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Fouling Control in a Submerged Flat Sheet Membrane System: Part I - Bubbling and Hydrodynamic Effects

N. V. Ndinisa[a]; A. G. Fane[b]; D. E. Wiley[b]
[a] Department of Chemical Engineering, Durban Institute of Technology, Durban, South Africa [b] UNESCO Centre for Membrane Science and Technology, University of New South Wales, NSW, Australia

To cite this Article Ndinisa, N. V. , Fane, A. G. and Wiley, D. E.(2006) 'Fouling Control in a Submerged Flat Sheet Membrane System: Part I - Bubbling and Hydrodynamic Effects', Separation Science and Technology, 41: 7, 1383 — 1409
To link to this Article: DOI: 10.1080/01496390600633873
URL: http://dx.doi.org/10.1080/01496390600633873

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Separation Science and Technology, 41: 1383–1409, 2006
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ISSN 0149-6395 print/1520-5754 online
DOI: 10.1080/01496390600633873

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Fouling Control in a Submerged Flat Sheet Membrane System: Part I – Bubbling and Hydrodynamic Effects

N. V. Ndinisa
Department of Chemical Engineering, Durban Institute of Technology, Durban, South Africa

A. G. Fane and D. E. Wiley
UNESCO Centre for Membrane Science and Technology, University of New South Wales, NSW, Australia

Abstract: Submerged flat sheet membranes are mostly used in membrane bioreactors for wastewater treatment. The major problems for these modules are concentration polarization and subsequent fouling. By using gas-liquid two-phase flow, these problems can be ameliorated. This paper describes a study of the use of gas-liquid two-phase flow as a fouling control mechanism for submerged flat sheet membrane bioreactors. The effect of various hydrodynamic factors such as airflow rate, nozzle size, intermittent filtration, channel gap width, feed concentration, imposed flux, and the use of membrane baffles were investigated. Experiments conducted on model feeds showed that fouling reduction increased with air flow rate up to a given value and beyond this flowrate no further enhancement was achieved. The effect of bubbling was also found to increase with nozzle size at constant airflow. Using intermittent filtration as an operating strategy was found to be more effective than continuous filtration and it also reduced energy requirements. The study showed the importance of the size of the gap between the submerged flat sheet membranes. As the gap was increased from 7 mm to 14 mm, the fouling became worse and the degree of fouling reduction by two-phase flow decreased by at least 40% based on suction pressure rise (dTMP/dt). This is the first study which has reported the effects of baffles in improving air distribution across a flat sheet submerged membrane. It was found that

Received 1 January 2006, Accepted 2 March 2006
Address correspondence to A. G. Fane, UNESCO Centre for Membrane Science and Technology, University of New South Wales, NSW 2052, Australia. E-mail: a.fane@unsw.edu.au

baffles could decrease the rate of fouling by at least a factor of 2.0 based on the dTMP/dt data, and significantly increase critical flux.

Keywords: Submerged membrane bioreactor, aeration, flat sheet membrane, membrane baffles, microfiltration, intermittent filtration, wastewater treatment

INTRODUCTION

Membrane bioreactor (MBR) technology offers several advantages over the conventional processes currently available; the treated water is clear (1); the plant can operate at very high volumetric loads—up to 20 kg COD/m^3 per day (2); organic and nitrogeneous compounds are eliminated efficiently (3, 4); the sludge production is low—about 0.25 kg SS/kg COD for long sludge residence times (5, 6); the footprint size of the plant is reduced significantly (7). This is possible because the separation of the biomass from effluent by means of membranes allows the concentration of mixed liquor suspended solids (MLSS) in the bioreactor to be increased significantly, thus reducing its size for a given sludge. The last decade has seen a rapid development in the field of membrane bioreactors. Within a short space of time the technology has progressed from laboratory-scale research to full-scale application for flows in excess of 70 000 m^3/d. Most commercial MBRs use submerged membrane modules which are either hollow fibers or flat sheets (8). The reason for this is that energy consumption of submerged MBRs is potentially lower than that of sidestream MBRs. Submerged MBRs systems have now been in operation for over 15 years and they have proven to be both reliable and simple to operate (9).

However, the development of membrane bioreactors has been limited by problems of membrane fouling during filtration of the activated sludge, which decreases the sustainable filtration flux and thus, the treated output water flow. Almost all commercial submerged MBRs use the technique of air scouring in order to combat membrane fouling. The air is also used by microorganisms in the aerobic biodegradation process. The air bubbles scour the surface of the membrane and generate the liquid crossflow velocity without the need for a recirculation pump. For submerged MBRs energy consumption rates have been reported as $\leq 1\,\mathrm{kWh \cdot m^{-3}}$ (10). More than 50% of this energy was used for air scouring. There is a need to reduce this fraction of air used for air scouring in order to make the MBR technology an even more commercially viable alternative to conventional wastewater treatment processes. To date there has been considerably more attention given to the application of two-phase flow in submerged hollow fibre systems than to submerged flat sheet membranes. Limited data of a fundamental nature have been published for bubble interactions with submerged flat sheet membranes. This limited data has largely come from commercial suppliers of membrane systems and, as a result, much of the know-how is not published. There is therefore a need to

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study the use of gas-liquid two-phase flow for submerged flat sheet membranes in order to fully understand the mechanisms involved in flux enhancement so that the process can be optimised.

The aim of this study was therefore to investigate the use of gas-liquid two-phase flow as a fouling reduction mechanism for a submerged flat sheet system employing a Kubota type membrane module. The motivation for this study arose from the importance of optimizing operating conditions for fouling control. Effects of various hydrodynamic conditions on fouling were investigated such as different airflow rates, different nozzle sizes, effect of concentration, effect of imposed flux, the effect of channel gap width between submerged flat sheet membranes and the effect of using membrane baffles. In addition, the impact of continuous and non-continuous permeate suction on trans-membrane pressure increase was evaluated. In order to access the effects of these different hydrodynamic conditions, it was decided that a model feed (yeast suspension) would avoid problems due to feed variability. However in order to confirm that the trends obtained with the yeast suspension were applicable for wastewater biomass, a suspension of waste activated sludge was also used as feed in some tests. Therefore it should be noted that the system studied here was not an actual MBR. However, the hydrodynamic conditions investigated were similar to those found in a typical MBR, and the results should be relevant to MBRs with flat sheet submerged membranes.

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MATERIALS AND METHODS

Experimental System

Experiments were done on a laboratory-scale unit. The experimental rig (Fig. 1) consisted of a 20 L acrylic tank (open to the atmosphere) with slots to fit up to eight submerged flat sheet membranes. However only one flat sheet membrane was utilized in this study, therefore the rest of the tank was cut-off by inserting an acrylic tank divider. The design of the experimental rig was based on a scaled down version of the Kubota submerged MBR geometry. The membrane used in this study was a Kubota flat sheet (A4 size) micro-filtration membrane with a nominal pore size of 0.4 μm and 0.1 m^2 filtration area. The membrane was supplied by Yuasa Cooperation of Japan. The gap between the membrane and the wall was kept at 7 mm for most of the experiments. This dimension is important as it defines the width of the flow channel available for bubble flow. Filtration in a submerged system occurs from the outside of the membrane and the permeate is forced to pass to the inside of the membrane. In these experiments, this was achieved by creating a reduced pressure on the permeate side using a Masterflex peristaltic pump which could provide a constant imposed permeate flux. The permeate flux was monitored by measuring the rate of change of weight of permeate collected on a beaker placed on an electronic balance which was

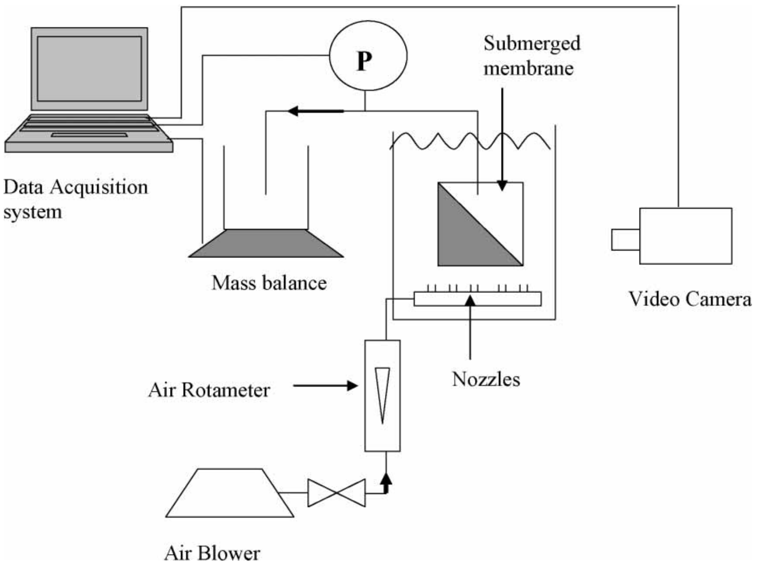

Figure 1. Schematic diagram of experimental setup.

connected to a data acquisition system. A maximum of 1 L of permeate was collected and thereafter, the permeate was returned to the feed tank by means of a timer-controlled solenoid valve. This ensured almost constant concentration of the feed in the feed tank.

The trans-membrane pressure (TMP) was monitored by a pressure transducer on the suction line between the suction pump and the membrane. A Labom pressure transducer was used and was connected to a data acquisition system for logging of TMP data. The values of TMP logged were negative (vacuum), however, for all the graphs shown in this paper, absolute values are plotted. Air required for scouring the membrane was introduced 10 cm beneath the membrane via a set of nozzles made by drilling 10 holes on a 12 mm (half inch) stainless steel tube. Circular nozzles of different diameters: 0.5, 1.0, 1.5, and 2.0 mm were used. A Hillblow air blower capable of delivering up to 80 L/min of air was used to supply the air. The required airflow rate was obtained by using regulator valve located next to a Gilmont air rotameter.

The geometry setup of the process tank utilized in this study (described above) resembled that of a narrow rectangular bubble column. Thus it was expected that the two-phase flow pattern in the tank would be similar to the kind of patterns usually reported for two-dimensional bubble columns. Indeed, observations revealed that the bulk of the air flowed towards the center of the column, resulting in an uneven distribution of bubbles scouring the membrane surface. This phenomenon has been observed in other bubble column studies such as those of Jakobsen et al. (11) and Lapin

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and Lübert (12). In response to this a series of experiments were done where baffles were inserted in the space between the membrane and the tank walls to correct this uneven distribution of bubbles. An example of the baffles used is depicted in Fig. 2.

Experimental Conditions and Procedures

Initially a suspension made from commercially available dry bakers yeast was chosen as the model feed. This type of suspension was selected based on its ease of availability and also because it has properties which imitate those of mixed liquor, such as cellular materials, cell debris, and extra-cellular materials. The feed suspension was prepared by measuring a desired amount of yeast and diluting it with water to a volume of one litre. This solution was then left to stand in an ultrasonic bath for 10 minutes; thereafter the solution was further diluted to fill up the process tank and was thoroughly mixed. The yeast was not washed during this process. In order to ensure similar starting conditions for all experiments, the membrane was soaked overnight in a cleaning solution made up of 0.5% w/w sodium hypochlorite. This treatment effectively restored membrane permeability. Another set of experiments were carried out using waste activated sludge as a model feed. The sludge was collected on a daily basis from the Northern Wastewater Treatment Works in the city of Durban. At the time of the tests this plant had an SRT of 15 days to 20 days, an HRT of about 10 hours and an MLSS concentration of about 6 g/L.

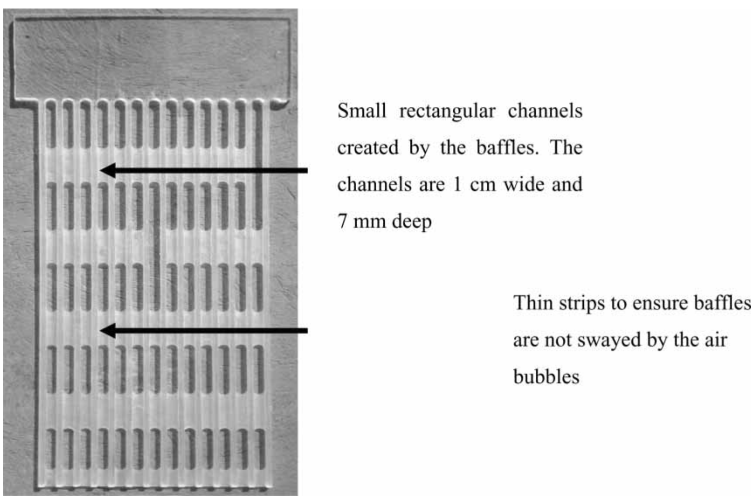

Figure 2. A photograph showing the structure of baffles inserted between the membrane and the wall.

Experiments were conducted at different aeration rates ranging from 2 to 20 L/min or from 20 to 200 L/min per m^2 of membrane area for cases with and without baffles. This range covered well the typical aeration rates used in commercial submerged flat sheet membranes although with submerged hollow fibers aeration rates as low as 10 L/min per m^2 of membrane area are now possible thanks to intermittent aeration (13). Experiments were also conducted at constant airflow rates but different nozzle sizes. For the yeast suspension investigations, experiments were done at three different feed concentrations of 5, 10 and 15 g/L. For all the experiments reported in this paper, the initial imposed flux was 40 l/m^2hr unless stated otherwise. Investigations were also carried out to determine the effect of the gap width between the membrane and the walls. Experiments were done with gap widths of 7 and 14 mm. Intermittent suction versus continuous suction was also studied to confirm its viability as an alternative fouling control strategy.

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RESULTS

Effects of Airflow Rate and Nozzle Size

In the initial yeast suspension experiments, the effects of aeration rates on fouling reduction for a submerged flat sheet membrane were investigated from 2 to 8 L/min airflow using nozzles of different sizes from 0.5 to 2.0 mm. The extent to which each flowrate and nozzle size was successful in minimizing fouling was judged by the degree to which the rise in TMP had been curbed. Figure 3 shows TMP versus time data for different flowrates with nozzles of 0.5 mm being used at a concentration of 5 g/L.

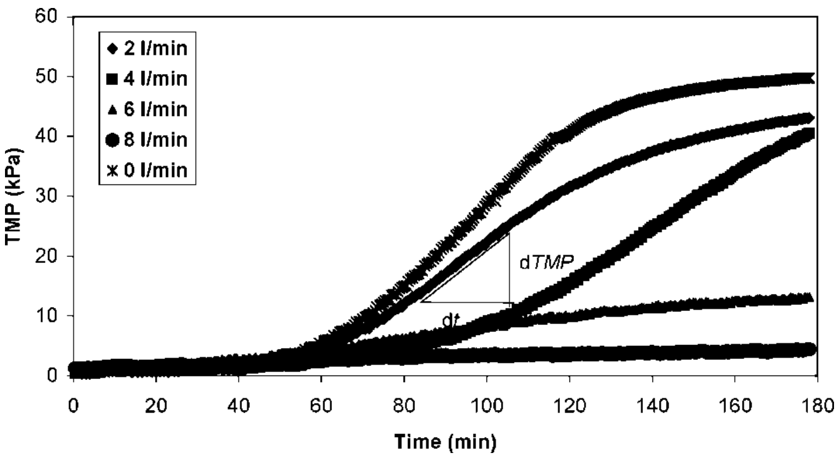

Figure 3. Variation of TMP with time at different airflow rates for the nozzle size of 0.5 mm and concentration is 5 g/L.

Similar trends were obtained for nozzles of other sizes. From this figure it can be seen that, for both no air (0 L/min) and low airflow (2 L/min), the system showed first a slow rise of the TMP followed by a significant TMP rise which slowed down approximately after 3 hours of operation. For the higher gas flow rates, TMP was still increasing after 3 hours. For the low gas flow rates, the TMP curve is composed of three distinct regions. Several researchers (14–16) have also reported such TMP trends in constant flux MBRs. During submerged MBR operation, Nagaoka et al. (14) observed such a transition in TMP and modelled this by assuming that fouling resistance was due to EPS deposition and that the foulant was compressible with a specific resistance that increased with TMP. Cho and Fane (16) studied the cross-flow MF of an anaerobic reactor effluent at nominally subcritical flux. They attributed the slow TMP rise to gradual EPS fouling, the distribution of this fouling was found to vary locally leading to a distribution of local fluxes. The sudden rise in TMP was explained as due to local fluxes in some areas exceeding the critical flux of the dominant foulant.

In the first part of the TMP curve, the membrane is relatively clean, there is low resistance across the membrane and thus low TMP. Eventually the cake layer increases and the cake becomes more compact, leading to a higher resistance. This causes the TMP to start to rise rapidly as in the second part of the curve, as the resistance continues to increase with the build-up of the cake. In the experiments with zero and low gas flow rates, the TMP reached 40 to 50 kPa after which the TMP rise slowed down (but was not zero). The explanation for this third stage is complex. One explanation is based on analogy with submerged hollow fibers where the rapid rise in TMP followed by a slower rise has been attributed to a shifting of the flux distribution as fouling occurs (17). Thus flux is initially located where the suction pressure is highest and then as this region fouls, with rapid TMP changes, the maximum driving force relocates so that eventually all zones of the membrane experience the surface averaged flux. The fact that TMP rise slows once TMP is relatively high (recall the driving force is suction) also suggests that a point is reached where the permeate pump is unable to maintain the desired flow. Decline of flux was most observed at the higher concentrations of 10 and 15 g/L. A similar flux decline for a submerged MBR system was also observed by Shimizu et al. (18) When high bubbling rates were employed, there would have been a more effective removal of particles from the membrane surface which explains why the TMP rise was slower and after three hours of operation the steady state TMP had not been reached yet.

With the yeast suspension, airflow rates of only up to 8 L/min were investigated, and no optimal bubbling rates were observed as can be seen in Fig. 3. Fouling reduction improved continually with an increase in the airflow, and the airflow rate of 8 L/min yielding the lowest TMP increases. A wider range of airflow rates (up to 20 L/min) were investigated with the waste activated sludge suspension in order to determine whether an optimum bubbling rate exists. Figure 4 shows steady state or final TMPs obtained

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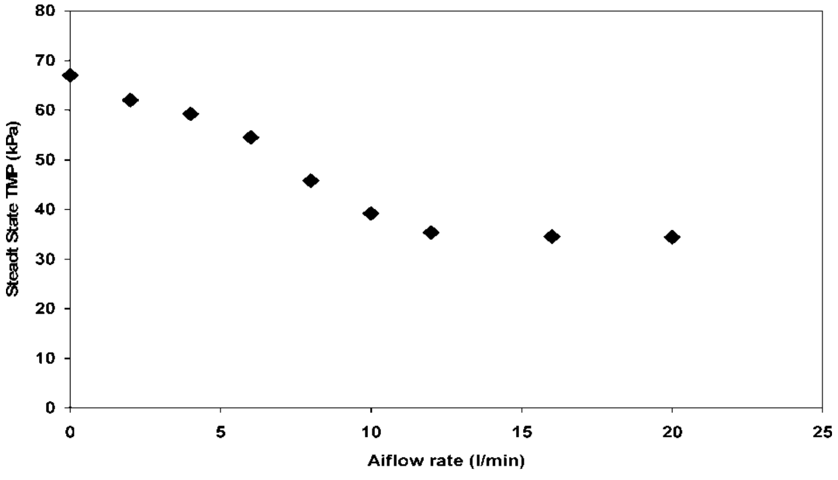

Figure 4. Final or steady state TMPs achieved with the waste activated sludge filtration at different airflow rates for a nozzle size of 2.0 mm.

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with the activated sludge suspension. It is clear from Fig. 4 that air bubbling, no matter how small, plays an important role in reducing the increase in TMP over time which indicates the fouling of the membrane.

Data in Fig. 4 suggests that the airflow rate of 12 L/min might be an optimal gas flow rate for this system. One way of explaining the optimal bubbling rate is that above a certain gas flow rate, a balance is reached between the rate at which particles are transported to the membrane wall due to the permeate flux and the rate at which they are carried away from the membrane due to shear induced by bubbling. Once this balance is reached any further increase in the gas flow rate does not have any significant effect on reducing fouling if the suction force is kept constant. It is also possible that during filtration, irreversible internal fouling of the membrane occurs which cannot be removed by any further increase in the gas flow rate. Another factor maybe due to the effect of bubbling on the floc size distribution, with small floc sizes developing due to breakup as the bubbling is increased.

In submerged flat sheet membrane bioreactors (MBRs), the gas is introduced into the tank containing the membranes by means of nozzles located on a diffuser which is placed underneath the membranes. The nozzle size can have an impact on the bubble size distribution and thus on the gas-liquid two-phase flow profile. This in turn may affect the cleaning efficiency of the two-phase flow. Commercial submerged flat sheet MBRs use nozzles of different sizes, for example, the Kubota MBR initially made use of circular nozzles of 10 mm in diameter and then changed to 4 mm diameter nozzles (19) and the Zenon Environmental Ltd. hollow fiber MBR uses large rectangular slots (8). Circular nozzles of different sizes have been used in this study in order to determine the extent to which the size of the nozzle affects two-phase flow and ultimately the flux enhancement. Figure 5 shows the rate of change of trans-membrane pressure (dTMP/dt) versus airflow rate and nozzle size for the yeast suspension. The dTMP/dt data shown in Fig. 5 were calculated after two hours of experimentation. The rate of change of TMP with time (dTMP/dt) represents the fouling rate; the higher the rate of change of TMP, the faster is the fouling rate. Figure 5 indicates that the greatest fouling rate occurs with the smallest nozzle and smallest air flow rate. The beneficial effect of larger nozzle size observed here for the submerged flat sheet has not been observed for submerged hollow fibers, where marginally better fouling control appears to come from smaller size nozzles (20). The reasons for these differences may be due to the different flow paths and effects bubbles can have between flat vertical walls and in and around flexible bundles of fibres.

In order to obtain further insights into the effectiveness of aeration rates and nozzle sizes on fouling reduction, TMP reduction factors were computed. In most previous studies in which gas-liquid two-phase has been studied, the flux enhancement factor was used as a measure of the effectiveness of bubbling (21–23). This criterion cannot be applied in this study as flux is fixed. In this study the TMP reduction factor, computed as follows, was used as a measure of the effectiveness of bubbling.

$$\phi = \frac{\text{Final TMP achieved without gas bubbling}}{\text{Final TMP achieved with gas bubbling}} \quad (1)$$

Thus $\phi > 1.0$ indicates improvement. Figure 6 shows TMP reduction factors for the runs at 5 g/L calculated using Equation (1). This figure

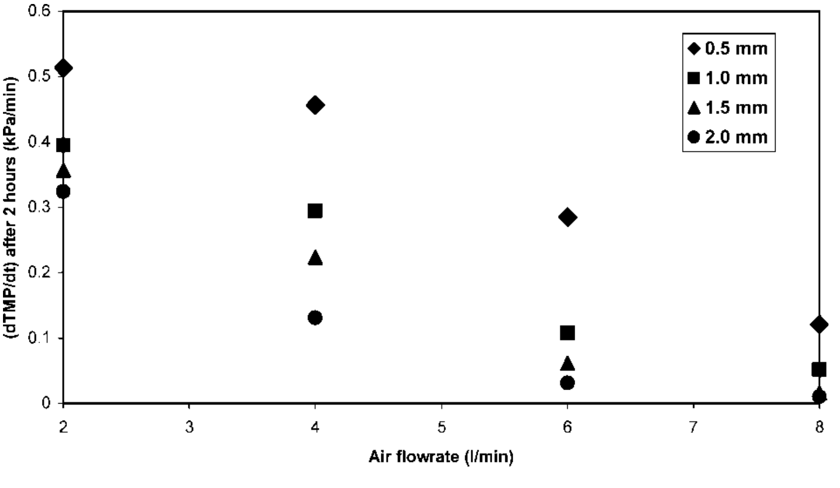

Figure 5. dTMP/dt values determined after two hours of yeast filtration for non–baffle cases.

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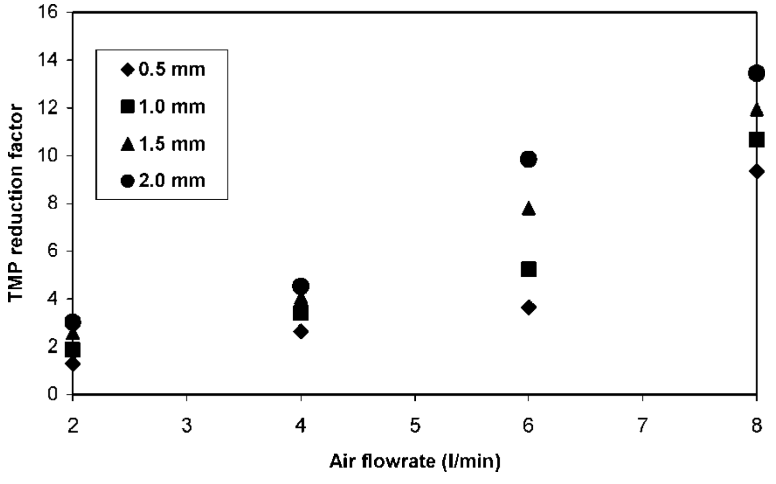

Figure 6. TMP reduction factors at two hours plotted against the air flow rate for runs without baffles.

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shows that the extent of TMP reduction increases with both the nozzle size and the airflow rate. This is somewhat contrary to findings in some other membrane studies (24, 25), where the advantage gained by bubbling was found to be the greatest with a smaller bubbling rate and to decrease when the bubbling rate was increased. However these studies were not for submerged membranes but for flow inside tubes or fibers. In the case of bubbles or slugs inside tubes an increase in air flow may increase the slug length, rather than the number of slugs (and slug wakes). The data here for submerged flat sheets can be compared to studies on submerged hollow fibers (17) where increase in bubbling also improves performance although the benefit reaches a "plateau" where further gas rate increase has little effect. The same trend could be anticipated for submerged flat sheets, as was observed with the activated sludge suspension as shown in Fig. 4.

Effects of Baffles

As noted earlier, in narrow rectangular bubble columns, migration of bubbles towards the channel centre is a well reported phenomenon (11, 12, 26). With the geometry setup of the experimental rig used in this study resembling that of a narrow rectangular bubble column, it was not surprising to observe bubbles moving away from the column walls as they rose. This uneven distribution of bubbles across the membrane surface caused spatial deposition of foulants across the membrane surface (these results are reported elsewhere (27)). In order to improve the distribution of bubbles across the membrane surface, baffles (Fig. 2) were inserted in the riser section between the membrane and the wall on both sides of the flat sheet membrane. Figure 7 shows two pictures comparing the two-phase flow profile in the channel under conditions when baffles are absent and when they are present. Clearly with baffles, there is a much better distribution of bubbles across the membrane. Experiments were then conducted with yeast and waste activated sludge suspensions in order to assess the effectiveness of baffles in reducing fouling. For the baffle experiments, only 0.5 and 2.0 mm nozzles were used.

Figure 8 shows typical dTMP/dt data calculated after 90 minutes of yeast filtration for a runs with and without baffles at different airflow rates. As expected the dTMP/dt decreases with an increase in airflow rate and it is lower for the cases with baffles than the cases without them. It is also evident from this figure that the difference in the dTMP/dt between the cases with baffles and those without them decreases as the air flow rate increase. This indicates that using baffles may be more effective at lower air flow rates. This suggests that when the air baffles are used, a lower gas flow rate may be necessary to achieve the same effect achieved at a high gas flow rate without baffles (see also Critical flux section below). Figure 9 shows steady state TMPs (for low gas flow rates) or final TMPs after two hours of experimentation for yeast filtration experiments with and without baffles. This again confirms that the biggest reduction of the final

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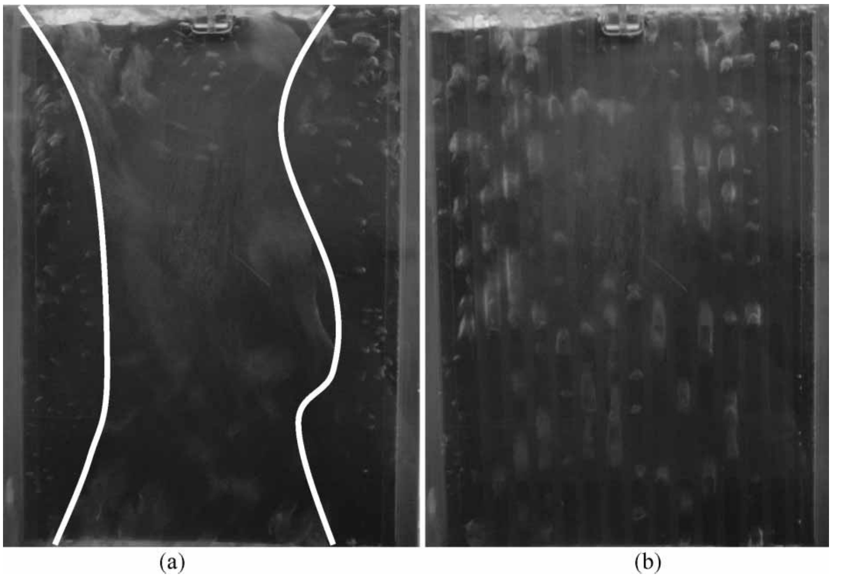

Figure 7. Comparison of flow two-phase profiles in non-baffled and baffled cases. The air flow rate is 8 L/min through a 2.0 mm nozzle.

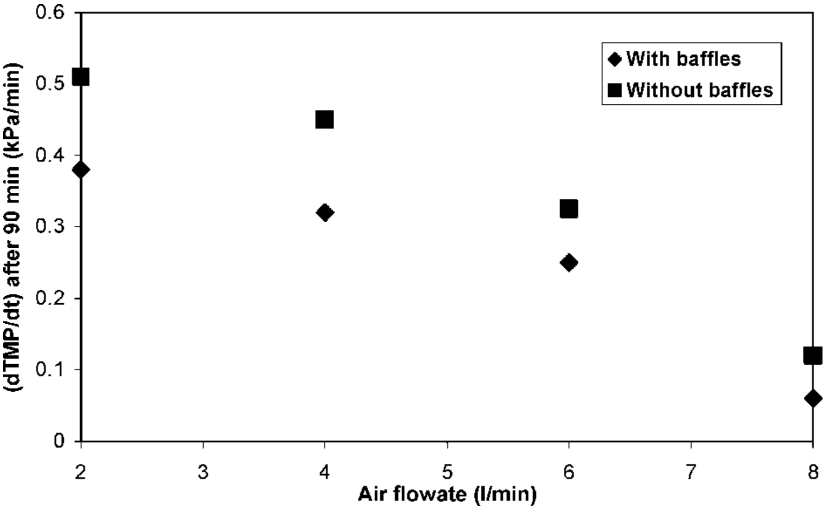

Figure 8. dTMP/dt values calculated after 90 minutes of filtration for runs with and without baffles for a 2.0 mm nozzle.

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TMP occurs with a smallest airflow rate of 2 L/min when baffles are used. At 8 L/min, the difference in the final TMP, for a case with and without baffles, is small. At an air flow rate of 2 L/min when baffles are used, TMP is reduced by 38% when compared to the case without baffles, and at 8 L/min it is reduced by 29%. If the data at 2 and 4 L/min are compared it can be seen that the 2 L/min-baffles run had a lower fouling rate than the 4 L/min-unbaffled

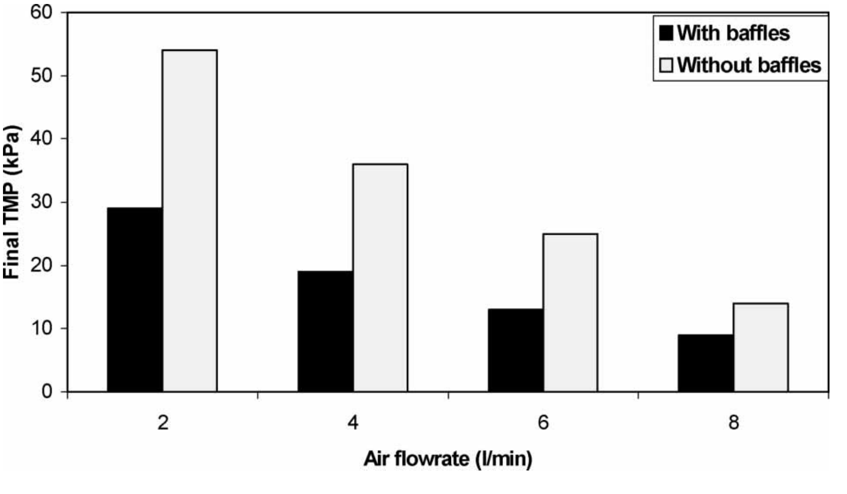

Figure 9. Final TMP obtained after two hours for runs with and without baffles.

run. The effectiveness of baffles was also tested on the waste activated sludge feed suspension as this would represent conditions which are closer to the conditions in a real MBR. The effects of baffles on the waste activated sludge suspension were found to be similar to those observed with the yeast suspension as can be seen in Fig. 10 which compares dTMP/dt data for experiments with and without baffles. The rate of fouling (dTMP/dt) is significantly reduced (typically halved) by the introduction of the baffles. This figure further indicates that by employing the baffles, the optimum aeration rate has been reduced from around 12 L/min to about 8 L/min.

Effect of Imposed Flux

For submerged MBRs, the initial imposed flux plays a crucial role in determining the rate of fouling of the membrane. A low imposed flux means low production rate, however, the buildup of the TMP is slow, thus allowing the MBR to be operated for a long time before any cleaning may be necessary. Conversely, a high imposed flux results in faster buildup of the TMP necessitating frequent cleaning which could increase operating costs. Most commercial MBRs operate below critical fluxes (see below), however, even at such conditions, slow fouling still occurs due to the interaction of the membrane with certain constituents of the MLSS such extracellular polymer substances (EPS) (28, 29). In this study, the effect of imposed flux on dTMP/dt was evaluated at different airflow rates using the yeast suspension as the

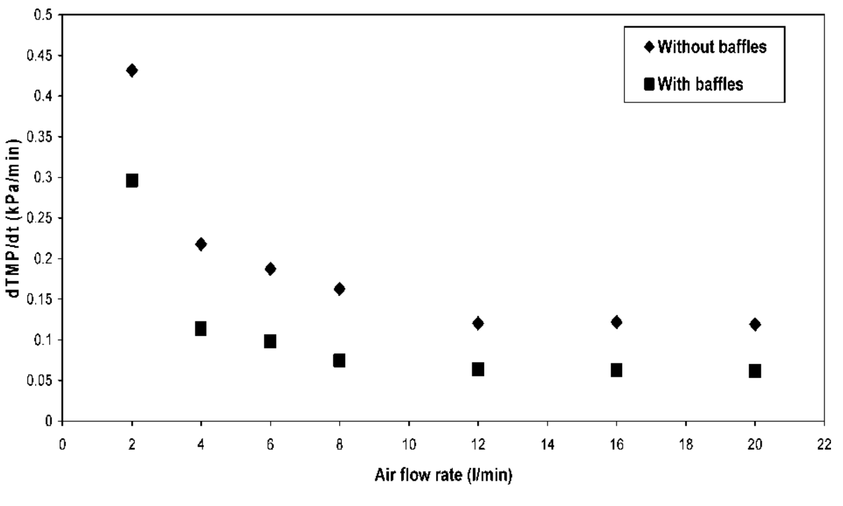

Figure 10. Variation of dTMP/dt with air flow rate for runs with and without baffles for the waste activated sludge suspension.

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feed. During this evaluation, the flux was held constant for about 30 to 40 minutes and then the overall dTMP/dt over that duration was evaluated. This was repeated for different fluxes at different air flow rates. The experiments were carried out only for the 0.5 and 2.0 mm nozzles at 5 and 10 g/L. Typical results obtained for a concentration of 5 g/L and a 0.5 mm nozzle are shown in Fig. 11. It is observed that dTMP/dt decreases with an increase in the air flow rate for all fluxes considered. For low fluxes, such as $15 l/m^2 \cdot hr$, the dTMP/dt value is close to zero for all airflow rates which indicates that the rate of fouling is extremely low, thus this flux may be below "critical flux."

At constant airflow rates, the dTMP/dt increases with an increase in flux which means that fouling is higher at higher fluxes. When the dTMP/dt are plotted versus flux for the lowest gas flow rate (2 L/min) (Fig. 12) it is evident that beyond a flux of about $20 l/m^2hr$ the TMP rise was rapid. This identifies the critical flux at this airflow rate. It shows that even at the lowest gas rate the system could be operated at a reasonably high flux. In practice the choice of flux and airflow rate would involve a balance of capital cost (flux related) and operating cost (airflow related).

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Effect of Aeration Rates and Baffles on Critical Flux

The critical flux concept, which describes long-term stability of membrane processes, was first proposed by Howell and his group in 1993. According to Field et al. (30) critical flux can be defined as a flux below which no deposition occurs on the membrane surface, above this flux fouling occurs. In constant flux processes, critical flux is often defined as the flux above

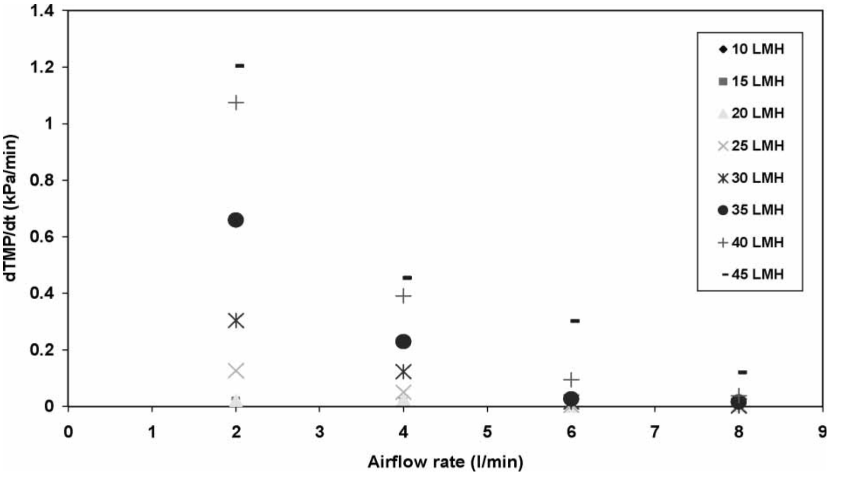

Figure 11. Effect of imposed flux on dTMP/dt at various airflow rates for the yeast suspension.

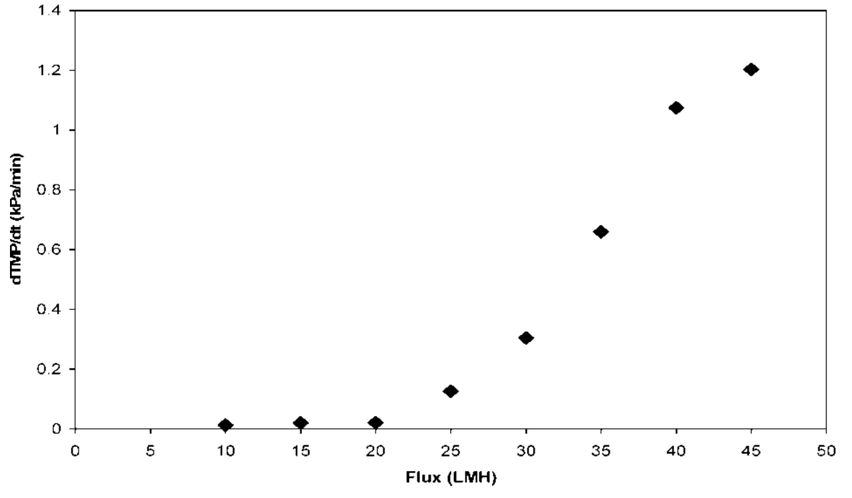

Figure 12. Variation of dTMP/dt with flux for an air flow rate of 2 L/min.

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which TMP starts to increase rapidly with time. In constant pressure processes operating in cross flow filtration, the decline of flux with time is inevitable as the cake builds up. Thus flux declines rapidly initially and is then followed by a period where there is very small decrease of flux with time. This stable flux, which changes negligibly over a long period of time, is known as the steady state flux and should not be confused with critical flux as stable flux is the limiting flux beyond which no further build up of the fouling layer occurs.

Critical fluxes were evaluated for both yeast and waste activated sludge suspensions and since the results were similar in pattern, only the results for the activated sludge will be shown as this is much closer to real conditions in a typical submerged MBR. The effective critical flux of the dominant foulant was determined using the stepwise method (28, 29, 31). The permeate flux was stepwise increased in increments of $5\,l/m^2hr$ with each step lasting for approximately 30 min (Fig. 13). Below the critical flux, the TMP either rises gradually or quickly reaches a stable value and above critical flux the TMP starts to rise very rapidly. The gradual increase of TMP with flux indicates that some degree of fouling is present below effective critical flux but changes dramatically when the critical flux of the dominant foulant is reached, leading to a steep rise on TMP probably due to pore blocking and/or cake formation. It can be seen in Fig. 13 that below critical flux, the TMP rose linearly with flux and above critical flux (in this case $\approx 35\,l/m^2hr$), the TMP started to rise exponentially. The rapid rise of the TMP is a strong indication that fouling in the form of cake deposit had started to occur. The effects of airflow rate and membrane baffles on this effective critical flux were determined.

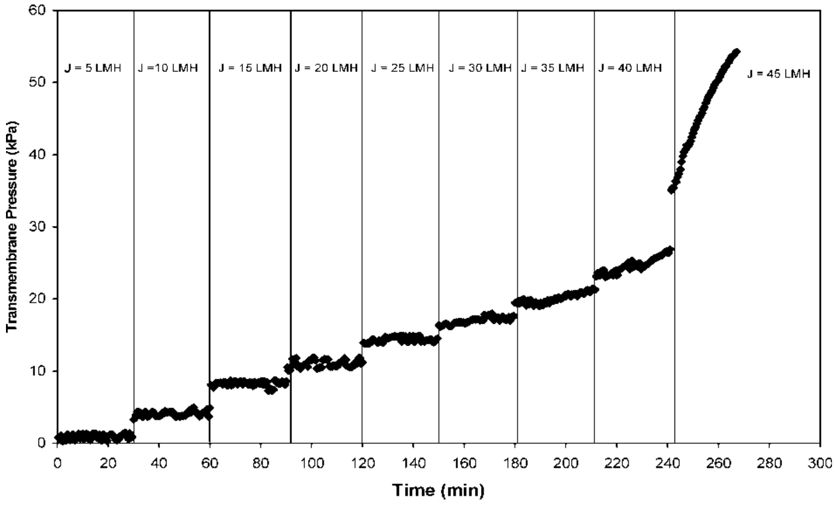

Figure 13. Critical flux determination with the flux-step method. The air flow rate is 12 L/min.

Figure 14 presents critical fluxes identified using the stepwise method at different gas flow rates for runs with and without baffles. This figure shows that for both arrangements an increase in the aeration rate increased the critical flux. Therefore an increase in the air flow promotes the back-transport of particles away from the membrane, minimising fouling and increasing the critical flux. For both cases the increase in critical flux with air flow rate seems to be approaching a limiting value implying that, above a certain gas

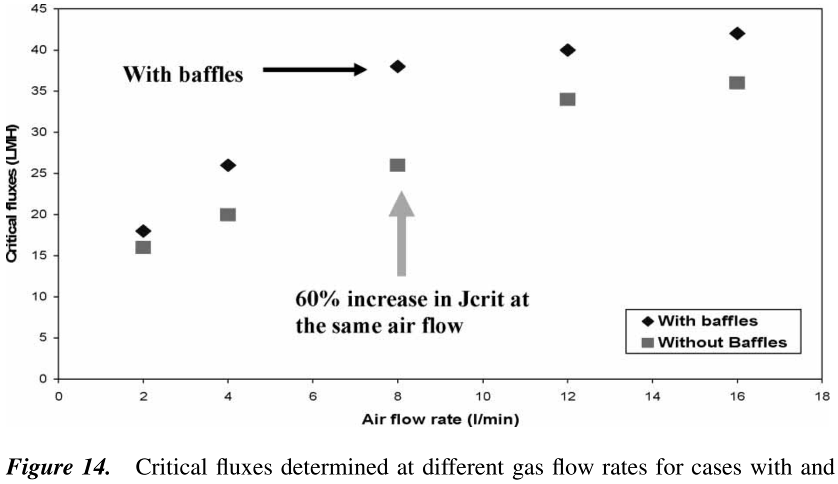

Figure 14. Critical fluxes determined at different gas flow rates for cases with and without baffles.

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flow rate, the critical flux becomes independent of the bubbling rate. Howell et al. (32), working with a submerged flat sheet MBR configured similarly to the one in this study, noted that it was difficult to raise the critical flux beyond $23\,l/m^2hr$ despite increasing the gas flow rate substantially. This is much less than the optimal critical fluxes observed in this study of around $40\,l/m^2hr$ when baffles were used. Howell et al. (32) postulated that this limiting critical flux is a function of the MLSS concentration in the bioreactor. The differences in the critical fluxes reported by Howell et al. (32) and those found in this study can be linked to a number of factors. Firstly, Howell et al. (32) used a synthetic sludge and not real waste activated sludge. The MLSS concentration in their reactor was in the range of 6.78 to 21.7 g/L which is much wider and higher than the range of 4–8 g/L used in this study. Therefore they could have had more solids which would tend to lower critical fluxes.

In this study the critical fluxes were always higher in the runs with baffles than those without baffles. The effects shown in Fig. 14 are very significant. Thus at an airflow of 8 L/min the critical flux was increased by 60% by the use of baffles. Another comparison shows that the critical flux at 16 L/min without baffles was achieved at 50% of the airflow (8 L/min) with baffles. These results confirm the potential benefit of baffles in the submerged flat sheet system. Further optimisation of baffle geometry may be possible, but was beyond the scope of this paper.

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Effect of Concentration

From the literature, it has been stated that bubbling is more effective under conditions which are more prone to fouling such as high TMP and high concentration (21, 33). Thus it has been concluded that flux enhancement by air bubbling is due to the disruption of the concentration polarization layer. In some studies, it has been observed that increasing the concentration can in fact improve the flux because if there are more particles present, particles will collide more often and in this way coagulation between the particles is promoted (34). When the larger coagulated particles are deposited on the membrane surface, they will tend to form a cake with a higher voidage and less resistance, and this will improve the performance.

In order to assess the effect of concentration on the effectiveness of bubbling, runs were carried out at three feed concentrations of 5, 10, and 15 g/L at nominal fluxes of $40\,l/m^2hr$. These experiments were only done with the yeast suspension. However, in this study, as shown in Fig. 15 increasing the concentration had a negative effect on TMP rise which means that fouling was more severe at a higher concentration. The rate of membrane fouling (dTMP/dt) was always the highest at the concentration of 15 g/L for all airflow rates, but it did decrease with the airflow. This result is not unexpected based on the well-known effects of feed concentration on the degree of polarization and rate of cake formation. In other words any notional benefits in

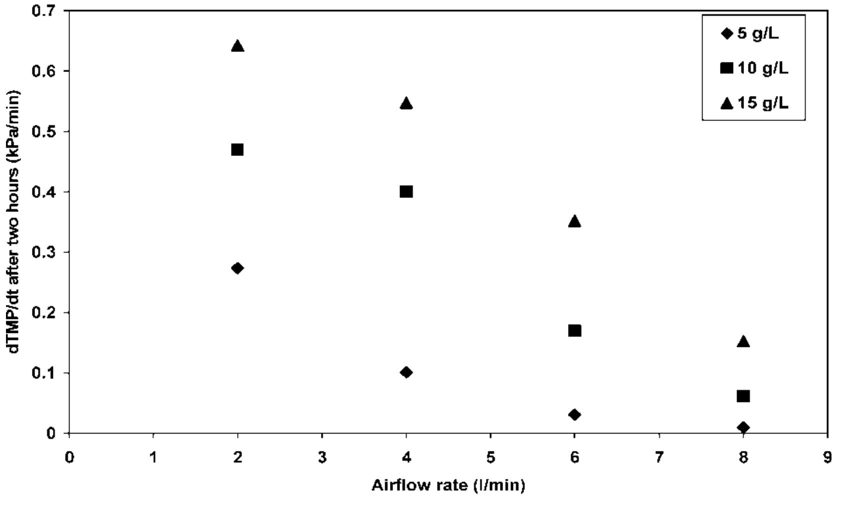

Figure 15. Effect of feed concentration on dTMP/dt at different airflow rates for the yeast suspension.

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decreasing specific cake resistance with concentration would have been swamped by the increased cake load due to concentration. Churchouse and Wildgoose (9) also observed that higher concentrations of the mixed liquor led to higher TMPs during evaluation of a submerged flat sheet MBR.

The extent of fouling reduction at different concentrations was also evaluated using the TMP reduction factor as shown in Fig. 16 for the 2.0 mm nozzle. Similar trends were obtained for nozzles of other sizes. As shown previously, the degree of TMP reduction increases with the air flow rate. However, at high concentrations of 10 and 15 g/L, the reduction is small, varying from 1.3 to 4.1 (as the air flow rate increased from 2 to 8 l/min) compared to varying from 2.5 to 11.6 at the low concentration of 5 g/L. Thus the apparent effectiveness of bubbles decreased as the fouling load increased. One possible reason for this is that suspension viscosity increases significantly with feed concentration, and at 15 g/L the viscosity could be 2.0 to 3.0 times that of water. This would tend to reduce bubble rise velocity and dampen the effects of bubble-induced surface shear.

Effect of Channel Gap Width

For submerged flat sheet membranes, the gap between adjacent membranes can have a significant effect on hydrodynamic conditions. The Kubota MBR system uses a gap of 7 mm between the flat sheet membranes (9) whilst the Pleiade MBR uses a gap of 5 mm (8). No systematic study of the effect of the gap width has been reported. In this study, only one membrane was used therefore it was the gap between the membrane and the adjacent walls

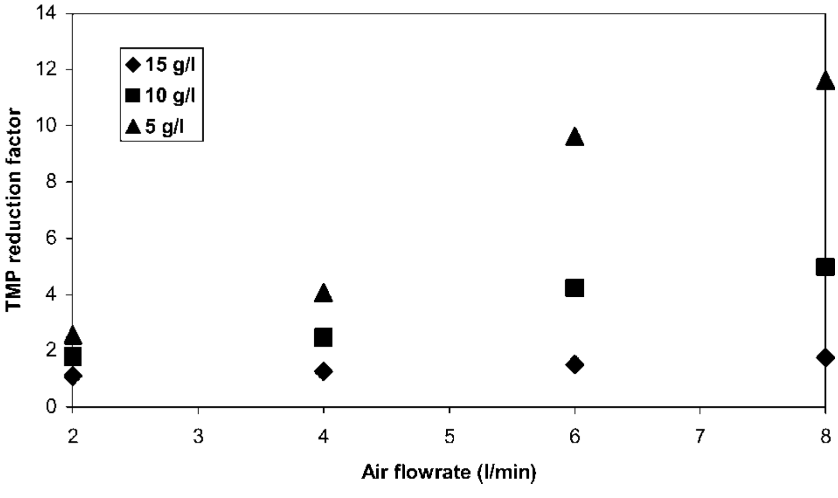

Figure 16. TMP reduction factors obtained at different concentrations for all airflow rates when a 2.0 mm nozzle was used.

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that was varied. Due to the tank design, the gap between the membrane and the walls could only be varied in increments of 7 mm. Therefore only two gap widths of 7 and 14 mm were studied. In both situations, the air diffuser was always located in line with and just underneath the membrane.

Figure 17 shows the final TMP (after two hours of experiments) for both gaps at all airflow rates and Fig. 18 shows the dTMP/dt after two hours of experimentation. The TMP increased more quickly and to a much higher level when the gap was 14 mm. This indicates that airflow rate always plays some role in

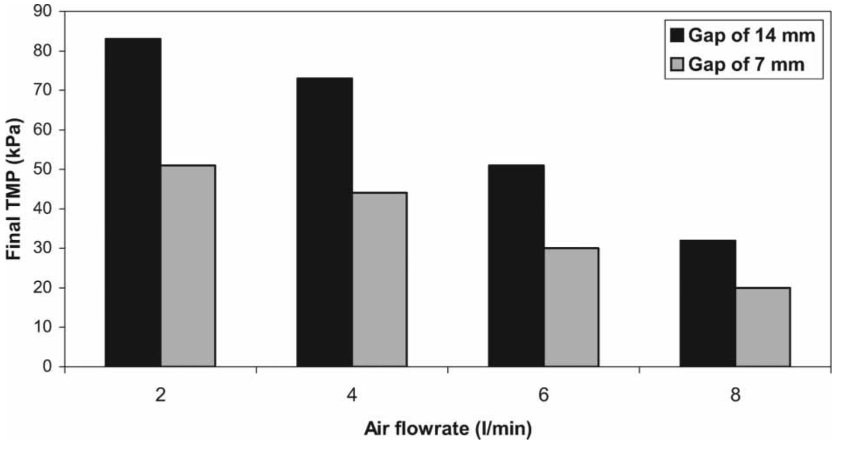

Figure 17. Final TMPs for runs with channel gaps of 7 and 14 mm.

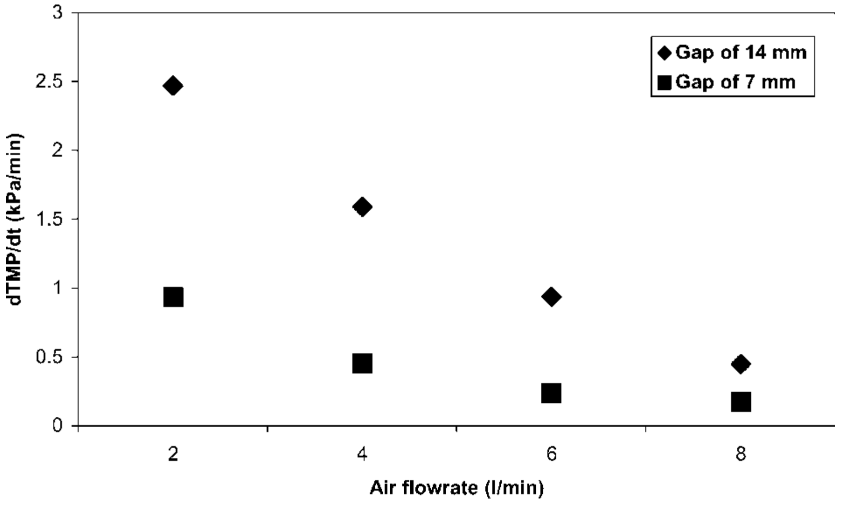

Figure 18. Variation of (dTMP/dt) with air flow rate for the gap of 7 and 14 mm at a yeast concentration of 5 g/L and a 2.0 mm nozzle was used.

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reducing fouling but that widening the gap had a negative effect on the shear stresses on the membrane. It has been found for tubular membranes that bubbles whose diameter is similar to the tube diameter (that is, slugs) are most effective in enhancing flux (21). Taking this into consideration, it may seem that by widening the channel gap, the number of bubbles whose diameter was larger than the channel gap was significantly decreased meaning that the actual number of bubbles that were scouring the membrane surface was reduced. This had a negative impact on the TMP. This result seems to suggest that for two-phase flow to be more effective in submerged flat sheet systems, the majority of bubbles must be at least as wide as the channel gap. The additional liquid recirculation induced by the movement of bubbles does not seem to generate sufficient shearing on the membrane to control the foulants.

The differences in final TMP between the gaps of 7 and 14 mm decrease with an increase in the air flow rate (Fig. 17). This suggests that as the air flow rate is increased, the number of large bubbles increases as well and hence there are more bubbles that are scouring the membrane surface. This also suggests that larger bubbles are more effective than smaller bubbles in submerged flat sheet membranes. Further analysis and discussion of these effects is reported elsewhere (27).

Effect of Intermittent Filtration

Using gas-liquid two-phase flow can be very effective in combating fouling as most recent studies have revealed (35–37), however, it could be energy expensive if not operated at an optimum point. One way of minimizing energy is to use intermittent filtration. In this method a period of filtration is followed by a period of non-filtration during which the suction pump is switched off and the TMP drops to zero. Intermittent filtration allows relaxation and reduces compression of the cake layer, thus resistance is reduced and better permeability is maintained (38, 39). When the filtration is stopped, the process of gas bubbling and hence shearing on the membrane surface is allowed to continue. The combination of this shear stress and no suction force makes it easier for the deposited particles to be removed from the membrane surface. When the filtration cycle is resumed again, the membrane is relatively clean compared to what it was when the filtration cycle was stopped. According to Howell et al. (32) intermittent filtration can be a very useful tool if an MBR is to be operated with a variable throughput. A variable throughput MBR is actually desirable since the influent to most wastewater treatment plants is not constant but varies diurnally. Thus at peak times the throughput of the MBR could be increased by reducing the time during which the suction pump is shut off.

The effect of intermittent filtration was investigated at a concentration of 5 g/L at various airflow rates with a 2.0 mm nozzle. Experiments were conducted with both yeast and waste activated sludge as feed and since the results obtained were similar in pattern, only the results with the yeast suspension will be presented. A relatively high flux of $40\,\mathrm{l/m^2 \cdot hr}$ was used to emphasize different responses. The experiments were also conducted with and without baffles. The filtration cycle was allowed to run for a duration of 20 min then stopped for a duration of 5 minutes. Typical TMP versus time data are shown Fig. 19 for runs with no baffles whilst Fig. 20 shows a

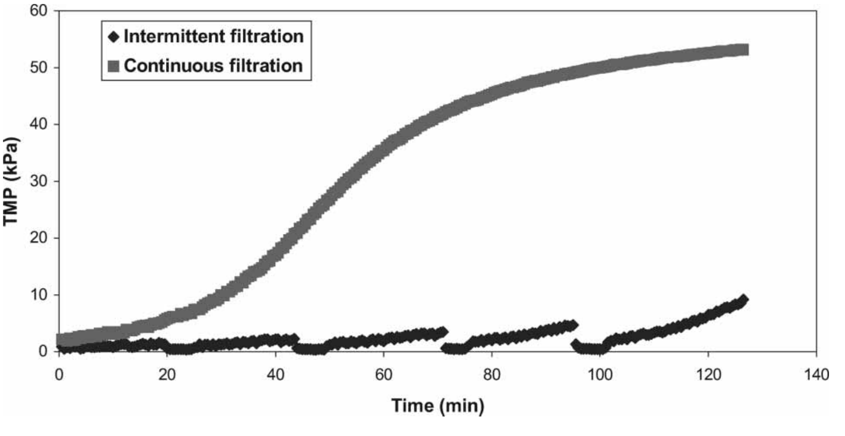

Figure 19. Variation of TMP with time during continuous and intermittent filtration. The air flow rate was $2\,\mathrm{L/min}$ and a 2.0 mm nozzle was used and the flux was $40\,\mathrm{L/m^2hr}$.

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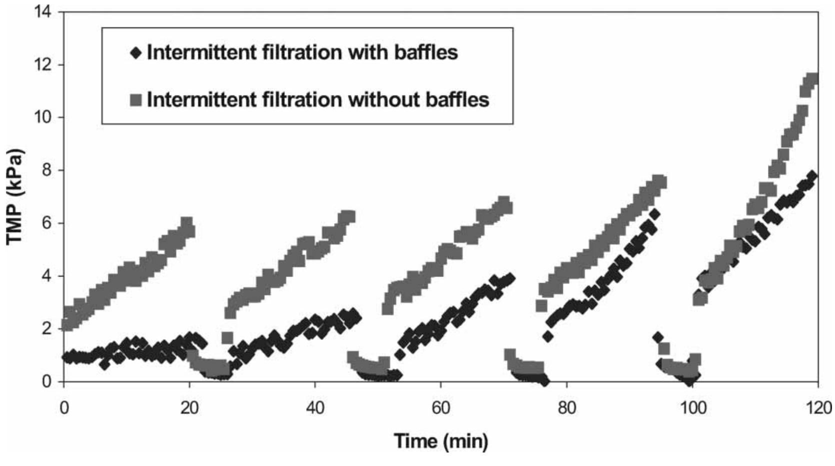

Figure 20. Variation of TMP with time during intermittent filtration for a run with and without baffles.

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comparison for a case with and without baffles. The results for all airflow rates clearly indicate that intermittent filtration was far more effective than continuous filtration, even for the smallest airflow rate of 2 L/min. For example, with continuous filtration, the TMP after two hours of filtration increased up to 52 kPa but with intermittent filtration it only reached 8 kPa. Figure 20 further shows that TMP was always lower for the case with baffles than the case without baffles. Thus, an economical way of operating a submerged flat sheet membrane system could be to use baffles with intermittent filtration at a lower gas flow rate.

As can be seen from Figs. 19 and 20 for the intermittent filtration run, each time the new filtration cycle starts, the TMP curve becomes steeper than the one in the previous cycle. This behavior can be explained as follows. At the end of the filtration cycle, there is a certain amount of foulant on the membrane. When the filtration is stopped, the air bubbles remove a certain portion of these foulants but not all foulants will be removed. Thus when the new filtration cycle starts, there is a higher resistance on the membrane than there was during the start of the previous cycle. This causes the membrane to foul at a faster rate than compared to the previous cycle thus the dTMP/dt becomes higher for each successive filtration cycle. In particular the residual fouling on the membrane could reduce the effective filtration area and cause increased "local" fluxes for a given average flux. The increased fluxes would lead to more irreversible fouling and less removal during the off period. This would cause the membrane to foul at a faster rate compared to the previous cycle thus the dTMP/dt would become higher for each successive filtration cycle, in a self-accelerating process.

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DISCUSSION

The main objective of this study was to evaluate how various hydrodynamic factors that govern the structure of two-phase flow between parallel submerged flat-sheet membranes affects the fouling retardation process. The key parameters that have been investigated are airflow rate, nozzle size, imposed flux, feed solution concentration, gap width, intermittent filtration, and the effect of baffles. Performance of two-phase flow was evaluated by determining the rate of change of TMP (dTMP/dt) at a certain specific time, from "critical flux" estimates, as well as by assessing the TMP reduction factor.

The benefit obtained by injecting the gas was found to increase with the gas flow rate for all nozzle sizes considered except in the cases where baffles were employed where the maximum benefit was obtained at the lowest air flow rate. For the activated sludge suspension an optimal bubbling rate of about 12 L/min (120 L/min per m^2 of membrane area) was observed. Although this air flow rate may seem high compared to the one which commercial plants are moving towards (which is 10 L/min per m^2 of membrane area), it has to be remembered that in this study only one membrane (0.1 m^2) was used and the same air flow rate could be delivered to a channel with membranes on both sides and extending over a greater height. The results obtained in this study also showed an increasing enhancement effect with nozzle size when the air flow rate was kept constant (Figs. 5 and 6). These results are difficult to explain as the amount of gas introduced into the system is the same regardless of the nozzle size. Therefore these results suggest that it is not just the volume of gas that matters but also the bubble size distribution. This indicates that different nozzle sizes give rise to different bubble population characteristics. In order to understand why fouling reduction increased with the airflow rate and nozzle size, further analyses were conducted using particle imaging software and CFD simulations. The results of these analyses can be found elsewhere (27). These analyses indicated that the greater reduction of fouling with increasing airflow rate and nozzle size was linked to an increase in the average bubble size, increase of bubble rise velocity, increase in the gas hold-up, and an increase in the percentage flow that ends up as large bubble flow, that is, flow consisting of bubbles larger than 10 mm in diameter. CFD simulations revealed that increasing the airflow rate increases the average shear stress on the membrane and that the liquid recirculation and degree of meandering of the gas stream increases with the airflow rate.

By employing baffles, a better distribution of the bubbles across the membrane surface was achieved. The use of baffles ensured that bubbles were constrained on all sides rather than on just two sides as is the case with no baffles. With constrained bubbles more liquid was forced to pass between the membrane and the bubble in a form of a thin falling film for bubbles whose diameter was larger than the channel gap. The shear stress in the thin falling film is known to be very high (21) compared to the regions ahead of the bubble and in the bubble wake. Thus by using baffles, slug flow was regularly achieved in the channel. Slug flow has been shown to be the most effective type of two-phase flow regime when it comes to flux enhancement (24, 34). This is one reason why the introduction of baffles yielded a significant increase in the fouling retardation process. The other reason is that the baffles promoted better bubble distribution across the surface and reduced the tendency of bubbles to flow to the center of the plate.

Experiments conducted to determine critical fluxes indicate that critical fluxes exist for the type of submerged membrane systems investigated here. Identified critical fluxes were found to increase with the air flow rate and decrease with concentration. The use of baffles improved the critical fluxes considerably under the given conditions. Operating below the nominal critical flux should allow operation for a long period of time before any chemical clean should be necessary. The values of critical flux observed in this study would be different from those typically found in a real MBR, and it has been suggested that for the MBRs the presence of EPS causes slow fouling at any flux. Thus MBRs operate at "nominally subcritical" fluxes. The appropriate conditions could be determined using the method used in this study.

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In this study, TMP was found to rise more rapidly with an increase in concentration at all bubbling rates. Gas-liquid two-phase flow has been found by some researchers to be more effective under conditions when fouling would be most severe (21) such as at high concentration, however in this study this was not the case. Higher TMP reduction factors (Fig. 16) were obtained at lower concentrations than at higher concentrations for all airflow rates considered. This observation puts into question the theory that two-phase flow works by disruption of the concentration polarization layer, at least for the submerged flat sheet membranes. It is probable that the presence of the gas phase minimizes the rate of formation of the concentration boundary layer rather disrupting an already formed layer. Thus, at higher concentrations, the tendency for the concentration layer to form is much higher, which lowers the effectiveness of gas bubbles. It is also possible that the increase in concentration also increased the suspension viscosity and that this would tend to slow bubble rise and attenuate the effect of shear transients.

Results obtained from varying the gap width between the membrane and the wall showed that increasing the gap width from 7 to 14 mm had a detrimental effect on the TMP rise during gas sparging. Similar observations were made by Lee et al. (40) during filtration of a cell suspension. They noted that a drastic reduction of the channel height in a cross-flow cell resulted in a high shear rate between the membrane surface and the air slug interface. Thus, a similar explanation could be adopted for the observations made in this study. A narrower gap results in higher shear rates which results in a slower increase of the TMP. Cui and Wright (24) found that, in narrower channels in cross-flow cells, only a small amount of gas is necessary to achieve flux enhancement, whereas on a wider channel, more gas would be required to achieve the same degree of flux enhancement. Thus, the gap width between the submerged membranes has an important role to play in the determination of shear stresses on the membrane.

Finally, intermittent filtration was shown to be more effective than continuous filtration. By ceasing the suction force, the pressure on the filter cake drops significantly, allowing the cake to decompress. Since bubbling is allowed to continue during the non-suction period, this facilitates easy removal of the cake from the membrane surface.

CONCLUSIONS

Overall, the results of this study showed that fouling reduction in submerged flat sheet membranes improved with an increase in airflow rate and nozzle size. An optimal aeration rate exists beyond which there is no further improvement in the fouling retardation process. The use of baffles can enhance the effect of bubbles by ensuring a better distribution of bubbles across the membrane and promoting slug flow and thus increasing overall shear stress on the membrane. The imposed flux affects the fouling process significantly; with low fluxes, a slow steady rise of the TMP over a long period of time can be achieved. A compromise must be made between higher fluxes and more frequent cleaning and low fluxes and lower production rates. Intermittent suction was a better operating strategy than continuous suction and it would also reduce the energy requirements.

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ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from AusAID in Australia and the NRF in South Africa.

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