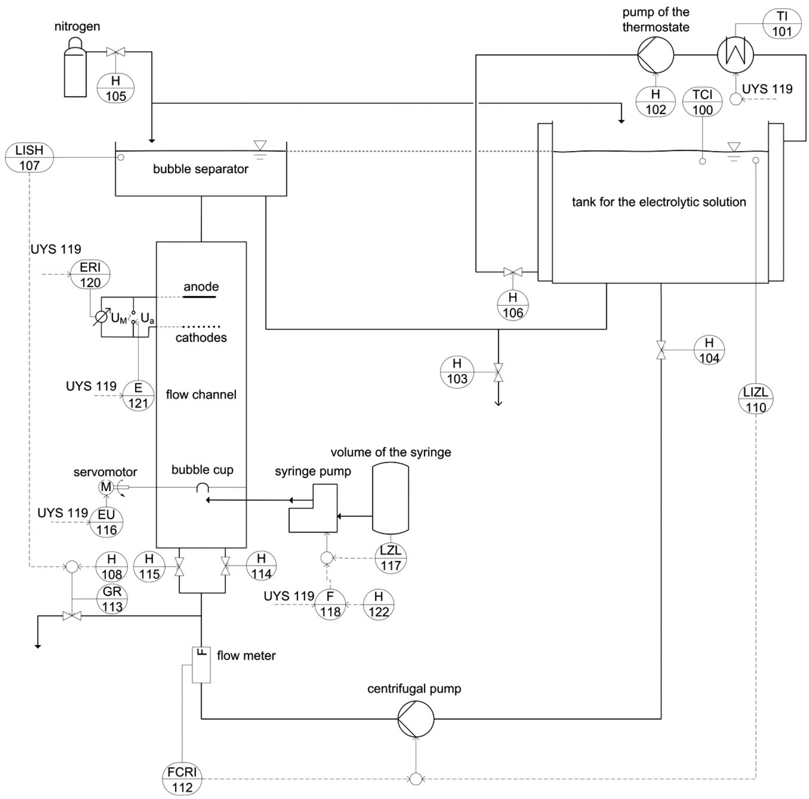

Fig. 1. Flow Sheet of the rig used for the EDM experiments

Rys. 1. Blokowy schemat działania urządzenia wykorzystywanego w eksperymentach EDM operated with a Harvard Apparatus Pump 11 Elite syringe pump which injects a specific volume of gas into a small cup which is fixed on a rotatable rod. This rotatable rod can be turned with a servo motor which again is located outside of the channel. Additionally inlets are located at the bottom of the channel through which liquid can be pumped with a defined volume flow. The system is automated with LabView so that the whole process of establishing a defined liquid volume flow, inserting a bubble, releasing a bubble and recording the measurement data works autonomic (Fig. 1). The automation is necessary to generate the amount of data necessary for the statistical analysis. Especially for the EDM approximately 1000 single bubble rises were recorded for each parameter combination to get statistically relevant results. For the PIV measurement not such a high number of single bubble rises are necessary but the automation allows a high-level repeatability which simplifies the analysis of the data. It is worth mentioning that the PIV experiments were done in new channels with fixed depths of 5 and 7 mm. These channels have a much better optical accessibility in comparison to the channels used for the EDM tests. Besides this the systems are basically the same.

2.2. Electrodiffusion Method

The EDM works with an electrochemical principle. For the EDM basically two electrodes and an electrolyte solution between these two are necessary. Usually a very small cathode (e.g. platinum or nickel) mounted flush on the wall where the measurements need to be taken and an anode (e.g. stainless steel) with a much larger surface is used. The anode or counter-electrode may be a specially added electrode or a (e.g. stainless steel) part of the experimental rig. Furthermore the electrolyte solution usually consists of water, two ions which differ only by its valence and inert ions. Applying a voltage between the cathode and the anode, a heterogeneous reaction takes place at the cathode and anode in which oxidizing ions take up an electron at the cathode. Transfer of the oxidizing ions to the cathode and the electron exchange leads to charge equalization between anode and cathode which induces a measurable current. The higher the mass transfers of the ions, the higher the measured value of the current. Therefore, since the rate of mass transfer of ions at the cathode is directly related to the hydrodynamic conditions at the proximity of the cathode in the system, the magnitude of current induced at the cathode can be used to measure shear stress. The well-known Leveque equation is used to correlate the measured current to the shear stress:

$$\tau = \mu \frac{I^3}{k_{Lev}^3} \tag{1}$$

To be precise, this correlation is only valid for steady flows and flows with slow fluctuations. E.g. Sobolik et al. [12] suggest a correction of the correlating function for transient flows but as there are several possibilities to correct the signal [13] of which none can claim to be completely correct the author decided for simplicity to just shows results calculated with the steady approach in this article.

As can be seen in equation (1) a calibration of the system is necessary to calculate the Leveque coefficient k_{Lev}. There are three ways to get the Leveque coefficient: a theoretical formula, a semi-empirical equation (both can be found in [2]) and a determination based on an experimental calibration. The first two are both rather unreliable as system parameters such as electrode size and ion concentration are part of the equations which can't be determined precisely. For the experimental calibration a known shear rate needs to be established at the electrodes which can be correlated to the measured current with the help of equation (1). As the Leveque coefficient changes over time due to e.g. temperature or ion concentration changes in the electrolyte solution, if possible this should be done consecutively. For the parameter combinations with liquid velocity this was included in the analysis of the data. For every single bubble rise event data was recorded when the bubble didn't influence the flow and the Leveque coefficient for every single run and every single electrode (there are 8 electrodes in the system arranged horizontally in the channel) was calculated and used for the analysis of the data that was influenced by the bubble. For the parameter combinations without liquid velocity this ongoing calibration was not possible. Therefore averaged values of experiments with liquid velocity were used as Leveque coefficients as the values were fairly constant over the duration of the parameter study.

For every single bubble rise event, a maximum shear stress value and the appearing shear stress in general was determined. For the analysis of the generally appearing shear stress a time of 0.5 s before the peak value and 1.5 s after the peak value were taken into account as this is the interval of the strongest influence of the bubble on the flow. From this data of approximately 1000 single runs per parameter combination the median value and standard deviation of the maximum value was determined. Based on the generally appearing shear stress data, cumulative probability functions are created.

2.3. Particle Image Velocimetry

PIV is a laser based measurement technique [14]. The system used for this study is a FlowMaster 2D-PIV system from LaVision. It consists of a pulsed Nd:YAG Laser with a maximum double pulse rate of 15 Hz. The images are recorded with a progressive-scan Imager Pro SX 5M CCD camera with a 12bit range and a resolution of 2456 pixel by 2058 pixel. LaVision's DaVis 8 is used for the data analysis. As the experiments are done with a multiphase flow, fluorescent particles and a cut-off filter for the lense are used to ensure that the CCD chip will not be destroyed by laser reflections from the bubble's surface. The data gained with this technique can be analyzed with respect to numerous turbulence criteria. In this study just the flow pattern i.e. the velocity field near the bubble is analyzed.

3. Results and Discussions

3.1. Results from the Electrodiffusion Method

Table 1 shows the maximum shear stress values that were measured when the single bubble passed by the sensors. Generally the trend is visible that with decreasing channel depth, increasing bubble size and increasing liquid velocity the maximum shear stress increases as well. The larger the bubble and the smaller the channel depth, the more the bubble is confined which results in thinner liquid films between the bubble and the wall and in larger areas with high shear stress values. From the data it can be seen that this trend is not as consistent for the parameter combination without liquid velocity in comparison to the ones with liquid velocity. Furthermore it also has to be stated that the standard deviations for the combinations without liquid velocity are in relative measures to the median value much higher than the standard deviations of the ones with liquid flow. Both facts are mostly due to the calibration problem mentioned above. The values are in the same order of magnitude but still slightly lower than the CFD values Prieske et al. [10] reported. This might also be due to shortcomings of the measurement technique. The local resolution of a CFD simulation cannot be reached with the EDM. Although 8 sensors are arranged in a horizontal line so that it is certain that bubble does not miss the array there is still the need of a certain distance between the sensors so that they do not affect each other. In this work the sensors have a distance of approximately 5mm. Tests are done with bubbles smaller than this distance which means that they can pass the sensor array between two sensors. Even if a bubble passes over one of the sensors the maximum shear stress value does not necessarily lie at the position of the bubble. Prieske et al. [10] showed that especially for the cases without additional liquid velocities the maximum shear stress occurs only on a very small area in the liquid film between the bubble and the wall. With liquid velocity the area of the maximum value is in the wake of the bubble and this area is by a few orders of magnitude larger in comparison to the cases without additional liquid velocity.

Table 1

Median values of the maximum shear stress (in [10^{-3}Pa]) with standard deviations

Channel depth [mm]		3		5		7	
Liquid velocity [cm/s]		0	20	0	20	0	20
Bubble size [mm]	0	--		--	243±10	--	175±13
	3	157±157	579±86	69±158	466±205	62±156	390±244
	5	224±370	867±151	157±103	689±216	212±187	463±141
	7	788±216	820±135	870±322	965±166	113±62	828±139
	9	--	--	521±136	1350±227	1501±541	990±137

'--' means that either the shear stress is 0 or the bubble is not stable and breaks

With at least 1000 test runs for one parameter combination it is sure that there will be runs for which the 'real' maximum shear stress can be measured by the sensors but in general it is more likely that the sensors will measure values which are lower as the peak value area does not hit the sensor completely.

Besides the maximum shear stress the fluctuation of the values is of special interest. Gaucher et al. [11] reported that fluctuating shear stress has a positive effect on the cleaning process. Fig. 2 shows the cumulative probability function of the generally appearing shear stresses for 5mm channel depth, 20 cm/s superimposed liquid velocity and different bubble sizes. It can be seen that all the curves arrange around a value of 0.25 Pa which is the value generated by the single phase liquid flow (see also Table 1). Taking into account the weak

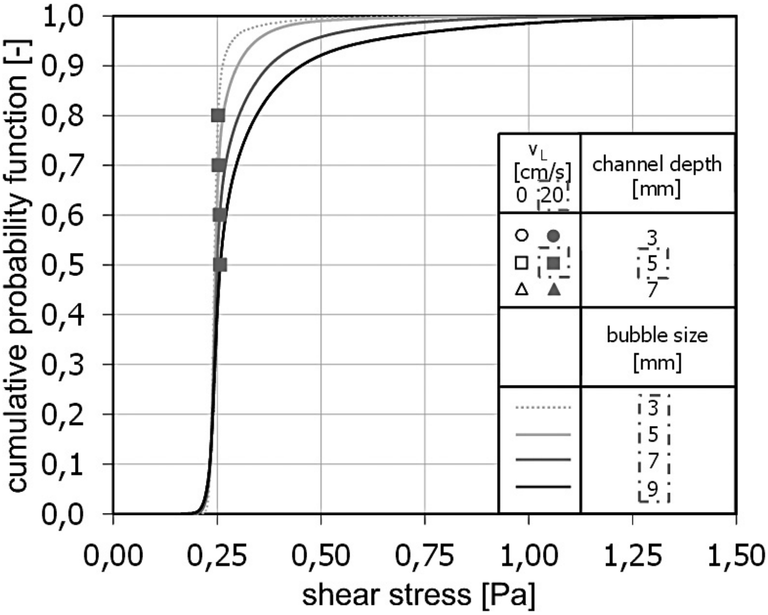

Fig. 2. Cumulative probability function of the generally appearing shear stress

Rys. 2. Skumulowana funkcja prawdopodobieństwa przy standardowym naprężeniu stycznym

fluctuation of 0.01 Pa for single phase flows, basically all shear stress values outside of the range of 0.25±0.01 Pa are due to the flows generated by the bubble. As expected, the diagram illustrates that with increasing bubble size the shear stress range increases. Taking 10% and 90% as the probability limits, the range increases from 0.23–0.26 Pa for a 3 mm bubble to 0.23–0.30 Pa for a 5mm bubble to 0.23–0.38 Pa for a 7 mm bubble and 0.23–0.45 Pa for a 9 mm bubble. As mentioned before, this can be explained by the simple fact that the larger the bubble, the larger the area that is affected by its generated pseudo-turbulence.

3.2. Results from Particle Image Velocimetry

Figure 3 shows the flow pattern of 5 mm bubble in a channel with 5 mm depth and no liquid velocity generated with CFD [10] and the flow pattern of 7 mm bubble in a channel with 5 mm depth and no liquid velocity produced with PIV. Both images have the same size relative to the bubble diameter. In both cases a serpentine around the vertical centerline of upwards flowing liquid with comparable velocities is visible. Prieske et al. [10] showed that the bubble rises with a periodic oscillation. The two flow patterns shown in Fig. 3 are not from the same moment in this rising period as for the PIV image three eddies are visible already. Nevertheless the images are comparable as the eddies that are visible in both images are almost at the same position relative to the bubble and have the same rotary direction. These images show the potential of the Chair's PIV system to – on the one hand side – be used to investigate turbulence indicators often analyzed in literature and – on the other hand – validate CFD data which offers a much higher local resolution and a wider range of analysis possibilities.

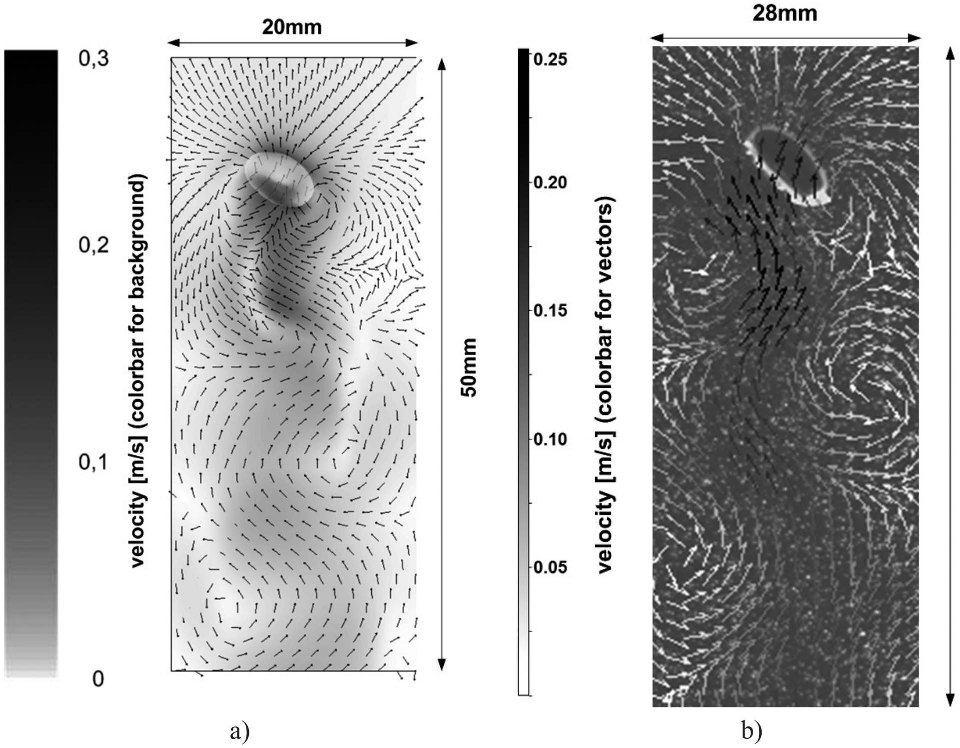

Fig. 3. Flow pattern in the wake of a bubble:
a) generated with CFD [10],
b) with PIV

Rys. 3. Blokowy schemat działania wskutek powstania pęcherzyka:
a) CFD [10],
b) PIV

4. Conclusions

The presented work shows the results of fundamental fluid dynamical investigations of the rise of single bubbles in a rectangular channel with a channel depth in the range of the equivalent bubble diameter. Potentials and shortcomings of the EDM are discussed. The shear stress is analyzed regarding its maximum value and its fluctuation range which are both crucial factors influencing e.g. the cleaning process of membranes in MBRs. As expected the maximum shear stress increases with decreasing channel depth, increasing bubble size and increasing liquid velocity.

Additionally fundamental investigations of the bubble rise behavior were performed with PIV. The flow pattern presented here shows its potential for using these results to validate CFD data generated at the Chair. From the PIV results itself, but even more from the CFD results, detailed information about the bubble rise behavior can be found. These information can be used to get a deeper insight into the fundamental topic of the rise of single bubbles in confined environments.

Symbols

I	–	current [A]
k_{Lev}	–	Leveque coefficient [$s^{-1}A^{-3}$]
μ	–	dynamic viscosity [Pa s]
τ	–	shear stress [Pa]

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