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A Pilot Study on Performance of a Membrane Bio-Reactor in Treating Fresh Water Sewage and Saline Sewage in Hong Kong

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Abstract: The results of two pilot studies of an immersed membrane bioreactor (MBR) treating fresh water and saline sewage in Hong Kong are presented. The objectives were to demonstrate suitability of the MBR technology to the treatment of Hong Kong sewage and its ability to achieve total nitrogen removal effectively. When operated in nitrification/denitrification mode, the MBR was able to achieve 98% BOD removal, 90–93% COD removal and 82–84% total nitrogen removal with a HRT of 6.8 hours and 300% internal flow recirculation. Very low effluent NH_4^+-N levels were observed throughout the study suggesting complete nitrification. The MBR was able to achieve full denitrification utilizing organic matter in the raw sewage as a carbon source. The nitrogen removal capacity of the MBR was limited by nitrogen loadings rather than the biological activity in the reactor. The results did not indicate any significant differences in treatment performances with fresh water and saline sewage except that a higher frequency of membrane cleaning was required for the latter.

Keywords: Saline sewage, submerged membrane bio-reactor, nitrogen removal, municipal sewage treatment

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INTRODUCTION

The volumetric treatment capacity of a conventional activated sludge system is typically low due to its low biomass concentration, thereby resulting in a large surface area for the reactor (1). With the emergence of new regulations concerning the quality of receiving waters, the release of high numbers of pathogenic viruses, bacteria, and parasites is another major concern with the conventional sewage treatment (2). These shortcomings of the activated sludge process could be overcome by integrating membrane filtration with biological degradation (1, 3). Using membrane filtration for solid-liquid separation, the biomass concentration in the reactor can be increased by several folds as compared to a conventional activated sludge process. This helps to achieve nitrification and denitrification without the need for extended aeration (3). Other notable advantages of the membrane bio-reactor (MBR) technology are the production of high-quality effluent in terms of organic matter and nutrients, rejection of pathogenic organisms which eliminates extensive disinfection (4), and the maintenance of higher biomass concentrations that lead to very compact treatment systems (5, 6). In addition, two major concerns of activated sludge processes, the washout of slowly growing nitrifiers and the sludge bulking due to filamentous growth, are not relevant anymore (2). Because of these advantages, the MBR has emerged as an alternative treatment process, especially in situations where space and water resources are limited and superior effluent quality is required, in particular for wastewater reuse.

Hong Kong municipal sewage contains a high concentration of chloride ($\sim$6000 mg Cl^-/L) and sulfate ($\sim$500 mg/L) due to seawater toilet flushing practice. The saline sewage may not only cause excessive sludge foaming in the existing sewage treatment plants, which may lead to a significant washout of nitrifiers in winter so that the nitrogen removal performances could be affected, but also create difficulties in disinfecting the effluent containing a high amount of bromide. The membrane bio-reactor (MBR) technology may provide a potential solution to these problems since it enables slowly growing nitrifying bacteria to develop and persist in the system even under a short HRT (1) and it is effective in rejecting coliform bacteria (3), thereby eliminating extensive disinfection and the corresponding hazards related to the disinfection by-products. In addition, Hong Kong needs a compact treatment technology as the land is at a premium, which makes the MBR a more attractive solution. With this in mind, the Drainage Services Department of the HKSAR Government initiated pilot trial of an immersed hollow-fibre membrane bioreactor (MBR). The pilot trial was conducted to evaluate suitability of the MBR technology in treating Hong Kong saline sewage and to assess its nitrogen removal performance. The results of two MBR pilot trials at Shek Wu Hui sewage treatment works (SWHSTW) and Stonecutters Island sewage treatment works (SCISTW) are presented in this paper.

MATERIALS AND METHODS

System Configuration

A 40-m^3/day MBR pilot plant, which was provided by Mitsubishi Rayon (Tokyo), was installed and operated consecutively at two sewage treatment works (STW): Shek Wu Hui STW treating fresh water sewage and Stonecutters Island STW treating saline sewage. The process schematic of the MBR pilot plant is shown in Fig. 1. The pilot plant with an effective volume of 11.25 m^3 was split into two compartments: a 4.5-m^3 anoxic compartment for denitrification followed by a 6.75-m^3 aerobic compartment for nitrification and organic removal. A polyethylene hollow fibre membrane (Sterapore® SUR) with pore size of 0.4 μm was immersed in the aeration chamber provided with coarse bubble diffusers for aeration. Accumulation of solids on the membrane surface was prevented by shearing action of uprising air bubbles. The pilot plant received raw screened sewage after grit removal from the respective STW. Both the pilot plants were seeded with return activated sludge from local sewage treatment plants.

Operation Conditions

The operating conditions of the pilot plant are listed in Table 1. The hydraulic retention time (HRT) was maintained at 6.8 hours and 300% internal flow recycling was provided for denitrification. The final effluent was withdrawn through the membrane filter using a suction pump operating on a timed cycle (13 min ON and 2 min OFF). A highly concentrated biomass

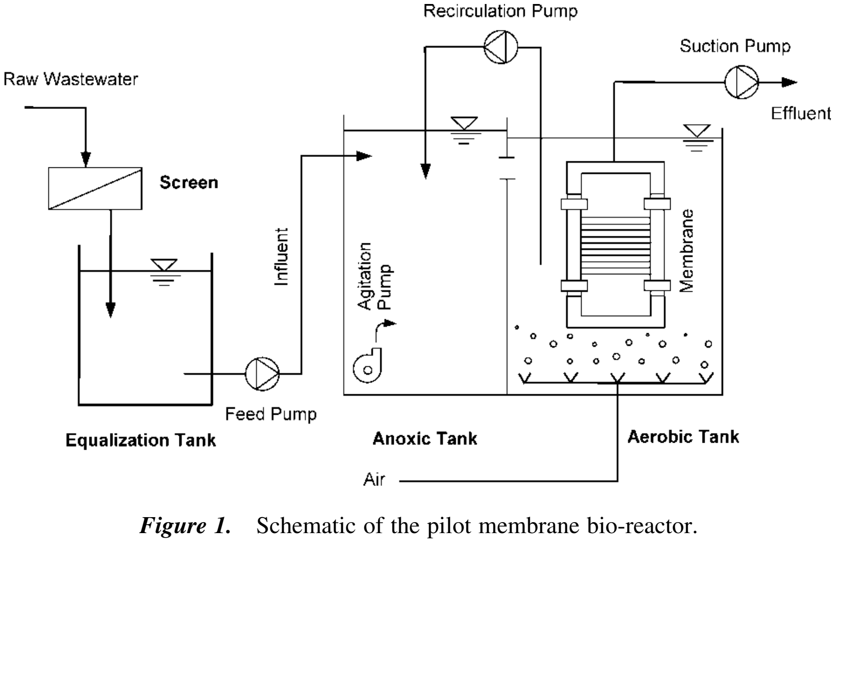

Figure 1. Schematic of the pilot membrane bio-reactor.

Table 1. Operating conditions of the MBR pilot plant

	Shek Wu Hui STW		Stonecutters Island STW	
Parameters	Phase I	Phase II	Phase I	Phase II
HRT (hr)	6.8	6.8	6.8	6.8
Internal flow recycle	300%	300%	300%	300%
Average MLSS (g/L)	8.1	10.8	8.4	12.3
Average DO in aeration tank (mg/L)	2.7	2.6	2.9	2.4
F/M ratio (kg COD/kg MLSS-day)	0.19	0.13	0.23	0.14
Volumetric loading				
COD (kg/m^3-day)	1.54	1.40	1.93	1.72
TKN (kg/m^3-day)	0.19	0.17	0.14	0.13
Wastewater temperature (°C)	18.1–26.9	22.0–28.3	26.3–35.8	24.9–28.8
Effluent discharge: suction-idle (min)	13 : 2	13 : 2	13 : 2	13 : 2

(8–12 g MLSS/L) was maintained in the reactor throughout the operation. Each pilot trial, which included two operational phases with different biomass levels, lasted for about 3 months. The wastewater temperature varied from 18 to 28°C for SWHSTW pilot trial and 25 to 36°C for SCISTW pilot trial. The dissolved oxygen (DO) level in the aeration tank was maintained at a minimum of 2 mg/L in both trials.

Sewage Characteristics

Raw sewage from the SWHSTW and SCISTW was treated in the respective MBR pilot plants. Characteristics of the sewage in two pilot trials are compared in Table 2. The sewage characteristics were found to vary considerably over the entire operation during each pilot trial. Except the chloride concentration and the TKN (Total Kjeldahl Nitrogen), the raw sewage characteristics for both the pilot trials were comparable. The chloride concentration in the raw wastewater at SCISTW was 3500–7870 mg/L, while the wastewater at the SWHSTW contained a very low chloride level. The raw sewage TKN for SWHSTW pilot plant was somewhat higher (mean = 53 mg/L) than that for SCISTW pilot plant (mean = 38 mg/L).

Sample Analysis

Twenty-four hour composite samples (both raw sewage and treated effluent) were collected using an auto-sampler and the samples were stored at 4°C

Table 2. Raw sewage characteristics

	Shek Wu Hui STW			Stonecutters Island STW		
Parameters	Max.	Mean	Min.	Max.	Mean	Min.
pH	7.6	7.1	6.5	7.7	7.0	6.4
Chloride (mg Cl^-/L)	—	—	—	7870	5916	3500
Alkalinity (mg/L as $CaCO_3$)	372	235	150	576	275	114
BOD_5 (mg/L)	345	167	106	410	186	62
COD (mg/L)	2204	458	146	1032	515	152
TKN (mg/L)	151	53	34	130	38	18
TSS (mg/L)	1806	191	64	896	206	26

prior to the analysis of BOD_5, COD, TKN, NH_4^+-N, NO_3^--N, NO_2^--N, and TSS. Dissolved oxygen level in the aerobic tank, oxygen reduction potential (ORP) in the anoxic tank, reactor MLSS/MLVSS concentrations, and influent/effluent pH and alkalinity were regularly monitored by analyzing the grab samples. All the parameters except TKN were analyzed in an on-site laboratory. COD was measured using a portable test kit (Hach). TKN was measured using an automated ion analyzer (Lachat QuikChem FIA+ 8000 series) after sample digestion, while a portable spectrophotometer (Hach) was used to measure NH_4^+-N, NO_3^--N, and NO_2^--N. The BOD_5, alkalinity and MLSS/MLVSS analyses followed Standard Methods (7). DO, pH, and ORP were analyzed using a DO meter (YSI), a pH meter (Orion), and an ORP meter (Orion), respectively.

RESULTS AND DISCUSSION

In both pilot trials, the excess sludge was periodically wasted to maintain the mixed liquor suspended solids at a pre-determined level. The pilot plant operation was closely monitored and its performance was regularly followed by determining the removal of carbonaceous matter, total nitrogen, and SS.

Plant Operation

The MBR pilot plant was first operated at Shek Wu Hui STW from December 2001 to March 2002. After 13 days of start-up operation, both the design flow rate of 40 m^3/day and target MLSS concentration of 8000 mg/L were reached and intended effluent quality could be maintained. However, abnormally high influent SS (800–1800 mg/L) during the following period caused high MLSS in the reactor and low DO level (<0.5 mg/L), thereby severely affecting nitrification. Thus, performance of the MBR pilot plant could only be stabilized after another week of operation. The pilot plant operation consisted of two phases: first phase with MLSS of about 8000 mg/L, which lasted for 9 weeks, and the second phase with MLSS of about 11000 mg/L, which lasted for another 4 weeks. The MLVSS/MLSS ratio for the reactor sludge was 0.85. The pH in the anoxic tank ranged between 6.3 and 7.1, while that in the aerobic tank was between 6.3 and 7.2. The DO level in the aerobic tank fluctuated between 0.1 and 6.5 mg/L with an average of 2.6 mg/L. As shown in Table 2, the raw sewage characteristics fluctuated considerably throughout the pilot trial. TKN in the influent consisted of 63% NH_4^+-N and the average COD to TKN ratio was 8.6. The MBR was operated at an F/M ratio of 0.19 kg COD/kg SS-day in Phase I and 0.13 kg COD/kg SS-day in Phase II. Operation at such a low F/M ratio is a typical characteristic of a membrane bioreactor (2, 5). The average sludge age was maintained at 46 and 109 days in Phase I and Phase II, respectively. Maintaining the design effluent flow rate resulted in a progressive increase in suction pressure. To protect the membrane from excessive suction pressure, in-line membrane cleaning was done only once during the entire operation.

After completion of the pilot study at Shek Wui Hui STW, the MBR was moved to Stonecutters Island STW. The pilot trial was conducted from August to November 2002. The design flow rate of 40 m^3/day and target MLSS concentration of 8000 mg/L were reached after 21 days of start-up operation. The first phase of the pilot-plant operation, which lasted for 11 weeks, was conducted with a MLSS level of about 8000 mg/L, which was later increased to about 12000 mg/L during the second phase of study lasting for 4 weeks. The MLVSS/MLSS ratio of the reactor sludge was 0.71. The pH in the anoxic tank was between 6.2 and 7.4, while that in the aerobic tank was between 6.2 and 7.5. The DO level in the aerobic tank fluctuated between 1.0 and 5.4 mg/L with an average of 2.7 mg/L. Similar to the previous operation at SWHSTW, the raw sewage characteristics varied considerably throughout the pilot trial. The influent TKN consisted of 69% NH_4^+-N and the average COD to TKN ratio was 13.6. The MBR was operated at a sludge loading of 0.23 kg COD/kg SS-day in the first phase and 0.14 kg COD/kg SS-day in the second phase, which corresponded to a sludge age of 19 days and 38 days, respectively. The suction pressure necessary for maintaining the design flow increased at a faster rate as compared to the previous operation at SWHSTW. During the entire operation, in-line membrane cleaning was carried out on three occasions.

Treatment Performance

MBR pilot plants at SWHSTW and SCISTW were operated under the conditions discussed above and 24-h composite samples were analyzed for influent and effluent BOD_5, COD, TKN, NH_4^+-N, NO_3^--N, NO_3^--N, and TSS. Both the pilot plants showed high and stable removal of BOD, COD, total nitrogen (TN) and TSS regardless of the fluctuations in raw sewage characteristics. The BOD and TN profiles of the influent and effluent over the entire operation are shown in Fig. 2. Both the nitrification and denitrification performances were excellent and total nitrogen was sufficiently removed in both the pilot trials. BOD and TN in the effluent remained within a narrow range in both trials and the change in MLSS level did not show any significant effect on the effluent quality. For SWHSTW pilot plant, the mean effluent BOD and TN were 3.5 ($\pm$2.9) mg/L and 10.5 ($\pm$3.8) mg/L, respectively, representing 98% BOD removal and 84% TN removal. For SCISTW pilot plant, the mean effluent BOD and TN were 3.0 ($\pm$2.3) mg/L and 7.6 ($\pm$3.4) mg/L, respectively, which indicated 98% BOD removal and 82% TN removal. Complete retention of the particulate matter by the membrane and diversified biomass population as the slowly growing microorganisms responsible for the removal of slowly biodegradable components as well as the nitrification could grow and persist in the system (8), contributed to its better treatment performance.

Very low effluent NH_4^+-N levels were observed throughout the study, thus suggesting efficient nitrification. This can be attributed to maintenance of a high MLSS level in the reactor through the membrane filtration. The higher sludge retention enabled slow-growing nitrifying bacteria to develop and persist in the system. Occasional low pH levels in the reactor did not show any significant effects on nitrification. An excellent denitrification

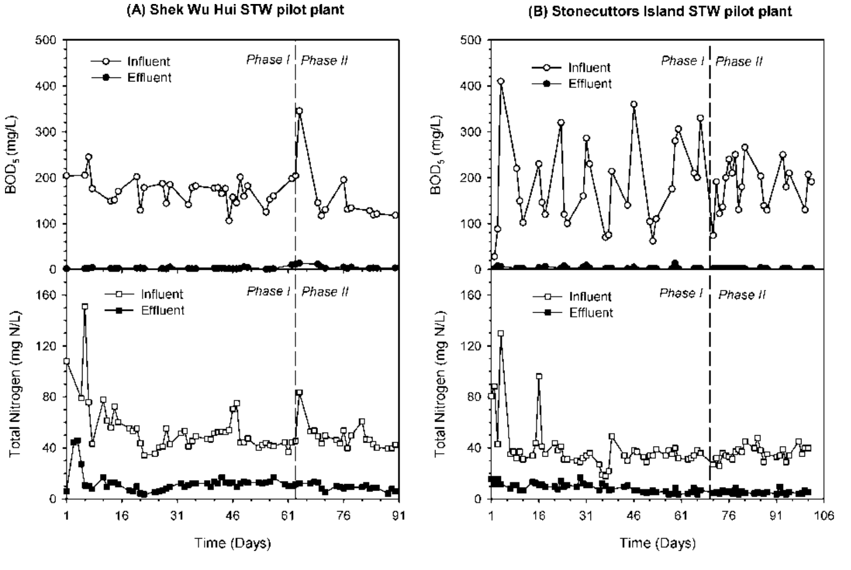

Figure 2. Influent and effluent BOD and TN profiles.

performance and hence total nitrogen removal could be achieved by recycling the nitrified mixed liquor from the aerobic tank to the anoxic tank. No external addition of carbon source was required in this operation since organic matter in the raw sewage could be effectively used as a carbon source for denitrification.

The probability plot of the effluent TN for the two pilot trials is compared in Fig. 3. As the figure shows, 95% of the time, the effluent TN for SWHSTW and SCISTW pilot trials were below 16.0 and 13.8 mg/L, respectively. The mean effluent TN for SWHSTW pilot plant was 10.5 mg/L, while that for SCISTW pilot plant was 7.4 mg/L. The lower effluent TN level in the latter case was most likely due to the lower influent TKN, higher influent COD/TKN ratio, and higher operating temperature. The compositions of the effluent for the two MBR trials also differed in terms of relative concentrations of different nitrogen species, most probably due to the differences in the raw sewage composition. Organic nitrogen, ammonium, nitrite, and nitrate nitrogen contents of the effluent for both the plants are shown in Fig. 4. The SWHSTW pilot plant effluent mostly contained organic nitrogen and nitrate nitrogen, although their proportion varied considerably over the time. Towards the end of the pilot trial, when the MBR operation was much stabilized, concentration of nitrate nitrogen was much higher than that of organic nitrogen. The SCISTW pilot plant effluent mostly contained nitrate nitrogen. The effluent NO_3^--N concentration was about 5–8 mg/L initially, which reduced to below 4 mg/L towards the end of the operation. A higher

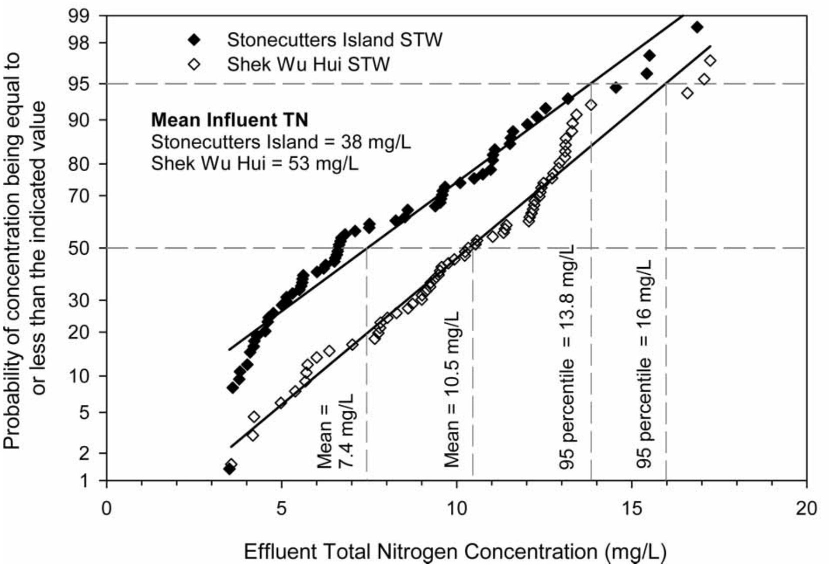

Figure 3. Probability plot of the effluent total nitrogen (TN).

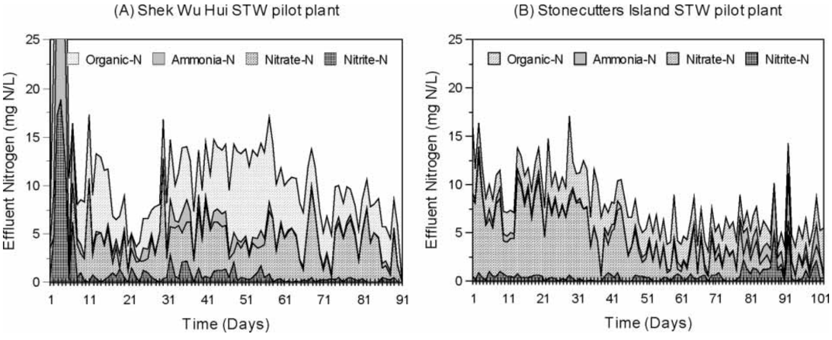

Figure 4. Organic nitrogen, ammonium, nitrite and nitrate nitrogen content of the effluent.

residual nitrate in the effluent suggested incomplete denitrification, while the organic nitrogen in the effluent indicated presence of slowly hydrolyzable organic nitrogen in the raw sewage. The recycle-to-influent ratio of 3 was found to be sufficient for complete denitrification in both the cases. When the operation was changed from Phase I to Phase II, no loss or impairment of nitrification/denitrification performance was observed.

Effect of Loading on the Treatment Performance

As it has been mentioned earlier, both the pilot plants showed high and stable BOD and TN removal rates regardless of variations in the loadings and the MLSS concentration. Fig. 5 shows the TN removal rate as a function of the TKN loading rate. The average TN removal rates were 84% and 82% for SWHSTW and SCISTW pilot plant, respectively. Since the TN removal rate was linearly proportional to the applied loading over the range

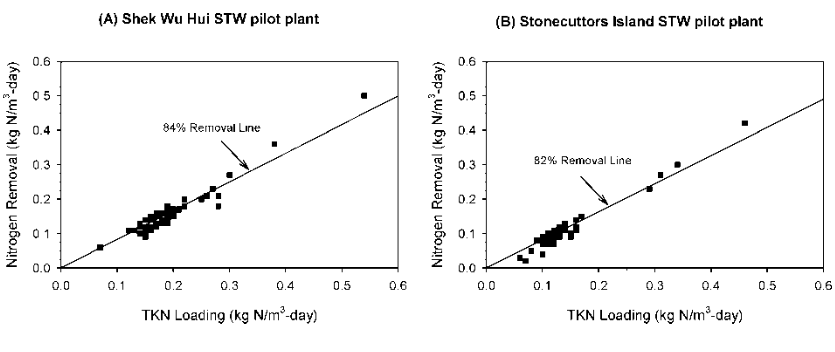

Figure 5. Effect of loading on total nitrogen removal.

employed in this study, the nitrogen removal capacity of the MBR was not limited by the bioactivity (i.e., the biomass level in the reactor). It was rather limited by the nitrogen loading.

Sludge Production

Since the MBR was operated at a low sludge loading (F/M ratio), low excess sludge production was expected (2, 3). The cumulative biomass production was estimated from the amount of daily sludge wastage and daily change in reactor MLSS level, while the cumulative COD removal was calculated from daily COD removal. Average rates of sludge production and COD removal were computed from the slopes of the straight line fit of the data for the cumulative sludge production and cumulative COD removal (results not shown). The observed sludge yield for both the pilot trials were then calculated as the ratio of the average rate of sludge production to that of COD removal, and it was found to be 0.24 kg SS/kg COD for SWHSTW pilot plant and 0.17 kg SS/kg COD for SCISTW pilot plant. The sludge yield was reduced by 30 to 50% as compared to a conventional activated sludge process, which typically shows sludge production of about 0.35–0.40 kg SS/kg COD.

Membrane Fouling and Control Measures

Coarse bubble aeration was used to prevent the fouling of the membrane by shearing off the solids accumulated on the membrane surface. To further facilitate the shearing off, a timed cycle (13 min ON and 2 min OFF) was used for the withdrawal of final effluent through the membrane filter using a suction pump. Even with these measures, a progressive increase in the suction pressure was required to maintain the design flow rate of 40 m^3/day (Fig. 6). To prevent the membrane from excessive suction pressure, in-line

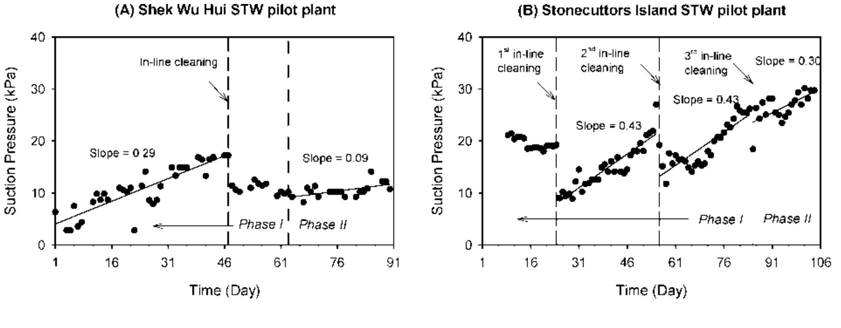

Figure 6. Suction pressure required to maintain a constant permeate flux.

chemical cleaning of the membrane was carried out periodically. For the MBR pilot plant at SWHSTW, the suction pressure increased steadily at an average rate of 0.29 kPa/day. The in-line membrane cleaning was done after one month of operation, which included the start-up period. After the completion of pilot study at SWHSTW, the membrane module was removed from the MBR and a major chemical cleaning was done. During the MBR operation at SCISTW, the increase in suction pressure was more rapid (0.43 kPa/day) as compared to that at SWHSTW. To avoid frequent in-line cleaning, the membrane was mostly operated at a higher suction pressure. In a notable contrast to the previous operation at SWHSTW, three in-line membrane cleanings were required over the entire operation period. It was evident from the observations that the treatment of saline sewage would require more frequent membrane cleaning as compared to the treatment of fresh water sewage. Further investigation is required to understand effects of salinity on membrane fouling and the hydraulic performance of the MBR treating saline sewage.

CONCLUSIONS

The performances of both the MBR pilot trials were highly stable and the MBR was able to maintain excellent effluent quality regardless of the operational conditions and fluctuations in raw sewage characteristics. With 300% internal recycling of the nitrified mixed liquor and utilization of organic matter in the raw sewage as the carbon source for denitrification, total nitrogen removal efficiency of 82–84% was achieved. In SWHSTW pilot plant, average effluent TN of 10.5 mg/L was maintained at a stable level with an influent TKN concentration of 53 mg/L. In SCISTW pilot plant, the average influent and effluent TN was 38 mg/L and 7.6 mg/L, respectively. The lower effluent TN in the latter case was most likely due to the lower influent TKN, higher influent COD/TKN ratio, and higher operating temperature. The salinity of the raw sewage apparently did not affect nitrogen removal in the MBR. Periodic in-line cleaning of the membrane was required to maintain the suction pressure to an acceptable level. The increase in the suction pressure was significantly higher in SCISTW pilot plant treating saline sewage than the SWHSTW pilot plant treating fresh water sewage for the same flow rate. Thus, higher frequency of in-line membrane cleaning was required in the former case. The sludge yield was 0.24 kg SS/kg COD removed for SWHSTW pilot trial and 0.17 kg SS/kg COD removed for SCISTW pilot trial. The sludge yield was reduced by 30 to 50% as compared to a conventional activated sludge process. The results did not indicate any significant differences in treatment performances with fresh water sewage at SWHSTW and saline sewage at SCISTW except that a higher frequency of in-line membrane cleaning was required for the latter.

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