Anaerobic membrane bioreactor for treatment of synthetic municipal wastewater at ambient temperature

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Abstract Non-woven fabric filter and poly-tetrafluoroethylene (PTFE) composite membrane were investigated to determine their applicability to treat low strength wastewater in an anaerobic membrane bioreactor (AMBR). Sludge cake resistance of the membrane was quantified using pure water flux of anaerobic sludge cake accumulated on the glass fiber filter of similar pore size. It is hypothesized that the formation of thin cake layer on the porous medium, e.g. non-woven and PTFE acts as a dynamic membrane. Thus, the capture of thin sludge cake inside the non-woven fabric matrix and accumulation on the PTFE membrane surface forms a membrane system equivalent to a commercial membrane system. The permeate quality was found to improve as the cake became more dense with filtration time. The PTFE composite membrane coated with thin PTFE film on the non-woven fabric filter enhanced the filtration performance by improving flux and minimizing the propensity of bio-fouling. The membrane flux was restored by back-flushing with permeate. The AMBR coupled with PTFE laminated membrane was operated continuously during the experiment at a cross flow velocity (CFV) of 0.1–0.2 m/sec and a transmembrane pressure (TMP) of 0.5–3 psi. Although about a month of acclimation was required to reach steady state, the effluent chemical oxygen demand (COD), volatile fatty acids (VFAs) as acetic acid, and suspended solids (SS) concentrations were below 30, 20 and 10 mg/L, respectively, during 90 days of operation with intermittent back washing. The lower operation TMP and CFV were subjected to less shear stress on the microbial community during continuous AMBR operation. In addition, thin sludge film accumulated on the membrane surface also acted as a biofilm bioreactor to remove additional COD in this study.

Keywords Ambient temperature; anaerobic membrane bioreactor (AMBR); municipal wastewater; non-woven filter; PTFE

Introduction

The anaerobic process has been widely employed for municipal and industrial sludge digestion because of several inherent merits, including high loading rate, generation of valuable methane gas, less sludge production and less energy consumption. Application of the aerobic process, as distinct from the anaerobic system, is primarily confined to wastewater with low organic loading rate due to the oxygen transfer limitation and high bacterial sludge production. Therefore, the low strength wastewater such as municipal sewage has been historically treated by an aerobic system. However, anaerobic treatment could be a good alternative for small wastewater treatment systems due to its simplicity and long-term sustainability. It requires no aeration and produces relatively less sludge, which could result in significant reduction in capital and operation costs. In addition, it is a net energy producer. However, the anaerobic process has been has been primarily applied to treat high strength wastewater due to its poor effluent quality and solid–liquid separation. As a result, many high-rate anaerobic processes have been developed to expand their application to medium and low strength wastewater treatment. Some of the high rate anaerobic processes include the anaerobic contact process, anaerobic filter, anaerobic fluidized bed, upflow anaerobic sludge blanket (UASB), and expanded granular...
sludge bed (EGSB) (Rittmann and McCarty, 2001). These processes essentially maintain long solids retention time (SRT) irrespective of hydraulic retention time (HRT) through sludge granulation, biofilm formation or internal/external solid–liquid separation. UASB and EGSB have been given much attention for sewage treatment. Lettinga (1995) reported that EGSB could be a sustainable alternative for a high rate anaerobic process under psychrophilic conditions due to its very high substrate affinity. Many full scale UASB/EGSB plants are currently in operation in tropical countries like India, Colombia and Brazil. However, the full-scale did not show good organic removal efficiency as compared to lab scale results (Seghezzo et al., 1998). Thus, often, anaerobic treatment is followed by a polishing step such as a trickling filter or stabilization pond.

Faced with these shortcomings, the membrane coupled anaerobic process has started to attract much attention for the treatment of low to medium strength wastewater (Baek and Pagilla, 2006; Hu and Stuckey, 2006). However, the high cost of the membrane is aggravating the wide spread application of membrane processes in wastewater treatment. Several researchers have tried to develop a cost effective membrane using low cost material such as non-woven filters (Pillay et al., 1994; Muhammad et al., 1997; Nomura et al., 1997; Chang et al., 2001; Seo et al., 2003). The goals of this research are to evaluate the AMBR performance to treat low strength wastewater at ambient temperature using poly-tetrafluoroethylene (PTFE) laminated non-woven filter and to develop a suitable operation strategy to control membrane fouling.

Methods
Anaerobic membrane bioreactors
Two completely stirred anaerobic reactors coupled with external membrane separation units were used. The schematic diagram of the AMBR system is shown in Figure 1. Non-woven filter made of polypropylene with a pore size of 12 µm and PTFE membrane laminated on the non-woven filter with pore size of 10 µm (KNH Enterprise Co., Ltd., Taiwan) were used. The dimensions of the membrane were 600 mm (length) and 8 mm (inner diameter) and the surface area of each membrane was 0.015 m². Anaerobic reactors were equipped with pH and oxidation–reduction potential (ORP) control units, and maintained at 25°C using a heating and cooling loop. Flux and fouling tests were conducted

![Figure 1](https://iwaponline.com/wst/article-pdf/55/7/79/439627/79.pdf)
using the flux test module. The seed sludge for AMBR start-up was obtained from a local municipal anaerobic digester located at Ames, IA, USA.

**Synthetic municipal wastewater**

Synthetic wastewater was prepared to represent a typical municipal sewage. The characteristics of the wastewater were modified from Syntho, which was developed to represent a settled domestic wastewater (Nopens et al., 2001). Table 1 shows the characteristics of influent used in this research. The major component for chemical oxygen demand (COD) was non-fat dry milk (NFDM). The properties of non fat dry milk and required trace elements were provided by Dague et al. (1998).

**Analysis**

COD, volatile fatty acids (VFA), suspended solids (SS), and mixed liquor suspended solids (MLSS) were measured as per Standard Methods (APHA, 1998). Soluble bioreactor COD was measured after filtration using a 0.22 μm filter. The microscopic observation of the surface of the PTFE laminated non-woven filter was carried out using a scanning electron microscope (SEM). Total resistance was calculated using the following equation:

\[
J = \frac{\Delta P}{\mu \cdot R_t}
\]

where \( J \) is the flux (L·T^{-1}·m/sec); \( \Delta P \) is the trans-membrane pressure (M·L^{-1}·T^{-2}·N/m^2); \( \mu \) is the dynamic viscosity (M·L^{-1}·T^{-1}·N·sec/m^2); \( R_t \) is total membrane resistance (L^{-1}·m^{-1}).

A flux test of the anaerobic sludge cake was conducted to evaluate the cake resistance. GF/C filters with pore size of 1.2 μm were used as a medium to attach a given amount of anaerobic sludge. Fine wire mesh with 50 μm opening was used to protect the flexible filter from breaking. A glass syringe was connected to the filter medium to apply positive pressure. Flux tests were carried-out until the three consecutive flux data varied less than 5%. The membrane modules were dissembled to collect the biomass accumulated on the membrane surface using mechanical brushing on 2, 3, 4 and 8 weeks of operation.

**Results and discussion**

**Sludge cake accumulation and resistance**

Anaerobic sludge cake resistance at different TMPs was measured to quantify dynamic membrane resistance. Controlling the dynamic membrane or secondary membrane thickness is a key issue in this research due to relatively large membrane pore size. Figure 2 (a) shows the attached sludge mass on the membrane surface at different operation times. The cake became more dense with filtration time which improved the permeate quality.

<table>
<thead>
<tr>
<th>Table 1 Characteristics of synthetic municipal wastewater</th>
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<td><strong>COD = 500 mg/L</strong></td>
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<tr>
<td>COD mg/L</td>
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<tr>
<td>Milk</td>
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On the other hand, the cake thickness or accumulated sludge layer increased with filtration time resulting in flux decline increase in resistance. According to Murkes and Carson (1998), the secondary membrane in this research can be classified as Class 2 which occurs when the pore size of the membrane is much larger than the particle size. The short initial pore filling was followed by thin cake deposition. Sludge cake grew rapidly at the beginning stage and then slowed down after about 20 days of operation. Thus, it can be hypothesized that the cake may not grow further after reaching steady state which is governed by the membrane operation conditions. The amount of sludge cake accumulated on the membrane surface increased from 12.5 g/m² on day 14 to 20 g/m² on 60 days. Choo and Lee (1996) also found a significant amount of biomass accumulation within the membrane system.

Figure 2 (b) shows anaerobic sludge resistance at different sludge densities and TMPs. The sludge cake resistance increased with an increase in attached cake density at a given TMP. One interesting fact is that there was no significant difference in resistance at 7 ~ 12 g/m² of sludge cake density. The sludge cake was broken and detached at low sludge cake density due to the insufficient cake layer development. The cake resistance rapidly increased after 12 g/m² of cake density or $10^{12}$ m⁻¹ of sludge resistance. Thus, it is essential to control the sludge cake density to less than 12 g/m², which occurred after about 12 days of continuous operation. In addition, lower CFV and TMP of 0.1 m/s and 0.5 psi, respectively required in the beginning especially with new membrane in order to develop sufficient thickness of secondary membrane. Thus, the class 2 type of secondary membrane cake captured inside of the non-woven fabric matrix and accumulated on the PTFE membrane surface could substitute the membrane and cake in the commercial membrane system with back washing every fortnight.

Figure 3 (a) shows the flux profile during a 20-day flux test with TMP variation. The flux of PTFE composite membrane varied from 4 to 12 L/m²/hr at TMP of 6.9 ~ 20 kPa
(1 ~ 3 psi) and CFV of 0.2 m/sec. Figure 3 (b) shows the flux decline under a constant TMP at the beginning of filtration. It was however possible to restored the flux to the original level with a daily back washing.

AMBR performance

A completely stirred anaerobic reactor coupled with PTFE composite membrane was operated for nearly 90 days. During the first 50 days of operation, influent COD was kept at 500 mg/L; whereas after day 50, it was increased to 1000 mg/L. It was essential to maintain a relatively low TMP and CFV due to the large pore size of the membrane. The operating TMP and CFV were 1 ~ 3 psi and 0.1 ~ 0.2 m/sec, respectively. The target flux was 5 L/m²/hr. The initial flux of the PTFE composite membrane was 12 L/m²/hr and it gradually decreased to 5 L/m²/hr.

Once the flux declined below 5 L/m²/hr, back flushing using permeate was carried-out to restore the flux. According to the sludge cake accumulation and resistance tests, back washing was done every 4 to 10 days depending on the flux. The flux was immediately restored right after the back flushing. However, after one day of operation, the flux again declined to about 5 L/m²/hr, and remained nearly constant. It was possible to achieve a constant flux of 5 L/m²/hr at 1.0 psi of TMP for more than 50 days of AMBR operation. After day 50, a higher TMP was needed to maintain the same flux. One of the reasons for the raised TMP was increased influent COD concentration.

Figure 4 (a) shows effluent COD, VFA, and SS levels at HRT of 18 hr and temperature of 25 ± 0.5°C. The influent COD concentration was then increased to 1000 mg/L after day 50. A long acclimation time of more than 30 days was required to reach a steady state. Furthermore, the effluent quality deteriorated temporarily at the higher influent COD level of 1000 mg/L; but the acclimation time was shorter than the start-up. The effluent (permeate) COD, VFA, and SS concentrations were below 30, 20 and 10 mg/L, respectively. During 90 days of operation, the reactor mixed liquor and effluent pHs were ranged from 6.8–7.0 and 7.6–7.8, respectively. The ORP varied from −220 to −270 mV. Figure 4 (b) shows biogas composition. The average methane and carbon dioxide contents were about 60% and 5% (by volume), and the remaining 35% was nitrogen. After the influent COD was increased to 1000 mg/L, methane and carbon dioxide contents were increased to about 80% and 10%, respectively. The permeate side was exposed to atmosphere, which allowed air to come in contact with the retentate stream. This might have caused a slightly higher ORP in the reactor. The initial MLSS and MLVSS concentrations were 9600 and 5900 mg/L, respectively [Figure 4(c)]. Sludge was not withdrawn from the reactor which infers that theoretical SRT was infinity. After day 50, MLSS and MLVSS concentrations reached 12,500 and 8200 mg/L, respectively. The increase in MLSS concentration was mostly contributed by biomass synthesis; since the synthetic wastewater used in this research was completely soluble. Thus, the increase in influent COD led to further increase in MLSS/MLVSS concentration in the bioreactor. Based on MLVSS and COD data, the biomass yield was about 0.05 gVSS/gCODremoved.

Figure 5 shows the SEM pictures of the surface of PTFE laminated non-woven filter before and after cake deposition. As apparent from the micrograph, the cake consisted of many different types of microorganisms such as rod, coccus, and spiral. It is hypothesized that the high MLSS concentration could compensate the low growth rate at low temperature. The biokinetic parameters of anaerobic sludge exposed to low strength wastewater would be different than that of high strength wastewater. Two distinct acetoclastic methanogens namely, Methanosaeta and Methanosarcina, have different substrate affinity and specific substrate utilization rates. It is expected that Methanosaeta, which has a higher substrate affinity and lower specific utilization rate than the Methanosarcina, would
become dominant over the latter under low substrate conditions. Thus, the mixed anaerobic sludge exposed to the low temperature and low strength wastewater as in this study, would have higher substrate affinity (and thus lower $K_s$ value) and lower specific substrate utilization rate.

**Challenge and opportunity of AMBR system**

Anaerobic technology is getting attention as a sustainable technology due to its several inherent merits over the aerobic one. However, there are many uncertainties associated with membrane coupled anaerobic systems. For successful application, the AMBR system requires maintenance of optimal microbial activity in the bioreactor with minimal membrane fouling. AMBR has not been considered as a suitable process to treat low
strength wastewater due to its high cost. Current aerobic membrane bioreactor (MBR) breakthroughs have also been somehow limiting the pace of AMBR development. However, if AMBR can take over the role of MBR, it would be a significant contribution for sustainable water quality.

There are two issues with membrane application in wastewater treatment and they are the cost of membrane and the cost of operation. The operation cost depends on the membrane performance and wastewater types. Stable flux and sustaining the time of membrane operation is more important than the initial flux with respect to the frequency of membrane cleaning and replacement. From this point of view, non-woven filter could be considered as an alternative for microfiltration for the anaerobic system. Non-woven fabric filter with PTFE surface modification can reduce the cake deposition effectively, which renders it suitable for operation at low pressure. It is important to point out that such a membrane system should be operated under low TMP and CFV in order to maintain a secondary membrane for particle free permeate. In most cases, anaerobic processes would not be applied as a sole treatment system due to the nutrient issues. However, it can be employed to remove organics and possibly inorganic nitrogen. Therefore, AMBR followed by biological aerated filter (BAF) for nitrification might be proposed for a small wastewater treatment system. Also, endocrine disrupting chemicals (EDCs) are becoming an issue for municipal sewage. There exists very little information on their fate and biodegradation in the AMBR system. Due to long SRT and secondary membrane, the AMBR system could enhance their removal more effectively. For example, an aerobic MF MBR with 10,000 mg/L of MLSS and 83.3 day SRT achieved an effluent estrogens of 2.2 ng/L as 17β-Estradiol (E2) and 10.3 ng/L as estrone (E1). On the other hand, the conventional activated sludge process with 1000 mg/L of MLSS and 4.8 day SRT could only achieve an effluent estrogen of 7.9 ng/L as E2 and 26.3 ng/L as E1 (Kikuta and Urase, 2003).

**Conclusion**

A completely stirred anaerobic reactor coupled with PTFE laminated non-woven filter was operated successfully to treat synthetic municipal wastewater at an HRT of 18 hrs without sludge withdrawal. A thin layer of anaerobic sludge cake accumulated on the porous medium, which acted as a dynamic membrane. This secondary membrane improved the permeate quality, although the membrane pore size was larger than the sludge particle size. Total amount of sludge attached on the membrane surface increased with time. Sludge cake grew rapidly at the early stage of filtration and then slowed down.
after about 20 days of operation when the sludge cake density reached 20 g/m². High biological activity on the membrane surface caused high biofouling potential. A lower CFV of 0.1 m/s and TMP of 0.5 psi were required in the beginning, especially with new membrane research in order to develop a secondary membrane of sufficient thickness. The effluent COD, VFA, and SS concentrations were below 30, 20 and 10 mg/L, respectively, during 90 days of operation with intermittent backwashing. The performance of an anaerobic CSTR coupled with PTFE composite membrane was comparable with granular sludge processes coupled with membrane module if operated with long SRT and would be ideal for a small wastewater treatment system.

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References