Membrane Water Treatment, Vol. 3, No. 4 (2012) 253-266
DOI: http://dx.doi.org/10.12989/mwt.2012.3.4.253

Hybrid salts precipitation-nanofiltration pretreatment of MSF and RO seawater desalination feed

Aiman Eid Al-Rawajfeh*[1,2]

[1]*Tafila Technical University (TTU), Department of Chemical Engineering, P.O. Box 179, 66110 Tafila, Jordan*
[2]*Jordan Atomic Energy Commission (JAEC), Shafa Badran, Amman, Jordan*

(Received September 11, 2012, Revised October 19, 2012, Accepted October 24, 2012)

Abstract. In this work, the effect of hybrid salts precipitation-nanofiltration (SP-NF) process on the scale deposits in thermal and membrane desalination processes has been studied. The analysis was carried out to study the scale formation from the Arabian Gulf seawater in MSF and RO reference processes by changing the percentage of pretreatment from 0 to 100%. Four different SP-NF configurations were suggested. A targeted Top Brine Temperature (TBT) of 130°C may be achieved if 30% portion is pretreated by SP and/or NF processes. As a rule of thumb, each 1% pretreatment portion increases the reference TBT of 115°C by 0.6°C. For both MSF and RO, parallel pretreatment of certain percentage of the feed by SP and the rest by NF, showed the lowest scale values. The case showed the best values for sulfate scale prevention and the highest values of increasing the monovalent ions relative to the divalent scale forming ions. Sulfate scale is significant in MSF process while carbonate scale is significant in RO. Salt precipitation was suggested because it is less costly than nanofiltration, but nanofiltration was used here because it is efficient in sulfate ions removal.

Keywords : pretreatment; desalination; salt precipitation; nanofiltration; scale deposition

1. Introduction

Desalination has become a promising alternative and viable way to bridge the gap between water demands and the deficit in fresh water supply and has been adopted by 120 countries in the world. Luckily, the Middle East and North Africa (MENA) enjoy a relatively high intensity renewable (RE), such as solar and wind energies and nuclear energy (NE) resources. Matching RE and NE with desalination systems present a real challenge. Widely available methods for desalting are the multi-stage flashing (MSF), multi-effect distillation (MED), vapor compression (VC), reverse osmosis (RO), electrodialysis (ED), etc. However, only two of the aforementioned desalination technologies namely, MSF and RO technologies, dominate the desalination market for large-scale production. The MSF plants are widely used in the MENA regions, and this can be attributed to two factors: (i) the higher seawater salinity in the regions and the frequent surface contamination from bacteria blooms (algae/red tides); (ii) the availability of low cost fossil fuels in the regions presents an easy integration of thermal desalination methods with the steam or gas turbine power plants.

According to Khamis and Kavvadias (2012), seawater desalination using nuclear energy is an inevitable option for the production of potable water. It is a reliable and economical way to alleviate global concerns on climate change and water scarcity issues. However, producing potable water

---

* Corresponding author, Ph. D., E-mail: aimanr@yahoo.com

from a co-located nuclear power plant raises some concerns regarding pathways of contamination of radioactivity to the final water. In order to eliminate all contamination pathways, the standard practices and innovative measures have to be taken during design and operation which are sufficient to prevent such contamination. Measures such as design of intermediate loop, implementation of pressure reversal, innovative measures like heat pipes and online or batch water monitoring during operation are proven to be sufficient to prevent radioactive contamination and drop it even to lower levels than conventional desalination plants. Yet, it cannot be predicted with sufficient certainty that nuclear desalination will be accepted by the public in every case. Therefore, proper communication based on facts must be established with the public in order to demonstrate the safety of this technology based on current experience. The dissemination of data from existing facilities in many countries could alleviate the concerns and improve the public perception for the nuclear desalination plants.

Because of economical reasons, the trend in desalination is to operate systems at as high a temperature and concentration factor as possible in order to increase purified water production at a lower cost. Safety concerns have also increased the need for acid feed elimination as a mean of controlling pH. These practices increased the scaling tendencies in MSF processes and created the need for more effective treatment programs to control scale formation on heat exchangers. Scale formation represents a major operational problem encountered in seawater desalination. Scale formation is mainly caused by crystallization of alkaline scales, e.g., $CaCO_3$ and $Mg(OH)_2$ and non-alkaline scale, e.g., $CaSO_4$. In today's operating plants, and to allow for a reasonable safety margin, sulfate scale deposition limits the top brine temperature (TBT) in multi-stage flash (MSF) distillers up to 110-112°C. Thermal processes have proven to be the reliable desalination technologies. The performance and economy of MSF and MED can be more superior if the TBT, which is limited by scale deposits, is increased.

Recently, Al-Rawajfeh (2008, 2010a) developed a model to simulate the simultaneous release of CO_2 with the deposition of $CaCO_3$ and investigated their mutual release-deposition relationship in MED (Al-Rawajfeh 2010a) and in the flash chambers in MSF distillers (Al-Rawajfeh 2008). The influence of CO_2 injection on the carbonate chemistry and the scale formation were also studied (Al-Rawajfeh and Al-Amaireh 2009). The model begins to calculate the $CaCO_3$-$Mg(OH)_2$ (alkaline) scale in the brine chambers, because part of the scale is deposited there and will be reduced from the total scale precipitate or reduce the ions available to precipitate $CaSO_4$ scale inside the tubes when it is recycled with the make-up. Details on the CO_2 release and alkaline scale modeling can be found in previous works (Al-Rawajfeh 2008, 2010a, Al-Rawajfeh *et al.* 2008, Al-Rawajfeh and Al-Amaireh 2009). The model were verified by comparing the calculated results of the model by experimental results from Hasson and Perl (1981) and model results of Chan and Ghassemi (1991). Hasson and Perl’s model gives average values. Chan and Ghassemi's model shows only excellent agreement at low calcium ion concentrations, which, indeed, are not the real conditions that prevail in seawater desalination. Chan and Ghassemi’s model fits very well the experimental values at low calcium ion concentrations, but it shows high deviation at higher concentrations. Our model shows an excellent agreement especially at higher calcium ion concentrations which is, indeed, the standard seawater and the Arabian Gulf concentration level. The pH values of the runs were low; the maximum value was 7.75 which was lower than the real seawater pH of 8.1 or higher. The importance of pH and its effect on the CO_3^{2-} concentration and the speciation of the carbonate species might be a reason. The processes such as nucleation, attachment and removal and surface properties such as roughness, which are difficult to be included in a model, could have some effect as well.

High pressure membrane desalination processes; i.e. nanofiltration (NF) and reverse osmosis (RO), are the prevalent desalination operation for various feed types and accounts for 55% (RO – 51%; NF – 4%) of the total water produced by desalination (44.1 Mm^3/day) (Antony *et al.* 2011). The unique property of RO membranes to reject inorganic species, while passing relatively pure water has led to its widespread use in desalination. Achieving high product recovery with less fouling formation and minimizing process cost is a major challenge in RO operation. The water product recovery for membrane desalination has to be sufficiently high, i.e. ≥70–80% to be economically feasible. Fouling, the accumulation of rejected constituents on the membrane surface, is a serious problem, resulting in permeate flux decline or increased transmembrane pressure. Inorganic fouling or scaling is the formation of hard mineral deposits on the membrane surface as the feed water becomes supersaturated by inorganic salts. The various operating conditions influence scale formation are: pH, temperature, operating pressure, permeation rate, flow velocity, and presence of other salts or metal ions. Importantly, concentration polarization plays a vital role in scale formation in high pressure membrane systems, as it leads to elevated salt concentrations near the surface of the membrane where particles may deposit.

In this work, the use of salts precipitators (SP) and nanofiltration (NF) for feed water pretreatment can improve the systems performance by removing the divalent ions. This will, therefore, reduces both soft and hard scales which lead to reduction in the capital expenditures (CAPEX), the operation expenditures (OPEX) and water production costs. The salts can be recovered, from the concentrated brine reject of pretreatment and desalination steps, as by-product and leading to zero brine discharge.

2. Scale modeling and water chemistry calculations

Modeling of the alkaline and non-alkaline scale inside the tubes of MSF evaporator can be achieved by dividing the tube, of a certain length and diameter, into volume elements (VE) as shown in Fig. 1. The water flowing in the first VE will be holding the characteristics of the feed and the outlet of this VE will be the inlet of the second VE, and so on. The temperature gradient is assumed to increase linearly from the temperature of the last stage (inlet) to the top brine temperature (TBT) at the first stage (exit). Inside a certain VE, the scale begins to precipitate if the condition of supersaturation is reached. $CaCO_3$ begins to precipitate followed by $Mg(OH)_2$ and then the $CaSO_4$ scale. $Mg(OH)_2$ will precipitate only if the pH of the water reached a certain value. Increasing the temperature is the driving force for sulfate scale (Al-Rawajfeh 2011, Al-Rawajfeh *et al.* 2012).

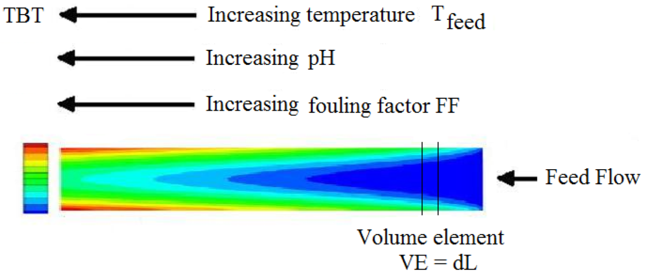

Fig. 1 Dividing the tube into volume elements (VE).

Sulfate scale potential (SSP) (Skillman *et al.* 1969) estimates the likelihood of calcium sulfate scaling. It is a ratio between the actual concentration, $[i]_{actual}$, of either calcium or sulfate and its theoretical or equilibrium concentration, $[i]_{eq}$, whichever is the limiting species

$$SSP = \frac{[i]_{actual}}{[i]_{eq}} \tag{1}$$

When calcium is the limiting reactant, the amount of calcium sulfate precipitated from the solution (CSPP), in mg/kg, can be calculated from

$$CSPP = Equivalent\ Weight \cdot ([i]_{actual} - [i]_{eq}) \tag{2}$$

The total fouling load and scale type percentage were calculated using an excel spreadsheet which has been developed specifically for the RO inorganic fouling assessment (ROIFA-4). The ROIFA software has been subjected to many laboratory tests and field investigations and found to be satisfactory (El-Manharawy and Hafez 2011). El-Manharawy and Hafez (2000) presented a comprehensive study covering water chemical analyses, and XRF analysis of scale samples from different RO-plant cases. The obtained results indicated a strong relationship between the feed water chemical characteristics and the generated scale potential and type. The "Dehydration Model" (El-Manharawy and Hafez 2002) provides reasonable explanation of the inorganic fouling mechanism happened during RO membrane dewatering. This study revealed that the solubility of carbonate and sulfate minerals increases, in different ways, with the increase of chloride concentration. The mathematical correlation between the theoretical and experimental fouling results proved that the proposed model is accurate and considered as a valuable tool for predicting inorganic fouling load.

The total fouling load (TFL) is the sum of the individual fouling flux of the investigated salts. The individual fouling load (FL_{Scale}) obtained from multiplying the compound analytical molar concentration (in mM/kg) by the estimated fouling fraction (F_f = 0-1) at a given Cl concentration

$$FL_{Scale} = [Scale] \cdot F_f \tag{3}$$

where F_f can be calculated from the concentration of chloride ions by a formula similar to

$$F_f = a[Cl^-] + b \tag{4}$$

where a and b are constants depend on the scale type and the chloride ion concentration level. They can be found elsewhere (El-Manharawy and Hafez 2011).

The fouling flux (F_x) of individual foulant could be predicted from its concentration in brine that flows in a 1 mm thickness layer spreading over 1 cm^2 of membrane surface per time, which is normally around 1 s

$$F_x = F_L \cdot F_f \cdot A_C \times 10^{-3} \tag{5}$$

where (F_x): number of hardness atoms found in 0.1 cm^3 per unit time (second), (F_L) is the fouling load, in mM/0.1 cm^3, (F_f) is the fouling fraction, (A_C) is the Avogadro's number.

In seawater desalination, NF is applied as a pretreatment of seawater feed before its processing by a desalination unit. The NF membrane pretreatment was found to be successful in removal of turbidity, significant removal of residual bacteria, scale forming hardness ions, lowering of the seawater TDS, and reducing energy and chemical consumption. NF has been proposed for divalent ions removal from seawater feed entering the thermal processes. In the current research, the theoretical simulation program developed by Hydranautics Nitto Denko Company (IMS software, Integrated Membrane Solutions) (IMSDesign 2010), was used for calculating NF rejection rate and membrane permeate flow. The NF permeate was used as an input of a newly developed model based on mass transfer with chemical reaction of solutes in the brine, to calculate scale formation in MSF evaporator. The IMS software was used for simulating NF pretreatment to seawater. ESNA1-LF2 nanofiltration membrane is classified as a softening element for seawater treatment. It has a high rejection rate to scale elements combined with moderate permeate flow rate. The compositions of feed water considered in this study were similar to that used by Awerbuch (2006) for typical Arabian Gulf seawater.

3. Results and discussion

3.1 Salt precipitation-nanofiltration pretreatment (SP-NF)

Pre-treatment of the feed water entering either thermal desalination units, such as MSF and MED, or membrane unit, such as RO, involves reduction of salinity and hence reducing or in some cases eliminating scale forming species to a certain level. This will increase the efficiency of the process, reduce the pumping power (in reverse osmosis (RO) systems), reduce or eliminate the scale and consequently reduce the cost. In this work, hybrid pretreatment processes including salt precipitation (Al-Rawajfeh and Al Zarooni 2008) and nanofiltration (SP-NF) (Hussain and Al-Rawajfeh 2009, Hussain 2007) will be investigated. Fig. 2 illustrates the SP-NF pre-treatment processes. They were divided into four cases:

- Case 1 (Fig. 2A): %(SP-NF), where % feed is treated by SP followed by NF and the product mixed with the rest (100-%) feed from the seawater and the product passed to a desalination unit.
- Case 2 (Fig. 2B): %SP followed by NF pretreatment of the whole feed, where % feed is treated by SP and mixed with the rest (100-%) from the seawater and then the mixture is subjected to NF treatment.
- Case 3 (Fig. 2C): parallel %SP and (100-%)NF pretreatment, where % feed is treated by SP and the rest (100-%) is treated by NF, and
- Case 4 (Fig. 2D): parallel %SP and %NF, where the feed is divided into two streams (50%/50%) portion of the first stream is treated by SP and the rest (50-%) mixed with the product of similar portion treatment of NF.

Precipitation process deals with supersaturating the saline solution by addition of chemical reagents which results in the precipitation, up to 80% or higher, of some of the salts in seawater. The purpose of co-precipitation process is to reduce the concentration of dissolved salts (solutes) in the feed water (solution), such as seawater, brackish water or industrial brine solutions so that it can be more effectively desalinated and higher percentage of fresh water can be recovered from it. Alkalization to pH > 10 by NaOH is a potential choice for treatment of high sulfate feeds by efficient removal of Ca^{2+} and Mg^{2+} ions. It can economically remove the scale forming ions and can strongly disinfect the treated feed.

When nanofiltration membrane is used (Jogand and Peron 2000), the concentrate, in which salts are supersaturated up to 80%, is subjected to the following steps: crystallization-coagulation treatment, flocculation, and finally settling. It is advantageous to recycle the brine blow-down because of the following reasons: (i) make use of the remaining initially-added compounds, (ii) discharging it to

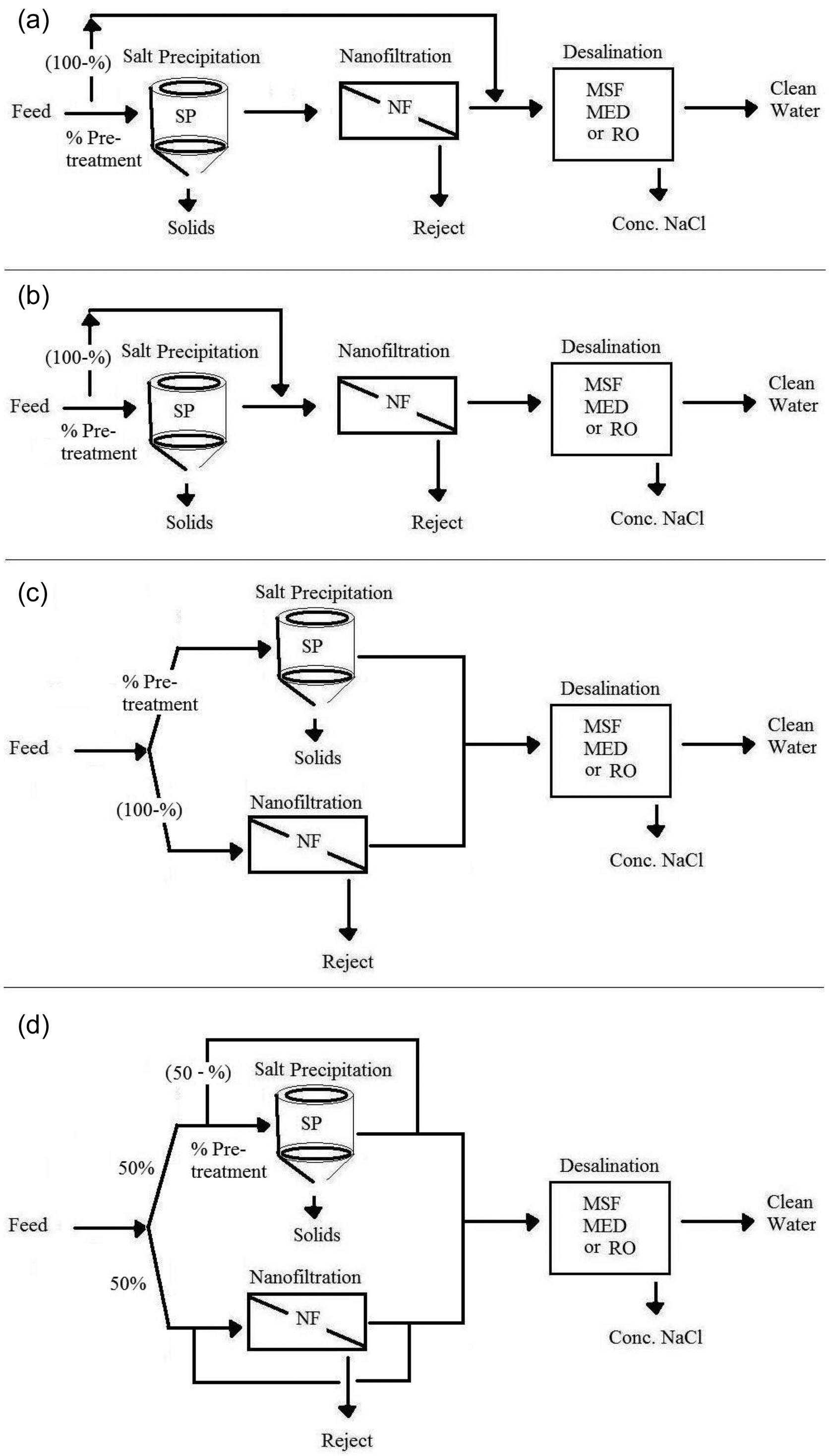

Fig. 2 The SP-NF pre-treatment processes; (a) %(SP-NF), (b) %SP followed by NF pretreatment of the whole feed, (c) Parallel %SP and (100-%)NF pretreatment, and (d) Parallel %SP and %NF.

Table 1 The maximum concentrations of the different species in the pretreated feed

Ions	Feed [ppm]	SP [ppm]	NF [ppm]	SP-NF [ppm]
Mg^{2+}	1550	15.5	272.4	2.724
Ca^{2+}	600	12	176.7	3.534
SO_4^{2-}	3440	1513.6	423.2	186.208
CO_3^{2-}	38	198.36	3.2	16.704

the ocean has high environmental impact and can damage the marine life, and (iii) if a thermal process is used, the heat can be recovered during recycling. Table 1 shows the concentrations of the different species in the SP-NF pretreated feed (only the most interesting species are shown). Salt precipitation was suggested because it is less costly than nanofiltration, but nanofiltration has been kept in use here because it is efficient in sulfate ions removal. A combination of the two processes needs detailed techno-economical study to enhance the decision of the treatment portion.

Tables 2, 3, 4, and 5 show the chemical composition of the feed water of the desalination unit, either thermal (MSF) or membrane (RO). The original concentration is the concentration of the intake water from the Arabian Gulf seawater at Doha, Kuwait (different than Doha of Qatar). The concentrations of calcium, magnesium, sulfate, and carbonate are 600, 1550, 3440, and 38 ppm, respectively. The salt precipitation pretreatment significantly decreases the concentration of these species lower than the original concentration but adds monovalent (Na^+) ions; i.e. softening step. Because the removal of sulfate by SP, from the original feed, is limited to a certain level, the concentration of sulfate increases with increasing the portion of SP in the pretreatment process, but stays under the original level. Nanofiltration significantly decreases the divalent ions, but has less influence on monovalent ions.

Alkalinity predominates the low-chloride water types while sulfate excessively occupies the higher chloride types. The sodium ion is mostly proportional with chloride at the higher salinity water types, but with lower chloride it seems that the calcium ion can be accepted better than sodium and

Table 2 SP-NF pretreatment of the desalination feed at different %(SP-NF); case 1

	Original	%(SP-NF)				
Ion	0	20	40	60	80	100
Mg^{2+}	1550	1243.1	936.2	629.3	322.4	15.5
Ca^{2+}	600	482.4	364.8	247.2	129.6	12
SO_4^{2-}	3440	3054.72	2669.44	2284.16	1898.88	1513.6
CO_3^{2-}	38	70.072	102.144	134.216	166.288	198.36

Table 3 SP-NF pretreatment of the desalination feed at different %SP followed by NF; case 2

	Original	% SP				
Ion	0	20	40	60	80	100
Mg^{2+}	1550	218.4649	164.5297	110.5944	56.65922	2.724001
Ca^{2+}	600	142.0668	107.4336	72.8004	38.1672	3.534
SO_4^{2-}	3440	375.8008	328.4025	281.0042	233.6059	186.2076
CO_3^{2-}	38	5.900833	8.601648	11.30246	14.00328	16.70409

Table 4 SP-NF pretreatment of the desalination feed at different %SP parallel to (100-%)NF; case 3

		%SP					
Ion	Original	0	20	40	60	80	100
Mg^{2+}	1550	272.4	221.02	169.64	118.26	66.88	15.5
Ca^{2+}	600	176.7	143.76	110.82	77.88	44.94	12
SO_4^{2-}	3440	423.2	641.28	859.36	1077.44	1295.52	1513.6
CO_3^{2-}	38	3.2	42.232	81.264	120.296	159.328	198.36

Table 5 SP-NF pretreatment of the desalination feed at different %SP parallel to %NF; case 4

		%SP					
Ion	Original	0	20	40	60	80	100
Mg^{2+}	1550	272.4	1268.79	987.58	706.37	425.16	15.5
Ca^{2+}	600	176.7	498.87	397.74	296.61	195.48	12
SO_4^{2-}	3440	423.2	2945.68	2451.36	1957.04	1462.72	1513.6
CO_3^{2-}	38	3.2	50.556	63.112	75.668	88.224	198.36

magnesium. Also, magnesium is favored over calcium in the high salinity water types (El-Manharawy and Hafez 2011).

The chemistry of the original feed (Arabian Gulf seawater) and the SP-NF treated feed, sulfate ratio to alkalinity (SO4/Alk) and the sodic/calcic ratio of monovalent to divalent ions (Na+K/Ca+Mg) are shown in Fig. 3. Case 3 shows the lowest sulfate scale potential and this potential decreases with the % treatment. Case 3 also shows the highest monovalent to divalent ration because of the high removal of Ca and Mg and addition of Na from the chemicals of the SP step. El-Manharawy and Hafez (2000, 2002) indicated a strong relationship between the feed water chemical characteristics and the generated scale type, as well as its potential in RO plants. It was clear that the molar ratio (SO4/HCO3) is gradually and positively correlated with the chloride molar concentration for most of the natural waters. The variation in most of natural waters is so tight that SO4/HCO3 ratio ranges

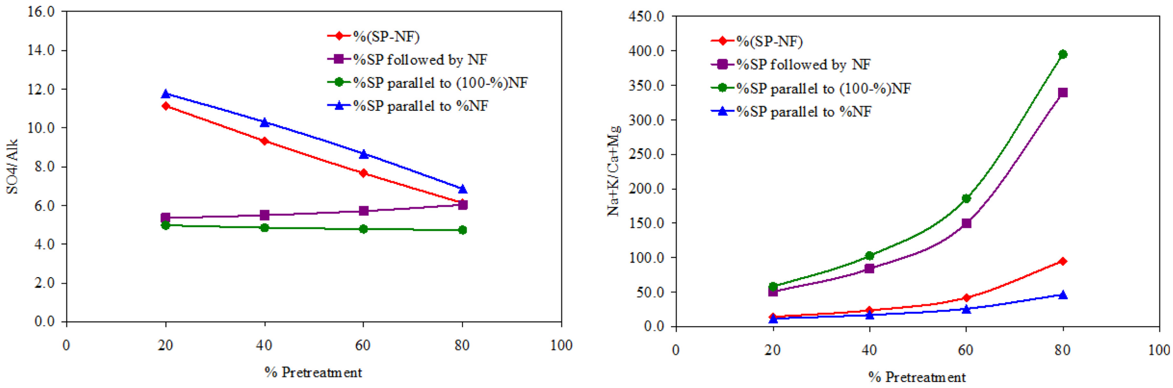

Fig. 3 The chemistry of the original and the treated feed, sulfate ratio to alkalinity (SO4/Alk) and the ratio of monovalent to divalent ions (Na+K/Ca+Mg) of the four SP-NF processes.

between 0 to ~20. For example, River Nile water is ~0.12, brackish ground waters 1-5, salty waters 5-10, oceanic water ~12, and Red Sea water ~13. Some anomalous sulfate-enriched groundwater brines could be as higher than 30.

3.2 Scale formation in MSF

In previous studies (Al-Rawajfeh 2011, Al-Rawajfeh *et al*. 2012), the sulfate scale potential, expressed by Skillman index, for seawater from 0 to 100% NF-treated make-up in BR-MSF reference plant were investigated. The scale potential increases with increasing temperature and decreases with increasing the percentage of NF-treated feed. The highest temperature is shifted to 120, 135 and 145°C when the NF-treated portion increased from 10, 25 and 50%, respectively. For 100% NF feed pretreatment, TBT can reach as much as 175°C.

Fig. 4 show the sulfate scale potential of the product of the four SP-NF cases. The sulfate scale potential of the Arabian Gulf seawater increases, exponentially, with the temperature. Case 2 and 3 are the best case regarding the scale formation. Fig. 5 shows changes in the sulfate scale with temperature for the four processes. For example, TBT may reach higher than 150°C for all pretreatment percentage. TBT may reach 136 and 140°C in case 1 and 4, respectively. As a rule of thumb, each 1% pretreatment portion increases the reference TBT of 115°C by 0.6°C. For example, if the 30% of the feed is treated, the TBT may reach 133°C. In a previous study (Al-Rawajfeh 2010b), the effect of calcium ion concentration in the feed for different feed water composition in different

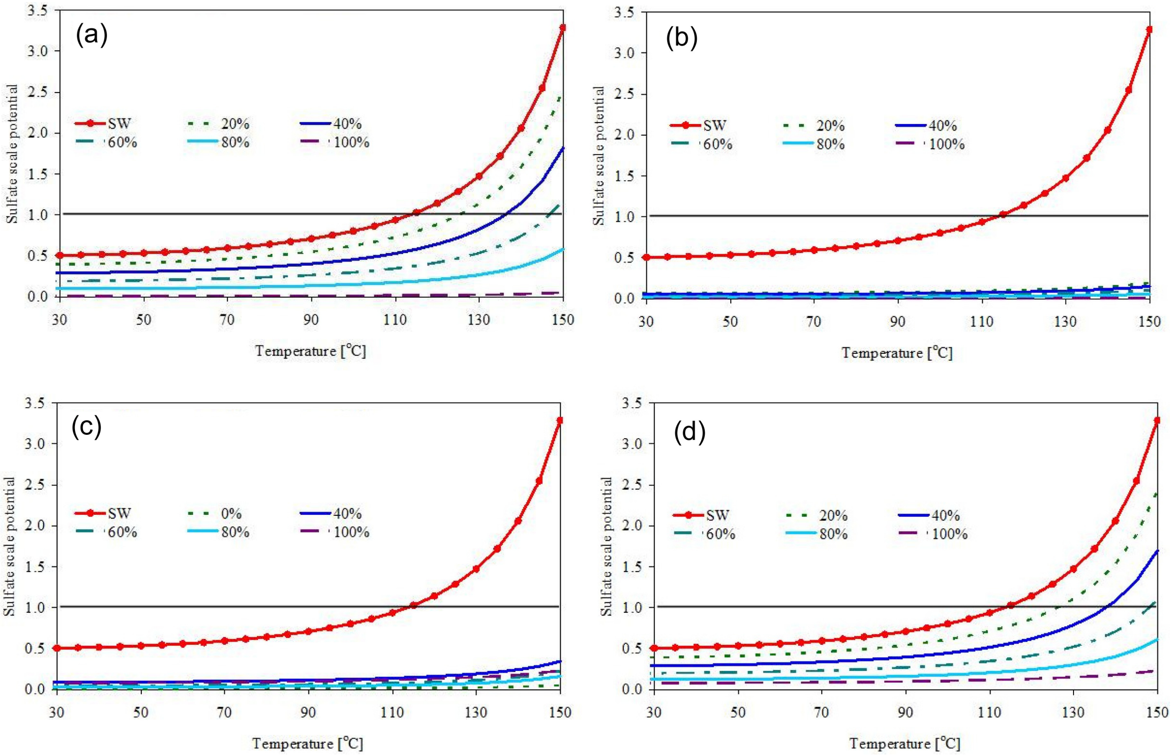

Fig. 4 Variations in sulfate scale potential with changing the temperature.

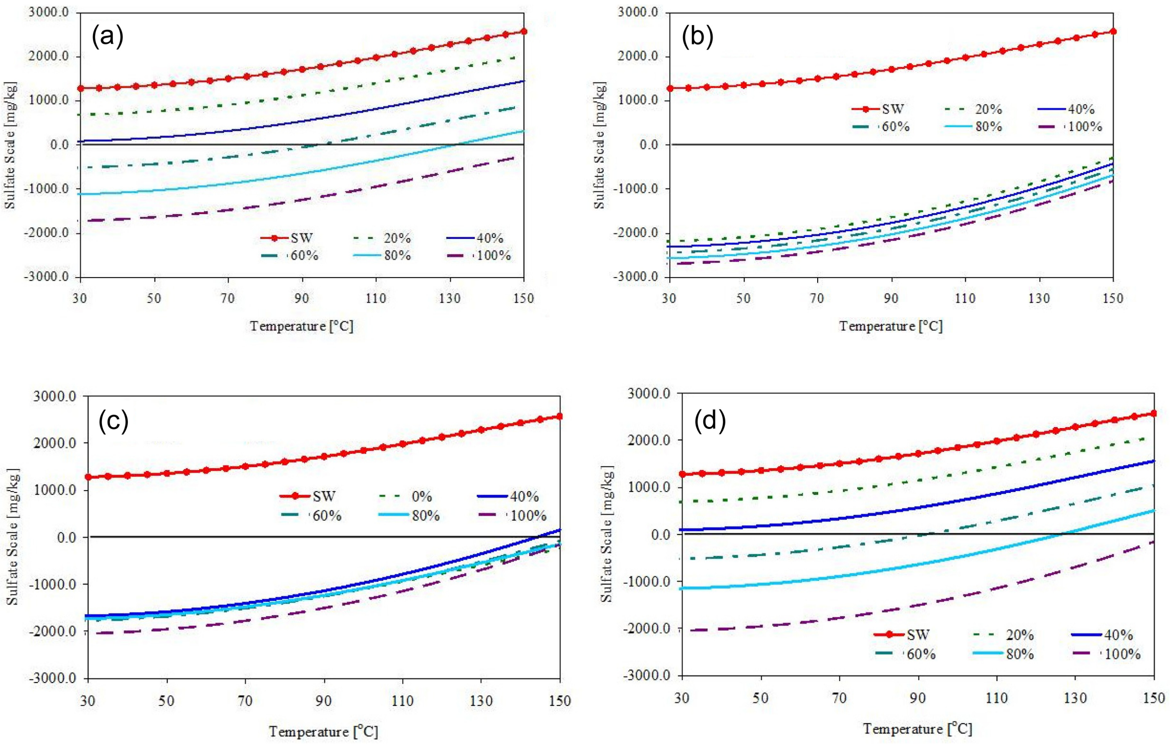

Fig. 5 Changes in the sulfate scale with temperature.

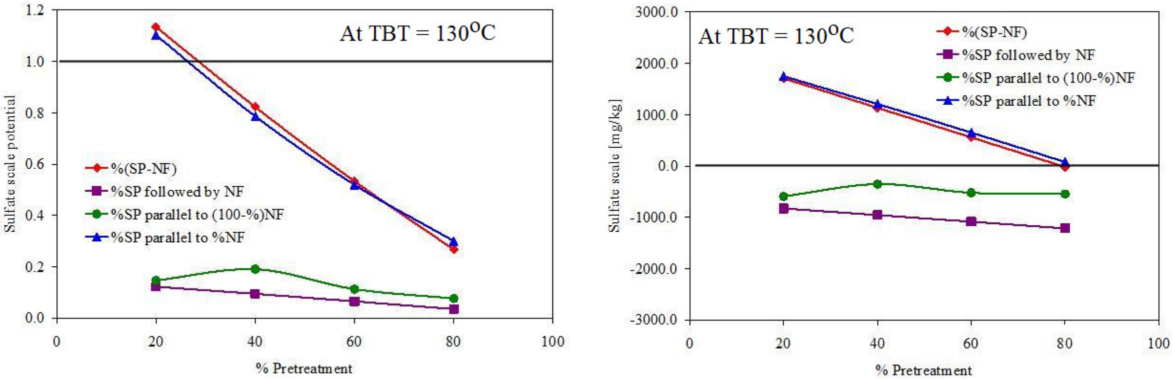

Fig. 6 The influence of the % pretreatment on the sulfate scale potential and scale amount for the different four cases at 130°C.

intakes from the Arabian Gulf for once-through (OT) and brine recycle (BR) MSF distillers, on sulfate scale, were investigated. The $CaSO_4$ scale potential increases with increasing the calcium ion content in the feed water. The effect of sulfate ion concentration in the make-up showed similar trend but calcium is the limiting species. The $CaSO_4$ scale potential increases with seawater salinity. This can be attributed to the fact that the solubility of sulfate scale decreases with salinity.

Fig. 6 shows the influence of the % pretreatment on the sulfate scale potential and scale amount for the different four cases at 130°C. Cases included successive NF pretreatment showed lower sulfate scale potentials, i.e. the second and the third cases. As a result, it was able to increase the TBT of MSF to >130°C. The recovery rate of MSF operating on NF permeate was found to reach 80% and 70% at TBT 130°C and 120°C, respectively. Three different types of NF membrane were tested for salt rejection and permeate flux. In a similarly related work, Awerbuch (2006) presented the benefit of using NF membranes in the removal of scale elements from seawater and suggested using NF permeate-seawater mixture feed (partial feed pretreatment) to thermal process to reduce the cost of NF pretreatment. The Awerbuch's study showed the feasibility to increase TBT in MSF up to 125°C with only 25% NF permeate mixture with seawater.

3.3 Scale formation in RO

Fig. 7 shows the total fouling load for the four pretreatment cases of the RO feed. The values were calculated using ROIFA-4A software (El-Manharawy and Hafez 2011). Fig. 8 shows the percentage of the scale type; sulfate or carbonate in the four investigated cases. Cases 2 and 3, shows the lowest total fouling load (TFL). The percentage scale type is constant in case 2; is about 50% sulfate to 50% carbonate, while in case 3, the change in scale type percentage is very small, sulfate scale decrease slightly with the percentage pretreatment and carbonate scale increases slightly. This may be attributed the addition of alkalinity from the SP chemical. Case 1 and 4 show higher

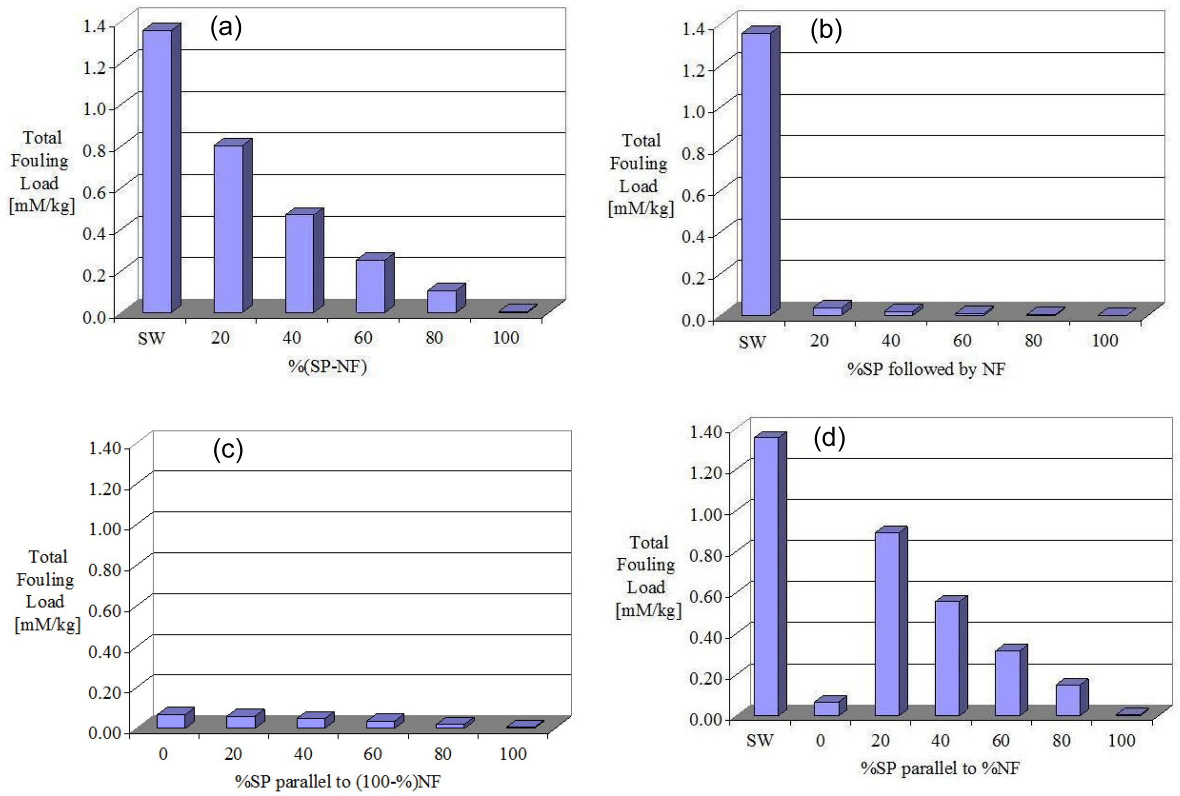

Fig. 7 The total fouling load (TFL) for the four pretreatment cases of the RO feed.

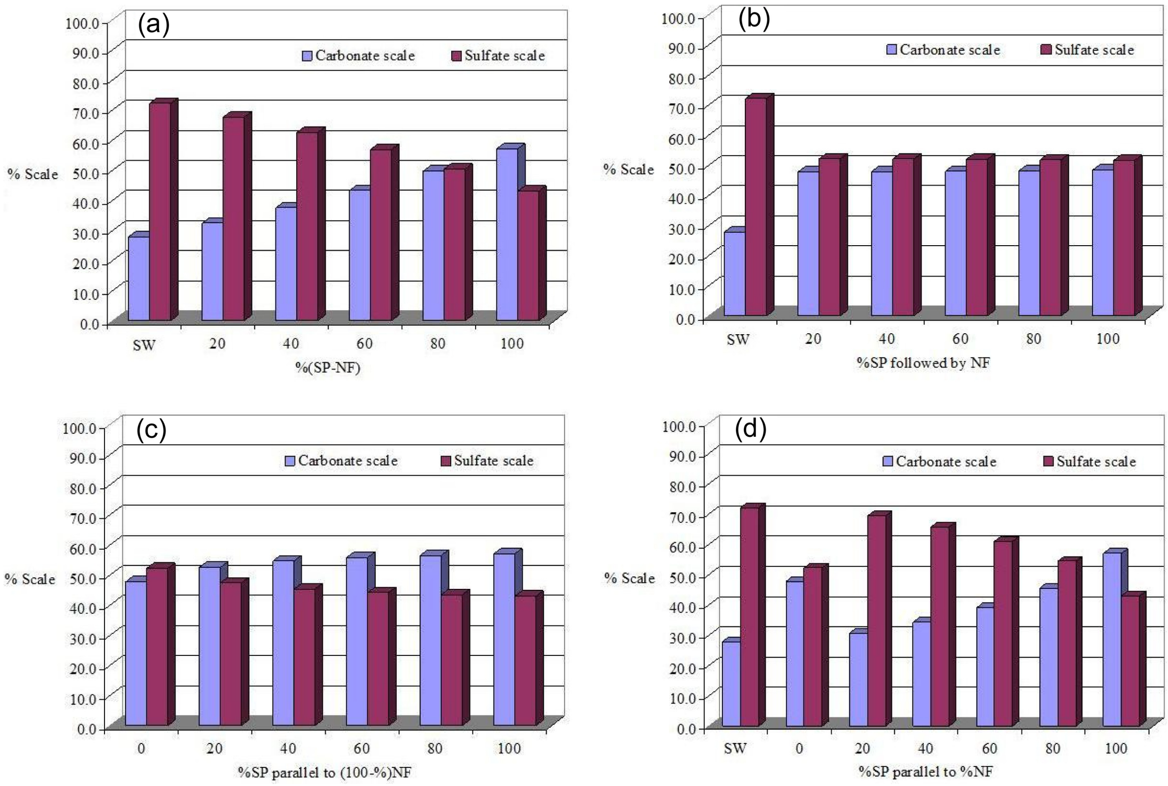

Fig. 8 The percentage of the scale type in the four investigated cases.

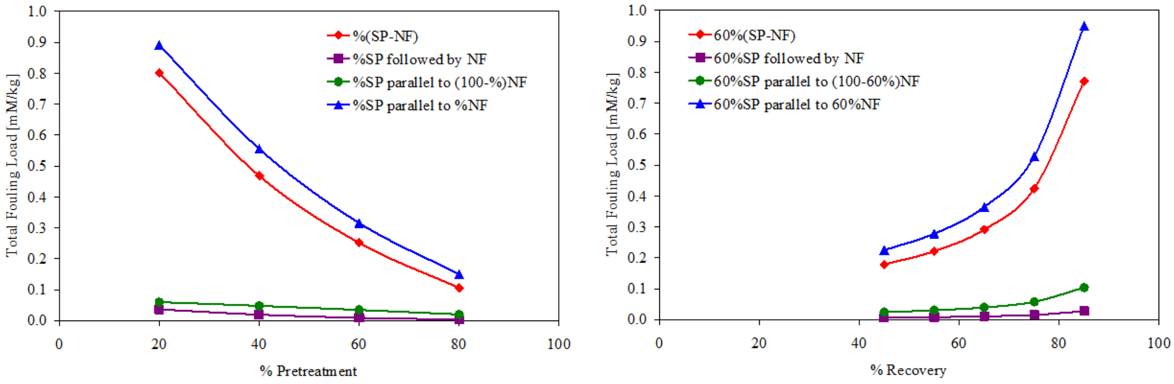

Fig. 9 (Left) The total fouling load (TFL) at different % pretreatment in RO system, and (Right) the influence of the RO recovery ratio on the TFL.

variation in the percentage scale type.

In MSF, scale formation in case 4 is slightly higher than case 1, while scale formation in case 1 is much higher than case 4 for RO. This may be attributed to the sulfate ion concentration in the feed; which has similar trend. Sulfate is significant in MSF plants. Carbonate ion concentration in case 1 is higher than case 4; consequently, carbonate scale is significant in RO. Although the SO4/Alk ration of case 3 is less than case 2 (see Fig. 3, Left), scale formation in both MSF and RO processes in case 3 higher than case 2 as concluded from Fig. 9 (Left) which is drawn from the values of 60% SP treatment, and sulfate ions concentration is much higher in case 3 while carbonate ions concentration is moderately higher in case 3. This is because of the increase in salinity, by the addition of monovalent ions, which, consequently, decreases the solubility of calcium carbonate and calcium sulfate in the solution (Al-Rawajfeh 2010). Fig. 9 (Right) shows the change of total fouling load (TFL) with increasing the RO recovery ratio from 45 to 85%. The TFL increases exponentially but significantly at recovery ratio higher than 75%.

4. Conclusions

Four different configurations of hybrid salts precipitation-nanofiltration (SP-NF) processes were suggested to prevent scale deposition in MSF and RO reference desalination plants by changing the percentage of pretreatment from 0 to 100%. The feed water characteristics were taken from the Arabian Gulf seawater analysis. The following points were concluded:

- The scale potential decreases with increasing the percentage of SP and/or NF-treated feed. The Top Brine Temperature (TBT) is shifted to a maximum value of 175°C if the feed is fully pretreated.
- A targeted TBT of 130°C may be achieved if 30% portion is pretreated by SP and/or NF processes.
- As a rule of thumb, each 1% pretreatment portion increases the reference TBT of 115°C by 0.6°C.
- Parallel pretreatment of the feed of MSF and RO by SP and the rest by NF of certain percentage showed the lowest scale values. The case showed the best values for sulfate scale prevention and the highest values of increasing the monovalent ions relative to the divalent scale forming ions.
- Sulfate scale is significant in MSF process while carbonate scale is significant in RO.
- Salt precipitation was suggested because it is less costly than nanofiltration, but nanofiltration has been kept in use here because it is efficient in sulfate ions removal.
- A combination of the two processes needs detailed techno-economical study to enhance the decision of the treatment portion. From scaling point of view, up to 30% pretreatment is enough to prevent the scale to an extent suitable to increase the TBT as much as 130°C.

Acknowledgement

The author would like to acknowledge the financial support from Abdul Hammed Shoman Foundation and thank Prof. S. El-Manharawy for supplying the ROIFA software. The reviewers of MWT journal are greatly acknowledged for their valuable comments. The International Atomic Energy Agency (IAEA) and Jordan Atomic Energy Commission (JAEC) are also acknowledged for supposing presenting this work at the IAEA's Technical Meeting on "Advances in Seawater Desalination Using Nuclear Energy" which has been held in Vienna from 2-4 July, 2012.

References

Al-Rawajfeh, A.E. (2008), "Simultaneous desorption-crystallization of CO_2- $CaCO_3$ in multistage flash (MSF) distillers", *Chem. Eng. Proc., Proc. Inten.*, **47**(12), 2262-2269.

Al-Rawajfeh, A.E., Al-Garalleh, M., Al-Mazaideh, G., Al-Rawashdeh, B. and Khalil, S. (2008), "Understanding $CaCO_3$-$Mg(OH)_2$ scale formation: A semiempirical MINDO-Forces study of CO_2-H_2O system", *Chem. Eng. Comms.*, **195**(8), 998-1010.

Al-Rawajfeh, A.E. and Al-Amaireh, M.N. (2009), "The influence of CO_2 injection on the carbonate chemistry and scaling in multiple-effect distillers", *Desalination Water Treat.*, **7**(1-3), 191-197.

Al-Rawajfeh, A.E. (2010a), "$CaCO_3$-CO_2-H_2O System in falling film on a bank of horizontal tubes: Model verification", *J. Ind. Eng. Chem.*, **16**(6), 1050-1058.

Al-Rawajfeh, A.E. (2010b), "Influence of seawater composition on CO_2 release and scaling in multi-stage flash (MSF) distillers from different Arabian Gulf intakes", *Int. J. Chem. Eng. Appl.*, **1**(1), 43-48.

Al-Rawajfeh, A.E. (2011), "Influence of nanofiltration pretreatment on scale deposition in multi-stage flash thermal desalination plants", *Thermal Sci.*, **15**(1), 55-65.

Al-Rawajfeh, A.E. and Al Zarooni, M. (2008), "New processes in seawater desalination", *Recent Patents Chem. Eng.*, **1**, 141-150.

Al-Rawajfeh, A.E., Fath, H.E.S. and Mabrouk, A.A. (2012), "Integrated salts precipitation and nano filtration as pre-treatment of multi stage flash desalination system", *Heat Transfer Eng.*, **33**(3), 272-279.

Antony, A., Low, J.H., Gray, S., Childress, A.E., Le-Clech, P. and Leslie, G. (2011), "Scale formation and control in high pressure membrane water treatment systems: A review", *J. Membrane Sci.*, **383**(1-2), 1-16.

Awerbuch, L. (2006), Water desalination process using ion selective membranes, US patent No. 6998053B2.

Chan, S.H. and Ghassemi, K.F. (1991), Analytical modeling of calcium carbonate deposition for laminar falling film and turbulent flow in annuli: Part I – Formulation and single-species model, *ASME J. Heat Transfer.*, **113**, 735-740 and Part II – Multispecies model. *ASME J. Heat Transfer*, **113**(3), 741-746.

El-Manharawy, S. and Hafez, A. (2011), "How to estimate inorganic fouling flux on RO membrane by using ROIFA-4?", *Desalination*, **277**(1-3), 407-413.

El-Manharawy, S. and Hafez, A. (2000), "Molar Ratios as useful tool for prediction of scaling potential inside RO-system", *Desalination*, **136**, 243-254.

El-Manharawy, S. and Hafez, A. (2002), "Dehydration model for RO-membrane fouling prediction", *Desalination*, **153**(1-3), 95-107.

Hasson, D. and Perl, I. (1981), "Scale deposition in a laminar falling-film system", *Desalination*, **37**(3), 279-292.

Hussain, A.A. and Al-Rawajfeh, A.E. (2009), "Recent patents on nanofiltration applications in oil processing, desalination, wastewater and food industries", *Recent Patents Chem. Eng.*, **2**, 51-66.

Hussain, A.H. (2007), Process for pre-treating and desalinating seawater, US patent No. 7198722.

IMSDesign2010 is the latest version of Hydranautics' projection software and can be downloaded from: http://www.membranes.com.

Jogand, H.L.A. and Peron, P.A.J.H. (2000), Method for desalinating and demineralizing solutions containing acids and/or metal salts, US patent No. 6036867.

Khamis, I. and Kavvadias, K.C. (2012), "Nuclear desalination: Practical measures to prevent pathways of contamination", *Desalination*, In press.

Skillman, H.L., McDonald, J.P. and Stiff, H.A. (1969), A simple, accurate, fast method for calculating calcium sulfate solubility in oil field brine, Paper No. 906-14-I, Spring Meeting of the Southwestern District, Division of Production, American Petroleum Institute, Lubbock, Texas.

CC