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Effect of on-line ultrasound on the properties of activated sludge mixed liquor and the controlling of membrane fouling in SMBR

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ABSTRACT

Membrane fouling is one of the major obstacles for further application of submerged membrane bioreactors (SMBRs). In this study, a bi-frequency on-line ultrasound of 25 kHz and 50 kHz was applied to a laboratory-scale SMBR (SMBR-US) to investigate the alleviating of membrane fouling by ultrasound. Experiments were also carried out in another laboratory-scale SMBR without ultrasound (SMBR-Control). The properties of the activated sludge including mixed liquor suspended solids (MLSS), particle size distribution, viscosity, extracellular polymeric substances (EPS) contents and the total organic carbon (TOC) in supernatant were analyzed. The membrane filtration resistance was then calculated to identify the membrane fouling type in two reactors. During the experiment period, the transmembrane pressure of SMBR-Control system increased very fast compared with the SMBR-US system, indicating a significant mitigating of membrane fouling with on-line ultrasound. The MLSS concentration and mean particle size in SMBR-US system was apparently lower than that of SMBR-Control system, which deduced that the ultrasound can reduce extra sludge production and disintegrate activated sludge flocs in reactors. The mixed liquor viscosity in SMBR-US was consistently lower than that of SMBR-Control system. The MLSS and supernatant TOC played a significant role in membrane filtration of SMBR-Control system, while viscosity had an apparent relationship with the filtration resistance in SMBR-US system. The total membrane filtration resistance in SMBR-US was of 51.85% lower than that of SMBR-Control after 35 days operation, which confirms that the ultrasound has a positive effect on mitigating membrane fouling. The membrane filtration resistance caused by blocking cake layers accounted for 86.63% of the total resistance in SMBR-US system, indicating that the blocking cake layer was the main reason for membrane fouling in SMBR-US system. The resistance caused by blocking cake layers and membrane pore blocks were all relatively high in SMBR-Control system, accounting for 59.26 and 38.18% of the total resistance, respectively, suggesting a higher irreversible membrane pollution in SMBR-Control system.

Keywords: Submerged membrane bioreactor; On-line ultrasound; Filtration resistance; Membrane fouling

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1. Introduction

Membrane bioreactors (MBRs) have been actively employed for municipal and industrial wastewater treatment for many years. MBRs can operate at a higher mixed liquor suspended solid (MLSS) concentration, which leads to a smaller reactor volume needed to treat the same wastewater [1]. However, membrane fouling is still a major obstacle for wider applications of MBRs. Traditionally, three factors are thought to affect membrane fouling, and they are membrane materials, sludge characteristics and operation conditions [2]. The complex interactions between these aspects complicate the understanding of membrane fouling.

In the case of submerged membrane bioreactors (SMBRs), membrane fouling is mainly caused by the sludge cake formation on membrane surface [3,4] and/or the feed water constituents in the membrane matrix (pore blocking and/or adsorption) [5,6]. During filtration, dissolved organic matter (DOM) compounds are adsorbed onto and/or into the membrane, tending to block membrane pores, and forming a partly irreversible gel structure on the membrane surface. Moreover, DOMs tend to provide an excellent base layer for the attachment of bacteria and they also serve as a possible nutrient source for attached bacteria growth and biocake formation [7]. Recently, the influence of Soluble Microbial Product (SMP) on MBR fouling has attracted much attention. Moreover, a direct relationship has been suggested that SMP in MBRs impacts membrane fouling significantly [8,9]. The concentration and composition of SMP would affect MBRs' fouling propensity [10]. However, different results have also been reported that SMP influence fouling only under certain conditions such as low sludge age and large pore size [8]. Another organic fraction that have been reported as key membrane foulants in MBRs is the Extracellular Polymeric Substances (EPS) of the biomass flocs that are composed of polysaccharide, protein, humic substances, uronic acid, and deoxyribonucleic acids [11–13]. More recently, a functional relationship between specific resistance, mixed liquor volatile suspended solid (MLVSS), transmembrane pressure (TMP), permeate viscosity and EPS was obtained by dimensional analysis [14]. EPS was found to have no effect on the specific resistance below 20 mg EPS/g MLVSS and above 80 mg EPS/g MLVSS but played a significant role on MBR membrane fouling between these two limits [15,16].

A number of studies for the control of membrane fouling have been undertaken, such as the improvement of membrane parameters [17–19], the adjustment of sludge characteristics [20–22], and the optimization of operational conditions including aeration, crossflow velocity, solid retention time, sustainable flux, backwashing, cleaning, etc. [23–28]. Ultrasonic technique provides an alternative method for membrane fouling control and cleaning. Ultrasound is a pressure wave that propagates through a medium with a vast amount of energy dissipation. The basic physical phenomenon behind the effect of ultrasound is cavitation, that is, the formation, growth and implosive collapse of bubbles in the liquid. Cavitation bubbles are formed when the pressure amplitude exceeds the tensile strength of liquid during the spread of sound waves. The cavitation bubble collapses with the compression cycle of sound waves. An average temperature of 4,200 K will be reached around the cavitation bubbles and the maximum temperature in the core area of bubbles might be of 17,000 K with a high pressure of 500 atm [29–31]. Further, the asymmetrically oscillation of cavitating bubbles near a solid surface will result in the generation of high velocity microjets or microstreams. Fluid flowing at these high velocities can decrease the thickness of boundary layers and diffusional resistance and therefore enhance the rates of mass transfer [32]. Dong Chen et al. [33] reported that ultrasound reduced ceramic membrane fouling at higher silica particle concentrations (≥ 0.8 g/L), the particle concentration effect was more pronounced when the membrane was close to the cavitation region. Lim and Bai [28] found using ultrasonic to clean membrane fouling in aerobic MBR, combined with water backwashing, could effectively remove the cake layer from membrane surfaces and achieve the best cleaning result [34].

Based on the above review, it is found that most research efforts have focused on enhancing membrane permeability and cleaning membrane fouling. Little attention has been paid to on-line controlling of membrane fouling. This study emphasized the influence of on-line ultrasound on the characteristics of activated sludge mixed liquor comparing with that in ordinary SMBR system. We also investigated the main factors giving rise to the membrane fouling and how ultrasound controls membrane fouling under the operation conditions.

2. Materials and methods

2.1. Membrane bioreactors

In order to identify the impact of on-line ultrasound on the properties of activated sludge mixed liquor in a SMBR system, a bi-frequency on-line ultrasound of 25 kHz and 50 kHz was applied to a laboratory-scale SMBR treating synthetic domestic wastewater, meanwhile an additional SMBR with the same structure and volume but without ultrasound was used as a control (SMBR-Control) (Fig. 1).

The working volume of each SMBR was 20L, and a curtain hollow fiber membrane module made of polypropylene (Kaihong Membrane Technology Co., China) with a filtration area of $0.2\,m^2$ and a pore size of 0.4 μm was submerged in each SMBR. Within the two reactors there were filled by suspended-carriers which were made by rubber powder, active carbon and adhesive and with a diameter of around 5 mm and the carrier dose in this study was 10% (carrier volume versus total effective volume of SMBR). To maintain the water levels of the SMBRs, dual head peristaltic pumps and liquid level controller were used to feed influents as well as to obtain effluents. Activated sludge taken from a sewage treatment plant's secondary sedimentation tank was used as seeding sludge for the experiment.

2.2. Operating conditions

The initial flux of both SMBR was set to 1.5 L/h, which was under the critical flux according to the previous study, and the air flow is $0.5\,m^3/h$. The power of the ultrasound generator (JXDP-06, JinXing Co. China) kept at 300 W with a mixed frequency of 25 kHz and 50 kHz, the ultrasound lasting time and the time interval was 3 min and 12 h.

2.3. Experimental water

The COD, BOD_5 and NH^{4+}-N of the synthetic domestic wastewater used in this study were occasionally measured and kept at 300–600, 160–300, and 30–50 mg/L, respectively. The average COD was 430 mg/L. Table 1 shows the inorganic metal ion composition of the synthetic wastewater solution.

2.4. Analysis items and methods

MLSS, MLVSS and the conventional water quality monitoring indicators were measured in accordance with standard methods. CTL-12 (Chengde, Huatong Co.) was adopted to measure COD. Particle size distributions of the sludge in SMBRs were measured using a laser light scattering method (Mastersizer, Malvern Co., UK). The apparent viscosity was determined using a rotational viscosity meter (DV-III Ultra Programmable Rheometer, Brookfield).

The extraction of EPS was performed according to the formaldehyde−NaOH method reported by Zhang Bin [35]. The extracted EPS was analyzed in terms of the level of total organic carbon (TOC) concentration relative to the amount of biomass.

The filterability of the activated sludge mixed liquor was estimated by filtration experiment. 20 L mixed liquor sample and a PP microfiltration membrane with a pore size of 0.4 μm and a total membrane

Table 1
Inorganic composition of feed solution

Element	Reagent	M.W.	Reagent (mg/L)	Element concentration (mg/L)
Na	$NaHCO_3$	84.01	75	20.54
K	KH_2PO_4	136.09	25	7.16
Fe	$FeCl_2$	126.75	3	1.32
Ca	$CaCl_2$	110.98	6	2.16

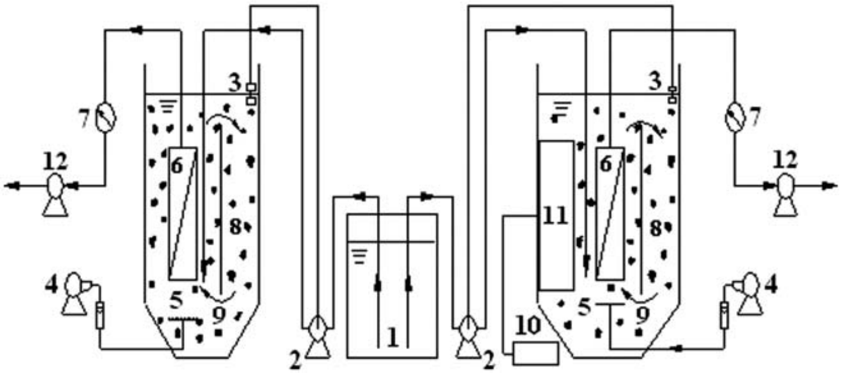

Fig. 1. A schematic diagram of experimental devices. (1) Feed reservoir; (2) Inlet pump; (3) Level controller; (4) Outlet pump; (5) Perforation aeration tube; (6) Membrane module; (7) Pressure gauge; (8) Filler carriers; (9) Cycle baffle; (10) Ultrasound generator and adjustor; (11) Ultrasound transmitter.

surface area of 0.02 m^2 were used in the filtration experiment. In the filtration process, the TMP and the flux of the membrane were recorded every 1 min for 20 min. The filtration resistance R_f was quantified by the Darcy law:

$$R_f = (\Delta P/\mu J) - R_m$$

where $R_f[L^{-1}]$ is the filtration resistance of mixed liquor, $\Delta P[L^{-1}MT^{-2}]$ is the TMP, $\mu[L^{-1}MT^{-1}]$ is the viscosity of mixed liquor at 20℃, J $[LT^{-1}]$ is the instantaneous permeate flux and $R_m[L^{-1}]$ is the initial membrane resistance.

3. Results and discussion

3.1. Effect of on-line ultrasound on TMP

Because of constant effluent flow as the operating mode, the membrane fouling is marked by the change of TMP. The higher the TMP, the more serious membrane fouling was. The TMP of SMBR-US increased with time and reached 28 KPa at day 39 while the TMP of SMBR-Control reached 44 kPa at day 33 as shown in Fig. 2. After that, both membrane modules were washed by chemical cleaning. The growth of TMP in SMBR-Control kept at a higher ascent rate than SMBR-US and it had a significant increase after day 29. Cho and Fane [36] stated that the slow rise of TMP in the initial running stage was mainly caused by the supernatant organic matter accumulated on the membrane surface, and then the sharp rise of TMP owed to the deposition of suspended sludge flocs. The presence of ultrasound slowed down the growth rate of TMP during the experiment and prolonged the operation cycle. This could be attributed to the acoustic streaming and ultrasonically generated turbulence which reduced the concentration polarization and obstructed the adhesion of supernatant organic matter on the membrane surface [37,38]. As a result, ultrasound effectively delayed the membrane fouling in SMBR-US system.

3.2. Effect of on-line ultrasound on MLSS

From Fig. 3, we can note that the MLSS in both SMBR systems had a growth tendency. The MLSS of SMBR-US system increased from 3,774 mg/L to 5,571 mg/L over 40 days operation, while the MLSS of SMBR-Control system increased from 3,421 mg/L to 6,910 mg/L, showing a higher concentration at the end of the operational period. The slower growth of sludge concentration in SMBR-US might be owed to the disruption of microbial cells by ultrasound. The break-up of microbial cell walls leads to a decreasing of MLSS concentration and a potential release of intracellular organic compounds into the sludge water phase [39]. Other researchers reported similar results [40]. It also can be deduced that the ultrasound can reduce extra sludge production in a long-term experiment.

3.3. Effect of on-line ultrasound on the properties of activated sludge mixed liquor

The properties of activated sludge mixed liquor of two systems were analyzed. Fig. 4 shows the volume average particle size of SMBR-Control changed from 125.41 to 164.22 μm during the operation period. Compared to SMBR-Control, the volume average particle size of SMBR-US had an obvious diminution from 146.34 to 90.05 μm at the beginning period then it had a slight fluctuation over 20 days. Ultrasound is well known to disintegrate sludge flocs and disrupt

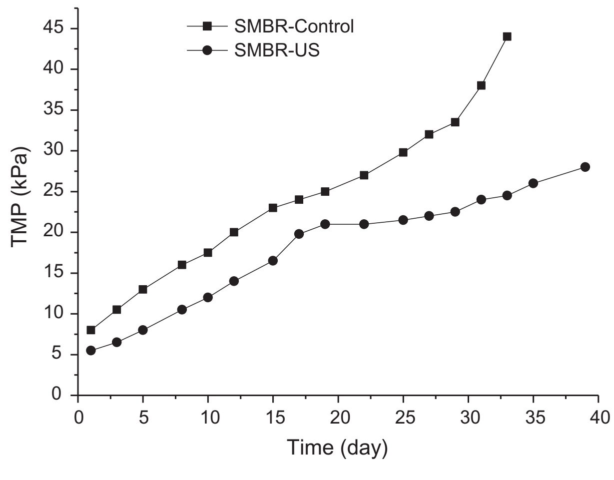

Fig. 2. Effect of on-line ultrasound on TMP.

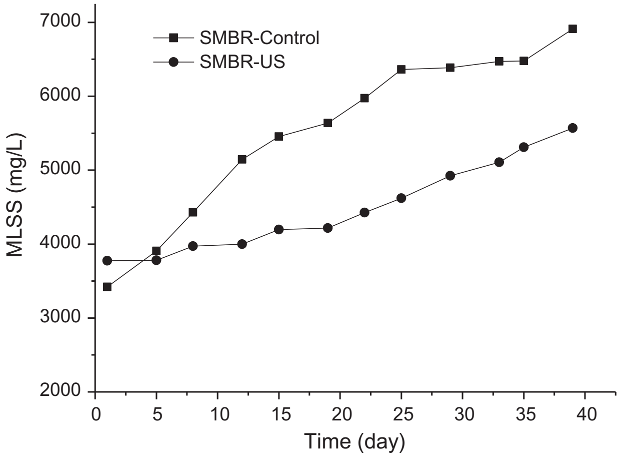

Fig. 3. The increase of MLSS in SMBR-US and SMBR-Control.

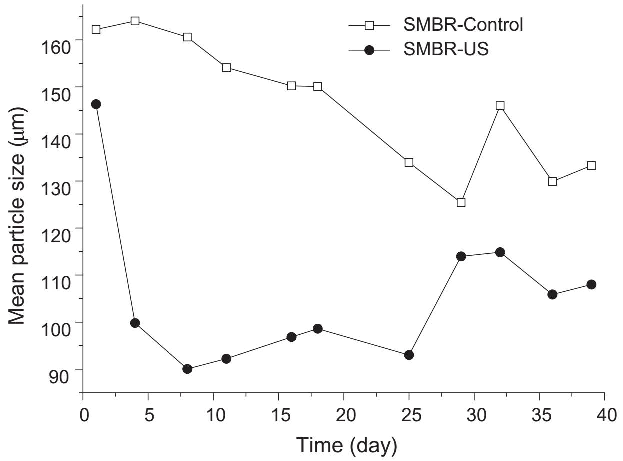

Fig. 4. Change of average particle size with time.

microbial cell walls, and it causes the release of soluble substances [41]. As a result, the mean particle size of SMBR-US was obviously less than SMBR-Control. The re-increase of volume average particle size in SMBR-US after 25 days might due to the increase of MLSS concentration and mixed liquor viscosity.

The content of EPS in SMBRs was characterized in terms of its TOC concentration. It can be seen from Fig. 5, EPS decreased from 187.64 to 87.91 mg/g SS and 164.68 to 82.68 mg/g SS in SMBR-Control and SMBR-US systems, respectively. Then, EPS increased slightly in both reactors. The decreases of EPS concentration in both SMBR in the initial stage may be caused by the low level of MLSS concentration. It gradually improved along with the increase of MLSS concentration. Since the EPS matrix plays an important role in the hydrophobic interactions among microbial cells and thus in the floc formation [42], it was proposed that a decrease in EPS level may cause floc deterioration. The relationships between mean particle sizes of flocs and EPS concentrations were depicted in Fig. 6(a) and Fig. 6(b). It can be seen that EPS concentration has a positive relationship with the mean particle size of flocs in both SMBR-Control and SMBR-US systems ($R = 0.638$ and 0.591, respectively). It implies that EPS is one of the main factors that decide the changing of particle sizes of flocs.

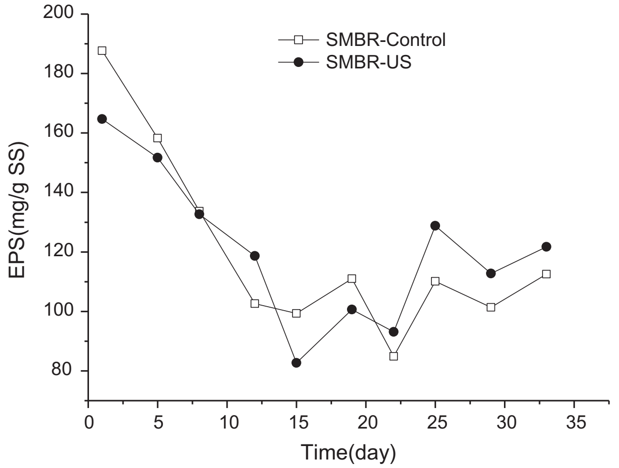

Fig. 5. Effect of on-line ultrasound on EPS.

Viscosity analysis results were shown in Fig. 7. The viscosity of mixed liquor of SMBR-Control system increased from 3.94 mPa s to 11.56 mPa s over the operation period. The viscosity of SMBR-US was a little bit higher than that in SMBR-Control system and it changed from 5.32 to 11.63 mPa s. Many factors can affect the viscosity, such as MLSS, temperature and EPS concentration. It has been reported that in SMBR, EPS accumulated both in the mixed liquor and on the membrane, which might have caused an increase in the viscosity of the mixed liquor [43]. The viscosity of

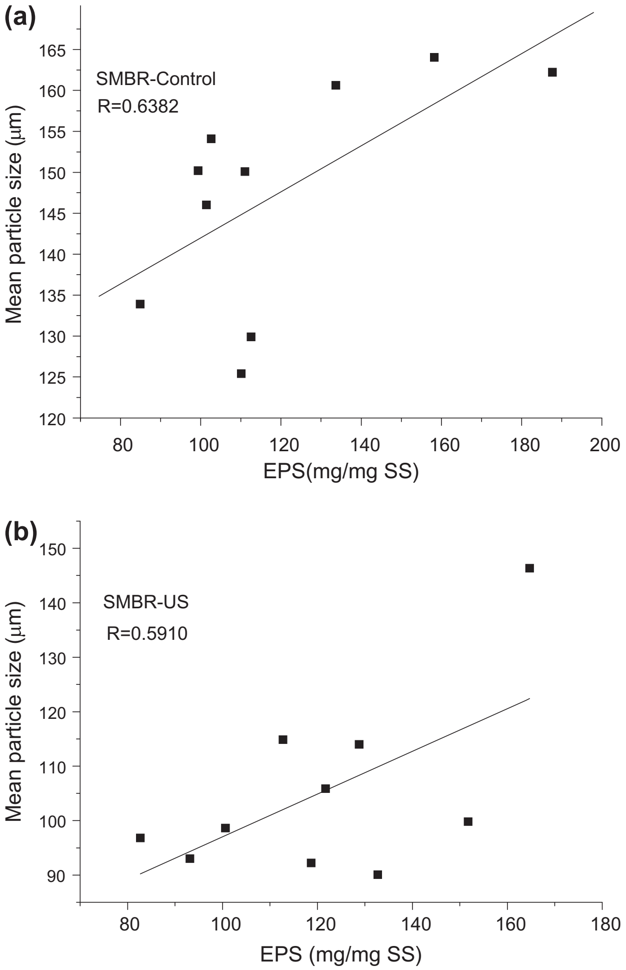

Fig. 6. Relationship between EPS concentrations and mean particle sizes of mixed liquor.

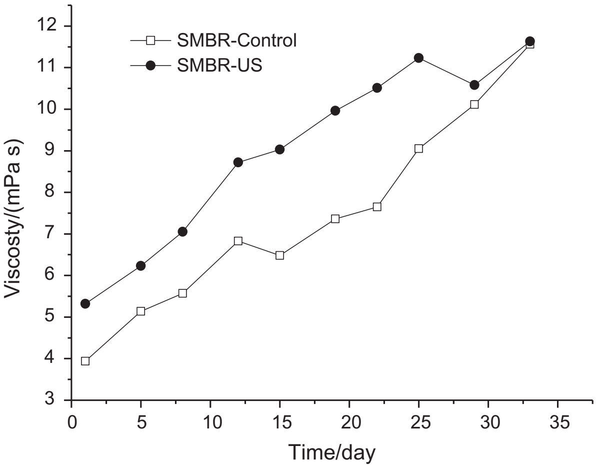

Fig. 7. Change of viscosity of activated sludge mixed liquor with running time.

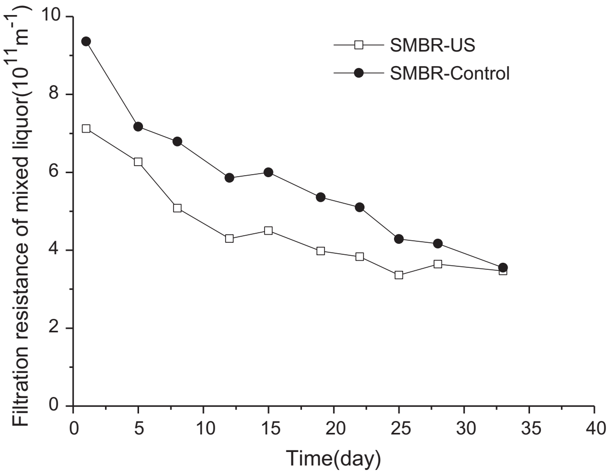

Fig. 8. Effect of on-line ultrasound on membrane filterability of mixed liquor.

mixed liquor in both SMBRs showed the similar growth trend with the MLSS concentration.

3.4. Relationship between mixed liquor properties and sludge filterability

The filtration resistance of mixed sludge liquor was measured by the filtration experiment as an indicator of the membrane filterability of the activated sludge mixed liquor and the fouling propensity of the mixed liquor. Higher filtration resistance indicates poorer membrane filterability of the mixed liquor. From Fig. 8, we can see that the filtration resistance in both SMBR systems has a downward tendency. Over the whole operation, the filterability of the mixed liquor in SMBR-US was significantly better than that in SMBR-Control. The filtration resistance reduced from 7.12 to $3.47 \times 10^{11}\,\mathrm{m}^{-1}$ in SMBR-US, while the resistance of mixed liquor changed from 9.36 to $3.55 \times 10^{11}\mathrm{m}^{-1}$ in SMBR-Control system over the operation time. It can be noted that applied ultrasound to the SMBR system can improve the membrane filterability of mixed sludge liquor.

As the calculation formula of the filtration resistance mentioned previously, the filtration resistance was proportional to the TMP and inversely proportional to the amount of water production and viscosity of the mixed sludge liquor. In the filtration experiment, the constant outflow mode of outlet pump leads to a roughly equal water production in the same period of time, and therefore, the filtration resistance was mainly determined by TMP and viscosity of the mixed sludge liquor. In our experiment, TMP after 33 days were 1.13 and 1.16 times of the initial TMP in SMBR-Control and SMBR-US system, respectively. Meanwhile, the viscosity of the mixed sludge liquor increased to 3.94 and 5.32 times of the initial viscosity. The viscosity grew faster than TMP, as a result there was a gradual decline of filtration resistance. From Fig. 8, we can see that R_f in SMBR-US was lower than SMBR-Control over the experiment, which indicated ultrasound improve the filterability of the mixed liquor sludge.

Univariate linear correlations (Pearson correlations and partial correlations) were employed to investigate the relationships between the filterability and other properties of the mixed liquor. Pearson correlations indicate the apparent correlations between two variables, while partial correlations indicate the independent correlations between two variables under the condition that other variables are kept invariable [44].

For Pearson correlation analyses, the correlationship between the properties and membrane filterability of the mixed liquor sludge was defined as significant at $p < 0.01$ (Table 2). In our Pearson analyses, R_f had a significant negative correlation with MLSS and viscosity ($R = -0.967$ and -0.945) in SMBR-Control. Lee et al. [45] reported that high MLSS concentration allowed for better filtration performance because a thick cake of MLSS formed and trapped supernatant organic matter, preventing it from attaching on the membrane directly. In our study the membrane filterability of mixed liquor get better while the concentration of MLSS grows in both SMBR system which indicated that the increase in MLSS concentration improve membrane filterability even at a low MLSS concentration. This may related to other factors such as viscosity, EPS and particle size et al. From Table 2, it can be concluded that the filtration resistance increased with the increasing mean floc diameter

Table 2
Results of Pearson and Partial correlation analyses between the mixed liquor properties and filterability of the mixed liquor in SMBR-Control

Properties	Pearson correlation		Partial correlation	
	R	p	R'	p'
MLSS ($mg\,L^{-1}$)	−0.967	0.000*	−0.795	0.059*
Viscosity (mPa s)	−0.945	0.000*	−0.781	0.067
Mean diameter (μm)	0.817	0.004*	−0.156	0.769
EPS content (mg TOC/mg SS)	0.818	0.004*	−0.594	0.308
SMP ($mg\,L^{-1}$)	0.592	0.071	0.927	0.008*

Table 3
Results of Pearson and Partial correlation analyses between the mixed liquor properties and filtration resistance of the mixed liquor in SMBR-US

Properties	Pearson correlation		Partial correlation	
	R	p	R'	p'
MLSS ($mg\,L^{-1}$)	−0.806	0.005*	0.098	0.854
Viscosity (mPa s)	−0.966	0.000*	−0.864	0.026*
Mean diameter (μm)	0.445	0.197	0.601	0.207
EPS content (mg TOC/mg SS)	0.709	0.022	−0.080	0.880
SMP (mgL^{-1})	0.498	0.143	−0.239	0.649

and EPS content ($R = 0.817$ and 0.818). As we discussed earlier, the mean floc diameter and EPS content had some positive correlations, for this reason their influences on the filterability of the mixed liquor sludge were similar.

In partial correlation analyses, correlations between a mixed liquor property and filtration resistance of the mixed liquor sludge after excluding all other properties' effects were defined as significant at $p' < 0.05$. When all other properties' effects were excluded, the correlation between MLSS and filtration resistance still existed ($R' = -0.795$, $p' = 0.059$) and SMP was significantly correlated with R_f ($R' = 0.927$, $p' = 0.008$), which implied that the influence of SMP on R_f was covered by other factors especially those negative factors like MLSS and viscosity in Pearson correlation analyses. The independent effect of SMP on R_f appeared after all other factors excluded. On the contrary, the independent effect of mean floc diameter and EPS content on R_f disappeared in partial correlation analyses, suggesting that these two factors had no independent relationship with filterability of the mixed liquor sludge, although they showed a significant correlation with filterability in Pearson correlation analyses.

The SMP was the major influencing factor for membrane filterability of the mixed liquor in SMBR-Control in the partial analyses. Based on the actual case, the decrease of SMP caused the improvement of membrane filterability of the mixed liquor for the first 15 days. After that, the SMP had an accumulation in reactors, so the effect of SMP on filtration resistance got weakened.

As shown in Table 3, the Pearson correlation analyses indicated that MLSS and viscosity had a significant negative correlation with the filterability of the mixed liquor sludge in SMBR-US ($R = -0.806$ and -0.966). Compared with SMBR-Control, the correlation of mean diameter and EPS content with R_f diminished. From Table 3, we can also see that only viscosity remained high correlation with R_f ($R' = -0.864$, $p' < 0.05$) independently, indicating that viscosity was the main factor affecting the filterability of the mixed liquor in SMBR-US.

3.5. Analysis of membrane fouling type

Concerning the volume average particle sizes of sludge mixed liquor in both SMBR systems were far greater than the mean diameter of membrane pores, we can confer that particulate matter is not a major factor to the membrane fouling but the blocking cake layer.

The membrane flux was measured after membrane fouling, water cleaning and chemical cleaning, respectively. According to the Darcy Law, the resistance of membrane caused by the membrane itself, blocking cake layer and membrane pore block can be calculated by the following formula:

$$R_m = \frac{\Delta P}{\mu_0 J_0}$$

$$R = \frac{\Delta P}{\mu J_1} = R_m + R_c + R_f$$

$$R_f = \frac{\Delta P}{\mu_0 J_2} - R_m$$

$$R_c = R_t - \frac{\Delta P}{\mu_0 J_2}$$

where R_m is the resistance of membrane itself; R is the total resistance of a fouled membrane module; R_c is the resistance caused by blocking cake layers; R_p is the resistance caused by membrane pore block; ΔP is TMP; μ is viscosity of water; J_0 is flux before membrane fouling; J_1 is flux after membrane fouling; J_2 is flux after water cleaning.

Table 4
Membrane fouling type and percentage of the total resistance of membrane

	Membrane in SMBR-US		Membrane in SMBR-Control	
Item	Resistance ($10^{12}\,\mathrm{m}^{-1}$)	Percentage of R_t	Resistance ($10^{12}\,\mathrm{m}^{-1}$)	Percentage of R_t
R_t	17.20		35.10	
R_m	0.55	3.02%	0.87	2.48%
R_c	14.90	86.63%	20.80	59.26%
R_p	2.34	13.60%	13.40	38.18%

The results are shown in Table 4. The total resistance of a fouled membrane module of SMBR-US was 51.85% smaller than that of SMBR-Control, which indicated that ultrasound played a significant role in controlling membrane fouling. It also can be noted that the resistance of blocking cake layer in SMBR-US was 86.63% of the total resistance, which confirms our previous inference that blocking cake layer was the most important factor to membrane fouling in SMBR-US. The main membrane fouling type in SMBR-Control was also blocking cake layer and the resistance caused by blocking cake layer accounted for

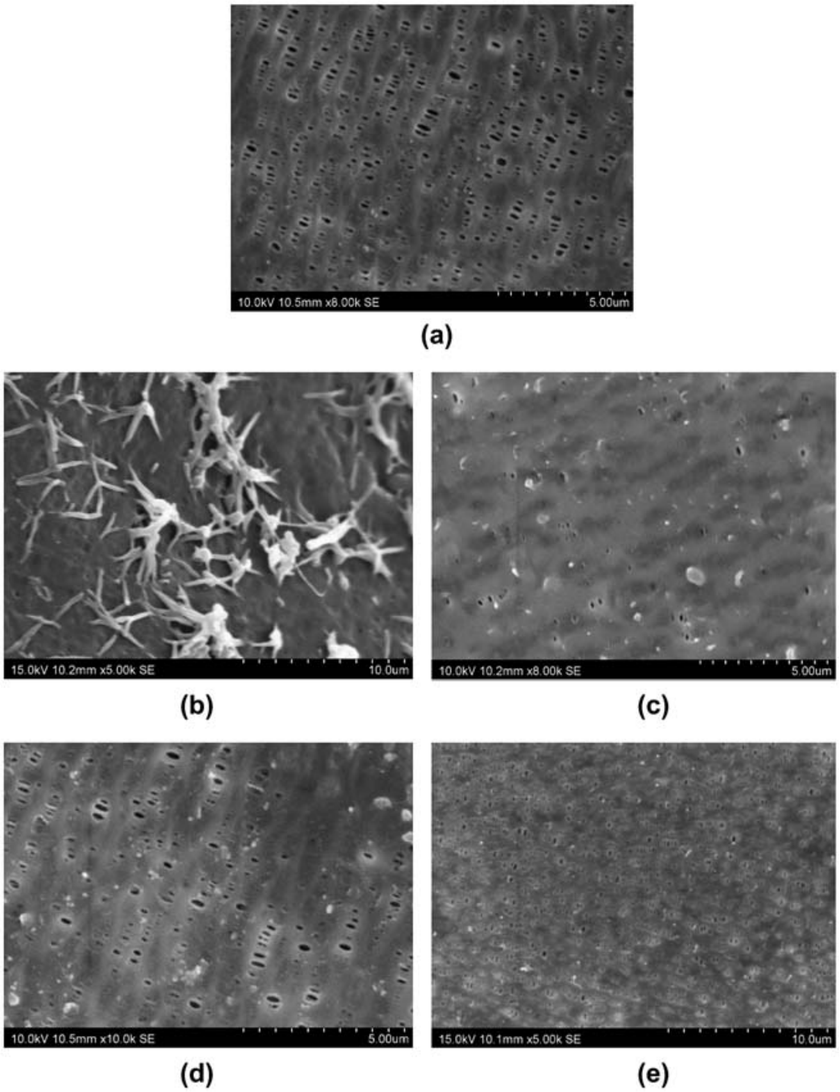

Fig. 9. SEM images showing the surfaces of clean membrane, fouled membrane and chemical cleaned membrane. (a) New membrane, (b) fouled membrane of SMBR-Control, (c) fouled membrane of SMBR-US, (d) chemical cleaned membrane of SMBR-Control, and (e) chemical cleaned membrane of SMBR-US.

59.26% of the total resistance. However, the resistance brought by membrane pore blocking was relatively high in SMBR-Control system, accounting for 38.18% of the total resistance, indicating that the proportion of irreversible pollution was higher than that in SMBR-US system. It can lead to more serious membrane pollution along with the growth of running time in the reactor.

In Fig. 9, the SEM images show the surfaces of clean membrane, fouled membrane and fouled membrane after chemical cleaning in two systems. New membrane surface was observed to be porous and free of particles (Fig. 9(a). The surface of the fouled membrane in SMBR-Control showed the presence of a large number of pollutants (Fig. 9(b). While the fouled membrane surface in SMBR-US was largely free of particles although it appeared to be less porous than the new membranes because of the cake layer (Fig. 9(c). There were still some cake fragments on the chemical cleaned membrane surface for both SMBRs as shown in Fig. 9(d) and Fig. 9(e). Chemical cleaning therefore could not get rid of the biofilm thoroughly, although it may increase the permeability of the cake layer [46]. However, the chemicals sometimes damage the membrane materials and cause secondary pollution [34]. As we have discussed previously, ultrasound can slow down the membrane fouling and lengthen the working hour of membrane module, so that it can reduce the frequency of chemical cleaning and therefore increase the service life of the membrane.

4. Conclusion

Membrane bioreactor with on-line ultrasound had a significant effect on mixed liquor properties and therefore on membrane fouling. The TMP of SMBR-Control system reached 44 kPa at the day of 33, while it increased slowly in SMBR-US system and reached 28 kPa at the day of 39, indicating a significant mitigating of membrane fouling by on-line ultrasound. MLSS increased over the experiment in both SMBRs; however, the growth rate of MLSS in SMBR-US was lower than that in control system, indicating the ultrasound can reduce extra sludge production and disintegrate activated sludge flocs in reactors. Ultrasound can break up the sludge flocs and cause the diminution of mean particle sizes of the flocs. The viscosity of the mixed liquor increased in both SMBRs, and it was consistently lower in SMBR-US than that of SMBR-Control system. The filterability of the mixed liquor improved especially in SMBR-US along the experimental period. MLSS and SMP played a significant role in the change of filtration resistance in SMBR-Control while viscosity had an apparent negative relationship with filtration resistance in SMBR-US.

The total membrane filtration resistance in SMBR-US was of 51.85% lower than that of SMBR-Control after 35 days operation, which confirms that the ultrasound has a positive effect on mitigating membrane fouling. The membrane filtration resistance caused by blocking cake layers accounted for 86.63% of the total resistance in SMBR-US system, indicating that the blocking cake layer was the main reason for membrane fouling in SMBR-US system. The resistance caused by blocking cake layers and membrane pore blocks were all relatively high in SMBR-Control system, accounting for 59.26 and 38.18% of the total resistance, respectively, suggesting a higher irreversible membrane pollution in SMBR-Control system.

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