The membrane fouling characteristics of MBRs with different aerobic granular sludges at high flux

Yaqin Wanga, Chen Zhonga, Dan Huangb, Yongjian Wanga, Jianrong Zhua,⇑

a School of Environment, Beijing Normal University, Beijing 100875, China
b State Key Laboratory of Water Simulation, Beijing 100875, China

HIGHLIGHTS
• Membrane fouling of aerobic granules MBR at high flux was investigated.
• Aerobic granules MBR performed a long term and stable operation 61 days at high flux.
• Pore blocking was the main contribution for membrane fouling in aerobic granules MBR.
• Dominant membrane fouling factor in flocculent or bulking sludge was cake resistance.
• Aerobic granules in MBR were quite stable during operation.

ARTICLE INFO
Article history:
Received 5 December 2012
Received in revised form 6 March 2013
Accepted 9 March 2013
Available online 16 March 2013

Keywords:
Membrane fouling
High flux
Aerobic granular sludge
MBR
Flocculent sludge

ABSTRACT
This experimental work investigated the property of membrane fouling for different sludges at high flux 20 L/(m² h). The MBR with good aerobic granular sludge performed the longest operation time 61 days, and TMP rose up in a steady overall rate, while only 10, 14 and 19 days for bulking, flocculent and small granular sludge, respectively, which clearly demonstrated the good and complete aerobic granules greatly retarded the membrane fouling. The pore blocking resistance 76.21% was the key fouling factor for aerobic granules, but the cake resistance 61.23% or 79.02% was the main factor for flocculent or bulking sludge. The difference in EPS composition of membrane foulants between granules MBR and flocculent sludge MBR led to the different behaviour of fouling. Aerobic granules were quite stable during operation. These results suggested MBR with aerobic granules might be operated at high flux, which was very valuable for practical application.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Membrane bioreactor (MBR) has already attracted more and more attention, and occupied an important position in wastewater treatment and reuse due to its high quality product water and compact design (Drews, 2010; Peng et al., 2012; Hwang et al., 2012). But membrane fouling is a primary challenge for the successful MBR operation, which can decrease the membrane filtration, and make a high cost for the cleaning or regeneration of membrane module (Le-Clech et al., 2006).

Generally, there are many factors affecting the membrane fouling, mainly including: (1) sludge particles and structure which would deposit and accumulate on membrane surface to form cake layer; (2) large soluble molecules plugging and narrowing the pores of membrane. Sludge characteristics were closely relevant to the membrane fouling. Typically, the activated sludge in MBR is flocculent form. Now, a new type existed as aerobic granular sludge has been extensively studied over past ten years (Beun et al., 1999; Adav et al., 2008; Lee et al., 2010). Compared to flocculent sludge, aerobic granule sludge has a regular and compact structure, excellent settleability, high biomass, diverse microbial community and great metabolic activity (de Kreuk et al., 2005; Lee et al., 2010). For its big particle size visible even by naked eye, aerobic granule is supposed to be very useful to retard membrane fouling, because it is not easy to adhere or attach to membrane pore. Li et al. (2005) firstly developed a membrane bioreactor with aerobic granular sludge (MGSBR), and observed the ability to control membrane fouling as the final flux of conventional MBR was 50.0% of MGSBR. Also, the system with aerobic granules indicated the excellent membrane permeability in a four-month continuous operation compared with the conventional MBR, and it was claimed that low membrane fouling was induced...
by the low compressibility of granular sludge biomass in surface cake (Tay et al., 2007). Zhou et al. (2007) noted the enhanced filterability for aerobic granular membrane over conventional flocculent membrane. There were other investigations on membrane fouling with aerobic granular sludge and flocculent sludge at 11.5 L/(m² h) (Tay et al., 2007), 10 L/(m² h) (Tu et al., 2010), or under 10 L/(m² h) (Li et al., 2005). But all these reports were dealing with research of aerobic granules MBR at conventional flux suggested by manufacturer, and its behaviour at high flux was still not launched.

The imposed flux of MBR had a great impact on fouling development, and low flux led to a slower increase of total membrane resistance compared with high flux in conventional MBR (Johir et al., 2012). Low flux could weaken the depositing as a result of suction and be helpful for controlling membrane fouling, reducing the chemical cleaning frequency of membrane. To date, full-scale membrane fouling with different sludges was concerned to find the fouling characteristics mostly at conventional defined fluxes. However, the high flux would lead to easy membrane fouling. The different performance of membrane reactor coupled with bulking sludge and normal flocculent sludge at a flux of 16 L/(m² h) was reported, and the result showed that bulking sludge resulted in more serious fouling in the MBR compared with the normal sludge (Pan et al., 2010). Considering their advantages, aerobic granules in reactor was believed to be helpful for MBR operation at high flux. Siembida et al. (2010) found the fouling layer formation was significantly reduced by abrasion using the granular material which was added into conventional MBR, and it was demonstrated that the MBR with granules could be operated at higher flux compared to a conventional MBR operation. However, there was less information for the application of aerobic granules in MBR at high flux up to now. Therefore, it is very interesting and necessary to explore what is the behaviour of MBR system with aerobic granular sludge at high flux operation, which was very meaningful to prolong the operation of membrane module and promote the treatment capacity.

This experiment aimed to investigate the membrane performance and fouling characteristics for the aerobic granular sludge MBR systems at a high flux of 20 L/(m² h) and compare the difference with other flocc sludge MBR. Two kinds of aerobic granular sludge were employed, and the flocculent sludge or bulking sludge was used as a control.

2. Methods

2.1. MBR and operation control

The experiments with different sludges were conducted in the same MBR system to get a completely equal condition. The reactor had a working volume of 60 L, 0.55 m L × 0.35 m W × 0.4 m H (Fig. 1), which was operated as sequencing batch reactor (SBR) at cycle time of 6 h. There was one-minute aeration for mixing after feeding. And the experiment was carried out at ambient temperature. An air flow rate of 1.5 m³/(m² membrane area h) was applied. Aeration was 0.75 m³/h, and the flow of feed pump or suction pump was 0.4 L/min or 0.01 m³/h, respectively. The seed aerobic granular sludge was cultivated by acetate as substrate and under alternative feed loading in our other lab SBRs. While the bulking sludge was collected from a SBR where the flocculent sludge turned to deterioration and then became the bulking sludge. The good granular sludge meant a big size (average diameter 903 μm) and complete granulation in reactor (Fig. 2). The small aerobic granular sludge had a less size (average diameter 434 μm) and contained parts of suspended flocs. The flocculent sludge came from Gaobeidian municipal wastewater treatment plant located in Beijing, which adopted conventional activated sludge process. During each experimental run of the different sludge, MBR discharged its effluent through submerged membrane filtration. The membrane module followed an intermittent suction effluent mode of 8 min-on/2 min-off. For high flux experiment, the membrane permeation was specially suctioned at the flux of 20 L/(m² h), which was almost the double as recommended by manufacturer. The membrane module was made of hollow fiber membrane (hydrophilized polyvinylidene) with a pore size of 0.4 μm (Mitsubishi Rayon, Tokyo, Japan), and had an effective area of 0.5 m² (405 × 160 mm). The MBR system was operated in constant flux condition, and TMP was used as the indicator of membrane fouling, recorded by the data collecting system on-line. To simulate the practical operation, the complete membrane fouling development was observed and examined for each different sludge, and TMP around 50–55 kPa was identified as the threshold for cleaning of membrane module based on the primary experiment. The all operation of the reactor was controlled by a programmable logic controller (PLC). Table 1 summarized the details of operational strategies in different configuration of the experiment.
The synthetic wastewater was used as the feed of MBR system. Table 2 gave the specific compositions of the influent.

### Table 1
Operational strategies of different sludge MBRs in the experiment.

<table>
<thead>
<tr>
<th>Configuration of experiment</th>
<th>Sludge</th>
<th>MLSS (g/L)</th>
<th>SVI30 (mL/g)</th>
<th>Cycle (h)</th>
<th>Feeding (min)</th>
<th>Anaerobic (min)</th>
<th>Aeration (min)</th>
<th>Settling (min)</th>
<th>Discharging (min)</th>
<th>Exchange ratio (%)</th>
<th>Filtration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>Good aerobic granules</td>
<td>10.1</td>
<td>14</td>
<td>6</td>
<td>5</td>
<td>65</td>
<td>270</td>
<td>10</td>
<td>10</td>
<td>67</td>
<td>150</td>
</tr>
<tr>
<td>Run 2</td>
<td>Small aerobic granules</td>
<td>3.5</td>
<td>20</td>
<td>6</td>
<td>5</td>
<td>65</td>
<td>270</td>
<td>10</td>
<td>10</td>
<td>67</td>
<td>150</td>
</tr>
<tr>
<td>Run 3</td>
<td>Flocculent sludge</td>
<td>7.0</td>
<td>70</td>
<td>6</td>
<td>5</td>
<td>65</td>
<td>270</td>
<td>10</td>
<td>10</td>
<td>50</td>
<td>110</td>
</tr>
<tr>
<td>Run 4</td>
<td>Bulking sludge</td>
<td>6.0</td>
<td>103</td>
<td>6</td>
<td>5</td>
<td>65</td>
<td>270</td>
<td>10</td>
<td>10</td>
<td>50</td>
<td>110</td>
</tr>
</tbody>
</table>

### Table 2
Composition of the synthetic wastewater.

<table>
<thead>
<tr>
<th>Components</th>
<th>Concentrations (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH\textsubscript{3}COONa</td>
<td>819.20</td>
</tr>
<tr>
<td>NH\textsubscript{4}Cl</td>
<td>152.85</td>
</tr>
<tr>
<td>KH\textsubscript{2}PO\textsubscript{4}</td>
<td>70.21</td>
</tr>
<tr>
<td>NaCl</td>
<td>160.00</td>
</tr>
<tr>
<td>MgSO\textsubscript{4} \cdot 7H\textsubscript{2}O</td>
<td>80.00</td>
</tr>
<tr>
<td>CaCl\textsubscript{2}</td>
<td>16.00</td>
</tr>
<tr>
<td>pH</td>
<td>7.0–7.4</td>
</tr>
</tbody>
</table>

By flushing the surface of membrane to wipe off the foulants at the end of each run, the foulants left in the deionized water, then was placed on a magnetic blender and well mixed. The samples of membrane foulants were prepared for extracellular polymeric substances (EPS) extraction.

Extraction of EPS was carried out according to the heating methods (Morgan et al., 1990). The mixed liquor samples were centrifuged at 5000 rpm for 5 min, and the supernatant was discarded. The precipitate was diluted with deionized water and intermixed. The mixture was heat-treated for 10 min at 80 °C, which let the EPS extract from the sludge. The solution was cooled down to room temperature, followed by the centrifugation at 7000 rpm for 10 min. The supernatant after filtration was used to determine the concentration. Then polysaccharides and protein in supernatant were determined. The proteins were measured by the Bradford method using bovine serum albumin as a standard (Bradford, 1976). Polysaccharides were determined according to phenol–sulfuric method using glucose as standard (Dubois et al., 1956).

Fluorescence Excitation-emission matrix (EEM) measurements of EPS extracted from membrane foulants were conducted using...
brane fouling resistance; resistance. was as follows (Wang et al., 2009). (1) 2000 (Malvern), which is based on laser diffraction scattering at and showed an increase within 11-days to 30.24 kPa, and a quick for another approximately interval of 20 kPa TMP. MBR system might be divided into 2 stages: slow increase (day 1–8) and quick exhibited the shortest operation time of only 10 days. TMP curve of membrane fouling of 4 runs of the membrane reactors with differ-

The analysis of membrane resistance was made according to Darcy law:

\[ R = R_m + R_f = R_m + R_p + R_c \]

R: total hydraulic resistance; \( R_m \): membrane resistance; \( R_f \): membrane fouling resistance; \( R_p \): pore blocking resistance; \( R_c \): cake layer resistance.

The experimental procedure on determine each resistance value was as follows (Wang et al., 2009). (1) \( R_m \) was measured by filtering deionized water using clean membrane module. (2) \( R \) was estimated by filtering deionized water using fouled membrane. Then \( R_f = R - R_m \). (3) After flushing the surface of membrane to wipe off the cake layer, membrane used to measure the resistance of \( R_f + R_m \) by filtering deionized water. And \( R_p \) was calculated then. (4) \( R_c = R_f - R_p \).

2.4. Other analytical methods

The measurements of MLSS, and SVI_{30} were analyzed by the Standard Methods (APHA-AWWA-WEF, 2005).

The particle size distribution was determined by Mastersizer 2000 (Malvern), which is based on laser diffraction scattering at range of 0.02–2000 μm.

3. Results and discussions

3.1. Operational performance and membrane fouling

At a high flux of 20 L/(m² h), the operational performance and membrane fouling of 4 runs of the membrane reactors with differ-
ent sludges are summarized in Fig. 3. MBR with bulking sludge exhibited the shortest operation time of only 10 days. TMP curve might be divided into 2 stages: slow increase (day 1–8) and quick rising (day 9–10). TMP reached 33.39 kPa from the initial 10.23 kPa within 8 days, and then sharply jumped to 52.45 kPa just in 2 days for another approximately interval of 20 kPa TMP. MBR system with floculent sludge experienced the similar TMP variation, and showed an increase within 11-days to 30.24 kPa, and a quick rising to 51.07 kPa in last 3 days. Noticeably, TMP profile of aerobic granular sludges displayed a different behaviour. The membrane fouling of MBR with small aerobic granules was improved much and maintained totally 19 days. TMP moved up to 29.26 kPa in initial 13 days, and then to 51.72 kPa in following 6 days, which illustrated that flocs sludge made a main contribution in fouling development of a mixed sludge MBR system, but aerobic granules could effectively reduce the membrane fouling. This phenomenon was further confirmed by good and complete aerobic granules. The performance of MBR with good aerobic granular sludge was operated for the longest time of 61 days, and TMP went up in a steadily overall rate during the whole membrane fouling process, despite there were 2 slight increases in a certain and short periods (The slight TMP increases at 15th and 45th day were speculated with the shift of membrane fouling formation, i.e. the blocking of sludge, attached growth of microorganisms and cake layer development). These results clearly demonstrated that different sludges exhibited the different TMP variations, in other word, the membrane fouling was closely linked with sludge morphology and structure, and aerobic granular sludge was really beneficial for slowing down the TMP increase rate and prolonging the filtration life at a high flux of 20 L/(m² h). Particularly, the good and complete aerobic granular sludge system could effectively and greatly retard the membrane fouling superior to floculent sludge and bulking sludge.

In literature, Tay et al. (2007) reported that the membrane fouling development of floculent sludge lasted 18 days, and also described the submerged membrane module with aerobic granular sludge was operated for about 73 days at a flux of approximate 11.5 L/(m² h). In this experiment, the operation 61 days of membrane module with good aerobic granular sludge was much longer than 14 days of the floculent sludge. Also, 61 days were quite comparable to the former report of 73 days although the flux in current experiment was almost the double as before. These results certified that aerobic granular sludge could greatly retard membrane fouling indeed. Siembida et al. (2010) investigated the effect of mechanical cleaning with granular material on the permeability of submerged membranes in the MBR process, and observed that the fouling layer formation was significantly reduced by abrasion using the granular material. The application of aerobic granule in this experiment confirmed the advantages of big sludge particles for long term operation as well.

In operation membrane flux always played an important impact. Johir et al. (2012) reported the effect of imposed flux on fouling behavior in high rate membrane bioreactor, and found that a lower flux of 20 L/(m² h) produced 75 times more water than a higher flux of 40 L/(m² h) in a flat sheet membrane module. At higher flux the deposition of the sludge onto the membrane surface should be faster and the cake layer should be well-built than at a lower flux. Li et al. (2012) investigated a novel aerobic granule (AG)-mesh filter MBR (MMBR) process. The reactor was run at the constant flux operation of filtration fluxes 60, 90 and 120 m²/(m² mesh h)\(^{-1}\), and detected the granules showed a lower fouling propensity than sludge flocs. This experiment firstly described the complete membrane fouling of MBR with good aerobic granule at high flux and made a comparison with other sludges. The excellent results 63 days operation from good aerobic granule MBR clearly indicated the aerobic granule was really helpful for maintaining a stable long term operation at high flux. That meant membrane module with aerobic granular sludge in reactor might be operated at a much higher flux than flocs sludge, which was very valuable for practical application.

---

**Fig. 3.** Membrane fouling profile in different sludge MBR systems.
3.2. Membrane resistance analysis

In order to investigate the mechanism of membrane fouling with different sludge systems, the contribution of different membrane resistance was analyzed. Table 3 presented the result of pore blocking resistance ($R_P$), cake layer resistance ($R_C$) and the specific resistances measurements. $R_C/R_f$ in run 3 and run 4 was 61.23% and 79.02%, respectively, which was much bigger than corresponding $R_P/R_f$. This implied that the cake layer resistance was the major factor of membrane fouling in flocculent sludge and bulking sludge. However, for aerobic granule in run 1, $R_P$ contributed to 76.21% of membrane fouling resistance, which was significantly larger than $R_C$ proportion. In run 2, $R_P$ was similarly up to 52.57% of membrane fouling resistance and bigger than $R_C$. These results suggested that the pore blocking was the key factor for membrane fouling in aerobic granular sludge.

During membrane fouling process, the deposition of sludge flocs was determined by two factors: the shear force, which was generated by aeration, and the suction force. With the membrane flux increased, the suction force became stronger. Due to suction force and the high compressibility of bioflocs, the small particles in flocculent and bulking sludge would easily and quickly accumulate on the membrane surface to build cake under high flux. The well-built cake was very compact, and led to severe cake fouling.

### Table 3
Measurements of membrane fouling resistances of the different sludge MBRs.

<table>
<thead>
<tr>
<th>MBR contained sludge</th>
<th>$R_m$ ($\times 10^{12}$ m$^{-1}$)</th>
<th>$R_P$ ($\times 10^{12}$ m$^{-1}$)</th>
<th>$R_C$ ($\times 10^{12}$ m$^{-1}$)</th>
<th>$R_f$ ($\times 10^{12}$ m$^{-1}$)</th>
<th>$R_P/R_f$ (%)</th>
<th>$R_C/R_f$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good granular sludge</td>
<td>0.72</td>
<td>9.10</td>
<td>2.84</td>
<td>11.94</td>
<td>76.21</td>
<td>23.79</td>
</tr>
<tr>
<td>Small granular sludge</td>
<td>0.72</td>
<td>7.06</td>
<td>6.37</td>
<td>13.43</td>
<td>52.57</td>
<td>47.43</td>
</tr>
<tr>
<td>Flocculent sludge</td>
<td>0.75</td>
<td>4.63</td>
<td>8.45</td>
<td>13.08</td>
<td>35.40</td>
<td>61.23</td>
</tr>
<tr>
<td>Bulking sludge</td>
<td>0.73</td>
<td>3.12</td>
<td>11.75</td>
<td>14.87</td>
<td>20.98</td>
<td>79.02</td>
</tr>
</tbody>
</table>

$R_m$: membrane resistance; $R_P$: pore blocking resistance; $R_C$: cake layer resistance; $R_f$: membrane fouling resistance.
Finally the cake layer resistance became the key factor of membrane fouling in flocculent sludge and bulking sludge. However, there were much fewer flocs in good aerobic granular sludge. The big aerobic granules had a larger size than the pores of membrane, and were not easy to attach or clog on the surface of membrane. Even they were forced to retain on the surface of module under high TMP, the formed cake layer had a loose structure with high gaps or was reversibly de-attached, which would benefit the long term and stable operation of MBR. Such distinctive character of aerobic granules described above consequently resulted in the pore blocking became the main factor for membrane fouling. In literature, Tay et al. (2007) measured that the main resistance of aerobic sludge MBR was 76.7% from colloids (39.2%) and dissolved molecules (37.5%), i.e. the pore blocking. The similar results were also reported by Thanh et al. (2010). The irreversible resistance or pore blocking in aerobic granules MBR systems varied in 59%. Though the most of researches above were conducted on filtration batch test, the continuous operation of current experiment also exhibited the similar result (i.e. 76.21%).

3.3. EPS property of membrane foulants

Essentially, the membrane fouling was closely relevant to the attached growth of the bacteria from the sludge. Thus, the EPS of sludge was supposed to have a significant function for membrane filtration, and its measurement might reveal much information. The composition of EPS, extracted from the foulants at TMP approximately 50 kPa was shown in Fig. 4. Three fluorescence peaks were identified as A, B, and C, which were associated with simple aromatic, tryptophan-like and humic-like organic compounds, respectively (Table 4). There were only two peaks A and B in foulants from aerobic granules, which implied that there were simple aromatic proteins (such as tyrosine) and tryptophan-like substance. Membrane foulants from flocculent or bulking sludges both exhibited peak A, B, and C. These results illustrated an EPS difference of membrane foulants between aerobic granular sludge and flocculent sludge, which was supposed to lead to the different behaviour of membrane fouling. In aerobic granular sludge, the bacteria were mainly aggregated to form the big particle with very dense and compact structure. Fewer small suspended flocs were formed and dispersed in the reactor system compared with very dense and compact structure. The small suspended solids in flocculent sludge were more easily to deposit on the membrane surface and form cake layer. So the difference from spatial structure of microorganism community resulted in the variation of EPS composition deposited on the membrane surface. The microorganisms between aerobic granular sludge and flocculent sludge were not the same, which was also reported by other researchers (Li et al., 2008; Su et al., 2012).

The EPS concentration and composition extracted from different cake layer foulants of the membrane module were shown in Fig. 5. The protein and polysaccharide in membrane foulants with flocculent sludge or bulking sludge was higher than that with aerobic granular sludge. The results suggested membrane foulants had a relation with sludge characteristics and fouling process.

Fig. 5. The EPS measurements of different membrane foulants in MBR.

3.4. Sludge characteristics in the reactor

As the distinctive character, the structure and stability of aerobic granules in reactor was a concerning focus. Fig. 6a showed the size distribution of aerobic granular sludge and flocculent sludge. The size of almost all sludge particles was bigger than that of membrane pore. Sludge under the size of 100 μm in flocculent sludge accounted for 80% of total sludge. However, about 90% of sludge in both good and small aerobic granular sludges was bigger than 100 μm. Although the average size of aerobic granular sludge decreased a little along with the operation of MBR, their morphology and structure remained quite stable (Fig. 6b). MLSS concentration did not show any big change as well. MLSS concentration of good granular sludge was only slightly increased from 10.1 to 10.3 g/L, and similar MLSS variation was observed in small granular sludge system. This good behaviour of stability was particularly useful in practical application.

The EPS analysis of the different sludges in reactors during the experiment was shown in Fig. 6c. Flocculent sludge and bulking sludge contained more polysaccharides than proteins in EPS. However, proteins were much high than polysaccharides in aerobic granular sludge. Although the total EPS of good aerobic granules was almost equal to that of flocculent sludge, there was a big difference in ratio of protein to polysaccharide. Proteins were hydrophobic, while polysaccharides were hydrophilic. Hydrophobic EPS such as proteins would be important for the formation of microbial aggregates. Tay et al. (2002) showed that the EPS content in granules was more than 2–3 times that in flocculated sludge. However, there were other reports claimed that there was no significant correlation between EPS and sludge granulation (Wang et al., 2010). The EPS content in flocculants was even higher than that in granules. The results of this experiment also supported the latter conclusion, and it seemed that the EPS composition and ratio of polysaccharides and proteins were much important than total concentration. The different experimental conditions would affect the EPS production and characteristics due to the variations in microorganism community, the composition of the wastewater. In addition, difference in the concentrations and distribution of

<table>
<thead>
<tr>
<th>Table 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>The coordinates of fluorescent components peaks in different membrane foulants samples.</td>
</tr>
<tr>
<td>Simple aromatic (peak A)</td>
</tr>
<tr>
<td>Ex (nm)</td>
</tr>
<tr>
<td>Good granular sludge</td>
</tr>
<tr>
<td>Small granular sludge</td>
</tr>
<tr>
<td>Flocculent sludge</td>
</tr>
<tr>
<td>Bulking sludge</td>
</tr>
</tbody>
</table>

Ex: Excitation wavelength, Em: Emission wavelength.
proteins and polysaccharides, and property of hydrophobicity was considered as important for granular stability (McSwain et al., 2005). In current experiment, stability of granular sludge was crucial for long stable performance of MBR and it ensured the capability of aerobic granular sludge on controlling membrane fouling.

4. Conclusion

The MBR with aerobic granular sludge performed a long and stable operation of 61 days at high flux of 20 L/(m² h), which was much better than flocculent sludge and bulking sludge for controlling membrane fouling. Cake resistance was the key factor of membrane fouling in flocculent sludge or bulking sludge. However, pore blocking resistance was the main factor in aerobic granular sludge. There was a difference in EPS composition of membrane foulants between aerobic granular sludge and flocculent sludge, leading to different behaviour of membrane fouling. The granular sludge in MBR was quite stable during operation.

Acknowledgement

This research project was financed by National Natural Science Foundation of China (NSFC) (No. 51078036).
References


