Operational factors of submerged inorganic membrane bioreactor for organic wastewater treatment: sludge concentration and aeration rate

E.J. Hwang, D.D. Sun and J.H. Tay
Environmental Engineering Research Center, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798

Abstract Various sludge concentrations and aeration rates were evaluated to find the optimal operation condition of a submerged ceramic membrane filtration system. 5.6 g/L of sludge was diluted with water to concentrations of 2.8 g/L and 1.4 g/L, and the three sludge concentrations were compared in terms of filtration characteristics such as pressure and filtrate flux. Flux was at the highest value of about 30 L/m².hr at 50 kPa when sludge concentration was 1.4 g/L. In contrast, when sludge concentrations increased to 2.8 g/L and 5.6 g/L, the flux at 50 kPa decreased significantly to 18 L/m².hr and 10 L/m².hr, respectively. It was concluded that the sludge concentration directly affected the filtration efficiency, and low sludge concentration was suitable for improving filtration efficiency. Adjusting the aeration rate from 2 L/min to 4 L/min at 5.6 g/L of sludge and 50 kPa of pressure increased flux from 10 L/m².hr to 13 L/m².hr. It was obvious that the vigorous aeration improved the filtration efficiency, but the aeration rate did not seem to be high enough to maintain flux lower than critical flux.

Keywords Aeration rate; fouling; ceramic membranes; membrane bioreactor; sludge concentration; submerged system

Introduction

Water supply in Singapore is an important issue due to rapid industrialization and land scarcity. Faced with this issue, extensive studies involving the recycling and reuse of wastewater have been carried out. Improving the quality of the treated wastewater is necessary in order to recycle it safely into clean water.

High performance of the wastewater treatment process can be developed by increasing the biomass concentration either by fixing it on a porous material or by favoring the growth of easy-settling microbial granules. The other way of increasing biomass concentration is solid-liquid separation techniques using membranes. Recently, following the development of a new generation of more productive and less expensive filtration membranes, the membrane bioreactor (MBR) has emerged and has been introduced into wastewater treatment technology as a viable alternative way of increasing biomass content and thus guaranteeing a higher efficiency. Using membrane filtration technology, the need for flocculation in conventional wastewater treatment processes is removed, and a highly active microbial population can be maintained regardless of its flocculating ability (Scott and Smith, 1997). With the microbial cells retained behind a membrane, it is possible to operate with biomass concentration of up to 20,000 mg/L, compared with 1,500–3,500 mg/L for a conventional activated sludge reactor (Yamamoto et al., 1989). Extensive studies have been conducted on the MBR system, and it was found that the MBR system could be operated for one to three years with simple and regular membrane cleaning operations (Buisson et al., 1998; Cicek et al., 1999; Lu et al., 2000).

Although many studies have shown the applicability of the MBR system, relatively little is known about biofouling of membranes. Liew et al. (1997) reported that high viscosity caused low flux in their tests filtrating various antifoam agents. Meanwhile, it was found...
that the relationship between sludge concentration and sludge viscosity was linear (Xing et al., 2001). Therefore, it can be deduced that the sludge concentration is related to membrane filtration efficiency; the higher the sludge concentration, the better the filtration efficiency is. However the effect of sludge concentration has not been clearly discussed in previous studies. Defrance and Jeffrin (1999) reported that 10,000 mg/L of MBR sludge showed higher flux than 3,000 mg/L of conventional activated sludge. Although the authors interpreted the result with an assumption that there was a difference in exopolymer concentration between the sludges, it was not clear if the sludge concentrations affected the filtration efficiency in the test. Fan et al. (2000) also reported a similar result that sludge concentration did not affect the filtration efficiency. However this data also seems not enough to discuss the effect of sludge concentration, since there were many variables other than sludge concentration in the experiment including sludge retention time, MBR influent quality, and exopolymer concentration of sludge. It is necessary to isolate sludge concentration from other variables in order to discuss the effect of sludge concentration itself on filtration efficiency. This can provide researchers with a useful relationship in interpreting experimental data as well as modeling the filtration system.

In this study, the relationship between sludge concentration and filtration characteristics such as pressure and flux was investigated in detail. To do this, sludge was diluted with water at different dilution rates and the diluted sludge was filtrated with ceramic membranes in a submerged MBR system. In addition, the effect of aeration rate on controlling membrane fouling was investigated. In all the tests, a ceramic membrane was used as an alternative to the organic membrane to prolong its life since the ceramic membrane is structurally stronger than its organic counterpart and can be easily regenerated.

Materials and methods

Reactor system

Figure 1 shows the cylindrical acrylic reactor system (45 mm inner diameter, 400 mm working depth) used in this study. Five ceramic membranes having 6 mm and 7 mm inner and outer diameters respectively and 300 mm length each were connected in parallel. The membrane surface area based on the outer diameter was 0.0064 m², total surface area was 0.032 m², and each membrane had a pore size of 0.5–1 µm. The membrane package was connected to a pressure gauge (0–100 kPa) and peristaltic pump (Masterflex). Air was supplied from the bottom of the bioreactor through an air flow meter that controlled the flow rate. Sludge was cultivated in a 4 L membrane bioreactor system equipped with the same devices as those of the small reactor system.

![Experimental reactor system](https://iwaponline.com/wst/article-pdf/47/1/121/426573/121.pdf)
Operation
Filtration tests were carried out when the sludge concentration reached 5.6 g/L. 500–1,000 mL of sludge liquor was taken out from the big MBR and diluted with water to designated concentrations. Having been filled with the sludge, the reactor was aerated for an hour, after which membrane filtration started. Four tests in total were conducted with different parameters as shown in Table 1. In R1, R2, and R3 tests, sludge concentration was the only variable and aeration rate was fixed to 2 L/min. In R4, sludge concentration was fixed to the same value as R1, but aeration rate was increased to 4 L/min instead. The tests were conducted one by one, and the membranes were regenerated and specific permeability was measured when each test ended. 500 mL of hot water (60–80°C), 200 mL of hypochlorite solution, 500 mL water, 100 mL of nitric acid, and 1 L of water were consecutively filtrated for membrane regeneration.

Analysis
Sludge concentration was measured according to the Standard Method (APHA/AWWA/WEF, 1995). Pressure and flux were monitored at 1–4 min intervals during the 140–160 min filtration tests. Flux was monitored with a mess cylinder. When filtration started, the two parameters were monitored at one-minute intervals and once the flux and pressure reached a steady-state filtration, the pumping speed of the peristaltic pump was adjusted to subsequent higher values.

Results and discussion
Figure 2 to Figure 5 show the changes in pressure and flux in each experiment. Pressure increased according to increasing rotational speed of the peristaltic pump head. In the R1 test where sludge concentration was 5.6 g/L, pressure increased sharply to 50 kPa in 20 minutes, and flux was maintained at 10 L/m².hr during this period. In contrast, pressure increased slowly in R2 and R3 where the sludge concentrations were low at 2.8 g/L and 1.4 g/L, respectively. The stabilized pressure in R2 and R3 was about 20 kPa and 10 kPa while filtration flux was at similar levels in the two tests. This apparently indicated that the membrane filtration was affected by sludge concentration. It was interesting to observe that the pressure profile was under the flux profile in Figure 4 while it was higher than the flux profile in Figure 2. The meaning of this was that the power requirement to filtrate the same

Table 1  Experimental condition

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge concentration</td>
<td>5.6 g/L</td>
<td>2.8 g/L</td>
<td>1.4 g/L</td>
<td>5.6 g/L</td>
</tr>
<tr>
<td>Aeration rate</td>
<td>2 L/min</td>
<td>2 L/min</td>
<td>2 L/min</td>
<td>4 L/min</td>
</tr>
</tbody>
</table>

Figure 2  Changes of pressure and flux in R1
Figure 3  Changes of pressure and flux in R2
amount of water was lower in R3 than in R1. Therefore it was concluded that low concentration of sludge is desirable for improving the filtration efficiency.

The reason for this phenomenon seemed that the sludge concentration changed the viscosity (Xing et al., 2001). The diluted sludge concentration resulted in low viscosity and this made filtration efficiency high. These results were in contrast with the data obtained in previous studies. Defrance and Jeffrin (1999) reported that 10,000 mg/L of MBR sludge was filtrated at a flux of 80–90 L/m².hr while 30–70 L/m².hr of flux was obtained with 3,000 mg/L of conventional activated sludge. In addition, the filtration of the MBR sludge was reversible, but the conventional activated sludge showed irreversible filtration. As the authors interpreted, possible differences in exopolymer concentration might be the cause of these results. It seemed that the effect of exopolymer concentration was bigger than the effect of sludge concentration in their study, although the sludge concentration affected the filtration efficiency.

The initial high pressure and low filtration efficiency in R1 could be overcome by increasing the aeration rate. In Figure 5, the increase in pressure was reduced significantly as compared to R1, although the flux was found to be slightly higher than 10 L/m².hr. The increased aeration seemed to provide membrane surface with sheer force vigorously, which is one of the important fouling control mechanisms. This coincided with the findings by Madaeni et al. (1999) that critical flow depended on cross-flow velocity in their cross-flow filtration tests. The critical flow in the tests became higher when the cross-flow velocity was controlled at higher value. However, when the peristaltic pump was operated at higher rotation speed in this study, the pressure increased sharply to about 70 kPa. It seemed that the aeration rate of 4 L/min was effective in improving the filtration efficiency only when it was applied at a low filtration rate.

In general, it is known that cross-flow velocity controls the formation of a cake layer on the membrane surface. Once the flux or transmembrane pressure increases to a certain amount, pores inside the membrane matrix begin to be clogged by sludge particles. As the clogging proceeds, membrane filtration efficiency drops down rapidly (Tardieu et al., 1998). This possibly explained the reason why the pressure increased rapidly in R4; increased aeration reduced the cake formation on the membrane surface at lower flux, but clogging of the pore proceeded at higher flux so that the pressure increased promptly.

Figure 6 and Figure 7 compared the pressure and flux change according to the sludge concentration and aeration rate respectively. As expected, pressure change was in the order of R1, R2, and R3 while flux was highest in R3 followed by R2 and R1. It was also found that the increase in aeration rate improved the filtration efficiency at a high sludge concentration.

Flux values in each steady-state filtration were averaged, and the averaged values were plotted with the matching pressure values as shown in Figure 8. When the pressure was
below 50 kPa the average flux was in the order of R3, R2, R4, and R1. In all the tests except R3, the flux reached a similar value when the suction pressure approached its maximum value of 80 kPa. Increased suction pressure in R2 and R4 resulted in little increase of flux, whereas the flux increased significantly in R3 by increasing the operating pressure. This implied that filtration was conducted under the critical flux limit at the lowest sludge concentration. At higher sludge concentrations, it seemed that the flux reached or exceeded the
critical limit at higher pressure and thus fouling proceeded. This caused little flux improvement by the pressure increase. Also it was concluded that high aeration rate improved the filtration efficiency but the sheer force caused by the high-rate aeration in this submerged membrane system was not sufficient to keep the process under the critical point.

**Conclusion**

The effect of sludge concentration and aeration rate on filtration characteristics of submerged ceramic membrane bioreactor system was studied. It was apparent that sludge concentration affected the filtration efficiency significantly within the range tested here. As expected, the low sludge concentration was favorable for reducing fouling, and increased aeration improved the filtration efficiency at high sludge concentration. However, as the MBR system is normally operated at high sludge concentrations, controlling the sludge at low concentrations may not be practical. Nevertheless, the data obtained in this study can be utilized in a further study on modeling the filtration system.

**References**


