Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.782087

51 (2013) 3832–3839
May

Taylor & Francis
Taylor & Francis Group

Optimization of the operating parameters for online ultrasonic on controlling membrane fouling in SMBR

Dingjin Li, Min Li*, Yuan Wang, Cunpeng Gong

College of Environmental Science and Engineering, Beijing Forestry University, Beijing 100083, China
Email: liminbjfu@126.com

Received 8 August 2012; Accepted 28 February 2013

ABSTRACT

In this study, bi-frequency online ultrasound was applied to a submerged membrane bioreactor (SMBR–US) to mitigate the membrane fouling. The transmembrane pressure (TMP) was used as an indicator of membrane fouling, and it was observed at different ultrasound parameters to investigate the alleviating effect of membrane fouling. The wastewater treatment experiments were then carried out to explore the effects of online ultrasound on effluent quality and activated sludge concentrations in SMBR system. The results show that the TMP were relatively low when the ultrasonic cleaning time continued for three minutes with an ultrasonic frequency at 50 kHz, or bi-frequency of 25–50 kHz, or tri-frequency of 25–50–90 kHz and an ultrasonic power of 200 or 300 W. The results of wastewater treatment experiments show that both the SMBR–US and the SMBR-Control system had high COD, ammonia, and TN removal efficiency, indicating that the ultrasound did not have a negative influence on the properties of activated sludge and effluent quality. The mixed liquor suspended solids (MLSS) in SMBR–US system decreased apparently, about 7.1% when comparing to the SMBR-Control system, after 40-day operation, which suggested that the ultrasound can reduce extra sludge production.

Keywords: Online ultrasonic cleaning; Submerged membrane bioreactor; Membrane fouling; Sludge reduction

1. Introduction

Membrane bioreactor (MBR) is a new wastewater treatment process with high efficiency. It is the combination of membrane separation technology and biological treatment [1]. The new type of submerged membrane bioreactor (SMBR) can improve N and P removal efficiency by introducing the biological to MBR. MBR has many advantages, such as high mixed liquor suspended solids, high wastewater treatment efficiency, low sludge production, and small covering area requirement. These make the more extensive application of MBR in wastewater treatment. However, the membrane fouling is still the key issue conditioning the stability of the process [2–4]. Membrane fouling results in increased operating costs due to the higher pressures needed to maintain permeate flux,

*Corresponding author.

Presented at the 2012 Qingdao International Desalination Conference June 26–29, 2012, Qingdao, China

the time and materials needed for membrane cleaning [5], and membrane replacement [6].

Membrane fouling is due to the physical and chemical effects in the particles, colloidal particulates or solute molecules in process materials [7]. Membrane fouling is also caused by concentration polarization on membrane surface and membrane pore blocking due to the adsorption and deposition of materials on membrane surface or in membrane holes [8–10]. In general, the fouling occurring in membrane bioreactors is attributable to three aspects: adhesion of macromolecules on membrane surface, deposition of sludge particle, as well as pore obstruction by small molecules.

Backwashing and chemical washing are the main methods for cleaning polluted membrane modules [11]. Backwashing applies to the removal of low-concentration solute particles on membrane surfaces using pulse caused by water, gas, or gas–water mixture. For the removal of microbes and macromolecules adhering in membrane pores, it does not work well [12]. In addition, backwashing is applicable only to tubular membrane module. Chemical washing can remove the contaminants on membrane module entirely. But this must be operated offline. And the membrane module is asked to be against the destruction from chemicals [13].

Compared with the proposed processes, ultrasonic techniques provide an alternative method for membrane fouling control and cleaning. Online ultrasonic cleaning has more advantages of simplicity in operation, such as ease for automatic control, wide applicability range and without secondary pollution [14]. Thus, ultrasonic cleaning of membrane fouling has gained a considerable amount of research [15–18]. In a liquid medium, ultrasound creates oscillating regions of high and low pressure. Cavitation bubbles are formed when the pressure amplitude exceeds the tensile strength of liquid during the rarefaction of sound waves [19].

In addition, there is a discrepancy in the literature regarding the integrity of membranes after exposure to ultrasound. Masselin et al. [20] observed damage to polyethersulfone membranes by ultrasound, while other researchers [21–25] showed that the integrity of membranes was maintained throughout sonication. The integrity of the membrane during sonication is of critical importance for the practical application of this technology to control membrane fouling. Therefore, the mechanism of membrane damage by ultrasound is examined in this study. But ultrasound inhibits the sludge activity [26]. Therefore, ultrasonic cleaning may affect the wastewater treatment efficiency.

The effect of ultrasonic cleaning is directly bound up with ultrasonic power, frequency and working time. With the exception of these, the ununiformity of the ultrasonic field distribution is also an important factor for membrane fouling control [27]. A single frequency ultrasound is accustomed to make a stationary wave field in the SMBR, which leads to an uneven distribution of ultrasonic field and a negative effect on the wastewater treatment efficiency. For this reason, an online ultrasound with three frequencies (25, 50 and 90 kHz) and adjustable operating power and time was adopted in this experiment. This article studies the effect of controlling the pollution of SMBR membrane by changing the combination of different ultrasonic frequency, ultrasonic power, and duration of the ultrasound [28].

2. Materials and methods

2.1. Experimental facilities

In order to identify the impact of operating parameters of ultrasound on fouled membrane in SMBR system, an online ultrasound with three frequencies (25, 50, and 90 kHz) and adjustable operating power was adopted in 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 20 L, 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 that were made by rubber powder, active carbon, and

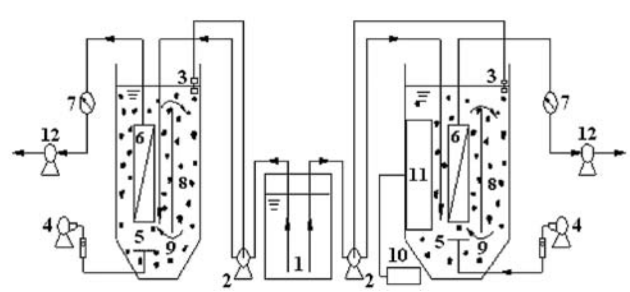

Fig. 1. A schematic diagram of experimental devices. (1) Feed reservoir; (2) inlet pump; (3) level controller; (4) outlet pump; (5) perforation aeration tube; (6) membrane module; (7) pressure gauge; (8) filler carriers; (9) cycle baffle; (10) ultrasound generator and adjustor; (11) ultrasound transmitter.

adhesive and with a diameter of around 5 mm and the carrier dose in this study was 10% (carrier volume vs. total effective volume of SMBR). Perforated pipe sparger was employed to aerate under the membrane module. To maintain the water levels of the SMBRs, liquid level controller and dual head peristaltic pumps 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. The activated sludge had not been discharged during the experiment.

While carrying out the experiment, synthetic wastewater was used as inflow. The COD, BOD_5, and ammonia concentration were kept at 300–600 mg/L, 160–300 mg/L, 30–50 mg/L, respectively. The COD of the influent was occasionally measured and the average COD was 430 mg/L. Table 1 shows the inorganic composition of the synthetic wastewater.

2.2. Operating condition

To investigate the alleviating effect of different ultrasound parameters on membrane fouling, batch experiments were carried out as follows: When the TMP of the SMBR membrane module increased up to 27–33 kPa, the membrane module was taken out from the microbial reactor and put into another reactor filled with water and an ultrasonic transmitter. The membrane module was then cleaned with an ultrasonic lasting time of 5 min every 15 min. The power of the ultrasound generator was kept at 300 W to get the best ultrasonic frequency combination for cleaning. We studied 7 kinds of frequency combinations, which were low frequency at 25 kHz, mid-frequency at 50 kHz, high frequency at 90 kHz, bi-frequency of 25 and 50 kHz, 50 and 90 kHz, 25 and 90 kHz, tri-frequency of 25, 50 and 90 kHz. The TMP of the membrane module was observed.

Based on the best operating frequency of ultrasonic gained from above experiments, the impact of ultrasonic executing time on cleaning effect was investigated. The ultrasonic lasting time was set to 2, 3, 5, and 7 min respectively, and the corresponding interval time was 13, 12, 10, and 8 min At last, the effect of ultrasonic power on membrane cleaning was carried out at 200, 300, 400, and 500 W, respectively. Each cleaning experiment process lasted for 180 min.

Table 1
Inorganic composition of feed solution

Element	Reagent	M.W.	Concentration (mg element/L)	Reagent (mg/L)
NH_4^+	NH_4Cl	53.49	30.28	90
Na	$NaHCO_3$	84.01	20.54	75
K	KH_2PO_4	136.09	7.16	25
Fe	$FeCl_2$	126.75	1.32	3
Ca	$CaCl_2$	110.98	2.16	6

We also studied the effect of online ultrasonic cleaning on sewage treatment efficiency during a long-term experiment. The initial flux of membrane module in each SMBR system was set to 1.5 L/h, which was under the critical flux according to previous studies, and the air flow of oxygen supply for reactors was $0.5\,m^3/h$. The operating parameters of ultrasonic used in the long-term experiment were based on the above batch experiments.

2.3. Analysis items and methods

MLSS and the conventional water quality monitoring indicators were measured in accordance with standard methods [29]. CTL-12 (Chengde, Huatong Co., China) was adopted to measure COD.

3. Results and discussion

3.1. The optimization of ultrasonic frequency combinations

The ultrasound generator could supply on the fouling membrane.

We investigated the effects of seven kinds of ultrasonic frequency combinations on TMP to confirm the suitable frequency combination. In this case, the change of TMP is a mark of the membrane fouling. The higher the TMP, the more serious membrane fouling was. The TMP values were measured every 15 mins, and the results were shown in Fig. 2.

When the ultrasonic cleaning started, TMP values declined quickly in the early stage, but the decline was not as steep as it in the initial 60 min over time. After 150 min operating, the TMP began to stabilize. Significant differences can be seen among the ultrasonic cleaning of different frequency combinations from Fig. 2.

The ultrasonic cleaning at high frequency of 90 kHz, bi-frequency of 90–50 kHz and 90–25 kHz did not have a telling cleaning effect. The TMP decreased rather slowly when compared with other ultrasonic combinations. Ultrasound at other frequency can make an obvious downtrend on TMP, which means a promising cleaning result.

It was also showed in Fig. 2 that the cleaning effects were corresponding with the low-frequency, mid-frequency and middle-low-frequency ultrasonic.

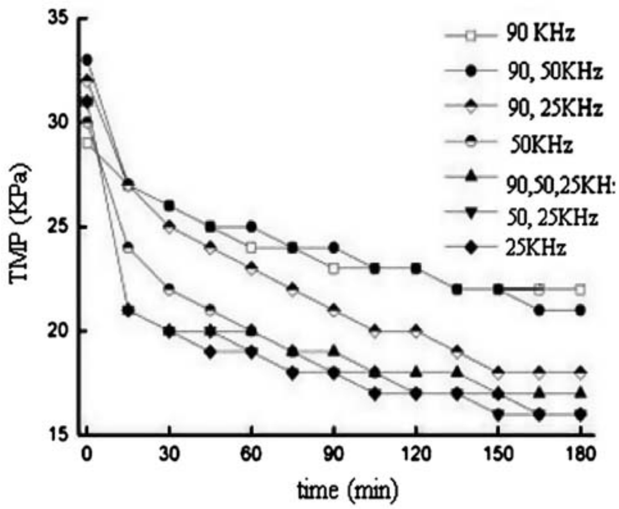

Fig. 2. Effect of different ultrasonic frequency combinations on TMP.

The TMP was declined to 16 kPa. Because the low-frequency ultrasound was used to cleaning the hard dirt, it may cause damage to fragile material [30]. Furthermore, low-frequency ultrasound creates noise jamming [29]. So, for a more comprehensive consideration, we chose mid-frequency, middle-low-frequency, and high-mid-low frequency in the following experiments, since there is no significant difference in membrane module cleaning effect for these frequency combinations. On one hand, it can reduce the injury on the membrane surface texture. On the other hand, it can form a relatively even sound field [31].

3.2. The optimization of ultrasound cleaning lasting time

We carried out the consecutive ultrasound experiments on the polluted membrane module at three optimized frequencies. The variation of the TMP was investigated to find out a suitable ultrasonic lasting time. The results were shown in Fig. 3.

Fig. 3 showed the cleaning effect of different ultrasonic lasting time to the fouled membrane when the ultrasonic power was at 300 W, and the ultrasound

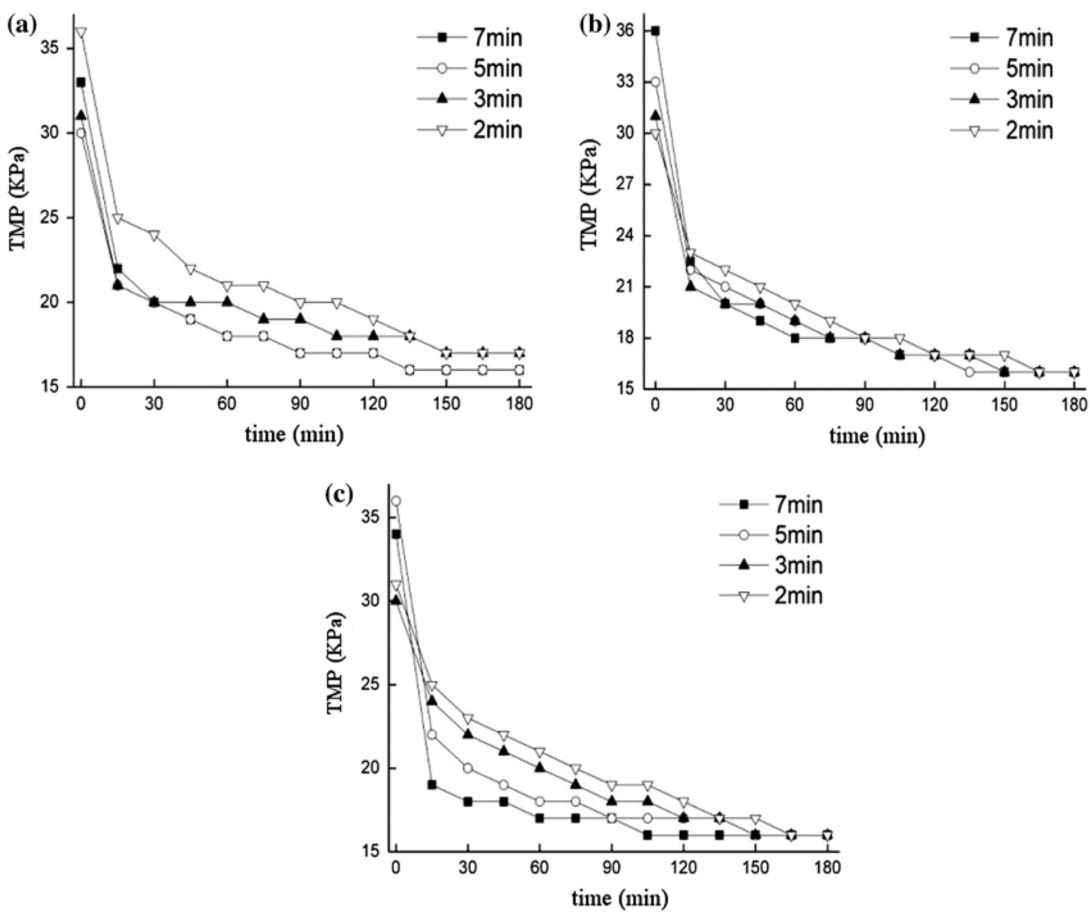

Fig. 3. The effect of ultrasonic lasting time on TMP. (a) High-mid-low frequency; (b) mid-low frequency; (c) mid-frequency.

was of high-mid-low frequency, mid-low frequency, and medium frequency, respectively. The downtrend of TMP was step down gradually with the extending of ultrasound time. The TMP became stable gradually when it reduced to a certain degree, and it would not continue to reduce along with the experiment time. This may explain that the membrane surface pollution could be removed by ultrasound cleaning, but because of the membrane pollution brought by the blocking of membrane hole internal, it would be removed hardly [32]. The conclusion was consistent with lots of results. This phenomenon was also probably due to parts of the micro-particles entering into the internal hole of membrane with the suction action of water pump when the sludge particles of membrane surface mud cake layer were broken by ultrasonic cavitation effect, which caused the film hole being blocked and led to a final stable TMP [33]. The cleaning effect at the early stage of operation was relatively poor when the ultrasound time was 2 or 3 min. But compared with the ultrasound time of 5 and 7 min, the difference of cleaning effect was nearly the same. Therefore, combining with the above analysis and considering the economic benefits, we chose a better ultrasonic cleaning time of 3 min which can confirm the cleaning effects and save cost.

3.3. The optimization of ultrasonic power

We carried out the consecutive ultrasound experiments on the polluted membrane at different ultrasonic powers of 200, 300, 400, and 500 W. The changes of TMP over time were shown in Fig. 4.

The higher the ultrasonic power was, the more the TMP decreased, suggesting a better cleaning effect with higher ultrasonic power. As the time going on, the downward trend had slowed. When the TMP fell to about 17 KPa, it was tending toward stability. We can also see from Fig. 4 that there is no significant difference of ultrasonic cleaning effects among different powers. Considering higher ultrasonic power could lead to the deterioration of mixed liquor characteristics and the damage of membrane module [33]. So 200 or 300 W would be suitable ultrasonic powers for a long-term experiment.

According to the above-mentioned experiment analysis we could draw a conclusion that the parameters suitable to the online ultrasonic cleaning were: 200 or 300 W, mid-frequency, mid-low frequency or high-mid-low frequency, 3-min ultrasound lasting time. Based on this, we chose 300 W, middle-frequency and 3-min ultrasound lasting time for the further wastewater treatment experiment.

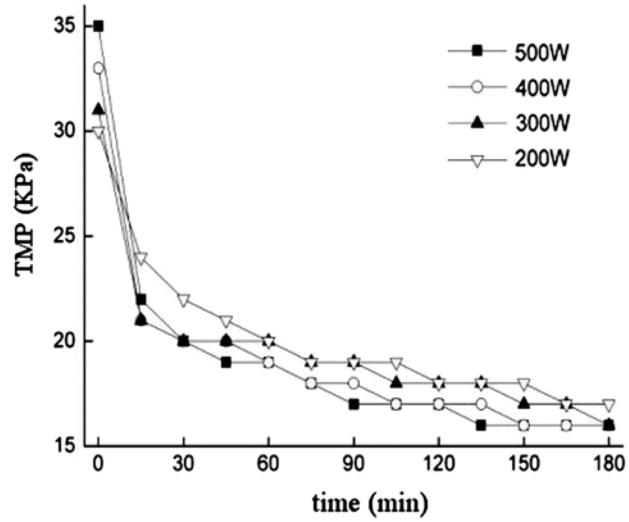

Fig. 4. Effect of different ultrasonic power on TMP.

3.4. The impacts of online ultrasonic on SMBR sewage treatment efficiency

During the ultrasonic cleaning, hydraulic shear force caused by the ultrasonic cavitation destroyed the microbial cell structures in the mixed liquor. The organic carbon in the microbial cells flew into the activated sludge mixed liquor, making the organic loading increased by changing the particulate COD into dissolved COD [34]. Fig. 5 shows the impacts of online ultrasonic cleaning on COD removal rate in SMBR systems.

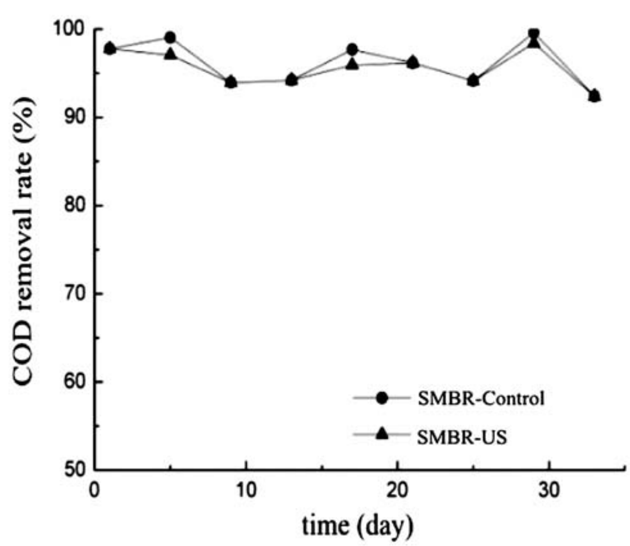

Fig. 5. Effect of online ultrasound on COD removal efficiency.

The COD removal rates of SMBR–US and SMBR-Control were 95.75 and 96.11%, respectively, while the ultrasonic cleaning was at 300 W, middle-frequency, making no significant difference, which indicated long-term online ultrasonic cleaning did not have much influence to the SMBR COD removal rate.

The average removal rate of ammonia nitrogen of the ordinary SMBR and ultrasound SMBR were 98.45 and 98.29% from Fig. 6. The ammonia nitrogen removal rates of two systems are all very high and relatively stable. Particulate filler was added in the membrane biological reactor and it helped the nitrifying bacteria attached and grew on it. So the systems could maintain a high ammonia nitrogen removal rate. Fig. 6 illustrated that online ultrasound almost had no effect on the ammonia nitrogen removal rate.

It can be seen from Fig. 7 that the average removal rate of total nitrogen of SMBR-Control and SMBR–US were 66.18 and 66.73%, respectively. The removal rate of total nitrogen presented an upward trend in the two systems at the later running period. However, the upward trend had not fully appeared due to the short system running time. The middle-frequency online ultrasound had no effect on the removal rate of total nitrogen. This showed that the middle-frequency ultrasonic radiation did not destroy the activated sludge flocculent structure which attached to the surface of the filler particles and had no effect on the microscopic oxygen-deprived environments in fillers' surface. Therefore, it had no obvious influence on denitrification.

MLSS was a key factor to the membrane fouling. A high MLSS could accelerate the process of membrane fouling [35]. As a result, we studied the changes of MLSS in the SMBR–US and SMBR-Control during the continuous ultrasonic cleaning. The results were showed in Fig. 8.

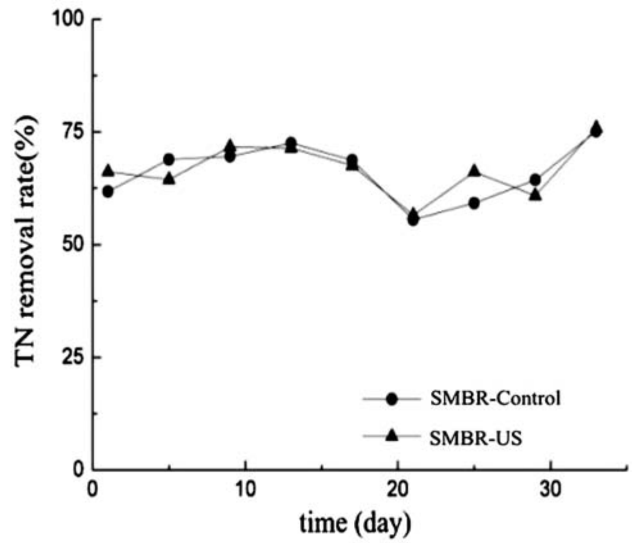

Fig. 7. Effect of online ultrasound on total nitrogen removal efficiency.

Because there was no mud discharge during the experiment, the MLSS of the SMBR–US and SMBR-Control both showed growth trends. When the system came to the 26th day, the MLSS of the SMBR–US was 500 mg/L lower than that of SMBR-Control, indicating that about 7.1% activated sludge was reduced by online ultrasonic.

This result suggested that the hydraulic shear stress caused by the ultrasonic caviation would

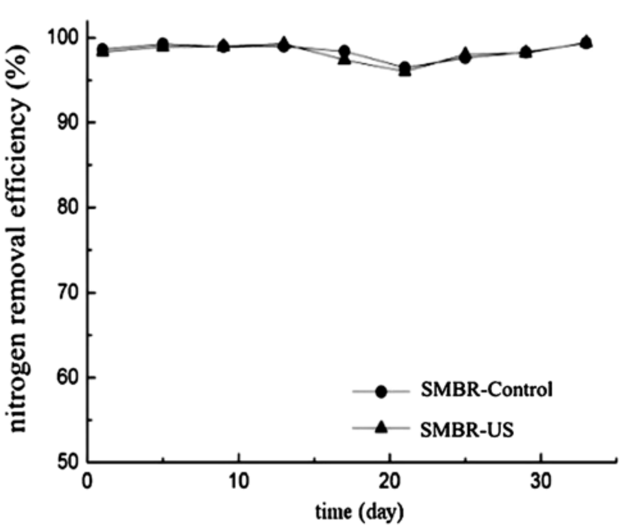

Fig. 6. Effect of online ultrasound on ammonia nitrogen removal efficiency.

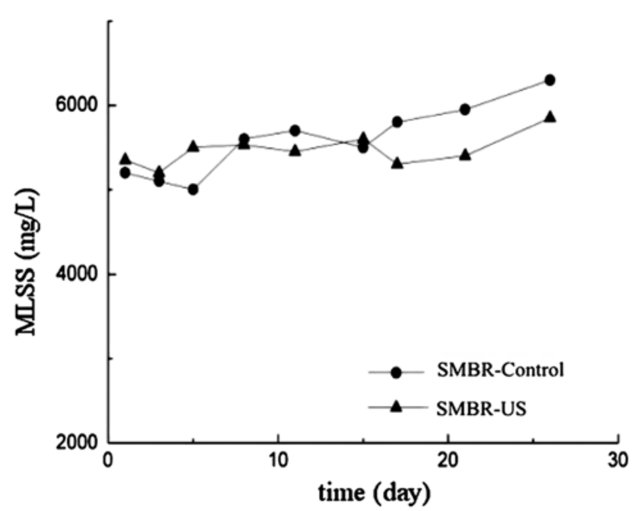

Fig. 8. Effect of online ultrasound on MLSS.

destroy the sludge flocculation and the microbial cell structure [36]. Then growth rate of the MLSS was restrained. As a result, long-term ultrasound may cause the reduction of sludge in the membrane bioreactor and help controlling the membrane fouling.

4. Conclusion

(1) When the ultrasonic frequency combinations were 50 kHz, or bi-frequency of 25–50 kHz, or tri-frequency of 25–50–90 kHz, ultrasonic powers were 200 or 300 W, ultrasonic lasting time was three minutes, the online ultrasonic could produce a good control of membrane fouling in SMBR system.

(2) In the process of continuous wastewater treatment operation, intermittent online ultrasound cleaning that continued for 3 min every 24 h with an ultrasonic frequency at 50 Hz, and an ultrasonic power of 300 W had no obvious influence on the COD, ammonia nitrogen and total nitrogen removal rate, indicating that the ultrasound did not have a negative influence on the properties of activated sludge and effluent quality.

(3) Sludge concentration in the online ultrasound SMBR system was significantly lower than that of SMBR-Control system. Because the low sludge concentration could slow down the membrane fouling to a certain extent, so it can be conclude that online ultrasound played a positive role in controlling membrane fouling.

Acknowledgment

This study was supported by the Beijing Science & Technology Star Plan (No. 2007B029).

References

[1] J. Sun, J. Rong, L. Dai, B. Liu, W. Zhu, Control of membrane fouling during hyperhaline municipal wastewater treatment using a pilot-scale anoxic/aerobic-membrane bioreactor system, J. Environ. Sci. 23(10) (2011) 1619–1625.
[2] A.L. Lim, R.B. Bai, Membrane fouling and cleaning in microfiltration of activated sludge wastewater, Membr. Sci. 216(1) (2003) 279–290.
[3] N. Lee, G. Amy, J.P. Croue, Identification and understanding of fouling in low-pressure membrane(MF/UF)filtration by natural organic matter(NOM), Water Res. 38 (2004) 4511–4523.
[4] H. Huang, N. Lee, T. Young, Natural organic matter fouling of low-pressure, hollow-fiber membranes: Effects of NOM source and hydrodynamic conditions, Water Res. 41 (2007) 3823–3832.
[5] B. Espinasse, P. Bacchin, P. Aimar, On an experimental method to measure critical flux in ultrafiltration, Desalination 146 (2002) 91.
[6] M.R. Wiesner, J. Hackey, S. Sandeep, J.G. Jacangelo, J.M. Laine, Cost estimates for membrane filtration and conventional treatment, AWWA 33 (1994) 86–94.
[7] P. Gui, X. Huang, Y. Chen, Y. Qian, Effect of operational parameters on sludge accumulation on membrane surfaces in a submerged membrane bioreactor, Desalination 151(2) (2002) 185–194.
[8] L. Defrance, Y.M. Jaffrin, B. Gupta, P. Paullier, V. Geaugey, Contribution of various constituents of activated sludge to membrane bioreactor fouling, Bioresour. Technol. 73(2) (2000) 105–112.
[9] J.G. Chio, T.H. Bae, J.H. Kim, T.M. Tak, A.A. Randall, The behavior of membrane fouling initiation on the crossflow membrane bioreactor system, J. Membr. Sci. 203(1–2) (2002) 103–113.
[10] V. Lahoussine-Turcaud, M.R. Wiesner, J.Y. Bottero, Fouling in tangential-flow ultrafiltration: The effect of colloid size and coagulation pretreatment, J. Membr. Sci. 52(2) (1990) 173–190.
[11] J.B. Wan, H.H. Wu, A study on reducing membrane fouling in membrane bioreactors, Indus. Water Wastewater 34(3) (2003) 5–8.
[12] X. Huang, L. Mo, Characteristics of membrane fouling and its cleaning in membrane bioreactors for water purification, China Water Wastewater 19(5) (2003) 8–12.
[13] X.J. Wang, J.X. Li, S.Q. Xia, Effect of chemical flocculation pretreatment on membrane fouling in MBR, China Water Wastewater 26(3) (2010) 18–21.
[14] J. Li, R.D. Sanderson, E.P. Jacobs, Ultrasonic cleaning of nylon microfiltration membranes fouled by Kraft paper mill effluent, J. Membr. Sci. 245 (2002) 247–256.
[15] Z. Ahmed, J. Cho, B.R. Lim, Effects of sludge retention time on membrane fouling and microbial community structure in a membrane bioreactor, J. Membr. Sci. 287(2) (2007) 211–218.
[16] Nobuhiro Yamato., Katsuki Kimura, Taro Miyoshi, Difference in membrane fouling in membrane bioreactors (MBRs) caused by membrane polymer materials, J. Membr. Sci. 280 (2006) 911–919.
[17] Z. Geng, E.R. Hall, A comparative study of fouling-related properties of sludge from conventional and membrane enhanced biological phosphorus removal processes, Water Res. 41(19) (2007) 4329–4338.
[18] K.D. Zoh, M.K. Stenstrom, Application of *n* membrane bioreactor for treating explosives process wastewater, Water Res. 36(4) (2002) 1018–1024.
[19] S. Muthukumaran, K. Yang, A. Seuren, S. Kentish, M. Ashokkumar, G.W. Stevens, F. Grieser, The use of ultrasonic cleaning for ultrafiltration membranes in the dairy industry, Sep. Purif. Technol. 39 (2004) 99.
[20] I. Masselin, X. Chasseray, L. Durand-Bourlier, J.M. Laine, P.Y. Syzaret, D. Lemordant, Effect of sonication on polymeric membranes, Membr. Sci. 181 (2001) 213.
[21] D. Chen, L.K. Weavers, H.W. Walker, J.J. Lenhart, Ultrasonic control of ceramic membrane fouling caused by natural organic matter and silica particles, J. Membr. Sci. 276 (2006) 135–144.
[22] K. Yasui, Effect of volatile solutes on sonoluminescence, Chem. Phys. 116(7) (2002) 2945.
[23] P. van der Marel, A. Zwijnenburgb, A. Kempermana, M. Wessling, H. Temmink, W. van der Meer, Influence of membrane properties on fouling in submerged membrane bioreactors, J. Membr. Sci. 348 (2010) 66–74.
[24] X. Chai, T. Kobayashi, N. Fujii, Ultrasound effect on cross-flow filtration of polyacrylonitrile ultrafiltration membranes, J. Membr. Sci. 148 (1998) 129.
[25] S. Muthukumaran, S. Kentish, S. Lalchandani, M. Ashokkumar, R. Mawson, G.W. Stevens, F. Grieser, The optimization of ultrasonic cleaning procedures for dairy fouled ultrafiltration membranes, Ultrason. Sonochem. 12 (2005) 29.
[26] A. Tiehm, K. Nickel, M. Zellhorn, U. Neis, Ultrasonic waste activated sludge disintegration for improving anaerobic stabilization, Water Res. 35(8) (2001) 2003–2009.

[27] M.O. Lamminen, H.W. Walker, L.K. Weavers, Mechanisms and factors influencing the ultrasonic cleaning of particle-fouled ceramic membranes, J. Membr. Sci. 237 (2004) 213–223.
[28] F. Wang, Y. Wang, M. Ji, Mechanisms and kinetics models for ultrasonic waste activated sludge disintegration, J. Hazard. Mater. B123 (2005) 145–150.
[29] EPA (Environmental Protection Administration of China), Monitoring and Analysis Method of Water and Wastewater, fourth ed., China Environmental Science Press, Beijing, 2003, p. 105.
[30] Z. Wang, Zhichao Wu, Xing Yin, Lumei Tan, Membrane fouling in a submerged membrane bioreactor (MBR) under sub-critical flux operation: membrane foulant and gel layer characterization, J. Membr. Sci. 325 (2008) 238–244.
[31] J. Zhang, H.C. Chua, J. Zhou, A.G. Fane, Factors affecting the membrane performance in submerged membrane bioreactors, J. Membr. Sci. 284(1–2) (2006) 54–66.
[32] L.H. Mikkelsen, The shear sensitivity of activated sludge: Relations to filterability, rheology and surface chemistry, Colloids Surf. A 182(1–3) (2001) 1–9.
[33] S. Rozenberger, M. Kraume, Filterability of activated sludge in membrane bioreactors, Desalination 151(2) (2003) 195–200.
[34] C. Wisniewski, A. Grasmick, Floc size distribution in a membrane bioreactor and consequences for membrane fouling, Colloid Surf. 138 (1998) 403.
[35] R. Shane Trussell, Rion P. Merlob, Slawomir W. Hermanowicz, David Jenkins, Influence of mixed liquor properties and aeration intensity on membrane fouling in a submerged membrane bioreactor at high mixed liquor suspended solids concentrations, Water Res. 41 (2007) 947–958.
[36] Seong-Hoon Yoon, Hyung-Soo Kim, Sangho Lee, Incorporation of ultrasonic cell disintegration into a membrane bioreactor for Zero sludge production, Process Biochem. 39(12) (2004) 1923–1929.