Membrane Bioreactor with Bubble-Size Transformer: Design and Fouling Control

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Bubbling requirements for membrane bioreactors (MBRs) are typically split into fine bubbles for aeration and larger coarse bubbles for fouling control. This article examines the possibility of reducing air requirements by using the same air supply to achieve both tasks for a submerged flat-sheet MBR. A bubble-size transformer (BST) comprising converging channels and a tube-bank unit was used to coalesce fine bubbles into coarse bubbles. The BST was located under the flat-sheet membrane modules and generated coarse bubbles to scour the membrane surfaces. Approximately 65% of the fine bubbles produced from fine ceramic air diffusers were transformed into coarse bubbles, and 35% of the fine bubbles were used for biological activities and to prevent the settlement of mixed liquor suspended solid (MLSS) in the bioreactor. Both bubble diameters and bubbling velocities were found increased after the transformations. The BST increased bubble diameters from 0.5-2 mm to 9-18 mm. The coarse bubbles after transformation were bigger than the gaps between the flat-sheet modules at 5 mm so that slug flow probably occurred in the module gaps. Long-term MBR experiments at air flowrates of 3 and 5 L/min with permeate fluxes of 22.5 and 35 L/m^2.h were used to evaluate the bubble-size transformation technique for the MBR. The benefit from the BST can be seen by comparing the "sustainable" flux period before a rapid rise in transmembrane pressure. © 2006 American Institute of Chemical Engineers *AIChE J,* 53: 243–248, 2007
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Introduction

Submerged membrane bioreactors (SMBRs) have played an important role for wastewater treatment because of small footprint, lower operating costs and capital costs per treated water volume, and superior treated water quality. The advantages and applications are well reviewed in Gander et al.,[1] Brindle and Stephenson,[2] and Yang et al.[3] The submerged flat-sheet membrane bioreactor is one of the MBR configurations that can offer benefits such as ease of changing membranes and maintenance. The flat sheet module arrangement provides precise locations of the module for good accessibility of bubbling[4] and well distributed bubbling over the membrane surfaces. The development of the flat-sheet SMBR has been successfully commercialized by Kobuta Corporation. Coarse bubbles are used in the commercial flat-sheet SMBR with relatively high flowrates to obtain both good fouling control and acceptable permeate quality.

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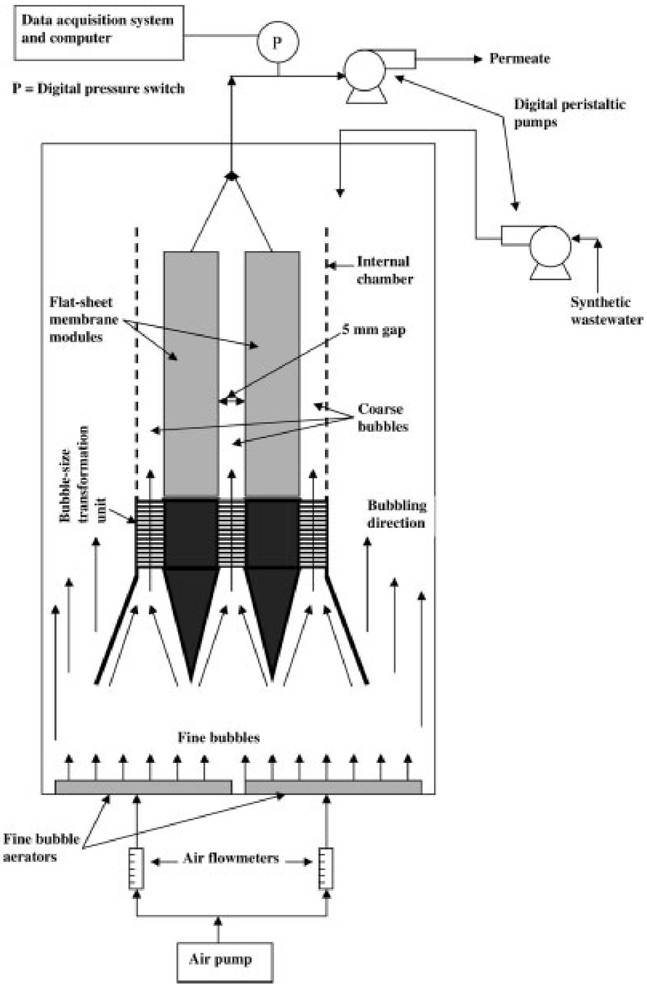

Figure 1. Experimental diagram for submerged flat-sheet MBR with bubble-size transformation unit.

Bubbling and aeration management are important and of interest for investigation in membrane bioreactors because aeration is one of the main operating costs. Optimization of bubbling for MBRs has been studied in various aspects such as bubble sizes, bubbling rates, and aeration methods to obtain minimum cost and effective fouling control.[4] Fine bubbles can provide relatively large oxygen-transfer surfaces, which are good for biological activities in the bioreactor, and high quality treated water can be obtained at relatively low air flowrates. However, fine bubbles do not control fouling effectively. Frequently, only one type of bubble is employed in MBRs, and coarse bubbles are still preferred, especially for submerged flat-sheet MBRs, for both aeration and fouling control.

In a recent study,[5] we have shown that larger bubbles generate greater maximum and average shear stress on the flat sheet submerged membranes. If both fine and coarse bubbles produced by different aerators are used simultaneously, higher air flowrates may be required, leading to extra cost. In terms of fouling control, coarse bubbles do not need to contain oxygen gas for scouring membranes, and low oxygen concentration in coarse bubbles may be able to help reduce bacteria growth/attachment on the membrane surfaces resulting in biological fouling. It would be interesting to have the advantages from both fine and coarse bubbles in MBR, and an innovative design with optimum operation is required to keep the aeration cost as low as possible. This article focuses on an alternative method to combine the benefits of fine bubbles and coarse bubbles for submerged flat-sheet MBRs. A bubble-size transformation technique is proposed in this article that could optimize bubbling management in submerged flat-sheet MBRs.

The bubble-size transformation (BST) unit can be used to coalesce fine bubbles into coarse bubbles. The basic concept for the submerged flat-sheet MBR featuring a BST unit is to generate coarse bubbles from fine bubbles after the fine bubbles containing fresh oxygen have been used for aeration in the bioreactor. Another possible method is to use 2 types of aerators in the MBR, which are fine bubble aerators and coarse bubble aerators. Compared to the MBR with BST, the MBR with 2 types of the aerators would tend to need higher air flowrates and also the coarse bubbling may not be well distributed over the flat sheet membrane surfaces. This article describes preliminary investigations to develop and design an effective bubble-size transformation unit. The performance of the BST was determined by: (i) the bubble transformation ratio, and (ii) the fouling control ability of the transformed coarse bubbles in a flat-sheet MBR. The effects of air flowrates on bubble-size transformation (hydrodynamic aspect) and on fouling control were investigated. The effect of the BST unit on the permeate quality was also observed. The results and conclusions obtained can be used to improve the design of submerged flat-sheet MBR systems with BST units.

Materials and Methods

The design of the submerged flat-sheet MBR with a bubble-size transformation unit is shown in Figure 1. The BST unit was installed under the flat-sheet membrane modules in order to transform fine bubbles from the fine bubble aerators into coarse bubbles. The gaps between the membrane modules were approximately 5 mm. The flat-sheet membrane modules were machined from high-grade acrylic plates with Viton sealing O-rings and designed to facilitate changing membranes (new membranes were used for all experiments). The membrane module had 2 faces in contact with the mixed liquor suspended solid (MLSS) in the bioreactor. Flat-sheet hydrophilic PVDF membranes (Millipore) with a nominal pore size of 0.22 μm were used in the membrane modules. Details of the membranes and membrane modules are summarized in Table 1.

The bubble-size transformation unit consisted of converging channels and slit tube-bank channels, depicted in Figure 2. The design of the BST unit was developed systematically and based on the fact that bubble coalescence occurs from bubble collisions. In addition, the idea to design the BST unit was initiated by direct observation from bubbling in a submerged membrane bioreactor. It was found that bubble coalescence occurred when the bubbles collide with membrane fibers. Many trials to design the bubble coalescence unit had been tested, including tube banks at various gaps and numbers of the rows in the tube banks, and converging

Table 1. Membrane Properties and Membrane Module Characteristics

Flat-Sheet Membranes		Module	
Property	Hydrophilic PVDF Membrane (Millipore)	Flat Sheet Membrane Module with Double Faces (Square Shape)	
Pore size (μm)	0.22	Membrane area	125 cm^2/module (62.5 cm^2/face) (12.5 cm $*$ 5 cm)
Wall thickness (μm)	125	Membrane support	stainless steel perforated screen
Porosity	80%	O-ring	Viton

channels. The combination of converging channel and tube bank at 2 mm gap was found to be the best design and gave a pressure drop of only 2 kPa. The converging channels were designed to sweep or collect fine bubbles, and the bubble coalescences occurred in the slit tube-bank channels with 5 rows of tubes (6 mm diameter). The average distance between the tubes in the tube banks was approximately 2 mm. The widths of the slit tube-bank channels were equal to the module gaps at 5 mm. The heights of the converging channel section and slit tube-bank channel section were 6 and 7 cm in this design, respectively. Bubble diameters before and after the transformations were measured by photographic methods. A digital camera, Panasonic FZ10, was used to take pictures of the fine bubbles before transformation and the coarse bubbles after transformation with a shutter speed of 1/2000 s. The pictures were analyzed by software Image-Pro Plus 5.1 and IQ base. For all experiments, sizes of the fine bubble diameters from the fine ceramic aerators were monitored and controlled with a standard deviation of 7%. New aerators were used if the fine bubble sizes deviated more than 7%.

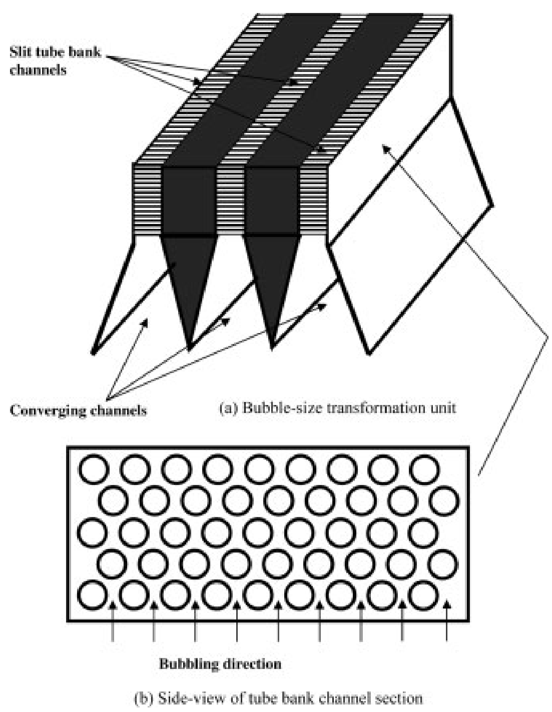

Figure 2. The structure and design of bubble-size transformation unit.

(a) Bubble-size transformation unit, (b) Side-view of the slit tube-bank channel.

Digital peristaltic Materflex pumps with Easy Load II pump heads and L/S 16 Tygon LFL tubing were used to control the permeate fluxes (fixed flux operation) and to feed the synthetic wastewater. An SMC high precision digital pressure switch (ZSE50F- compound pressure: -100 kPa to 100 kPa range) was used to monitor the transmembrane pressures of the submerged flat-sheet MBR. The pressure switch was connected to a National Instrument data acquisition card, and software LabView Express 7 was used with data collecting interval time of 1 min. Dwyer air flowmeters were used to control air flowrates at the required values. Two fine bubble ceramic aerators with 11.3 cm diameter were used to produce fine bubbles in the submerged MBR. The air flowrates were varied from 0.5 to 3.5 L/min for each aerator.

The reactor with a 20 L effective volume had an internal chamber to provide the location for flat-sheet membrane modules, and 5 mm gaps between the membrane modules were used The activated sludge had been cultured for approximately 3 months until both extracellular polymeric substance (EPS) concentrations and MLSS concentrations were relatively stable. Properties of the synthetic wastewaters and MLSS are summarized in Tables 2 and 3. Sludge retention times (SRT) were controlled at 20 days for all experiments. Hydraulic retention times (HRT) depended on flux rates and were 1.4 day for a permeate flux of 22.5 L/m^2.h and 0.93 days for a permeate flux of 35 L/m^2.h. In order to compare the fouling control and the transmembrane pressure (TMP) characteristics of the MBR with and without the BST, the experiments were performed at the same air flowrate under similar MLSS concentrations and EPS concentrations. Both EPS and MLSS were thoroughly checked before new experiments were started. The EPS prevalent for each air flowrate are summarized in Table 4. Total organic carbons

Table 2. Compositions of Synthetic Wastewater

Synthetic Wastewater	
Substances	Concentration*
Glucose	3.6–4.6 g/L
Peptone	0.58–0.74 g/L
Protose	0.43–0.55 g/L
$NaHCO_3$	0.55–0.69 g/L
$MgSO_4$	0.047–0.059 g/L
KH_2PO_4	0.12–0.15 g/L
K_2HPO_4	0.09–0.11 g/L
$Fe_2SO_4 \cdot 7H_2O$	0.12–0.15 g/L

*Varied with permeate flow rates at constant COD and TOC loadings.

Table 3. Average Influent Wastewater and MLSS Properties for Experiments

Properties of Synthetic Wastewater and MLSS	
COD	5,547 mg O_2/L (total 0.112 kg/day)
TOC	1,236 ppm (total 0.025 kg/day)
Total COD loading per bioreactor volume	5.61 kg.m$^{-3}\cdot$ day^{-1}
Total TOC loading per bioreactor volume	1.25 kg.m$^{-3}\cdot$ day^{-1}
pH	6.82–7.57
Conductivity	0.76–0.91 s/m
Temperature	25 ± 1°C
MLSS	14.33–16.47 g/L

(TOC) were measured by a Shimadzu TOC analyzer (TOC-Vcsh), and COD were measured by MERCK COD test kits with a Jasco V-550 UV/VIS spectrophotometer tested in triplicate. MLSS were measured by Standard Methods with a Whatman glass microfiber filter GF/C. The methods to analyze EPS, protein, and polysaccharide were based on the literature.[6–10] Soluble and non-soluble parts of EPS in the MLSS were separated by centrifuge, and the supernatant obtained was the soluble part. Polysaccharide concentrations were determined by the phenol-sulfuric acid method with a UV spectrophotometer at 490 nm, and protein concentrations were determined by the Bradford-bovine serum albumin (BSA) method with UV spectrophotometer at 595 nm. Dissolved oxygen concentrations in the bioreactor were measured by YSI 5000 Dissolved Oxygen Instrument.

The experiments were divided into 2 parts: (i) bubble-size transformation and hydrodynamic study, and (ii) study of fouling control by the transformed coarse bubbles in the MBR. For the first part, only tap water was used, and the hydrodynamics of the bubble-size transformation and bubble distributions were investigated. The effect of air flowrate on the bubble sizes before and after the transformation was elucidated. The velocity and liquid circulation paths were observed. For the second part, flat-sheet submerged MBR experiments were performed, and the sustainable flux periods with and without the BST unit were compared at different air flowrates and permeate fluxes.

Results and Discussion

The average bubble sizes before and after the coalescing transformation are shown in Figure 3. The mean diameters of the fine bubbles from fine bubble aerators increased slightly with increasing total air flowrates from 0.85 mm at 1 L/min to 1.2 mm at 7 L/min. After the coalescing transformation by the BST unit depicted in Figure 2, the bubbles were 10-14 times larger than the original fine bubbles before the transformation. At total air flowrates of 3 and 5 L/min, the average transformed coarse bubble diameters were 12.7 mm and 13.4 mm, respectively. The coarse bubble sizes after the transformations noticeably increased with increasing total air flowrates. This implied that the degree of bubble coalescence increased with the air flowrate due to the greater number of fine bubbles entering the BST unit. The transformation ratio is defined as the ratio of the average coarse bubble diameter after the transformation (D) to the average fine bubble diameter before the transformation (d), and is used to characterize the coalescing performance of the BST. From Figure 3, the ratio increased with the total air flowrate until the air flowrate reached about 3 L/min, and then the ratio became relatively constant at about 13.3. However, the numbers of bubbles existing in the bioreactor after the transformation were substantially reduced due to the coalescence.

The movies and pictures recorded by the digital camera revealed that the velocities of the coarse bubbles transformed from the fine bubbles were relatively faster than the original fine bubbles. This agrees with our two-phase flow characterization in another recent study[5] and agrees with theory. The BST unit effectively acts as a secondary aerator, which transforms the fine bubbles to the coarse bubbles. In addition, the coarse bubbles produced by the BST were well distributed over the membrane surfaces. Since the diameters of the transformed coarse bubbles were larger than 5 mm (gaps between the modules), slug flow would tend to occur in the module gaps and help to scour the membrane surfaces. In the second part of this study, the fouling control provided by many fine bubbles (no BST) was compared with that provided by relatively few large bubbles (with BST).

Fouling in MBRs is characterized by the transmembrane pressure (TMP) profile over time. Greater fouling typically shows a greater TMP rise (dTMP/dt) and a more rapid transition to a steep dTMP/dt, or TMP jump.[11] Figures 4 and 5 compare transmembrane pressures (TMP) of the flat-sheet MBR with the BST unit and without the BST unit to evaluate the fouling control efficiency at different permeate fluxes and total air flowrates. After the BST unit was installed, approximately 65% of the fine bubbles flowed to the BST and the internal chamber and were transformed to coarse bubbles (calculations based on areas of aerators, and the

Table 4. Average EPS Compositions at Total Air Flowrates of 3 and 5 L/min

Total Air Flowrate		3 L/min With BST	3 L/min Without BST	5 L/min With BST	5 L/min Without BST
Protein (mg/L)	Soluble	13.5 ± 11%	12.3 ± 11%	6.5 ± 11%	4.3 ± 12%
	Non-soluble	298.1 ± 10%	264.4 ± 13%	176.2 ± 11%	184.8 ± 14%
	Total	311.6 ± 10%	276.7 ± 10%	182.7 ± 11%	189.1 ± 14%
Polysaccharides (mg/L)	Soluble	192.7 ± 13%	219.3 ± 12%	271.6 ± 11%	218.9 ± 13%
	Non-soluble	378.4 ± 10%	357.5 ± 9%	394.2 ± 11%	387.3 ± 8%
	Total	571.1 ± 10%	576.8 ± 9%	665.8 ± 11%	606.2 ± 8%
Extracellular polymeric substance, EPS (mg/L)	Soluble	206.2 ± 14%	231.5 ± 12%	278.1 ± 11%	223.2 ± 13%
	Non-soluble	675.5 ± 11%	621.9 ± 8%	570.4 ± 11%	572.1 ± 9%
	Total	882.7 ± 11%	853.5 ± 8%	848.5 ± 11%	793.2 ± 9%

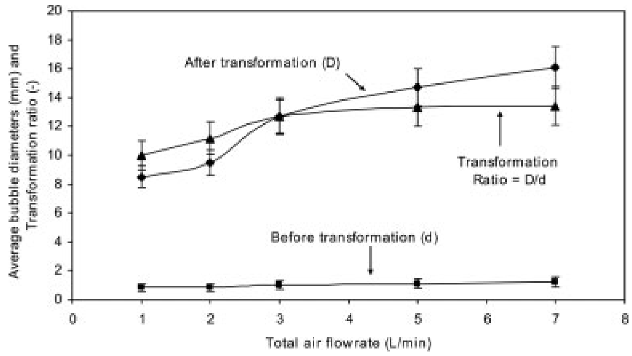

Figure 3. Average bubble diameters of fine bubbles before the transformation and coarse bubbles after the transformation, and the transformation ratio.

cross-sectional area of the BST and the internal chamber). Slightly smaller amounts (58%) of the fine bubbles flowed to the internal chamber for the experiments without the BST. This slight difference in the amounts of bubbles entering the module chamber could be ignored for fouling and aeration effects.

At a permeate flux of 22.5 L/m^2.h and a total air flowrate of 3 L/min, the jumps in the transmembrane pressures (Figure 4) were found on the 9th day for the SMBR without the BST unit and on the 16th day for the SMBR with the BST unit. TMP jumps occurred sooner when higher permeate flux or a lower air flowrate was used. At a permeate flux of 35 L/m^2.h and a total air flowrate of 5 L/min, the TMP jumps (Figure 5) were found on the 3rd day for the SMBR without the BST unit and on the 10th day for the SMBR with the BST unit. The delayed TMP jumps for the experiments with the BST confirm the improved fouling control obtained by the larger bubbles generated by the BST. The initial TMP rises (dTMP/dt) show less clear-cut evidence for the first 4 days (Figure 4) or 2 days (Figure 5), but then the dTMP/dt became steeper for the experiments without the BST.

Interestingly, an effect of the BST on the permeate qualities in terms of TOC was found (see Table 5). Lower TOCs were found at higher air flowrates. However, the TOC of the permeates were higher when the BST was installed for both air flowrates. The permeate qualities were slightly lower after the fine bubbles were transformed to the coarse bubbles. There are two possible explanations for this. One is that the fine bubbles were better than the coarse bubbles for aeration and biological activities. With the BST, the total bubble surfaces for oxygen transfer were substantially reduced because of coalescence. These coarse bubbles would not significantly contribute to aeration because the coarse bubbles leave the bioreactor immediately after they exit the membrane stack. Dissolved oxygen (DO) concentrations for both air flowrates with and without the BST are shown in Table 3. Without the BST, DO concentrations in the bioreactor for both 3 and 5 air flowrates were higher than those with the BST by approximately 24%. This confirms the importance of adequate contact between MLSS and the fine bubbles in the lower part of the bioreactor. The BST and air flowrate changes had a slight effect on the total EPS concentrations in the bioreactor (see Table 4). Polysaccharides were predominant in the total EPS (60-80%). The other explanation for the effect of the BST on the permeate quality is that in MBRs the membranes tend to provide some retention of macromolecular TOC. The major reason for this is the "dynamic" membrane formed by membrane fouling.[11] Thus, the effect of the BST on fouling control could have slightly reduced the retention ability of the "dynamic" fouling layer. This potential limitation of BST usage could be overcome by using UF flat sheet membrane, rather than an MF membrane.

It is difficult to compare the results obtained here with existing flat-sheet SMBRs such as Kobuta for aeration efficiency because the modules used in the experiments were not optimally designed. Usually, aeration efficiency is determined by the ratio of aeration rate to membrane area, approximately 14 L/min per membrane area of 1 m^2. A high aeration rate-to-membrane area

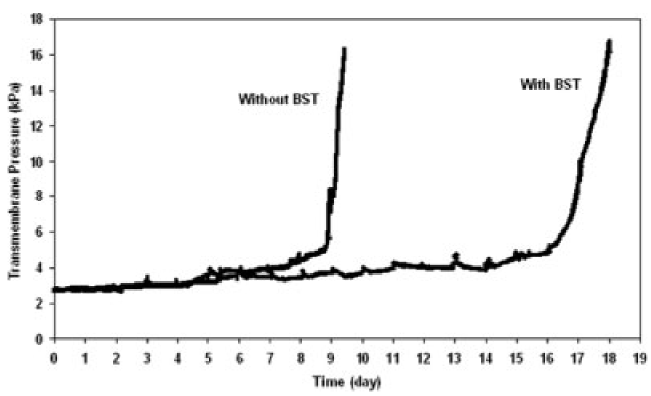

Figure 4. Transmembrane pressure change during long-term constant flux operation for the submerged flat-sheet MBR with and without the bubble-size transformation (BST) unit at permeate flux of 22.5 L/m^2.h and total air flowrate of 3 L/min.

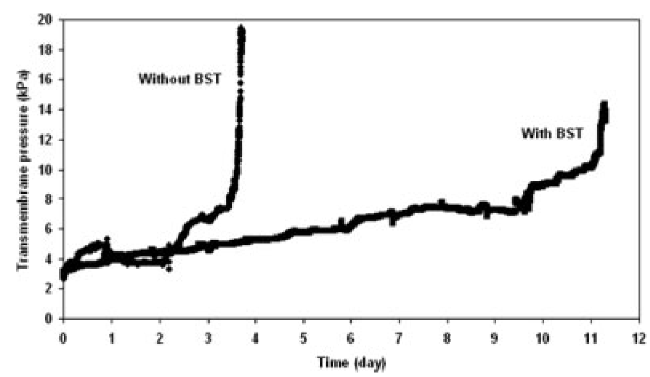

Figure 5. Transmembrane pressure change during long-term constant flux operation for the submerged flat-sheet MBR with and without the bubble-size transformation (BST) unit at permeate flux of 35 L/m^2.h and total air flowrate of 5 L/min.

Table 5. Average Total Organic Carbons (TOC) in Permeates and Dissolved Oxygen (DO) Concentrations in the Bioreactor

Configuration	Air Flowrate = 3 L/min and Permeate Flux = 22.5 L/m^2.h		Air Flowrate = 5 L/min and Permeate Flux = 35 L/m^2.h	
	TOC (ppm)	DO (ppm)	TOC (ppm)	DO (ppm)
With BST	86 ± 12%	1.9	69 ± 10%	2.6
Without BST	67 ± 13%	2.4	44 ± 11%	3.2

ratio means that the bubbles are effectively used. Vertically aligned flat-sheet membrane modules are always preferred because more membrane surface area can contact the coarse bubbles at the same air flowrate. The height for the module in the experiments was rather short, only 12.5 cm, compared with 80 cm for commercial systems. The ratio of height to width of the membrane module is also important for submerged flat-sheet MBR design, approximately 2 for the Kubota's flat sheet modules. The optimum height-to-width ratio of the module for the SMBR with a BST may be different, and further investigations are required.

A simply modified SMBR with a BST could be as proposed. The proposed SMBR has 3 sections: (i) bioreactor section with fine bubbles, (ii) bubble-size transformation section to coalesce fine bubbles into coarse bubbles, and (iii) membrane module section for filtration. In the first section, air is pumped to the aerator to produce the fine bubbles used for aeration of the MLSS. The volume of MLSS in section 1 should probably be more than 85% of the total MLSS volume. The majority of the MLSS should be in good contact with fine bubbles as much and as long as possible to improve biological activity and potentially improve permeate quality due to this activity. Oxygen transfer rate to the MLSS could be possibly high. The fine bubbles partially depleted of oxygen move upward to the bubble-size transformation unit (2nd section) to be transformed to coarse bubbles. The height of the BST unit may range from 12 to 30 cm, depending on how large the bubbles are required to be. The total airflow entering the BST and the membrane module sections may be slightly lower because some oxygen (~20% in air) has been consumed in the bioreactor section. In the 3rd section having the flat-sheet membrane modules, the coarse bubbles scour the membrane surfaces for fouling control. The anticipated advantages from the proposed design of the flat-sheet MBR are: (i) lower aeration rates may be required, and (ii) permeate quality may be improved. Some disadvantages can be expected: (i) the total size of the system (bioreactor BST modules) would be larger than the conventional flat-sheet SMBR, and (ii) the ratio of membrane surface per bioreactor volume may be lower than conventional because of the larger bioreactor. The new design could be similar to Kobuta's SMBR, except for use of fine bubbles and the BST unit being employed.

Conclusions

A bubble-size transformation unit consisting of converging channels and slit tube-bank channels was designed for flat-sheet SMBR to coalesce the fine bubbles into coarse bubbles. The bubble diameters could be increased by approximately 14 times, and the coarse bubbles obtained were well distributed over the membrane surfaces. The transformed coarse bubbles were used for the fouling control in an MBR, and a longer sustainable flux period was obtained when the BST were used. The coarse bubbles controlled fouling effectively. The permeate qualities were slightly affected by the type of bubbles such that the transformed coarse bubbles gave a lower permeate quality, possibly as a consequence of the better control of the dynamic fouling layer. The experimental results on fouling control and permeate quality have provided useful information and suggest improvement in the design of the flat-sheet SMBR.

Acknowledgments

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