Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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Online publication date: 20 February 2003

To cite this Article Tay, Joo-Hwa , Zeng, Jack Luhai and Sun, Darren Delai(2003) 'Effects of Hydraulic Retention Time on System Performance of a Submerged Membrane Bioreactor', Separation Science and Technology, 38: 4, 851 — 868
To link to this Article: DOI: 10.1081/SS-120017630
URL: http://dx.doi.org/10.1081/SS-120017630

SEPARATION SCIENCE AND TECHNOLOGY
Vol. 38, No. 4, pp. 851–868, 2003

Effects of Hydraulic Retention Time on System Performance of a Submerged Membrane Bioreactor

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ABSTRACT

To investigate the effect of hydraulic retention time (HRT) on system performance in a submerged membrane bioreactor (MBR) with a prolonged sludge retention time (SRT) for the treatment of industrial wastewater, six runs of a laboratory scale MBR with HRTs of six days, three days (two runs), one day, 12 hours, and 6 hours, respectively, were conducted. The MBR process was capable of achieving over 90% COD removal, on average, almost independent of HRT. Membrane rejected 70–90% of residual COD in bioreactor to ensure high quality of effluent even if the biological treatment process mal-functioned. With declining HRT, sludge concentration in the bioreactor increased accordingly, while the ratio between mixed liquor volatile suspended solid (MLVSS) and mixed liquor suspended solid (MLSS) remained constant in each run. The governing equation in activated sludge process was re-examined and found

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DOI: 10.1081/SS-120017630 0149-6395 (Print); 1520-5754 (Online)

applicable in MBR systems with a prolonged SRT. The mean particle size at different HRTs were in the range of 24.4 to 58.18 μm, lower than that in activated sludge process. Filtration performance was found to be associated with the stability of mean particle size. Constant or superior filtration performance was studied during the experiment period to search the cues of the potential solution for the fouling problem. Based on the system performance at different HRT, an optimal HRT of 12 hours was suggested to optimize MBR system performance—to achieve economy in design and a constant and superior filtration performance in operation.

Key Words: Membrane bioreactor; Hydraulic retention time; Submerged ceramic membrane; Prolonged sludge retention time; Fouling; Optimal HRT.

INTRODUCTION

Activated sludge processes have been developed and applied in the wastewater treatment for more than a century. Though one of the most prevailing solutions for biological wastewater treatment,[1] this conventional treatment technology has produced a huge amount of excess sludge, of which the treatment and disposal represents 50% of total treatment cost.[2] Little improvement has been achieved in controlling sludge yielding, largely due to the inherent relationship between sludge retention time (SRT) and hydraulic retention time (HRT)[3]:

$$X_{\mathrm{r}} = \frac{SRT \times Y_{ob} \times (S_i - S_o)}{HRT} \quad (1)$$

Where X_{r} is the sludge concentration in the bioreactor, S_{i} and S_{o} are the substrate concentration in influent and effluent, respectively, and Y_{ob} is observed sludge yield. Since activated sludge process separates the sludge from the supernatant by gravitational settling, the settleability requirement in settling tank has limited X_{r} to be less than 5 g/L, mixed liquor suspended solids (MLSS).[4] Thus, SRT and HRT are highly interdependent to maintain X within such a narrow range, according to Eq. (1).

Membrane Bioreactor (MBR) has been developed to replace the settling tank in activated sludge process by a membrane unit, which possesses excellent solid–liquid separation abilities to retain virtually all biomass, and therefore produce a high bacteria concentration, MLSS of 5–20 g/L.[5,6] This unique feature has generated many promising results, such as the shortening of HRT from the typical range of 5–14 hours to as low as 2 hours.[7] Enormous research attentions have been drawn to materialize the low HRT and derive high MLSS, while only a few researchers have reported the study on long SRT. The effect of sludge retention time on microbial behavior in a submerged membrane bioreactor was reported by Xia Huang et al.[8] Muller et al.[9] proved the feasibility of infinite SRT, for they performed effectively zero sludge discharge for an MBR system. Subsequently, the practices of infinite SRT or extremely long SRT, for instance, 3120 days,[10] were explored for the benefits of minimizing the sludge discharge, and the ensuing substantial saving in sludge treatment and disposal cost. However, the influents used in their experiments were municipal or synthetic municipal wastewater, containing low COD strength.

For industrial applications, inorganic suspended solids from influents might cause adverse effects on MBR systems, if effectively zero sludge discharge practice is adopted for the long run. To strike a balance, a study was conducted to investigate the feasibility of the prolonged SRT in the MBR system for the treatment of industrial wastewater. Moreover, since SRT and HRT have been decoupled due to the presence of the membrane, the present work focused on the effects of HRT on system performance of the MBR system with a prolonged SRT in order to identify the optimal HRT for a given MBR system.

MATERIALS AND METHODOLOGY

Figure 1 shows the configuration of the submerged MBR system: a bioreactor with a submerged tubular ceramic membrane unit. The ceramic membrane was manufactured by USF Filtration, France, and had an external Al_2O_3 layer at pore size of 0.20 μm, with external diameter of 1 cm. An activated sludge reactor with working volume of 4.0 L was fed with the synthetic wastewater. The on-line sensors were installed to maintain the constant water surface level in the bioreactor, via the solenoid valve to control feeding speed. Therefore HRT was solely dependent on effluent flowrate, which was regulated by a suction pump.

The feed used in this study simulated high-strength industrial wastewater containing high amounts of glucose and protein. Synthetic wastewater with COD of 2400 mg/L was used. Table 1 listed the concentrations of all the necessary inorganic and micronutrients, as well as nitrogen, phosphorous, and carbon sources.

Sludge was taken from Jurong wastewater treatment plant, Singapore, and assimilated for four weeks before the MBR operation. The experiment was performed in six runs with HRT varying from 6 days to 6 hours. The SRT of MBR

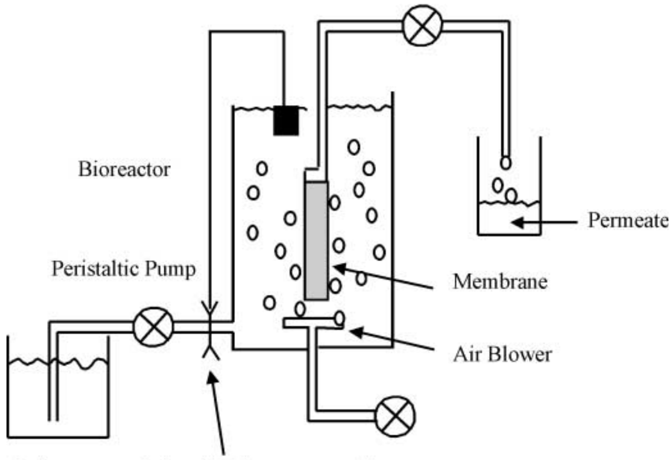

Figure 1. Schematic diagram of the submerged tubular ceramic membrane bioreactor.

was chosen at 200 days to avoid both the adverse effect of accumulated nonbiodegradable substances in MBR system, resulting from effectively zero sludge discharge, and large quantity of discarded sludge yielded due to typical short SRT. This prolonged SRT remained unchanged throughout all six runs. To supply sufficient oxygen for bacteria activities, aeration was supplied at 4L-air/L min to maintain dissolved oxygen (DO) greater than 4 mg-O_2/L, as well as to alleviate the fouling problem along the membrane surface. Tubular ceramic filtration membranes were backwashed whenever the suction pressure became higher than 30 kPa. Temperature of the mixed liquor was maintained at 25°C

Table 1. Synthetic high-strength feed composition.

Components	Concentration (mg/L)	Components	Concentration (mg/L)
COD	2400	K_2HPO_4	45
Glucose	1400	$CaCl_2-2H_2O$	30
Peptone	800	$MgSO_4-7H_2O$	25
Beef extract	2500	$FeSO_4-7H_2O$	20
NH_4Cl	200		

Table 2. Operating conditions of the membrane bioreactor.

Run	Duration (day)	SRT (day)	HRT	DO (mg-O/L)	Food loading (g-COD/day)
Run 1	31	200	6 days	>4	0.6
Run 2	49	200	3 days	>4	1.2
Run 3	33	200	3 days	>4	1.2
Run 4	57	200	24 hours	>4	2.4
Run 5	52	200	12 hours	>4	4.8
Run 6	46	200	6 hours	0.2–2.1	9.6

within a temperature-controlled room. Operating conditions of the six runs are summarized in Table 2. The only difference in operation between run 2 and run 3 was that the former was the continuation from run 1, while the latter started when a deliberate disturbance occurred to the sludge at the end of run 2. For each run, the experiment halted when the MBR system reached steady state, which is defined as a state with constant MLSS and mixed liquor volatile suspend solids (MLVSS), constant sludge particle size, and constant quality of effluent.

The organic compounds and particulate matter in the mixed liquor of the submerged MBR system were monitored at less twice per week for the rest of the experiment duration, except for the startup stage of each run, where a daily record was kept. The analytical methods used were in accordance with the Standard Methods for Examination of Water and Wastewater (1998).[11] COD was analyzed according to the method of 5220C; MLSS and MLVSS followed methods of 2540D and 2540E, respectively; specific oxygen utilization rate (SOUR) followed the method of 2710B; sludge volume index (SVI) taken by the method of 2710D. Following parameters were measured by respective analysis equipment: total organic carbon (TOC) by a Shimadzu TOC analyzer, Model 5000, size distribution by a Malvern Mastersizer, Model Microplus, suction pressure by Druck digital pressure indicator, model DPI 260. A Scanning Electron Microscope (SEM) was utilized to examine the structural characteristics of the membrane surface.

RESULTS AND DISCUSSION

COD Removal Performances

COD removal obtained in an MBR system when the process reached steady state under different HRT conditions is shown in Fig. 2(a). The removal

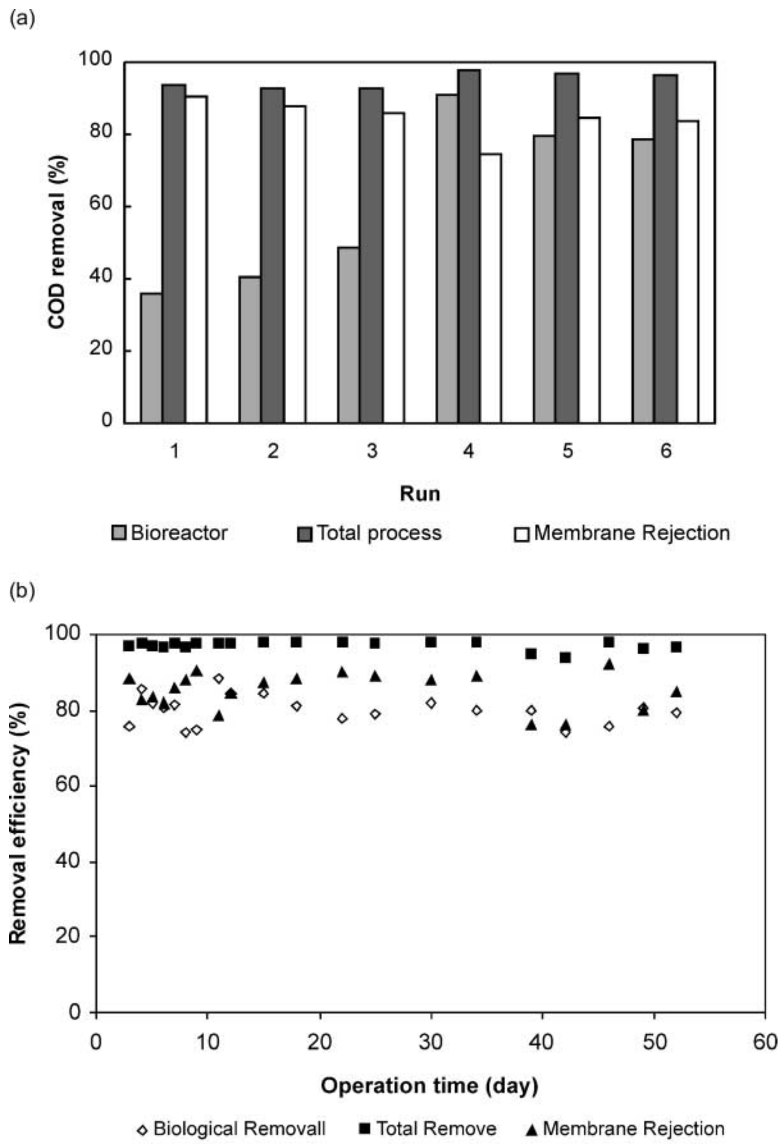

Figure 2. (a) COD remove efficiency in bioreactor and total process and membrane rejection performance at different HRTs; (b) COD remove efficiency in bioreactor and total process and membrane rejection performance through run 5.

efficiencies were based on the data of the centrifuged supernatant liquor and membrane-filtered effluent, respectively. The former were mainly due to biological degradation in the bioreactor, while the later is attributed to membrane separation mechanism. In runs 1 to 3, biological removal efficiencies, measuring the biological degradation efficiency between COD in influent and that in bioreactor, were less than 50%, substantially less than the corresponding values of 80–90% in runs 4 to 6. SOUR tests were conducted to monitor the bacteria metabolism activities. The measured values indicate an ailing microbial community in runs 1 to 3 with SOUR of 20–30 mg-O/ g-MLVSS hr, compared to the typical values in runs 4 to 6 of 50–200 mg-O_2/ g-MLVSS hr. The different bacteria activities levels explained the large differences of biological removal efficiencies among various runs.

Although the biological treatment efficiency in run 1 was not as effective as compared with run 4, COD removal of 35.7% vs. 90.74%, but the COD remove efficiencies of the total process for both system were above 90%, as shown in Fig. 2(a). In fact, COD remove efficiencies of the total process for all runs of experiment were above 90%. The difference between the removal efficiency of the bioreactor and that of the total system indicated that a fraction of dissolved COD components, probably microbial soluble products (MSP) with a relatively large molecular weight, could be retained by the membrane to some extent. To highlight the effect of membrane separation mechanism on COD removal, membrane rejection was included in Fig. 2(a), which is defined as the COD removal efficiency cross-membrane. Generally, when biological degradation is less effective, membrane unit will produce a greater cross-membrane COD removal efficiency, as depicted in Fig. 2(a). Overall, membrane could further reduce 70–90% of residual COD in the bioreactor. Therefore, it plays an important role in maintaining high and stable COD removal. In addition, a typical COD removal efficiencies history diagram in run 5 in shown in Fig. 2(b) to illustrate the stable COD removal performance throughout the operation phase.

Sludge Growth and Kinetic Parameters

In a biological treatment process, sludge concentration is an important design parameter. It ensures biological treatment ability and at the same time affects the excess sludge yield. Figure 3 showed the sludge concentration at the steady states for each run. With the declining HRT, stabilized sludge concentration increased accordingly. MLSS concentration under HRT condition of six days stabilized in 2.4 g/L, and reached about 20 g/L when HRT reduced to six hours, a tenfold increment in MLSS, and far exceeded that

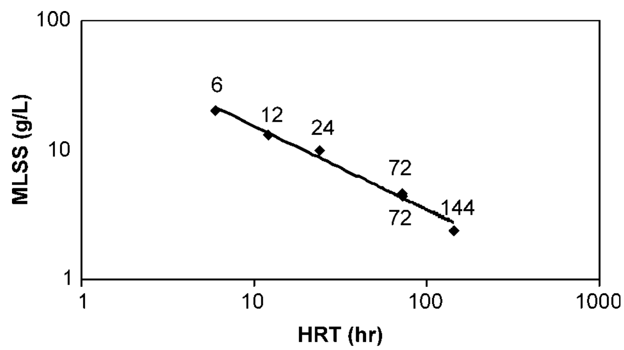

Figure 3. Stabilized sludge concentrations in MBR system at different HRTs.

in an activated sludge process. The high MLSS enhanced nutrient removal and produced better effluent quality. More importantly, it also showed that the bioreactor volume could be reduced as the system could be operated at higher organic loading, as indicated in Table 2. The following power function relationship between stabilized MLSS (X) and HRT was developed by the regression analysis

$$X = 67.906\,\mathrm{HRT}^{-0.6465} \tag{2}$$

On the other hand, the ratio of MLVSS/MLSS was almost constant during the experiment period. For instance, Fig. 4 showed the changes of sludge

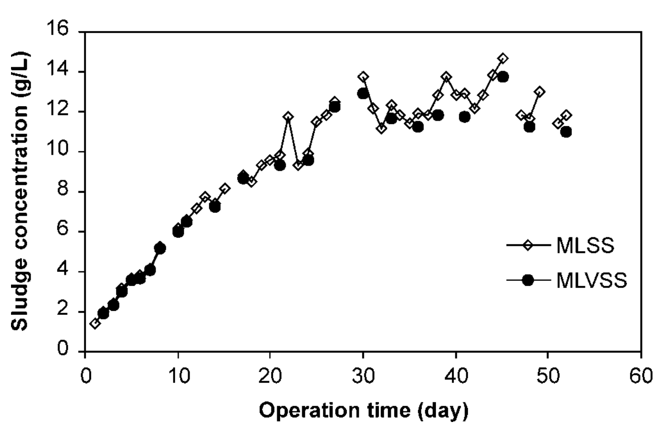

Figure 4. Changes of sludge concentration in MBR system at HRT = 12 hours.

concentration in the MBR system at HRT of 12 hours, run 5. The MLVSS/MLSS was in the range of 0.9–1.0, which indicated no obvious accumulation of inorganic matters in the bioreactor.

With the presence of membrane unit, Eq. (1), which was derived from the activated sludge process, might not be applicable to the MBR system. Therefore, the conventional sludge growth model had to be re-examined to accommodate the changed operation system. The objective of this analysis was to establish the relationship among HRT, SRT, bacteria metabolism, substrate concentration, and sludge concentration. To apply mass balance with respect to substrate, sludge, and water to the MBR system, the following equations were attained:

$$V\mathrm{d}S_r/\mathrm{d}t = Q_iS_i - (Q_oS_o + Q_wS_w) + r_sV \tag{3}$$

$$V\mathrm{d}X_r/\mathrm{d}t = Q_iX_i - (Q_oX_o + Q_wX_w) + r_gV \tag{4}$$

$$Q_i = Q_o + Q_w \tag{5}$$

where V(L) is the volume of the bioreactor, Q(L/day), S(mg-COD/L), and X(mg-MLVSS/L) are the flow rate, substrate concentration, and sludge concentration, respectively, and the subscripts i, o, and w refer to influent, effluent, and disposed liquid, respectively. The sludge generation rate, r_g (mg-MLVSS/L day) and substrate utilization rate r_s (mg-COD/L day) were defined as follows[3]:

$$r_g = -Yr_s - k_dX_r \tag{6}$$

$$Y_{ob} = -\frac{r_g}{r_s} \tag{7}$$

where Y and Y_{ob} are the maximum and observed yield coefficients (mg-MLVSS/mg-COD), respectively. k_d (/day) is endogenous decay coefficient.

X_r was a few orders of magnitude greater than X_i and X_o, for membrane retained virtually all sludge. Q_i, Q_o were in the same order of magnitude as V_r in this case. Thus, it was assumed that Q_iX_i and Q_oX_o equal to 0 in Eqs. (3) and (4), hence,

$$r_g = \left(\frac{Q_w \times X_w}{V} + \frac{dX_r}{dt}\right) \tag{8}$$

$$-r_s = \left[\frac{Q_o(S_i - S_o)}{V} + \frac{Q_w(S_i - S_w)}{V} - \frac{dS_r}{dt}\right] \tag{9}$$

In this study, SRT was kept at 200 days, and S_w equals to S_r, and X_w to X_r, so SRT and HRT could be obtained by the following equations:

$$\mathrm{SRT} = VX_r/(Q_wX_w + Q_oX_o) = V/Q_w \tag{10}$$

$$\mathrm{HRT} = V/Q_o = V/Q_i \tag{11}$$

At the steady state, both substrate and sludge concentration were constant, therefore Eqs. (8) and (9) could be further simplified:

$$r_g = X_r/\mathrm{SRT} = -Yr_s - k_dX_r \tag{12}$$

$$\begin{aligned} r_s &= -[(S_i - S_o)/\mathrm{HRT} + (S_i - S_r)/\mathrm{SRT}] \\ &= -(S_i - S_o)/\mathrm{HRT} \quad [(S_i - S_o) > (S_i - S_r) \text{ and} \\ &\qquad \mathrm{HRT}/\mathrm{SRT} = 0.125 \sim 3\%] \end{aligned} \tag{13}$$

Solving Eqs. (7), (12), and (13), the following expressions can be obtained:

$$X_r = \frac{SRT \times Y_{ob} \times (S_i - S_o)}{HRT} \tag{14}$$

$$Y_{ob} = \frac{Y}{(1 + k_d \times SRT)} \tag{15}$$

Eq. (14) was derived from the simplification of Eqs. (8) and (9), based on the assumptions for submerged MBR system with a prolonged SRT. It is identical to Eq. (1), which is used in the design of activated sludge process.

In this study, SRT was kept constant and $(S_i - S_o)$ and MLVSS/MLSS were almost constant. Generally, Y_{ob} fluctuates within a narrow range. Therefore, X_r will increase with declining HRT, according to Eq. (14). This provided the theoretical explanation for the data presented in Fig. 3. However, the regression expression, Eq. (2), showed that X_r, which was a fixed fraction of X, and HRT was not in strict inverse proportion relationship, though linked by a power equation.

To investigate the sludge yield with varying HRT, Y_{ob} was calculated according to Eq. (14). Table 3 showed that the observed sludge yield, Y_{ob}, decreased from 0.0288 to 0.0097, when HRT was declining from six days to six hours. The possible explanation was that when HRT dwindled, X_r increased and then impeded effective oxygen transfer at high sludge concentration. The variation of Y_{ob} resulted in the insufficiency of Eq. (14) to predict the stabilized sludge concentration, X_r, for the design of MBR system.

Table 3. Observed sludge yields of MBR system at different HRTs.

Run	HRT (day)	MLVSS (g/L)	($S_i - S_o$) (g-COD/L)	Y_{ob}
1	6	2.16	2.25	0.0288
2	3	4.14	2.23	0.0279
3	3	3.96	2.23	0.0267
4	1	9	2.34	0.0192
5	0.5	11.7	2.33	0.0126
6	0.25	18	2.32	0.0097

Hence, a more comprehensive study should be carried out to establish a database for Y_{ob} under different HRT, SRT, substrate consumption, and bacteria metabolism activities for the design of commercial application of MBR system.

According to Eq. (14), an increase in SRT will increase the stabilized sludge concentration, X_r. This statement is well supported by the research efforts of Xia Huang et al.,[8] who found MLVSS, X_r, increased from the range of 0.5–0.7 g/L to 4.9 g/L when SRT prolonged from 5 days to 40 days. Similarly, due to poorer oxygen transfer at higher sludge concentration, observed sludge yield, Y_{ob}, would decline with an increasing SRT. Eq. (15) was employed to analyze Y_{ob} with SRT, based on data from a paper published by Xia Huang et al.[8] The calculated results had confirmed the prediction of declining Y_{ob}, as shown in Table 4.

Table 4. Observed sludge yields of MBR system at different SRTs.

SRT[a] (day)	Y^a (g-VSS/G-COD)	$k_d{}^a$ (/day)	Y_{ob}
5	0.37	0.32	0.1423
10	0.38	0.17	0.1407
20	0.35	0.18	0.0761
40	0.33	0.09	0.0717
80	0.28	0.05	0.0560

[a] Data are quoted from Xia Huang et al.[8]

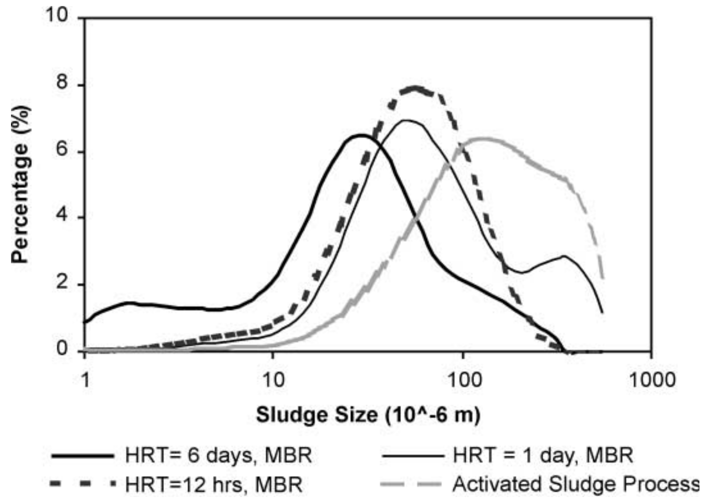

Figure 5. Sludge particle size distributions at steady state in MBR system with different HRTs and in activated sludge process.

Particle Size

Figure 5 showed the activated sludge particle size distributions at steady state in MBR systems with different HRTs and in activated sludge process, which could be characterized by a normal distribution in this logarithm scale drawing. The average of particle sizes of activated sludge in MBR systems at HRTs of 6 days, 1 day, and 12 hours were 24.00, 58.18, and 48.41 μm, respectively. This study showed that different HRTs did not exert influential effect on particle size distribution, though mean sludge particle sizes fluctuated within a narrow band of 24 to 60 μm for all six runs. Although the size distributions were widely dispersed and varied with different HRTs, the sludge was far different from its counterpart in activated sludge process, where it was large and even wider distributed, as shown in Fig. 5. This reduction in particle size was attributed to the fact that the aeration in the MBR system, which was to provide sufficient oxygen supply and prevent fouling on the membrane surface, broke down the mean size of sludge flocs. Moreover, the smaller sludge particles are desirable, as they enhance mass transfer process so that it induces a higher organic removal rate and better oxygen utilization.

The present measured values are similar to those of Xia Huang for the submerged MBR[8] but are larger than that those of the external MBR system.[12] The external MBR system is different from submerged MBR systems by putting the membrane filtration unit outside the bioreactor. A strong shear stress has to be maintained to drive the mixed liquor through the recycling pump system. This force will decrease the bonding force holding the sludge fabric, and then destroy large sludge flocs. Therefore, mean sludge particle size in the external MBR system is smaller than its counterpart in the submerged MBR system.

Filtration Performance and Optimal HRT

The permeate flux rate was set to a constant value so that HRT remained unchanged, during every run of the experiment by means of vacuum pump. Undesirably increasing pressure was built up cross-membrane, due to fouling phenomenon. Specific flux rate (SFR), defined as flux rate per unit transmembrane pressure, was adopted in this study to denote permeability quantitatively. The filtration performance in runs 4 to 6 was reported in Fig. 6. The general filtration performance in runs 1 to 3 were in the range of 20–40 L/m^2 hr bar, which was generally much slower than the prevailing filtration range of 70–450 L/m^2 hr bar as shown in Fig. 6.

It is clear that SFR varies drastically during the operation period. Also, SFR was continuously declining, signifying the accumulation of fouling layer on the membrane surface and continuous deterioration in filtration performance. In general, SFR is much lower than the initial value, corresponding to the new membranes against mixed liquor. The peaks

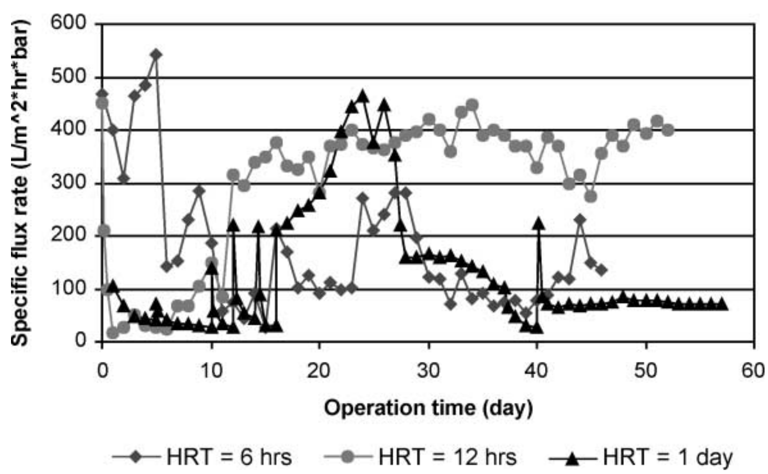

Figure 6. Filtration performance of submerged MBR in runs 4 to 6.

appearing in the filtration performance curve represented the events of backwash, which resorted partially the SFR value, as illustrated in Fig. 6.

There were two particular periods in filtration performance in run 4 that deserved close examination. The first period occurred after the backwash on day 17: SFR was not subjected to the usual immediate and rapid decline, instead, it rapidly increased to about 450 L/m^2 hr bar, which is much greater than the typical SFR for MBR systems, 20 to 200 L/m^2 hr bar.[12] Then, this super-high SFR fluctuated within 350–450 L/m^2 hr bar, before it suddenly dwindled to 160 L/m^2 hr bar, subsequently to as low as 27 L/m^2 hr bar. The second period took place after backwash on day 40: the superior filtration performance phenomenon was not observed; following the immediate decrease of SFR, the permeability remained constantly within 70–80 L/m^2 hr bar, till the end of the experiment run 4.

Though there might be many factors contributing to two special periods, particle size of sludge could play an influential role in the occurrence of these two periods. Figure 7 correlated the permeability performance of membranes with mean particle size of sludge in run 4. It is obvious that the super performance phenomenon occurred when the mean particle size of sludge remained at about 130 μm. The decline of SFR might well be a result of the collapse of sludge size, as shown in Fig. 7. The second period could be well explained by sludge size as well, since both SFR and mean particle size of sludge maintained constant.

Although the superior filtration performance phenomenon only existed for a short period, its implications are far-reaching. First, it suggested that

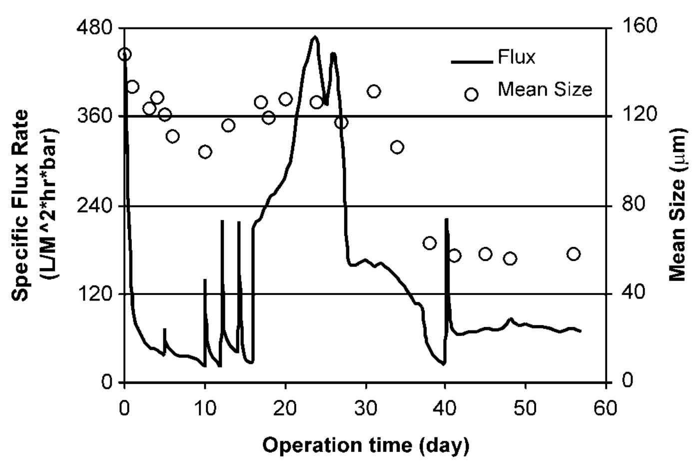

Figure 7. Correlation between specific flux rate and mean size of sludge in run 4.

there might be an optimal particle size for filtration performance of MBR, where high permeability can be attained, and the fouling problem is substantially mitigated. Second, even if the optimal particle size cannot be achieved due to other operation conditions, a stable filtration performance can result from a constant particle size, as shown in the second special period in Fig. 7.

Judging from Fig. 6, the filtration performance in run 5 was superior to others, as the MBR system obtained a constant and superior permeability, where its mean particle size is almost constant during the superior filtration performance period, as shown in Fig. 8. This supported the proposed hypothesis derived from the analysis of run 4 filtration performance. More importantly, this valuable advantage induced the concept of optimal HRT. As shown in the present study, for a given prolonged SRT, MBR system enabled the employment of different HRTs in the operation. However, when HRT is too long, the treatment process is not economic. On the other hand, if HRT is too short, according to Eq. (14), the stabilized sludge concentration will be extremely high, causing detrimental effects to the system, such as depleted DO and volatile filtration performance (requiring frequent backwash). Thus, in the design of the MBR system with a prolonged SRT, it is crucial to identify a suitable HRT value to optimize the system performance. In the present study, the MBR system with an HRT of 12 hours has produced the most desirable results—constant and superior filtration performance.

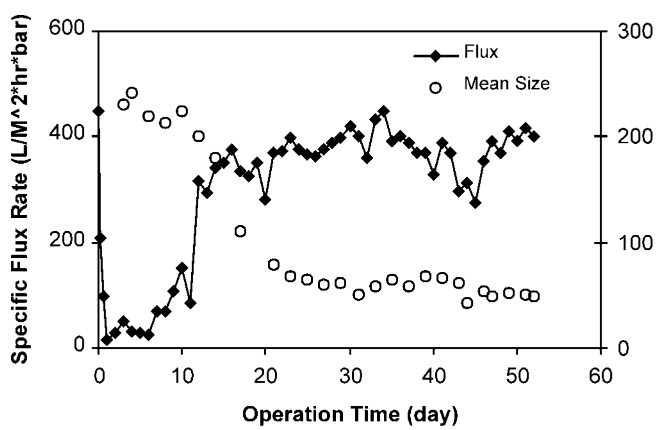

Figure 8. Correlation between specific flux rate and mean size of sludge in run 5.

CONCLUSION

Based on the results obtained from this study, the following conclusions can be drawn:

1. The membrane bioreactor with a prolonged SRT of 200 days was capable of removing over 90% COD, almost independent of hydraulic retention time. Membrane successfully rejected 70–90% residual COD in the bioreactor, and therefore ensured the high removal efficiency even when the biological treatment process did not function effectively.
2. With a given prolonged SRT, sludge concentration at steady state, X, increased with decreasing HRT. The regression analysis based on the experiment results showed that X is associated with HRT in a power function. Moreover, the MLVSS/MLSS ratio of 0.9–1.0, remained almost constant throughout the operation time, indicating no accumulation of inorganic matter in the bioreactor.
3. The mean sludge particle size at different SRT was in the range of 24.4 to 58.18 μm, lower than that in activated sludge process.
4. Filtration performance was studied to search the cues of potential solutions for membrane fouling program. The stability of particle size was correlated to filtration performance.
5. The concept of optimal HRT was derived to optimize MBR system performance and achieve economy in design and a constant and superior filtration performance in operation.
6. A set of equations was derived to establish the relationship of various parameters for the MBR system.

SYMBOLS

HRT	hydraulic retention time
k_d	endogenous decay coefficient
Q_i	flow rate of influent
Q_o	flow rate of effluent
Q_w	flow rate of disposed liquid
r_{g}	sludge generation rate
r_{s}	substrate utilization rate
S_{i}	substrate concentration in influent
S_{o}	substrate concentration in effluent

S_w	substrate concentration in disposed liquid
S_r	substrate concentration in the bioreactor
SRT	sludge retention time
t	time
X	sludge concentration
X_i	sludge concentration in influent
X_o	sludge concentration in effluent
X_w	sludge concentration in disposed liquid
X_r	sludge concentration in the bioreactor
Y	maximum yield coefficient
Y_{ob}	observed yield coefficient
V	volume of the bioreactor

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