Effect of sludge retention time on characteristics of dynamic membrane in sequencing bioreactors

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ABSTRACT

The characteristics of self-forming dynamic membrane (DM) in sequencing bioreactors under different sludge retention times (SRT) (SRT = 5, 10, 20, 40, 60 days) were studied using a scanning electron microscope, particle sizing distribution and others. The results indicated that the SRT has an evident effect on the characteristics of DM. The content of extracellular polymeric substances and protein decreased with the increase of SRT. The change of polysaccharide was small regardless of SRT. The filtration resistance of the DM was divided into two stages: an initial slowly-rising stage and a fast-rising later stage which were both irrespective of SRT. With the increase of SRT, the filtration resistance increase extent reduced and the running cycle became longer. Compared to the lower SRT, the particle size distribution of mixed liquor and DM has a decreasing trend at higher SRT. The average particle size of DM was larger than that of the mixed liquor irrespective of SRT. The amounts and types of microorganisms on the surface of DM were more abundant as SRT increased. Low SRT produced the DM surface with some Cocci while the high SRT gave the DM dominated with Cocci, Filamentous and Bacillus.

Key words | dynamic membrane bioreactor, filtration resistance, particle size distribution, scanning electron microscope, sludge retention time

INTRODUCTION

The membrane bioreactor (MBR), which uses micro-/ultra-filtration membranes to separate solids and liquids in the bioreactor, has been attracting increasing interest in the field of wastewater treatment due to its reliability, high efficiency, good rejection of suspended solids (SS), high biomass concentration, small footprint, and low sludge production (Holakoo & Nakhla 2007; Williams & Pirbazari 2007). However, the high cost of membranes impedes its widespread applications. The self-forming dynamic membrane (DM) coupled bioreactor is a new membrane technology using a coarse pore-sized material module, such as mesh, non-woven fabric, filter-cloth, etc., instead of micro-filtration and ultra-filtration to separate solids from liquids in the bioreactor (Fan & Huang 2002; Chu & Li 2006). Some researchers begin to have interest in filtration bio-reactors that are equipped with non-woven fabric as an alternative advanced wastewater treatment system (Moghadam & Satoh 2002). Sequencing batch reactors (SBRs) are often used in small communities or resort areas (Wang & Peng 2008). The SBRs have the following advantages: simple design, easy and flexible operation, and simultaneous removal of Biochemical Oxygen Demand (BOD₅) and nitrogen (Cho & Chang 2003). Most recently, the SBR systems coupled with membrane filtration, have been drawing attention since they possess the advantages of both SBRs and MBRs (Bae et al. 2005).

Many factors that might influence the membrane biofouling in MBR include floc size, mixed liquor suspended solids (MLSS) concentration, viscosity of mixed liquor, and soluble and bound exopolymeric substances (Chang & Clech 2002; Kimura & Yamato 2003). These parameters are related to the sludge retention time (SRT). SRT not only affects the mixed liquor characteristics but also changes the physiological state of microorganisms, resulting in variation of membrane fouling substances such as the EPS and soluble microbial products (SMP) (Chang & Lee 1998). Attention has already been given to the relationship between SRT and extracellular polymeric substances (EPS) formation in previous studies (Chang & Lee 1998; Cho & Song 2005). However, the data in the literature regarding the effects of

SRT on membrane bio-fouling are inconsistent. Several studies have demonstrated that the EPS increases as SRT increases (Cho & Song 2005; Han & Bae 2005) while others have shown the opposite trend (Ng & Hermanowicz 2005).

To date, most of the related studies have focused on the effect of sludge characteristics and operational parameters on membrane fouling. Limited information is available regarding the analysis of the DM characteristics. A detailed characterization of the cake layer formed on the membrane surface would be helpful in defining the optimum range of operational parameters for sequencing dynamic membrane bioreactors (SDMBRs). The aim of this study is to investigate the effect of SRT on the DM bio-fouling and the microbial community structure in the SDMBRs. The effect of SRT on the particle size distribution (PSD) and the EPS content of DM will also be analyzed in laboratory-scale sequencing batch reactors using synthetic wastewater.

MATERIALS AND METHODS

Experimental set up

The schematic diagram of the experimental set up is presented in Figure 1. Five identical SDMBRs having the same type of membrane module with identical reactor volume were operated simultaneously in this study to prevent different operations temporal fluctuations in different operations. The bioreactor equipment consisted of two parts, a reactor tank and an automatic control system. A DM filter (polyethylene (PE) non-woven filter module, as shown in Figure 2) was situated in the reactor tank. The total and working volume of the bioreactors tank were 25 and 20 L, respectively. The DM filter was submerged in the reactor tank with a double-sided effective filtration area of 0.12 m². The non-woven filter module was made of a 5 mm thick non-woven polyester fabric which has a 100 mm nominal pore size and a specific weight of 0.70 kg/m².

Diameter of the cylindrical support was 18 cm. The system employed two peristaltic pumps (Enertech ENPD-100 Optima, India), one for intermittently feeding the influent and the other for withdrawing permeate from the filter module. The pump supplying and withdrawing water to and from the bioreactor was controlled by the constant speed to maintain a constant water volume in the bioreactor. The five laboratory-scale bioreactors were operated in parallel at a hydraulic retention time (HRT) of 6 h and different solids retention times (SRT) of 5, 10, 20, 40 and 60 days being controlled by discharging the mixed liquor from the bioreactor once a day. The membrane flux was set at around 60 L/m²/h. An aeration unit was placed below the filter module serving for aeration of the activated sludge. The total aeration flow rate was 2.6–4.5 L/min and the dissolved oxygen (DO) concentration was between 2 and 4 mg/L. A temperature control system was installed and temperature fluctuation ranged between 20 and 22 °C according to ambient conditions. The five reactors were run automatically in sequencing-flow mode, in which the time of filling, anaerobic, aerobic and discharging was 30, 150, 150 and 30 min, respectively. The bioreactors were firstly inoculated with 2,500 mg/L seed activated sludge from a local municipal wastewater treatment plant (China, Nanjing). Table 1 shows operating condition of SDMBRs system. The transmembrane pressure (ΔP) was constantly monitored by a pressure sensor in the suction line which indicating the

Table 1 | Operating conditions of the SDMBRs system

| Flux (L/m²/h) | 60  |
| Temperature (°C) | 20–22 |
| HRT (h) | 6 |
| SRT (days) | 5, 10, 20, 40, 60 |
| Membrane flux | 62 |
| Reactor volume (L) | 25 |
| Effective filtration area (m²) | 0.15 |
| Dissolved oxygen (DO) concentration (mg/L) | 2 to 4 |
extent of membrane fouling. In this study, the relationship between the operation pressure which equals the trans-membrane pressure, and filtration resistance, can be readily calculated using the Darcy’s law

$$R = \frac{\Delta P}{\mu J} \quad (1)$$

where \( R \) = filtration resistance \((m^{-1})\), \( \Delta P \) = trans-membrane pressure \( (Pa) \), \( J \) = design flux \((m/s)\), and \( \mu \) = filtrate viscosity \( (Pa\cdot s)\).

### Analytical equipment and methods

The bio-cake on the membrane surface was detached in sterilized deionizer water for analysis of the EPS (Park & Lee 2005), which was extracted from the suspended bio-cake using heat treatment (Morgan & Forster 1999). The extract was analyzed for total polysaccharides and proteins, which were the dominant components in the EPS. The sum of polysaccharides and proteins was regarded as the total amount of the EPS (Bura & Cheung 1992). The polysaccharides in EPS were determined using the phenol/sulfuric acid method with glucose as the standard (Dubois & Gilles 1956). The proteins were quantified using a modified Lowry method (Lowry et al. 1951).

### SEM analysis

After filtration, a piece of membrane fiber was cut from the middle of the membrane module for SEM characterization. The sample was fixed with 3.0% glutaraldehyde in 0.1 mol/L phosphate buffer of pH 7.2. The sample was dehydrated with ethanol and silver-coated by a sputter, and then was observed using the SEM (JEOL JSM-5600LV, Tokyo, Japan).

### Particle size analysis

The sludge PSDs of washed liquid and sludge suspension were determined by focused beam reflectance measurement (FBRM) (Model M400L, Lasentec, Redmond, United States). The PSD of the supernatant of washed liquid was measured using a Malvern counter (Zeta100, United Kingdom).

### Analysis of other parameters

Measurements of chemical oxygen demand (CODcr), pH in the influent and membrane effluent, mixed liquor suspended solids (MLSS) and volatile suspended solids (VSS) in the system were performed according to Chinese NEPA standard methods (Chinese SEPA 2002).

### Synthesis wastewater

In order to minimize effects from variations in feed conditions, synthetic wastewater was supplied to the SDMBRs. The composition of the synthetic wastewater used was as follows: acetate, 1,000 mg/L; NH4Cl, 190 mg/L; KH2PO4, 224 mg/L; MgSO4, 90 mg/L; KCl, 37 mg/L and trace elements \((in \ mg/L)\): EDTA, 50; ZnSO4·7H2O, 22; CaCl2·2H2O, 8.2; MnCl2·4H2O, 5.1; FeSO4·7H2O, 5.0; \((NH4)_6Mo7O24·4H2O, 1.1; CuSO4·5H2O, 1.8; CoCl2·6H2O, 1.6 (Fu et al. 2009). The influence pH value was adjusted to 7.0 through the dose of 1 mol/L HCl and NaOH. The quality of synthetic wastewater is displayed in Table 2.

### RESULTS AND DISCUSSION

### DM structure

Before normal filtration, the biomass layer is carried out to form DM on the support membrane. DM can be divided into cake layer and gel layer (Fu et al. 2009). The formation of DM structure is very important to membrane operation and fouling. Hence there is a need to characterize the structure of the DM. In this study, the DM structure at different SRT was investigated repeatedly and the average data are shown in Table 3. The content of the EPS in the DM decreased from 2.23 to 1.42 g/m2 whilst the content of volatile suspended solids (VSS) varied from 25.96 to 31.22 g/m2 when SRT increased from 5 to 60 day. Organic removal with average values at different SRT was shown via investigation of the average ef fluent CODcr and removal efficiency was maintained in the range of 22.05–23.81 mg/L. From the analysis, it could be calculated that more than 93.5% CODcr removal rate was achieved regardless of SRT. The volatile suspended solids (VSS) were the major

<table>
<thead>
<tr>
<th>Analysis Items</th>
<th>CODcr (mg/L)</th>
<th>NH3-H (mg/L)</th>
<th>TN (mg/L)</th>
<th>TP (mg/L)</th>
<th>pH</th>
</tr>
</thead>
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<tr>
<td>Value range</td>
<td>173–506</td>
<td>36.9–79.1</td>
<td>50.7–93.4</td>
<td>1.57–6.43</td>
<td>7–8</td>
</tr>
<tr>
<td>Average</td>
<td>294</td>
<td>57.2</td>
<td>72.8</td>
<td>3.57</td>
<td>7.5</td>
</tr>
</tbody>
</table>
contributors to the biomass of the DM, indicating that the DM has a high biological activity (Fu et al. 2019). Though the contents of EPS and salts in the cake layer were small, they had strong impacts on the DM structure and fouling since their deposition/adsorption on the membrane surface could result in severe pore blocking. Similar trends have been reported by other researchers (Fu et al. 2019). Figure 3 shows the naked non-woven fabrics: it reveals that the non-woven fabrics have non-uniform pore size and surface roughness. On the other hand, the DM structure which was attached to the membrane material gave a bigger porosity as shown in Figure 4.

Comparison of the filtration resistance

The total filtration resistance of the DM of the SDMBRs at different SRT could be calculated from Equation (1). As shown in Table 3, the first filtration resistance ($R_0$) varied from $2.45 \times 10^6$ to $2.53 \times 10^6$ m$^{-1}$. Figure 5 shows the experimental results of the filtration resistance ratio ($R/R_0$) of the SDMBRs at different SRT. A closer look at the fouling profiles of the five SDMBRs revealed that the DM exhibited a distinct two-stage process. Stage 1 reflected a slow term rise in the filtration resistance and Stage 2 occurred with a sudden rise in the filtration resistance, which was commonly referred to as the filtration resistance jump. This phenomenon has also been reported by other researchers (Ke & Liu 2009). The monitoring of the filtration resistance in the SDMBRs provided evidence that the membrane bio-fouling was more rapid at a shorter SRT. An abrupt increase of the filtration resistance occurred in SDMBRs at the end of each operation. The mechanism of the filtration resistance jump has been clearly clarified by analyses on fouling layers, which helped to reveal the contribution of the different fouling. This could be attributed to irreversible membrane fouling caused by the fouling in membrane pores, which could not be removed by chemical cleaning.

Comparison of concentrations of EPS

The EPS is an important material which primarily acted as a film of pollutants (Chang & Lee 1998). It was investigated...
that the differences in the fouling degrees in the SDMBRs originated from the different characteristics of the EPS produced at different SRT. Concentrations of the EPS are a good indicator of fouling propensity (Chang & Lee 1998). Figure 6 shows the concentrations of the EPS on the DM at the end of each operation. In the controlled experiment with little fluctuation conditions, the concentrations of the EPS at lower SRT were higher throughout the operation, as compared to higher SRT. Similar trends have been reported by other researchers (Ke & Liu 2009). The content of EPS and protein decreased with the increase of SRT. The change of polysaccharide was small regardless of SRT. The change of protein concentration was in a positive correlation to that of DM resistance, because the proteins themselves were a high viscosity substance, which could

![Graph](image1)

**Figure 6** | EPS Concentrations in the SDMBRs at different SRT.

![Graph](image2)

**Figure 7** | Particle size distribution of sludge at different SRT in the SDMBR (a) 5 days, (b) 10 days, (c) 20 days, (d) 40 days and (e) 60 days.
be adsorbed on the membrane surface and directly plug in the membrane pores. Proteins contained a variety of functional groups of the hydrophobic polymer, which could adsorb more pollutants, which speeded up the membrane fouling. With the increase of SRT, the activated sludge was less likely to release enzymes to carry out a variety of biochemical reactions, and the protein content also was reduced, allowing reduced membrane fouling.

**Comparison of PSD**

PSD is an important parameter in SDMBRs since it affected the characteristics of the cake formed (Meng et al. 2007). The PSD at different SRT might be explained by the growth rate of cells (Kim et al. 2001). In this study, the PSD measurement for both DM and the mixed liquor are presented in Figure 7. The DM had a broader range profile of size distribution. Results indicated that more than 80% of the particles are distributed in sizes ranging from 80 to 200 μm on DM. With the mixed liquor, 80% of the particles were distributed in the size ranging from 60 to 15 μm. The average size in the profile of DM was also different from those of the mixed liquor with the increase of SRT. The PSD of mixed liquor and DM decreased with increase of SRT.

**Comparison of microbial community structure**

In this study, the SEM observations of the DM in the SDMBRs were conducted after filtration, as shown in Figure 8. The previous study showed that a dense layer of porous dynamic film was formed in the non-woven surface (Fu et al. 2009). Fan and Huang reported that the DM in the SDMBRs had a variety

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**Figure 7** | SEM picture of DM surface at different SRT in the SDMBR (a) 5 days, (b) 10 days, (c) 20 days, (d) 40 days and (e) 60 days.

**Figure 8** | SEM picture of DM surface at different SRT in the SDMBR (a) 5 days, (b) 10 days, (c) 20 days, (d) 40 days and (e) 60 days.
of microbes, such as Coccus, Bacillus, chainlike Coci, filamentous bacteria, etc. (Fan & Huang 2002). The amounts and types of microorganisms changed at different SRT. In this study, at SRT of 5 and 10 days, some Cocci were seen retained on the DM. With the increase of SRT, the DM was dominated with Cocci, Filamentous and Bacillus. For example, SEM images of the DM surface at SRT of 60 d were composed of Filamentous bacteria, Cocci and Bacilli. This was mainly due to the formation of sludge microbial populations and because the micro-environment was different under different sludge ages. As the SRT increased, the mixture in a longer generation time of bacteria could get a better breeding, the types of microorganisms were more diverse, and the amounts and types of microorganisms on the surface of the DM were more abundant.

CONCLUSIONS

The characteristics of self-forming DM in sequencing batches under the different SRT (SRT = 5, 10, 20, 40, 60 days) has been explored using scanning electron microscope, particle sizing distribution analysis measurements and others. Based on the results and analyses, the following conclusions are drawn.

1. The SRT has evident effects on characteristics of the DM. The content of EPS and protein decreased with the increase of SRT. The change of polysaccharide was small regardless of SRT.
2. The filtration resistance of the DM was divided into two stages: an initial slowly-rising stage and a fast-rising later stage, which were both irrespective to SRT. With the increase of SRT, the filtration resistance decreased and the running cycle became longer.
3. Compared to the lower SRT, the PSD of mixed liquor and DM had a decreasing trend at higher SRT. The average particle size of DM was larger than that of the mixed liquor irrespective of SRT.
4. The amounts and types of microorganisms on the surface of the DM were more abundant as SRT increased. Low SRT produced the DM surface with some Cocci while the high SRT gave the DM surface dominated with Cocci, Filamentous and Bacillus.

REFERENCES


