Desalination and Water Treatment
www.deswater.com

32 (2011) 339–344
August

doi: 10.5004/dwt.2011.2719

Comparison of different pretreatments for seawater desalination

Seung-Hyun Kim[a]*, Choong-Sik Min[a], Jaeweon Cho[b]

[a]*Civil Engineering Department, Kyungnam University, Republic of Korea*
Tel. +82 55 249 2671; Fax +82 505 999 2165; email: shkim@kyungnam.ac.kr
[b]*Department of Environmental Science and Engineering, Gwangju Institute of Science and Technology, Republic of Korea*

Received 13 July 2010; Accepted in revised form 13 November 2010

ABSTRACT

The performance of different processes applicable for seawater desalination pretreatment was evaluated in this study. These processes include dual media filter (DMF), pore controllable filter (PCF) and filter adsorber (FA). The particle removal performance was evaluated by turbidity, particle number (> 2 μm), SDI of the filtrate. The organic reduction performance was evaluated by COD, UV-254 and molecular weight distribution (MWD) of the filtrate. According to this study, PCF showed the best performance in the particle removal, while FA showed the best performance in the organic reduction. There were three peaks for raw seawater (180, 800, 28,000 Da) and the highest peak was recorded at 180 Da. All processes successfully reduced organic fraction of large MW (28,000 Da). FA reduced small fractions (180, 800 Da) better than DMF and PCF. FA was also good in the particle removal. The particle removal performance of FA was comparable to that of DMF. Both FA and DMF showed the similar behavior of initial breakthrough.

Keywords: Seawater desalination; Pretreatment; Media filtration; Filter adsorber; Fiber filtration; Molecular weight distribution

1. Introduction

A crucial drawback of seawater reverse osmosis (SWRO) desalination is the susceptibility to membrane fouling [1,2]. Once fouled, operation cost increases due to higher energy demand, increased cleaning frequency and reduced membrane lifetime [3]. Therefore, undesirable contaminants in raw seawater should be removed before it is fed into RO membrane. These contaminants, which lead to membrane fouling, consist of silica colloids, adsorbed organic compounds, particulate matter of iron and aluminum colloids, microorganisms and metallic oxides [4]. Among these contaminants, adsorption of colloids and organic matter is the most crucial factor accelerating the development of membrane fouling [5]. It was reported that membrane with severe biofouling was found to contain 60% organic foulants [5].

Direct filtration using mono media, dual media or mixed media is the most commonly adopted pretreatment technology prior to RO system [1] due to its effectiveness in the particle removal. However, direct filtration is ineffective in the organic reduction [6], while adsorption is effective in the organic reduction. It was reported that powdered activated carbon (PAC) adsorption could successfully remove the majority of the molecular weight (MW) fractions in the range of 200–3,500 Da (i.e., refractory organic matter, hydrophobic organic matter) and a small portion of the large MW fraction [7]. PAC adsorption was however ineffective in removing very small MW fractions (< 300 Da) or large MW fraction (> 17,000 Da) [8]. These results suggest that adsorption could be a

* Corresponding author.

Presented at the Third International Conference on Challenges in Environmental Science & Engineering, CESE-2010
26 September – 1 October 2010, The Sebel, Cairns, Queensland, Australia

pretreatment technique to adopt when organic matter is the major contaminant in raw seawater.

Recently, fiber filtration has been introduced in Korea. In place of sand, polymeric fibers were installed in fiber filtration. Fiber filtration demonstrated good results of particle removal when applied for tertiary treatment of wastewater [9]. It also showed promising results as a pretreatment of SWRO desalination. Fiber filtration decreased turbidity of raw seawater from 1.75 NTU to 0.16 NTU with in-line coagulation and to 0.49 NTU without in-line coagulation [10]. As far as the organic reduction is concerned, fiber filtration was more effective in removing relatively large MW organic fractions (730, 960 Da) than small fractions (330, 220 Da) [10].

In this study, the performance of different processes applicable for pretreatment of SWRO desalination was evaluated. Dual media filter (DMF), PCF (pore controllable filter) and filter adsorber (FA) were selected for this purpose. PCF was selected because fiber filtration demonstrated promising results as a pretreatment of SWRO desalination. In FA, activated carbon replaces anthracite of DMF. Activated carbon is installed at the top layer and sand at the bottom layer. By this installation, both adsorption and media filtration are expected to occur in FA. FA was selected because of its adsorptive capacity of organic matter. DMF was selected as a reference. Their performance was evaluated in terms of the particle removal as well as the organic reduction because particles and organic matter are the major pollutants in SWRO desalination.

2. Materials and methods

2.1. Raw seawater

Table 1 shows characteristics of raw seawater during the study period. Raw seawater was taken from the south-east part of Korea. The study was conducted from June to September 2009. Average pH of raw seawater was 8.0 and average concentration of total dissolved solids (TDS) was 36.5 g/L. These are values commonly found in typical seawaters. Average turbidity of raw seawater was 5.43 NTU, while average particle count per mL (> 2 μm) was 7,562. Turbidity peaked when it rained. Average concentration of chemical oxygen demand (COD) was 3.4 mg/L, while average UV-254 was 1.4 m^{-1}. $KMnO_4$ was used as an oxidant. Average chlorophyll-α concentration was 1.8 mg/m^3.

Table 1
Characteristics of raw seawater during this study period

Parameter	Concentration*
Temperature, °C	17.5–26.0 (22.8)
pH	7.8–8.1 (8.0)
Conductivity, mS/cm	49.6–52.0 (50.9)
Total dissolved solids (TDS), g/L	34.8–37.9 (36.5)
Suspended solids (SS), mg/L	22–52 (36)
Turbidity, NTU	1.61–17.4 (5.43)
Particle count per mL (> 2 μm)	5,207–8,932 (7,562)
Chemical oxygen demand (COD)**, mg/L	2.0–8.4 (3.4)
UV-254, 1/m	0.7–2.3 (1.4)
Chlorophyll-a, mg/m^3	1.2–2.8 (1.7)

* Values in parenthesis indicate the average
**$KMnO_4$ was used for oxidant

2.2. Methods

2.2.1. PCF

PCF is a pore controllable fiber filter made of polypropylene. Two thousand six hundred fibers (Ø 43 μm, L 920 mm) were interwoven to form one fiber unit. Two hundred twenty fiber units were included in a PCF device (Sseng, Korea) used in this study. These fiber units surround the perforated pipe located at center of the device, which collects the filtrate. The diameter and length of the device are 391 mm and 1,140 mm. Total fiber area is 0.6 m^2. PCF was operated at 5.2 m/h producing 75 m^3/d. The PCF was backwashed using the filtrate for 30 s when its trans-fiber pressure reached 0.7 bar. Backwash consists of simultaneous air scouring and water, which was provided for three minutes before air scouring was terminated. Then, water wash continued for 30 s more. Water wash rate was 50 L/min and air scouring rate was 3 m^3/min. There were four backwashes daily so that one filtration cycle became six hours. The recovery of PCF was calculated 99%. In order to aid particle destabilization, polyaluminum chloride (Al_2O_3 17%) was added at 5 ppm before seawater was fed into PCF.

Pore size was controlled by two different methods. The first method is related to installation of fiber units. Thick and thin fiber units are gradually located in the flow direction. Thick fiber units are located at the surface, while thin units near the central perforated pipe. As seawater flows through from thick fiber units to thin units, pore size gradually decreases. The rotation number during fabrication determines thickness of a fiber unit. The more the rotation is provided, the thinner the fiber unit becomes. Pore size can be also controlled by lifting. Fiber units were lifted by 60 cm during filtration and lowered to its original position during backwash. Pore size became tight when fiber units were lifted, which helped the particle removal. Pore size became loose during backwash so as to aid dislodgement of particles captured inside fiber units.

2.2.2. DMF

Anthracite and sand were filled in the DMF column of 13 cm in diameter. Effective sizes of anthracite and sand are 1.0 mm and 0.6 mm. Uniformity coefficient of anthracite and sand is less than 1.6. Media depth is 1 m (50 cm of anthracite and 50 cm of sand) so that the ratio of media depth to effective size (L/d) becomes 1,330. DMF was operated at 5 m/h and backwashed once a day with the filtrate. Simultaneous air scouring and water wash was provided during backwash. Backwash was initiated by air scouring at 0.3 m/min, which continued for two minutes before water wash at 0.3 m/min. After simultaneous air and water backwash continued for three minutes, air scouring was terminated. Water wash rate was then increased to 0.8 m/min and continued for five more minutes. The recovery of DMF was calculated 96%. Ferric chloride ($FeCl_3$) was added at 4 mg/L before seawater was fed into DMF for particle destabilization.

2.2.3. FA

Activated carbon and sand were filled in the FA column. Effective size of activated carbon (Filtrasorb 40, Calgon, USA) is 0.9 mm and its uniformity coefficient is less than 1.6. Media depth of FA is the same as that of DMF (50 cm of activated carbon and 50 cm of sand) so that the L/d ratio becomes 1,388. FA was backwashed in the same manner as DMF. Ferric chloride was added at 4 mg/L before seawater was fed into FA.

2.2.4. Analysis

The filtrate sample was collected once a day to measure the filtrate quality. The particle removal performance of different pretreatment processes was evaluated using water quality parameters such as turbidity, particle count and fouling index of SDI (silt density index). The organic reduction performance was evaluated using COD and UV-254. These parameters were measured in accordance with Standard Methods [11]. SDI was measured in accordance with ASTM D4189-07 [12]. Dead-end filtration at 207 kPa through a hydrophilic filter paper of 47 mm (Advantec A045A047A, Japan) was performed for SDI measurements. High pressure size exclusion chromatography (HPSEC, Shimadzu Corp., Japan) with SEC column (Protein-pak 125, Waters, Milford, USA) was used to determine molecular weight distribution (MWD) of organic matter. A UV detector was used at 254 nm. Calibration was conducted with the standard solution of polystyrene sulfonates with known MW (210, 1,800, 4,600, 8,000, 18,000 Da).

3. Results and discussion

3.1. Particle removal performance

Turbidity of the PCF, DMF and FA filtrate is shown in Table 2. According to Table 2, turbidity of the PCF filtrate was the lowest. Turbidity of raw seawater ranged from 1.61 to 17.4 NTU. PCF successfully reduced the turbidity level resulting in the filtrate average value of 0.29 NTU. Turbidity of the DMF filtrate (average value of 0.39 NTU) and the FA filtrate (average value of 0.35 NTU) was higher than that of the PCF filtrate. PCF maintained the consistent performance of turbidity reduction and all values of its filtrate turbidity remained in the range of 0.29–0.30 NTU. Turbidity of the DMF and FA filtrate was more scattered. Turbidity of the FA and DMF filtrate was in the range of 0.31–0.39 NTU and 0.34–0.43 NTU, respectively. The SDI of the PCF, DMF and FA filtrate is shown in Table 2. According to Table 2, the SDI of the PCF filtrate was the lowest in agreement with the turbidity results. It was in the range of 2.1–3.7 (average value of 3.1). The SDI of the DMF filtrate was in the range of 3.1–4.7 (average value of 4.0) and that of the FA filtrate in the range of 3.0–4.8 (average value of 3.8). This study results show that PCF successfully satisfied the membrane manufacturer's SDI requirement (< 3–4) for the RO influent.

Particle counts of the PCF and DMF filtrates are compared in Fig. 1. Particle counts were grouped into two categories based on their size: 2–7 μm and > 7 μm. As expected, both processes removed large particles (> 7 μm) more effectively than small particles (2–7 μm). PCF was more effective in the particle removal than DMF, regardless of the particle size. PCF was able to achieve about 1-log removal of small particles and about 2-log removal of large particles.

Pore size is important for the particle removal in PCF operation as particle size for media filtration of DMF. As pore size gets smaller, more particles can be removed. It

Table 2
Comparison of the filtrate qualities from different pretreatment processes

Parameter	Concentration		
	PCF	DMF	FA
Turbidity, NTU	0.29–0.30(0.29)	0.34–0.43(0.39)	0.31–0.39(0.35)
Silt density index	2.1–3.7(3.1)	3.1–4.7(4.0)	3.0–4.8(3.8)
COD, mg/L	1.6–2.8(2.3)	1.6–3.1(2.2)	1.4–2.9(2.1)
UV254, 1/m	1.2–1.7(1.5)	1.2–1.5(1.4)	0.6–1.1(0.9)

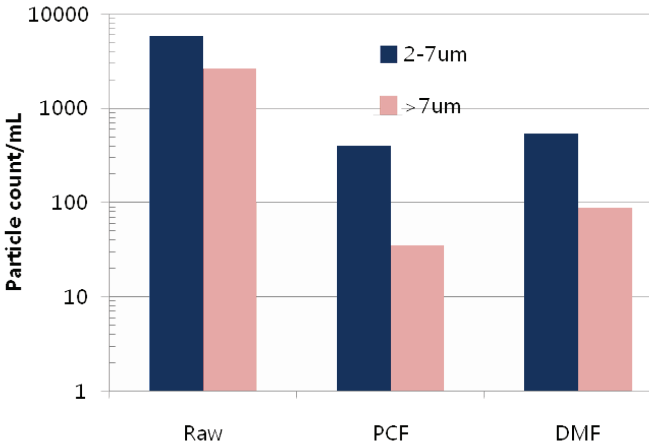

Fig. 1. Comparison of the filtrate particle counts of PCF and DMF.

seemed that PCF pores are small enough to outperform DMF and FA in the particle removal. The particle removal performance of FA was comparable to that of DMF because their particle sizes are similar. As mentioned above, effective size of anthracite is 1.0 mm and that of activated carbon is 0.9 mm. Filtrate quality is affected by media depth and size in media filtration. Filtrate quality improves as the media size gets smaller and the bed deeper [13,14]. Since both FA and DMF have the media of similar size in the same depth (50 cm top layer and 50 cm layer of bottom layer), their filtrate qualities concerning the particle removal became comparable.

The problem of PCF is residual aluminum in the filtrate. Residual aluminum concentration in the PCF filtrate was significantly high, exceeding the Korean drinking water standard (0.2 mg/L). Residual aluminum should be reduced because it can foul RO membrane. Unlike aluminum, no residual iron was detected in the filtrate of DMF and FA, at which ferric chloride was added. The difference in residual aluminum and iron is related to their solubility. High concentration of residual aluminum was detected in the PCF filtrate because aluminum hydroxide is more soluble than iron hydroxide. Although data are not shown here, residual problem was eliminated after coagulant was changed to ferric chloride.

3.2. Organic reduction performance

The COD concentration of the PCF, DMF and FA filtrate is shown in Table 2 together with the corresponding UV-254 concentration. FA was anticipated to perform well in the organic reduction because its top layer is filled with activated carbon, which is famous for its excellent adsorption capacity. As expected, FA was effective in reduction of UV-254. Average UV-254 reduction efficiency of FA was 50 %, while the corresponding values of PCF and DMF were 17% and 22%. Unlike UV-254, results of the COD reduction were not satisfactory. FA marginally outperformed DMF and PCF in the COD reduction. According to Table 2, the difference in the filtrate COD levels among these pretreatments was insignificant. Based on average values, PCF, DMF and FA reduced the COD concentration of raw seawater by 23–30%.

The organic reduction is different depending on the pretreatment process type. As mentioned above, media filtration is ineffective in the organic reduction. Coagulation can improve the organic reduction through complex formation between metal ions and organic matter in raw seawater [15]. The corresponding complexes can be removed during media filtration. Coagulation also increases the particle size and changes the particle characteristics [16], which makes organic matter more susceptible to removal by media filtration. When artificial seawater containing 10 mg/L of humic acid (HA) was filtered by DMF, only marginal DOC reduction (about 10%) was obtained. Fe coagulation improved the DOC reduction efficiency substantially to over 60% [17]. This result clearly shows the beneficial effect of coagulation during media filtration. In addition to media filtration, adsorption can contribute to the organic reduction in FA. Consequently, FA was more efficient in the organic reduction than DMF and PCF.

UV absorbance at 254 nm detects mostly constituents of organic matter with π–bonded molecules. These constituents include humic substances of HA and fulvic acid and hydrophobic aromatic organic matter, which absorb UV light more than other constituents. Relatively high efficiency of UV-254 reduction by FA suggests that adsorption preferentially reduced humic substances and hydrophobic organic fraction from raw seawater.

In order to determine the exact organic constituents reduced by various pretreatments, the MWD analysis was conducted using the LC-SEC technique. Fig. 2 shows the MWD results for the filtrates of PCF, DMF and FA as well as raw seawater. According to Fig. 2, there were three peaks (180, 800, 28,000 Da) in raw seawater and the highest peak was observed at 180 Da. These were different from other study results [13]. Shon et al. found five peaks (90, 250, 650, 950, 1,200 Da) from the South-West seawater of Korea. The MWD can be different from places to places and from seasons to seasons. According to previous study [18], MW of 28,000 Da may be attributable to polysaccharide, 800 Da to humic substances, and 180 Da to amphiphilics.

The MWD distribution can give insight of effectiveness of pretreatment processes in reduction of different organic fractions. According to Fig. 2, all processes successfully reduced organic fractions of high MW (28,000 Da). It was interesting to note that FA was effective in reducing organic fractions of high MW because activated carbon is known to be ineffective in reduction of high MW organic fraction. Lin et al. reported that PAC adsorption is ineffective in removing organic fractions of > 17,000 Da [8]. FA was able to reduce organic fractions

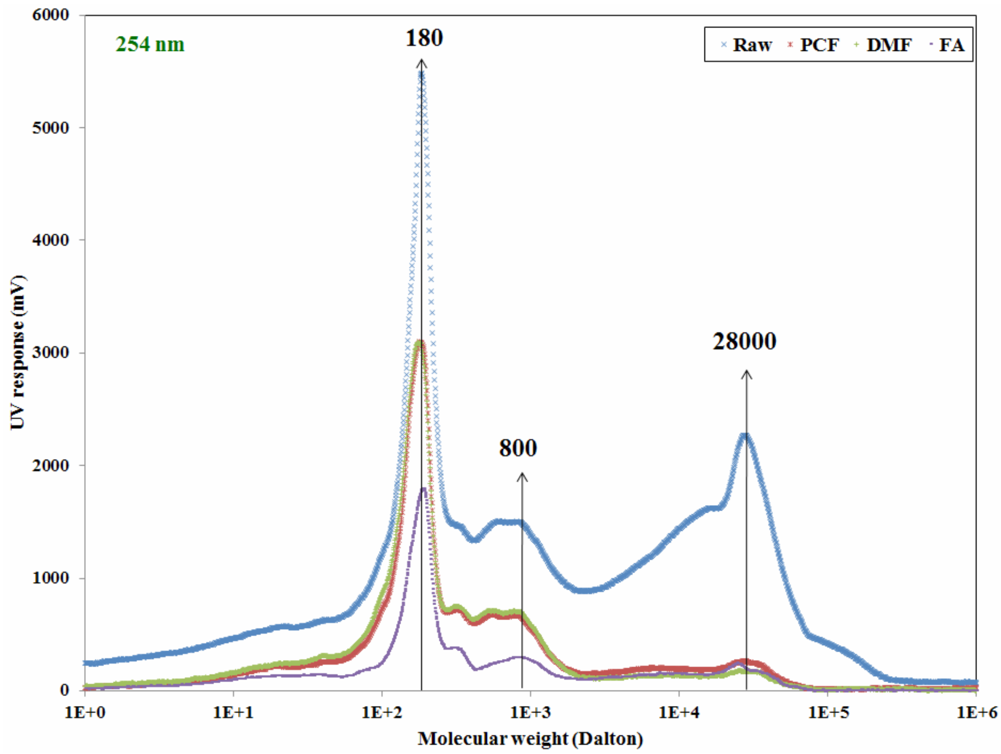

Fig. 2. MWD distribution of the PCF, DMF and FA filtrates together with raw seawater.

of high MW (28,000 Da) due to bottom layer of sand, at which media filtration occurred. The organic reduction efficiency of DMF and PCF deteriorated as MW of organic fractions decreased. Unlike DMF and PCF, FA was able to reduce organic fraction of small MW (800 Da) almost completely due to adsorption. However, FA showed its limitation in reducing very small MW fraction (180 Da). This is understandable because adsorption is shown to be ineffective in reducing very small organic fraction (<300 Da) [8].

3.3. *Initial breakthrough*

Initial breakthrough behavior of a filter is important for evaluation of the filter performance. A filter is backwashed so as to dislodge captured particles and restore its particle removal capacity at the end of the filtration cycle. After backwash, some portion of dislodged particles remains in a filter. This backwash remnant is discharged as filtration begins causing an increase in the filtrate turbidity. This is called initial breakthrough. The duration of initial breakthrough should be short and the turbidity peak should be low in order to keep the filtrate turbidity level low. Initial breakthroughs of DMF and FA were therefore compared and the results are shown in Fig. 3. According to Fig. 3, initial breakthrough behavior of FA is comparable to that of DMF.

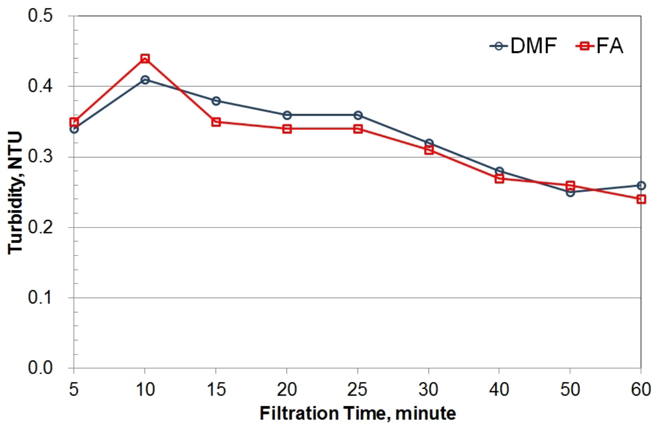

Fig. 3. Comparison of initial breakthroughs of FA and DMF.

4. Conclusion

The performance of different processes applicable for pretreatment of seawater desalination was evaluated in this study. These processes include DMF, PCF and FA. The parameters used for the evaluation are the particle removal performance, the organic reduction performance and initial breakthrough. The particle removal performance was evaluated by turbidity, particle number (>2 μm), SDI of the filtrate. The organic reduction performance was evaluated by COD, UV-254, and molecular weight distribution (MWD) of the filtrate. According to this study, PCF demonstrated the best performance in the particle removal, while FA showed the best performance in the organic reduction. FA was also good in the particle removal comparable to DMF. The initial breakthrough behavior of FA was very similar to that of DMF. FA is more effective in the organic reduction than PAC adsorption. Unlike PAC adsorption, FA was effective in reducing large MW organic fraction (> 17,000 Da) due to media filtration at the bottom layer.

Acknowledgements

This research was supported by a grant 07Sea-HeroB0102-03 from Plant Technology Advancement Program funded by Ministry of Construction and Transportation of Korean government.

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