Desalination and Water Treatment
www.deswater.com

29 (2011) 20–28
May

doi: 10.5004/dwt.2011.1281

Study of a depth filter (Disruptor™) for the novel application of reducing SWRO membrane fouling

Ibrahim M. El-Azizi[a]*, Achim Schmalenberger[b], Rodney Komlenic[c], Robert G.J. Edyvean[d]

[a]*Tajoura Research Center, Tajoura SWRO Desalination plant, P. O. Box: 30878, Tajoura, Tripoli, Libya*
Tel. +218 (21) 3614130/37; Fax +218 (21) 3614142/43; email: el_azizi2001@yahoo.com
[b]*Department of Chemical and Process Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK*
Tel. +44 114 2225776; Fax +044 2114 2227501; email: r. edyvean@sheffield.ac.uk
[c]*Cell-Mineral Research Centre, Kroto Research Institute, Broad Lane, Sheffield, S37HQ, UK*
Tel. +44 (114) 2225736, email: A.Schmalenberger@sheffield.ac.uk
[d]*Rodney Komlenic, Alstrom Filtration LLC, 122 W. Bulter Street, PA 17065-0238, USA*
Tel. +1 711 748 6 6401; email: rod.komlenic@ahlstrom.com

Received 29 April 2009; Accepted in revised form 26 October 2010

ABSTRACT

The removal efficiency of a nanoalumina depth filter (Disruptor™) was tested using raw seawater from the North Sea in a laboratory scale filtration unit and reverse osmosis (RO) test unit. Permeate flux was measured against time using untreated and pre-filtered seawater. Untreated seawater exhibited a rapid permeate flux decline. Seawater pre-filtered through the Disruptor™ showed showed high flux that declined only slightly after 120 min of operation due to increasing of osmotic pressure and formation of scaling on the membrane surface. The surface morphologies of clean and fouled RO membranes were examined using scanning electron microscope (SEM). The surface of the membrane fouled by untreated seawater was completely covered by a fouling layer, while the membrane surfaces exposed to Disruptor™ pre-filtered seawater were clean and only scaling was detected. The functional groups on clean and fouled RO membrane samples were investigated by attenuated total reflection — Fourier transform infrared spectroscopy (ATR–FTIR). The spectra of the RO membrane fouled by untreated seawater showed absorption bands at 1025, 1006 and 915 cm^{-1}, indicating that the fouling materials were polysaccharides and silica clay materials. The spectrum on the RO membrane exposed to pre-filtered seawater through the Disruptor™ was indistinguishable from that of the clean RO membrane. The involvement of transparent exopolymer particles (TEP) in the establishment of biofouling and development of biofilm was investigated. Results showed that TEP size increased as well as the number of bacteria with time of incubation. However, the number of TEP decreased by about 80% in seawater pre-filtered through the Disruptor™.

Keywords: Reverse osmosis; Fouling; Disruptor™; Nano-alumina depth filter

* Corresponding author.

1. Introduction

Reverse osmosis (RO) membranes are widely used in desalination of sea and brackish waters. Moreover, they have found uses in the production of ultrapure water, food processing and waste water treatment. Fouling is the major obstacle for efficient operation of RO membrane process [1]. RO membrane systems using open seawater intake systems can be fouled by inorganic precipitates, particles, precipitated metals, microorganisms, organic matter, and hydrocarbons [2,3]. The presence of components in the water sources such as transparent exopolymer particles (TEP) play an important role in conditioning of surfaces for biofouling and biofilm development [4,5]. Generally, fouling deteriorates membrane performance, increases operation and maintenance costs and shortens membrane life [6,7]. Pre-treatment processes for the clarification of seawater upstream of RO membranes include disinfection, coagulation/flocculation, multimedia filters followed by cartridge filters and membrane separation (microfiltration and ultrafiltration) [8–10]. These technologies are variously used in SWRO desalination plants to remove turbidity, suspended solids and microorganisms to meet the standards required of RO feed water. However, conventional pretreatment must be optimized and developed depending on the variation of feed water quality [9]. Membrane separation processes such as microfiltration (MF) and ultrafiltration (UF) require frequent backwashing and chemical cleaning due to blockage of membrane channels by foulants [11]. Some researchers [12–14] report that UF as pre-treatment upstream of RO membranes increases flux, plant recovery, RO membrane life and decreases chemical cleaning, while others [15,16] reported that MF/UF is limited in removing organic matter molecules with a small molecular weight cutoff. Despite high removal efficiency, MF/UF membranes require an extensive monitoring and protection by screens (500–50 μm according to the membrane supplier). This increases the operational costs [16]. Nanofiltration (NF) can be used upstream of reverse osmosis and thermal desalination processes, especially to remove boron from seawater [17]. However nanofiltration membranes require an efficient pretreatment similar to RO membranes. Recently, automatic backflush filters and automatic self-cleaning filters have been used to remove fine sands from untreated water prior to cartridge filters and RO membranes. They offer advantages over traditional multi media filters in terms of capital and installation costs. They can extend the lifetime of the cartridge filter elements and prevent sand from entering the reverse osmosis membranes.

Transparent exopolymer particles (TEP) play important role in the establishment of organic fouling and the development of biofilm [4,5]. TEP are microscopic particles, (0.4~200 μm) in size and form from polysaccharides released by microorganisms and are not detectable by traditional particle size techniques [18,19]. A recent study [5] at the Adom desalination plant, Ashkelon, showed that conventional pretreatment technology (sand and micron filters) can not effectively remove TEP. Therefore, an alternative efficient pre-treatment upstream to RO membranes is required.

The Disruptor™ is an electropositive, submicron polishing medium that removes a variety of submicron contaminants through adsorption rather than mechanical filtration. The nanoalumina filter medium has a dense electropositive zeta potential of +50 mV at pH 7.2, which is well maintained in fresh, brackish and seawater. A typical 2.5″×10″ pleated cartridge has more than 10,000 m^2 of active surface area with a capability to remove contaminants down to a few nanometers including endotoxins, cell debris, colloids, virus, bacteria and certain metals such as iron lead, copper and silver [20].

This study explores the use of the Disruptor™ in reducing RO membrane fouling in raw seawater.

2. Materials and methods

2.1. Raw seawater

Coastal seawater was collected from the North Sea and transported to the University of Sheffield and stored for two weeks at 4°C in a dark refrigerator before the experiments. This seawater has a pH = 8.3, and total dissolved solids (TDS) = 25,500 mg/l.

2.2. Pre-treatment methods

The cartridge filters selected for this study were made of polypropylene and had a pore size of 1 μm and 5 μm, respectively. The Disruptor™ is made of nanoalumina fibres attached to a microglass fibre and had a pore size of about 2 μm. The filter medium contains 32% by weight of nano fibers the alumina mineral boehmite (AlOOH). These nanoalumina fibers are attached to microglass carrier fibers, appearing as hair-like strands approximately 2 nm in diameter and about 250 nm long, with a surface area of approximately 500 square meters per gram of nanoalumina fiber. The nanoalumina fibers have a powerful electokinetic potential due to the Al^{3+} charge on the surface of each fiber that extends up to one micron from the end of the nanofiber. The cartridge filters and the Disruptor™ were supplied by "Amazon" Filtration Ltd, UK.

2.3. Reverse osmosis membrane

A Toray seawater reverse osmosis (SWRO) membrane was used in all fouling experiments (Table 1).

2.4. Filtration and cross-flow membrane filtration unit

Fouling tests were carried out using a laboratory scale filtration unit and plate and frame cross-flow RO test unit. The filtration unit consists of a feed water tank and two

Table 1
Specifications of the selected SWRO membrane

Membrane	SWRO
Manufacturer	Toray, Japan
Material	Polyamide
Surface charge at pH 7	Negative
Salt rejection, %	99.75
Flux, $l/m^2.h$	9.58

10 inch cartridge filter casings "Amozon" Filters Ltd-UK. The cross-flow RO test unit is a commercially available stainless steel unit (Osmonics, Desal, USA). It consists of a feed water tank, high pressure pump, and two test cells with pressure gauges and regulators (Fig. 1). The unit can be operated with feed pressure up to 1000 PSI and provides an effective membrane surface area of 81 cm^2.

The fouling tests were conducted in a recycling mode where both the permeate and concentrate flow recycled back to the feed water tank. The feed flow rate through the cross flow filtration unit is 4.2 $L.min^{-1}$. Each filtration experiment conducted over a period of 6 h. The filtration experiments were carried out on different days in which each filtration experiment was carried out twice and similar results were obtained.

2.5. Membrane characterisation

Membranes were characterised by contact angle, surface morphology and membrane roughness. The clean and fouled RO membrane coupons dried carefully in a laminar flow cabinet prior to the contact angle and SEM measurements because drying of membrane samples could cause severe distortion to the biofilm.

The contact angle values of clean and fouled membranes measured by the sessile drop method using a contact angle meter (KRUSS – DSA100) according to the methods used by Shon et al. [21]. Membrane hydrophilicity measured by depositing a 5 μl droplet of ultra pure water onto the dried membrane surface using a micro-syringe. The average contact angle of 5 droplets determined.

A scanning electron microscope (FEI Instruments) used for surface morphology measurements of clean and fouled RO membranes. 1 cm^2 membrane coupons cut from the clean and fouled RO membranes mounted on the test disc and coated with gold prior to SEM imaging.

The clean and fouled DisruptorTM filter and RO membrane analysed for functional groups using attenuated total reflection–Fourier transform infrared spectroscopy (ATR–FTIR) (PerkinElmer FTIR spectroscope). In order to reduce the interference of water the filter and membrane samples dried prior to ATR–FTIR measurements. The clean and fouled DisruptorTM filters and clean and fouled membrane samples pressed against each side of a germanium (Ge) reflection element (6 mm, 45°). All spectra recorded with 100 scans and a wave number resolution of 4 cm^{-1} resolution.

2.6. Transparent exopolymer particles (TEP) measurement

The numbers of TEP in raw and pre-filtered North Sea seawater through DisruptorTM were measured according to the method described by Bar-Zeev et al. [5]. 500 ml of raw and pre-filtered seawater was collected in sterile glass beakers. Sterile glass microscope slides were suspended in the water in each glass beaker. The glass beakers were then incubated at 25°C with 100 rpm agitation. Slides from each beaker were removed after 48, 72 and 168 h and transferred into sterile Petri dishes and stained with 0.02% Alcian blue for 7 min, and rinsed twice by DI water to remove access dye. The slides were covered with cover slips and viewed under the light microscope (Zeiss

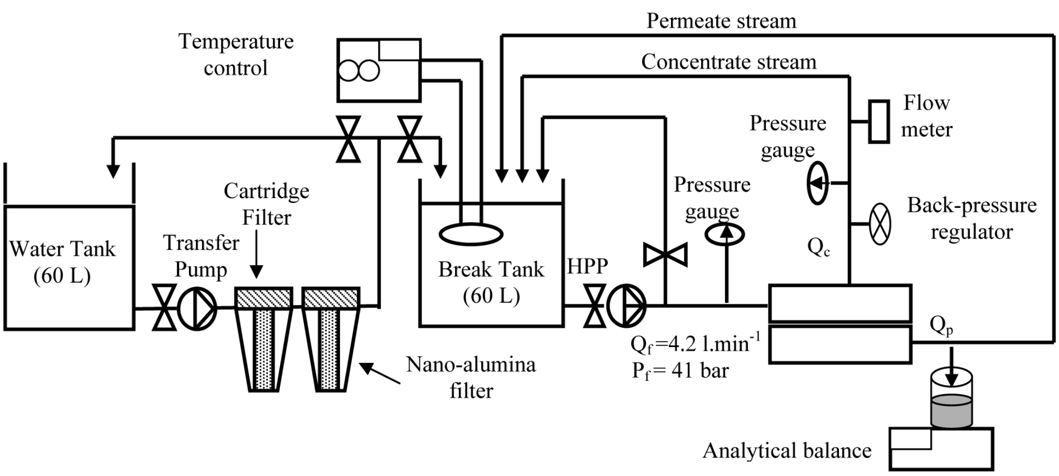

Fig. 1. Schematic diagram of bench scales filtration and cross-flow RO membrane filtration units.

Axioplan 2, Zeiss Instruments). 20 microscope fields were taken at random from the glass slide at a magnification of 200× and the TEP were counted in each microscope field.

In order to quantify the attached bacteria, slides of the same treatment were stained with 10 µl of 4′,6-diamidino-2-phenylindole (DAPI, concentration 3 µg ml^{-1}) for 7 min in the dark. A drop of immersion oil (Olympus, Fisher) was placed onto each glass slide and flattened by placing a cover slip on the top of the slide and then viewed under an epifluorescence microscope. DAPI stained bacteria were counted in 20 microscope fields taken from the glass slide at a magnification of 1000×. The average number of bacteria cells per cm^2 in raw seawater and that pre-filtered through a Disruptor™ was calculated using the Imag J software.

The percentage removal of TEP and bacteria by the Disruptor™ was calculated using the following equation:

$$\text{Percentage of rejection } R(\%) = \frac{N_f - N_p}{N_f} \times 100\% \quad (1)$$

where N_f is the number of TEP or bacteria cells in the raw seawater, N_p is the number of TEP or bacteria cells in pre-filtered seawater through the Disruptor™.

2.7. Membrane fouling study

Prior to all fouling tests, circular RO membrane coupons (81 cm^2 in area) were cut and mounted in a stainless steel, cylindrical membrane test cell and then rinsed with DI water at 100 psi for 30 min in order to remove the impurities attached to the membrane surface. As the membrane coupons to be tested had a small surface area and would be affected by the compaction under high operating pressure, the permeate flux was measured with high quality RO permeate at an operating pressure of 600 psi and stable temperature (25±1°C) until a constant flux was achieved. For the fouling tests, first, the North Sea raw seawater (untreated) was added to the feed tank and pumped directly to the RO test unit containing a previously conditioned flat sheet SWRO membrane in order to investigate the effect of composite fouling on permeate flux. Next, the seawater was filtered through a Disruptor™ filter alone, through a 5 µm cartridge filter alone and through a 1 µm cartridge filter alone in order to investigate the removal efficiency of each filter separately. The pre-filtered seawater from each filter was pumped into the RO test unit containing a clean and conditioned RO membrane and the permeate flux over operating time was measured. In addition, the performance of the Disruptor™ filter was investigated by filtering raw seawater thorough 1 µm filter followed by the Disruptor™ filter. Fouling filtration tests were preformed in duplicate. The permeate flux was determined at stable temperature (25±1°C) and constant feed pressure (600 psi) by weighing the permeate using an electronic balance. The conductivity and pH of feed and permeate were measured during the experiments using an electrical conductivity meter (Model CON 410, OAKTON, Eutech Instruments) and microcomputer pH meter (HI 8424-HANNA Instruments).

Permeate flux (J_w), the flow rate of permeate product (Q_p) per membrane area (A) was calculated as follows [Eq. (2)]:

$$J_w = \frac{Q_p}{A} \quad (2)$$

Permeate flux is a function of temperature and all permeate flux values were corrected to 25°C using Eq. (3) (adapted from the American Society for Testing and Materials (ASTM)) [22]:

$$J_S = J_A 1.03^{(T-25)} \quad (3)$$

where J_S is standard permeate flux, J_A is actual permeate flux, and T is temperature, respectively.

At the end of each fouling experiment, the feed tanks were emptied and the filtration and cross-flow RO unit were rinsed with high quality RO permeate water. After rinsing both filtration units were cleaned by re-circulating NaOH solution (0.1%) at pH 11 for 30 min and HCl solution (0.1%) at pH 2 for another 30 min. After chemical cleaning, both units were rinsed with high quality RO permeate water for 30 min.

3. Results and discussion

3.1. Characterisation of an SWRO membrane

The membrane characteristics before and after exposure to Disruptor™ filtered seawater are summarised in Table 2.

The clean SWRO membrane exhibits a medium contact angle and a rough surface. The decreased contact angle of the fouled membrane suggests the hydrophilic nature of fouling materials. The membrane surface rough-

Table 2
Characterisation of SWRO membrane before and after using Disruptor™ filter

Code	New membrane	Fouled membrane (raw seawater)	Pre-filtered seawater (Disruptor™)
Membrane contact angle	52.5 ± 0.42	41.6 ± 1.19	51.9± 4.17
Membrane roughness, nm	49.144	78.254	53.988

ness was increased by 59% due to the fouling layer that accumulated on the membrane surface. However, when using Disruptor™ filter for pre-treatment prior to the RO membrane only a slight change in the contact angle and membrane roughness was observed when compared to a new membrane.

3.2. Membrane fouling by raw and pre-filtered seawater

The effect of fouling on permeate flux investigated by filtering untreated and treated (pre-filtered) seawater through SWRO membranes. Raw seawater and seawater filtered through 1 μm, 5 μm, a Disruptor™ filter and a 1 μm filter followed by a Disruptor™ filter tested for the effect of fouling on permeate flux (Fig. 2).

Untreated seawater exhibited rapid and flux decline of 41% over 6 h due to accumulation of fouling materials (particles, colloids and bacteria). Similar studies [2,3] report that accumulation of small particles and colloids on the membrane surface results in a large hydraulic resistance to permeate flow and thus fast permeate flux decline. Seawater pre-filtered raw through 1 μm, 5 μm filters, respectively exhibited similar trends, with the permeate flux being stable in the first 90 min followed by a rapid decline due to formation of colloidal fouling and scaling on the membrane surface. These treatments showed an overall permeate flux decline of about 36% and 50% respectively. However, using the Disruptor™ filter alone, as well as downstream of the 1 μm filter resulted in much slower permeate flux decline (25% and 15%, respectively). Decrease of the permeate flux of seawater pre-filtered through the Disruptor™ filter was only noticed after 120 min of filtration. This decrease is possibly due to increase in osmotic pressure, the effect of the concentration polarization and/or formation of scaling on the membrane surface. Concentration polarization can contribute permeate flux decline due to increasing salt concentration near the membrane surface which leads to formation of scaling and increasing osmotic pressure [5]. Despite the short time of filtration experiments (6 h), the results clearly demonstrate that using a Disruptor™ filter upstream to the RO membranes can reduce fouling.

3.3. SEM

The SEM images of the membrane receiving raw seawater and seawater pre-filtered through the Disruptor™ filter are shown in Fig. 3 and Fig. 4, respectively.

RO membrane receiving seawater pre-filtered through the Disruptor™ filter showed some scaling but little difference from the new membrane surface.

Precipitation of scaling on the membrane surface is attributed to the high pH of seawater The SEM image demonstrates higher removal efficiency when using a Disruptor™ filter as pre-treatment prior to RO membranes. The majority of foulants were removed from RO feed water and only scaling was detected. Scaling problems can be prevented by adjustment of the seawater pH using hydrochloric acid (HCl) and/or sulfuric acid (H_2SO_4).

3.4. ATR–FTIR

ATR–FTIR spectra of a clean Disruptor™ filter and one fouled by raw seawater (Fig. 5) and a clean RO membrane and those fouled by raw and filtered seawater (Fig. 6) were investigated and the functional groups were determined.

It can be seen that all high absorption bands of clean RO membranes are located in the amide and carbohydrates regions (750–1750 cm^{-1}) (Fig. 6) [23]. These high absorption bands were reduced in the spectra of the RO membrane fouled by raw seawater due to the fouling covering the membrane surface. The RO membrane fouled by unfiltrered seawater showed a large peak between

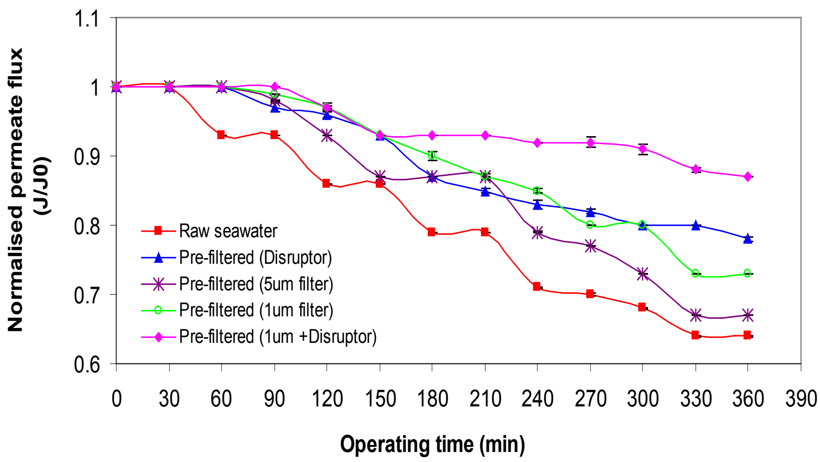

Fig. 2. Comparative permeate flux decline of untreated seawater and pre-filtered using 1 μm filter, 5 μm filter, Disruptor™ filter and 1 μm filter followed by Disruptor™ filter, respectively.

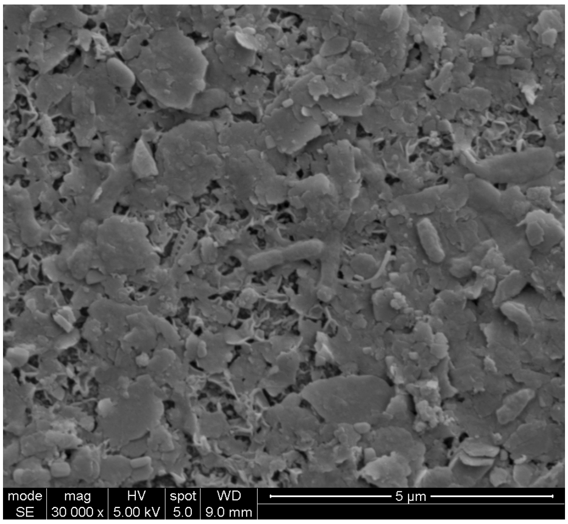

Fig. 3. SEM image of fouled RO membrane by the North Sea raw seawater.

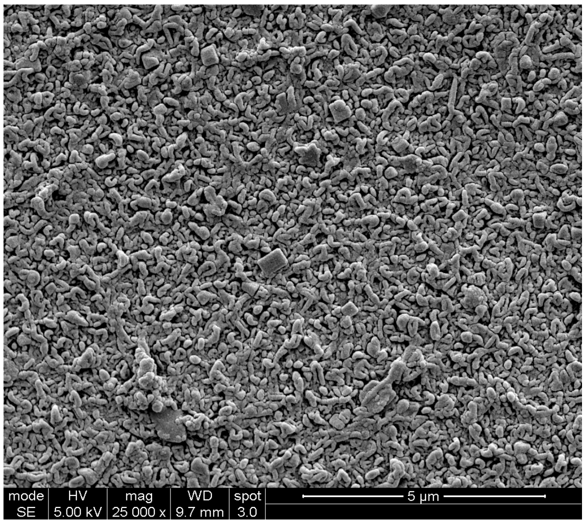

Fig. 4. SEM image of RO membrane with Disruptor™ pre-filtered North Sea water.

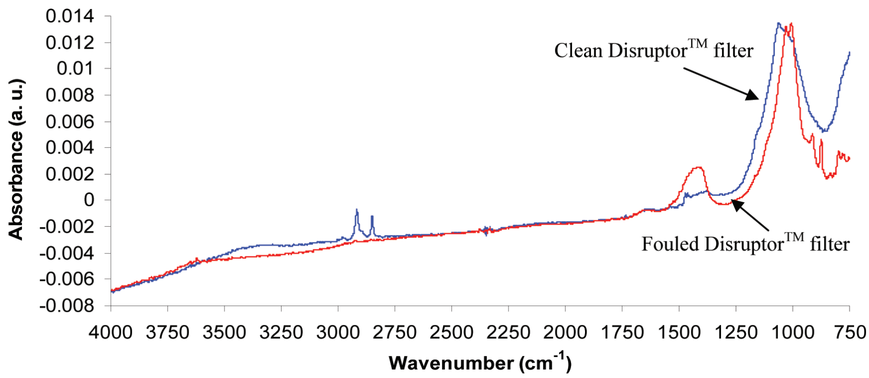

Fig. 5. FTIR spectra of clean and fouled Disruptor™ filter by raw seawater.

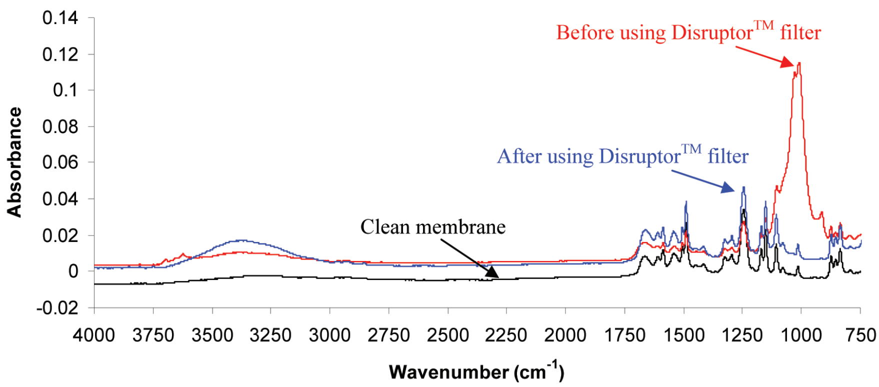

Fig. 6. FTIR spectra of clean and fouled RO membranes before and after using Disruptor™ filter as pre-treatment prior to the RO membrane.

900 and 1100 cm^{-1} suggesting that the RO membrane is fouled by polysaccharides or silica colloids [23–25]. This large peak is not present after using a Disruptor™. The spectra of the clean RO membrane and that after using Disruptor™ filter are almost identical. This shows that a Disruptor™ filter removes the majority of substances that may foul the RO membrane.

3.5. Number of transparent exopolymer particles (TEP) and bacterial cells

The number of transparent exoploymer particles (TEP) and bacteria cells were counted in the glass slides suspended in raw (untreated) and pre-filtered seawater through Disruptor™ filter. After 24 h of incubation in the raw sea water small size TEP and a few bacteria were found (Figs. 7a and b).

However, after 168 h of incubation the TEP areas became larger in size and a high number of bacteria were observed (Figs. 8a and b). The results indicate that presence of TEP in the water increases the biofouling potential. Similar results were reported by Bar-Zeev et al. [5] where the size of stained TEP and number of bacteria increased with increasing time of incubation.

The results from seawater pre-filtered through the Disruptor™ filter show smaller sized TEP particles and no bacteria in the first 24 h of incubation (Fig. 9). However, a few cells were observed on the glass slide after 168 h of incubation.

The number bacterial cell and TEP were counted on the glass slides after 24 h and 168 h of incubation and the results are summarized in Table 3.

4. Conclusions

Laboratory scale experiments were carried in order to investigate the efficiency of a Disruptor™ filter in removing substances responsible for fouling SWRO membranes. Results showed that the Disruptor™ medium

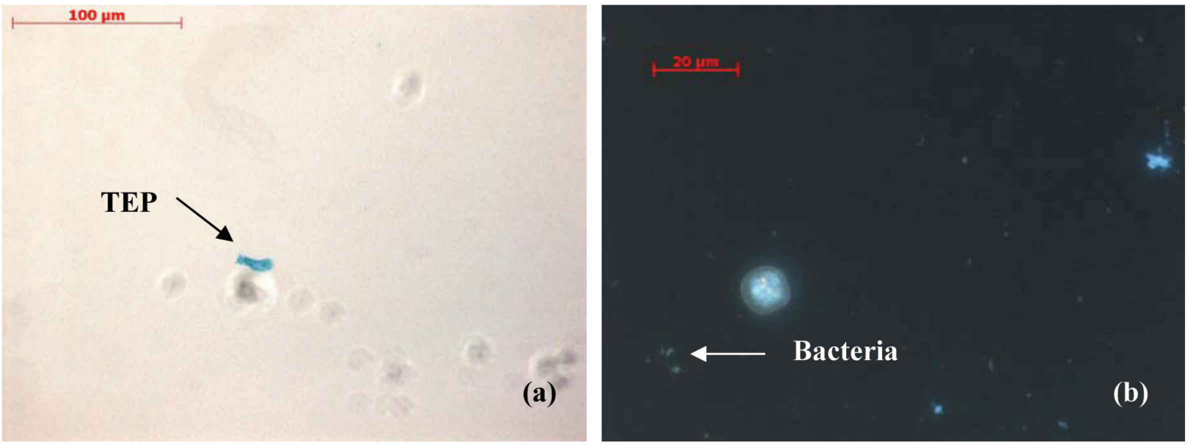

Fig. 7. Microscope images of TEP (a) and bacterial cells (b) on glass slide after 24 h of incubation in raw seawater.

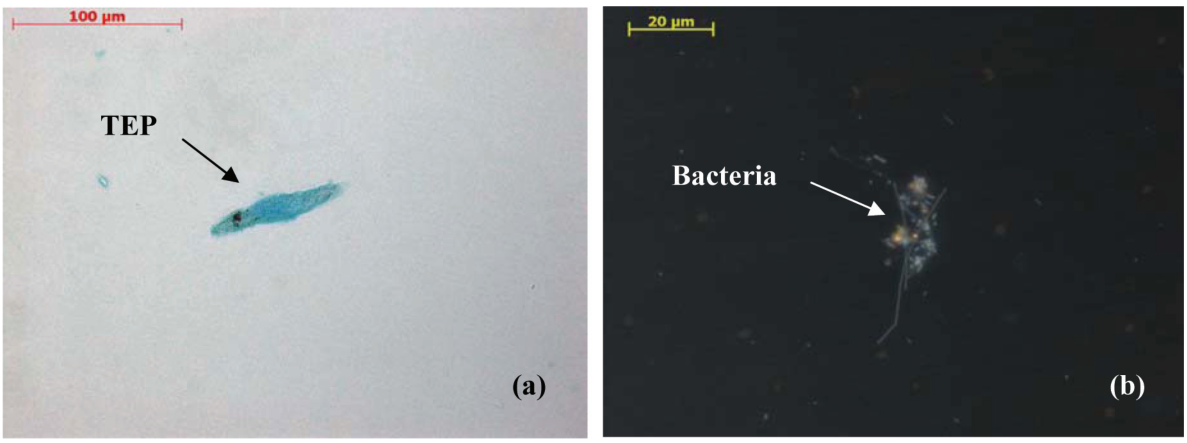

Fig. 8. Microscopic images of TEP © and bacterial cells (d) on glass slide after 168 h of incubation in raw seawater.

Table 3
Number of bacterial cells and TEP on glass slides after 24 h and 168 h of incubation

Water sample	Number of bacteria (cell.cm^{-2})	Number of TEP (TEP.cm^{-2})
Raw seawater (24 h)	1.75×10^5	45
Raw seawater (168 h)	3.38×10^5	120
Pre-filtered seawater (24 h)	0	15
Pre-filtered seawater (168 h)	2370	24

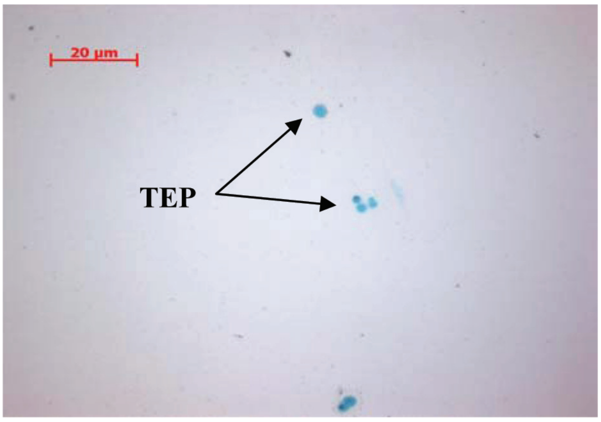

Fig. 9. Microscopic images of TEP after 168 h of incubation in seawater pre-filter through Disruptor™.

can substantially reduce RO membrane fouling. Permeate flux was maintained over 6 h. SEM and ATR–FTIR results demonstrated the high removal efficiency of the Disruptor™ medium. The role of TEP in biofouling and biofilm development was investigated. Large numbers of TEP colonized by bacteria were found on the glass slides after 168h of incubation in untreated seawater, indicating the involvement of these particles in the development of biofouling. However, it was found that the Disruptor™ medium can remove about 80% of these particles. From this study, it can be concluded that the Disruptor™ medium can substantially reduce the severity of fouling and biofilm formation in SWRO membrane systems. Pilot plants or full scale testing at SWRO plant are necessary to quantify the commercial benefits to be obtained by reducing membrane fouling through the use of Disruptor™ filter.

Acknowledgments

The authors would like to thank Ahlstrom Filtration LLC, USA and Amazon Filtration Ltd, UK for supporting this study. The authors also thank Jesus Ojeda, Kieran Baker and John Heneghan for their assistance in FTIR, epifluorescence microscope and contact angle instruments.

References

[1] P. Xu, J. E. Drewes, T. Kim, C. Bellona and G. Amy, Effect of membrane fouling on transport of organic contaminants in NF/RO membrane applications, J. Membr. Sci., 179 (2006) 165–175.
[2] S. Lee, J. Cho and M. Elimelech, Influence of colloidal fouling and feed water recovery on salt rejection of RO and NF membranes, Desalination, 160 (2004) 1–12.
[3] V. Bonnelye, M.A. Sanx, J. Durand, L. Plasse, F. Gueguen and P. Mazounie, Reverse osmosis on open intake seawater: pretreatment strategy, Desalination, 167 (2004) 191–200.
[4] T. Berman and M. Holenberg, Don't fall foul of biofilm through high TEP levels, Filtr. Separ., 42(4) (2005) 30–32.
[5] E. Bar Zeev, I. B. Frank, B. Liberman, E. Raha, U. Passow and T. Berman, Transparent exopolymer particles: Potential agents for organic fouling and biofilm formation in desalination and water treatment plants, Desal. Wat. Treat., 3 (2009) 136–142.
[6] C.Y. Tang, Y. Kwon and J.O. Leckie, Fouling of reverse osmosis and nanofiltration membranes by humic acid — Effects of solution composition and hydrodynamic conditions, J. Membr. Sci., 290 (2007) 86–94.
[7] C. Park, Y.H. Lee, S. Lee and S. Hong, Effect of cake layer structure on colloidal fouling in reverse osmosis membranes, Desalination, 220 (2008) 335–344.
[8] R.J. Xiea, E.K. Tanb, S.K. Limc, E. Haw, C.P. Chiewc, A. Sivaramanc, A.N. Puahc, Y.H. Lauc and C.P. Teo, Pre-treatment optimisation of SWRO membrane desalination under tropical conditions, Desal. Wat. Treat., 3 (2009) 136–142.
[9] C.V. Vedavyasan, Pretreatment trends — An overview, Desalination, 203 (2007) 296–299.
[10] M. Kumar, S.S. Adham and W.R. Pearce, Investigation of seawater reverse osmosis fouling and its relation to pretreatment type, Environ. Sci. Technol, 40 (2006) 2037–2044.
[11] M. Wilf and M.K. Schierach, Improved performance and cost reduction of RO seawater systems using UF pretreatment, Desalination, 135 (2001) 61–68.
[12] S.C.J.M. van Hoof, A. Hashim and A.J. Kordes, The effect of ultrafiltrationas pretreatment to reverse osmosis in wastewater reuse and seawater desalination applications, Desalination, 124 (1999) 231–242.
[13] A. Teuler, K. Glucina and J.M. Lainé, Assessment of UF pretrearment prior RO membranes for seawater desalination, Desalination, 125 (1999) 89–96.
[14] P. Glueckstren, M. Priel and M. Wilf, Filed evaluation of capillary UF technology as a pretreatment for large seawater RO systems, Desalination, 147 (2002) 55–62.
[15] K.A. Bu-Rashid and W. Czolkoss, Pilot tests of multibore UF membrane at Addur SWRO desalination plant, Bahrain, Desalination, 203 (2007) 229–242.
[16] V. Bonnelye, L. Guey and J. Del Castillo, UF/MF as RO pretreatment: the real benefit, Desalination, 222 (2008) 59–65.
[17] S. Sarp, S. Lee, X. Ren, E. Lee, K. Chon, S.H. Choi, S. Kim, In S. Kim and J. Cho, Boron removal from seawater using NF and RO membranes, and effects of boron on HEL 293 human

embryonic kidney cell with respect to toxicities, Desalination, 223 (2008) 23–30.
[18] M.D. Kennedy, F.P.M. Tobar, G. Amy and J.C. Schippers, Transparent exopolymer particle (TEP) fouling of ultrafiltration membrane systems, Desal. Wat. Treat., 6 (2009) 169–176.
[19] U. Passow, Transparent exopolymer particles (TEP) in aquatic environments, Prog. Oceanog., 55 (2002) 287–333.
[20] R. Komlenic, Water filtration media: Talking about a revolution, Filtr. Separ., June (2007) [pages??].
[21] H.K. Shon, S.H. Kim, S. Vigneswaran, R. Ben Aim, S. Lee and J. Cho, Physicochemical pretreatment of seawater: Fouling reduction and membrane characterization, Desalination, 238 (2009) 10–21.
[22] B.A.Q. Darwish, M. Abdel-Jawad and G.S. Alyon, The standardization of performance data for RO desalination plants, Desalination, 74 (1989) 125.
[23] V. Freger, J. Gilron and S. Belfer, TFC polyamide membranes modified by grafting of hydrophilic polymers: an FT-IR/AFM/TEM study, J. Membr. Sci., 209 (2002) 283–292.
[24] J. Cho, G. Amy, J. Pellegrino and Y. Yoon, Characterisation of clean and natural organic matter (NOM) fouled NF and UF membranes, and foulants characterization, Desalination, 118 (1998) 101–108.
[25] J. Schmitt and H.C. Flemming, FTIR-spectroscopy in microbial and material analysis, Int. Biodeter. Biodegrad., 41 (1998) 1–11.