Membrane Water Treatment, *Vol. 4, No. 3 (2013) 175-189*
DOI: http://dx.doi.org/10.12989/mwt.2013.4.3.175

Comparison study on membrane fouling by various sludge fractions with long solid retention time in membrane bioreactor

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(Received November 22, 2012, Revised April 19, 2013, Accepted April 22, 2013)

Abstract. A membrane bioreactor (MBR) with sludge retention time (SRT) of 300 days was maintained for over 2 years. Polypropylene microfiltration (MF) membrane with pore size of 0.2 μm was used in the MBR system. The fouling behaviors of various sludge fractions from the MBR were studied and sub-divided resistances were analyzed. It was observed that R_{cp} was a dominant resistance during the filtration of activated sludge, contributing 63.0% and 59.6% to the total resistance for MBR and sequential batch reactor (SBR) respectively. On the other hand, R_c played the significant role during the filtration of supernatant and solutes, varying between 54.54% and 67.18%. Compared with R_{cp} and R_c, R_{if} was negligible, and R_m values remained constant at $0.20 \times 10^{12}\ m^{-1}$. Furthermore, resistances of all sludge fractions increased linearly with rising mixed liquor suspended solids (MLSS) concentration and growing trans-membrane pressure (TMP), while the relationship was inversed between fraction resistances and cross flow velocity (CFV). Among all fractions of activated sludge, suspended solid was the main contributor to the total resistance. A compact cake layer was clearly observed according to the field emission scanning electro microscopy (FE-SEM) images.

Keywords: long SRT; MBR; membrane fouling; solutes; suspended solids

1. Introduction

The membrane bioreactor reactor (MBR) process was first introduced in the late 1960s, almost the same time when commercial scale ultrafiltration (UF) and microfiltration (MF) membranes were available (Judd 2006). It combines the conventional activated sludge (CAS) process with a direct solid–liquid separation by membrane filtration. By using UF or MF membranes, MBR systems allow complete physical retention of bacterial flocs and virtually all suspended solids retained within the bioreactor, henceforth resulting in high biomass concentration up to 30 g/L (Yamamoto *et al*. 1989, Le-Clech *et al*. 2006). A higher biomass concentration would lead to a more stable reactor performance even at fluctuating organic loading conditions.

Besides, the MBR process has other advantages over conventional processes, including small footprint, easy retrofit and upgrade of old wastewater treatment plants (Judd 2006). As a result, the MBR process has now become an attractive option for the treatment and reuse of industrial and municipal wastewaters. Over the years, MBR has developed to operate with a long sludge retention time (SRT) ranging from 25 to 300 days to maintain high biomass concentrations, reduce

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http://www.techno-press.org/?journal=mwt&subpage=7 ISSN: 2005-8624 (Print), 2092-7037 (Online)

solids production and minimize reactor volume. Some studies on long SRT MBR with no sludge discharge or little sludge discharge have been reported (Muller *et al*. 1995, Rosenberger and Kraume 2002, Pollice *et al*. 2005, Liu et al. 2005, Pollice *et al*. 2004).

However, due to the limited knowledge on microorganisms' behaviour (Ross *et al*. 1998, Han *et al*. 2005, Hay *et al*. 2009), the industrial application of MBR with long SRT is restricted. More dead or inactive microorganisms were found in MBR as compared with CAS and the specific activities of nitrification, denitrification and organic removal were lower than those in the CAS processes (Han *et al*. 2005, Zhang and Yamamoto 1996, Hay *et al*. 2009). Those studies revealed that long SRT operation of MBR results in the change of microorganism compositions of the mixed liquor.

In addition, membrane fouling, which is the main cause for the decline in flux and increase in MBR operation costs, represents the main obstacle to the practical application of MBRs. It is the result of deposition of organic and inorganic materials onto and into membrane, that attributes to the interactions between activated sludge compounds and membrane. All the parameters involved in the design and procedure of MBR operation would affect membrane fouling (Le-Clech *et al*. 2006), including sludge characteristics, the composition of microbial products and etc.

Results from previous studies (Hay *et al*. 2009, Bae and Tak 2005, Sun *et al*. 2006, Bouhabila *et al*. 2001, Lee *et al*. 2003) which attempted to study the degree and characteristics of fouling caused by sludge fractions, i.e., suspended solids, colloids and solutes, were rather different from each other. Those differences arose due to the nature of the substrate, fractionation methods, membrane materials and biomass characteristics (Bouhabila *et al*. 2001). Therefore, the fouling contributions by various fractions of activated sludge of long SRT may be different from CAS, and change according to mixed liquor suspended solids (MLSS) concentration, trans-membrane pressure (TMP) and cross-flow velocity (CFV).

This study aimed to investigate the contributions of different fractions of the activated sludge from a SRT (300-day) MBR to membrane fouling and thus evaluate the effects of MLSS concentrations, TMP and CFV on the relative contributions.

2. Experimental and methods

2.1 Activated sludge and membranes

The activated sludge used in this study was taken from a submerged MBR with SRT of 300 days (Hay *et al*. 2009) and an sequential batch reactor (SBR) with SRT of 10 days. The operating conditions of MBR and SBR systems are listed in Table 1. These two bioreactors were both fed with the same synthetic wastewater based on milk powder. The feed water had pH of 6.10, and components are shown as follows: COD: 1000 mg/L, soluble COD: 813.4 mg/L, NH_4^+-N (mg/L):12.6 mg/L, NO_3^--N (mg/L): 5.64 mg/L, NO_2^- -N (mg/L): 0.8 mg/L.

MF polypropylene membranes with effective pore size of 0.2 μm (GHP-200, Pall Corporation) were employed in the cross-flow filtration experiments. The new membrane was first rinsed by letting it float in deionized water for 24 hours. Before each experiment, a filtration with deionized water was performed for 30 minutes in order to stabilize the permeate flux and operating conditions.

2.2 Experimental set up and procedure

Table 1 Operating conditions of MBR and SBR systems

Parameters	300-day MBR	10-day SBR
Working volume (L)	20	5
HRT (hr)	24	25
SRT (d)	300	10
Flux (L/m^2·hr)	5.78	
VLR (kgCOD/m^3·d)	1	1.44
Temperature (°C)	25	25

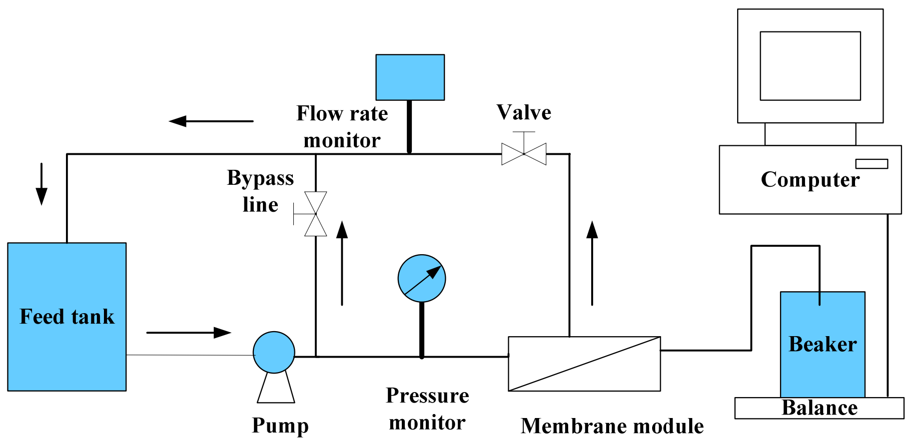

Fig. 1 Schematic diagram of crossflow membrane unit

Fig. 1 illustrates the schematic diagram of the cross-flow membrane unit, Model C10-T (Nitto Denko Co., Japan), with an effective membrane surface of 60 cm^2. The feed was pumped across the membrane module and recirculated back to the feed tank, which was placed on the magnetic stirrer to ensure homogeneity. TMP and CFV were the controlled constants separated by inlet/outlet valves. The permeate was collected by a beaker placed on a digital balance, which was connected to the computer. Both retentate and permeate were returned back to the feed tank to keep concentration constant.

During the study, TMPs were varied among 0.5, 10, 1.5 and 2 bar and the CFV were set to 0.156, 0.279 and 0.438 m/s while MLSS concentrations were adjusted to 320 mg/L, 685 mg/L and 1285 mg/L using deionized water.

2.3 Analytical methods

MLSS and mixed liquor volatile suspended solid (MLVSS) concentrations were measured based on Method 2540D and 2540E (AWWA 1998) respectively. The particle size distribution of activated sludge and its supernatant were detected using Malvern Master Sizer Model Hydro 2000S. Molecular weight distribution was measured by the HPSEC (Perkinelmer 200 with a Shodex KW 802.5 SEC column). The filed emission scanning electron microscopy (FE-SEM) imaging analysis was conducted using JEOL, JSM-6340F.

2.4 Fouling resistances analysis

According to the resistance-in-series model (Listiarini *et al*. 2009, Sun and Wu 2012), the total resistance equals to the sum of all sources of filtration resistance. It can be expressed as

$$J = \frac{\Delta p}{\mu R t} = \frac{\Delta p}{\mu(R_m + R_{cp} + R_c + R_{if})} \quad (1)$$

where R_t, R_{cp}, R_c and R_{if} are the overall filtration resistance (m^{-1}), the concentration polarization layer resistance (m^{-1}), the cake resistance (m^{-1}) resulted from the cake layer formed by the deposited particles and other solutes, and the membrane internal fouling resistance (m^{-1}) resulted from membrane plugging and/or adsorption of foulants, respectively.

Among all these resistances, R_{cp} can be removed by rinsing with deionized water; R_c can be removed by cleaning the membrane surface with sponge while R_{if} can be removed by chemical cleaning (Li *et al*. 2007). Therefore, these different resistances can be determined as follows

$$R_m = \frac{\Delta p}{\mu J_{w1}} \quad (2)$$

$$R_t = R_m + R_{cp} + R_c + R_{if} = \frac{\Delta p}{\mu J_{AS}} \quad (3)$$

$$R_m + R_c + R_{if} = \frac{\Delta p}{\mu J_{w2}} \quad (4)$$

$$R_m + R_{if} = \frac{\Delta p}{\mu J_{w3}} \quad (5)$$

where J_{w1}, J_{w2}, J_{w3} are the deionized water flux ($m^3/m^2 \cdot s$), the deionized water flux after removing the polarization layer by rinsing with deionized water ($m^3/m^2 \cdot s$) and the deionized water flux after removing the cake layer using sponge, followed by rinsing with deionized water ($m^3/m^2 \cdot s$). Then, each resistance can be calculated using equations above.

2.5 Contributions of different sludge fractions

It was assumed that the activated sludge used in this study consisted of three components, i.e., suspended solids, colloids and solutes. Any interactions among these fractions are neglected, which means that the overall resistance of the activated sludge equals to the sum of the resistances of each fraction. It can be expressed as

$$R_{AS} = R_{SS} + R_{col} + R_{sol} \quad (6)$$

where R_{AS} is the resistance of the activated sludge, R_{ss} is the resistance of the suspended solids, R_{col} is the resistance of colloids and R_{sol} is the resistance of the solutes respectively.

In order to separate these fractions from each other, a series of membrane crossflow filtration were operated. The activated sludge were centrifuged at 3000 rpm for 10 minutes to acquire the supernatant which contained only the colloids and the solutes, while the solutes were obtained by filtration of the activated sludge with 0.45 μm MF membrane (Nylon).

The resistances of each fraction can be measured from the filtrations of different feeds:

For activated sludge

$$R_{AS} = R_t - R_m = \frac{\Delta p}{\mu J_{AS}} - R_m \tag{7}$$

For supernatant contained the colloids and the solutes

$$R_{\text{sup}} = R_{col} + R_{sol} = \frac{\Delta p}{\mu J_{\text{sup}}} - R_m \tag{8}$$

For the solutes

$$R_{sol} = \frac{\Delta p}{\mu J_{sol}} - R_m \tag{9}$$

where R_t is the total resistance r (m^{-1}), R_m is the intrinsic membrane resistance (m^{-1}), R_{sup} is the resistance of supernatant (m^{-1}), ΔP is the trans-membrane pressure (Pa), μ is the viscosity of permeate ($N \cdot s/m^2$), J_{AS}, J_{sup}, and J_{sol} are the fluxes of the activated sludge, the supernatant and the solutes at steady state ($m^3/m^2 \cdot s$) respectively. R_{AS}, R_{ss}, R_{col} and R_{sol} were calculated by Eqs. (6) to (9).

3. Results and discussion

3.1 Characteristics of activated sludge from MBR and SBR

The mean particle size of the MBR activated sludge suspension was 54 μm, whereas for SBR, the mean particle size was 125 μm, relatively larger than that in the long SRT MBR. This phenomenon was confirmed by Zhang and Yamamoto (1996), who found that the size distribution of flocs were smaller in MBRs at 7 to 40 μm than 70 to 300 μm in CAS. The smaller sludge particles in the bioreactor would enhance the mass transfer for both carbon and oxygen, thus enabling the system to perform more sustainably with a higher organic removal rate.

In supernatant which was assumed to contain colloids and solutes only, the mean particle size for MBR was 30 μm. Particles larger than 60 μm were almost removed by centrifugation. On the other hand, there were two peaks of particle size for supernatant from SBR, 40 μm and 400 μm. This could possibly due to that some large particles formed by bacterial cells adhered to each other were not readily settled down and stayed floating on the surface of supernatant. Therefore, the supernatant used in this study contained some large particles called super-colloids besides the colloids and solutes. However, we still call those substances, which remained when solutes separated from the supernatant, colloids for convenience.

Results of molecular weight distributions of solutes revealed no obvious difference between the solutes from MBR and SBR, thus various membrane fouling caused by supernatant should mainly attributed to the colloids. There were mainly two peaks for both solutes, one was at 15-20 Da, while the other was around 80 Da.

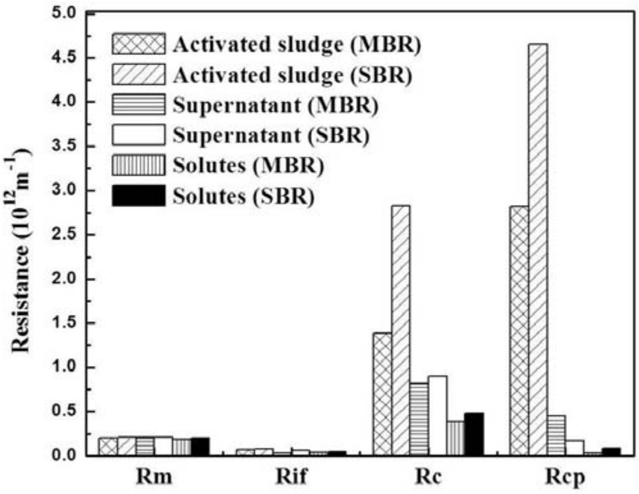

Fig. 2 Filtration resistances analysis

Table 2 Relative contributions of filtration resistances in different influents

	Activated sludge %		Supernatant %		Solutes %	
	MBR	SBR	MBR	SBR	MBR	SBR
R_{cp} / R_t	64.04	59.95	29.86	12.84	4.10	10.51
R_c / R_t	30.90	36.42	54.54	67.18	60.27	59.34
R_{if} / R_t	1.55	0.99	1.94	4.27	6.62	5.31
R_m / R_t	4.51	2.64	13.66	15.71	29.01	

3.2 Filtration resistances analysis

To have a further understanding of the fouling resistance during the membrane filtration of different influents, sub-divided resistances, i.e., R_m, R_{cp}, R_c and R_{if}, were analyzed. Fig. 2 presents the resistances of various influents. The relative contributions to the total resistance are shown in Table 2.

It appeared clearly that in both types of activated sludge from MBR with SRT of 300 days and SBR with SRT of 10 days, R_{cp} was the dominant contributor to the total filtration resistance. This coincides with the results obtained by Choi *et al*. (2005), who studied the influence of CFV on membrane performance for MF and UF membranes, that R_{cp} was dominant in all cross-flow velocities for MF. The values of R_{cp} for 300-day SRT MBR and 10-day SRT SBR were 2.82 × 10^{12} m^{-1} and 4.65 × 10^{12} m^{-1}, with 63.0% and 59.6% contributions to the total resistances respectively. On the other hand, R_c also played a remarkable role to the total filtration resistance for both MBR and SBR. The R_c values for 300-day SRT MBR and 10-day SRT SBR were 1.38 × 10^{12} m^{-1} and 2.83× 10^{12} m^{-1}, taking up 30.90% and 36.42% of the total resistances respectively. Although the MLSS concentration for these two types of activated sludge were adjusted to the same level, the particle size distributions of the two differed from each other. Large particles presented in SBR led to higher cake resistance. In addition, the contribution of internal fouling was insignificant compared with the contributions of cake layer and concentration polarization for the activated sludge from MBR and SBR. Therefore, it seemed that R_{if} was negligible. Furthermore, R_m remained constant values around 0.20×10^{12} m^{-1} as it was not affected by the characteristics of influents.

When the feed influent changed from activated sludge to supernatant and the solutes, the main contributor for filtration resistance shifted from concentration polarization to cake layer simultaneously. For the solutes, there was no significant difference between various resistances for MBR and SBR, implying the similar characteristics of soluble matters in MBR and SBR. While for the supernatant which contained colloids and solutes, the existence of higher colloids content in activated sludge from MBR with SRT of 300 days was confirmed again by the various R_{cp} values for MBR and SBR.

3.3 Influence of MLSS concentration on membrane fouling

Filtration resistances of suspended solids, colloids and solutes for all activated sludge with different MLSS concentration were calculated using Eqs. (6) to (9). Figs. 3(a_1) and (a_2) show the relationship between filtration resistances of sludge constituents and the MLSS concentration of activated sludge from MBR. R_{AS} fit well to the trend line with a high correlation coefficient of 0.9969. For individual sludge fractions, R_{ss} and R_{sol} both displayed a linear relationship with the MLSS concentration, presenting a correlation coefficient of 0.9660 and 0.9664, respectively. Unlike R_{ss} and R_{sol}, R_{col} increased firstly when the MLSS concentration increased from 320 mg/L to 685 mg/L, and then decreased slightly when the MLSS was over 1200 mg/L, resulting in a low correlation coefficient of 0.5173 of the fit line. This phenomenon might result from that during the process of separating the supernatant from activated sludge with 685 mg/L MLSS, some large particles, which should be classified into suspended solids, floated on the top of centrifugal tube and were transferred to the feed tank as part of the supernatant. Therefore, the R_{col} in the MLSS of 685 mg/L deviated from the fit line significantly.

As the slopes of the trend lines for R_{AS} and R_{ss} were 0.0022 and 0.0013 respectively, the relative contribution of suspended solids changed a little with the increase of MLSS concentration, from 69.8% to 60.4%, as shown in Fig. 3(a_2). It revealed that the suspended solids remained as the predominant fraction in membrane fouling when MLSS concentration varied between 320 mg/L and 1285 mg/L. This is in agreement with results reported by other researchers (Hay *et al*. 2009, Lee *et al*. 2003, Bae and Tak 2005).

However, it seems that colloids which mainly contributed to the formation of concentration polarization, should be the dominant fouling fraction based on the results shown in Section 3.2. This contrary result may be due to the low MLSS concentration, i.e., small amount of particles for cake layer formation. Moreover, R_{cp} is defined as a flitration resistance which can be recovered by "*rinsing*" the membrane where only the feed solution is replaced with deionized water at the same operating condition (Cheryan 1998). The "*rinsing*" may result in the derangement of the boundary layer, the increase in back-diffusion of retained materials, and the decrease in trans-membrane pressure (Bader and Veenstra 1996, Sablani *et al*. 2001).

For MBR, the higher MLSS concentration, the lower contribution of the suspended solids to membrane fouling was. Simultaneously, the significance of solutes increased along with the increasing MLSS concentration while the relative contribution of colloids first increased and then decreased slightly.

Results for SBR with SRT of 10 days are shown in Figs. 3(b_1), (b_2). For individual fractions,

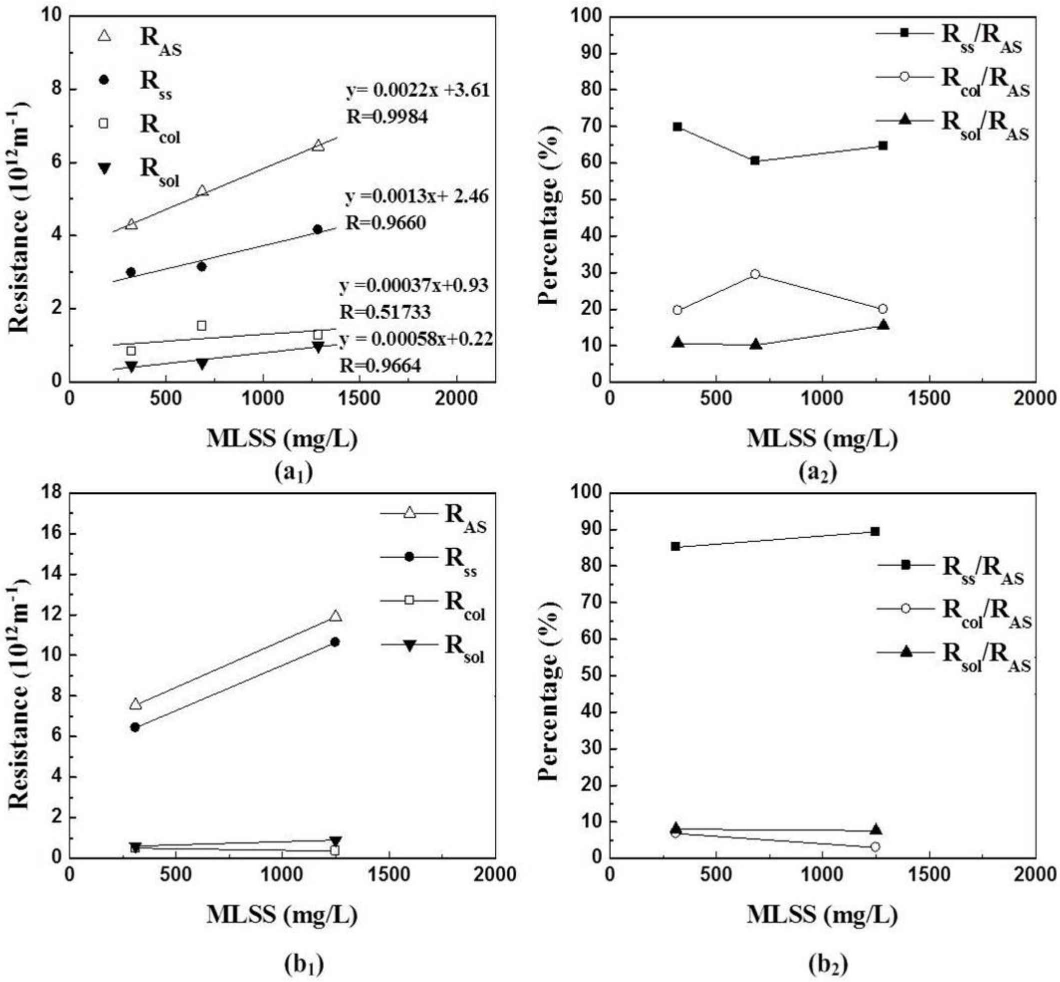

Fig. 3 Resistances of different sludge fractions according to MLSS concentration
(a_1), (a_2) MBR; (b_1), (b_2) SBR (TMP = 1 bar, CFV = 0.438 m/s)

the similar patterns of resistances were observed. As MLSS concentration increased, the resistance due to suspended solids increased rapidly while resistance of colloids and solutes increased gradually. Nevertheless, the relative contribution of suspended solids remained constant around 85.17% to 89.38%, higher than that in MBR activated sludge. Moreover, the secondary dominant fraction shifted from colloids to solutes. It can be easily explained by more colloids and solutes produced under long SRT condition (Orhon and Artan 1994) and their complete retention by the membrane. Based on recent reports, it seems that the higher MLSS concentration leads to higher fouling resistances (Chang and Kim 2005, Cicek *et al*. 1999, Achili *et al*. 2011). Furthermore, the MLSS concentration did not influence the relative contribution of sludge fractions significantly. This might be due to the small range of MLSS concentration used in this study. The fouling behaviors of sludge fractions in higher MLSS concentration should be investigated in a separate study.

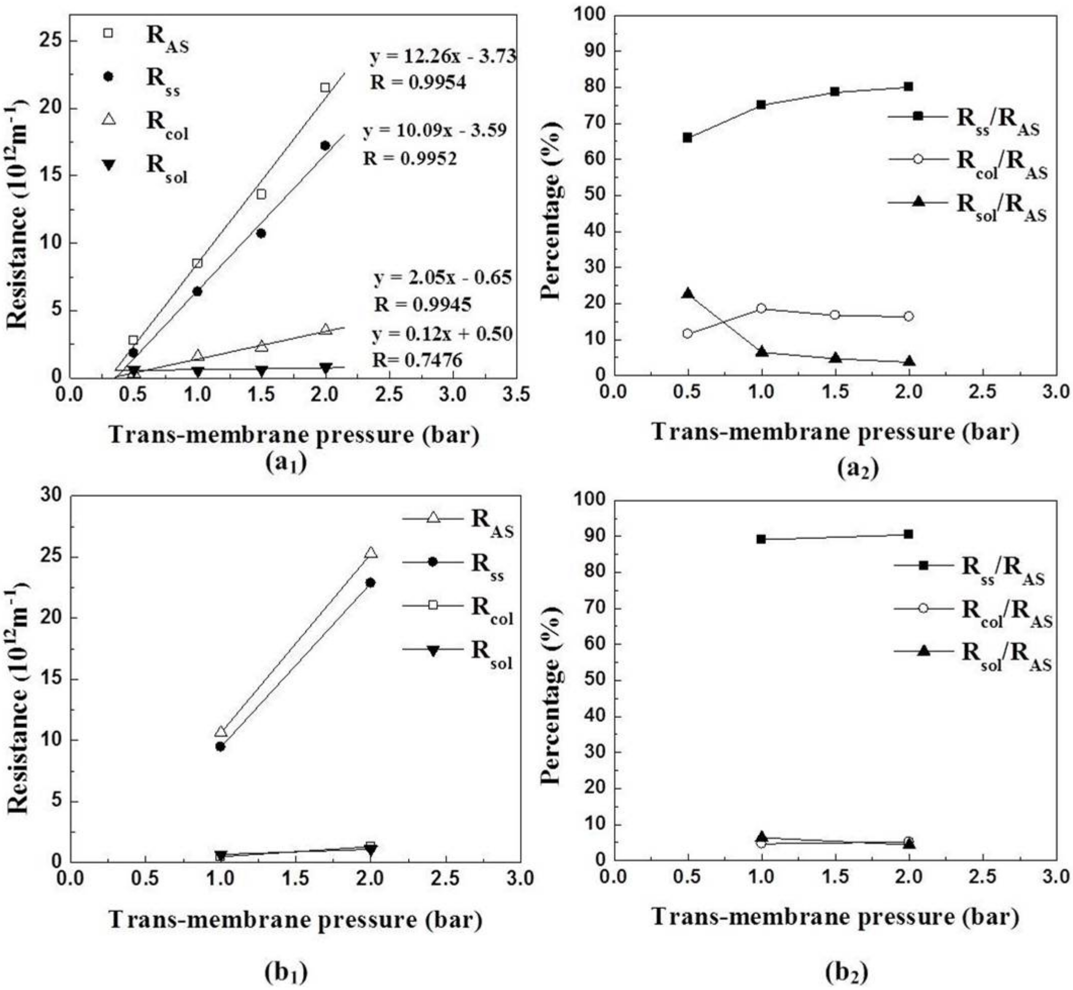

Fig. 4 Resistances of different sludge fractions according to trans-membrane pressure (a_1), (a_2) MBR; (b_1), (b_2) SBR (MLSS = 320 mg/L, CFV = 0.156 m/s)

3.4 Influence of trans-membrane pressure on membrane fouling

Fig. 3 demonstrates contributions of different sludge fractions, i.e., suspended solids, colloids and solutes, to the membrane fouling. As shown in Fig. 4(a_1), resistances of all sludge fractions were proportional to the trans-membrane pressures.

TMP is the main driving force in the cross-flow filtration of Darcy's law. Accordingly, the increase in the initial filtrate flux is proportional to the trans-membrane pressure. However, this improvement of mass transfer gives a more significant transport of foulants towards the membrane. Some solutes are readily penetrating through the porous medium and cause fouling or pass into the filtrate. Likewise, enhancement of the convective flow of particles towards the membrane, resulting from an increase in TMP, leads to the polarization and deposition of particles. As a result, R_{AS} of MBR grew linearly according to the increasing TMP from 0.5 bar to 2 bar, with a high correlation coefficient of 0.9954. Such high correlation was also observed for suspended solids and colloids: 0.9952 and 0.9945 respectively. Whereas the fitting line of R_{sol} with increasing TMP had a lower correlation coefficient of 0.7476.

Moreover, the slopes of the lines in Fig. 4(a_1) are 10.09, 2.05 and 0.12 for R_{ss}, R_{col} and R_{sol}, respectively. This implies that although the resistances of all sludge fractions were proportional to the trans-membrane pressure applied, the degree of this proportion varied among the sludge fractions. Meanwhile, the influence of trans-membrane pressure on membrane fouling increased with the particle size of foulants at the same cross-flow velocity. Therefore, regardless of trans-membrane pressure, the contribution of R_{ss} to the total resistance was higher than that of any other fraction as shown in Fig. 4(a_2). This was because that the suspended solids was the main fraction of the activated sludge and played a key role in the formation of the cake layer, with the relative contribution to the total resistance varied from 65.92% to 80.01%. Simultaneously, the relative contribution of colloids and solutes ranged from 11.53% to 18.48% and 22.55% to 3.7%, respectively.

For SBR, the predominant resistance was suspended solids as well, with the relative contribution remain around 90%. Colloids and solutes took up 5% of the total resistance respectively. Hence, it was confirmed again that the activated sludge from 300-day SRT MBR contains more colloids than that from 10-day SRT SBR.

3.5 Influence of cross-flow pressure on membrane fouling

The values of various resistances of sludge fractions from 300-day SRT MBR and 10-day SRT SBR as a function of cross-flow velocity are demonstrated in Fig. 5. CFV is a very important operating parameter for the filtration of complex solutions. Unlike MLSS concentration and trans-membrane pressure, CFV has a negative effect on membrane fouling, indicating that higher cross-flow velocity could prevent membrane fouling effectively. It appears clearly from Fig. 4 that all fraction resistances decreased with the increasing CFV. This coincided with the result observed by Choi *et al*. (2005) that the permeate flux increased linearly with increasing cross-flow velocity. Once again, the different slopes of these trend lines revealed that the cross-flow velocity influenced fractions to various degrees. Suspended solids were most influenced by cross-flow velocity, i.e., R_{ss} was reduced the most steeply. Furthermore, the decrease of R_{AS} was mainly caused by the variation of R_{ss}. Colloids and solutes linearly decreased with relatively low correlation coefficient of 0.6645 and 0.4364 respectively. This low correlation implies fluctuation of resistances analysis.

According to the study conducted by Bae and Tak (2005), all sludge fractions during the cross-flow filtration are influenced by drag force and the back transport. The drag force increased with operation flux, TMP and particle size. For back transport velocity, it is complex to predict its effect. It is considered to consist of Brownian diffusion, inertial lift and shear-induced diffusion (Belfort *et al*. 1994). All forces except for Brownian diffusion, which are generated by cross flow, tend to increase with cross-flow velocity and particle size, while Brownian diffusion had an inverse relationship with particle size. Nevertheless, the influence of Brownian diffusion is extremely small because the activated sludge contains huge amount of large flocs and small amount of solutes. Hence, the back transport velocity increases with particle size. Therefore, the fraction of the largest size, i.e., suspended solids, were most influenced by cross-flow velocity. As a result, fouling control for suspended solids appears to be simpler than for other fractions.

From results shown in Fig. 5(a_2), it was clear that suspended solids remained the main

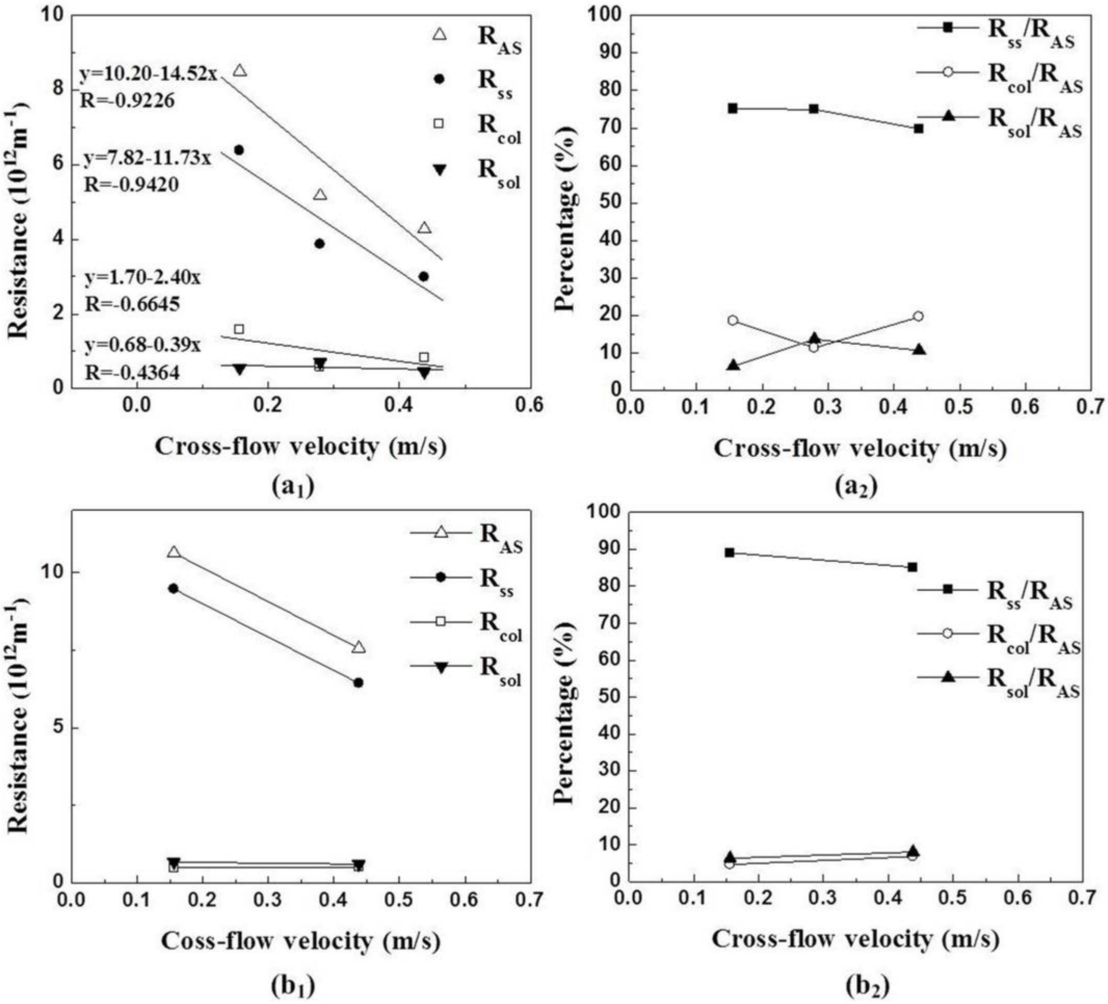

Fig. 5 Resistances of different sludge fractions according to cross-flow velocity
(a_1), (a_2) MBR; (b_1), (b_2) SBR (MLSS = 320 mg/L, TMP = 1 bar)

contributor to membrane fouling though the values of R_{ss} changed significantly. The relative contribution of R_{ss} varied between 69.77% and 75.06%. Simultaneously, the relative contributions of colloids and solutes changed in the range of 11.37 to 19.57% and 6.46 to 10.66%, respectively.

Likewise, the same fouling phenomena were observed in the filtration of sludge fractions from SBR. R_{AS} and R_{ss} both decreased significantly with the increasing cross-flow velocity, while R_{col} and R_{sol} were not affected by cross-flow velocity significantly. Furthermore, the relative contributions of R_{ss}, R_{col} and R_{sol} stayed around 86%, 5% and 9% respectively. It seems that the variation of cross-flow velocity between 0.156-0.438 m/s do not change the relative contributions of sludge fractions though the values of resistances decreased significantly according to cross-flow velocity.

3.6 FE-SEM imaging

Observation of fouled membrane was also conducted using FE-SEM. Fig. 6 presents the FE-SEM images of fouled membranes at different operation stages. From these images, a compact cake layer, consisted of all these sludge fraction: suspended solids, colloids and solutes, was clearly observed in Figs. 6(a) and (b). The existence of biomass was demonstrated obviously in Fig. 6(a). No other obvious differences between the cake layer of MBR and SBR can be detected barely using FE-SEM. Fig. 6(c), a cross-sectional image of the fouled membrane by activated sludge from MBR, gives more detailed information about the cake layer. According to the scale at the top right corner, the thickness of cake layer was estimated to be around 4 to 6 μm. However, accurate results could not be obtained due to the limitation of the equipment and the pretreatment of membrane samples. Therefore, the observation of membrane morphology could be a possible direction for the future study.

On the other hand, the physical cleaning seemed to be able to remove the cake layer. Simultaneously, the pore size was reduced compared with the new membrane, demonstrating the internal fouling.

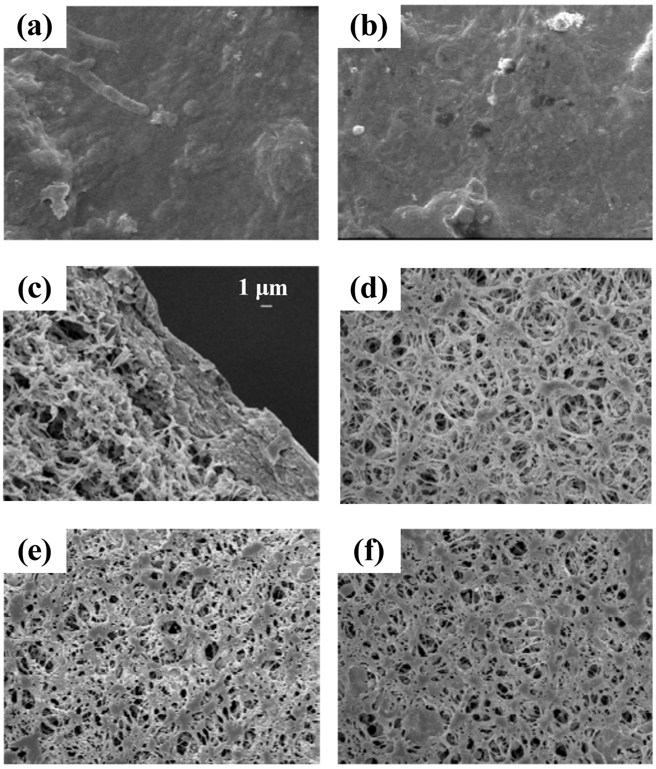

Fig. 6 Images of membrane morphology: (a) Fouled membrane (MBR, 8000×); (b) Fouled membrane (SBR, 8000×); (c) Fouled membrane (MBR, cross section, 4500×); (d) New membrane (4000×); (e) Fouled membrane after physical cleaning (MBR, 4000×); (f) Fouled membrane after physical cleaning (SBR, 4000×)
(MLSS = 320 mg/L, TMP = 1 bar, CFV = 0.438 m/s)

4. Conclusions

For MBR with SRT of 300 days, the mean particle size of activated sludge was 54 μm, relatively smaller than that for SBR with SRT of 10 days. For supernatant, larger particles were also observed for SBR compared with MBR. However there was no obvious difference between the two types of solutes.

For the MF membrane used in the MBR system, it was found that, R_{cp} was dominant resistance during the filtration of activated sludge, contributed 63.0% and 59.6% to the total resistance for MBR and SBR respectively. The cake resistance, R_c played the significant role during the filtration of supernatant and solutes, varied between 54.54% and 67.18%. Compared with them, the internal fouling, R_{if} was negligible, and membrane resistance, R_m remained constant values around 0.20 x 10^{12} m^{-1} because it was not affected by the characteristics of influents.

Resistances of all sludge fractions increased linearly with rising MLSS concentration and growing TMP, while the relationship was inversed between fraction resistances and CFV. Among all fractions of activated sludge, suspended solid was the main contributor to the total resistance. A compact cake layer, consisted of all these sludge fraction: suspended solids, colloids and solutes, was clearly observed and examined with FE-SEM images. The physical cleaning was able to remove the cake layer completely.

Acknowledgements

This work was supported by School of Civil and Environmental Engineering, Nanyang Technological University (NTU) of Singapore. Scholarship for Miss Shushu Liu was funded by the NTU.

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RJ

Notation

R_t	=	Overall filtration resistance (m^{-1})
R_{cp}	=	concentration polarization layer resistance (m^{-1})
R_c	=	the cake resistance (m^{-1})
R_{if}	=	internal fouling resistance (m^{-1})
R_m	=	Membrane resistance (m^{-1})
ΔP	=	Trans-membrane pressure gradient (Pa)
J_{w1}	=	deionized water flux($m^3/m^2 \cdot s$)
J_{w2}	=	deionized water flux after removing the polarization layer by rinsing with deionized water($m^3/m^2 \cdot s$)
J_{w3}	=	deionized water flux after removing the cake layer using sponge, followed by rinsing with deionized water($m^3/m^2 \cdot s$)
R_{AS}	=	resistance of the activated sludge (m^{-1})
R_{ss}	=	resistance of the suspended solids (m^{-1})
R_{col}	=	resistance of colloids (m^{-1})
R_{sol}	=	resistance of the solutes (m^{-1})
R_{sup}	=	resistance of supernatant (m^{-1})
μ	=	viscosity of permeate ($N \cdot s/m^2$)
$J_{AS,}$	=	flux of the activated sludge ($m^3/m^2 \cdot s$)
J_{sup}	=	Flux of the supernatant ($m^3/m^2 \cdot s$)
J_{sol}	=	Flux of the solutes ($m^3/m^2 \cdot s$)