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Advantageous and detrimental effects of air sparging in membrane filtration: Bubble movement, exerted shear and particle classification☆

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ABSTRACT

In various membrane applications air scour is applied to minimise fouling and to remove cake layers. Optimisation of module design and operating conditions (e.g., geometry and aeration intensity) requires knowledge of the most suited hydrodynamic conditions for the filtration task. However, many fundamentals of this multiphase flow in membrane modules are still unknown and difficult to access experimentally. Using experimental and numerical investigations it was shown that air sparging can have advantageous but also detrimental effects: depending on membrane plate spacing, wall shear can decrease with bubble size. Additionally, particle classification or segregation which increases the cake's hydraulic resistance must be taken into account. Based on such findings, it will be possible to derive optimum bubble sizes, membrane spacing, aeration intensities and start-up strategies.

1. Introduction and aim

In various membrane applications for either production processes or wastewater treatment, continuous or intermittent air scour is applied to minimise fouling and to remove cake layers during air flush cleanings. Optimisation of module design and operating conditions (e.g., tubular diameter or distance between flat sheet membranes, crossflow velocity, aeration intensity, etc.) requires knowledge of the most suited hydrodynamic conditions for the filtration task. However, many fundamentals of this multiphase flow in membrane modules are still unknown and difficult to access experimentally.

1.1. Gas/liquid flow

A number of studies on the influence of bubble movement have been carried out for hollow fibre membranes (e.g., [1]). Fundamental investigations on bubble motion in unconfined environments [2], or of slugs within tubes [3] have also been carried out decades ago, but much less work has been published on bubbly flow between flat plates and the resulting shear stress on the membrane surface (see Table 1).

In a rather widely spaced channel, Nagaoka et al. [4] found that 50% of the total shear stress could be attributed to the pure water flow while 50% were due to bubble wall interactions. In a 5 mm gap, 15.9 mm bubbles were found to rise at 18 to 38 m/s [7]. This wide range might be caused by the low height of the set-up which did not enable the terminal rise velocity to be reached. Ducom et al. [5,6] found that permeate flux increased with averaged shear stress. This increase due to aeration was max. 70%.

In membrane filtration, bubbles typically do not move in stagnant but in flowing liquids. E.g., in submerged membrane bioreactors (MBR), bubbles cause the liquid to rise at velocities depending on the tank and module geometry as well as on the superficial gas velocity. Hence, the surrogate effect of the contributions of both phases is important to know.

1.2. Solid/liquid flow

Mainly three hydrodynamic forces are acting on particles in crossflow filtration: the drag forces incurred by the crossflow velocity (CF) and by the permeate flux (PF) and the lift force caused by the velocity gradient near the wall. The latter two counteract: If $F_{drag,PF} > F_{lift}$, a particle deposits on the membrane, if $F_{drag,PF} < F_{lift}$, it does not. The forces can be calculated as follows [9]:

$$F_{drag,CF} = 6.325 \cdot \pi \cdot \mu \cdot d_P \cdot v_{d_P/2} \quad (1)$$

Stokes: (2)

$$F_{drag,PF} = 3 \cdot \pi \cdot \mu \cdot d_P \cdot J$$

$$F_{lift} = 0.761 \cdot \frac{\tau_W^{1.5} \cdot d_P^3 \cdot \rho^{0.5}}{\mu} \quad (3)$$

By formation of differently structured deposition layers, particle classification is thought to have a great influence on permeability.

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Table 1
Summary of studies on bubbles between flat sheet membranes.

Ref.	Add. liq. crossflow	Height [mm]	Spacing [mm]	Method	System	Parameter
[4]	Yes	1000	32	Exp.	Air/water	Shear
[5,6]	Yes	147	5	Exp.	Air/water	Shear, flux
[7]	No	147	5	Exp./num.(2D)	Air/water	Velocity
[8]	No	490	7–14	Exp./num.(3D)	Air/water	Bubble size, shear stress

Corresponding observations were made in the filtration of yeast cells [10], milk [11] and fouling by humic acid [12].

1.3. Aim

Thus, the aim of this study is the fundamental investigation of bubble movement in flat sheet modules of technical size and spacing, the corresponding wall shear stresses and the effect of air and liquid velocity on mixed liquor particle deposition and classification. Using experimental and numerical methods, the optimum bubble size and air flow rate for fouling control in relation to the respective plate distance shall be determined.

2. Materials and methods

2.1. Experimental

The movement of differently sized air bubbles (equivalent spherical diameter = 3–24 mm) rising in stagnant water between differently spaced flat plates (gap width: 3–11 mm, height: 700 mm, see Fig. 1) was recorded using a highspeed camera (MV-D752, Photonfocus AG). From this, the terminal bubble rise velocity was determined which together with the observed bubble shape serves as a validation for the numerical investigations. A stop watch was used to measure terminal rise velocities in MBR mixed liquor because of to its opaqueness. At least 15 bubbles were recorded for each size/spacing combination and the standard deviation was found to be less than 5%.

To assess the influence of gas and liquid superficial velocities on particle classification, flux stepping experiments were carried out in a crossflow filtration cell (eff. membrane area: 0.0088 m^2, PVDF, pore size: 0.2 µm, 5 mm channel). The test cell runs were performed at constant flux (see Fig. 1) which was increased in a stepwise manner every 15 min. Filtration trials were carried out with fresh mixed liquor (TS = 8–10 g/L) from a pilot scale MBR fed with municipal wastewater, and a virgin membrane was used for each run.

2.2. Numerical

To determine the flow field around single bubbles rising between plates and especially the wall shear stresses on the membrane surface, 3D CFD simulations (Fluent) in combination with the volume of fluid (VOF) method (water/air, constant surface tension, time step 10^{-6}–10^{-4} s) were carried out.

To calcultae the hydrodynamic forces acting on particles in sludge, the velocity profile between membrane plates were carried out using CFX11. Rheological properties of typical MBR mixed liquor were used (power-law-fluid, $k = 0.081$ Pa $s^{0.42}$, $n = 0.42$). Based on these results, the hydrodynamic forces acting on single particles in the range of 0.1 to 20 µm were calculated.

3. Results

3.1. Single bubble experiments

Fig. 2 shows experimental results on the movement of single bubbles between differently spaced membrane plates while Fig. 3 shows the respective exerted wall shear determined numerically. Both need to be known in order to optimize bubble size and wall distance for fouling control and efficient cleaning procedures. Small bubbles move as predicted by the correlations for unconfined environments [2]. Above a certain diameter, however, which is smaller for narrow channels, bubbles slow down as the deceleration effect caused by the walls becomes significant. With further increased size, the presence of the walls drastically changes the bubble shape: they become flat cap bubbles (see Fig. 4). Due to the thus decreased projected area, bubbles larger than 10 mm overcome the deceleration effect and achieve rise velocities between plates that are even higher than in unconfined environments. Although, surprisingly, this acceleration is independent of channel width, the plate distance influences the maximum possible stable bubble size. Due to the increased rigidity of their surfaces, bubbles move approx. 15–20% slower in mixed liquor, but the same trend is observed.

Numerical results were validated by comparing values with experimental rise velocities (data not shown) and observed bubble shapes (see Fig. 4). A reasonably good agreement was achieved which means that calculated shear stresses can be trusted. Recent studies applying an improved numerical procedure (publication currently in preparation) have shown that shear stresses shown here are somewhat overestimated, but the order of magnitude and trends are similar. As expected, highest shear is reached in 3 mm channels which, however, would become clogged too easily in high solids/viscosity systems. Hence, 5 mm channels can be taken to be appropriate, and 5 mm bubbles in 5 mm channels appear to be

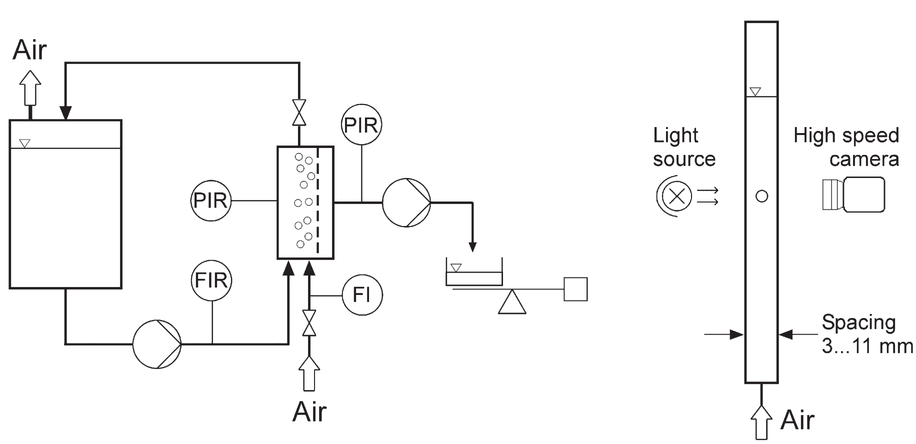

Fig. 1. Experimental set-ups: crossflow test cell (left), bubble rise channel (right).