Journal of Hazardous Materials 192 (2011) 1509–1514

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Enhanced performance of a submerged membrane bioreactor with powdered activated carbon addition for municipal secondary effluent treatment

Hongjun Lin[a,*], Fangyuan Wang[a], Linxian Ding[a], Huachang Hong[a], Jianrong Chen[a,**], Xiaofeng Lu[b]

[a] College of Geography and Environmental Sciences, Zhejiang Normal University, 688 Yingbin Avenue, Jinhua, Zhejiang Province 321004, PR China
[b] Shanghai Institute of Applied Physics, Chinese Academy of Science, Shanghai 201800, PR China

ARTICLE INFO

Article history:
Received 7 February 2011
Received in revised form 28 May 2011
Accepted 26 June 2011
Available online 1 July 2011

Keywords:
Membrane bioreactor
Membrane fouling
Powdered activated carbon
Secondary effluent

ABSTRACT

The aim of this study was to investigate the feasibility of PAC-MBR process treating municipal secondary effluent. Two laboratory-scale submerged MBRs (SMBR) with and without PAC addition were continuously operated in parallel for secondary effluent treatment. Approximately 63%TOC, 95% NH_4^+–N and 98% turbidity in secondary effluent were removed by the PAC-MBR process. Most organics in the secondary effluent were found to be low molecular weight (MW) substances, which could be retained in the reactor and then removed to some extent by using PAC-MBR process. Parallel experiments showed that the addition of PAC significantly increased organic removal and responsible for the largest fraction of organic removal. Membrane fouling analysis showed the enhanced membrane performance in terms of sustainable operational time and filtration resistances by PAC addition. Based on these results, the PAC-MBR process was considered as an attractive option for the reduction of pollutants in secondary effluent.

1. Introduction

Reuse of treated municipal wastewater (municipal secondary effluent) has been long proposed [1,2], and the worldwide water scarcity has increased its interest. This is particularly true in arid and semi-arid regions where domestic, industrial and agricultural demands compete for limited resources. Specifically, municipal secondary effluent can be reused to agriculture at all levels, urban and industrial uses, aquifer recharge, etc. [3]. Further treatment of secondary effluent is usually required in order to maintain adequate levels of sustainable agriculture production, decelerated salinisation processes of the ground waters and to prevent long range adverse effects of gradual environmental pollution [4], as well as to comply with the reusable standard. This involves the removal of turbidity, pathogenic microorganisms, organic and inorganic matter presented in secondary effluent. Membrane technology is one development that now plays an increasingly important role in providing such treatment. Direct membrane filtration of secondary effluent with microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) has been extensively studied to date [3,5–7]. However, secondary effluent is a type of water abundant in residual organic substances and fine colloids, which will induce serious membrane fouling in direct filtration process. Furthermore, membranes like MF and UF could hardly efficiently retain soluble organic and inorganic substances. Insufficient pollutants removal and membrane fouling appeared to remain the persistent technical hindrances of direct filtration processes.

Membrane bioreactor (MBR) is one of membrane processes combining membrane units responsible for physical separation, and biological process responsible for biodegradation of the waste compounds. Due to the advantages over conventional activated sludge process with highly improved permeate quality, reduced footprint occupation and sludge production [8–10], MBR has emerged as one of the promising technologies for wastewater treatment and reuse [11]. In general, MBR was mostly used for industrial or municipal wastewater treatment, while less applied in further treatment of secondary effluent. This is mostly because of the relatively low organic strength and the refractory presented in the secondary effluent [8]. However, the presence of biomass in MBR system was expected to be capable of degradation or bioabsorption of the residual organic substances and fine colloids to some extent in secondary effluent, which would benefit membrane fouling control and improve permeate quality. Evidences have shown that certain levels of mixed liquor suspended solids (MLSS) are required to scour the membrane surface and enhance the membrane flux in MBR systems [12]. Meanwhile, it is envisaged that addition of adsorbents such as powdered activated carbon (PAC) directly into the MBR can lead to significant retention of soluble pollutants. Due to the complete retention of sludge by the membrane and application of longer SRT, the retained pollutants may be efficiently removed in an MBR to which PAC has been added.

* Corresponding author. Tel.: +86 579 82282273.
** Corresponding author. Tel.: +86 579 82283589.
E-mail addresses: hjlin@zjnu.cn (H. Lin), cjr@zjnu.cn (J. Chen).

0304-3894/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2011.06.071

Table 1
Physical characteristics of membrane module.

Characteristics items	
Membrane materials	PVDF
Geometric characteristics	Dimension: 17 cm (L) × 24 cm(H) × 0.5 cm (W)
MWCO (kDa)	140
Membrane area (m^2)	0.4 (0.08 m^2 ×5)
Membrane type	Flat sheet

Moreover, addition of PAC into the MBR has been frequently confirmed to benefit membrane fouling mitigation [12–15].

Although PAC-MBR process shows the potential in the secondary effluent treatment application, perusal of the literature shows that the research and application efforts in the field are very limited. Only one peer-reviewed paper [16] in the literature explored the removal of residual organic matter in the biologically treated swine wastewater. Although the study confirmed improved removal efficiency, a comprehensive understanding of the involved phenomena is yet to be developed to propel the application of PAC-MBR process in secondary effluent treatment forward. In this study, two laboratory-scale submerged MBRs (SMBR) with and without PAC addition were operated in parallel for secondary effluent treatment. The characteristics of secondary effluent, system performance in terms of pollutants removal and membrane fouling were investigated. The present work focused on the feasibility of PAC-MBR process for secondary effluent treatment.

2. Materials and methods

2.1. MBR system description

Two identical laboratory-scale SMBRs were used in this study. Each SMBR with an effective total volume of 37.5 L (25 cm × 32 cm × 47 cm length × width × height) was divided into a riser zone and two down-comer zones by two baffle sheets. A membrane module composed of an array of flat sheet membrane (effective filtration area was 0.4 m^2) with 140 kDa molecular weight cut-off (MWCO) was submerged in the riser zone. All membranes used in this study were made of polyvinylidene fluoride (PVDF) materials using the phase inversion method (supplied by Shanghai SINAP Membrane Science & Technology Co. Ltd., China). The physical characteristics of membrane module are listed in Table 1. Air was supplied through a tubular air diffuser located at the base of membrane module in order to supply oxygen demanded by the microorganisms and to create sufficient cross-flow velocities on the membrane surface. The water level was maintained constant by a level sensor connected to an electromagnetic valve in the influent pipe. The filtrate was intermittently obtained by using a suction pump at a fixed filtration flux. A suction mode of 5-min-on and 1-min-off was adopted. All electric devices were connected to a self-made programmable logic controller (PLC) to automatically control the whole system. Fig. 1 presents a scheme of each reactor set-up.

The secondary effluent used in this study came from a wastewater treatment plant (WWTP) located in Shanghai, which utilized a traditional active sludge process. The mean values of monitored parameters in the influent (secondary effluent) are shown in Table 2. Prior to the experiment, sludge taken from a local wastewater treatment plant was acclimated with the secondary effluent in the reactor for approximately 2 weeks in order to ensure that the experiment achieved "relatively steady state" (consistent performance over time) quickly. The seed sludge concentration was initially around 4.5 g/L and no sludge was discharged except sludge sampling in the whole process. PAC was sieved (180–200 mesh) and rinsed several times to remove impurities, and then a dose

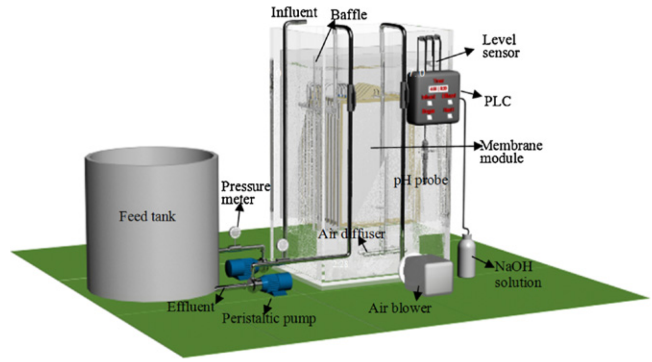

Fig. 1. Schematic diagram of experimental MBR.

of 750 mg/L was added to the MBR1 after sludge acclimation process. The added dose was based on the literature data [11]. In order to assess the effects of PAC on the performance, an identical MBR (MBR2) without PAC addition was operated in parallel. The main operational conditions during operational period are summarized in Table 3.

2.2. Resistance analysis

Darcy's Law is a phenomologically derived constitutive equation that describes the flow of a fluid through a porous medium. In pressure-driven membrane operations, Darcy's law is often used in the form [17]:

$$J = \frac{\Delta P - \Delta \Pi}{\mu R_t} \quad (1)$$

where J is the permeate flux ($m^3/(m^2\,h)$), ΔP is the trans-membrane pressure (TMP) (Pa), $\Delta \Pi$ is osmotic pressure (Pa), μ is the permeate viscosity (Pa s), R_t is the total resistance (m^{-1}). The calculation equation of osmotic pressure is:

$$\Delta \Pi = \Delta C \times RT \quad (2)$$

where ΔC is a concentration difference between measured solution and a reference solution ($mol\,L^{-1}$), R is the gas constant ($8.31\,kPa\,L\,K^{-1}\,mol^{-1}$) and T the temperature (K). For MBR system, ΔC was usually quite low as most of solutes in the supernatant can go through the MF or UF membrane used. A detailed calculation showed that the contribution of osmotic pressure to total pressure was lower than 0.02% in this study, and could be ignored. Therefore, filtration resistance of membrane can be defined by the followed equation:

$$R_t = R_m + R_p + R_{ef} + R_{if} = R_m + R_c + R_{if} = \Delta P/(\mu \times J) \quad (3)$$

where R_m is the intrinsic membrane resistance (m^{-1}), R_p is the polarization layer resistance (m^{-1}), R_{ef} is the external membrane resistance (m^{-1}), R_{if} is the internal membrane resistance (m^{-1}), and R_c is cake layer resistance (m^{-1}).

Darcy's law is only valid for slow, viscous flow. Typically, flow with a Reynolds number less than 1–10 is laminar, and it would be valid to apply Darcy's law [17]. For this reason, batch filtration tests were performed to investigate the filtration resistance using sludge liquor samples from the two MBRs. The filtration setup consists of a cylindrical vessel (effective volume = 0.35 L), a stirrer (stir rate = 400 rpm) and a flat-sheet membrane (effective filtration area = 0.004 m^2) same to the membrane used in the MBRs. For all tests in this work, the pressure was regulated at 20 kPa by using nitrogen gas. There was no stirring operation involved in the batch filtration process to get the flux value, corresponding to a Reynolds number close to zero. The experimental procedure to obtain each resistance value was as follows [18,19]: (1) R_m was estimated by

Table 2
Characteristics of the secondary effluent.

Parameter	Mean	Max	Min	Standard deviation
TOC (mg/L)	10.70	12.31	8.93	1.32
NH_4^+–N (mg/L)	1.51	3.86	0.22	1.82
TP (mg/L)	0.11	0.25	0.08	0.07
Turbidity (NTU)	2.6	3.6	1.5	0.7
pH	7.6	8.0	7.1	0.3

measuring the water flux of de-ionized (DI) water; (2) R_t was evaluated by the final flux of sludge filtration; (3) the membrane surface was then flushed with water under stirring condition for 5 min, After that, the DI water flux was measured again to get the resistance of $R_m + R_{ef} + R_{if}$; (4) After step 3, the membrane was cleaned with a sponge to remove the cake layer, the DI water flux was then measured to get the resistance of $R_m + R_{if}$. From these steps, R_t, R_m, R_p, R_c, R_{ef} and R_{if} could be calculated.

2.3. Organics removal calculation

Removal efficiency from biodegradation and PAC adsorption was calculated by dividing the reduced pollutant content in the supernatant from the influent by the influent content. Removal efficiency from membrane interception was calculated by dividing the reduced content in the filtrate from the supernatant by the influent content. Furthermore, efficiency from PAC adsorption could be quantified by difference of mean removal efficiency between the two MBRs, and then removal efficiency from biodegradation could also be evaluated. This calculation method was based on Whang et al. [16].

2.4. Analytical methods

All items on the quality of the influent, supernatant and effluent, together with liquor suspended solids (MLSS) were measured according to the standard methods [20]. TOC was characterized using TOC analyzer (TOC-5000A, Shimadzu Corporation, Japan). The turbidity was measured with a digital turbidimeter (WGZ-1, Shanghai Third Optical Instruments, China). Floc size distribution of activated sludge was measured by using a particle size analyzer (Mastersizer 2000, Malvern Instruments, UK) based on a laser light-scattering method. TOC fraction was achieved by using three membranes with MWCO of 2000, 6000 and 30000 Dalton to filtrate the secondary effluent and the permeate.

3. Results and discussion

3.1. Pollutants removal

Two laboratory-scale SMBRs were continuously operated for 45 days for real municipal secondary effluent treatment. The influent and permeate quality was periodically monitored, and the organics content in term of TOC concentration in the influent and effluent of the two MBRs are shown in Fig. 2. The influent TOC concentrations ranged from 8.9 to 12.3 mg/L with an average value of 10.7 ± 0.78 mg/L, and the mean effluent TOC concentrations of MBR1 and MBR2 were 4.0 ± 0.84 mg/L and 8.98 ± 0.62 mg/L, respectively, corresponding to a mean TOC removal efficiency of 62.7 ± 7.7% for MBR1 and 16.1 ± 4.6% for MBR2. The significant difference in TOC removal indicated that addition of PAC in MBR significantly improved the organics removal. It should be emphasized that this removal efficiency (62.7%) was achieved at condition of a low organic loading rate (F/M) (0.014 ± 0.001 kgTOC/kgMLSS d), which was only about 1/20–1/3 of that suggested by Water Environment Federation [21] for sludge process. This suggested that it is possible to achieve fairish organics removal efficiency even at a very low organic loading with PAC addition.

Other items on quality of the influent and effluent were also determined. NH_4^+–N in influent ranged from 0.22 to 3.86 mg/L with an average value of 1.51 ± 1.82 mg/L. The presence of ammonia in the secondary effluent was also confirmed by some other studies [22,23]. Despite the variation of NH_4^+–N concentration in the influent, NH_4^+–N in the effluent from both MBRs was lower than 0.07 mg/L. The mean removal efficiency was more than 95% for both MBRs. This implied almost all the NH_4^+–N was removed by biological nitrification in the reactor. This phenomenon can be explained by 2 aspects. One is the complete retain of the nitrifying microorganisms in the reactors. These autotrophic nitrifiers could therefore proliferate without any loss. The other one is the low organic loading for secondary effluent treatment. Nitrifying bacteria meet less competition from other heterotrophic microorganisms that are also active consumers of oxygen [24]. Consequently, a higher nitrification could be achieved in the MBRs regardless of PAC addition.

With respect to turbidity removal, both permeates from the two MBRs have turbidity lower than 0.2 NTU, corresponding to a mean removal efficiency of over 98% for two systems. At such a low turbidity level, the permeate is suitable for many industrial applications. PAC appeared to have no visible impact on turbidity removal although PAC was expected to serve as an adsorbent and coagulant for suspended solids and colloids in sludge liquor [25]. It is envisaged that PAC effect could be neglected compared to membrane interception. It has been widely reported that membranes

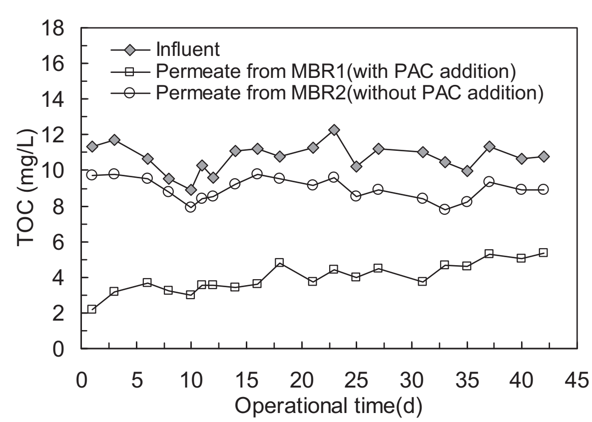

Fig. 2. Variation of TOC with operational time.

Table 3
Operational parameters of laboratory-scale SMBR apparatus.

Operational parameter	Value
Influent TOC (mg/L)	10.7 ± 1.32
Temperature (°C)	21 ± 3
Hydraulic retention time (HRT) (h)	4
Mixed liquor suspended solids (MLSS) (g/L)	~4.5
Organic loading rate (OLR) (kg TOC/kg MLSS d)	0.014 ± 0.001
Flux (L/m^2 h)	30

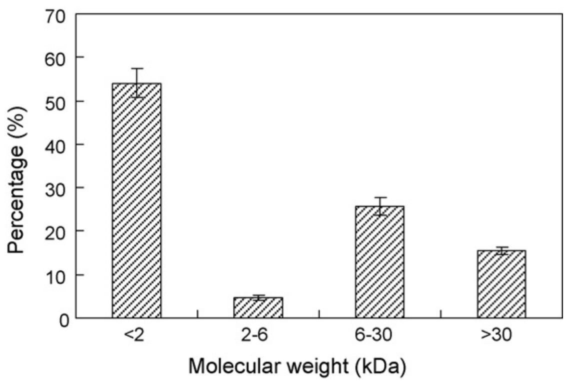

Fig. 3. TOC fraction in the secondary effluent.

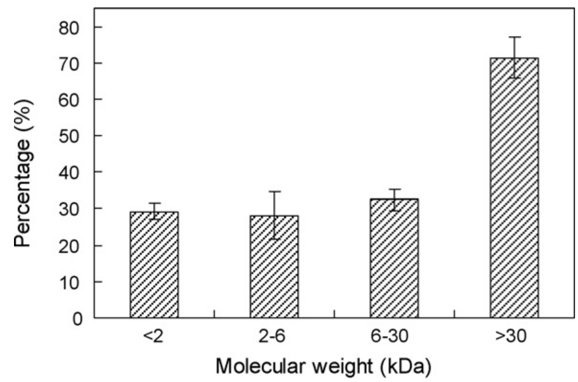

Fig. 4. Removal of TOC fraction (permeate from MBR1 was analyzed).

treatment could produce permeate almost completely free of SS [26]

3.2. TOC fraction of secondary effluent and its removal

The TOC fraction in the secondary effluent in term of apparent molecular weight (MW) distribution is shown in Fig. 3. It can be seen that about 54.2%, 4.8%, 25.7% and 15.4% of organics in the secondary effluent were in the MW range of lower than 2 kDa, 2–6 kDa, 6–30 kDa and higher than 30 kDa, respectively. The distribution was in line with Lee et al. [27]. The organic components in the secondary effluent are rather complicated. Lee et al. [27] found that the TOC in secondary effluent comprised 64% hydrophilic acid, 31%fulvic acid and 6% humic acid. It has been also reported that the certain amount of the soluble organic matter in the effluent from the biological treatment processes is actually soluble microbial product (SMP) [28]. Nevertheless, it is apparent from this study that most organics in secondary effluent were low MW matters, suggesting that they should pass through the UF membrane with MWCO of 140 kDa used in this study if no other measures involved. The UF and MF membrane processes are considered as cost-effective options in terms of higher permeate flux compared to NF and RO [29]. This study demonstrated that direct filtration of secondary effluent with UF or MF membrane would not be technical feasible if organics removal is of the interest. Even by using RO membrane, Hu et al. [6] reported that small MW fraction of the hydrophilic TOC in secondary effluent could preferentially transported through the membrane. Therefore, it might be necessary to combine several processes for advanced treatment of secondary effluent. Significant TOC removal shown in this study indicated that PAC-MBR process presented an attractive option for treatment of secondary effluent.

Removal of different TOC fraction can be calculated by comparison of influent and permeate from MBR1 with PAC addition. The results are shown in Fig. 4. In general, the results were consistent with the total TOC removal achieved in the PAC-MBR system. It also can be seen that the removal efficiency increased with MW. Certain removal of low MW matters can be attributed to the PAC adsorption, biological degradation and membrane interception (when membrane was fouled and thus membrane pores were narrowed [8]).

3.3. Contribution of various constituents to organics removal

The PAC-MBR system is a process which integrates physical adsorption, biological degradation and membrane filtration into one unit. Pollutant removal is achieved not only by biological degradation but also by PAC adsorption and membrane interception. The MBR without PAC removed only 16.1% of the influent organic matters. However, the addition of PAC to the MBR increased the removal efficiency up to 62.7%. Out of the total removal efficiency of 62.7%, it appeared that 46.6% was removed by PAC adsorption, 13.3% by biological degradation, and 2.8% by membrane separation, according to above calculation method. The results were consistent well with the data reported by Whang et al. [16].

Fig. 5 shows the adsorption characteristics when added PAC in the secondary effluent with a dosage of 750 mg/L. It can be seen from Fig. 5, equilibrium of PAC adsorption could be attained within 30 min. Its adsorption capacity and TOC removal efficiency were calculated as 7.5 mgTOC/gPAC and 50.1%, respectively. Direct PAC adsorption for secondary effluent treatment would cost lots as the ability of PAC adsorption to organics would be lost as soon as equilibrium of PAC adsorption reached. The TOC removal efficiency was very close to 46.6% fraction of PAC adsorption in PAC-MBR system. Continuous stable organics removal in PAC-MBR process highly indicated that there existed a mechanism to recover the ability of PAC absorption. It appears that the action of biomass and the PAC is mutual and synergistic. The presence of PAC increases the surface available for liquid–solid contact and facilitates the adsorption of microbial cells, enzymes and organics. This, in turn, provides an enriched environment for microbial metabolism, enabling the retained organic matters to be efficiently removed even at very low organic loading rate, and finally changes the microbial community. The interaction of biomass and the PAC should be further studied.

3.4. Membrane fouling analysis

Continuous experiments were operated initially at a fixed flux of 30 L/m^2·h without any cleaning or additional fouling control measures with the exception of the imposed tangential shear and intermittent filtration operation. Evolutions of TMP were

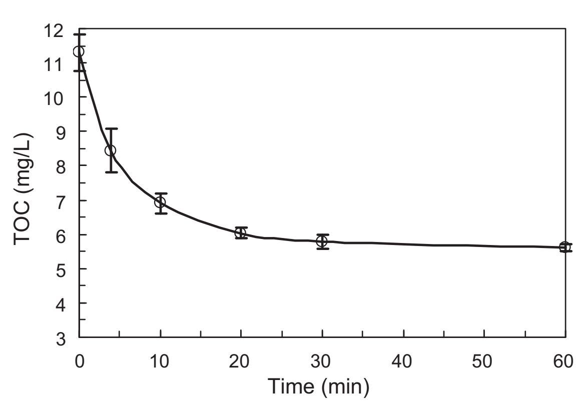

Fig. 5. TOC absorption by PAC as a function of operational time (PAC dose of 750 mg/L).

Table 4
Resistances of filtrating the sludge liquor obtained from the two MBRs.

	R_m (10^{11} m^{-1})	R_p (10^{11} m^{-1})	R_{ef} (10^{11} m^{-1})	R_c(= R_p + R_{ef}) (10^{11} m^{-1})	R_{if} (10^{11} m^{-1})	R_t (10^{11} m^{-1})
MBR1	1.59(39.92)[a]	1.53(38.43)[a]	0.78(19.70)[a]	2.31(58.13)[a]	0.08(1.95)[a]	3.97(100)[a]
MBR2	1.63(33.97)[a]	2.57(53.91)[a]	0.47(9.67)[a]	3.04(63.18)[a]	0.14(2.85)[a]	4.81(100)[a]

[a] Percentage of the total resistance R_t shown in parentheses.

monitored as shown in Fig. 6. An obvious two-stage TMP profile was observed with a period of slow TMP rise followed by a transition to a rapid TMP rise. Similar TMP profile was observed in other research works, although their interpretation with respect to flux sustainability is still debated [30]. Comparison of the two curves shows that the first period was prolonged by up to approximately 2 times for MBR1. If the first period was chosen as the actual sustainable operating time without membrane cleaning, the result indicated that the sustainable operating time was extended by up to 2 times for MBR1. It can be concluded from above analysis that addition of PAC alleviated membrane fouling.

Batch filtration tests were performed to assess the effects of PAC on the filtration characteristics of the sludge liquor from the two MBRs. Although the filtration resistance values obtained from batch filtration experiment may be somewhat different from those in real operation of MBRs, a comparison of them should be able to reflect some general aspects of sludge liquor filtration characteristics in the MBRs. Resistances for sludge filtration in the batch filtration tests are summarized in Table 4. As shown in Table 4, the cake layer resistance was dominant while the resistance caused by adsorption or pore plugging was marginal for the two MBRs. In addition, the polarization layer resistance and the total resistance for MBR1 were about 40.5% and 17.4% lower than those for MBR2, respectively. However, R_{ef} increased for the PAC-MBR system. This might be attributed to the increase in solid concentration of MBR1 by PAC addition. These results indicated that the reduction in membrane fouling mainly stemmed from the decrease in the polarization layer resistance and the cake layer resistance.

In MBR system, membrane fouling development was influenced by the fluid dynamics as well as sludge properties. These effects were then discussed to address the underlying causes of the alleviated membrane fouling in MBR1. Reynolds number was calculated as 11494 for MBR1 and 9261 for MBR2 according to the methods suggested by Meng et al. [31]. The higher Reynolds number value in MBR1 was mostly due to the lower dynamic viscosity of sludge suspension, and should partly contribute to the lower membrane fouling potential in MBR1. The values were comparable with some literature data [31,32], reflecting a turbulent hydrodynamics conditions. Previous studies have identified extracellular polymer substances (EPS) and colloids as the important factors affecting

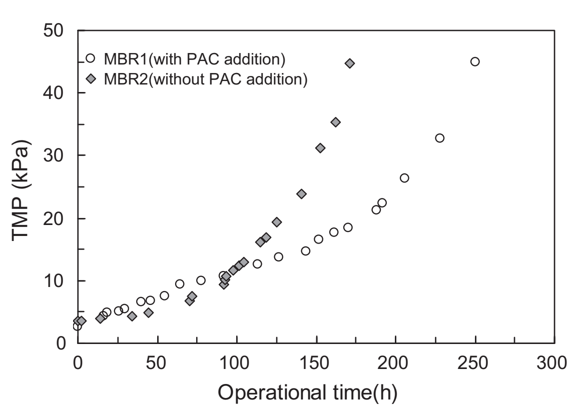

Fig. 6. Variation of TMP with time during operation of the two MBRs (MLSS = 4.5 g/L, flux = 30 L/m^2 h, PVDF flat sheet membrane).

membrane fouling [33,34]. Since PAC could serve as a coagulant to adsorb these substances, the reduction of membrane fouling was most likely attributed to PAC adsorption effect. A significant decrease in EPS content by PAC addition in MBR system has been reported [35]. Membrane fouling was also significantly controlled by the sludge floc size [36]. Examination of the bulk sludge liquor from the MBRs showed the mean floc size of 84 μm for MBR1 and 56 μm for MBR2. The increase in floc size, which could also be attributed to the PAC effect, should be another contributor of the reduced membrane fouling in MBR1. Our recent study [37] indicated that some bacterial strains play key role in cake formation on membrane surface. Therefore, a study regarding microbial community would be beneficial to better understand the mechanism underlying the membrane fouling mitigation in PAC-MBR process, and would be conducted in the future investigation. Nevertheless, this study demonstrated the feasibility of PAC-MBR treating secondary effluent in terms of applied membrane flux and sustainable operational period.

4. Conlusions

The study showed the long term enhanced performance of a PAC-MBR process for secondary effluent treatment in terms of organics removal and membrane fouling alleviation. Approximately 63%TOC, 95% NH_4^+–N and 98% turbidity in secondary effluent were removed by the PAC-MBR process. Parallel experiment showed that PAC addition increased organic removal significantly but had no visible influence on NH_4^+–N and turbidity removals. Most organics in secondary effluent were low MW matters, which could be retained in the reactor and then removed to some extent by using PAC-MBR process. PAC-MBR process treating secondary effluent was also found to have low membrane fouling potential. Based on these results, the PAC-MBR process was considered as an attractive option for secondary effluent treatment.

Acknowledgement

Financial support of Scientific Research Foundation for Doctor of Zhejiang Normal University (No. ZC304010040), Zhejiang Provincial Natural Science Foundation of China (No. Y5110157), and Youth Foundation of Zhejiang Normal University (No. KYJ06Y10196) is highly appreciated.

References

[1] C. van Riper, J. Geselbracht, Water reclamation and reuse , Water Environmental Research 71 (1999) 720–728.
[2] K. Zhang, K. Farahbakhsh, Removal of native coliphages and coliform bacteria from municipal wastewater by various wastewater treatment processes: implications to water reuse , Water Research 41 (2007) 2816–2824.
[3] J.L. Acero, F.J. Benitez, A.I. Leal, F.J. Real, F. Teva, Membrane filtration technologies applied to municipal secondary effluents for potential reuse , Journal of Hazardous Materials 177 (2010) 390–398.
[4] M. Rebhun, Desalination of reclaimed wastewater to prevent salinization of soils and groundwater , Desalination 160 (2004) 143–149.
[5] L. Fan, T. Nguyen, F.A. Roddick, J.L. Harris, Low-pressure membrane filtration of secondary effluent in water reuse: pre-treatment for fouling reduction , Journal of Membrane Science 320 (2008) 135–142.
[6] J.Y. Hu, S.L. Ong, J.H. Shan, J.B. Kang, W.J. Ng, Treatability of organic fractions derived from secondary effluent by reverse osmosis membrane , Water Research 37 (2003) 4801–4809.

[7] G. Inoue, H. Ogasawara, C. Yanagi, Y. Murayama, Advanced treatment of secondary sewage effluent by membrane process , Desalination 39 (1981) 423–434.
[8] H.-S. Shin, S.-T. Kang, Characteristics and fates of soluble microbial products in ceramic membrane bioreactor at various sludge retention times , Water Research 37 (2003) 121–127.
[9] F.G. Meng, H.M. Zhang, Y.S. Li, X.W. Zhang, F.L. Yang, J.N. Xiao, Cake layer morphology in microfiltration of activated sludge wastewater based on fractal analysis , Separation and Purification Technology 44 (2005) 250–257.
[10] K. Kimura, N. Yamato, H. Yamamura, Y. Watanabe, Membrane fouling in pilot-scale membrane bioreactors (MBRS) treating municipal wastewater , Environmental science and technology 39 (2005) 6293–6299.
[11] Z. Ying, G. Ping, Effect of powdered activated carbon dosage on retarding membrane fouling in MBR , Separation and Purification Technology 52 (2006) 154–160.
[12] A.Y. Hu, D.C. Stuckey, Treatment of dilute wastewaters using a novel submerged anaerobic membrane bioreactor , Journal of Environmental Engineering 132 (2006) 190–198.
[13] J.S. Kim, C.H. Lee, Effect of powdered activated carbon on the performance of an aerobic membrane bioreactor: comparison between cross-flow and submerged membrane systems , Water Environment Research 75 (2003) 300–307.
[14] G.T. Seo, S. Ohgaki, Y. Suzuki, Sorption characteristics of biological powdered activated carbon in BPAC-MF (biological powdered activated carbon-microfiltration) system for refractory organic removal , Water Science and Technology 35 (1997) 163–170.
[15] Y. Satyawali, M. Balakrishnan, Performance enhancement with powdered activated carbon (PAC) addition in a membrane bioreactor (MBR) treating distillery effluent , Journal of Hazardous Materials 170 (2009) 457–465.
[16] G.D. Whang, Y.M. Cho, H. Park, J.G. Jang, The removal of residual organic matter from biologically treated swine wastewater using membrane bioreactor process with powdered activated carbon , Water Science and Technology 49 (2004) 451–457.
[17] B. Van Der Bruggen, C. Vandecasteele, T. Van Gestel, W. Doyen, R. Leysen, A review of pressure-driven membrane processes in wastewater treatment and drinking water production , Environmental Progress 22 (2003) 46–56.
[18] J. Lee, W.-Y. Ahn, C.-H. Lee, Comparison of the filtration characteristics between attached and suspended growth microorganisms in submerged membrane bioreactor , Water Research 35 (2001) 2435–2445.
[19] H.J. Lin, K. Xie, B. Mahendran, D.M. Bagley, K.T. Leung, S.N. Liss, B.Q. Liao, Sludge properties and their effects on membrane fouling in submerged anaerobic membrane bioreactors (SAnMBRs) , Water Research 43 (2009) 3827–3837.
[20] APHA, Standard Methods for the Examination of Water and Wastewater , twentieth ed., American Public Health Association/American Water Works Association/Water Environmental Federation, Washington, USA, 2005.
[21] Water Environment Federation, Design of Municipal Wastewater Treatment Plants MOP 8 , McGraw-Hill Professional Publishing, 2009.
[22] Q.Y. Wu, Y. Li, H.Y. Hu, Y.X. Sun, F.Y. Zhao, Reduced effect of bromide on the genotoxicity in secondary effluent of a municipal wastewater treatment plant during chlorination , Environmental Science and Technology 44 (2010) 4924–4929.
[23] H. Palmer, M. Beutel, S. Gebremariam, High rates of ammonia removal in experimental oxygen-activated nitrification wetland mesocosms , Journal of Environment Engineering-ASCE 135 (2009) 972–979.
[24] S. Chaize, A. Huyard, Membrane bioreactor on domestic wastewater treatment: sludge production and modeling approach , Water Science and Technology 23 (1991) 1591–1601.
[25] Y.-Z. Li, Y.-L. He, Y.-H. Liu, S.-C. Yang, G.-J. Zhang, Comparison of the filtration characteristics between biological powdered activated carbon sludge and activated sludge in submerged membrane bioreactors , Desalination 174 (2005) 305–314.
[26] A.G. Fane, Membranes for water production and wastewater reuse , Desalination 106 (1996) 1–9.
[27] C.W. Lee, S.D. Bae, S.W. Han, L.S. Kang, Application of ultrafiltration hybrid membrane processes for reuse of secondary effluent , Desalination 202 (2007) 239–246.
[28] J. Chudoba, Inhibitory effect of refractory organic-compounds produced by activated-sludge microorganisms on microbial activity and flocculation , Water Research 19 (1985) 197–200.
[29] H.K. Shon, S. Vigneswaran, I.S. Kim, J. Cho, H.H. Ngo, Effect of pretreatment on the fouling of membranes: application in biologically treated sewage effluent , Journal of Membrane Science 234 (2004) 111–120.
[30] J. Zhang, H.C. Chua, J. Zhou, A.G. Fane, Factors affecting the membrane performance in submerged membrane bioreactors , Journal of Membrane Science 284 (2006) 54–66.
[31] F.G. Meng, B.Q. Shi, F.L. Yang, H.M. Zhang, New insights into membrane fouling in submerged membrane bioreactor based on rheology and hydrodynamics concepts , Journal of Membrane Science 302 (2007) 87–94.
[32] C. Psoch, S. Schiewer, Dimensionless numbers for the analysis of air sparging aimed to reduce fouling in tubular membranes of a membrane bioreactor , Desalination 197 (2006) 9–22.
[33] H. Nagaoka, S. Ueda, A. Miya, Influence of bacterial extracellular polymers on the membrane separation activated sludge process , Water Science and Technology 34 (1996) 165–172.
[34] Z. Wu, X. Wang, Z. Wang, X. Du, Identification of sustainable flux in the process of using flat-sheet membrane for simultaneous thickening and digestion of waste activated sludge , Journal of Hazardous Materials 162 (2009) 1397–1403.
[35] J.S. Kim, C.H. Lee, H.D. Chun, Comparison of ultrafiltration characteristics between activated sludge and BAC sludge , Water Research 32 (1998) 3443–3451.
[36] A.L. Lim, R. Bai, Membrane fouling and cleaning in microfiltration of activated sludge wastewater , Journal of Membrane Science 216 (2003) 279–290.
[37] H.J. Lin, W.J. Gao, K.T. Leung, B.Q. Liao, Characteristics of different fractions of microbial flocs and their role in membrane fouling , Water Science and Technology 63 (2011) 262–269.