Double-Deck Aerated Biofilm Membrane Bioreactor with Sludge Control for Municipal Wastewater Treatment

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Alternative designs of an aerated moving-bed biofilm reactor and a flat-sheet membrane module for a biofilm membrane bioreactor process have been investigated to overcome a membrane clogging problem and to determine the performance of a new membrane module. Double-deck aerated biofilm reactor with integrated designs of sludge hopper, thickener, and velocity-zone concept for particle settlement was evaluated for the suspended solid control and removal. Hydrodynamics of bubbling, liquid, and solid particles were arranged in the bioreactor to obtain a particle settlement. New membrane modules used under low suspended solid environment having smaller membrane gaps were evaluated for filtration performance and clogging problems for long-term operation. The average suspended solids concentration in the bioreactor effluent was 44.6 mg/L. Relaxation applied with the membrane module provided the most optimum result for fouling control, and no clogging problems in the modules were observed in the system after continuous operation of 3 weeks. © 2009 American Institute of Chemical Engineers *AIChE J,* 55: 1291–1297, 2009

Keywords: biofilm membrane bioreactor, bioreactor design, sludge control, moving-bed biofilm, flat sheet membrane modules

Introduction

Developments of membrane bioreactor (MBR) processes for commercialization have been accelerated by high demands in clean water for human activities and a necessity to treat both municipal and industrial wastewaters due to more stringent environmental regulations. Activated sludge membrane bioreactors (AS-MBR) have been commercialized and applied at full-scale plants worldwide. The power consumption from aeration demands (biological and membrane scouring) is typically a major contribution for overall power consumption in MBR processes, where values around 80% have been reported. High viscosity from high suspended solids in AS-MBR is one of the main challenges for the MBR process and causes many drawbacks, including (i) limitations in oxygen mass transfer and high energy demand for mixing (normally by air bubbling), and (ii) a serious membrane clogging problem.[1] A variety of research studies are currently being conducted to minimize net energy demand for aeration per cubic meter of treated water produced and to overcome membrane clogging problems in membrane bioreactor processes. A possible approach to diminish high viscosity effects from suspended solids (activated sludge) in conventional AS-MBR is to utilize carriers to attach biomass (sludge) in the bioreactor. Biofilm formation on the carriers performs biological degradation of organic pollutants in wastewaters.

Biofilm membrane reactors (BF-MBR) were developed as an alternative technology to AS-MBR in wastewater treatment applications. Typically, BF-MBR can be categorized

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into two groups[1,2]: (i) extractive BF-MBR where biofilms grow on carriers and suction is applied to membranes (filtration) to draw a permeate (similar to extractive AS-MBR), and (ii) membrane-aerated biofilm reactor (MABR) or diffusive BF-MBR or aerated biofilter where biofilms grow on gas-permeable membrane surfaces without vacuum applied, and which are aerated by air diffusing through the membranes. The membrane-aerated biofilter processes have been used for both wastewater and waste gas treatments.[3,4] Different from the extractive BF-MBR process, a membrane in the MABR provides (i) a support for biofilm growth and (ii) air/oxygen supplying passage to biofilm (not involved in filtration as separation). Although this technology of membrane aerated biofilm reactor is still under development because of the long-term stability limitations, it offers a promising efficiency to remove poorly water-soluble pollutants in gas streams such as toluene and chlorinated hydrocarbons.[4] The extractive BF-MBR processes provide a superior effluent quality and good long-term stability, which are attractively used for wastewater treatment applications in commercial scales. Therefore, this article focuses on the extractive BR-MBR only. A unique characteristic of the BF-MBR can be described as a low suspended solid environment in the system due to attachment of biomass or biofilms on carriers. Relatively low suspended solid concentrations in the BF-MBR can offer many advantages over the AS-MBR such as (i) lower viscosity of mixed liquor suspended solid (MLSS) reducing energy consumption from the aeration system, ii) potentially less problems of cake deposition, clogging in membrane modules, and (iii) potentially less biofouling in BF-MBR.[5] The BF-MBR can utilize both fixed biofilm and moving biofilm reactors for organic degradations. The moving-medium biofilm reactor is an interesting alternative and offers both better mixing and higher mass transfer for oxygen/organic diffusions, and hydrodynamics for substrate-oxygen distribution compared to fixed biofilm reactors.[6–8] The biological processes of moving-medium biofilm reactors can be typically classified into four main groups,[6] i.e., (i) the rotating biological contactor, (ii) the moving-bed biological reactor,[8] (iii) the vertically moving biofilm reactor, and (iv) the fluidized-bed reactor. These processes are not prone to a clogging problem by particulate matter or high suspended solids when compared with a fixed biofilm process. The moving-bed biofilm reactor technology was chosen for investigation in this study. The BF-MBR, coupling the moving-bed biofilm reactor with external membrane filtration configuration, has been developed for municipal wastewater treatment[9–11] and for industrial wastewaters such as saline wastewater from a fish canning production[12] and landfill leachate.[13] The typical total suspended solid (TSS) concentration in the moving-bed biofilm reactor (MBBR) effluent is ~200 mg/L which relates to TSS accumulated in the external membrane tank greater than 1000 mg/L at steady-state operation depending on set operating parameters (i.e., recovery).[9–11,14,15] Clogging problems are potentially possible in the membrane module for the conventional BF-MBR, especially for a submerged module configuration, if TSS is not well controlled. Moreover, design of the biofilm reactor used for membrane filtration may be different from a conventional moving-bed biofilm reactor in many aspects such as hydrodynamics of moving beds and air bubbles, and membrane module designs. An improvement of the biofilm reactor designs in aspects of hydrodynamics and suspended solid control in the MBBR which has the potential of reducing the solid concentrations to the external membrane filtration unit should be considered.

Therefore, this study was aimed to develop the designs of a biofilm reactor and new membrane module for the BF-MBR used under low suspended solid environments. Minimization of TSS concentrations may provide benefits for operation and maintenance as problems from clogging, and solid depositions in the MBR system are overcome. Additional benefits of low TSS operations in the biofilm MBR process can be described as (i) lower water and chemical consumptions for membrane cleaning due to less accumulation of sludge or particles in the system, leading to fewer amounts of wastes generated from the cleaning activity (friendly to environment), and (ii) when the clogging problem is not obvious in the membrane module due to low TSS environment, higher membrane packing densities can be obtained, leading to more compact membrane modules and lower space requirement for installation. A double-deck bioreactor with moving-bed biofilm carriers and integrated particle settlement zone was designed to control TSS inside the bioreactor and subsequently produce a low TSS concentration in the effluent. Hydrodynamics of aeration and mass transfer of oxygen were designed and arranged to reduce energy consumption of aeration. The performance of the new design of the biofilm reactor was determined for TSS control and effluent quality, and membrane filterability. A new membrane module specially designed for the BF-MBR with low TSS environment can have smaller membrane gaps than the module designed for the AS-MBR because the degree of membrane clogging problem is potentially less. Long-term operation (2–3 weeks) for membrane filtration was used to evaluate the potential of membrane clogging in the new module designed for the BF-MBR process. The effects of aeration and membrane relaxation on membrane fouling control were investigated in the new BF-MBR module.

Materials and Methods

The BF-MBR process for the experiments was configured as an external submerged membrane reactor using a flat-sheet membrane module. Figure 1 shows the experimental setup for the double-deck aerated biofilm reactor with external membrane filtration unit. The biofilm reactor had two biofilm chambers, each confined by a partially perforated sloping plate on the top of the chambers and a grid plate at the bottom. The upper biofilm chamber was larger than the lower biofilm chamber, contributing around 66% of total hydraulic retention time. Fine bubble aeration was generated from three ceramic fine aerators (diameter of 7 cm). The void fraction of the grid plates for both chambers was ~70%. Coalescence of the fine bubbles takes place in the lower chamber when the bubbles collide with the partially perforated plate on the top of the lower chamber (Figure 1). Coarse bubbles generated from the lower chamber entered the upper chamber and provided aeration/mixing. The sloped plate in the lower chamber was installed to increase the contact time between the air bubbles and the biofilm carriers.

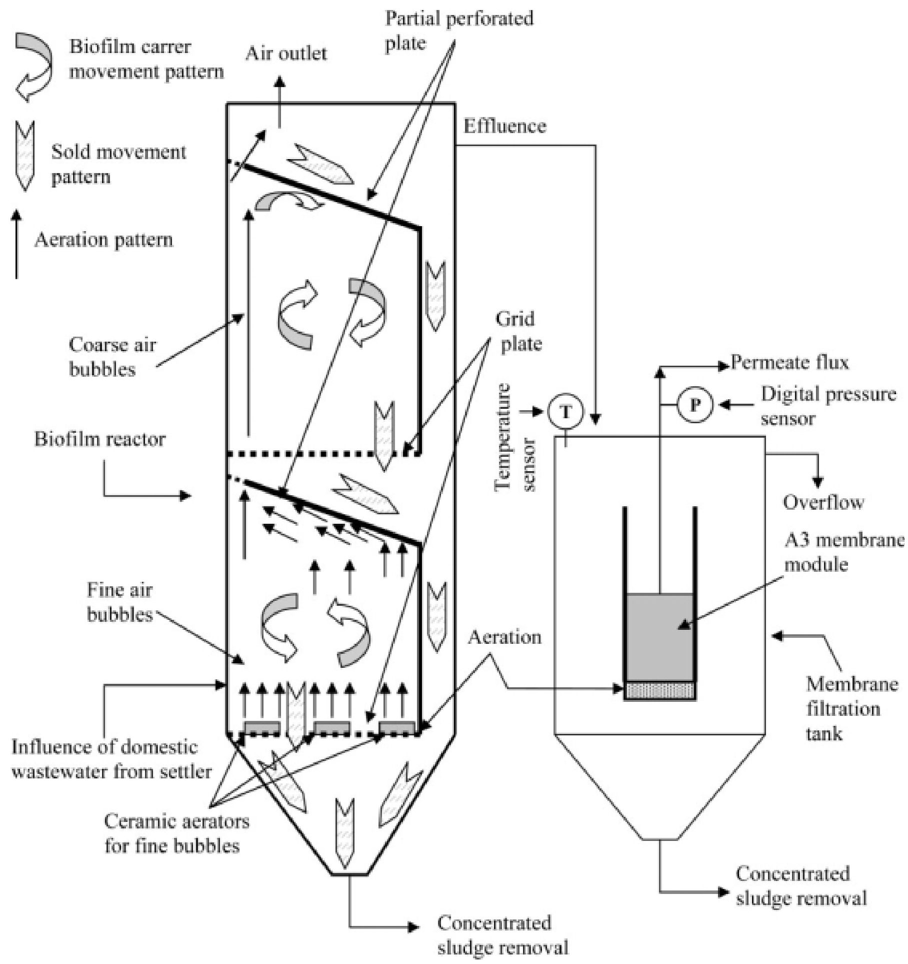

Figure 1. Hydrodynamic, aeration pattern, and solid movement pattern designed in double-deck aerated biofilm reactor, and experimental setup for the biofilm MBR.

The internal walls inside the biofilm reactor created high and low velocity zones in which the high velocity zone was for mixing (high mass transfer coefficient) and the low velocity zone was to establish the pathway for biomass particle settling. The bottom of the biofilm reactor was designed as a sludge hopper to enhance sludge settling and to collect the excess sludge generated in the biofilm reactor. The concentrated sludges settled at the bottom of the bioreactor and the membrane filtration tank were removed periodically when the set limits were reached. The characteristics and operating conditions of the biofilm reactor are listed in Table 1. Effluent from the biofilm reactor gravitationally flowed to the membrane tank. Two different designs of the flat-sheet membrane modules tested with the biofilm reactor were supplied from A3 Water Solutions GmbH, Germany, which are (i) standard membrane module designed for AS-MBR, and (ii) new membrane module designed for BF-MBR. The specifications of both A3 membrane modules are shown in Table 2. The BF-MBR membrane modules had smaller gaps between the membrane surfaces which allowed higher superficial air velocities for fouling control. The biofilm reactor was originally based on the MBBR process, AnoxKaldnes (Veolia), Norway.[8] The K1 media as biofilm carrier are made of HDPE and are shaped as short cylinders with a cross internally and wavy surface externally to obtain high surface areas. The filling fractions for the biofilm carrier in the chambers were 60 and 67% of the chamber volumes giving effective specific surface areas of 300 and 335 m^2/m^3 in the upper chamber and the lower chamber, respectively. Municipal wastewater collected from a public sewer was used in this study, pretreated by a gravity settler and fed to the biofilm reactor. The effluent from the biofilm reactor flowed by gravity to the external membrane filtration unit. The effective volume of the membrane tank was ~59.6 L. The membrane modules were submerged in the membrane tank,

Table 1. Characteristics and Average Operations of Double-Deck Aerated Biofilm Bioreactor

Characteristics/Operations	
Effective volume of upper biofilm chamber (L)	74.3
Effective volume of lower biofilm chamber (L)	42.1
Apparent hydraulic retention time—HRT (h)*	7.2
Volumetric COD loading (kg O_2/m^3 day)	0.92
Volumetric FCOD loading (filtered) (kg O_2/m^3 day)	0.45
Aeration (L/min)	9
Ratio of aeration to total bioreactor volume (L/min L)	0.08

*Effective HRT was 6.12 h.

Table 2. A3 Flat-Sheet Membrane Module Characteristics and Operating Conditions

Properties/Conditions	A3 Flat-Sheet Module for AS-MBR	New A3 Flat-Sheet Module for BF-MBR
Membrane material	PVDF, pore size of 0.1 μm, membrane layer of 50 μm (composited on Poly olefin)	
Housing material	PVC	
Average membrane gap (mm)	7	4
Module dimension W × H × L (cm)	20.1 × 17.8 × 11.6	17.8 × 16.1 × 9.9
Effective membrane area (m^2)	0.539	0.603
Effective membrane area per module volume (m^2/m^3)	124.5	212.5
Aeration for membrane scouring	32–48 L/min (medium-sized bubbles: 6–12 mm diameters)	

and the aerator for membrane scouring was placed 5 cm below the module. Coarse bubbles (∼0.5–1.5 cm diameters) were used for membrane scouring with air flow rates ranging from 32 to 48 L/min. Average properties of the wastewater influent, bioreactor effluent, and permeate are listed in Table 3. MasterFlex computerized peristaltic pumps with speed control of ±0.25% (RS-232 connections) and WinLIN software (Cole Parmer) were used to control the flow rate of the wastewater and to create the vacuum for permeate production. SMC digital pressure sensor: PSE563-NO1 (compound pressure) and temperature sensor: IPAQ-H with Pt-100 were used to monitor the transmembrane pressures and temperatures in the membrane tank, respectively. National Instrument DAQ card: USB 6210 and LabVIEW 8.2 were used for data acquisition.

Spectral absorbance measurements were carried out at the wavelengths 254 and 436 nm by UV-Visible Hitachi U-3000 spectrophotometer. Color was measured by Norwegian standard method at wavelength of 410 nm.[16] Total organic carbons (TOC) and dissolved organic carbons (DOC) were measured by Tekmar Apollo 9000 TOC Combustion Analyzer. Turbidities were monitored by Hach 2100N Turbidimeter. Conductivities, pH, and dissolved oxygen concentrations were measured by Mettler Toledo SG3 with InLab 737, Mettler Toledo SG2 with InLab 413, and WTW Oxi 330i with DO probe CellOx 325, respectively. Total suspended solid concentrations were measured by standard weighting method with glass filter. Chemical oxygen demands (COD), filtered COD, ammonium concentrations ($N\text{-}NH_3$), and total nitrogen concentrations in the biofilm MBR system were measured by Hach-Lange cuvette test kits: LCK 114, 314, 614, 114, 302, 303, 238, and 338. The Hach-Lange photometric cuvette tests had been calibrated and evaluated to well meet the standards with ISO 8466-1, DIN 38402 A51, and DIN 32645. Concentrations of soluble microbial products (SMP) were not measured in this study because the membrane fouling in BF-MBR is likely to be controlled by submicron particles.[11,14,15]

The alternative biofilm membrane reactor design was evaluated for suspended solids control, the effluent quality, and membrane filtration performances. Experiments were carried out in two parts to evaluate the membrane modules used in the study. First, the performances of the A3 module for AS-MBR and the A3 module designed for BF-MBR were determined and compared under controlled conditions. Second, new A3 modules designed for BF-MBR were investigated for clogging problems, aeration effect, and relaxation operating mode. As a short-term critical flux measurement may not be useful for long-term operation, the tests in this study were focused on long-term operation (sustainable flux condition) for actual applications. Experimental conditions for tests of the membrane modules are listed in Table 4. The changes of transmembrane pressure (TMP) over the operating times were monitored for fouling rate experiments.

Results and Discussion

The characteristics of the effluent from the biofilm reactor compared to the wastewater influent are listed in Table 3. Average total suspended solid (TSS) concentration in the

Table 3. Average Characteristics of Domestic Wastewater Influents, Treated Effluents, and Permeates

Characteristics	Influent to the Bioreactor (Wastewater)	Effluent from the Bioreactor		Permeate	
		Value	% Removal	Value	% Removal
Chemical oxygen demand—COD (mg O_2/L)	273.4	57.5	78.97	–	–
Filtered chemical oxygen demand—FCOD (mg O_2/L)	135.2	30.8	77.2	23.7	82.4
Total suspended solid—TSS (mg/L)	114.7	44.6	61.1	–	–
Total organic carbon—TOC (mg/L)	73.6	22.5	69.4	–	–
Dissolved organic carbon—DOC (mg/L)	42.4	14.7	65.3	10.6	75.0
Turbidity (NTU)	89.3	12.9	85.5	0.3	99.6
$N\text{-}NH_3$ (mg/L)	29.7	4.8	83.8	1.6	94.6
Total nitrogen (TKN) (mg/L)	41.3	25.3	38.7	22.4	45.7
UV absorbance at 254 nm—UV_{254} (m^{-1})	42.2	36.9	12.5	27.9	33.8
Spectral absorbance at 436 nm—A_{436} (m^{-1})	2.1	1.37	34.7	1.1	47.6
Specific UV absorbance at 254 nm—SUVA at 254 nm (L/m mg)	0.9	2.5	–	2.6	–
Specific spectral absorbance at 436 nm—SA at 436 nm (L/m mg)	0.05	0.09	–	0.1	–
Conductivity (μS/cm)	906.4	734.6	–	711.8	–
pH	7.3	7.8	–	7.5	–
Color (mg Pt/L)	n/a	42.7	–	38.2	–

Table 4. Experimental Conditions of A3 Membrane Module Tests for the Biofilm MBR

Experiments/Conditions	Exp. I	Exp. II	Exp. III	Exp. IV	Exp. V
Module	Module designed for AS-MBR	Module designed for BF-MBR			
Net permeate flux (L/m^2 h)	17.91	17.91	12.93	17.91	18.09
Aeration rate and superficial air velocity	32 L/min and 4.27 cm/s	32 L/min and 6.41 cm/s		48 L/min and 9.61 cm/s	32 L/min and 6.41 cm/s
Specific aeration demand based on membrane area (SAD_m, m^3/h m^2)*	3.56	3.18		4.77	3.18
Operation	Continuous				1 min relaxation every 9 min of operation with flux of 19.9 L/m^2 h

*SAD_m are relatively high because the lab-scale modules are short.

biofilm reactor effluent was relatively low at 44.6 mg/L (small deviation in the range of 32.8 to 59.2 mg/L) through the experimental period, which implies that the alternative biofilm reactor design was able to control the suspended solids. Low turbidity and filtered COD in the effluent were obtained because both particles and organics were removed. At HRT 7.2 h, nitrification occurred in the biofilm reactor leading to low ammonium concentrations in the effluent (~6 mg/L). The average dissolved oxygen (DO) concentrations in the lower and upper chambers were 4.4 and 3.6 mg/L, respectively. Higher DO in the lower chamber possibly resulted from the fine bubble aeration used and better mixing patterns. The sloped plate to increase contact time of bubbles in the bioreactor may be useful for minimizing aeration demands in the moving-bed biofilm reactor; however, more investigations are required for the optimum design. TSS concentrations in the external membrane filtration tank slowly increased and became stable after the 6th day of operation with the concentration range of 103.1 to 143.6 mg/L. No floating sludge was observed in the membrane tank during the experiments, and the concentrate sludges, with concentration in a range of 2 to 5 g/L, were removed from the bottom of the biofilm reactor and the membrane tank. The amount of the concentrated sludge removed from the biofilm reactor was observed to be more than that removed from the membrane tank. Thus, most of the biomass particles were captured in the biofilm reactor.

The performance comparison between the A3 AS-MBR membrane module (Exp. I in Table 4) and the A3 BF-MBR membrane module (Exp. II) for the filtrations with permeate flux of 17.9 L/m^2 h and aeration of 32 L/min is shown in Figure 2. The A3 BF-MBR module with smaller gaps had lower fouling rates (slower increase in TMP) for the filtration period, and the superficial air velocity in the A3 BF-MBR module was ~50% higher than that in the A3 AS-MBR module for the same air flow rate applied. Average rates of transmembrane pressure increase over time were 0.086 and 0.046 bar/day for the AS-MBR module and the BF-MBR module, respectively. The new module design with the smaller space gaps in the A3 BF-MBR module also occupied ~35% less space than the module designed for the AS-MBR process. Lower space requirement for installation of new designed membrane module can be expected if optimum module design is applied. Since both A3 modules had similar membrane area, specific aeration demands (SAD) based on membrane surface area (SAD_m) of both modules should be very similar. However, SAD based on a permeate production (SAD_p) for the new BF-MBR module (SAD_p ~178) should be lower than that for AS-MBR module (SAD_p ~199) because the BF-MBR module can be operated at higher permeate flux. However, SADs for both lab-scale membrane modules were relatively high due to short modules which are not optimum for industrial operations. The new A3 BF-MBR modules were further investigated for the effect of varying aeration, relaxation operation compared to continuous operation, and long-term operation for clogging problem monitoring. Figure 3 shows the change of transmembrane pressure over 3 weeks at flux of 12.93 L/m^2 h and aeration of 32 L/min (Exp. III). Linear increases in the TMP were found for the Exp. III, and TMP jumping phenomena from large particle deposition and cake formation did not occur in the filtration period monitored. The average magnitude of d(TMP)/dt, which represents fouling rates, for Exp III was found at 0.016 bar/day. No clogging was observed in the BF-MBR module during 3 weeks operation. Low suspended solids effluent produced by the new designed biofilm reactor contributed to overcome the clogging problems in the membrane module often observed in the conventional MBR processes.

Attempts to obtain more stable TMP and lower d(TMP)/dt were conducted by using higher air flow rates for membrane

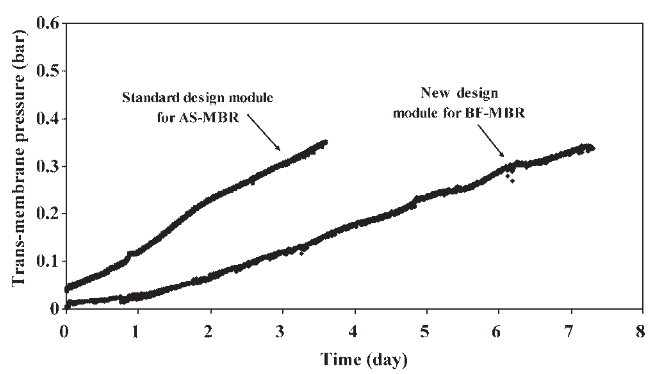

Figure 2. Comparison in transmembrane pressure increases over times between original module design for activated sludge MBR and new module design for biofilm MBR.

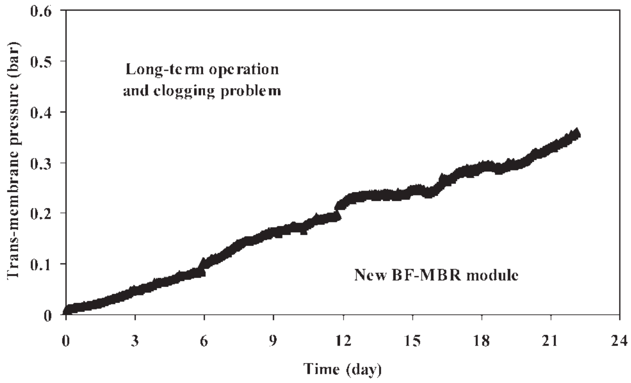

Figure 3. Development of transmembrane pressures for the A3 BF-MBR module with flux of 12.93 L/m^2 h and air flow rate of 32 L/min.

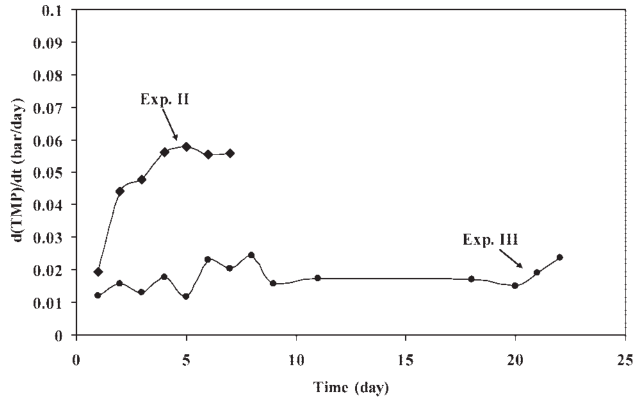

Figure 5. Rates of changes of transmembrane pressures over times for Exps. II and III.

scouring and using relaxation mode of operation applied to the membrane module with the conditions listed in Table 4 for the experiments IV and V. Higher air velocity refers to stronger shear rate from air bubble scouring to remove fouling on the membrane surface, and membrane relaxation was aimed to slow foulant deposition rate on the membrane surface. Figure 4 shows comparisons in TMP changes over time for Exps. II, IV, and V. The fouling rate from Exp. IV with 50% higher air flow rate was lowest. The average TMP increase rates were 0.031 and 0.039 bar/day for Exps. IV and V, respectively. Compared to Exp. II, the fouling rates of Exps. IV and V were reduced ~31 and 15% by 50% higher aeration and 10% membrane relaxation, respectively. Higher energy demand was required for the larger amount of aeration in Exp. IV, whereas membrane relaxation may not need any additional energy for membrane scouring. With slightly higher *d*(TMP)/*dt* of Exp. V than Exp. IV, the membrane relaxation technique in Exp. V appears to be more interesting as lower operating costs, compared with needs for higher aeration demand.

In AS-MBR, TMP increase resulting from fouling is described by a three-stage mechanism,[17] where a TMP jump occurs in the last stage, expressed as a sudden rise in TMP. However, for the BF-MBR investigated in this study, no TMP jump was observed. Fouling mechanisms for the BF-MBR with low TSS condition may be different from that for AS-MBR due to small amount of large particles and very low TSS. Lack of TMP jump within the time of operation implies that overall fouling rates of BF-MBR may be lower than that of AS-MBR. Colloidal particles may play the most important role for fouling characteristics in the BF-MBR[11,14,15] and cause a main reason for different fouling mechanisms. Preliminary investigations on fouling in BF-MBR can be performed by considering characteristics of TMP variations. Figure 5 shows rates of changes of TMPs over times (*d*(TMP)/*dt* vs. *t*) for Exps. II and III. The operating conditions in Exp. II gave an accelerated increase of TMP in the initial period and then reached a plateau after the 4th day. Fouling mechanisms in Exp. II may have two stages because there are two characteristics of TMP changes. A different fouling characteristic was found in Exp. III which was carried out under lower flux than Exp. II. *d*(TMP)/*dt* are likely to be relatively stable and varied in a short range of 0.013 to 0.023 bar/day, and only one fouling mechanism may take place in Exp. III. The A3 modules were found likely to require relatively high superficial air velocity for fouling control. Only Exp. III was found to have a sustainable flux condition during the operation. The membrane module samples with PVDF membranes seemed to have relatively low flux operations which may be slightly lower than ~12 L/m^2 h and required a minimum superficial velocity of ~6.4 cm/s to obtain a sustainable flux condition for long-term operation.

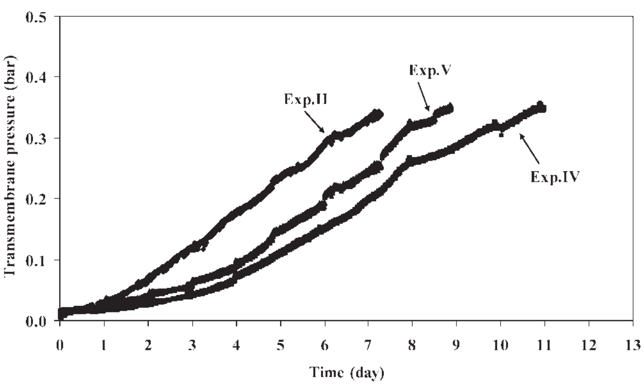

Figure 4. Comparison in changes of transmembrane pressures over times of the A3 modules designed for biofilm MBR between high aeration and membrane relaxation.

Conclusions

New design of a biofilm membrane reactor consisting of a double-deck biofilm reactor and an external submerged membrane filtration unit was evaluated for minimization of the total suspended solid concentrations in the biofilm reactor effluent for municipal wastewater treatment. Concept and benefits of the alternative biofilm membrane reactor process operated under low suspended solid conditions were discussed. Double-deck design of the biofilm reactor with sludge trap was used to produce an effluent with low total suspended solid concentration. The external membrane reactors also featured sludge traps used for enhanced removal of biomass particles. The A3 flat-sheet membrane module was redesigned to be suitable for BF-MBR processes operated under low TSS environment, having smaller membrane gaps than those in the module designed for conventional AS-MBR. Experimental investigations including clogging problems in the module, filtration performance, and fouling characteristics were carried out. Clogging problems in the membrane modules were not found in all experiments due to low suspended solid concentrations in the bioreactor effluent. The BF-MBR module provided lower fouling rates than the AS-MBR module at the same aeration rate and permeate flux due to higher superficial air velocity, which implied better hydrodynamics in the module. High aeration rate in the module to scour membrane surfaces provided a lower fouling rate than membrane relaxation. However, the operation of membrane relaxation appears to be more useful in aspect of lower aeration demand. Smaller space for a membrane module installation and low TSS concentrations in the BF-MBR can be recognized as unique characteristics of the BF-MBR process to overcome clogging problems in the module. More investigations for hydrodynamic design in both the biofilm reactor and membrane filtration unit are required to optimize the BF-MBR system performance in aspect of treated water production, and low total operating costs (including membrane cleaning and chemical waste management).

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