Formation and performance of self-forming dynamic membrane (SFDM) in membrane bioreactor (MBR) for treating low-strength wastewater

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ABSTRACT

This study introduces a self-forming dynamic membrane (SFDM) with large-pore mesh filter materials instead of conventional MF/UF membranes for wastewater treatment. Development of SFDM on the mesh filter surface plays a major role in reducing the wastewater turbidity and its performance in a self-formation dynamic membrane bioreactor (SFDMBR). To evaluate formation of the dynamic membrane, biological and hydrodynamic parameters, including mixed liquor suspended solids (MLSS) and aeration rate, were examined. The experimental results showed that with elevation of MLSS in the bioreactor (up to MLSS = 9,000 mg/L), the effluent turbidity diminishes with rapid formation of SFDM, with the shortest formation time (5 min) obtained in SFDM operations, though it results in increased membrane fouling. SFDM was well formed at low aeration rates of 2.5 L/min and 5 L/min, due to very low shear stress on the mesh filter surface, given the results of turbidity in comparison with aeration rates of 10 L/min and 15 L/min. The filtration performance of SFDM in treatment of synthetic wastewater was tested under a constant operational flux (58 L/m² h). Total chemical oxygen demand (COD) and NH₄-N removals were 88–93% and 96–98.8%, respectively. These results indicated that the treatment process can be performed effectively by SFDMBR.

Key words | aeration rate, MLSS, self-forming dynamic membrane (SFDM), wastewater treatment

ABBREVIATION

COD | Chemical oxygen demand
DO | Dissolved oxygen
MLSS | Mixed liquor suspended solids
MLVSS | Mixed liquor volatile suspended solids
NH₄-N | Ammonium-nitrogen
PN | Protein
PS | Polysaccharide
SFDM | Self-forming dynamic membrane
SFDMBR | Self-formation dynamic membrane bioreactor
TMP | Trans-membrane pressure

INTRODUCTION

The shortage of available water resources is one of the major problems for countries with limited water reserves. Lack of facilities and necessary investments in wastewater treatment, especially in small cities and rural areas, have developed progressive concern for contamination of groundwater tables (Ren et al. 2010; Wang et al. 2012). The conventional activated sludge process is one of the most applicable processes for wastewater treatment in developing countries, which degrades organic contaminants using a high volume of microorganisms (Wang et al. 2017a). However, it requires large sedimentation tanks, and huge aeration and energy consumption.

To compensate for this energy consumption, addition of a denitrifying anoxic/anaerobic methane oxidation-based technology to wastewater treatment facilities was proposed. This can cause significant reduction in energy consumption thanks to the capabilities of activated sludge (Iinas-Limaa et al. 2004; Wang et al. 2017b, Wang & Wang 2017). However, the activated sludge process has some problems including bulking, foaming, and altered quality of the effluent under environmental disturbances. Membrane bioreactor (MBR) technology is a substitute for the
sedimentation and clarification units of activated sludge—a combination of biological process with physical separation by membrane (Judd 2008).

MBR is considered a progressive technology in developing countries for wastewater treatment. This process enjoys many advantages, including high treatment efficiency within the shortest time, low applied scale, desirable output quality, and less sludge production through preserving a high concentration of biomass in the bioreactor. However, it has some major disadvantages including the very expensive membrane module, high energy consumption, need for operational care, and very difficult membrane fouling control, such that, in some cases, the membrane module should be replaced (Liu et al. 2009; Lin et al. 2012). In recent years, extensive research has been conducted to solve these problems. For economic justification of the MBR process, the self-forming dynamic membrane (SFDM) has been considered as a substitute for MBR polymer membranes (Fan & Huang 2002; Wang et al. 2012; Gong et al. 2014). For development of SFDM, a layer of sludge particles is developed on the surface of an inexpensive and porous membrane such as nonwoven fabric, woven nylon fabric, fabric filters, and mesh filters under special conditions (Seo et al. 2007; Duan et al. 2011; Li et al. 2012; Xu et al. 2015). Unlike conventional MBRs, in these self-forming dynamic membrane bioreactors (SFDMBRs), separation of sludge—liquid is generally dependent on suitable development of SFDM on the mesh filter surface. Furthermore, over-aggregation of sludge particles on the mesh filter surface and sludge properties (such as protein (PN) and polysaccharide (PS), size of sludge floc, etc) result in diminished flux and increased fouling (Kiso et al. 2000; Liang et al. 2013). To recover operational flux and decrease energy consumption, without expending any cost, the cake layer is easily removed by top water or brushes (Al-malack & Anderson 1997). However, there is one major problem in this process, which is the inappropriate formation of SFDM on the mesh filter surface. This causes the tiny particles of sludge to pass easily through the pores of the mesh filter, thereby decreasing the effluent quality in the formation stage (Chang et al. 2007).

In this regard, different results have been reported. In some of them, with increased shear stress on the mesh filter surface, the effluent turbidity has been influenced by the shear stress, thereby decreasing the quality (Kiso et al. 2000; Fuchs et al. 2005). On the other hand, in other studies, effluent turbidity has not been heavily influenced by shear stress (Alavi Moghaddam et al. 2002). Therefore, SFDM formation is very important.

So far, various studies have been conducted on the structure and performance of SFDM in wastewater treatment. Kiso et al. (2000) examined the performance of MBR filtration equipped with mesh filters made of nylon with pore sizes of 100 μm, 200 μm, and 500 μm, where the mesh with pore size of 100 μm had the best performance in rejecting sludge flocs. Fuchs et al. (2005) studied the performance of an SFDM system for treating urban wastewater. The results showed that the treatment was very effective, where SS concentration and average chemical oxygen demand (COD) in the effluent were less than 12 mg/L and 45 mg/L, respectively. Therefore, the performance of wastewater treatment and stability of SFDMBR operation are highly dependent on filtration characteristics such as suitable formation of SFDM, filtration resistance, and SFDM fouling.

In this study, a mesh filter, which is far less expensive than MF/UF membranes, is used in the bioreactor. Due to its large pores, the mesh filter has a high effluent turbidity. Thus, first suitable formation of SFDM should be examined for reducing the effluent turbidity. In order to increase the effluent quality, SFDM formation process on the surface of the mesh filter is examined by changing biological and hydrodynamic parameters including mixed liquor suspended solids (MLSS) and aeration rate. At this stage, for evaluating SFDM, effluent turbidity and trans-membrane pressure (TMP) are investigated. Also, to investigate the potential of this system in removal of contaminants, SFDM filtration performance for treating synthetic wastewater in SFDMBR is evaluated.

**MATERIALS AND METHODS**

**Experimental setup**

The schematic process flow diagram of experimental setup is illustrated in Figure 1. The experiments were done inside a rectangular plexiglas vessel, 0.17 m wide, 0.2 m long, and 0.5 m high. A polyester monofilament mesh filter was used with a mean pore size of 30 μm with an initial hydraulic resistance of 5.86*10^-7 m^-1. The effective area of the membrane module was 160 cm^2_. The TMP through the filter medium was measured by an accurate sensor close to the membrane module, which was reported as the difference between the input pressure and permeability pressure.

In order to adjust the rate of flow passing through the membrane, a peristaltic pump was used, which sucks the liquid through the mesh filter in a predetermined flow intensity. In the formation stage, the treated flow was transferred...
to the bioreactor using a recycle line, so that the bioreactor level remained constant. In long-term operations, the effluent flow was transferred to the permeate tank. The effluent flow was measured by a calibrated flowmeter. The bioreactor was equipped with five spargers of air pipe equally placed in the bottom of the bioreactor. One of them was placed in the very bottom of the membrane module to clear the mesh filter surface periodically during long-term operations. To adjust the air flow rate in each pipeline of the sparger, an automatic control valve was used individually. The pipe sparger had an inner diameter of 0.002 m for generating fine bubbles.

**Operation conditions of continuous bioreactor**

The working volume of the reactor was 9 L. During short-term filtration operations, a certain exerted flux (145 LMH) was used to optimize SFDM formation at MLSS concentrations of 3,000 mg/L, 5,000 mg/L, 7,000 mg/L, and 9,000 mg/L as well as aeration rate of 2.5 L/min, 5 L/min, 10 L/min, and 15 L/min. When MLSS was changed, the aeration rate was constant and equal to 5 L/min. When the aeration rate was altered, MLSS was constant and equal to 6,000 mg/L. Next, throughout the long-term operations of treatment by SFDM, the flux of the effluent flow rate and hydraulic retention time (HRT) were adjusted at 58 LMH and 10 h, respectively. Further, aeration intensity with a rate of 5 L/min was employed to keep the dissolved oxygen (DO) concentration within the range of 2.5–4.5 mg/L. The bioreactor temperature was set in the range of 21–24 °C. The bioreactor operated with synthetic wastewater. The COD:N:P ratio of the influent was 100:5:1, containing 562.5 mg/L glucose, 77.972 mg/L ammonium nitrate and 22.258 mg/L ammonium di-hydrogen phosphate. NaHCO₃ was used as a buffer to adjust the pH at around 7 (if required).

**Analytical procedures**

The turbidity of the effluent flow was measured by spectrophotometer (Spectroquant Multy, Merck, Germany). DO was measured using DO meter (WTW 340 i, Germany).
After the end of each test, protein (PN) and polysaccharide (PS) concentrations of SMP in the sludge supernatant were measured according to the Lowry method (Lowry et al. 1951) and Dubois method (Dubois et al. 1956), respectively.

COD, ammonia (NH\textsubscript{3}-N), MLSS and mixed liquor volatile suspended solids (MLVSS) in the bioreactor were measured according to the standard methods (APHA 2006).

RESULT AND DISCUSSION

Formation of the dynamic membrane

The SFDM formation process was examined first. In this process, due to formation of a layer of activated sludge on the mesh filter surface to enhance the effluent quality and then due to the fouling developed in this type of membrane, the effluent turbidity and TMP parameters are important.

The initial short period when the effluent turbidity declines (below 5 NTU), considering SFDM formation, is called the formation time. During this time, TMP remains almost constant. Thereafter, when SFDM thickness is equalized and the effluent turbidity and TMP have an almost stable level, the time passed during this stage is called the stability time.

The effect of MLSS on the SFDM formation

Figure 2 demonstrates the diagram of effluent turbidity and TMP versus time under the MLSS concentrations of 3,000 mg/L, 5,000 mg/L, 7,000 mg/L, and 9,000 mg/L.

For each MLSS, in the initial stages of SFDM formation stage, i.e. in the first 5 min, the effluent turbidity diminished significantly, such that the effluent turbidity at an MLSS concentration of 9,000 mg/L, was obtained to be less than 5 NTU. This can be related to formation of SFDM with a high thickness at high MLSS at very early times (Ozaki & Yamamoto 2001; Alibardi et al. 2016). This short-term initial period, in which the turbidity drops significantly and no tangible change is observed in TMP, is related to SFDM formation on the mesh filter surface (Xiong et al. 2014). Over time, with suitable formation of SFDM, the effluent turbidity reached a stable state.

According to Figure 2(a), the formation time decreased with elevation of MLSS, where this reduction at the time of formation is very considerable for high MLSS. The formation time for MLSS concentrations of 3,000 mg/L, 5,000 mg/L, 7,000 mg/L, and 9,000 mg/L was 120 min, 80 min, 40 min, and 5 min, respectively.

Considering Figure 2(b), elevation of MLSS had a huge impact on blockage of the mesh filter, such that TMP for MLSS of 9,000 mg/L in the very first hour increased significantly, suggesting SFDM fouling. In addition, at MLSS of 3,000–5,000 mg/L, TMP was almost constant and no tangible change was observed in it. These results can be due firstly to the rheological properties of activated sludge, where elevation of MLSS from 5,000 mg/L to 9,000 mg/L leads to increased non-Newtonian viscosity of active sludge, eventually resulting in rapid growth of TMP and SFDM fouling. Secondly, at low concentrations of activated sludge, SFDM is formed on the mesh filter surface with a low thickness. Therefore, over-aggregation of particles on the mesh filter surface is minimized, which can lead to delayed fouling in the membrane bioreactor. These results are completely congruent with previous studies (Itonaga et al. 2004; Chuang et al. 2011; Wang et al. 2015).
Therefore, for long-term operations, with elevation of MLSS from 5,000 to 9,000, in spite of reduced formation time, fouling occurs quickly, which demands energy consumption. Thus, based on this result and other results (Alavi Moghaddam et al. 2002; Fuchs et al. 2005; Kiso et al. 2005), to initiate long-term operations, MLSS was considered as 3,900 mg/L.

The effect of aeration rate on the SFDM formation

One of the most important factors in SFDM formation is good mixing and development of a suitable crossflow in the bioreactor membrane module region. Figure 3 reveals the diagram of turbidity and TMP versus time for aeration rates of 2.5 L/min, 5 L/min, 10 L/min, and 15 L/min.

According to Figure 3(a), at 2.5 L/min and 5 L/min rates, the effluent turbidity diminished rapidly at the beginning of the process (the first 5 min), and an almost equal formation time was obtained. On the other hand, SFDM was not formed at aeration rates of 10 L/min and 15 L/min, where the SFDM effluent turbidity is larger than 5 NTU. Based on Figure 3(a) at high aeration rates, after going through an initial descending and then constant trend, the effluent turbidity in SFDM formation grows dramatically. This can be due to the large shear stress exerted on the mesh filter surface, resulting in destruction of the SFDM layer of the mesh filter surface. Further, since activated sludge particles diminish due to the shear stress developed by aeration (especially at high aeration rates), the effluent turbidity increases dramatically due to passage of tiny activated sludge particles through the degraded sites or incompletely formed SFDM. In this regard, similar results have been obtained by Fuchs et al. (2005). They reported that in an MBR system equipped with a mesh filter, with elevation of shear stress on the mesh filter surface, the concentrations of suspended solids grow in the effluent flow.

As can be observed in Figure 3(b), with elevation of aeration rate the TMP increased progressively and in turn SFDM fouling occurred. In this regard, the SFDM stability time declined with elevation of aeration, such that the shortest stability time was related to an aeration rate of 15 L/min and equal to 5 min.

According to Figure 4, these results can be due to the biological behavior of activated sludge under high shear stress and release of PN and PS, such that with elevation of the aeration rate from 5 L/min to 15 L/min, the PN content of the mixed liquor in the bioreactor increases significantly and acts as a major cause of SFDM fouling in the formation
stage. This fouling tendency of SFDM in the MBR has been reported in previous investigations (Drews 2010; Sabaghian et al. 2018). They reported that when the aeration rate grows in the bioreactor, a great shear stress is exerted to the activated sludge particles, causing cellular death and release of PN and PS. Further, considering the hydrophobicity and superficial charge of sludge flocs in the SFDM layer, the progressive tendency of absorption of PN in the SFDM layer on the mesh filter surface increases, which can cause early fouling of SFDM in the MBR. Therefore, for long-term operations, to prevent early fouling of SFDM, the aeration rate was kept at about 5 L/min.

To develop the possibility of suitable comparison for SFDM formation under different conditions, the results obtained from all conditions have been summarized in Table 1.

**Permeate quality of long term operation**

As explained previously, with suitable formation of SFDM on the mesh filter surface, it is possible to have the activated sludge develop both a mesh filter and a secondary microfilter membrane. Therefore, the rejection capacity of solid materials present in the bioreactor by the SFDM is one of the essential parameters in evaluation of SFDMBR properties. Figure 5 reveals the effluent turbidity and TMP in the course of the operations.

According to Figure 5(a), the effluent turbidity was obtained as below 10 NTU in the first day, and following 48 h, the effluent turbidity was less than 6 NTU. In many times of the operation, the turbidity of the treated water was less than 3 NTU, though the turbidity of the input to the reactor fluctuated between 125 NTU and 268 NTU. In this study, it was observed that the effluent turbidity results were in line with the results obtained from a membrane bioreactor equipped with non-woven fabric by Wang et al. (2012). They reported that the effluent turbidity reached 1.8 after 3 days, which remained at this level during most of the operation. Thus, SFDM has a key role in reducing the effluent turbidity. Therefore, the filtration operation by SFDM has a close relationship with its behavior and properties. TMP variations over time during 20 days of operation have been shown in Figure 5(b) with a treatment flow at a constant flux of 58 LMH. TMP variations were very trivial and stable in the initial days of operation. However, after a period of around 15 days of filtration, TMP increased significantly, reaching 360 mbar. Therefore, membrane fouling occurred at this stage and the operation was terminated.

The concentration of dissolved oxygen (DO) in the bioreactor was 2.5–4.5 mg/L, and its pH was kept almost within the range of 7 ± 0.05. Adjusting pH within this range is important since based on previous studies, pH around 7 caused increased filtration time and delayed SFDM fouling. Within this range, there are very suitable conditions for nitrification inside the bioreactor (Kiso et al. 2005; Ren et al. 2010).

Figure 6 shows the changes of MLSS and MLVSS in the bioreactor. As can be seen, the ratio of MLVSS to MLSS was 0.77. Considering Figure 6, the concentration of activated sludge inside the bioreactor typically increased over time. However, with increase of MLSS in the bioreactor, no sensible change is observed in the effluent turbidity. This can be due to the suitable performance of SFDM and its high retention capacity in rejection of sludge particles. These results are in full congruence with the results of previous studies (Chuang et al. 2011; Zahid & El-Shafai 2011; Wang et al. 2012).

The treatment performance of SFDMBR was examined considering COD and NH4-N removal. Figures 7 and 8 demonstrate COD and NH4-N variations in the influent and effluent flow in the course of operations. As can be observed, COD of the effluent flow was stable and became constant at less than 65 mg/L. The mean COD removal efficiency was 92% (88–93%).

According to Figure 8, in the course of filtration and with MLSS rise, NH4-N removal efficiency almost increased, whose range was 96.6–98.8% with an average of 98%. Removal of pollutants such as NH4-N is mostly related to activated sludge biodegradation. In this regard, it has

<table>
<thead>
<tr>
<th>Items</th>
<th>MLSS (mg/L)</th>
<th>Aeration rate (L/min)</th>
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<tbody>
<tr>
<td></td>
<td>3,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Formation time (min)</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>Stability time (min)</td>
<td>250</td>
<td>265</td>
</tr>
<tr>
<td>Lowest effluent turbidity (NTU)</td>
<td>7</td>
<td>4</td>
</tr>
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</table>

*a^SFDM was not formed.*
been reported that an MBR system coupled with a mesh filter can remove a high percentage of NH₄-N of around 98% (Wang et al. 2015). It was also observed that the results of COD and NH₄-N removal were similar to the findings obtained by Li et al. (2015) regarding an MBR equipped with a mesh filter. Therefore, based on the above results and the studies conducted in this regard, SFDMBR enjoys the advantages of great effectiveness in solid-liquid separation, high organics removal, high nitrification efficiency, etc. (Ren et al. 2010; Wang et al. 2015).

CONCLUSIONS

The suitability of the mesh filter was examined as a substitute for bioreactor polymer membranes in wastewater
treatment. In the running phase, the mesh filter had an ordinary behavior, such that turbidity diminished significantly at the beginning of each filtration. Therefore, the mesh filter could separate activated sludge effectively in the initial stages of the process (the first 5 minutes). The effluent turbidity was obtained to be below 5 NTU with an MLSS concentration of 9,000 mg/L. Although the high concentration of activated sludge can lead to very rapid formation of SFDM, over time it resulted in shortened stability time and increased fouling. Elevation of aeration rate also resulted in increased fouling. Therefore, based on the obtained results, the fouling could be a result of elevated MLSSs and aeration rate due to rheological and biological behavior of the activated sludge, respectively.

During much of the long-term operation, the turbidity of the filtered flow was less than 3 NTU, though the turbidity of the influent flow to the bioreactor fluctuated between 125 NTU and 268 NTU. The mean COD and NH4-N removal was 92% and 98%, respectively. Based on the results, it seems that SFDMBR is an outstanding and economical technology, when compared with MBR for wastewater treatment. It can change into unparalleled process to be used in low populated regions especially rural areas. However, it has still the technical challenges of suitable formation of SFDM and fouling. Thus, further research is required for optimization of SFDMBR.

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