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Journal of Hazardous Materials 154 (2008) 535–542
Journal of Hazardous Materials
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Application of flat-sheet membrane to thickening and digestion of waste activated sludge (WAS)

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Received 4 September 2007; received in revised form 15 October 2007; accepted 16 October 2007
Available online 22 October 2007

Abstract

The feasibility of using flat-sheet membrane for waste activated sludge (WAS) thickening and digestion was studied in this paper. The characteristics of the processes including the thickening efficiency, effluent water quality and filtration properties of the membrane for sludge thickening process (MST), digestion efficiency, effluent water quality and membrane permeability of the membrane for sludge simultaneous thickening and digestion process (MSTD) were investigated. Test results showed that good sludge thickening efficiency and superior effluent water quality were obtained in the MST process under hydraulic retention time (HRT) 0.26 and 2 d operation of each cycle, and the membrane fouling was mainly due to the increase of apparent viscosity of mixed liquors and the decrease of the cross-flow velocity (CFV) along membrane surfaces during one thickening cycle. Membranes were also selected for the processes and M1 membrane of polyvinylidene fluoride (PVDF) material with pore size 0.2 μm demonstrated better permeability compared with other three membranes. About 80% MLSS destruction rate and 73% MLVSS destruction rate were achieved under HRT 1 d, dissolved oxygen (DO) concentration 0.5–1.5 mg/L, temperature 20–28 °C and 15 d operation for one cycle in MSTD process, and membrane fouling of MSTD process was attributed to not only the reason of MST process mentioned above, but also the change of sludge properties such as the increase of soluble COD and microbial polymeric substances including EPS, carbohydrate and nucleic acids, etc. of the mixed liquors.

Keywords: Flat-sheet membrane; Membrane filtration; Sludge thickening; Sludge digestion; Waste activate sludge (WAS)

1. Introduction

Conventional activated sludge (CAS) process is a cost-effective and efficient method for wastewater treatment; however, it produces excess biomass as waste activated sludge (WAS) that is difficult and expensive to handle and dispose of, particularly in plants adapted for biological nutrient removal (BNR). The cost of WAS treatment and disposal can account up to 60% of the total operating cost in wastewater treatment plants (WWTPs) [1]. Due to the stringent effluent criteria and restrictions to landfill WAS, processing and disposal is becoming a more difficult and complex problem.

For volume reduction, thickening and dewatering is usually practiced. Sludge thickening is particularly important because it influences the reliability and performance of the entire sludge treatment system [2]. Sludge thickening is generally accomplished by physical means, including gravity thickening, dissolved air flotation (DAF) thickening, centrifugal thickening, etc. Several problems and disadvantages are still existing among the typical sludge thickening technologies, e.g., the large footprint and low thickening efficiency and the release of phosphorus under long sludge retention time (SRT) with gravity thickening process, lower quantity of sludge storage and higher energy cost with DAF thickening compared with gravity thickening, and much higher energy cost and advanced maintenance

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doi:10.1016/j.jhazmat.2007.10.057

Nomenclature

CFV	cross-flow velocity (m/s)
COD	chemical oxygen demand (mg/L)
DO	dissolved oxygen (mg/L)
E_{Di}	digestion efficiency of day *i* (%)
HRT	hydraulic retention time (d)
MLSS	mixed liquor suspended solids (mg/L)
MLVSS	mixed liquor volatile suspended solids (mg/L)
Q_i	influent sludge flow of day *i* (m^3/d)
SOUR	specific oxygen uptake rate (mgO_2/g-SS h)
SRT	sludge retention time (d)
TMP	trans-membrane pressure (Pa)
V	effective volume of the digestion reactor (m^3)
X_i	influent sludge concentration of day *i* (g/L)
X_{vi}	sludge concentration in the digestion reactor of day *i* (g/L)

requirements with centrifugal thickening technology [3–5]. If sludge thickening could not perform reliably, it would lead to an increase in volume load on the sludge dewatering process, a decrease in dewatering performance and an increase in pollution load of the return flow [2,6].

In order to solve some problems with conventional sludge thickening technologies, to provide an alternate process for sludge thickening and to improve its efficiency and reliability, the flat-sheet membrane for sludge thickening (MST) process was developed in this paper. In the MST process, the utilization of advanced membrane separation enables the independent control of sludge retention time (SRT) and hydraulic retention time (HRT) and thus ensures the thickening efficiency, and in the meantime the effluent quality of the process can be improved as well. In WWTPs, sludge digestion treatment is standard practice, for medium and large scale WWTPs, to have a stabilization step after thickening process in order to achieve its stabilization, detoxification and minimization, etc. [3]. In order to incorporate thickening and digestion in a single reactor and to reduce footprint of sludge treatment plant, the process of employing flat-sheet membrane for simultaneous sludge thickening and digestion (MSTD) was also developed. Although micro-filtration, ultra-filtration, nanoflitration and other processes coupled membrane solid–liquid separation such as membrane bioreactor (MBR) have been intensively studied and widely used for the treatment of municipal wastewater, industrial wastewater and surface water/drinking water in past decades [7–9], studies on the application of membrane to WAS thickening in published literatures could hardly be found. Therefore, the research on membrane for sludge thickening and digestion could be much valuable and might be very helpful to expand the application of membrane technology to WAS treatment field in WWTPs.

In this study, the characteristics including thickening efficiency, effluent water quality and membrane filtration properties of MST process, digestion efficiency, effluent water quality and membrane permeability of MSTD process were critically studied by employing the two processes for the treatment of WAS in a WWTP. The results obtained in this study are expected to provide a sound understanding of the MST and MSTD processes.

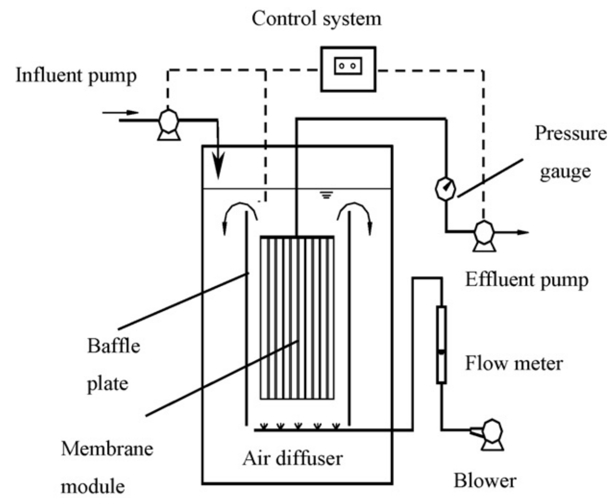

Fig. 1. Schematic flow diagram of the MST and MSTD processes.

2. Materials and methods

2.1. Experimental setup

The MST and MSTD reactors, which were located in Quyang Municipal WWTP of Shanghai, had similar configurations as shown in Fig. 1 but different sizes. The MST reactor had a total volume of 0.576 m^3 (0.6 m × 0.4 m × 2.4 m length × width × height) and effective volume of 0.456 m^3 with water level 1.9 m while MSTD reactor had a total volume of 0.0945 m^3 (0.45 m × 0.3 m × 0.7 m length × width × height) and effective volume of 0.075 m^3 with water level 0.56 m. Each of the reactors was divided into a riser zone and two down-comer zones by two baffle sheets, and membrane modules were located in the riser. Air was supplied through an axial perforated tube which was below the membrane modules in order to supply oxygen demanded by the microorganisms and induce a cross-flow velocity (CFV) along the membrane surfaces. Activated sludge of aerobic basin of the WWTP, which employs anoxic/oxic process for BNR of classic municipal wastewater, was supplied to the reactors. The properties of the activated sludge are listed in Table 1. The influent pump was controlled by a water level sensor to maintain a constant water level in the reactors over

Table 1
Influent sludge properties

Items	Value
MLSS (g/L)	3.4 ± 1.4
MLVSS (g/L)	2.6 ± 1.1
SV	95%
pH	7.2 ± 0.3
SCOD (mg/L)[a]	50 ± 10
NH_3–N (mg/L)[a]	8 ± 4

[a] It represents SCOD or ammonium concentration of the filtrates which were obtained by filtering influent sludge samples with pore size 0.45 μm filter paper.

Table 2
Operating conditions of the two processes

Items	MST	MSTD
Effective reactor volume (L)	456	75
Number of modules	10	1
Total filtration area (m^2)	7.3	0.15
Flux (L/(m^2 h))	5–15[a]	25
Average HRT (d)	0.26	1
One cycle time (d)	2	15
Aeration intensity (m^3/h)	6	2
DO (mg/L)	0.5–6	0.5–1.5
Temperature (°C)	20–28	20–28

[a] Although constant flow rate mode was adopted, the membrane flux of M4 membrane was reduced during one cycle due to severe membrane fouling.

the experimental period. The membrane-filtered effluent was then obtained by suction using a pump connected to the modules. The effluent flow rate and the trans-membrane pressure (TMP) were monitored by a water meter and a pressure gauge, respectively.

2.2. Membrane modules and operating conditions

The membranes provided by Shanghai Zizheng Environmental Technology Co. Ltd. (China) were made of polyvinylidene fluoride (PVDF) with different pore sizes. The mean pore size of membrane M1, M2, M3 and M4 was 0.20, 0.25, 0.3 and 0.4 μm, respectively. Two kinds of modules with different size were also provided, i.e., effective filtration area of each module 0.73 m^2 for the MST reactor and effective filtration area of each module 0.15 m^2 for the MSTD reactor. Filtration operation of the two reactors was conducted with the constant flow rate by employing constant flow pumps. Intermittent filtration (10-min filtration and 2-min pause) was carried out during the whole experiment. Other parameters and operational conditions are described in detail in Table 2.

2.3. Analytical methods

Measurements of COD, ammonia, nitrate and nitrite in the membrane effluent, mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS) and pH of the influent sludge and in the pilot-pant were performed according to Chinese NEPA standard methods [10]. Soluble COD (SCOD) samples were obtained by filtering the mixed liquors through filter paper with mean pore size 0.45 μm. CFV was determined using Cup-type Current Meter (Model LS45A, Chongqing Hydrological Instrument Incorporated, Chongqing, China). DO concentration in the reactor was measured by a dissolved oxygen meter (Model YSI 58, YSI Research Incorporated, Ohio, USA). The mixed liquor viscosity was measured by a revolving viscosity meter (Model NDJ, TJ Environmental Facility Incorporated, Shanghai, China) at a shear rate of 940 1/s. The phenol–sulfuric acid method of Dubois et al. [11] was used for carbohydrate determination. Glucose was used as a standard. The method described in the literature for the assay of nucleic acids [5] was adopted. The procedures for EPS assay were according to the thermal treatment method presented by Chang and Lee [12]. Specific oxygen uptake rate (SOUR) was determined according to the standard procedure provided by Zhang [13].

The digestion efficiency in terms of MLSS destruction or MLVSS destruction of MSTD process is calculated according to Eq. (1):

$$E_{Di} = \frac{\sum_0^i Q_i X_i - V X_{vi}}{\sum_0^i Q_i X_i} \times 100\% \quad (1)$$

where E_{Di} is the digestion efficiency of day i, Q_i the influent sludge flow of day i (m^3/d), X_i the influent sludge concentration of day i (g/L), V the effective volume of the digestion reactor (m^3), and X_{vi} the sludge concentration in the digestion reactor of day i (g/L).

3. Results and discussion

3.1. Efficiency of the MST process

3.1.1. MLSS variations

Fig. 2 shows the variations of MLSS and MLVSS during the 10 cycles of sludge thickening. It can be seen that during one cycle (2 days) the MLSS increases from low concentration to about 30 g/L. At the end of one cycle, the thickened sludge was discharged, and then the reactor was filled with new activated sludge of the WWTP and the next cycle of sludge thickening continued. It has to be pointed out that the initial sludge concentration of one cycle in the reactor may be higher than that of the influent sludge because the thickened sludge cannot be drained out completely (about 10% left in the reactor) due to the reactor's configuration. We also controlled the drainage of thickened sludge in cycles 4–6 in order to test the thickening performance of MST process under different initial sludge concentration. About 60% of the thickened sludge at the end of cycle 4 and cycle 5, and 70% of the thickened sludge at the end of cycle 6 were drew off, and correspondingly the initial sludge concentration in the reactor of cycle 5, cycle 6 and cycle 7 was about 15, 16 and 11 g/L, respectively. In cycles 5–7 under high initial sludge concentration, about 30 g/L thickened sludge was also achieved. The variations of MLVSS during the ten cycles were similar to those of MLSS during the ten cycles, and the con-

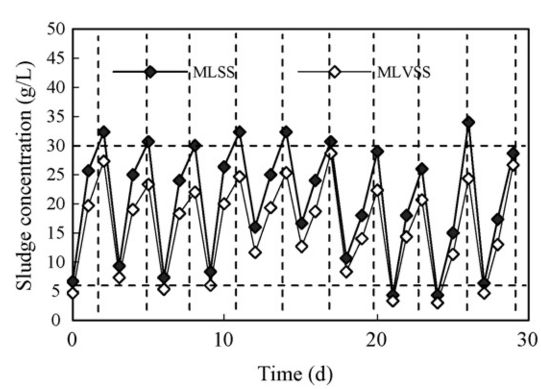

Fig. 2. The variations of Sludge concentration of the process.

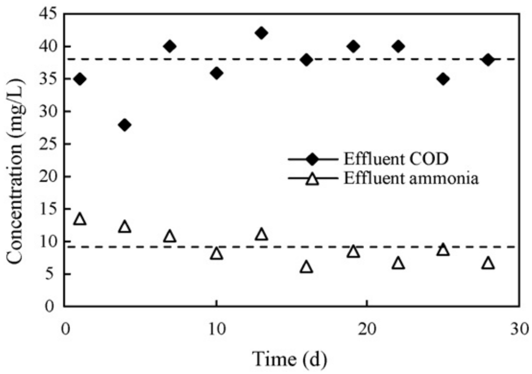

Fig. 3. The effluent COD and ammonia of the 10 cycles.

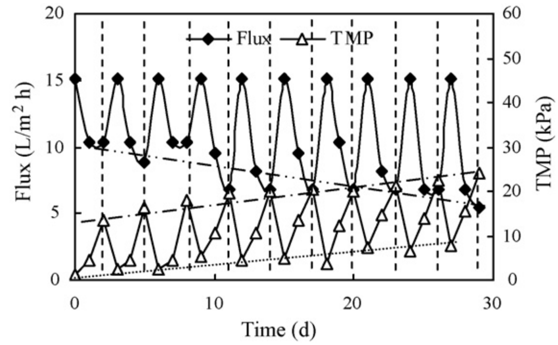

Fig. 4. The variations of flux and TMP during the ten cycles.

centration of MLVSS increased to about 25 g/L under different initial sludge concentration in the reactor.

In one cycle, DO concentration in the reactor decreased as the sludge concentration increased. The initial DO concentration of the mixed liquors was about 6 mg/L with sludge concentration about 5 g/L under most of the cycles, and DO concentration was reduced to about 0.5 mg/L at the end of one cycle with thickened sludge concentration about 30 g/L. The reduction of DO concentration is mainly due to the decrease of oxygen transfer coefficient at high sludge concentration [14,15].

3.1.2. Effluent water quality

The effluent COD and ammonia of MST during the ten cycles are illustrated in Fig. 3. The effluent COD was in the range of 28.0–42.0 mg/L and the average concentration 37.2 mg/L; the effluent ammonia was ranging from 6.3 to 13.5 mg/L and the average concentration 9.3 mg/L. The effluent water was free of SS during the 10 cycles. However, the effluent COD of gravity thickening and DAF thickening reported by Ding and Chen [16] in WWTPs was 1028 and 428 mg/L, respectively. Hu et al. [17] adopted a novel cavitation air flotation (CAF) process for WAS thickening, and the effluent SCOD of this process was about 30–40 mg/L and the effluent SS 200–250 mg/L with the addition of polymer coagulant FO4440SH 1 kg/*t* DS (Dried sludge). Compared with the effluent quality of the conventional sludge thickening processes, the effluent quality of MST process is very superior.

3.1.3. Membrane filtration characteristics

The variations of TMP and membrane flux (membrane M4) during the 10 cycles are shown in Fig. 4. It can be observed that during one cycle the TMP increases as the sludge concentration in the reactor increases. The initial TMP and the ultimate TMP of one cycle tended to increase from cycle 1 to cycle 10. The initial TMP and the ultimate TMP of the first cycle was about 1.3 and 13.3 kPa, respectively; the initial TMP and the ultimate TMP of the second cycle became 2.3 and 16.4 kPa, respectively; and at the tenth cycle, the initial TMP and the ultimate TMP increased to 7.7 and 24 kPa, respectively. It indicated that the fouling which occurred at one cycle accumulated gradually and thus the initial and ultimate TMP values of the next cycle were higher than those of the previous cycle. It can be found that the ultimate membrane flux of one cycle also decreases as the number of cycles keeps increasing. The initial membrane flux of each cycle was controlled at about 15.0 L/(m^2 h) and the mode of constant flow rate for filtration was carried out, but the flux during one cycle tended to decrease due to the dramatic TMP increase and the severe membrane fouling. At the first cycle, membrane flux decreased from the initial 15.0 to 10.3 L/(m^2 h), and the membrane flux of the second cycle ranged from 15.0 L/(m^2 h) to the ultimate 8.9 L/(m^2 h), and the ultimate fluxes of the next cycles kept reducing and the ultimate flux of the tenth cycle was just about 5.5 L/(m^2 h).

The membrane fouling mechanism during one cycle sludge thickening could be mainly attributed to two aspects: one was the increase of apparent viscosity of the mixed liquors in the reactor, and the other was the decrease of CFV along membrane surfaces. Fig. 5 illustrates the variations of apparent viscosity of the mixed liquors during the 10 cycles. It is clear that apparent viscosity goes up with the increase of sludge concentration during each cycle. The results are well consistent with the study conducted by Khongnakorn et al. [18]. The apparent viscosity increased from about 2 to about 30 mPa s as sludge concentration was enhanced from about the initial 5 g/L (except the cycles 5–7 with part of thickened sludge left in the reactor) to about 30 g/L. It is worth pointing out that the apparent viscosity in the end of second cycle (see Fig. 5) is much higher than those of other cycles though the sludge concentration (as shown in Fig. 2) is closed to those in the end of other cycles. It might be attributed to the fact the screen with 0.9 mm pores through which the raw sludge was fed into the

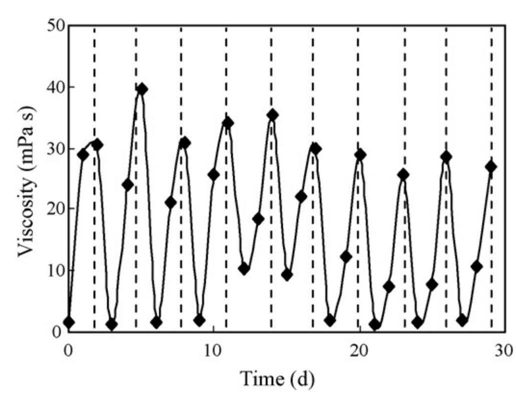

Fig. 5. Apparent viscosity variations during ten cycle operation.

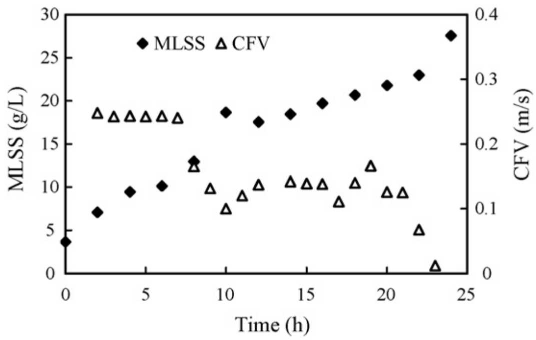

Fig. 6. CFV variations with MLSS concentration during one cycle operation.

reactor was broken during the second cycle, and that might cause particles or other substances to enter the reactor and result in different sludge characteristics from the rest cycles. The increase of apparent velocity had an effect on membrane permeability and thus resulted in membrane fouling. In fact, it has been reported that apparent viscosity has a significant influence on membrane fouling and membrane filtration operation in submerged MBRs [19,20].

It is well known that CFV has a positive influence on membrane filtration operation, and the increase of CFV can help control membrane fouling and enhance the membrane permeability [21–23]. The variations of CFV along membrane surfaces in the reactor with the increase of MLSS concentration during one cycle (24 h) are shown in Fig. 6. The CFV was about 0.25 m/s with the sludge concentration in the range of 4.0–10.0 g/L, and it began to decrease as sludge concentration increased above 10.0 g/L and then leveled off at 0.14 m/s with sludge concentration ranging from 17.0 to 22.0 g/L, and when sludge concentration was over 22.0 g/L, it started to decrease again and finally it reached about 0.01 m/s at sludge concentration 28 g/L. Therefore, the decrease of CFV during sludge thickening process could be one of key factors influencing membrane fouling in this study.

3.2. The selection of membranes for MST process

In order to classify the effect of membrane properties on filtration performance of the MST process, four membrane modules were used and the permeability of each membrane for sludge thickening was studied. The variations of membrane flux and TMP of the four membrane modules during one cycle (24 h) are presented in Fig. 7. In Fig. 7(A), it can be observed that the membrane fluxes of M1, M2 and M3 are in the range of 20–27 L/(m^2 h) and membrane flux of M1 is a little larger especially during the first 12 h operation; however, the membrane flux of M4 decreases rapidly during the operation. As shown in Fig. 7(B), the TMP of M4 membrane increases dramatically while the TMP values of M1, M2 and M3 do not vary greatly during the operation, and the M1 membrane has lower TMP values compared with the other three membranes. Therefore, according to the permeability property of the four membranes, it could be concluded that M1 membrane was more suitable for the MST process.

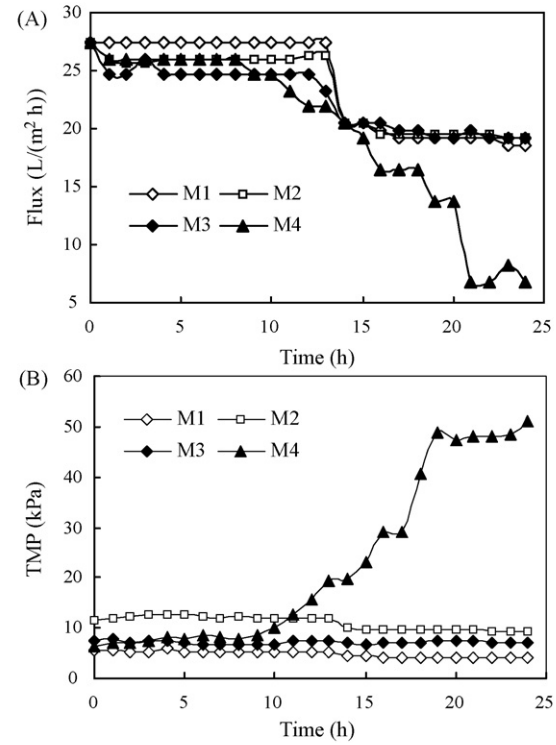

Fig. 7. The variations of membrane flux (A) and TMP (B) of four membrane modules.

In our study, the M1 membrane with smallest pore size was found to have best permeability compared the rest membranes with big pore size. It might be due to the fact that membrane modules with big pore size could have more severe membrane fouling at the early stage of filtration [24]. In fact, other researchers also have found that membrane modules with smaller pore size show better permeability than that of those with bigger pore size [25] when they investigated the filtration characteristics in an anaerobic membrane bioreactor. It also needs to point out that the conditions of this study were different from those experiments mentioned in above literatures and the detailed mechanisms are worth further studying.

3.3. Membrane for simultaneous sludge thickening and digestion (MSTD)

3.3.1. MLSS, MLVSS variations and digestion efficiency

The variations of MLSS and MLVSS with operation time in MSTD reactor at HRT 1 d, DO concentration 0.5–1.5 mg/L and temperature of the mixed liquors 20–28 °C are illustrated in Fig. 8(A). It is worth pointing out that the DO concentration decreased with the increase of MLSS during the thickening process and that might have a negative effect on the destruction efficiency especially at the late period of one cycle. During 1 day, the temperature of mixed liquors varied from 20 to 28 °C and that could affect the digestion efficiency due to the temperature variations; however, the variations of each day during the 15-day operation were almost the same and thus the influence of the temperature change on digestion efficiency during one cycle was not discussed in detail here. The MLSS concentration could

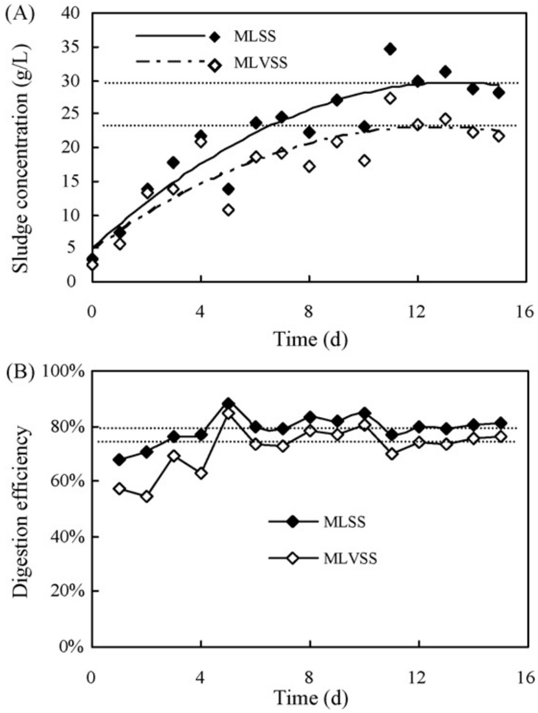

Fig. 8. The variations of MLSS and MLVSS (A) and digestion efficiency (B) during the operation in the MSTD process.

achieve about 30 g/L and MLVSS concentration reached about 23 g/L after 15 d operation. The digestion efficiency of MLSS and MLVSS, as shown in Fig. 8(B), was about 80% and 73%, respectively.

The destruction efficiency of MLSS and MLVSS, specific oxygen uptake rate (SOUR) are the two commonly used parameters to indicate the performance of aerobic digestion [26]. In this study, about 80% destruction efficiency of MLSS and 73% destruction efficiency of MLVSS were achieved at the end of the operation (15 d) and DO concentration 0.5–1.5 mg/L in the MSTD process, which are higher than those reported by other researchers using conventional aerobic digestion process for WAS treatment. Bernard and Gray [26] found that a reduction of 42–53% MLSS and 53–64% MLVSS was achieved under SRT 35 d at ambient temperature (about 20 °C) when they used aerobic digestion process to treat three domestic sludges with feeding MLVSS 3–5 g/L; about 50% MLVSS destruction rate was also reported by Novak et al. [27] under SRT 50 d, initial total solids (TS) 10–13 g/L and digestion temperature 20 °C. Arunachalam et al. [28] further studied the effect of DO concentration on sludge digestion efficiency and observed that about 62% MLVSS destruction efficiency was reached by employing aerobic digestion process under DO 0.2–1 mg/L, initial TS 28 g/L and SRT 19 d at room temperature about 20 °C and about 62.5% MLVSS destruction under DO 3–4 mg/L, initial TS 16 g/L and SRT 15 d. The higher digestion efficiency achieved in the MSTD process could be attributed to the fact that in this process the influent undigested sludge with low concentration was continuously fed into the reactor and the influent undigested sludge would be blended with the previously digested sludge existing in the reactor to continue the digestion process. In fact, it has been proven

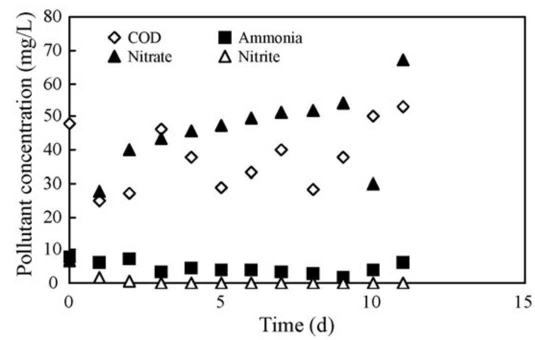

Fig. 9. Effluent water quality during the operation.

that the destruction efficiency of MLSS and MLVSS in aerobic digestion can be enhanced by addition of digested sludge into the digester filled with undigested WAS and the digested sludge could serve as the source of viable cell mass needed for degradation of organic solids [29]. The MSTD process could naturally utilize the mechanisms and thus the digestion efficiency was higher compared to the conventional aerobic digestion process.

The SOUR of the MSTD process during the operation was also determined and the results showed that the SOUR decreased gradually form initial value 4.5 to 0.98 mgO_2/g-SS h and 78% reduction of SOUR was achieved. It is in agreement with the SOUR reduction in conventional aerobic digestion process reported by Khalili et al. [29].

3.3.2. Effluent water quality

The effluent water quality of the MSTD process during 15 d operation is shown in Fig. 9. The effluent COD was ranging from 25.0–53.0 mg/L despite the high SCOD concentration in the mixed liquor (133–728 mg/L as shown in Fig. 11), which might due to the fact that the cake layer formed on the membrane surfaces and, to some extent, prevented some soluble microbial products from entering the effluent water. The increase of SCOD in the process demonstrated that organic substances were released into the mixed liquor attributed to sludge destruction. The effluent ammonia was in the range of 1.8–8.0 mg/L, and the nitrate concentration kept increasing during the operation and reached higher than 67.0 mg/L while nitrite was about 0–1.9 mg/L. The continuous increase of nitrate concentration of the effluent indicated that the nitrogen released into the reactor due to sludge destruction was mainly oxidized to nitrate and accumulated in the reactor.

3.3.3. Membrane filtration characteristics and membrane fouling

The M1 membrane was used in the MSTD process, and its TMP and flux profiles during the operation are illustrated in Fig. 10. It can be seen that the membrane flux is maintained at about 25 L/(m^2 h) during the 15 d operation while the TMP keeps increasing from 3.5 to 27 kPa.

The TMP profile of MSTD process shows rapid increase especially after day 6, which indicates the corresponding membrane fouling occurs dramatically. One of membrane fouling reasons could be the increase of sludge concentration in the reac-

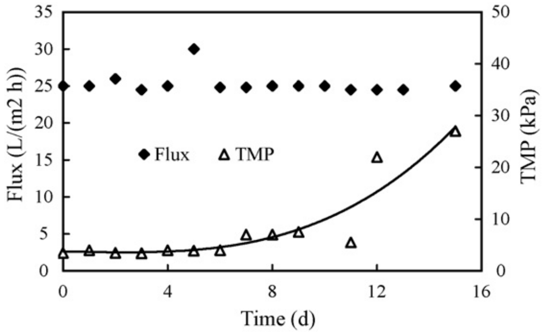

Fig. 10. TMP and membrane flux variations of MSTD during 15 d operation.

tor which thus caused large apparent viscosity and low CFV as mentioned in MST section. In addition, other factor contributing to the membrane fouling of MSTD process should be the variations of the sludge characteristics. Fig. 11 illustrates the SCOD variations and the change of polymeric substances of the mixed liquor during the operation, respectively. It can be observed from Fig. 11(A) that the SCOD concentration of the mixed liquors in the reactor increases rapidly with the operation time. It has been verified that SCOD has a significant effect on membrane fouling during membrane filtration operation [15,30,31]. The polymeric substances of microorganisms including EPS, carbohydrates, nucleic acids and proteins, as shown in Fig. 11(B), also demonstrated a general tendency of increase with operation time. It was also reported that severe fouling was caused by microbial polymeric substances [19,32,33], and the main fouling mechanisms of those microbial polymeric substances could be deposition, accumulation and consolidation of them on membrane surface [19] and/or reduction the permeability by filling the void spaces between cell particles [34].

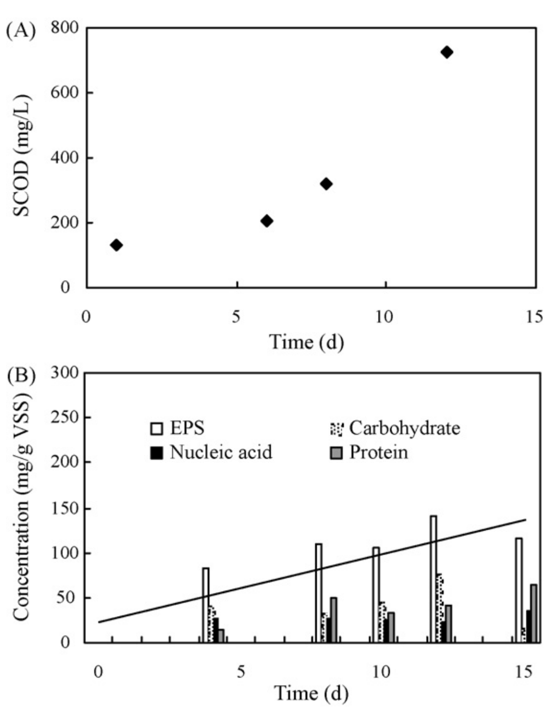

Fig. 11. SCOD variations (A) and polymeric substances (B) of the mixed liquors during the operation (*Note*: the protein was approximately calculated by subtracting carbohydrate and nucleic acids from EPS).

4. Conclusions

The characteristics of using flat-sheet membrane for WAS thickening and digestion were studied, and the following conclusions could be drawn.

(1) WAS could be successfully concentrated from initial concentration about 5 g/L (except cycles 5–7 with part of thickened sludge left in the reactor) to about 30 g/L by employing the MST process at HRT 0.26 d, temperature 20–28 °C and 2 d operation (one cycle). The effluent COD and ammonia of the process was in the range of 28.0–42.0 mg/L and 6.3–13.5 mg/L, which was much better than those of conventional sludge thickening processes reported in literatures.
(2) In the MSTD process, about 80% MLSS destruction efficiency and 73% MLVSS destruction efficiency were achieved after 15 d operation under HRT 1 d, dissolved oxygen (DO) concentration 0.5–1.5 mg/L, temperature 20–28 °C. Superior effluent water quality was also obtained in the process, and the effluent COD, ammonia, nitrate and nitrite were 25.0–53.0 mg/L, 1.8–8.0 mg/L, 7.0–67.2 mg/L and 0–1.9 mg/L, respectively.
(3) Membrane M1 of PVDF material with membrane pore size 0.2 μm was more suitable for the MST process because it demonstrated higher membrane flux at relatively lower TMP compared with the other three membranes with the same material but with different pore size (0.25, 0.3 and 0.4 μm).
(4) The membrane fouling of the MST process was mainly due to the fact that the increase of sludge concentration in the reactor resulted in the increase of apparent viscosity and the decrease of CFV along membrane surfaces during one cycle of operation. Membrane fouling of MSTD process was attributed to not only the increase of sludge concentration which resulted in high apparent viscosity and low CFV, but also the change of sludge properties such as the increase of soluble COD and microbial polymeric substances including EPS, carbohydrate and nucleic acids, etc. of the mixed liquors with the operation time.

Acknowledgement

This study was financially supported by Science and Technology Commission of Shanghai Municipality (STCSM) under grant No. 052312046.

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