The importance of fluid dynamics for MBR fouling mitigation

Lutz Böhm[a], Anja Drews[b], Helmut Prieske[a], Pierre R. Bérubé[c], Matthias Kraume[a]

[a] Technische Universität Berlin, Chair of Chemical and Process Engineering, Straße des 17. Juni 135, Sekr. MA 5-7, 10623 Berlin, Germany, +49-30-31423701, lutz.boehm@tu-berlin.de, helmut.prieske@tu-berlin.de, matthias.kraume@tu-berlin.de

[b] HTW University of Applied Science Berlin, Engineering II, School of Life Sci. Eng., Wilhelminenhofstr. 75A, 12459 Berlin, Germany, +49-30-50193309, anja.drews@htw-berlin.de

[c] The University of British Columbia, Department of Civil Engineering, 6250 Applied Sci. Ln., Vancouver BC, V6T1Z4, Canada, +1-604-8225665, berube@civil.ubc.ca

Abstract

The importance of the multiphase fluid dynamics for fouling mitigation in MBR systems has been widely acknowledged with air sparging having been applied commercially for about 20 years. However, the effects of air scouring are still not fully understood since the transient orthogonal and parallel flows as well as turbulent eddies created by bubbling generate complex hydrodynamic flow fields in the vicinity of a membrane. There is no generally valid model that describes the relationship between fouling rate and fluid dynamics. So, a reliable and universally applicable model to optimize membrane module and tank geometries, air scouring and filtration cycles is still pending.

In addition to providing a discussion on the importance of multiphase fluid dynamics for fouling control, this review aims at developing guidelines to choose appropriate experimental and numerical methods for fluid dynamics investigations in MBR systems.

Keywords: fouling; air scour; hydrodynamic optimisation; MBR design; shear stress

1 Introduction

The main drawback of MBR[1] systems in comparison to the conventional activated sludge (CAS) processes remains the high operating cost of MBRs. This is mainly because up to 70 % of the total energy demand for MBR systems is for fouling mitigation by air scouring (Fletcher et al. 2007, Judd 2006, Verrecht et al. 2008). Operating data from full-scale systems suggest that the energy used for fouling mitigation is only optimally used 10 % of the time (Drews 2010), and therefore, there are significant opportunities to reduce total energy demand for MBR systems.

Fouling is caused by the deposition of particulate, colloidal or soluble material inside the pores or on the membrane surface. The layers which deposit on the surface can be removed by hydrodynamic forces. These forces, however, do not only affect the deposition layer but might also be responsible for negative effects like SMP release and decrease in floc sizes.

Due to the high costs associated with fouling, a substantial number of studies have focused on the cause and control of fouling in MBRs over the past decade. Approximately 30 % of all published literature from studies dealing with MBRs focus on fouling. Of this fraction, only 8 % contain keywords such as “hydrodynamics” or “fluid dynamics”. The importance of the multiphase fluid dynamics for fouling control has been widely acknowledged with air scour having been applied commercially to generate favourable hydrodynamic conditions for about 20 years. However, the effects of air scouring are still not fully understood since the transient orthogonal and parallel flows as well as turbulent eddies created by bubbling generate complex hydrodynamic flow fields in the vicinity of a membrane. There is currently no generally valid model that describes the relationship between fouling rate and fluid dynamics.

---

[1] Abbreviations: ADV: acoustic Doppler velocimetry, BOP: bi-optical probe, CAS: conventional activated sludge process, CFD: computational fluid dynamics, DO: direct observation (incl. high speed camera and image processing), EDM: electrodiffusion method, EPS: extracellular polymeric substances , EVM: electromagnetic velocity meter, FS: flat sheet, HF: hollow fibre, HWA: hot wire anemometry, MBR: membrane bioreactor, IA: impeller anemometer, MF: micro filtratration, NMR: nuclear magnetic resonance imaging, OP: orifice plate, PIV: particle image velocimetry, PP: polypropylene, RNG: renormalization group, SAD: specific aeration demand, SMP: soluble microbial products, SSS: shearing strain sensor, UF: ultrafiltration, VOF: volume of fluid

So, a reliable and universally applicable model to optimize membrane module and tank geometries, air sparging and filtration cycles is still pending. As a result, the operation of MBRs currently relies only on manufacturers' recommendations and operators' experience.

In addition to providing a discussion on the importance of multiphase fluid dynamics for fouling control, this review aims at developing guidelines to choose appropriate experimental and numerical methods for fluid dynamics investigations in MBR systems.

2 Fundamentals of multiphase flow and fouling mitigation

Air scouring is used to induce favourable hydrodynamic flow fields in the vicinity of a membrane surface to promote fouling control. These flow fields are induced by the complex interactions between orthogonal as well as crossflows and turbulent eddies created by the rising bubbles.

2.1 Influence of flux (orthogonal flow)

For most submerged membrane systems, for which the permeate flux is typically in the order of 20 to 50 L/($m^2 \cdot h$) for wastewater and drinking water applications, respectively, and the bulk liquid velocity at the membrane surface is typically greater than 0.1 m/s (i.e. resulting in a suction rate, defined as the ratio of uniform suction velocity to bulk inlet velocity, of less than 0.01 %), the effect of permeation on the hydrodynamic conditions at the membrane surface is expected to be minimal (Sofialidis and Primos 1997). In contrast, Gaucher et al. (2002a) reported that the influence of the flux on the shear stress cannot be neglected. However, the electrochemical measurement approach they used to estimate shear stress at the membrane assumes that the convective flux towards the membrane is negligible, and therefore their estimated shear stress may not accurately reflect the true conditions at the membrane surface.

Kimura et al. (2008) observed a difference in the composition of the deposition layer accumulating on hollow fiber membranes immersed in a pilot-scale MBR depending on the imposed flux. Regarding particles, this can be explained by a momentum balance as discussed in Section 2.3. Metzger et al. (2007) and Wu et al. (2008) compared the effect of different filtration modes (with or without backwash or relaxation, constant flux or higher instantaneous flux) with the same net flux or permeate productivity on fouling and deposit structure. They found that the extent of fouling depends on the applied instantaneous flux (investigated range: 20 – 40 $L/(m^2 \cdot h)$) rather than on the filtration modes themselves. Cyclic filtration with backflush or relaxation periods are commonly used strategies for fouling mitigation. Every time the filtration is restarted, a new deposition layer is formed whose structure depends on hydrodynamic conditions near the membrane (Wu et al. 2008).

2.2 Influence of the multiphase crossflow (parallel/turbulent flow)

Gas/liquid two-phase crossflow has been demonstrated to significantly enhance the performance of various membrane processes and has been applied extensively since the 1990s for fouling control (Cui et al. 2003). Yet, many fundamentals of this multiphase flow in MBRs are still unknown and difficult to observe experimentally. Therefore, applied aeration rates are normally based on empirical operating experience. Aeration demand is often given in terms of relative values: air flow rate per membrane surface area (SAD_m in $m^3/(m^2h)$) or, economically important, air flow rate per permeate flow produced (SAD_p in m^3/m^3). In full-scale MBRs, SAD_m values range from 0.18 to 1.28 $Nm^3/(m^2 \cdot h)$ and SAD_p from 10 to 65 (Judd 2006). However, to characterise the effects of hydrodynamics induced by the air scouring in fouling control, more absolute values, such as superficial air velocity (air flow rate per channel cross-section area) have been reported to be more appropriate (Drews 2010).

The sparging intensity (i.e. gas flow rate) can significantly affect fouling control in submerged membrane systems. Increasing the sparging intensity results in better fouling control, however, a plateau is typically reported above which further increasing the sparging intensity does not further improve the extent of fouling control (Bérubé and Lei 2006, Chang and Fane 2001, Ueda et al. 1997). Besides aeration rate, diffuser port size and the correlating bubble size, module and tank geometry (membrane spacing, fiber slackness, liquid level, cross-sectional areas of riser and downcomer, etc.) have decisive effects on the achieved crossflow velocity (see Section 5), shear stress and bubble-membrane-contact. A systematic hydrodynamic investigation will thus need to take into account several fundamentals of this gas/liquid flow, starting from single bubble movement in submerged modules to bubble swarms and finally to gas/liquid motion in the whole membrane tank.

2.3 Influence of fluid dynamics on particle behaviour

The loss of membrane performance within the first seconds or minutes of MBR operation is dominated by the build-up of a cake layer, consisting of solid particles and colloids. Hydrodynamic conditions have a strong impact on the thickness and structure of this deposit.

Belfort et al. (1994) provides an extensive review on particle backtransport mechanisms and models, including concentration polarisation, shear-induced diffusion and the inertial lift model. They showed that for particle sizes larger than 1 µm the back-transport is dominated by hydrodynamic forces and depends on the shear rate and the particle size. For particles smaller than 0.1 µm, molecular diffusion is the dominant mechanism for transport away from the membrane surface. Tardieu et al. (1999) applied these models to compare fouling rates at different crossflow velocities and filtration fluxes in MBRs for wastewater treatment with tubular membranes. In simulations and experiments, an improved particle back-transport and reduced fouling was achieved by increasing crossflow velocity.

With a focus on tubular MBR and submicron particles, Jiang et al. (2007) developed a model to predict the effect of particle size, dry solids content, crossflow velocity and geometrical parameters on particle transport. It was concluded that submicron particles were highly likely to deposit, and the worst fouling conditions were for particle radii around 0.1 µm and crossflow velocities below 0.5 m/s. Simply increasing the crossflow velocity did not completely prevent colloidal particle deposition.

Altmann et al. (1997) developed a microscopic model of the layer formation and cake growth considering the hydrodynamic, adhesive and friction forces acting on a single particle during the filtration process. This model, in combination with a CFD based analysis, was used by

Drews et al. (2010) to predict a critical diameter of particles likely to deposit in a cake layer depending on the hydrodynamic forces acting on the particles (see Figure 1a). Particles larger than this critical value will be removed by the lift force while smaller ones are transported to the membrane and form a cake layer. Figure 1b shows calculated permeate drag forces at critical flux values, which were experimentally obtained for the respective crossflow velocities v_{CF} in test cell experiments (Drews et al. 2010). It can be observed that the critical diameter, obtained at the interception of the curves for the lift and drag forces, decreases with higher crossflow velocities. In other words, the removal of particles smaller than 1 µm by hydrodynamic forces can only be achieved during the relaxation period. As a result of this particle classification, the deposit consists of smaller particles resulting in a higher specific resistance, i.e. higher velocities can even have a detrimental effect.

This is consistent with results by Le-Clech et al. (2006a) who reported that cakes formed at high crossflow velocities had higher specific resistances than those at lower crossflow velocities and with the particle packing model developed by Zhang et al. (2011).

It is worth mentioning that the publications above base on flows without bubbles. Nevertheless is it possible to predict certain flow conditions which are beneficial for the cleaning process and which can be reached more easily or even be enhanced by bubbling.

2.4 Influence of fluid dynamics on biological films

Rochex et al. (2008) investigated the effect of shear stress on biofilm communities. In the investigated range of shear stresses (0.055 - 0.27 Pa), they reported that as shear stress increased, diversity and maturation of the communities decreased. So, hydrodynamic factors affecting fouling cannot be regarded independently from biological factors. Ochoa et al. (2007) and Lelièvre et al. (2002) reported that in addition to the mean shear stress, temporal fluctuation in the shear stress also affected biofilm detachment. Shear stress can also affect the release of EPS and SMP (Wang et al. 2009), which might additionally increase viscosity and can also contribute to fouling in MBRs. The little knowledge about the linkage between these two crucial topics in MBR research indicates that more research should be done in this field.

2.5 Conclusions

The hydrodynamic conditions at the vicinity of a membrane surface govern the critical particle size deposited, the thickness and structure of the cake, as well as the biofilm communities in an MBR and on a membrane surface. Air scouring significantly increases shear rates but its effect on fouling control levels off above a threshold value or can even be detrimental. In practical applications, air scouring as a means of fouling mitigation remains an art, which encourages the operation of MBRs based on experience rather than on a physical understanding of the conditions.

3 Methods used to monitor fluid dynamics in MBRs

The ideal experiment is as close to the real conditions as possible. Therefore, the measurement technique should be direct but non-intrusive and the system should consist of real membranes for parallel filtration. This gives the opportunity to observe a direct link between changes in the fluid dynamics and the fouling mitigation. The geometrical dimensions should either – for single bubble experiments – be tall enough to create fully developed flows to make it at least possible to compare results or – for full module experiments – the dimensions should be as close to a real module design as possible. The suspension being filtered should be real wastewater sludge to show the influence of the rheology, surface tension and even particulate and dissolved components. Air should be provided with commercial aerators and liquid recirculation should be possible as this airlift loop effect is often used in real systems.

Considering all these requirements, to date, the published investigations have a number of different shortcomings resulting from often inevitable assumptions and simplifications made to enable experimental or numerical investigation of the complex and interacting system. Typically, set-up heights are too low to allow terminal bubble rise velocities or circulating flow to fully develop, air/water systems are used or only 2D CFD simulations are carried out which do not capture the wall shear stress as depending on the orientation of the symmetry plane, there are either no walls apparent in the model or the bubble shape and thus its motion is not captured (see Table 1). Also, the influence of circulating flow which can be faster in full scale MBRs due to the higher liquid level and downcomer regions, is sometimes neglected or underestimated when just investigating hydrodynamics inside a module or using lab-scale set-ups.

3.1 Measurement techniques and experimental setups

A wide range of measurement techniques are used in hydrodynamic studies of membrane systems. The publications dealing with hydrodynamics (Table 1) can roughly be categorized by the following attributes:

Measurement technique. Several measurement techniques with various scientific goals are used in the hydrodynamic investigation of membrane systems. These can roughly be divided into direct and indirect as well as into optical, mechanical, thermal and chemical measurement principles. Non-intrusive techniques are favourable to ones affecting the flow by adding hardware to the system or adding substances necessary for the measurement that alter the fluid properties (e.g. the surface tension).

Measured quantity. The measured quantities focus mostly on bubble size and shape characterization, bubble/liquid velocities and shear stress determination. Most publications try to find a relation between membrane cleaning and the design and operational conditions of membrane systems. Especially for the shear stress it is worth mentioning that many authors focus on the shear stress (in [Pa]) and not on the shear forces (in [N]) which are the area weighted shear stresses. This is of importance for the cases where maximum shear stresses are presented which might only be present on small surface areas and which therefore might not have a substantial effect on the cleaning process. As an alternative to focusing on shear stresses, some studies have reported mass transfer coefficients at membrane surfaces.

Although both parameters express different phenomena, they are dependent (Zhang et al. 2009).

Membrane geometry. Commonly flat sheet and hollow fiber systems are investigated as these are most widely used in wastewater applications. Most of the studies are performed with lab modules or filtration cells which are smaller than commercial systems. This is the reason for some of the problems related to the results mentioned earlier (e.g. measuring in not fully developed flow regimes). If filtration is included, the conditions will also be different to those in real systems as the influence of the hydrostatic head on the filtration is not the same.

Single membranes / several membranes / modules. As the complexity and experimental accessibility of real membrane systems with several membranes combined in modules are rather high regarding factors influencing the fluid dynamics, many publications deal with single membrane systems. A few use several membranes, even less investigate complete modules.

Model system / real membrane. For the investigation of fluid dynamics, optical access to the experimental rig is often necessary. Therefore, transparent material is used to allow the application of optical measurement techniques. Even in the cases with real membrane materials e.g. in the investigation of flat sheets at least one side of the channel is typically made of acrylic glass.

Single phase / multiphase. As mentioned before, most publications focus on the influence of aeration on the cleaning of the membrane. Therefore, multiphase systems are most common, starting from the investigation of single bubble behaviour up to bubble swarms. For certain measurement techniques and in cases of additional filtration particles are added which make it a three-phase system.

Filtration. Approximately half of the mentioned publications investigate the fluid dynamics in systems with simultaneous filtration. As mentioned earlier the effect of filtration on the hydrodynamic conditions at the membrane surface is expected to be minimal but vice-versa the effect of hydrodynamics on filtration is crucial. Therefore filtration should be included in the experiment if possible to get a direct link between these two parameters.

Properties of the liquid. The rheology of the investigated liquid has a large influence on fluid dynamics. In many MBR systems the activated sludge behaves as a non-Newtonian fluid (Rosenberger et al. 2002). Due to the need for transparency most investigators use water, some change the viscosity or add certain materials w.r.t. the applied measurement technique but most do not use a non-Newtonian liquid. In experimental studies often carboxylmethyl cellulose (CMC) (Ratkovich et al. 2010) or xanthan gum (Rosenberger et al. 2001) is used to adjust the viscosity. It should be noted that besides viscosity also other differences in experimental conditions between studies, which are not always reported (e.g. the surface tension, bubble shape, coalescence and breakage behaviour, bubble size, bubble rise velocity etc.), are expected to affect the hydrodynamic conditions in the system.

3.2 Numerical simulations

Computational fluid dynamics (CFD) is an established and reasonable tool that can be used to gain deeper insights into the relationship between fluid dynamics and fouling. Due to the complexity of the interacting phenomena commercial CFD-programs based on the finite volume method like FLUENT or CFX are mostly used because they provide the necessary models to consider the effects of turbulent and/or multiphase flow.

Publications related to CFD and fouling in MBR can be grouped into two classes which differ in topics, observed scales in space and time and also in the numerical models used. Investigations of local flow phenomena in the proximity of the membrane were often performed with the VOF method to capture the multiphase flow. Single bubbles were resolved directly as well as the membrane surface. The aim is frequently to determine the effect of geometrical and/or operational parameters on the shear stress on the membrane which was identified as the most important parameter for fouling mitigation.

For the second class of investigations the overall flow throughout the MBR is of interest. Due to the large geometrical scales and the high computational effort for VOF-simulation the multiphase flow is typically simulated using the Eulerian-Eulerian model. Especially in cases of three-dimensional simulations the membrane modules are often modelled as a porous region and not resolved directly. The focus of these investigations is typically the impact of geometrical variations or operational parameters on the distribution of the gas phase and the cross flow velocity inside the membrane module. Therefore, the orientation and the position of the membranes, the location of the aerators and the dimensions of the reactors can be explored.

Despite the progress in the development of numerical models and computational resources there are still essential limitations for the flow simulation in MBR which can be summarised as follows:

- The properties of the real liquid are not completely mapped. Usually only the rheological behaviour of the non-Newtonian liquid is specified. Interactions with and between particles, filaments or flocculation are not considered.
- For VOF simulations of directly resolved bubbles there is currently no model available to describe the coalescence or break up in a realistic manner.
- In case of Eulerian-Eulerian simulations, a constant and uniform bubble diameter is commonly used. This is caused by the huge numerical effort for simulations with multiple bubble diameters and the lack of models that describe coalescence and break up.
- Membranes were regarded as having a fixed geometry. Swaying of membrane fibres or oscillation of membrane panels is typically neglected.
- The interaction between flow and biology (e.g. shear stress and EPS release) is not taken into account.

A selection of references with a focus on CFD and fouling in membrane processes is given in Table 2. Further publications about this topic can be found in the literature review from Gihdossi et al. (2006).

4 Results from Recent Studies

A comprehensive review of recent published literature on the effect of air scouring and membrane system geometry on these hydrodynamic conditions and fouling control is presented in the sections that follow.

4.1 Fundamental effects of bubbles on shear stress

Current investigations focus on the shear stresses that are induced by the gas-liquid flow. Significantly different types of shear stress conditions are induced by gas sparging in confined (e.g. tubular inside-out, flat sheet outside-in) and unconfined (e.g. submerged outside-in) membrane systems (Chan et al. 2012).

4.1.1 Tubular systems

Different types of two-phase flow profiles are possible in gas sparged tubular membrane systems (i.e. fine bubble flow, large slug bubble flow, churn flow and annular flow), each of which can induce different shear stress at the membrane surface. Conditions that generate large slug type flow have been reported to promote optimal fouling control (Cui et al. 2003, Smith et al. 2006).

Shear stresses induced by single slug bubbles have been investigated numerically (i.e. CFD) and experimentally (Ratkovich et al. 2011a,b, Taha and Cui 2002). In this type of flow, three distinct zones can be observed: a liquid zone preceding the bubble, a falling film zone surrounding the bubble and a wake zone following the bubble (Figure 2a). The magnitude of shear stress in each zone differs significantly and is largest and most variable in the wake zone of the rising slug bubble. Typical shear stress profiles, determined numerically and measured experimentally, for a single slug bubble, are illustrated in Figures 2b and 2c, respectively. Considering that large and variable shear stress promotes fouling control, it is likely that the wake zone is responsible for most of the fouling control (Chan et al. 2012). Zones of low pressure, which could also contribute to fouling control, have also been reported in the wake zone of rising slug bubbles (Mercier-Bonin et al. 2000).

In systems with multiple trailing slugs, bubble coalescence can occur, resulting in bubbles of different sizes, and therefore different shear stress profiles, over time (Figure 2d). Ratkovich et al. (2011a) introduced shear stress histograms to characterize the range of shear stress, and the relative frequency of occurrence of a particular shear stress that the membrane surface experiences for their system. It was reported that power consumption in an airlift tubular membrane is minimized and shear stress is optimized when the gas flow rate is approximately four times that of the liquid flow rate.

4.1.2 Hollow fibers

Because neither the sparged bubbles nor the membrane are confined in submerged HF membrane systems, the hydrodynamic conditions in these systems are more complex than those in tubular membrane systems, and the shear stress profiles differ substantially. Shear stress profiles in submerged HF systems are highly spatially and temporally variable (Fulton et al. 2011a), as presented in Figure 3a. Note that because of the complex nature of the hydrodynamic conditions in submerged HF systems, it is not possible to use numerical (i.e. CFD) analysis to accurately estimate the shear stress induced on membrane surfaces by gas sparging in these types of systems. Nonetheless, numerical analysis can be used to provide some insight into the bulk flow distribution in these systems.

The extent of fouling control has been reported to be greatest when the turbulence or shear stress induced by gas sparging are highly variable (Beier and Jonsson 2007, Chan et al. 2012, Ueda et al. 1997). A number of relationships have been considered to relate the effect of time variable shear forces to fouling control (e.g. time averaged shear stress, standard deviation of shear stress, amplitude of shear stress, peak of shear stress, frequency of shear events, ratio of two-phase time averaged shear stress to single phase wall shear stress, root mean square of shear stresses). Of these, Chan et al. (2012) reported that the extent of fouling control is most significantly correlated to the root mean square (RMS) of the shear forces. However, caution should be used when interpreting the effect of variable surface shear forces on fouling control using the RMS of surface shear forces, as the frequency of shear events, which can significantly affect fouling control, is not accurately reflected by this summary parameter. Chan et al. (2012) reported that shear force profiles characterized by repeating shear forces of short duration result in optimal fouling control, compared to constant shear forces, or repeating shear forces of longer duration. Also, fouling control is inhibited when the frequency of the shear force peaks is too high.

4.1.3 Flat sheet systems

For flat sheet systems, many geometrical and operational design parameters still need to be optimised (e.g. bubble size and membrane spacing). The presence of the walls can drastically change the bubble shape. When the bubble diameter equals the membrane spacing a further increased bubble size leads to flat cap bubbles. For all investigated membrane spacings (3-11 mm) bubbles larger than 10 mm overcome the deceleration effect caused by the walls due to the decreased projected area in flow direction and even achieve higher rise velocities between plates than in unconfined environments (Drews et al. 2008). Although rise velocity is independent of channel width, the plate distance influences the maximum possible stable bubble size. In comparison to bubbles rising in unconfined geometries, in narrow channels smaller bubbles break due to the apparent higher shear. In activated sludge, the increased rigidity of the bubble surfaces results in approximately 15-20 % slower rise velocity than that in water (Drews et al. 2008). As expected, highest shear can be achieved for narrow channels, however, narrow channels can become clogged too easily in sludge systems.

Zhang et al. (2009) investigated the influence of bubble size and frequency on shear stress (i.e. mass transfer coefficient) in a 20 mm channel. As with tubular systems they reported an increase in the mass transfer coefficient as a function of both bubble size and frequency.

However, a plateau was observed for the mass transfer coefficient above a critical bubble size and frequency.

For a rather widely spaced channel, Nagaoka et al. (2001) observed that the wall shear stress induced by the two-phase flow was about twice that of single phase flow. This can be attributed to bubble-wall-interactions. Ducom et al. (2003, 2002) observed an even higher increase of wall shear stress in systems with two-phase flow (up to 420 %) compared to those with single phase flow. They also observed an increase in the permeate flux with rising averaged shear stress. At the highest shear stresses considered, a 70 % increase in the permeate flux was observed.

Prieske et al. (2010) carried out CFD studies using the VOF method to quantify the maximum wall shear stress exerted by rising bubbles in differently spaced channels (see Figure 4). As expected, the highest shear stresses were obtained for systems with the smallest channels. An increase in the size of the bubble above a critical diameter did not yield higher shear stress. This is in agreement with Ndinisa et al. (2006a) who observed that as bubble size increased, so did the cleaning effect. However, when bubbles became larger than the channel width, a further increase in size only had a minor effect on fouling control. The maximum shear stress reported by Ndinisa et al. (2006a) (i.e. 0.7 Pa) at the highest air flow rate used was considerably smaller than that observed by Prieske et al. (2010) (i.e. 4 Pa). However, the system investigated by Ndinisa et al. (2006a) was not designed to promote recirculating flow with an upflow section within the membrane module and a downflow section at the sides of the module (i.e. downcomer) so that the unavoidable recirculating flow due to continuity happened within the examined gap whereby the overall flow was slowed down.

The shear stress values induced by bulk liquid and bubble flow have been reported not to be equal to the sum of those induced by single-phase flow and by bubbles rising in stagnant water (Prieske et al. 2010). Most often the stresses were higher, which might be attributed to the lack of flow reversal in the liquid film when there is overall upward motion (Cui and Taha

2003). Sometimes, however, the total shear stress was considerably lower. This demonstrates that in flat-sheet modules, the hydrodynamic conditions are more complex than those in tubular membranes because liquid can flow downwards at the unconfined sides of the rising bubble. Nonetheless, shear stresses achieved in two-phase flow were at least three times higher than those obtained by single-phase flow.

Figure 5 which is original work from the authors and will be discussed in another publication illustrates maximum shear stresses measured experimentally for different bubble sizes. Although maximum shear stress values obtained experimentally are lower than those obtained from CFD analyses (cf. Fig. 4) for some of the parameter combinations, both the results obtained experimentally and numerically demonstrate that the maximum shear stress value levels off when bubble size is equal or bigger than the channel width.

4.2 Module design and fluid dynamics

As previously discussed, the shear stress can be heterogeneously distributed, especially in unconfined systems such as HF and flat sheet membrane systems. Changes in the system geometry, which can affect the extent of confinement, influence the magnitude and distribution of surface shear stress.

4.2.1 Hollow Fibers

In submerged HF membrane systems, the fiber and module geometry as well as the sparging approach can significantly affect the magnitude and distribution of shear stress.

Fiber geometry. Chang and Fane (2002, 2001) reported that sparging was more effective at controlling fouling for small diameter compared to large diameter fibers. The beneficial effect of smaller fiber diameters is likely due to their slenderness, and therefore the greater ability of smaller diameter fibers to sway, as discussed below (Chang and Fane 2002, Wicakasana et al. 2006). However, the head loss through fibers, and therefore the spatial distribution of the permeate flux, can be significantly affected by the fiber diameter, especially for smaller diameter fibers, potentially resulting in zones within the fiber that operate at greater than critical flux (Chang and Fane 2002, 2001).

Fouling in systems with loosely held fibers is typically less than in systems with tightly held fibers (Bérubé and Lei 2006, Chang and Fane 2002, Wicaksana et al. 2006, Yeo et al. 2007). Fiber sway on its own can induce average shear forces that are comparable in magnitude to those induced by gas sparging alone (Chan 2010) and contributes to fouling control (Chang and Fane 2002, Wicaksana et al. 2006). Also, swaying fibers can collide, inducing high shear forces that can be up to an order of magnitude greater than those induced by gas sparging alone (Bérubé et al. 2006, Chan et al. 2007). Note that the extent of fiber sway, and potentially fouling control from fiber sway, can be dampened when filtering solutions with high viscosities (Wicaksana et al. 2006). In addition, shear forces are more homogeneously distributed in systems with loosely held fibers (Chan et al. 2007a). This is likely because sparged bubbles and entrained liquid can flow more freely through loosely held fibers (Chan et al. 2007b).

Greater fouling has been observed at higher fiber packing densities (Bérubé and Lei 2006, Chang and Fane 2002, Yeo et al. 2006, Yeo and Fane 2005). The packing density can significantly affect the extent of shielding, potentially resulting in zones with fibers that receive little to no surface shear forces (Bérubé et al. 2006, Chan et al. 2007a,b) or with limited bulk-liquid movement, which can promote sludging (Yeo et al. 2006). For high fiber packing densities, shear forces are also only induced onto sections of the fibers that face rising bubbles (Chan et al. 2007a,b). Permeate competition between fibers can also reduce the permeate flux in fibers within bundles (Yeo et al. 2006). The extent of fiber contact can potentially be greater with a higher packing density, and therefore, the effect of packing density should not be investigated in isolation from other factors that can promote fouling control.

System geometry. The geometry of the system (i.e. distribution of modules and system tank) also significantly affects the hydrodynamic conditions. Nguyen Cong Duc et al. (2008) reported that higher bulk crossflow velocities can be maintained between membrane modules when baffles are installed at the periphery of their system tank. High crossflow velocities likely contribute to sludging control by preventing zones of stagnant liquid in the system (Yeo et al. 2006). However, high bulk crossflow velocities on their own may not significantly contribute to shear forces at membrane surfaces (Bérubé et al. 2006), fiber sway (Liu et al. 2010), or fouling control (Bérubé and Lei 2006). Fulton and Bérubé (2011b) reported that the spacing of the modules significantly affects the distribution of shear forces. For narrow module spacing, the narrow gap between modules provided sufficient resistance to prevent sparged bubbles, and entrained liquid, from rising between modules, resulting in zones of lower shear forces between modules, compared to those at the periphery of the modules. A more homogeneous distribution of shear forces throughout the system could be achieved by widening the gap between the modules, which enables more bubbles, and entrained liquid, to rise between the modules.

Bubble characteristics. Although high shear forces are induced by rising bubbles, no statistically significant correlation exists between sparged bubble characteristics (i.e. bubble count, size or rise velocity) and surface shear forces (Fulton et al. 2011a). This lack of direct correlation is likely due to the fact that in addition to the shear forces induced by the turbulent zones surrounding rising bubbles, other mechanisms that are also induced by sparged bubbles, but not directly related to their characteristics (e.g. fiber sway and contact), can contribute to surface shear forces on membrane surfaces. Although bubble characteristics cannot provide insight into the magnitude of shear forces, it can nonetheless provide insight into bulk-liquid movement throughout a system (Fulton et al. 2011a, Liu et al. 2010, Nguyen Cong Duc et al. 2008).

For a given gas flow rate, the rate of fouling with large spherical cap bubbles (200 – 400 mL) sparging is approximately four times lower than that with coarse bubble sparging and three times lower than with intermittent coarse bubble sparging (Ye 2012). This is likely because large spherical cap bubble sparging generates profiles characterized by repeated shear events of short duration (Figure 2b), similar to the ones reported by Chan et al. (2012) to be optimal for fouling control. Fouling control was also observed to be better when the large spherical cap bubbles rose through stagnant compared to up-flowing liquid (Ye 2012).

It should be noted that some studies have reported that optimal fouling control could be achieved using smaller coarse bubble sparging (Fane et al. 2005, Yeo et al. 2007), or have reported no effect of bubble size on fouling control (Martinelli et al. 2010) which appears to contradict the more effective fouling control reported by Ye (2012) using large spherical cap bubble sparging. This discrepancy may be due to the significant difference in the size of the bubbles considered in previous studies (i.e. ranging from 0.1 to 40 mL), and that of larger coarse and spherical cap bubbles (i.e. > 40 mL). For smaller bubbles, the wake volume is approximately equal to that of the bubble itself, while for larger bubbles, the turbulent wake volume can be more than an order of magnitude greater than that of the bubble itself (Clift et al. 1978). The strong secondary flows generated in the wakes of rising bubbles have been linked to fouling control (Yeo et al. 2007, 2006). The effect of bubble size on fouling control has also been reported to be affected by fiber sway (Yeo et al. 2007). Therefore, the effect of bubble size should not be investigated in isolation from other factors that can promote fouling control.

4.2.2 Flat sheets

As for submerged HF membrane systems, the module geometry as well as the sparging approach can significantly affect the magnitude and distribution of shear stress in FS membrane systems.

Module geometry. A number of different channel spacings and module heights are used in commercial flat sheet membrane systems (Prieske et al. 2010) indicating that optimisation still needs to be done. As reported by Prieske et al. (2008), increasing membrane spacing results in higher liquid crossflow velocities.

System geometry. Much of the recent research has focused on characterizing the hydrodynamic conditions near the membrane surface. However, the effect of the tank geometry on bulk liquid movement has received limited attention. Bulk liquid movement can affect the distribution of sparged bubbles and frictional losses in flat sheet membrane system. Ndinisa et al. (2006a) introduced baffles into flat sheet modules for better bubble distribution across one panel. This increased the scoured area but led to a decrease in circulation velocity due to the additional resistance caused by the baffles. Prieske et al. (2010) reported that the bulk liquid velocity is a function of the cross-sectional areas of the upflow and downflow (i.e. downcomer) sections, and that frictional loss could be minimized by providing a smoother transition between the downflow and upflow sections of the system (see Figure 6). The position of the aerators used for scouring also affects the bulk liquid velocity in a submerged FS system (Prieske et al. 2010, Tacke et al. 2008), e.g. locating the aerators at the bottom of the tank and not at the entrance to the draft tube where they block the available cross-section and slow down the flow increases the internal circulation. The combined effect is shown in Figure 6. Beyond a critical superficial gas velocity, the superficial liquid velocity remains relatively constant. This plateauing effect is consistent with the diminishing benefits on fouling control of increasing the air scouring rate beyond a critical value, as discussed in Section 2.

4.3 New developments in fluid dynamics approaches to MBR system

In order to improve fouling control by hydrodynamic forces and thus reduce the energy demand, several new operational or geometrical approaches are currently emerging.

4.3.1 Intermittent and alternating aeration

Guibert et al. (2002) reported that the extent of fouling could be reduced by using cyclic (e.g. 10 seconds on, 10 seconds off) rather than continuous coarse bubble sparging. In addition to lower the extent of fouling, the operating costs can be substantially reduced using cyclic aeration as the sparged air flow to sections of the membrane system is periodically interrupted (Germain et al. 2007, Judd 2006, Nywening et al. 2009). These results are consistent with those reported by Fulton and Bérubé (2011a), for which the RMS of surface shear stress for intermittent sparging was approximately 50 % greater than that for continuous sparging, and results by Ye (2012), for which the fouling rate for intermittent aeration was 30 % less than that for continuous sparging, even though the volume of sparged gas used for intermittent sparging was half of that used for continuous sparging.

Large spherical cap bubble sparging has recently been introduced as an alternative to continuous or intermittent coarse bubble sparging in submerged hollow fiber membrane systems for fouling control (Memcore MemPulse^{TM} and GE Leap^{TM} aerators). As previously discussed, the rate of fouling when using large spherical cap bubbles is significantly lower than that observed using continuous or intermittent air sparging. As a result, reported gas sparging power consumption has decreased by approximately 30 % compared to intermittent coarse sparging, and 70 % compared to continuous coarse bubble sparging.

4.3.2 Three-phase fluidised bed

In order to enhance physical scouring at the membrane surface, some researchers have introduced particles that circulate with the liquid flow. Ngo et al. (2008) added polyester-urethane sponges at a volume fraction of 10 %. In addition to improved fouling control, the addition of sponges also improved the quality of the permeate. The sponges also acted as attachment media for biomass, reduced the suspended biomass concentration and decreased the rate of fouling (Lee et al. 2006, Leiknes et al. 2006). Even without physical membrane scouring by attachment media, their presence has been reported to reduce the extent of fouling (Sombatsompop et al. 2006), even though attached biomass has a much higher fouling potential than suspended biomass (Lee et al. 2001). Siembida et al. (2009) could operate an MBR for 20 months without chemical cleaning by adding 2-3 mm PP granules. The permeability remained almost constant even when flux was doubled while that of a parallel system decreased by approximately 50 % of its original permeability after 80 days.

4.3.3 Turbulence Promoters

In order to increase the mass transfer rate near the membrane, the use of turbulence promoters, such as helical baffles or membranes with structured surfaces, has frequently been considered (e.g. Al-Bastaki et al. 2001). While turbulence promoters are commonly used in membrane processes such as reverse osmosis, their use is not feasible in high solid loads applications such as MBR because of the danger of channel blockage. Recently, a new type of membrane spacer was specifically designed for high solid loads (Fritzmann et al. 2010). It consists of helically wound strips with no flow obstacles perpendicular to the direction of the bulk flow. In test cell experiments with individually controlled liquid and gas velocities, significant increases in critical flux were observed. It remains to be seen, however, if the additional resistance by wall shear slows down the two-phase flow inside a module too much whereby it would counteract its positive fouling control effect. Liu et al. (2011) developed a helically wound flat sheet membrane which rotates in the sludge. Permeability was enhanced in comparison to a rotating flat sheet and this was further augmented by applying a low intensity electrical field.

5 Mathematical modelling of global flow

Some submerged MBRs have a configuration similar to that of airlift loop reactors. Several authors modified the well-known air lift loop reactor model of Chisti et al. (1988) to predict the bulk liquid crossflow velocities in submerged modules in MBRs (McAdam et al. 2005, Sofia et al. 2004). These investigations aimed at an improved understanding of hydrodynamics in MBRs enabling a subsequent optimisation of geometrical and operating parameters.

Based on a modified Chisti equation, Sofia et al. (2004) successfully modelled the crossflow velocity in a nitrification chamber equipped with a single commercial flat sheet membrane. As only a single membrane plate was introduced into the riser section the flow resistance caused by the presence of the membrane was marginal compared to that of a commercial scale module which has multiple membrane plates. Such additional resistance, however, impacts the driving force for the liquid circulation (difference in gas hold-ups and hence hydrostatic pressures between riser and downcomer section) and changes the flow itself due to the increased wall friction. Prieske et al. (2010, 2008) modified the Chisti model to account for both these aspects to comprehensively model the bulk crossflow velocity for an MBR equipped with a flat sheet module. In contrast to the slender airlift reactors studied by Chisti et al. (1988), the model accounted for the fact that MBR tanks typically have significantly different width/height and riser/downcomer cross-section area (A_r/A_d) ratios, which affects the distribution of the gas hold-up in the upflow and downflow sections of the system. The effect of the additional membrane wall friction, estimated according to Lockhart and Martinelli (1949) with a two-phase corrective factor, was also incorporated into the model. The resulting modified Chisti equation contains geometrical parameters of the tank (e.g. cross-section areas) and the module (e.g. height, width, spacing) and therefore enables an optimisation of the tank geometry. As presented in Figure 6, the modified model correctly predicts the trend of increasing bulk upflow superficial velocity with increasing gas superficial velocity. However, further improvements to the model are required to accurately predict the magnitude of the upflow liquid velocity (Prieske et al. 2010). Additionally, the modified model needs to be adapted to account for the effect of different bubble sizes (e.g. fine vs. coarse), as the size has been reported to affect the bulk upflow velocity (Sofia et al. 2004).

6 Conclusions

Fouling in MBR is a complex problem caused by interacting biological, chemical and physical phenomena. Recent research has led to the emergence of engineering design tools to optimize module and tank geometry as well as operating parameters based on a more fundamental understanding of the effect of the hydrodynamic conditions in MBRs on fouling control. These have contributed to the development of new sparging strategies that have resulted in up to 70 % reduction in power costs for fouling control. But still no valid model yet exists that can comprehensively describe the relationship between fouling rate and the hydrodynamic conditions.

References

Al-Bastaki, N., Abbas, A., 2001. Use of fluid instabilities to enhance membrane performance: a review. Desalination 136 (1-3), 255-262.

Altmann, J., Ripperger, S., 1997. Particle deposition and layer formation at the crossflow microfiltration. J. Membr. Sci. 124 (1), 119-128.

Belfort, G., Davis, R. H., Zydney, A. L., 1994. The behaviour of suspensions and macromolecular solutions in crossflow microfiltration. J. Membr. Sci. 96 (1-2), 1-58.

Beier, S.P., Jonsson, G., 2007. Separation of enzymes and yeast cells with a vibrating hollow fiber membrane module. Sep. Purif. Technol. 53 (1), 111-118.

Bérubé, P.R., Lei E., 2006. The Effect of Hydrodynamic Conditions and System Configuration on the Permeate Flux in Submerged Hollow Fiber Membrane Systems. J. Membr. Sci. 271 (1-2), 29-37.

Bérubé, P., Afonso, G., Taghipour, F., Chan, C., 2006. Quantifying the shear at the surface of submerged hollow fiber membranes. J. Membr. Sci. 279 (1-2), 495-505.

Bütehorn, S., Volmering, D., Vossenkaul, K., Wintgens, T., Wessling, M., Melin, T., 2011. CFD simulation of single- and multi-phase flows through submerged membrane units with irregular fiber arrangement. J. Membr. Sci. 384 (1-2), 184-197.

Chan, C., Bérubé, P.R., Hall, E.R., 2012. Relationship between types of surface shear stress profiles and membrane fouling. Water Res., in press.

Chan, C., 2010. Gas Sparging for Fouling Control, PhD Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, Canada.

Chan, C., Bérubé, P., Hall, E., 2007a. Shear profiles inside gas sparged submerged hollow fiber membrane modules. J. Membr. Sci. 297 (1-2), 104-120.

Chan, C., Bérubé, P.R., Hall, E.R., 2007b. Shear Stress at Radial Positions of Submerged Hollow Fibers under Gas Sparging and Effects of Physical Contact Between Fibers on Shear Profiles. Proc. American Water Works Assoc. Membrane Technol. Conf., Orlando, USA.

Chang, S., Fane, A.G., 2002. Filtration of Biomass with Laboratory Scale Submerged Hollow Fiber Module-Effect of Operating Conditions and Module Configuration. J. Chem. Technol. Biotechnol. 77(9), 1030-1038.

Chang, S., Fane, A.G., 2001. The Effect of Fiber Diameter on Filtration and Flux distribution – Relevance to Submerged Hollow Fiber Modules. J. Membr. Sci. 184(2), 221-231.

Chen, V., Li, H., Fane, A. G., 2004. Non-invasive observation of synthetic membrane processes - a review of methods. J. Membr. Sci. 241 (1), 23-44.

Chisti, M.-Y. Halard, B., Moo-Young, M., 1988. Liquid circulation in airlift reactors, Chem. Eng. Sci. 43(3), 451-457.

Chung, K.Y., Edelstein, W.A., Belfort, G., 1993. Dean vortices with wall flux in a curved channel membrane system: 6. Two dimensional magnetic resonance imaging of the velocity field in a curved impermeable slit. J. Membr. Sci. 81 (1-2), 151-162.

Clift, R., Grace, J.R., Weber, M.E., 1978. Bubbles, Drops and Particles. Academic Press, New York.

Cui, Z.F., Chang, S., Fane, A.G., 2003. The use of bubbles to enhance membrane processes. J. Membr. Sci. 221, 1-35.

Cui, Z.F., Taha, T., 2003. Enhancement of ultrafiltration using gas sparging: a comparison of different membrane modules. J. Chem. Technol. Biotechnol. 78, 249-253.

Drews, A., 2010. Membrane fouling in membrane bioreactors – Characterisation, contradictions, cause and cures. J. Membr. Sci. 363, 1-28.

Drews, A., Prieske, H., Meyer, E.-L., Senger, G., Kraume, M., 2010. Advantageous and detrimental effects of air sparging in membrane filtration: Bubble movement, exerted shear and particle classification. Desalination 250 (3), 1083-1086.

Drews, A., Prieske, H., Kraume, M., 2008. Optimierung der Blasen- und Zirkulationsströmung in Membranbelebungsreaktoren (in German). Chem. Ing. Tech. 80 (12), 1795-1801.

Ducom, G., Puech, F.P., Cabassud, C., 2003. Gas/Liquid Two-phase Flow in a Flat Sheet Filtration Module: Measurement of Local Wall Shear Stresses. Can. J. Chem. Eng. 81 (3-4), 771-775.

Ducom, G., Puech, F.P., Cabassud, C., 2002. Air sparging with flat sheet nanofiltration: a link between wall shear stresses and flux enhancement. Desalination 145 (1-3), 97-102.

Essemiani, K., Ducom, G., Cabassud, C., Liné, A., 2001. Spherical cap bubbles in a flat sheet nanofiltration module: experiments and numerical simulation. Chem. Eng. Sci. 56 (21-22), 6321-6327.

Fane, A.G., Yeo, A. Law, A., Parameshwaran, K., Wicaksana F. Chen, V., 2005. Low pressure membrane processes – doing more with less energy. Desalination, 185, 159-165.

Fimbres-Weihs, G.A., Wiley, D.E., 2007. Numerical study of mass transfer in three-dimensional spacer-filled narrow channels with steady flow. J. Membr. Sci. 306 (1-2), 228-243.

Fletcher, H., Mackley, T., Judd, S., 2007. The cost of a package plant membrane bioreactor. Water Res. 41, 2627-2635.

Fritzmann, C., Hausmann, M., Doyen, W., Wessling, M., Melin, T., 2010. Spacers in MBR!? Towards low air sparging in flat sheet membrane-bioreactors. In: AMS6/IMSTEC 2010, Sydney, Australia, 22-26Nov 2010 P-332.

Fulton, B., Redwood, J., Tourais, M., Bérubé, P., 2011a. Distribution of surface shear forces and bubble characteristics in full-scale gas sparged submerged hollow fiber membrane modules. Desalination 281, 128-141.

Fulton, B., Bérubé, P.R., 2011b. Optimizing the Sparging Condition and Membrane Module Spacing for a ZW500 Submerged Hollow Fiber Membrane System. Desal. Water Treatm., in press.

Gaucher, C., Jaouen, P., Legentilhomme, P., Comiti, J., 2003. Influence of fluid distribution on the ultrafiltration performance of a ceramic flat sheet membrane. Sep. Sci. Technol. 38 (9), 1949-1962.

Gaucher, C., Jaouen, P., Legentilhomme, P. Comiti, J., 2002a. Suction effect on the shear stress at a plane ultrafiltration ceramic membrane surface. Sep. Sci. Technol. 37 (10), 2251-2270.

Gaucher, C., Legentilhomme, P., Jaouen, P., Comiti, J., Pruvost, J., 2002b. Hydrodynamics study in a plane ultrafiltration module using an electrochemical method and particle image velocimetry visualization. Exp. Fluids 32, 283-293.

Gaucher, C., Jaouen, P., Comiti, J., Legentilhomme, P., 2002c. Determination of cake thickness and porosity during cross-flow ultrafiltration on a plane ceramic membrane surface using an electrochemical method. J. Membr. Sci. 210 (2), 245-258.

Gaucher, C., Legentilhomme, P., Jaouen, P., Comiti, J., 2002d. Influence of Fluid Distribution on the Wall Shear Stress in a Plane Ultrafiltration Module Using an Electrochemical Method. Chem. Eng. Res. Des. 80 (1), 111-120.

Germain, E., Nelles, F., Drews, A., Pearce, P., Kraume, M., Reid, E., Judd, S., 2007. Biomass effects on oxygen transfer in membrane bioreactors. Water Res. 41(5), 1038-1044.

Ghidossi, R., Veyret, D., Moulin, P., 2006. Mass transfer in gas-sparged ultrafiltration: Upward slug flow in tubular membranes., Chemical Engineering and Processing. 45 (6), 437-454.

Ghosh, R., Cui, Z.F., 1999. Mass transfer in gas-sparged ultrafiltration: Upward slug flow in tubular membranes. J. Membr. Sci. 162, 91-102.

Guibert, D., Ben Aim, R., Rabie, H., Côté, P., 2002. Aeration Performance of Immersed Hollow-Fiber Membranes in a Benotnite Suspension. Desalination 148, 395-400.

Heath, C.A., Belfort, G., Hammer, B.E., Mirer, S.D., Pimbley, J.M., 1990. Magnetic resonance imaging and modeling of flow in hollow-fiber bioreactors. AIChE J. 36 (4), 547-558.

Jiang, T., Kennedy, M. D., Yoo, C., Nopens, I., van der Meer, W., Futselaar, H., Schippers, J. Vanrolleghem P. A., 2007. Controlling submicron particle deposition in a side-stream membrane bioreactor: A theoretical hydrodynamic modelling approach incorporating energy consumption. J. Membr. Sci. 297, (1-2), 141-151.

Judd, S., 2006. The MBR Book, Elsevier Amsterdam.

Kang, C.-W., Hua, J., Lou, J., Liu, W., Jordan, E., 2008. Bridging the gap between membrane bio-reactor (MBR) pilot and plant studies. J. Membr. Sci. 325, 861-871.

Khalili, A., Mehrnia, M., Mostoufi, N., Sarrafzadeh, M., 2009. Flow Characteristics in an Airlift Membrane Bioreactor. In: Proc. of Chemical Product and Process Modeling, Vol. 4.

Khalili-Garakani, A., Mehrnia, M. R., Mostoufi, N. & Sarrafzadeh, M. H. 2011. Analyze and control fouling in an airlift membrane bioreactor: CFD simulation and experimental studies. Process Biochem. 46 (5), 1138-1145.

Kimura, K., Miyoshi, T., Naruse, T., Yamato, N., Ogyu, R., Watanabe, Y., 2008. The difference in characteristics of foulants in submerged MBRs caused by the difference in the membrane flux. Desalination 231, 268-275.

Le-Clech, P., Chen, V., Fane, A.G., 2006a. Fouling in membrane bioreactors used in wastewater treatment. J. Membr. Sci. 284, 17-53.

Le-Clech, P., Cao, Z., Wan, P., Wiley, D., Fane, A., 2006b. The application of constant temperature anemometry to membrane processes. J. Membr. Sci. 284 (1-2), 416-423.

Lee, J., Ahn, W.-Y., Lee, C.H., 2001. Comparison of the filtration characteristics between attached and suspended growth microorganisms in submerged membrane bioreactor. Water Res. 35, 2435-2445.

Lee, W.-N., Kang, I.-J., Lee C.H., 2006. Factors affecting filtration characteristics in membrane-coupled moving bed biofilm reactors. Water Res. 40, 1827-1835.

Leiknes, T., Bolt, H., Engmann, M., Ødegaard, H., 2006. Assessment of membrane reactor design in the performance of a hybrid biofilm membrane bioreactor (BF-MBR). Desalination 199, 328-330.

Lelièvre, C., Legentilhomme, P., Gaucher, C., Legrand, J., Faille, C. & Bénézech, T. 2002. Cleaning in place: effect of local wall shear stress variation on bacterial removal from stainless steel equipment. Chem. Eng. Sci. 57 (8), 1287 - 1297.

Li, J., Yang, F., Liu, Y., Song, H., Li, D., Cheng, F., 2012. Microbial community and biomass characteristics associated severe membrane fouling during start-up of a hybrid anoxic–oxic membrane bioreactor. Bioresour. Technol. 103, 43 – 47.

Li, Q., Ghosh, R., Bellara, S., Cui, Z., Pepper, D., 1998. Enhancement of ultrafiltration by gas sparging with flat sheet membrane modules. Sep. Purif. Technol. 14 (1-3), 79-83.

Liu, L., Gao, B., Liu, J., Yang, F., 2011. Techniques for membrane fouling reduction in separation MBR and enhancement in water treatment efficiency, 6th IWA-MTC, Aachen 4-7 Oct. 2011, 6136.

Liu, N., Zhang, Q., Chin, G.L., Ong, E.H., Lou, J., Kang, C.W., Liu, W., Jordan, E., 2010. Experimental Investigation of Hydrodynamic Behavior in a Real Membrane Bio-Reactor Unit. J. Membr. Sci. 353, 122-134.

Lockhart, R.W., Martinelli, R.C., 1949. Proposed correlation of data for isothermal two-phase, two-component flow in pipes. Chem. Eng. Prog. 45, 38-48.

McAdam, E., Judd, S.J., Gildemeister, R., Drews, A., Kraume, M., 2005. Critical analysis submerged membrane sequencing batch reactor operating conditions. Water Res. 39 4011-4019.

Martinelli, L., Guigui, C., Line, A., 2010. Characterisation of hydrodynamics induced by air injection related to membrane fouling behaviour. Desalination 250 (2), 587-591.

Mercier-Bonin M., Maranges C., Lafforgue C., Fonade C. 2000. Hydrodynamics of slug flow applied to cross-flow filtration in narrow tubes. AIChE Journal 46(3), 476-488.

Metzger, U., Le-Clech, P., Stuetz, R.M., Frimmel, F.H., Chen, V., 2007. Characterisation of polymeric fouling in membrane bioreactors and the effect of different filtration modes. J. Membr. Sci. 301, 180-189.

Nagaoka, H., Tanaka, A., Toriizuka, Y., 2003. Measurement of effective shear stress working on flat-sheet membrane by air-scrabbling. Water Sci. Technol.: Water Supply 3 (5-6), 423-428.

Nagaoka, H., Tanaka, A., Miyamoto, Y., 2001. Measurement of aeration-induced shear stress acting on flat-sheet membrane in submerged-type membrane bioreactor. In: Proc. Asian Waterqual. 2001.

Ndinisa, N.V., Fane, A.G., Wiley, D.E., 2006a. Fouling Control in a Submerged Flat Sheet Membrane System: Part I – Bubbling and Hydrodynamic Effects. Sep. Sci. Technol. 41 (7), 1383-1409.

Ndinisa, N.V., Fane, A.G., Wiley, D.E., Fletcher, D.F., 2006b. Fouling Control in a Submerged Flat Sheet Membrane System: Part II – Two-Phase Flow Characterization and CFD Simulations. Sep. Sci. Technol. 41 (7), 1411-1445.

Ngo, H.-H., Guo, W., Xing, W., 2008. Evaluation of a novel sponge-submerged membrane bioreactor (SSMBR) for sustainable water reclamation. Bioresource Technol. 99, 2429-2435.

Nguyen Cong Duc, E., Fournier, L., Levecq, C., Lesjean B., Grelier P., Tazi-Pain, A., 2008. Local Hydrodynamic Investigation of the Aeration in a Submerged Hollow Fiber Membrane Cassette. J. Membr. Sci. 321(2), 264-271.

Nywening J.-P., Zhou H., 2009. Influence of filtration conditions on membrane fouling and scouring aeration effectiveness in submerged membrane bioreactors to treat municipal wastewater. Water Res. 43(14), 3548-3558.

Ochoa, J.-C., Coufort, C., Escudié, R., Liné, A. & Paul, E. 2007. Influence of non-uniform distribution of shear stress on aerobic biofilms. Chem. Eng. Sci. 62 (14), 3672 - 3684.

Ozaki, N., Yamamoto, K., 2001. Hydraulic effects on sludge accumulation on membrane surface in crossflow filtration. Water Res. 35 (13), 3137-3146.

Pangrle, B., Walsh, E., Moore, S., DiBiasio, D., 1992. Magnetic resonance imaging of laminar flow in porous tube and shell systems. Chem. Eng. Sci. 47 (3), 517-526.

Pangrle, B. J., Walsh, E. G., Moore, S., DiBiasio, D., 1989. Investigation of fluid flow patterns in a hollow fiber module using magnetic resonance velocity imaging. Biotechnol. Tech. 3, 67-72.

Phattaranawik, J., Fane, A.G., Pasquier, A.C.S., Bing, W., 2007. Membrane bioreactor with bubble-size transformer: Design and fouling control. AIChE J. 53 (1), 243-248.

Poh, C.K., Hardy, P.A., Liao, Z., Huang, Z., Clark, W.R., Gao, D., 2003. Effect of Flow Baffles on the Dialysate Flow Distribution of Hollow-Fiber Hemodialyzers: A Nonintrusive Experimental Study Using MRI. J. Biomech. Eng. 125 (4), 481-489.

Prieske, H., Böhm, L., Drews, A., Kraume, M., 2010. Optimised hydrodynamics for membrane bioreactors with immersed flat sheet membrane modules. Desalin. Water Treat. 8 (1-3), 270-276.

Prieske, H., Drews, A., Kraume, M., 2008. Prediction of the circulation velocity in a membrane bioreactor. Desalination 231 (1-3), 219-226.

Ratkovich, N., Chan, C.C., Bérubé, P.R., Nopens, I., 2011a. Analysis of shear stress and energy consumption in a tubular airlift membrane system. Water Sci. Technol. 64 (1), 189-198.

Ratkovich, N., Bérubé, P., Nopens, I., 2011b. Assessment of mass transfer coefficients in coalescing slug flow in vertical pipes and applications to tubular airlift membrane bioreactors. Chem. Eng. Sci. 66 (6), 1254-1268.

Ratkovich, N., Chan, C.C.V., Bérubé, P.R., Nopens, I., 2010. Investigation of the effect of viscosity on slug flow in airlift tubular membranes in search of a sludge surrogate. Water Sci. Technol. 61 (7), 1801-1809.

Ratkovich, N., Chan, C.C.V., Bérubé, P., Nopens, I., 2009. Experimental study and CFD modelling of a two-phase slug flow for an airlift tubular membrane. Chem. Eng. Sci. 64 (16), 3576 - 3584.

Rochex, A., Godon, J.-J., Bernet, N., Escudié, R., 2008. Role of shear stress on composition, diversity and dynamics of biofilm bacterial communities. Water Res. 42, 4915-4922.

Rosenberger, S., Kubin, K., Kraume, M., 2002. Rheology of Activated Sludge in Membrane Bioreactors. Eng. Life Sci. 2 (9), 269-275.

Rosenberger, S., Drews, A., Kraume, M., 2001. Comparison of Microfiltration Behaviour of Activated Sludge and Model Suspensions in a Novel Membrane Test Cell. Chem. Ing. Tech. 73 (6), 597-597.

Siembida, B., Cornel, P., Krause, S., Zimmermann, B., 2009. Untersuchungen zum Permeabilitätsverlust in Membran-Bioreaktoren. In: Membrantechnik in der Wasseraufbereitung und Abwasserbehandlung (in German). 8. Aachener Tagung Wasser und Membranen, 2009, A20/1-10.

Smith, S.R., Field, R.W., Cui, Z.F., 2006. Predicting the performance of gas-sparged and non-gas sparged ultrafiltration. Desalination 191, 376-385.

Sofia, A., Ng, W. J., Ong, S. L., 2004. Engineering design approaches for minimum fouling in submerged MBR. Desalination 160 (1), 67-74.

Sofialidis, D., Primos, P. 1997. Fluid flow and heat transfer in a pipe with wall suction, International Journal of Heat and Mass Transfer 40 (15), 3627-3640.

Sombatsompop, K., Visvanathan, C., Ben Aim, R., 2006. Evaluation of biofouling phenomenon in suspended and attached growth membrane bioreactor systems. Desalination 201, 138-149.

Tacke, D., Pinnekamp, J., Prieske, H., Kraume, M., 2008. Membrane bioreactor aeration: investigation of the velocity flow pattern. Water Sci. Technol. 57 (4), 559-565.

Taha T., Cheong, W.L., Field, R.-W., Cui Z.F., 2006. Gas-sparged ultrafiltration using horizontal and inclined tubular membrane - A CFD study. J. Membr. Sci., 279 (1-2), 487-494.

Taha T., Cui Z.F., 2002. CFD Modelling of gas-sparged ultrafiltration in tubular membranes. J. Membr. Sci., 210, 13-27.

Tardieu, E., Grasmick, A., Geaugey, V., Manem, J., 1999. Influence of hydrodynamics on fouling velocity in a recirculated MBR for wastewater treatment. J. Membr. Sci., 156, 131-140.

Ueda, T., Hata, K., Kikuoka, Y., Seino, O., 1997. Effect of Aeration on Suction Pressure in a Submerged Membrane Bioreactor. Water Research 31(3), 489-494.

Verrecht, B., Judd, S., Guglielmi, G., Brepols, C., Mulder, J.W., 2008. An aeration energy model for an immersed membrane bioreactor. Water Res. 42, 4761-4770.

Wang, Z., Wu, Z., Tang, S., 2009. Extracellular polymeric substances (EPS) properties and their effects on membrane fouling in a submerged membrane bioreactor. Water Res. 43, 2504-2512.

Wereley, S.T., Akonur, A., Lueptow, R.M., 2002. Particle-fluid velocities and fouling in rotating filtration of a suspension. J. Membr. Sci. 209 (2), 469-484.

Wicaksana, F., Fane, A.G., Law, A.W.-K., 2009. The use of Constant Temperature

Anemometry for permeate flow distribution measurement in a submerged hollow fibre system. J. Membr. Sci. 339 (1-2), 195-203.

Wicaksana, F., Fane, A.G., Chen, V., 2006. Fiber Movement Induced by Bubbling using Submerged Hollow Fiber Membranes. J. Membr. Sci. 271 (1-2), 186-195.

Wu, J., Le-Clech, P., Stuetz, R.M., Fane, A.G., Chen, V., 2008. Effects of relaxation and backwashing conditions on fouling in membrane bioreactors. J. Membr. Sci. 324, 26-32.

Yamanoi, I., Kageyama, K., 2010. Evaluation of bubble flow properties between flat sheet membranes in membrane bioreactor. J. Membr. Sci. 360 (1-2), 102-108.

Ye D. 2012. Large spherical cap bubble sparging for fouling control. MASc Thesis. Department of Civil Engineering, The University of British Columbia, Vancouver, Canada.

Ye, Y., Chen, V., Le-Clech, P., 2011. Evolution of fouling deposition and removal on hollow fibre membrane during filtration with periodical backwash. Desalination, in press.

Yeo, A.P.S., Law, A.W.K., Fane, A.G., 2007. The Relationship Between Performance of Submerged Hollow Fibers and Bubble-Induced Phenomena Examined by Particle Image Velocimetry. J. Membr. Sci. 304, 125-137.

Yeo, A.P.S., Law, A.W.K., Fane A.G., 2006. Factors Affecting the Performance of Submerged Hollow Fiber Bundles. J. Membr. Sci. 280, 969-982.

Yeo, A., Fane, A.G., 2005. Performance of Individual Fibers in a Submerged Hollow Fiber Bundle. Water Sci. Technol. 51(6-7), 165-172.

Zhang, H., Gao, J., Jiang, T., Gao, D., Zhang, S., Li, H., Yang, F., 2011. A novel approach to evaluate the permeability of cake layer during cross-flow filtration in the flocculants added membrane bioreactors. Bioresour. Technol., 102, 11121 – 11131.

Zhang, K., Cui, Z., Field, R.W., 2009. Effect of bubble size and frequency on mass transfer in flat sheet MBR. J. Membr. Sci. 332 (1-2), 30-37.

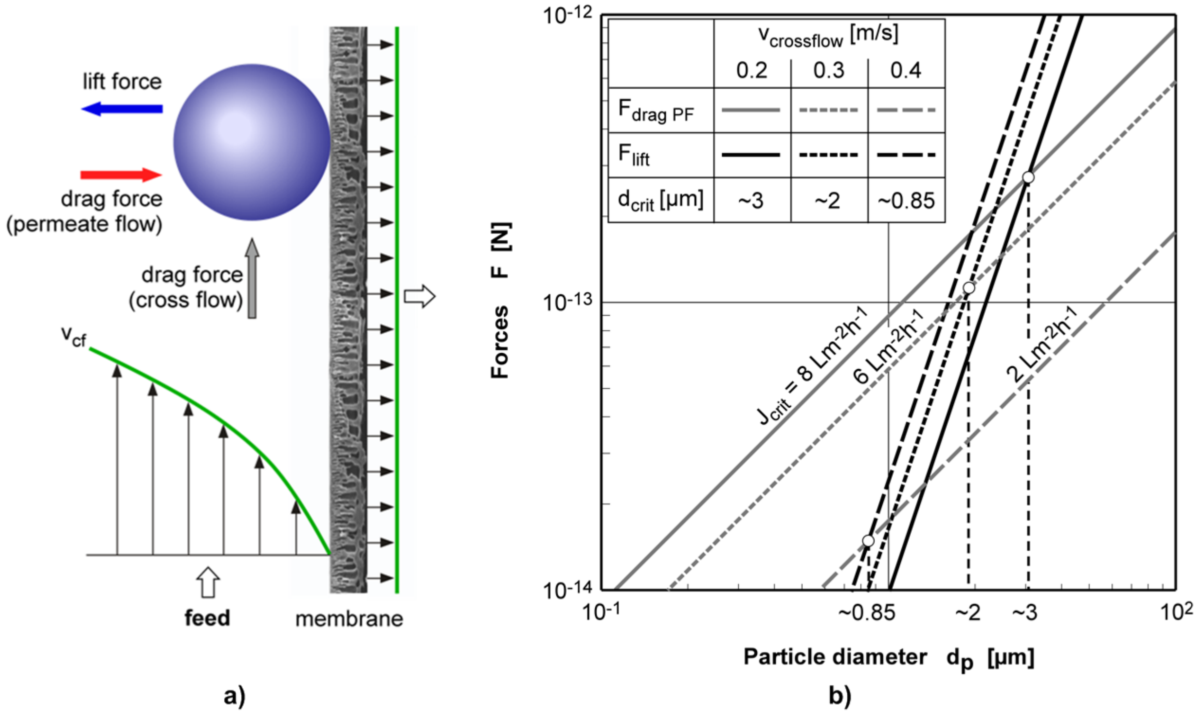

Figure 1. a) Illustration of the hydrodynamic forces acting on a single particle, b) theoretical critical particle diameter (FS, membrane gap 5mm, Drews et al. 2010)

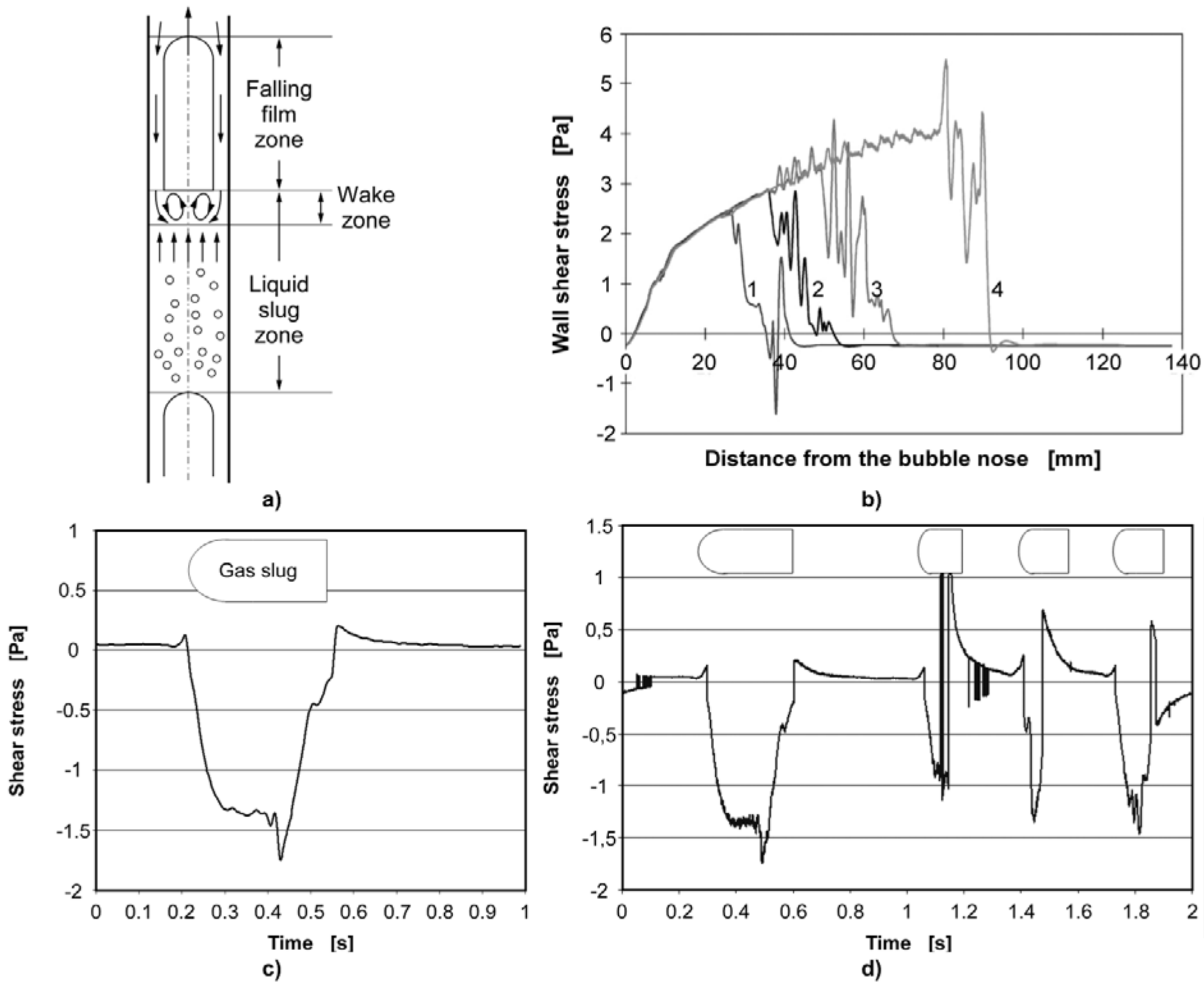

Figure 2. a) slug bubble flow zones (adapted from Ghosh and Cui 1999) and wall shear stress values derived b) numerically (CFD) for slug bubbles of different volumes [1: 2.2 mL; 2: 3.3 mL; 3: 5.0 mL; 4: 8.3 mL] (Taha and Cui 2002); c) experimentally for a single slug bubble (Ratkovich et al. 2009); d) experimentally for series of coalescing slug bubbles (Ratkovich et al. 2011a,b); location of gas slug(s) with respect to shear stress measurements provided schematically for figures c and d.

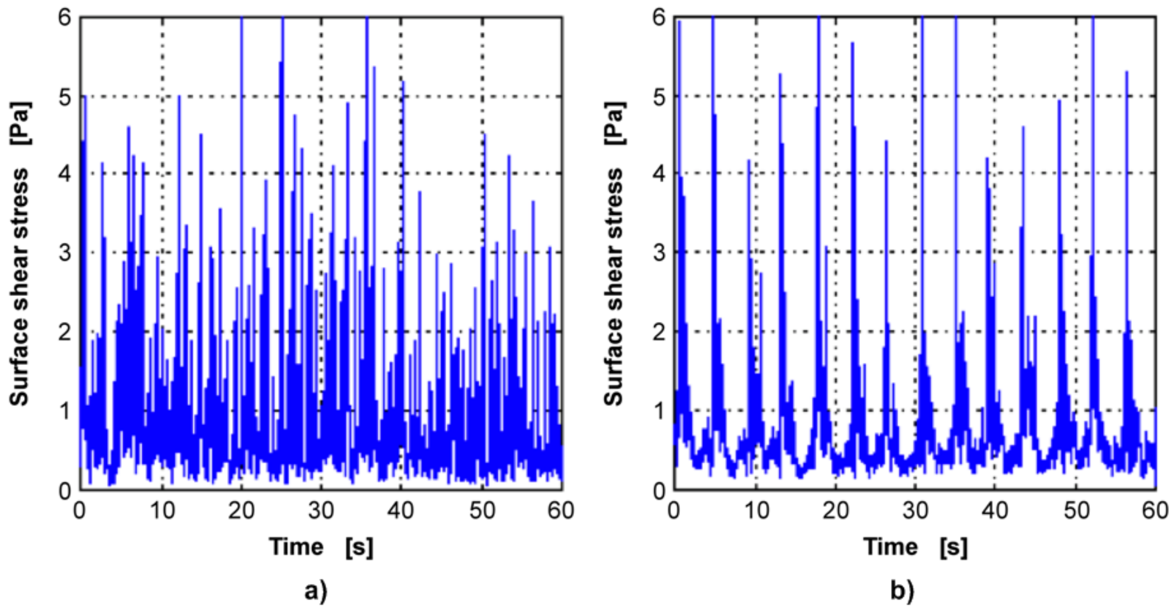

Figure 3. Typical shear stress induced on HF for different sparging approaches (a: continuous coarse bubble sparging; b: large spherical cap bubble sparging; note: same flow rate applied to both conditions) (Ye 2012)

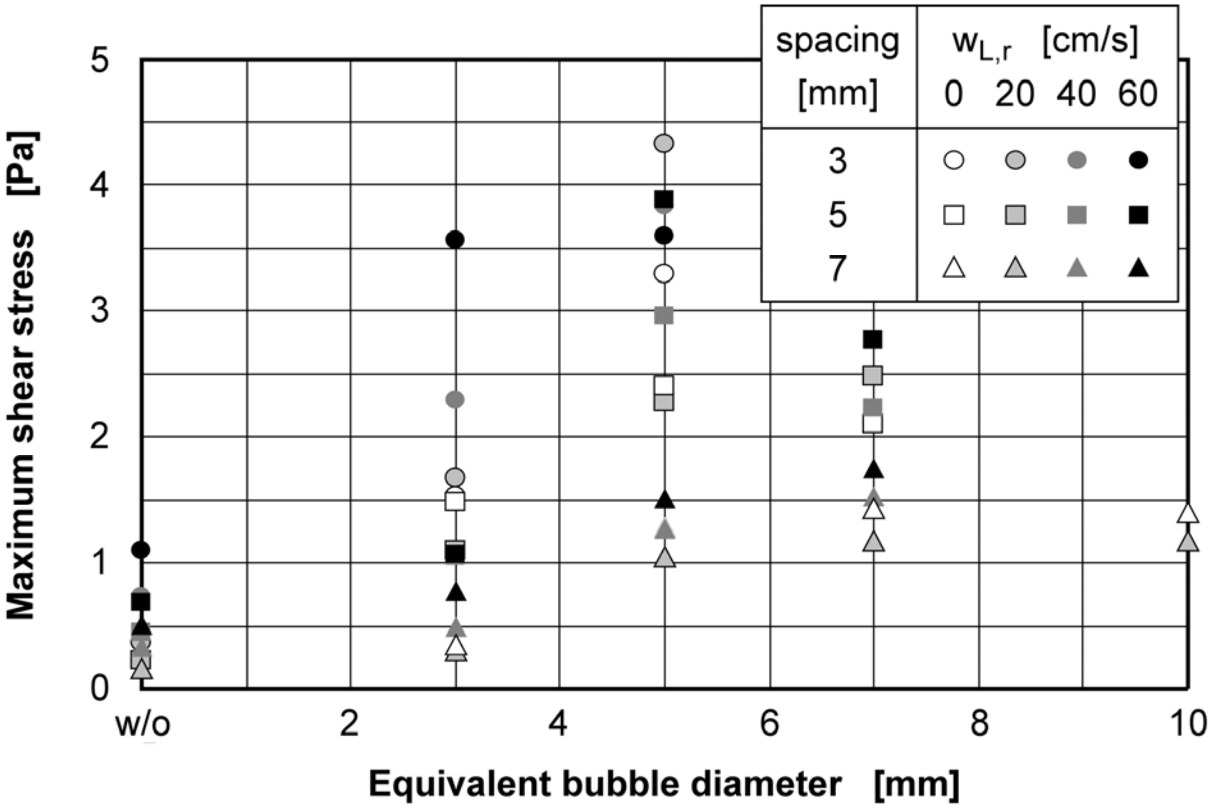

Figure 4. CFD determination of maximum wall shear stress exerted by differently sized bubbles rising at terminal rise velocity in channels of different widths (Prieske et al. 2010).

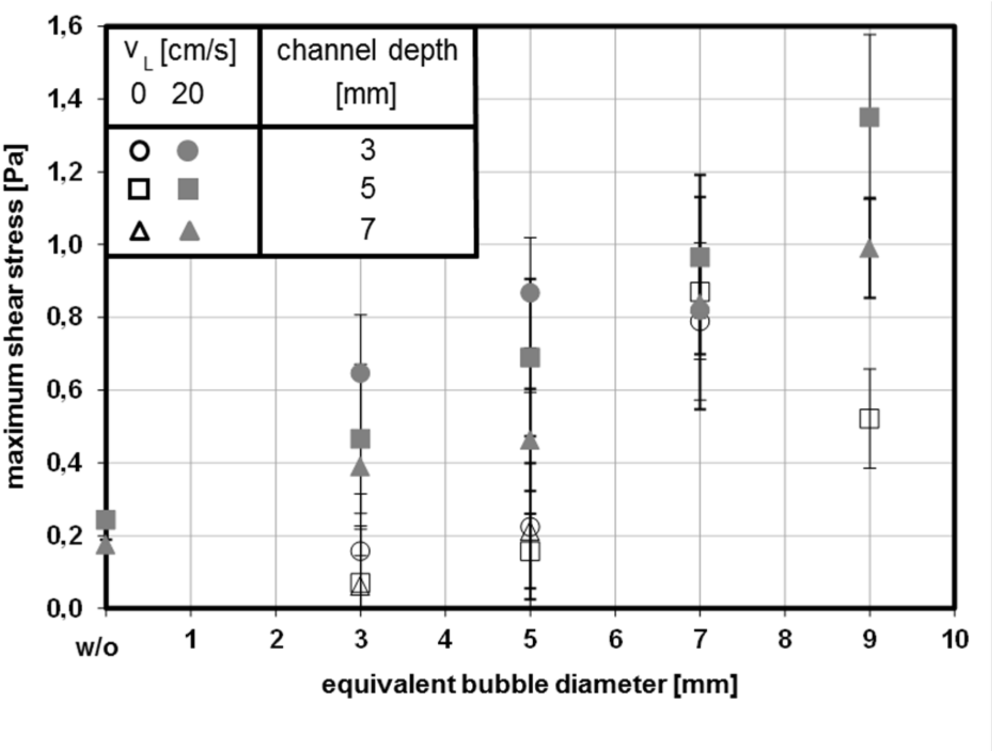

Figure 5. Experimental results for maximum wall shear stress exerted by differently sized bubbles rising at terminal rise velocity in channels of different widths.

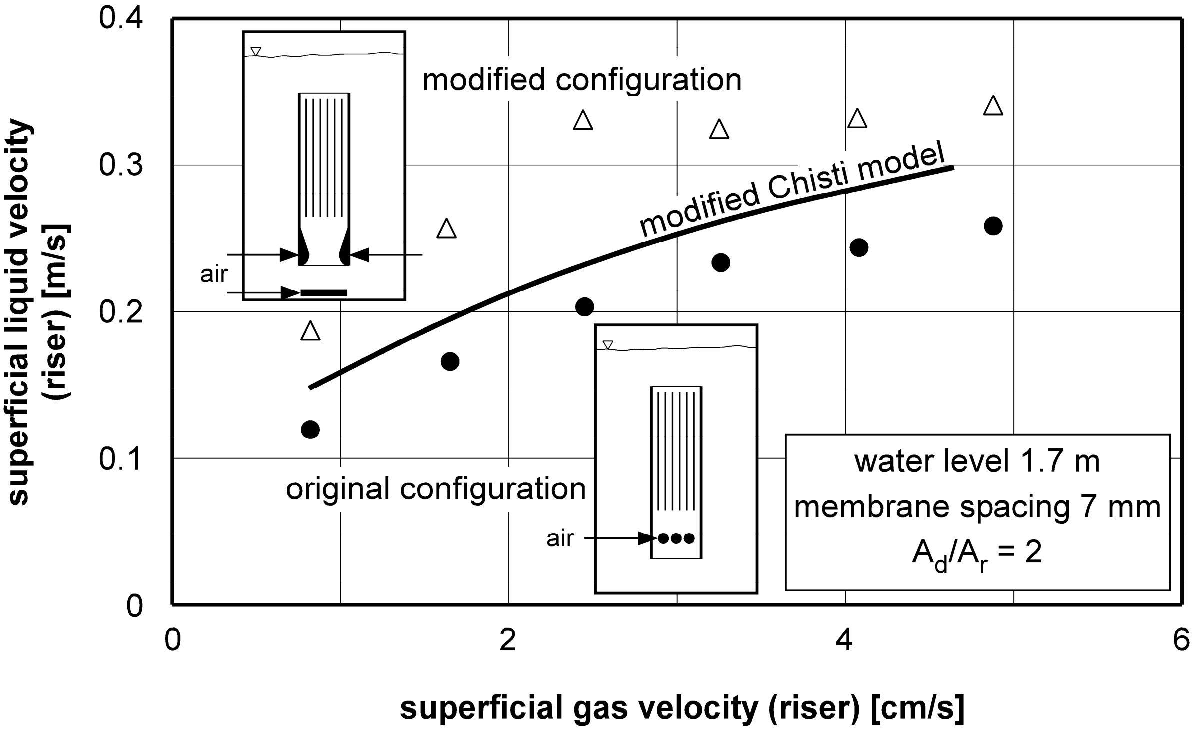

Figure 6. Increase in liquid velocities achieved by modified aerator and installed flow bodies (adapted from Prieske et al. 2010): (●) original and (Δ) modified configuration and comparison with the modified Chisti model for the original configuration (see Section 5).

Table 1: Publications dealing with fluid dynamics in membrane research sorted by the different measurement techniques (see also Chen et al. 2004)

Ref.	Measurement technique	Membrane geometry / single, several	Set-up height [mm]	System	filtration	Varied parameters	quantity	Brief result
Bérubé et al. 2006	EDM	hollow fiber / single	~500	air/ electrolytic solution	no	single/two-phase, fiber swaying and tightness	shear stress	two-phase flow produces higher shear stress than single phase
Chan et al. 2007a	EDM	hollow fiber / several	~150	air/ electrolytic solution	no	packing density	shear stress	Fiber packing density and looseness, as well as bubble size affect shear stress
Ducom et al. 2003, 2002	EDM	flat sheet / single	147	air/ electrolytic solution	yes	aeration rate	shear stress, flux	shear stress not evenly distributed on the membrane
Fulton et al. 2011a,b	EDM	hollow fiber / real module	2160	air/ electrolytic solution	no	aeration rate	shear stress	3-D maps of the shear stress distribution
Gaucher et al. 2003, 2002a,b,c,d	EDM	flat sheet / single	122	air/ electrolytic solution (with particles)	yes	channel width, liquid distributor shapes, viscosity	shear stress, flux	fluctuating shear stress has positive effect on the cleaning
Ratkovich et al. 2011a,b, 2010, 2009	EDM	tubular/ single	2000	air/ electrolytic solution	no	liquid flow rate, gas flow rate, viscosity	shear stress	conditions for fluctuating shear stress
Zhang et al. 2009	EDM	flat sheet / single	1000	air/ electrolytic solution	no	air flow rate, bubble size and frequency	shear stress	strong influence of bubble size and frequency on shear stress
Essimiani et al. 2001	DO	flat sheet / single	147	air/ water	no	-	bubble velocity	results for bubble behaviour
Khalili-Garakani et al. 2011, 2009	DO	flat sheet / module	700	air/ act. sludge	yes	riser and downcomer area, air flow rate	bubble size, shear stress, resistance	influence of the flux on the shear stress
Li et al. 1998	DO	flat sheet / single	96	protein solution	yes	liquid flow rate	cake thickness	composition of the cake depends on the liquid flow rate
Ndinisa et al. 2006a,b	DO	flat sheet / single	490	air/ water or synthetic wastewater	yes	aerator configuration, baffles	bubble size + distribution	influence of design and operating conditions on the filtration
Phattaranawik et al. 2006	DO	flat sheet / module	~125	air/ synthetic wastewater	yes	air flow rate, flux, bubble size	bubble size	larger bubble size better for bubble distribution and fouling control

L. Böhm, A. Drews, H. Prieske, P. R. Bérubé, M. Kraume, The importance of fluid dynamics for MBR fouling mitigation, Bioresource Technology, Volume 122, October 2012, Pages 50-61, ISSN 0960-8524, 10.1016/j.biortech.2012.05.069

Table 1: Publications dealing with fluid dynamics in membrane research sorted by the different measurement techniques (continued)

Ref.	Measurement technique	Membrane geometry / single, several	Set-up height [mm]	System	filtration	Varied parameters	quantity	Brief result
Prieske et al. 2008	DO	flat sheet / module	1700	air/ water	no	air flow rate, bubble size	gas holdup, bubble distribution	model for the liquid circulation velocity in air lift loop configurations
Ratkovich et al. 2010	DO	tubular / single	2000	air/ electrolytic solution (with carboxy methyl	no	liquid flow rate, air flow rate	gas slug rising velocity	gas slug behaviour in Non-Newtonian liquids
Drews et al. 2008	DO	Flat sheet / single	1700	air/ water, air/ act. sludge	(yes)	channel width, bubble size, air flow rate, liquid flow rate	bubble velocity, liquid velocity	air and liquid flow affect the composition of the cake
Ye et al. 2011	DO	hollow fiber / single	50	bentonite and sodium alginate solutions	yes	backwash periods	cake thickness	composition of the cake depends on the hydrodynamics
Nagaoka et al. 2003	SSS	flat sheet / single	1000	air/ water (with methyl cellulose)	no	air flow rate, Newtonian viscosity of the liquid	shear stress	influence of different Newtonian viscosities on the shear stress
Yamanoi et al. 2010	SSS	flat sheet / single	600	air/ water	no	air flow rate, channel width, aerator type	shear stress, resistance	mean and standard deviation of the shear stress can be regarded as one parameter
Le-Clech et al. 2006a	HWA	flat sheet / single	105	air/ whey-based solution	no	Feed concentration, sensor position, gas flow rate	liquid velocity	potentials and limitations of HWA in membrane applications
Wicaksana et al. 2009	HWA	hollow fiber / several	~250	water with particles	yes	various operating conditions	permeate flow distribution	potentials and limitations of HWA in membrane applications
Gaucher et al. 2002b	PIV	flat sheet / single	122	air/ water (with particles)	yes	channel width, liquid distributor shapes,	shear stress, flux	fluctuating shear stress has positive effect on the cleaning
Martinelli et al. 2010	PIV	hollow fiber / several	~820	air/ water (with particles)	yes	air flow rate, bubble size	liquid velocity, shear	air flow rate is more important for the high shear stress than bubble size
Wereley et al. 2002	PIV	rotating disc / single	~450	glycerol-water with salt and particles	no	type of fluid and particles	velocity profiles	distribution of the particles

Table 1: Publications dealing with fluid dynamics in membrane research sorted by the different measurement techniques (continued)

Ref.	Measurement technique	Membrane geometry / single, several	Set-up height [mm]	System	filtration	Varied parameters	quantity	Brief result
Chung et al. 1993	NMR	curved flat sheet / single	~350	water doped with copper(II) sulphate	no	liquid flow rate	Dean vortices	turbulence promoters suggested
Heath et al . 1990	NMR	hollow fiber / single/ several	~310	water doped with copper(II) chloride	no	liquid flow rate	liquid flow distribution	improvements of the design and operation
Pangrle et al. 1989, 1992	NMR	hollow fiber / module	50	water	no	liquid flow rate	liquid flow distribution	comparison of measurement methods
Poh et al. 2003	NMR	hollow fiber / module	~220	water doped with copper(II) sulphate	no	liquid flow rate, baffles	liquid flow distribution	baffles did not improve the liquid flow distribution
Nguyen Cong Duc et al. 2008	BOP	hollow fiber / module	3150	air/ water	no	air flow rate	bubble size + distribution,	gas distribution in a membrane tank
Prieske et al. 2010	IA	flat sheet / module	1200	air/water	no	channel width, air flow rate	rise velocity, shear stress, liquid velocity	aerator modification for better bubble distribution, model describing the liquid circulation velocity
Ozaki and Yamamoto 2001	OP	flat sheet / single	570	water / act. sludge	yes	channel width, air flow rate	liquid velocity	hydrodynamic results obtained with water can be used for sludge as well
Sofia et al. 2004	EVM	flat sheet / single	400	air / act. sludge	yes	air flow rate	liquid velocity	smaller bubbles preferable for higher circulation liquid vel.
Yamanoi et al. 2010	EVM	flat sheet / single	600	air / water	no	air flow rate, channel width, aerator type	liquid velocity	mean and standard deviation of the shear stress can be regarded as one parameter
Tacke et al. 2008	ADV	flat sheet / module	3080	air / water (with glycerol)	no	aeration rate	liquid velocity, flow	bubbles unevenly distributed in the module

Table 2: Publications dealing with computational fluid dynamics and fouling mitigation in membrane research

Ref.	Objective	Membrane geometry	Fluids	filtration	CFD-code / modells	Brief result
Bütehorn et al. 2011	Impact of irregular fiber arrangement on aeration efficiency	HF with irregular orientation as a porous region	air/ model solution	no	FLUENT , VOF, Eulerian, k-ε RNG	higher local porosity leads to higher local velocity and less turbulence, averaged turbulence increases with inlet velocity and reduced solid concentration
Essemiani et al. 2001	Shape and motion of large bubbles in FS	FS / single gap without downcomer	air / water	no	n.s., VOF	VOF is able to compute the shape and the motion of a bubble, 2D simulation without wall effects
Fimbres-Weihs et al. 2007	impact of spacers in 3D-channel on mass transfer	3D membrane channel	air/ model solution	yes	FLUENT	enhanced mass transfer in the wake of the spacer was observed, implication of an improved spacer mesh were discussed
Kang et al. 2008	hydrodynamic characteristic of MBR (plant level)	HF modules as porous regions	air/ sludge model	yes	FLUENT, Eulerian	3D results for the gas and velocity distribution in the reactor, geometrical modifications of the MBR derived
Khalili-Garakani et al. 2011, 2009	Multiphase flow characterisation in an airlift loop	FS / single panel	air/ water, or sludge	no	n.s., Eulerian, k-ε	Influence of aeration intensity, liquid level and baffle inclination on circulation velocity in an airlift loop configuration
Ndinisa et al. 2006b	flow characterisation in FS module with and without baffles	FS / single gap without downcomer	air/ water	no	CFX, Eulerian, k-ε	flux enhancement primarily due to increase of the overall shear stress, enhanced cleaning effects for increasing bubble diameters until bubble size and membrane distance are in the same range
Prieske et al. 2010	shear stress around single bubbles, circulation velocity in an aerated MBR	FS / single membrane gap and MBR	air/ water	no	FLUENT, VOF, CFX, Eulerian	optimal values for bubble size and membrane spacing, mathematical model for the liquid circulation velocity in air lift loop configurations
Ratkovich et al. 2009	shear stress and velocity distribution around gas slugs	tubular / single	nitrogen/ water	no	FLUENT, VOF, k-ε RNG	validation of calculated shear stress by experimental data (EDM)
Taha et al. 2006	shear stress and flow field around gas slugs in UF	single tubular/ with different inclinations	air/model solution	yes	FLUENT, VOF	Highest shear stress for inclination of 45°, enhancement of mass transfer particularly in the turbulent wake region