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Effects of membrane orientation on permeate flux performance in a submerged membrane bioreactor

Tsun Ho Lee and Stephanie Young*

Faculty of Engineering and Applied Science, University of Regina, Regina, Canada

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Abstract. The aeration provided in a Submerged Membrane Bioreactor (SMBR) improves membrane filtration by creating turbulence on the membrane surface and reducing membrane resistance. However, conventional hollow fiber membrane modules are generally packed in a vertical orientation which limits membrane scouring efficiency, especially when aeration is provided in the axial direction. In the present research, 3 innovative hollow-fiber membrane modules, each with a different membrane orientation, were developed to improve membrane scouring efficiency and enhance permeate flux. Pilot testing was performed to investigate the permeate flux versus time relationship over a 7-day period under different intermittent modes. The results indicated that the best module experienced an overall permeate flux decline of 3.3% after 7 days; the other two modules declined by 13.3% and 18.3%. The lower percentage of permeate flux decline indicated that permeate productivity could be sustained for a longer period of time. As a result, the operational costs associated with membrane cleaning and membrane replacement could be reduced over the lifespan of the module.

Keywords: hollow fiber membrane; membrane orientation; permeate flux; membrane fouling; submerged membrane bioreactor; membrane replacement, operation, and maintenance; commercialization; membrane technology

1. Introduction

Membrane Bioreactor (MBR) process for wastewater treatment has been studied for the past 40 years. The MBR combines biological degradation and membrane filtration into one system, where most of the organic compounds are biodegraded by microorganisms and solid residuals are separated from the effluent by a membrane filtration unit. The separated solid residuals, including microorganisms, are retained in the bioreactor. Very often, the submerged MBR process configuration is considered because of its low energy consumption and small environmental footprint (Kwon *et al.* 2008). Compared to the conventional activated sludge process, a submerged MBR produces better effluent quality, a higher biomass concentration, less sludge production, and a more compact plant design (Judd 2006).

Despite the unique advantages of a submerged MBR, the increase in operational and maintenance costs associated with membrane fouling and membrane replacement still limits the growth of the MBR process. Membrane fouling, which causes flux decline and system degradation, is an inevitable and dynamic process which varies from system to system due to variations in influent characteristics, membrane properties, and operating conditions. However, membrane fouling can be limited by

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* Corresponding author, Professor, E-mail: stephanie.young@uregina.ca

improving the operating conditions and by adopting new module designs (Fane *et al.* 2002, Zhou *et al.* 2008).

The application of aeration has been considered a standard practice to control membrane fouling and enhance the permeate flux (Bellara *et al.* 1996, Cui and Wright 1996, Bouhabila *et al.* 1998, Cheng *et al.* 1999, Bouhabila *et al.* 2001, Cheng 2002, Guibert *et al.* 2002, Hong *et al.* 2002, Cui *et al.* 2003, Yu *et al.* 2003, Taha *et al.* 2006, Ghosh 2006, Berube *et al.* 2008). In a submerged MBR, aeration has three important roles which include creating turbulence on the membrane surface to enhance permeate flux and reduce fouling, providing oxygen for biological degradation, and maintaining the activated sludge in suspension. As the air bubbles rise, they reduce the concentration polarization on the membrane surface and thus enhance the permeate flux. Conventional membrane modules are orientated in a vertical position. However, with this type of module orientation, the membrane area in contact with the rising air bubbles is very limited. Recent research revealed that as the flat-sheet or tubular membrane module is submerged and inclined at a certain angle, permeate flux can be enhanced at a given aeration rate (Cheng *et al.* 1999, Cheng 2002, Taha *et al.* 2006, Cheng and Lee 2008). The objectives of this research were to develop and pilot test hollow fiber modules with different fiber orientations to determine the best module for commercialization. The membrane module chosen for commercialization can be submerged and installed vertically while maintaining the unique advantage of module inclination to enhance permeate flux. In addition, the modules were pilot tested to investigate the permeate flux versus time relationship under different intermittent operation modes.

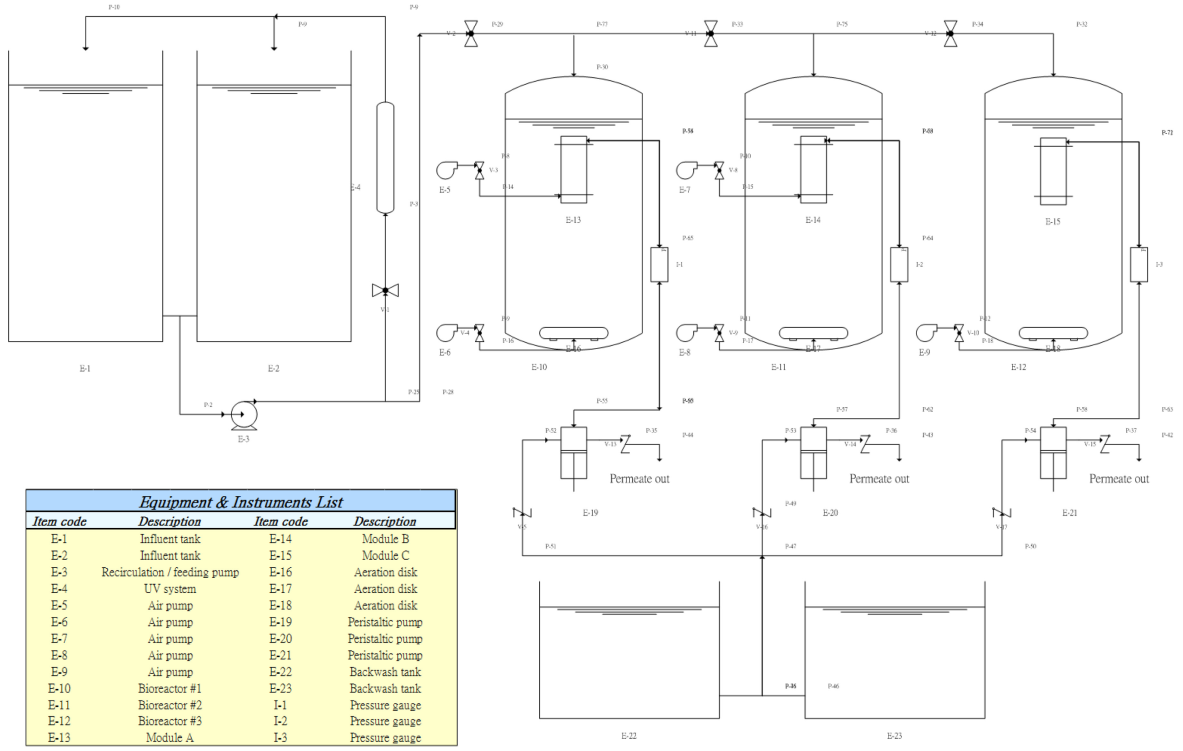
2. Experimental

2.1 Equipment setup

The experiments in this study were carried out using a pilot scale MBR system. The schematic diagram is shown in Fig. 1. The MBR system consisted of two 1,500 L influent tanks, a recirculation/feeding pump, 3 cylindrical bioreactors, with a working volume of 500 L, 3 Masterflex® L/S® peristaltic pumps with Easy-Load II® pump heads, and two 120 L backwash tanks. The three different modules developed in this study were submerged into the corresponding bioreactors simultaneously to investigate the permeate flux performance and membrane resistance under different operating

Table 1 Chemical compositions of synthetic greywater for COD of 400 mg/L

Chemical name	Molecular formula	Dosage
Starch	$C_6H_{10}O_5$	450 g
Dextrose	$C_6H_{12}O_6$	210 g
Peptone	n/a	216 g
Beef extract	n/a	153 g
Sodium carbonate	Na_2CO_3	540 g
Sodium bicarbonate	$NaHCO_3$	279 g
Urea	NH_2CONH_2	72 g
Ammonium sulfate	$(NH_4)_2SO_4$	78 g
Tap water	H_2O	3000 L



Equipment & Instruments List

Item code	*Description*	*Item code*	*Description*
E-1	Influent tank	E-14	Module B
E-2	Influent tank	E-15	Module C
E-3	Recirculation / feeding pump	E-16	Aeration disk
E-4	UV system	E-17	Aeration disk
E-5	Air pump	E-18	Aeration disk
E-6	Air pump	E-19	Peristaltic pump
E-7	Air pump	E-20	Peristaltic pump
E-8	Air pump	E-21	Peristaltic pump
E-9	Air pump	E-22	Backwash tank
E-10	Bioreactor #1	E-23	Backwash tank
E-11	Bioreactor #2	I-1	Pressure gauge
E-12	Bioreactor #3	I-2	Pressure gauge
E-13	Module A	I-3	Pressure gauge

Fig. 1 Schematic diagram of the pilot scale MBR system

conditions. A synthetic greywater influent containing a chemical oxygen demand (COD) of 400 mg/L was used to maintain homogeneity and to produce consistent greywater characteristics so that the results were comparable. The chemical compositions of the synthetic greywater are summarized in Table 1.

2.2 Membrane module designs and specifications

In this research, a total of 18 hollow fiber modules with 3 different innovative designs were successfully manufactured and pilot tested. To simplify discussion in the following sections, anonymous names were given to each module according to its physical appearance and hollow fiber membrane orientation:

Module *A* was assigned to the “vertical” module (i.e., vertical fiber orientation).

The physical appearance of Module *B* cannot be described due to a patent restriction.

Module *C* was assigned to the “loop” module (i.e., looping fiber orientation).

The 3 modules listed above were manufactured from the same type of hollow fiber membrane, supplied by SINO Filtration Technology (Tianjin) Co., Ltd. The specifications of the hollow fibre membrane are summarized in Table 2. The module was formed from 720 membrane fibres with an effective length of 46 cm. The effective surface area was approximately 1.32 m^2.

The design of Module *A* was a mimic of the conventional modules with vertical hollow fiber alignment. It functioned as a control test throughout the experiment to see if other modules with

Table 2 Membrane specifications of the innovative modules

	Description
Membrane type	Hollow fiber for outside-in operation
Membrane manufacturer	SINO Fiber Company Limited
Membrane material	Polyvinylidene fluoride (PVDF)
Nominal pore size	0.1 μm
Outer fiber diameter	1.3 mm
Inner fiber diameter	0.7 mm
Maximum TMP pressure	60 kPa
Operating pH range	4 - 10
Potting material	Proprietary epoxy compound

different fiber orientations would retain better performance than Module *A*. The overall module, mainly supported by acrylic, consisted of a top and a bottom membrane potting plate and an air-tight permeate collection tube. A John Guest push connect fitting was installed on the tubing to allow for peristaltic pump connection and to facilitate permeate collection. As well, an aeration stone was installed at the centre of the bottom potting plate to supply air for membrane scouring. The overall supporting structures of Module *B* were identical to Module *A*. Although the detailed hollow fiber orientation of Module *B* was not described due to patent restriction, the principle design was based on the unique advantage of module inclination resulting in an increased air-membrane scouring area. Module *C* had only one membrane potting plate and the design utilized a looping fiber pattern to reduce the membrane potting holes by half when compared to Module *A* and Module *B*. An air-tight permeate collection tube and a John Guest push connect fitting were installed on the potting plate for permeate collection. In addition, Module *C* has its unique characteristic of free moving membrane fibers whereas the membrane fibers installed in Module *A* and *B* were fixed by their top and bottom potting plates. Since Module *C* did not have a bottom potting plate, this design did not have an aeration stone installed for membrane scouring. Since the membrane fibers could move freely in water, membrane scouring was achieved solely by the bioreactor aeration system. As with Module *A* and Module *B*, Module *C* had a design effective length of 46 cm and an effective surface area of approximately 1.32 m^2.

2.3 MBR operation

The synthetic greywater was pumped into the bioreactors where contaminants were biologically degraded. At the same time, the effluent was continuously filtered by the modules. The water levels in the bioreactors were controlled by flow valves installed on the influent pipes. The hydraulic retention time (HRT) was established at 8 hours when the experiment started. The mixed liquor suspended solids (MLSS) concentration and the dissolved oxygen (DO) level were maintained between 4500 mg/L to 5000 mg/L and 2.5 mg/L to 3.0 mg/L, respectively.

In the pilot scale MBR system, Modules *A*, *B*, and *C* were submerged into bioreactors #1, #2, and #3, respectively and the treated permeate was extracted therein by Masterflex® L/S® peristaltic pumps. The aeration rate in each bioreactor was maintained at 1.68 m^3/hr. Due to the unique design of Modules *A* and *B*, additional air was supplied for membrane scouring with the aeration rate maintained at 0.84 m^3/hr. In addition, two different intermittent operation modes were tested throughout the experiment which included: 1) 8.5 minutes of permeation, 45 seconds of relaxation, and 45 seconds of backwash, and 2) 9 minutes of permeation, 30 seconds of relaxation, and 30 seconds of backwash. Based on the flow balance equation of the bioreactor, the actual permeate flow rate for each operating condition listed above was 1340 mL/min and 1230 mL/min, respectively. Due to the space limitation in each bioreactor, a maximum number of 3 modules were connected in parallel and tested at the initial permeate fluxes between 18.6 L/m^2/hr to 20.3 L/m^2/hr. In each operating condition, the experiment was carried out for 7 days. When the experiment began, the peristaltic pump's speed was initially adjusted so that the first actual permeate flow was identical to the operating condition requirement. Throughout the test, the initial pump's speed remained constant. As membrane fouling developed, the actual permeate flow rate decreased while the observed transmembrane pressure (TMP) increased simultaneously. The actual permeate flow and TMP data were taken manually every 12 hours. To improve data consistency, the actual permeate flow was measured and taken as the average of 3 different periods during the permeation cycle. TMP data were acquired by reading the values on the pressure gauge.

2.4 Membrane filtration resistance

According to the resistance in series model (Choo and Lee 1996, Lee *et al.* 2001, Lee *et al.* 2001, Meng *et al.* 2006), the relationship between permeate flux, TMP, and membrane resistance is given by

$$J = \frac{\Delta \mathrm{P}}{\mu_{\mathrm{T}}(R_m + R_s + R_{if})} \tag{1}$$

where J is the permeate flux (m^3/m^2/s), ΔP is the transmembrane pressure (Pa), μ_T is the permeate viscosity at temperature T (N-s/m^2), R_m is the intrinsic membrane resistance (m^{-1}), R_s is the membrane surface resistance (m^{-1}), and R_{if} is the internal membrane resistance due to pore adsorption and pore blocking (m^{-1}). In Eq. (1), the intrinsic membrane resistance R_m was first determined by filtering the virgin membrane modules with de-ionized water prior to operation. Since the values of R_s and R_{if} were theoretically zero prior to operation, the intrinsic membrane resistance was calculated by measuring the initial permeate flux and TMP values. At the end of the experiment, the final permeate flux and TMP were recorded and the calculated resistance was contributed to the total of R_m, R_s, and R_{if}. When the experiment was completed, the modules were dismantled from the bioreactors and any cake layer deposited onto the membrane surface was physically removed with tap water. The modules were then filtered with de-ionized water. Again, the permeate flux and TMP values were recorded. The calculated resistance was mainly due to R_m and R_{if}, as the surface resistance was negligible. The individual values of R_s and R_{if} can be calculated accordingly.

3. Results and discussion

3.1 Intermittent operation mode I: 8.5 min. permeation, 45 s relaxation, and 45 s backwash

The objective of testing the pilot scale MBR system at this operating condition was to demonstrate the effects of relatively long relaxation and backwashing duration on permeate flux while still maintaining an acceptable permeate production rate. The operation produced permeate at 85% of the time. For the remaining 15% of the time, the system was non-productive. As discussed previously, the MBR was operated at a hydraulic retention time of 8 hours and therefore, the initial permeate flux was 20.3 L/m^2/hr. Continuous aeration was provided to the bioreactors and the modules for biological growth and membrane scouring, respectively. After 7 days of operation, the results for permeate flux and TMP are summarized in Fig. 2. In terms of permeate flux decline, Modules *A*, *B*, and *C* contributed to a drop of 7.4%, 3.7%, and 5.2% respectively, and the corresponding hydraulic retention time was increased to a range between 8.3 hours to 8.6 hours which was still acceptable in a normal MBR operation. The flux decline was attributed to foulants deposited onto the membrane surface or within the membrane pores. When the experiment was completed, all the modules were removed for a surface wash and chemical cleaning. Clean water flux and TMP were also measured after each cleaning step and the individual membrane resistance was calculated and summarized in Fig. 3. Besides the intrinsic membrane resistance, the resistance caused by foulants deposited onto the membrane surface was the main contributor to flux decline and TMP increase. While the internal foulants had not yet developed in 7 days, a longer run should be considered once the best

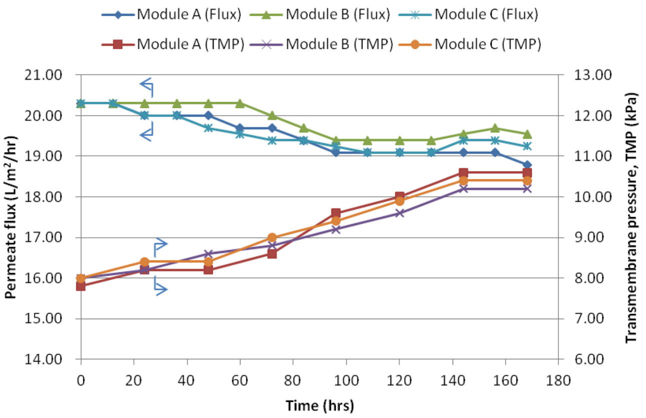


Fig. 2 Permeate flux and TMP performance of Modules *A*, *B* and *C* at operating conditions of 8.5 min permeation, 45 s relaxation, and 45 s backwash

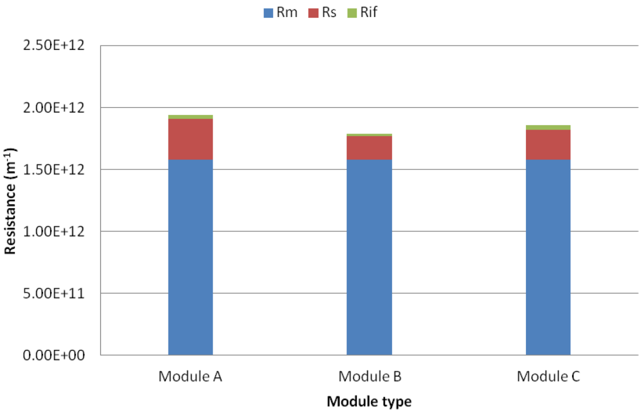


Fig. 3 Membrane resistance developed in Modules *A*, *B* and *C* at operating conditions of 8.5 min permeation, 45 s relaxation, and 45 s backwash

module was identified at a later stage. In summary, there was no significant difference in terms of permeate flux performance after the 7 day experiment. The results also suggested that a longer relaxation and backwash duration could have provided beneficial effects to minimize membrane fouling; however, the drawback is a slightly shorter permeate production time.

3.2 Intermittent operation mode II: 9 min. permeation, 30 s relaxation, and 30 s backwash

This operating condition represented a relatively short duration in relaxation and backwashing in the pilot scale MBR operation. The process produced permeate 90% of the time, while the remaining 10% of the time was non-productive. Hydraulic retention time was initially maintained at 8 hours and the resulting permeate flux was 18.6 L/m^2/hr. Fig. 4 summarizes the results of permeate flux and TMP after 7 days of operation. By increasing the permeation time from 85% to 90% and reducing the total relaxation and backwashing time from 15% to 10%. Module *A* and Module *C*

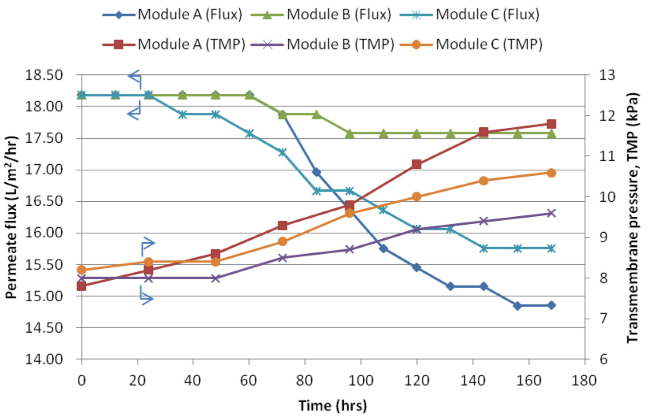


Fig. 4 Permeate flux and TMP performance of Modules *A*, *B*, and *C* at operating conditions of 9 min permeation, 30 s relaxation, and 30 s backwash

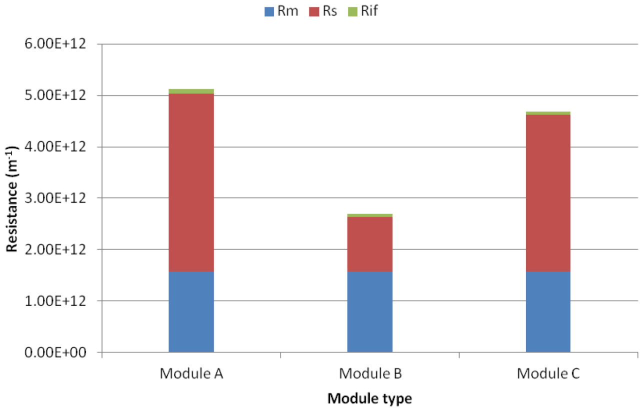


Fig. 5 Membrane resistance developed in Modules *A*, *B*, and *C* at operating conditions of 9 min permeation, 30 s relaxation, and 30 s backwash

experienced a flux decline of 18.3% and 13.3%, respectively. The influence of flux decline on Module *B* was minimal under this operating condition. Only 3.3% of permeate flux decreased after 7 days and the increase in TMP was insignificant compared to Module *A* and Module *C*. The results suggest that the reduction of relaxation and backwashing duration could lead to an increased amount of foulants deposited onto the membrane surface or within membrane pores, causing flux decline. The situation could worsen much quicker if membrane scouring was less effective. Therefore, according to Fig. 5, a large amount of surface foulants accounted for the increase in surface resistance at Module *A* and Module *C*. Due to the unique membrane fiber orientation, Module *B* promoted effective membrane scouring which minimized foulant deposition onto the membrane surface. This allowed the permeate flux to be sustained for a given period of time.

4. Conclusions

The permeate flux performance of hollow fiber modules with different membrane orientations has been investigated under various intermittent operation modes. Permeate flux decline caused by membrane fouling in a MBR was mainly due to a concentration polarization and cake layer formation on the membrane surface. Different membrane fiber orientations could induce different levels of membrane scouring caused by module aeration. Under the long permeation mode, the accumulation of membrane surface resistance led to a reduction of permeate flux in Module *A* and Module *C*. This indicated that the vertical and looping fiber orientations did not enhance membrane scouring effects. In terms of permeate productivity and ease of maintenance, Module *B* was recommended for commercialization because of its effective membrane scouring which minimized the amount of foulants deposited onto the membrane surface. As a result, permeate flux could be sustained for a longer period of time. The configuration of Module *B* has been patented and is to be commercialized in the near future.

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