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Applications of flat sheet ceramic membrane for surface water and seawater treatments – introduction of performance in large-scale drinking water plant and seawater pretreatment pilot system in Singapore

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Abstract

PUB, Singapore's National Water Agency, has been using polymeric UF membrane in drinking water plants to produce high quality water whilst requiring a smaller footprint. Submerged polymeric hollow-fiber membrane has been used since 2003 in Chestnut Avenue Water Works (CAWW). PUB decided to use submerged-type ceramic membranes for enhancement of production capacity at CAWW. The flat-sheet ceramic membrane system was retrofitted into two spare, empty tanks with a combined design capacity of 36,400 m^3/d. The system has been successfully put into operation, running at a net flux of 160 L/m^2-h (LMH) since June 2017. Membrane integrity testing is automatically carried out once a week to ensure the membranes' integrity. Stable filtrate quality has been achieved with a low turbidity of 0.018 NTU on average. Pretreatment for seawater desalination is another application in which a ceramic membrane system can be operated at higher flux compared to that for polymeric membranes. A pilot scale system was installed at PUB R&D facility in Tuas to investigate sustainable operating flux and permeate quality. $FeCl_3$ was used as a coagulant before ceramic filtration, with a dosage of 4–6 mg/L. It was shown that sustainable flux can be 181–249 LMH in seawater treatment system with flat sheet ceramic membranes. The silt density index and turbidity of permeate were 1.6–2.2 and 0.04–0.10 NTU, respectively, which indicates that the system can produce high quality water for feed of reverse osmosis systems.

Key words: ceramic membrane, drinking water, retrofit, seawater desalination, surface water

INTRODUCTION

Application of membrane technology for various water treatment processes is growing significantly in recent years due to increased robustness and stable product water quality. PUB, Singapore's National Water Agency, has utilized polymeric membranes in a drinking water plant. A submerged hollow-fiber membrane was first installed in Chestnut Avenue Water Works (CAWW) and started operation in 2003. PUB and Meiden have been conducting pilot testing with flat-sheet ceramic membranes to treat surface water. Ceramic membrane systems have the advantage of a longer lifespan and energy savings (Hamingerova *et al.* 2015; Fard *et al.* 2018). PUB decided to use the flat-sheet ceramic membrane system for enhancement of production at CAWW. This is the first drinking water plant in Singapore to use submerged flat-sheet ceramic membranes to treat surface water. The flat-sheet ceramic membrane system was retrofitted into two spare, empty tanks with a total design capacity of 36,400 m^3/d. Pretreatment for seawater desalination is another application in which ceramic membrane systems can be operated at a higher flux compared to polymeric membranes. There are

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many references of full scale membrane systems (Burashid & Hussain 2004; Moore *et al.* 2009; Valavala *et al.* 2011) using polymeric microfiltration (MF)/ultrafiltration (UF) membranes as pretreatment for seawater reverse osmosis (SWRO) systems. The flux rate range from 52 to 65 L/m^2.h (LMH) for the submerged and 40–100 LMH for pressurized polymeric membranes (Abdulrahima *et al.* 2017). Although larger scale ceramic membrane systems have been installed in drinking water and wastewater treatment plants (Noguchi *et al.* 2016; DeCarolis *et al.* 2017; Pankrats 2017), investigation of ceramic MF/UF systems for pretreatment of SWRO is limited to small scale investigations (Dey *et al.* 2013). Insufficient results to prove the benefit and high capital cost of ceramic membrane are the reasons for their lack of use in SWRO. PUB encouraged industrial players to testbed promising products or technologies for desalination at PUB's R&D facility in Tuas. A pilot scale plant using a flat sheet ceramic membrane was installed at this R&D facility and operating conditions optimized for the ceramic membrane system. This paper describes the performance of a flat-sheet ceramic membrane for the treatment of surface water and seawater to show higher sustainable flux rates and permeate quality.

SYSTEM INFORMATION

Drinking water treatment plant in CAWW

A schematic flow diagram of the treatment system with ceramic membrane in CAWW is shown in Figure 1. A combined process of coagulation and filtration is used for the treatment of raw water from the Upper Pierce Reservoir. The quality of the raw water is shown in Table 1. Coagulant (Alum) is added to screened raw water before it enters the flocculation chamber. There is no sedimentation tank and the flocculated water is directly fed to the membrane filtration trains. Lime for pH adjustment and chlorine for disinfection are added to permeate to obtain product water. Some of the data are confidential due to the nature of the public facility and thus omitted.

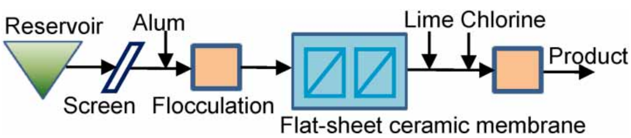

Figure 1 | Schematic flow diagram of water treatment in CAWW.

Table 1 | Quality of raw water for design in CAWW

Parameters	Max.	Min.	Ave.
pH (–)	7.0	6.8	6.9
Turbidity (NTU)	3.0	1.2	2.0
Color (Hazen)	20	5	14
Conductivity (μS/cm)	311	270	287
Chloride (mg/L)	49	40	43
Total alkalinity (mg/L)	19	16	18
Ammonia as N (mg/L)	0.04	0.02	0.03
TOC (mg/L)	3.0	2.2	2.5
Total hardness (mg/L)	113	42	73
Iron as Fe (mg/L)	0.206	0.046	0.097
Manganese as Mn (mg/L)	0.013	0.003	0.008

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The flat-sheet ceramic membrane supplied by Meidensha Corporation has a nominal pore size of 0.1 μm, normally categorized as MF. Figure 2 shows pictures of the membrane tank and the membrane unit. Features of the ceramic membrane system are as follows:

- Higher flux during membrane filtration
- Siphon filtration with relift pumping system
- Lower energy consumption due to infrequent need for air scouring
- High recovery rate
- Automatic MIT (Membrane Integrity Test) system

Figure 2 | Pictures of the membrane tank (left) and the membrane unit (right) in CAWW.

The membrane trains have an automatic MIT system to check the membranes' integrity once a week. Automatic MIT ensures the integrity of the membrane system and helps prevent contamination in treated water. MIT is carried out according to ASTM D 6908-03 (ASTM 2003). The designed net flux for ceramic membrane is 160 LMH. The filtration/backwash cycle is set to 20 minutes with backwash for 45 seconds. Membrane scouring is operated only during backwashing, which results in energy saving. Maintenance cleaning (MC) is scheduled once a week by using sodium hypochlorite.

Seawater pretreatment pilot system in Tuas

Figure 3 shows a process flow diagram of the seawater pretreatment pilot system in Tuas. Feed water was open-intake seawater filtered by coarse/fine screen and then delivered to the influent tank via a common seawater tank in PUB's R&D facility in Tuas. 0.5 mg/L of NaOCl was injected into influent to ensure a residual chlorine concentration of 0.2 mg/L in the membrane tank and 4–6 mg/L of $FeCl_3$ was added before membrane filtration. Permeate was tapped out of ceramic membrane by filtration pump. The effective membrane area of the ceramic membrane pilot system is 25 m^2. The flat-sheet ceramic membrane was supplied by Meidensha Corporation and has a nominal pore size of 0.1 μm. Operating conditions are shown in Table 2. Testing was conducted under three different conditions: Run A, B and C, starting

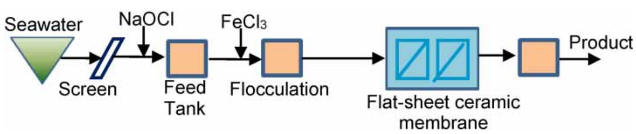

Figure 3 | Schematic diagram of the seawater pretreatment pilot system.

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Table 2 | Operating conditions for the seawater pretreatment pilot system

	Run-A	Run-B	Run-C
Flux (LMH)	181	218	249
Backwash flux (LMH)	240	288	336
Filtration/Backwash cycle (min)	14.5/0.5	14.5/0.5	11.5/0.5
Recovery (%)	95.8	95.8	94.8
$FeCl_3$ coagulant (mg/L as $FeCl_3$)	4	4–6	6

with conservative flux for Run-A and then higher fluxes for Run B and C. Backwash cycle was set to be 15 or 12 minutes. MC was carried out two or three times per week with citric acid. Membrane scouring was operated only during backwash, the same as for the ceramic membrane system in CAWW.

RESULTS AND DISCUSSION

Drinking water treatment plant in CAWW

Performance of membrane filtration

The ceramic membrane system has been operating since June 2017. Figure 4 shows the transmembrane pressure (TMP) trend in the ceramic membrane filtration system. Permeate flow was kept almost constant at 850 m^3/h during this operation period, while TMP increase between MCs was about 10 to 14 kPa. TMP was able to recover to its starting value at 26 kPa after each MC. This indicates that the ceramic membranes are capable of achieving stable filtration even with the new regime of air scouring only during backwashing. More data showing stable operation will be collected and reported in the near future.

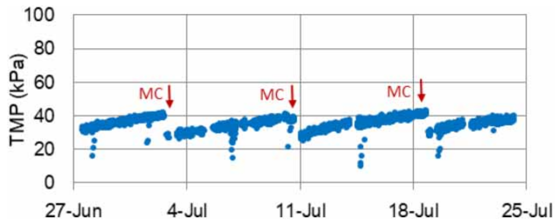

Figure 4 | TMP trend for the ceramic membrane train in CAWW.

Permeate quality

To ensure the performance of the membranes as specified, turbidity and particle count are continuously monitored by online analysers. Figure 5 shows the trend of turbidity during the same operation period as per Figure 4. Average turbidity for this operation period was 0.018 NTU. Turbidity was under 0.1 NTU for all times and was below 0.02 NTU most of the time (Figure 5), which indicates

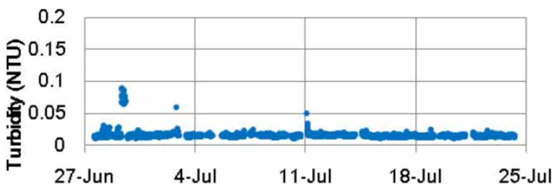

Figure 5 | Turbidity of permeate for the ceramic membrane train in CAWW.

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that target level of turbidity (<0.1 NTU for 95% of the time and <0.2 NTU for 100% of the time) was achieved for the ceramic membrane filtration system. Other parameters of membrane permeate such as residual aluminium (<0.1 mg/L) is within PUB drinking water standards. Some data are confidential due to the nature of the public facility and are thus omitted.

Energy consumption

As the membrane system uses siphon filtration, energy consumption is primarily from air scouring and backwashing. Table 3 shows energy consumption for a ceramic membrane and polymeric membrane system. Energy for scouring in the ceramic system is 0.013 kWh/m^3, which is about 56% lower than that for the polymeric membrane system. Air scouring of the membranes is only carried out during backwash, which results in a reduction of energy consumed by the ceramic membrane system. It should be noted that the polymeric membrane system requires cyclic (10 sec on/10 sec off) air scouring at CAWW. Energy for backwashing is 0.0046 kWh/m^3 in the ceramic membrane system and is 24% higher than that in the polymeric membrane system. This is because of the higher flow rate required for backwashing for ceramic membranes. The sum of energy for scouring and backwashing is estimated to be 0.0176 kWh/m^3 for the ceramic membranes, which translates to a 46% energy reduction as compared to polymeric membranes.

Table 3 | Energy consumption for membrane systems in CAWW

Energy consumption (kWh/m^3)		
	Ceramic (New)	Polymeric (Existing)
Air scouring	0.013	0.029
Backwashing	0.0046	0.0037
Sum	0.0176	0.0327

Seawater pretreatment pilot system in Tuas

Performance of membrane filtration

Figure 6 shows the TMP trend of run-A with flux of 181 LMH. TMP increased from 15 kPa at the beginning to 30 kPa at day 4 of operation. MC on day 5 was effective to recover the TMP to 15 kPa and operation remained stable until day-11 of operation. The wave pattern TMP trend instead of a typical straight/curved TMP trend between two MCs might be due to fluctuation of feed water turbidity and hence varied solid loading in the membrane tank. After day 11, MC was conducted and testing continued with other operating conditions.

With the stable TMP trend during run-A with lower fluxes, pilot operation was continued for run-B with a higher flux of 218 LMH. The TMP trend during run-B is shown in Figure 7. The TMP trend became more stable towards the end of the run-B although MC was not as effective to recover the baseline TMP back to 20 kPa at the beginning of operation as shown in Figure 7. Baseline TMP increased and stabilized at around 30 kPa. This increase might be due to accumulation of foulants on the ceramic membrane.

Figure 8 illustrates TMP trend of run-C with highest flux of 249 LMH. Generally, TMP increased approximately by 5–8 kPa during the first few hours of operation and remained stable until the next MC, except on day 7 where TMP sharply increased by 25 kPa. Although higher feed turbidity normally didn't cause such an impact, the turbidity spike during this period might cause a sharp TMP increase.

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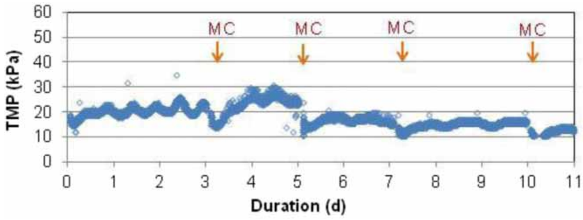

Figure 6 | TMP trend of run-A (181 LMH) in the seawater pretreatment pilot system.

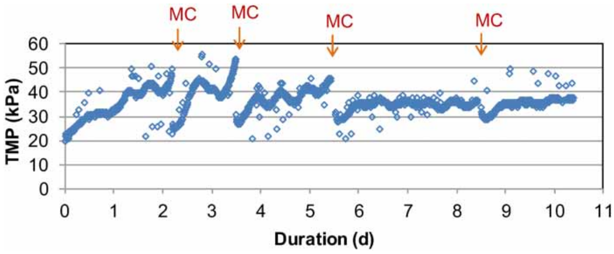

Figure 7 | TMP trend of run-B (218 LMH) in the seawater pretreatment pilot system.

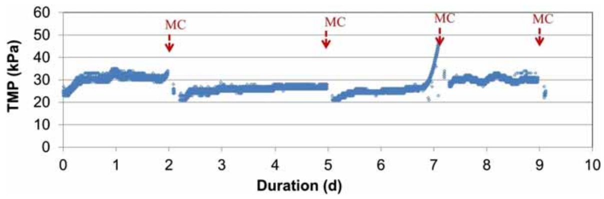

Figure 8 | TMP trend of run-C (249 LMH) in the seawater pretreatment pilot system.

Water quality

Figures 9 and 10 show the feed and permeate turbidity during operation of the run-B condition over a longer period. While feed water turbidity normally varied between 2.0–17.2 NTU with some spikes of >20 NTU (Figure 9), permeate turbidity remained stable at 0.04–0.10 NTU (Figure 10).

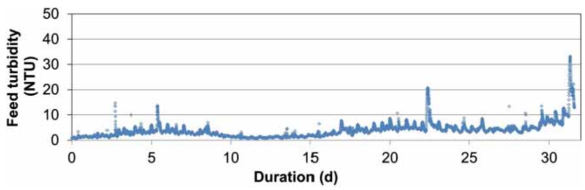

Figure 9 | Feed turbidity during run-B condition in the seawater pretreatment pilot system.

Feed and permeate qualities of each run are shown in Table 4. TOC of feed water ranged from 1.12 to 2.15 mg/L and feed turbidity was from 2.0 to 32.3 NTU during all runs.

SDI_{15} of permeate was measured one time during run-A, four times for run-B and twice for run-3 to evaluate the impact to reverse osmosis (RO) after ceramic membrane filtration. SDI_{15} ranged from 1.6 to 2.2 and it was below 3.0 in all measurements. Residual Fe in permeate was measured twice per week and found to be below 0.006 mg/L, which met criteria for feed of the RO system

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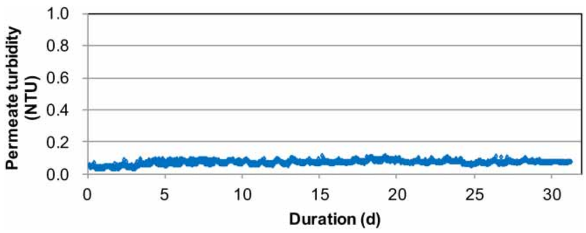

Figure 10 | Permeate turbidity during run-B condition in the seawater pretreatment pilot system.

Table 4 | Analysis result of feed and permeate for the seawater pretreatment pilot system

	Run-A		Run-B		Run-C	
Parameter	**Feed**	**Permeate**	**Feed**	**Permeate**	**Feed**	**Permeate**
TOC (mg/L)	1.64	1.57	1.27–2.15	1.11–2.01	1.12–1.92	1.04–1.73
Turbidity (NTU)	2.5–3.6	0.04–0.10	2.0–32.3	0.04–0.10	2.0–17.2	0.04–0.10
Fe (mg/L)	1.38	<0.003	1.38–2.07	<0.003	2.07	<0.003–0.006
SDI_{15}	–	1.6	–	1.8–2.2	–	1.9–2.2

(Reiss *et al.* 2007). It was shown from these results that ceramic membrane filtration with pre-dosing of $FeCl_3$ can produce permeate with acceptable quality for feed of RO system.

CONCLUSIONS

A ceramic membrane system with submerged flat-sheet ceramic membranes installed in the spare tanks in CAWW membrane plant is for the enhancement of the plant's production capacity for sustainable output over longer periods. The system has been successfully put into operation at a net flux of 160 LMH since June 2017. TMP recovery after MC was almost constant and turbidity of permeate is well below 0.1 NTU at all times. It is concluded from these results that stable filtration can be achieved by backwash, air scouring only during backwashing and weekly MC for the ceramic membrane filtration system.

Results of the pilot scale ceramic membrane system operated at PUB's R&D facility in Tuas show that ceramic membranes can be used for pretreatment of seawater desalination at a flux of 249 LMH. Owing to lower total organic carbon in feed water, it was observed that the net flux of ceramic membrane for desalination application is higher than that for surface water application. Turbidity and SDI_{15} of permeate water were consistently lower than 0.1 NTU and 3. It is concluded that the ceramic membrane system can be operated with a flux up to 249 LMH to produce acceptable quality of permeate for feed of the RO system.

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