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Fluid Dynamic Optimization of Flat Sheet Membrane Modules – Movement of Bubbles in Vertical Channels

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Fouling is one of the key challenges in the operation of membrane bioreactors. Aeration is a simple but cost-intensive measure to clean the membranes. The aim of this project is to deepen the understanding of the behavior of the bubbles in such geometries to be able to optimize the cleaning of membrane systems and make them more cost-effective. Therefore, with respect to flat sheet membrane modules, the rise of a single bubble in a rectangular channel was investigated experimentally and numerically. The experimental part was performed with a high speed camera and the images were analyzed with the help of NI LabView, Vision Development Module and MS Excel. The software was used to determine the centre of mass of the bubble on each image which provides the rising path when combined. This rising path is determined for different parameter combinations varied bubble sizes and superimposed liquid velocities. The same parameter combinations were investigated numerically with the help of Ansys Fluent. Based on the rising paths, a comparison of the simulation and experiments is possible. Specifically the terminal rise velocity, the oscillation frequency and the amplitude are used for comparison.

1. Introduction

Aeration 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 used in membrane bioreactors (MBR) to clean the surfaces from deposition layers (Böhm et al., 2012). Especially in MBRs flat sheet membranes are often 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 on the membrane surfaces. The space between the cushions has a rectangular shape and is aerated to generate flows for mixing purposes and the generation of 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 cross flows. This makes the system with its multiphase flow in multiple rectangular channels fairly complex.

In this project single bubbles and bubble swarms are investigated experimentally in a single gap with the electrodiffusion method for the determination of shear stresses, with particle image velocimetry for the determination of the flow surrounding the bubble and with a high speed camera for the determination of the bubble movement. Additionally the system is investigated numerically with computational fluid dynamics (CFD). The rather academic single bubble approach is chosen 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 behaviour of the entire bubble swarm. Starting from the 'simplified' system with single bubbles the complexity can be increased and a deeper understanding of more complex systems can be gained.

This article focusses on the investigation of single bubbles with a high speed camera and CFD. The unique feature of this project is the investigation of single bubbles rising in rectangular channels which

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have dimensions comparable to the dimensions found in real flat sheet membrane modules. At the same time, the equivalent diameters of bubbles are in the same range as the gap distance of the rectangular channel.
In literature, investigations of the motion of bubbles in multiple geometries and under multiple operating conditions can be found. Clift et al. (1978) give a general overview over the behaviour of solid and fluid particles. Especially the behaviour of free rising bubbles is described in detail. Wall effects are discussed as well but not for rectangular cross-sections. Several authors discussed the rise of bubbles with the help of high speed cameras in other geometries (e.g. annuli Li et al., 2008), square channels (e.g. de Vries et al., 2002) and rectangular channels with small bubbles or Taylor bubbles (e.g. Bhusan et al., 2009). Only (Essemiani et al., 2001) worked on a rectangular channel with single bubbles in the size range of the gap distance but the experimental apparatus was too small for the bubble to reach a steady state and no parameters were varied. In general, terminal rise velocities, rising paths, oscillation frequencies and oscillation amplitudes are commonly analysed.

2. Materials and Methods

2.1 Experiments

The three parameters gap distance (5-7 mm, in this article only results for 5 mm are shown), air bubble size (expressed as the equivalent spherical diameter, 3 and 5 mm) and superimposed liquid (i.e. water) velocity (0 - 0.2 m/s) based on typical values in MBRs (Prieske et al., 2010) were chosen to be varied in this investigation. A detailed description of the apparatus can be found in Böhm et al. (2013). As the centre piece of the apparatus two channels were used that each have fixed gap distances of 5 and 7 mm respectively, a width of 160 mm and a height of 1,500 mm (Figure 1a). The field of view (Figure 1b) is at a height of approximately 1,000 mm to ensure that the flow is fully developed and the bubble behavior is in a steady state. The material and construction of the channels are optimized for optical accessibility of the field of view. The superimposed liquid velocity is varied as MBR systems are often constructed as air lift loop reactors.

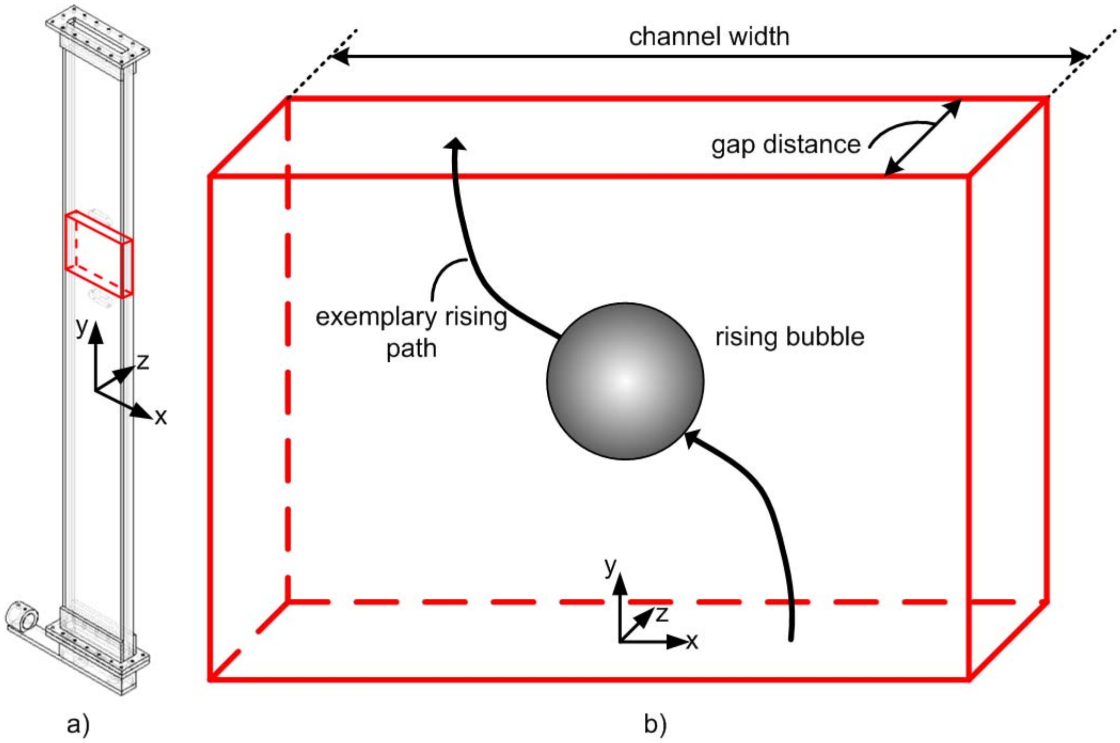

Figure 1: Schematic drawing of a) the rectangular test channel and b) the field of view

For the experiments reported here, approximately 1 s rising time of 50 single bubble rises were recorded for each parameter combination to get statistically significant results. For the high speed image acquisition a Photonfocus MV-D752-160 with diffuse backlight illumination is used at a frame rate of 200 Hz (x-y-plane) or 100 Hz (y-z-plane), respectively. National Instruments Vision Development Module and LabView were used for the post-processing of the data and the automated analysis of the images in combination with Microsoft Excel.

2.2 Simulations

The same parameters (gap distance, bubble size and superimposed liquid velocity) as in the experiments are varied in the simulations as well. A detailed description of the simulations can be found in Prieske et al. (2010). In comparison to earlier simulations, the model was improved by simulating the full channel instead of only half of the channel depth. This is expected to improve especially the simulations with bubble sizes smaller than the gap distance as the bubble is able to oscillate normal to the long edge as well.

3. Results and Discussions

3.1 Experiments

For each recorded image, the position of the centre of mass of the bubble is determined. Recordings are performed with the camera normal to the long edge of the channel (x-y-plane) and normal to the short edge (y-z-plane) (see also coordinate system in Figure 1). From this data, the rising path of the bubble can be assembled. Figure 2 shows the terminal rise velocities (as commonly used in literature this is the velocity in y-direction) that can be determined from a sufficient number of bubble rises. Values for free rising bubbles in pure and contaminated systems from Clift et al. (1978) and values determined experimentally and numerically by the authors are shown. The experimentally determined values have a standard deviation of 1 % in average. All values except of the numerical result for the 7 mm bubble are close to the terminal rise velocities of free rising bubbles in a contaminated system. The deformation of the bubble and the increased friction due to the confinement leads to a slow-down of the bubble in comparison to the unconfined system. Between the experiment and the simulation a difference of 4 %, 6 % and 16 % for the 3 mm, 5 mm and 7 mm bubble, respectively, is found.

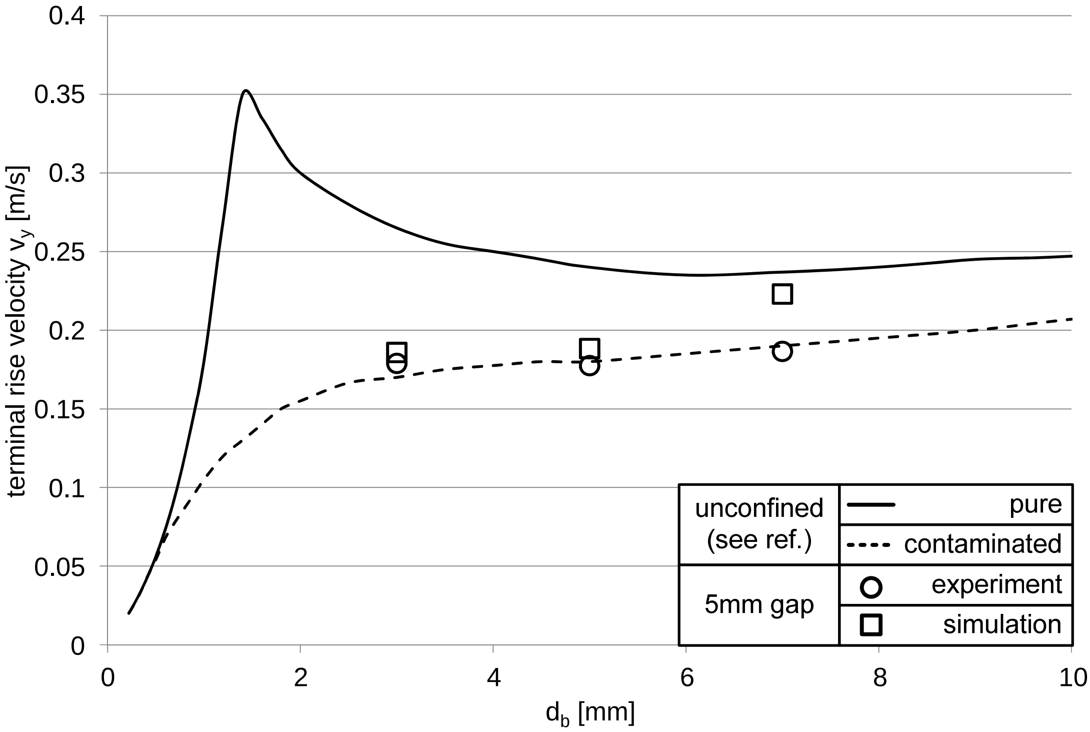

Figure 2: Experimentally and numerically determined terminal rise velocities v_y for different bubble sizes in a 5 mm gap without superimposed liquid velocity in comparison to terminal rise velocities of bubbles in an unconfined pure and contaminated system (*Clift etal., 1978*)

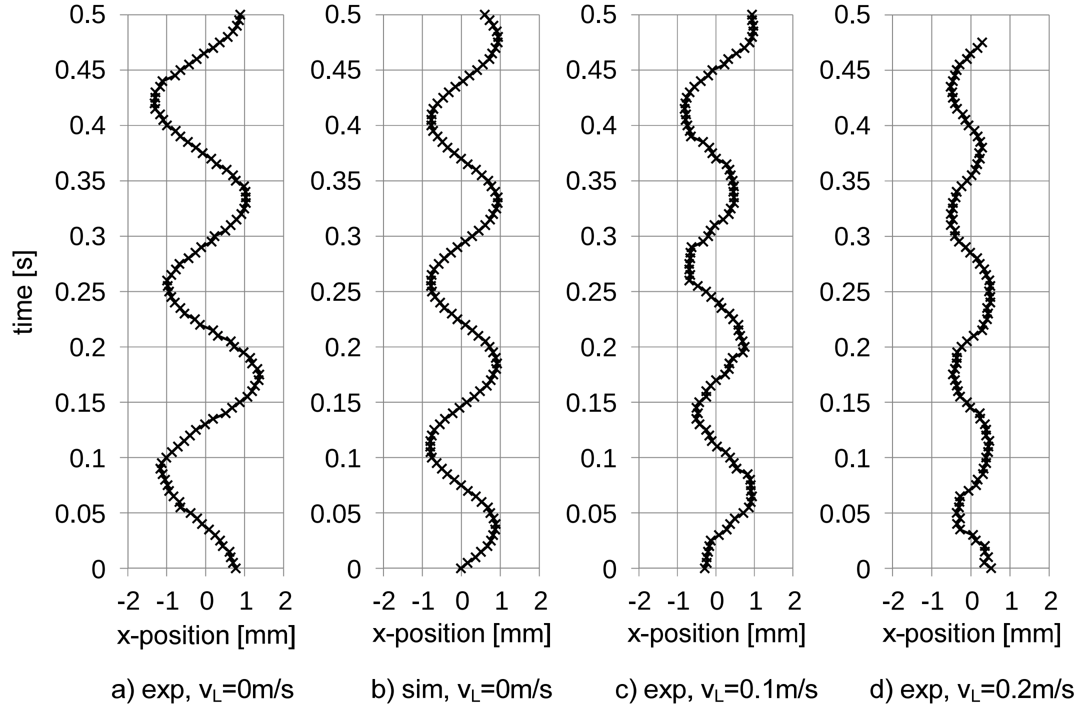

Figure 3: Experimentally (exp) and numerically (sim) determined rising paths of a 5 mm bubble in a channel with a 5 mm gap distance a) and b) without and c) with a superimposed liquid velocity of 0.1 m/s and d) 0.2 m/s with the view normal to the long edge

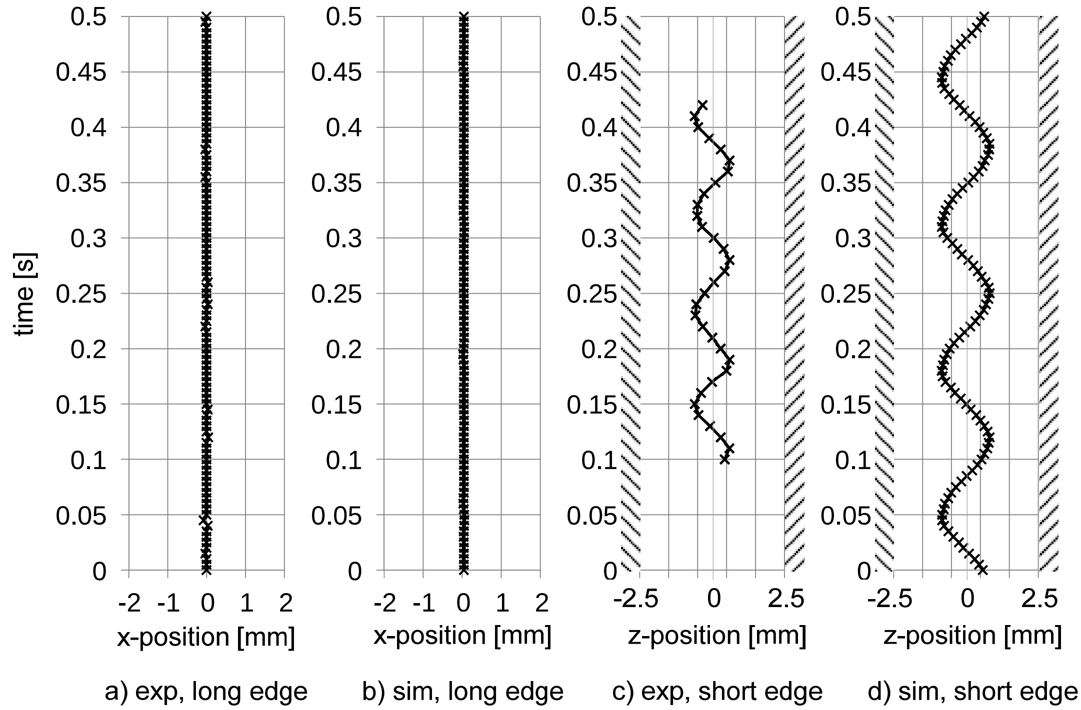

Figure 4: Experimentally determined rising paths of a 3 mm bubble in a channel with a 5 mm gap distance without superimposed liquid velocity determined a) experimentally and b) numerically with the view normal to the long edge of the channel and c) experimentally and d) numerically with the view normal to the short edge of the channel

Figure 3a, c and d show the experimental results of the rising paths of a 5 mm bubble in a channel with a 5 mm gap distance for different superimposed liquid velocities v_L. In all cases, an oscillating movement of the bubble is found which is known from free rising bubbles which typically rise on a zigzagging or spiralling path (e.g. de Vries et al., 2002). This movement is beneficial for the cleaning process of the membranes as a larger area is affected by the bubble and the retention time of the bubble in the module increases. With increasing liquid velocity, this oscillation is damped where, from v_L=0 m/s to v_L=0.1 m/s, only a slight decline of the oscillation amplitude is visible. Both are in the range of 0.8-1 mm. The decline is more emphasized for a liquid velocity of v_L=0.2 m/s where the amplitude decreases to appr. 0.5 mm. Regarding the oscillation frequency, for the three given examples, the frequency increases from 6.2 Hz to 8.2 Hz and 8.8 Hz for superimposed liquid velocities of 0 m/s, 0.1 m/s and 0.2 m/s, respectively. For 5 mm bubbles rising in unconfined systems without superimposed liquid velocity, from Miyahara and Yamanaka (1993) an oscillation frequency of 6.2 Hz is known.

The y-z-plane is of special interest for cases with the bubble size smaller than the gap distance. Figure 4a and c show the experimental results of the movement of a 3 mm bubble in a channel with a gap distance of 5 mm in the x-y- and y-z-plane. In comparison to Figure 3 it is evident in Figure 4a, that no oscillation in the x-y-plane is apparent. Besides the non-existing oscillating movement, this also shows the stability of the shape of the bubble. A change of the shape of the bubble would lead to a change of the position of the centre of mass. In Figure 4c the movement of the bubble in the y-z-plane is shown. It is worth mentioning here that as there was only one camera in use the two planes x-y and y-z were investigated after each other and with different recording frequencies which explains the differences of the positions of the centre of mass on the time axis. A clear oscillation normal to the long edge is apparent. In contrast to the 5 mm bubble where the oscillation appears together with a shape deformation, in case of the 3 mm bubble this oscillation is mostly due to wall effects. For the given case, the amplitude is appr. 0.6 mm and the oscillation frequency is 16.7 Hz. Miyahara and Yamanaka (1993) give a value of 5.3 Hz for free rising bubbles. Further investigations need to be performed to confirm this frequency increase for the confined system. With respect to the amplitude, assuming a perfectly spherical shape of the bubble, at the inflexion point of the oscillation a liquid film thickness between the bubble and the wall of 0.4 mm is apparent in the channel with a gap distance of 5 mm. This is again of special interest for the cleaning process of the membrane surface, as small liquid films will presumably lead to high shear stress values and will counteract the fouling.

It is worth mentioning that for bubble sizes equal or larger than the gap distance an oscillation of the centre of mass of the bubble is visible as well but this is mainly due to changes in the bubble shape and not to an emphasized oscillating rising path.

3.2 Simulations

Figure 3b, 4b and 4d show the numerical results of the rising paths of bubbles under different conditions in a channel with a gap distance of 5 mm. Figure 3b shows the path of a 5 mm bubble in the x-y-plane without superimposed liquid velocity. These are the same conditions as discussed in Figure 3a for the experimental work. The oscillation has an amplitude of appr. 0.85 mm and a frequency of 6.8 Hz. Both values fit the experiments very well.

Figure 4b and d show the rising path of a 3mm bubble in the x-y- and y-z-plane. These are the same conditions as described in Figure 4a and c, respectively. As can be found in the experiments (Figure 4a), no oscillating movement of the bubble is apparent parallel to the long edges of the channel. An oscillation normal to the long edges of the rectangular channel is observable in the simulation as well (compare with Figure 4c). With 0.8 mm the amplitude of the oscillation is slightly larger than in the experiments while, with 7.5 Hz, the frequency is less than half of the one found in the experiments. The value of 7.5 Hz is in the same range as the oscillation frequencies found experimentally for the oscillation of larger bubbles in the x-y-plane and therefore seems to be reasonable but the experiments proof different for the 3 mm bubble. A further investigation of the reasons for this difference is necessary. As usual in CFD, an increase of the number of cells might increase the quality of the results up to a certain point as well but, on the downside, the time or cost, respectively, for the calculation increases too.

4. Conclusions

The rise of a single bubble in a rectangular channel was investigated experimentally and numerically. The experimental part was performed with a high speed camera and the images were analyzed with the help of NI LabView, Vision Development Module and MS Excel. The software was used to determine the centre of mass of the bubble on each image which provides the rising path when combined. This rising path is determined for different parameter combinations of one gap distance and varied bubble sizes and superimposed liquid velocities. The same parameter combinations were investigated numerically with the help of Ansys Fluent. Based on the rising paths, a comparison of the simulations and experiments was possible. Specifically the terminal rise velocities, oscillation frequency and amplitude are used for comparison. Especially for the 3 mm and 5 mm bubble the terminal rise velocity agree very well. Both frequency and amplitude of a 5 mm bubble agree very well for the oscillation parallel to the long edges of the rectangular channel with 5 mm spacing. For the 3 mm bubble, in both cases no oscillation parallel to the long edge is found but only an oscillation normal to the long edge. This is possible as the bubble is smaller than the gap distance. Still for this parameter combination, the amplitude in the simulation is 30 % larger and the frequency is more than 50 % smaller in comparison to the experiments which needs further investigation.

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