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Prospects for improving the performance of SWRO plants by implementing advanced NF/RO techniques: Part-II

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ABSTRACT

SWCC DTRI adopted a highly ambitious research program in which nanofiltration (NF) membranes operated on pretreated seawater to improve its scaling and fouling potential. NF membrane seawater pretreatment was introduced commercially at SWCC Umm Lujj SWRO plant, where NF and SWRO processes operated at 65% and 50% recovery, respectively, with an overall recovery of 32.5%. Therefore, this paper presents (Part-II) of this project, which deals with NF product as a superior RO feed with the main objective of increasing the water production at Umm Lujj NF/SWRO plant and improve its overall economics. In order to achieve the same, several approaches were adopted which includes long-term performance evaluation of NF membrane seawater pretreatment, SWRO and BWRO processes at recoveries of 90%, 52% and 92%, respectively. The results revealed that Umm Lujj NF/SWRO plant overall recovery can be increased from 32.5% to 44%.

Keywords: NF membrane seawater pretreatment; Hybrid and nonhybrid SWRO designs; Split partial two pass RO; Permeate TDS and boron

1. Introduction

Producing potable water of acceptable quality with minimum cost is the major goal of the water industry. In this context, in the last few years, SWRO desalination technology has gone through a remarkable transformation and gained widespread acceptance. The number and capacity of large SWRO plants have increased significantly. The major reasons for the increase in popularity of the SWRO desalination process are its simplicity and the significant reduction in cost. To make the process more economical, various approaches have been recently applied to many of the newly built SWRO plants. Since these new concepts have been introduced into the SWRO process design, equipment and operations during the last decade have resulted in an increase in water product recovery with a sharp decrease in the unit water production cost at less than US$ 1/m^3 [1,2].

Therefore, SWCC has a major interest in studying such recent design approaches for two different streams, Gulf seawater feed and NF feed, to improve the performance and economics of SWCC SWRO plants in terms of water product recovery and water quality. The SWCC is responsible for desalting seawater, and faces several challenges, such as high feed salinity with high feed temperature and very stringent permeate quality standards (TDS < 50 mg/L, chloride < 25 mg/L, and boron < 2.4 mg/L). Most plants employ hollow fiber membrane SWRO technology, with smaller plants operating at 30%–35% recovery rates, whereas larger plants operate at an approximately 42% recovery rate [3]. Further reduction in overall recovery up to 33%–38% is obtained due to employing 2nd pass RO. The typical permeate boron concentration in SWCC SWRO plant is between 2

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and 3 mg/L [4]. The Umm Lujj NF/SWRO plant utilizes NF pretreatment and operates at an approximate overall recovery of 32.5% (the NF and SWRO processes operate at approximately 65% and 50% recoveries, respectively).

Results obtained from Part-I of this study [5] confirmed the following:

- The utilization of spiral wound membrane technology with recent design approaches for Gulf seawater succeeded in maximizing the overall recovery to 45%–46% compared with the existing SWCC SWRO plants' overall recovery of 33%–38%.
- The boron concentrations in the 1st pass RO permeate and total permeate were approximately 1.3 and ≥1 mg/L, respectively, compared with the values for existing SWCC SWRO plants of approximately 2–3 mg/L with hollow fiber membrane SWRO technology.

This paper presents Part-II of this study, which deals with NF product as a superior RO feed. The main objective is to maximize the water product recovery of Umm Lujj NF/SWRO plant. To achieve this target, the following design approaches were considered and studied on the NF/SWRO configuration.

1.1. Eight SWRO elements in a single pressure vessel

In the past, SWRO array (brine staging) was usually configured with six elements per pressure vessel to operate at a recovery rate of 35%–40%. Recent advances in membrane technology have resulted in the transition of plant design from a two-stage to the single-stage configuration, which enabled an increase in the number of elements per vessel up to eight elements. This results in a higher feed-brine flow rate and a higher cross-flow velocity coupled with a lower concentration polarization. Consequently, an 8-element array is adopted for high recovery operation in this study. From the point of view of cost effectiveness, the SWRO system employing six elements per vessel requires 34% more pressure vessels than a system using the same membrane area, but configured with eight elements per vessel [6,7]. It has also been shown that a significant savings in capital cost up to 24.7% can be achieved with longer pressure vessel configurations [6,7]. In addition, the same result was confirmed at SWCC DTRI for an NF system, where the study revealed that an 8-element array at 65% recovery is found to be the best choice for a single-stage NF seawater pretreatment process compared with the conventional array of six elements [8].

1.2. Split partial two-pass SWRO design configuration

Many plants utilize a second pass BWRO to meet the demand of low TDS, as well as boron content, in the final product. For this reason, instead of sending the entire product from the first pass SWRO, it has been the practice to split the permeate into two portions, one exiting from the feed side and the other from the brine side. The permeate collected from the feed end is of lower salinity and flows directly as product water. The fraction of permeate collected from the brine end has the highest salinity value and is therefore polished using second pass RO. This split partial two-pass SWRO design is achieved by taking advantage of the intrinsic salinity gradient present inside the pressure vessel of the 1st pass SWRO. The utilization of this salinity gradient in RO arrays to produce permeates of various salinities was studied in 1975 [9]. Recently, this technique has been successfully applied in the Tampa, Larnaca and Ashkelon SWRO plants to reduce the capital cost of the second pass and energy consumption coupled with improvements in RO permeate quality [2,10].

1.3. Internally staged designs in SWRO process

Internally staged designs have been introduced into SWRO desalination plants mainly to decrease the capital and operating costs of SWRO plants [11]. This hybrid design employs high energy consumption elements in front of the vessel and lower energy elements in the back of the vessel. This approach results in a feed pressure and a permeate salinity value between those of the two membranes. The advantage of this design is that the low permeability lead elements will have a lower flux, resulting in a more balanced element flux distribution, especially at high feed temperatures and high recovery operations. Furthermore, the concept of mixing lower flow elements and higher flow elements leads to improved operation and performance of SWRO plants in terms of feed pressure, recovery rate, flux rate and membrane fouling.

1.4. Second pass concentrate recirculation

The 2nd pass concentrate can be circulated to the main RO feed line of the 1st pass, resulting in reducing the operating feed pressure and improving the permeate TDS, because the TDS of the 2nd pass concentrate is much lower compared with seawater feed TDS. In addition, the amount of feed for the 1st pass can be reduced via better SWRO economics [12,13].

1.5. Membrane pretreatment techniques

To obtain the best performance from the SWRO membrane and to operate SWRO at high flux and recovery, it is very essential to have extremely good quality pretreated feed, free from suspended solids and microbes [14]. Therefore, SWCC DTRI adopted a highly ambitious research program in which nanofiltration (NF) membranes operated on pretreated seawater to improve its scaling and fouling potential [15,16]. Following the excellent and encouraging results obtained at the pilot and demonstration plant stages, NF membrane seawater pretreatment was applied successfully at Umm Lujj SWRO plant.

The Umm Lujj SWRO plant operates with NF seawater pretreatment at an NF recovery of 65%, utilizing a conventional array consisting of six NF 8″ spiral wound elements, To make the NF/SWRO process economically more attractive, several studies have been conducted. One such study was done at Jubail SWRO plant site, during 2005–2007, utilizing two-stage NF with energy boosting turbo charger in between, where a recovery of 70% was achieved. Additionally, a study was conducted utilizing beach well seawater feed at Al-Birk during 2006–2007 utilizing two-stage NF, where a recovery ratio of 75% was achieved.

Another major study was started in the year 2006 for about 3 years to optimize NF membrane seawater pretreatment at the highest possible recovery with lowest energy consumption [17,18]. Additionally, recently another interesting achievement has been made by operating NF/SWRO configuration at high pH, which resulted in significant reduction in the seawater boron content up to 0.1 mg/L, compared with conventional techniques [19–21].

In a continuation of the previous research activities for further improvements in the cost effectiveness of the Umm Lujj NF/SWRO plant, the current paper presents the second part of the KACST funded project, which focused on optimizing the NF/SWRO configuration for the highest possible recovery. The aim is to demonstrate a high recovery NF/SWRO process while maintaining strict limits on permeate quality based on SWCC regulations. To achieve these objectives, the following investigation areas are considered: (1) the operation and optimization of NF membrane seawater pretreatment process at the maximum possible recovery, (2) employing 8-element array as the recommended SWRO configuration for high recovery operation based on results obtained from Part-1 of this study [5], (3) the comparative performance of four different hybrid and nonhybrid SWRO designs varying in membrane characteristics in terms of salt rejection and productivity to select the optimum membrane arrangement for high recovery operation and (4) based on results obtained, the optimum membrane arrangement and process design parameters for high recovery operation were drawn and adopted in hybrid split partial two-pass design for long-term operation and investigation.

2. Experimental work

2.1. Biological count procedure

Samples were collected aseptically, throughout the course of the experiment from the intake, after dual media filter (DMF), NF product, NF brine, and cartridge filter waters, as well as low and high salinity product waters. Samples were assayed for bacterial concentration using colony forming units (CFUs) in accordance with standard method ASTM D5465.

2.2. Description of pilot plants

2.2.1. Seawater supply and pretreatment system

Seawater is fed from non-chlorinated seawater intake. The pretreatment unit is comprised of a DMF followed by a fine sand filter with a capacity of 17 m^3/h. Ferric chloride was dosed as a coagulant at a concentration of 1–3 ppm as $FeCl_3$. The pretreated seawater SDI was maintained between 2.5 and 4. There are three chemical dosing systems in the pretreatment for ferric chloride, the coagulant aid and sulfuric acid.

2.2.2. NF unit

This experimental unit contains 18 lower rejection NF elements of size 8″ × 40″ adopted in a two-stage NF process (12 elements in the first stage and 6 elements in the second stage). Fig. 1 shows the schematic flow diagram of NF skid, consisting of a booster pump (6 bar, 18 m^3/h), a high-pressure

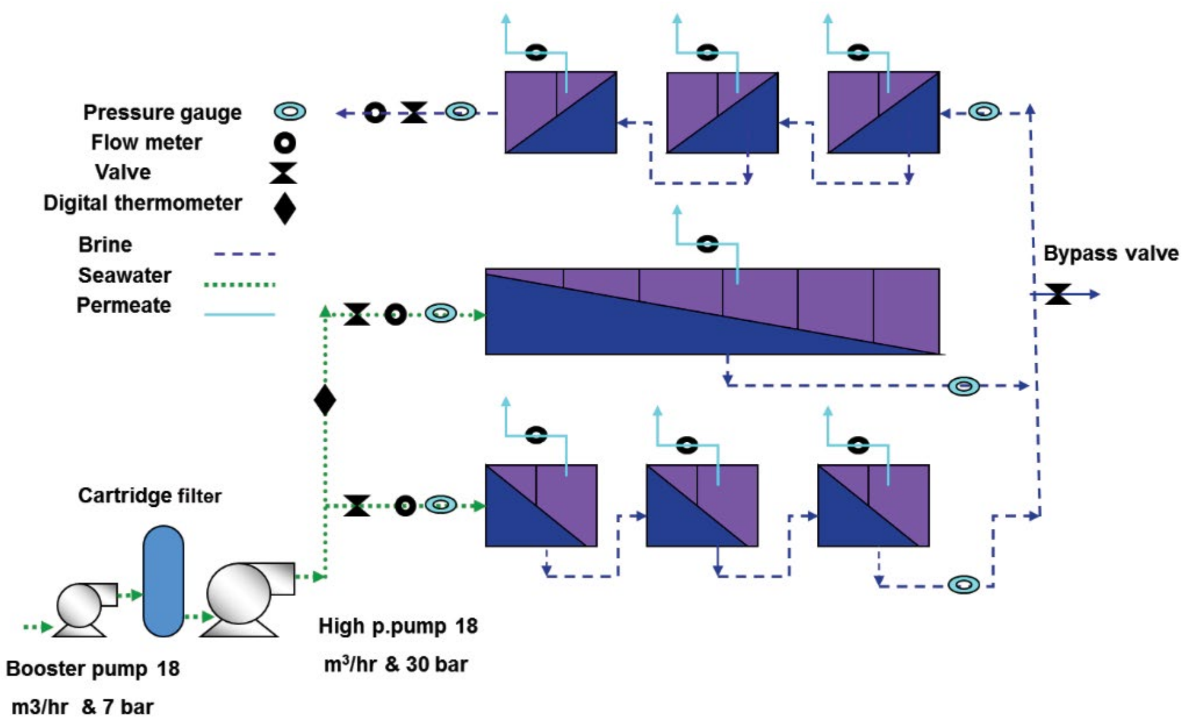

Fig. 1. NF skid adopted in two-stage utilization of 18 NF elements of 8″ × 40″.

pump (30 bar and 18 m^3/h), and a 5-micron cartridge filter. There are two chemical dosing systems for antiscalant and sulfuric acid.

2.2.3. SWRO unit

The SWRO unit consists of eight SWRO elements of size 8″ × 40″ connected in series (two higher rejection [HR] SWRO elements followed by six higher flow [HF] SWRO elements). This unit is designed to use the hybrid split partial technique with an average element flow rate of 31.8 m^3/d. Based on the preliminary test results obtained, this design option was operated at 52%–53% recovery and 14.9 L/m^2/h flux rate. The antiscalant was dosed at a concentration of 2.5 mg/L. Fig. 2 shows a schematic flow diagram of an SWRO skid. It consists of a booster pump (5 bar, 12 m^3/h), a high-pressure pump (82 bar and 12 m^3/h), a 5-micron cartridge filter, a flushing pump and four pressure vessels connected in series, each containing two SWRO spiral wound elements of 8″ × 40″. There are three chemical dosing systems. In addition, there is a provision to test single element performance.

2.2.4. BWRO unit

The BWRO unit receives the brine end product of SWRO. The brine produced by the BWRO, having lower salinity than the NF feed, is recycled upstream of the SWRO feed. Fig. 3 shows a schematic flow diagram of the BWRO skid. It consists of a booster pump (6 bar, 7 m^3/h), a high-pressure pump (18 bar and 7 m^3/h), a 5-micron cartridge filter, a flushing pump (7 bar, 8 m^3/h), a brine recirculation pump (6 bar, 1 m^3/h) and 14 BWRO elements of 4″ × 40″ (2 × 4 elements in the first stage and 6 elements in the second stage). The second pass high pressure pump motor is equipped with a variable frequency drive to operate the second pass at different fluxes/capacities. There are two chemical dosing systems for the antiscalant and NaOH. The second pass has the flexibility to change the pH, feed flow, recovery and other operational parameters to meet seasonal needs and research requirements.

2.3. Operating conditions of trials

2.3.1. Testing the performance of NF membrane seawater pretreatment on Gulf seawater

Lower rejection NF membranes were used in this trial. Table 1 lists the NF membrane specifications under standard test conditions. The performance evaluation of NF membrane seawater pretreatment was conducted at various recovery ratios and flux rates ranging from 65% to 90% and 16.8 to 21.6 L/m^2/h, respectively. The operating feed pressure ranged from 12 to 19 bar at feed temperature range of 19°C–38.4°C, whereas seawater feed conductivity was in the range of 59,500–63,500 μS/cm. The antiscalant was injected at a dose rate of 3.5 ppm to prevent scale formation. Sulfuric acid was dosed to maintain pretreated seawater at a pH of 7. The operation and performance parameters were collected on a daily basis. Chemical and biological analyses were performed for seawater, permeate and reject at various stages of the study. An inter stage bypass valve and NF feed booster pump were employed to flush NF membranes with pretreated seawater every 20 d for 1 h. The flushing process is performed by directing most of the pretreated seawater feed to the brine side of the NF membranes to flush any fouling materials accumulated on membrane surface. During NF

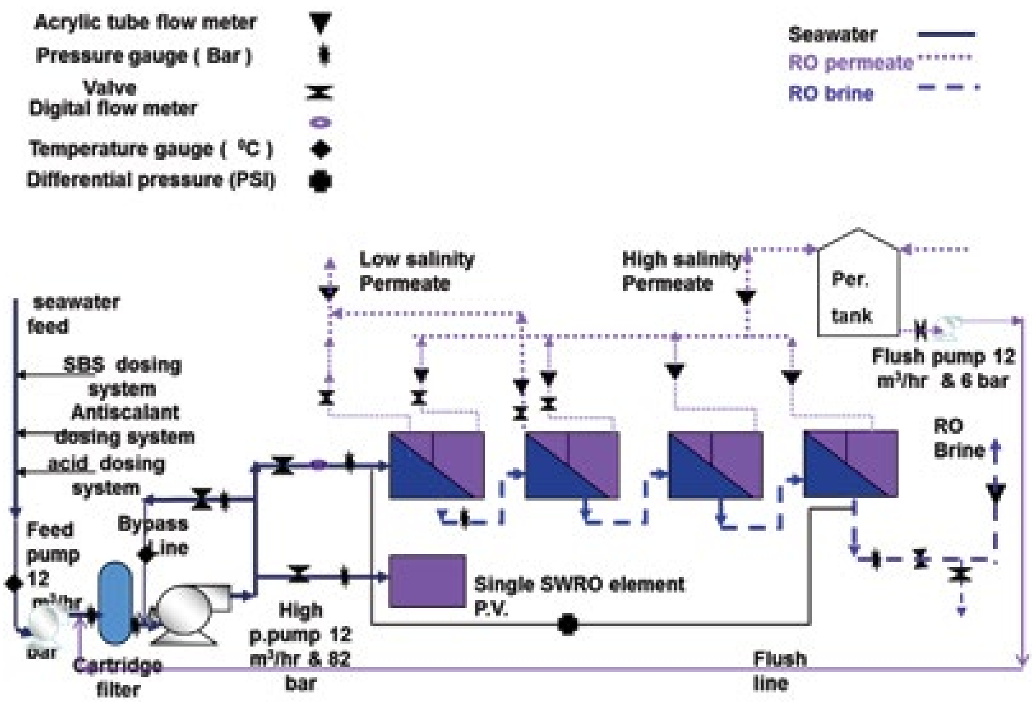

Fig. 2. SWRO unit (eight SWRO elements of 8″ × 40″ connected in series).

membrane flushing, the NF process runs at approximately 15%–20% recovery.

2.3.2. Testing performance of various hybrid and nonhybrid designs on NF feed

This trial employs the same SWRO membranes used in part-1 of this study as listed in Table 1. Additionally, based on results drawn from part-1 of this study, an 8-element array is employed as the recommended configuration for high recovery operation. Four cases, including hybrid and nonhybrid designs, were operated on NF feed and investigated under constant operating conditions (50% recovery, 15 L/m^2/h flux rate, 25°C–26°C ambient feed temperature) as per the following:

- *Nonhybrid designs*: This approach represents a standard design (basic design) in which only one type of SWRO membrane element is used. Two nonhybrid designs with different membrane characteristics in terms of salt rejection and productivity were examined as follows:
- Case # 1: An 8-element array employing a moderate rejection (MR) membrane of 99.80% salt rejection with an average element flow of 28 m^3/d.
- Case # 2: An 8-element array utilizing a high flow (HF) membrane of 99.75% salt rejection with an average element flow rate of 34.1 m^3/d.
- *Hybrid designs*:
- Case # 3: The first hybrid utilizes two very high rejection (VHR) elements in the lead position and six MR elements in the rear positions with an average element flow rate of 26.8 m^3/d and identified as 2 VHR/6 MR.
- Case # 4: The second hybrid (2HR/6HF) uses two higher rejection (HR) elements in the lead position followed by six higher flow (HF) elements in the rear positions with an average element flow rate of 31.8 m^3/d. Only case #4 was operated at 50% and 52% recoveries.

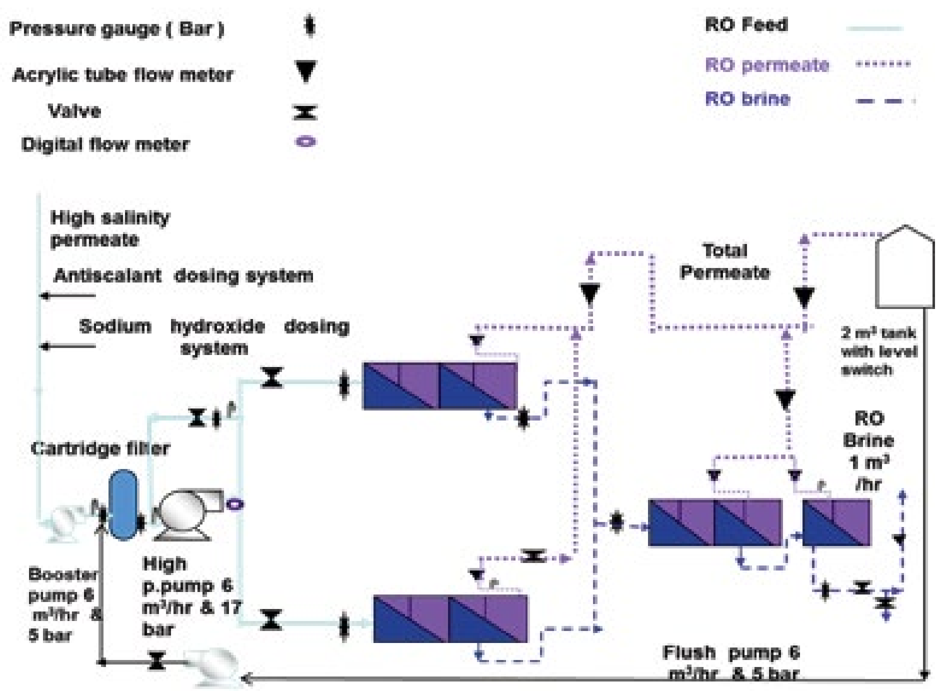

Fig. 3. BWRO unit (2 × 4 BWRO elements of 4″ × 40″ in first stage and 6 elements in second stage).

Table 1
Characteristics of various SWRO and NF elements at standard test conditions

Element description	Brand	Area m^2	Flow rate m^3/d	Salt rejection %	Boron rejection %	$MgSO_4$ rejection %
Highest rejection VHR	SW30 HR	37.1	23	99.80	93	–
High rejection HR	SWC4+	37.1	24.6	99.80	93	–
Moderate rejection MR	SW30HRLE	37.1	28	99.80	93	–
High flow HF	SWC5	37.1	34.1	99.75	92	–
NF elements	NF270-400	37.1	47	–	–	97

SWRO elements standard test conditions (NaCl feed of 32,000 mg/L, recovery of 8%, 25°C, 55 bar, pH of 8).
NF elements standard test conditions: ($MgSO_4$ feed of 2,000 mg/L, recovery of 8%, 25°C, 70 psi).

2.3.3. Operating conditions of the BWRO unit

The BWRO unit received rear end permeate of SWRO and operated at an approximately 92% recovery rate to maintain the desired permeate quality. The BWRO membrane arrangement in the second pass was designed to maintain the necessary flux of 24 and 36 L/m^2/h during the winter and summer months, respectively.

3. Results and discussion

3.1. Performance evaluation of NF membrane seawater pretreatment on Gulf seawater

3.1.1. Seawater feed

Seawater is fed from a non-chlorinated seawater intake as previously described and feed water conditions during the test period is as shown in Table 2.

The performance evaluation of NF consisted of four phases of operations: (1) 500 operating hours at 65%–75%, (2) 2,500 operating hours at 80%–82.5% recovery, (3) 2,300 operating h at 85% and (4) 2,700 operating hours at 88%–90% recovery.

3.1.2. Performance evaluation of NF process at 65%–75% recovery

At the beginning, the NF process was operated for 500 h at 65%–75% recovery as a reference for higher recovery trials. At 65% recovery, operating feed pressure showed the lowest values and ranged from 8 to 8.3 bar corresponding to a feed temperature range of 20°C–21.3°C. Feed flow rate was maintained at approximately 16 ± 0.1 m^3/h and the results at recovery of 65% are summarized in Table 3. At 70% recovery, operating feed pressure increased by 0.6 bar with no significant change in energy consumption compared with 65% recovery. During the changeover from 70% to 75% recovery, operation and performance parameters were carefully checked to evaluate the exact variations in operation parameters. Operating feed pressure, energy consumption, feed temperature, productivity and permeate conductivity were 9 bar, 0.42 kWh/m^3, 23.5°C, 11.4 m^3/h and 57,500 µs/cm at 70% recovery, whereas at 75% recovery, they were 9.6 bar, 0.42 kWh/m^3, 23.7°C, 12 m^3/h and 57,800 µs/cm, respectively. There is no significant change in energy consumption and total permeate conductivity.

3.1.3. Performance evaluation of NF membrane seawater pretreatment at 80%–82.5% recovery

NF process was operated successfully at 80% and 82.5% recoveries for approximately 2,600 h, and steady operation was achieved. At the beginning of this trial, during the changeover from 75% to 80% recovery, feed pressure and energy consumption, feed temperature, productivity and permeate conductivity were 10 bar, 0.44 kWh/m^3, 23°C, 12.05 m^3/h and 57,500 µs/cm at 75% recovery while at 80%, they were 11.1 bar; 0.45 kWh/m^3; 23°C; 12.8 m^3/h and 57,400 µs/cm, respectively. Increasing recovery from 75% to 80% resulted in a slight increase in feed pressure by 1 bar,

Table 2
Feed seawater condition during the test period

Parameter	Minimum	Maximum	Average	Samples
Feed temperature (°C)	19.3	38.4	30.1	Daily
Pretreated seawater SDI	2.3	4	3.46	Daily
Seawater conductivity (µS/cm)	59,500	63,500	61,640	Daily
Pretreated seawater TOC (mg/L)	1.1	2.1	1.36	Biweekly
Feed seawater boron concentration (mg/L)	5	6.4	5.65	Biweekly

Table 3
Performance of NF process at different recovery ratios based on the average values

Parameter	Recovery%				
	65	75	80	85	90
Feed temperature (°C)	21.4	23	23.5	34	34.7
Feed conductivity (µS/cm)	62,100	61,575	62,285	61,806	61,392
Feed pressure bar	7.9	10	12.1	11.9	15.3
Differential pressure ΔP (bar)	2.1	1.9	2.2	2.4	3
Product flow rate (m^3/h)	10.5	12.1	12.94	1,360	14.4
NF product conductivity (µS/cm)	57,590	56,350	57,791	58,783	58,633
[a]Energy (kWh/m^3)	0.40	0.44	0.50	0.46	0.56

[a]Energy consumption was calculated from the following equation:
Energy (kWh/m^3) = $[Q_f \cdot H_f \rho/366\ Q_p \cdot e]$
where Q_f and Q_p are the feed and product quantities in terms of m^3/h; H_f is the pressure head in m, ρ is the density of seawater (1.03); e is the pump efficiency normally about 0.85.

and its effect on energy consumption was compensated by increasing productivity from 12.05 to 12.8 m^3/h; there was no significant change in energy consumption, which remained steady at 0.44–0.45 kWh/m^3.

At 80% recovery, feed pressure varied between 11 and 13.6 bar corresponding to the feed temperature range of 23°C–28°C. First stage feed flow rate was maintained at an average value of 15.9 ± 0.1 m^3/h corresponding to the second stage feed flow rate of approximately 5 ± 0.1 m^3/h. Fig. 4 represents the plots of recovery ratios and product flow rates. First stage recovery was remarkably constant with an average value of 63.8% while the average recovery for the second stage was 45.7% and overall recovery was kept at 80.4%. Consequently, first and second stage showed stable product flow rates averaging 10.3 and 2.60 m^3/h, respectively, while total product was kept at an average value of 12.9 m^3/h. In addition, average permeates conductivities for first stage, second stage and total were 56,274; 63,628 and 57,790 µS/cm, respectively. At 82.5% recovery, feed pressure varied between 12 and 13 bar corresponding to a feed temperature range of 27°C–29.7°C.

The product flow rates for first, second stage and total averaged 10.42, 2.88 and 13.24 m^3/h corresponding to average recoveries of 64.9%, 50.9% and 82.3% while their corresponding conductivities averaged 57,621; 63,296 and 58,796 µS/cm, respectively. At 80%–82.5% recovery, differential pressure for first stage and second stage remained steady and averaged at 1.6 and 1 bar, respectively, whereas total ΔP reached approximately 2.6 bar.

3.1.4. Performance evaluation of NF process at 85% recovery

This investigation describes the performance of NF process for 2,300 operating hours at 85% recovery. Switching from 82.5% to 85% recovery was accompanied by a slight increase in feed pressure from 11.7 to 12.4 with no significant increase in energy consumption, which was maintained at 0.47 kWh/m^3 for the same reason as mentioned earlier. During this trial, NF membranes were exposed to a gradual increase in feed temperature from 28°C to 38.5°C and then decreased to 35°C at the end of this trial owing to seasonal variations. Accordingly, feed pressure varied between 10.0 and 12.4 bar to maintain overall recovery at 85%. First and second stage feed flow rates were controlled at average values of 16.0 and 5.46 m^3/h, respectively.

First stage recovery was stable at an average value of 65.9% whereas the average recovery for the second stage was 56% and overall recovery averaged 85.1%. Consequently, first and second stages showed stable product flow rates of 10.4 ± 0.1 and 3.2 ± 0.1 m^3/h, respectively, while total product

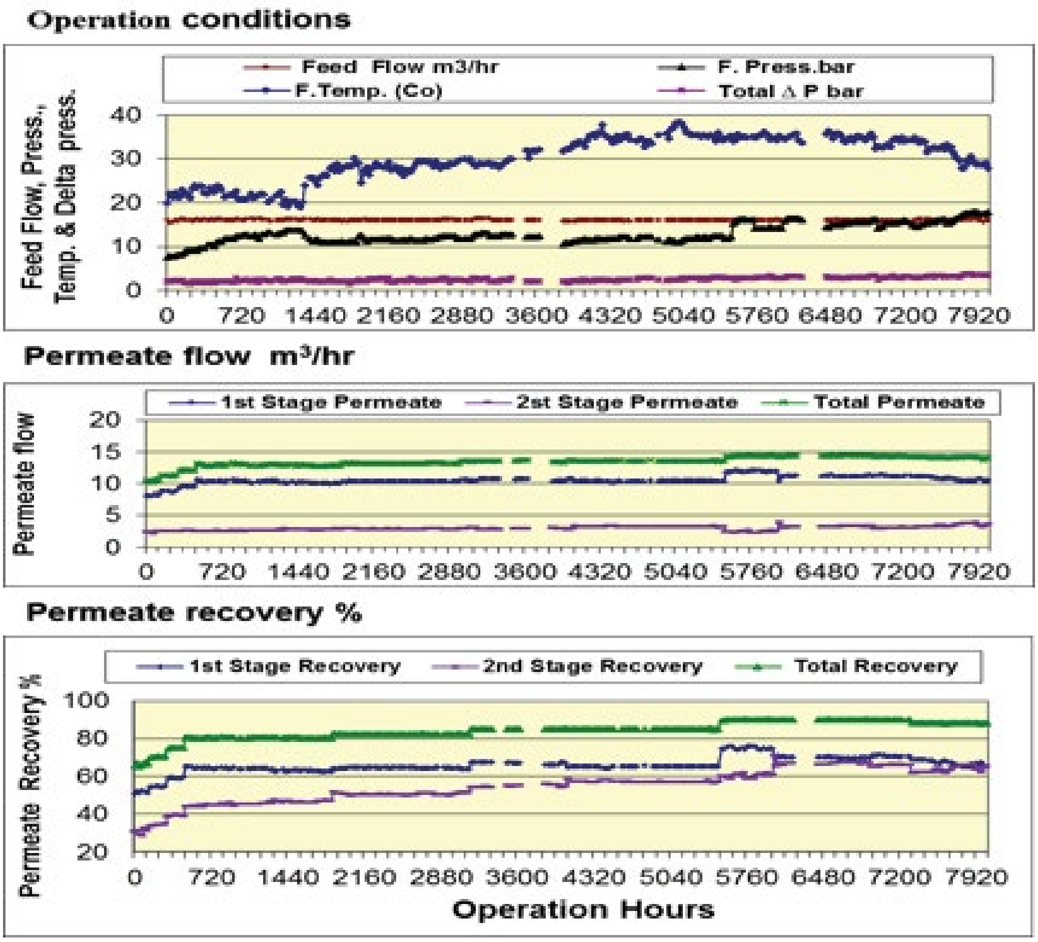

Fig. 4. Operation and performance parameters of NF process at different recoveries (65%–90%).

averaged 13.6 m^3/h as shown in Fig. 4. In addition, average permeate conductivities for first stage, second stage and total were 57,610; 62,107 and 58,563 µS/cm, respectively. Differential pressure for first stage and second stage remained steady at 1.2–1.7 bar and 1.0–1.5 bar, respectively, and total ΔP reached approximately 2.2–3.2 bar. However, membrane flushing with pretreated seawater was done every 20 d for 60 min. Alkaline chemical cleaning was performed on the 1st NF stage after 3,600 operating hours.

3.1.5. Performance evaluation of NF process at 90% recovery

NF process was operated at 90% recovery for approximately 2,200 h. During the changeover from 85% to 90% recovery, feed pressure and energy consumption, productivity and permeate conductivity were 12.1 bar; 0.46 kWh/m^3; 13.62 m^3/h and 58,200 µs/cm at 85% recovery while at 90%, they were 15.2 bar; 0.55 kWh/m^3; 14.4 m^3/h and 58,500 m^3/h, respectively. Increasing the recovery from 85% to 90% resulted in an increase in feed pressure by 3 bar whereas energy consumption increased only from 0.46 to 0.55 kWh/m^3.

At the beginning of the 90% recovery trial, as a result of increasing recovery ratio and feed temperature, the effects of employing permeate backpressure valve on 1st stage NF process was investigated. Operation and performance parameters were carefully checked with and without employing the permeate valve. Table 4 presents the effects of 1st stage permeate valve on operation and performance parameters of the NF process. Without employing the permeate valve, 1st stage and 2nd stage recoveries operated at 75.5% and 58.9% in a wide range and the first two elements at 32.5% recovery and 35 L/m^2/h flux rate. While employing permeate valve, feed pressure increased by 1 bar and 1st stage and 2nd stage recoveries were optimized at 70% and 66.7% recovery whereas the first two elements recovery ratio and flux rate reduced to 24% and 25.6 L/m^2/h, respectively. Employing the permeate valve on 1st NF stage led to better membrane hydraulic performance with no significant increase in feed pressure.

Optimization of antiscalant dosing rate and the weight of last NF element in the second stage was determined periodically to ensure that there was no scale formation on the membrane surface. For the first 1,000 operating hours at 90% recovery, there was no increase in the last element weight. However, for the second 1,000 h of operation, it was observed that the weight of last NF element increased approximately by 2.5 kg. The last NF element was subjected to autopsy and analyses. Visual inspection indicated the presence of white deposits on membrane surface at the brine outlet. Chemical analysis of white deposits confirmed the formation of calcium sulfate scale. The main reason behind this increase may be the failure of the antiscalant dosing system. Additionally, it is important to mention that the brine conductivity, sulfate and calcium reached approximately 82,000 µs/cm; 27,200 mg/L and 1,500 mg/L, respectively. Therefore, NF process recovery was reduced and operated at 88% for 1,000 h. Results at this recovery resulted in smooth operation and there was no increase in the weight of the last NF element, with a membrane autopsy confirming the same.

3.1.6. Permeate SDI and SDI reduction

Fig. 5 shows seawater feed SDI and NF permeate SDI at different recoveries vs. operation time. Seawater feed SDI values ranged from 2.5 to 4.1, mostly between 3 and 4 and a few days at 2.5 and 4.1. NF permeate SDI shows another trend. For the first 1,800 operation hours at recovery ratios 65%–80%, the NF permeate SDI was below 1.0 with 85% reduction in SDI value. As recovery ratio was increased from 80% to 90% and feed temperature from 29°C to 38°C, permeate SDI increased from 0.6 to 2.2 with 37%–71% reduction in SDI values.

3.1.7. Permeate TDS and TDS rejection

NF membranes used in this trial had a limited TDS rejection <20%. TDS rejection by the NF membranes was affected by many different variables, including increasing the recovery ratio from 65% to 90%, as well as changes in operating conditions, such as feed pressure, temperature and conductivity. At 65%–75% recovery, seawater feed and total permeate conductivities were 62,300 and 57,000 µS/cm, respectively, with 17% TDS rejection. At the end of the trial, at 88% recovery, seawater feed and total permeate conductivities were 61,300 and 57,500 µS/cm, respectively, with 13.5% TDS rejection. NF permeate conductivity was directly proportional to variations in seawater feed temperature and conductivity, with any slight increase or decrease in feed conductivity reflecting the same ratio on permeate conductivity change, as shown in Fig. 5. Accordingly, NF feed conductivity shows four different average values of conductivity starting with 58,441; 57,650; 58,920 µS/cm and ending with 57,100 µS/cm owing to variations in feed conductivity and temperature.

3.1.8. Actual and projected performance of NF process

Table 5 presents the actual and projected performance of the NF process after 1,000 and 5,500 operating hours under two different conditions (80% recovery at 20.6°C and 85% at 35.3°C), respectively. The projected performance is obtained using the membrane manufacturer's design software by

Table 4
Effect of 1st stage permeate valve on NF process at 90% recovery and 37.8°C feed temperature

Parameters	Feed pressure	Feed m^3/h		Recovery ratio%		Product m^3/h		Cond. µs/cm	
		1st stage	2nd stage	1st stage	2nd stage	1st stage	2nd stage	Total	Brine
Without valve	13.8	16	3.9	75.5	58.9	12.1	2.3	58,600	80,500
With valve	14.8	16	4.8	70	66.7	11.2	3.2	58,500	80,600

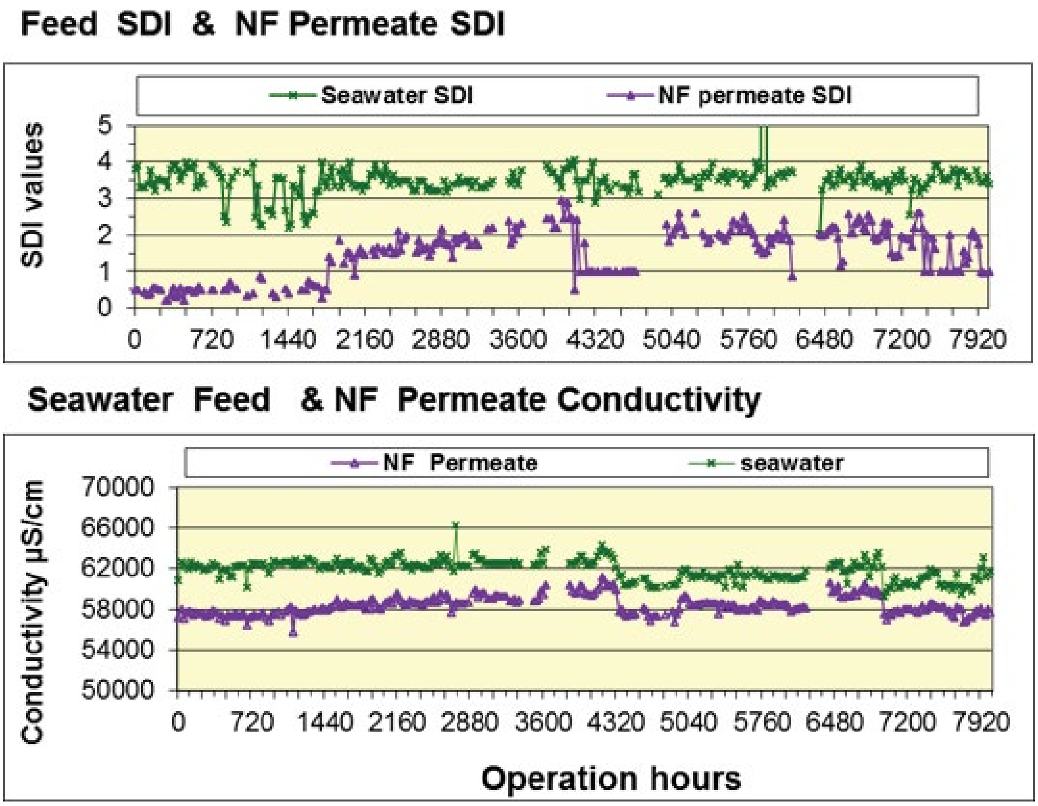

Fig. 5. SDI and conductivity of seawater feed and NF permeate vs. operation time.

Table 5
Actual and projected performance of NF membrane seawater pretreatment

Data	January 1, 2018		July 29, 2018	
	1,000 operation hours		5,500 operation hours	
	Projected	Actual	Projected	Actual
Feed, mg/L	45,496		44,633	
Feed temp, °C	20.6		35.3	
Perm flow, m^3/h	12.80	12.73	13.6	13.62
Recovery, %	80	80	85	85.2
Feed pressure, bar	32.5	13	21.9	12.1
Press. drop, bar	2.3	3.1	1.8	2.9
Total perm, mg/L	29,939	37,884	35,631	40,153

inputting operational data. The analysis results are listed in Table 6 based on data taken on January 1 and July 29, 2018. Results indicated that there is significant difference between the actual and projected performances for both cases in terms of feed pressure and permeate TDS. At 80% and 85% recoveries, the projected feed pressures are higher than actual readings by 19.5 and 9.8 bar, respectively. Additionally, at 80% and 85% recoveries, the actual permeate TDS increased by 7,945 and 4,522 mg/L compared with the projected TDS values, respectively. Therefore, normalization of NF performance data is not possible with the existing NF projection software programs as confirmed from the previous NF trials connected at DTRI. Based on long operational experience with NF seawater pretreatment process, lead element flux rate and recovery ratio, operation and performance parameters, as well as tools, such as periodic membrane weights and membrane autopsies are used to verify stable NF process performance.

3.1.9. Seawater ion rejection

Based on chemical analysis results, the concentration of Mg^{++}, Ca^{++}, SO_4^-, HCO_3^- and Cl^- in seawater feed averaged 1,600; 533; 3,200; 150 and 23,750 mg/L, respectively. The analysis results of the NF feed indicated that there are five different rejection levels for Mg^{++}, Ca^{++}, SO_4^-, HCO_3^- and Cl^- according

Table 6
Performance of hybrid and nonhybrid 8-element arrays at 50%–52% recovery

Case	SWRO array	Recovery %	Element flow	Feed pressure	TDS	Energy
			m³/d	bar	mg/L	kWh/m³
Nonhybrid-1	8 MR elements	50	28	69.8	315	4.87
Nonhybrid-2	8 HF elements	50	34.1	68	376	4.76
Hybrid-1	2 VHR / 6 MR elements	50	26.8	70.6	295	4.93
Hybrid-2	2 HR / 6 HF elements	50	31.7	69.6	341	4.83
Hybrid-2	2 HR / 6 HF elements	52	31.7	72	343	4.85

to NF membrane selectivity towards different ions. At the beginning of the trial, rejection levels of Mg^{++}, Ca^{++}, HCO_3^- and Cl^- were 53.6%, 40%, 33% and 11% and decreased with operation time and increasing recovery, reaching approximately 47.8%, 21.5%, 21.9% and 8.7%, respectively. The concentration of Mg^{++}, Ca^{++}, HCO_3^- and Cl^- in NF permeate ranged between 560–940; 300–380; 100–120 and 21,000–22,800, respectively. Sulfate ion rejection at the beginning of the trial showed a remarkable rejection level of 98.6% and decreased at the end of the trial and reached approximately 96.8%. Consequently, the concentration of SO_4^- in the NF permeate ranged from 60 to 140 mg/L.

3.2. Performance of various hybrid and nonhybrid SWRO designs on NF feed at high recovery

To investigate the optimal membrane arrangement for high recovery operation, an analysis was carried out to study the effect of element placement on the performance and operation parameters of the SWRO process. The goal of the design was to maximize water product recovery from NF feed while maintaining very strict permeate quality standards. The permeate recovery and average permeate flux were determined to be 50%–52% and 15 L/m²/h, respectively. Four different cases, including hybrid and nonhybrid designs of 8-element arrays, were investigated. The hybrid and nonhybrid designs have different membrane characteristics in terms of rejection and productivity. Table 6 lists the average element flow of each array, which ranged from 26.8 to 34.1 m³/d and reflected the system performance in terms of feed pressure and permeate TDS. The four different arrays were operated at constant operating conditions (50% recovery, 15 L/m²/h flux rate and ambient feed temperature of 29°C–30°C). Only Hybrid-2 was tested at 50% and 52% recovery. During the trial, NF feed conductivity was in the range of 58,500–59,000 μS/cm. The results of the trial are presented in Table 6.

A higher flow (HF)-element array with an average element flow of 34.1 m³/d led to a decrease in feed pressure and an increase in permeate TDS. This array showed the lowest feed pressure and the highest permeate TDS, which were 68 bar and 376 mg/L, respectively. The projected performance exhibited the highest lead element flux and recovery, which reached approximately 37.8 L/m²/h and 16.3%, respectively, resulting in unbalanced flux with a higher fouling rate in the lead elements. It is clear that higher flow elements cannot be used alone, especially at higher feed temperature and salinity. Hybrid design is the recommended option to take advantage of the higher flow elements in terms of lower feed pressure and higher productivity while optimizing the flux rate in lead elements. Decreasing the array average element flow from 34.1 to 28 m³/d in the array with eight MR elements led to an increase in feed pressure and a decrease in permeate TDS, which were 69.8 bar and 315 mg/L, respectively. However, the projected lead element flux rate and recovery stayed at approximately 35 L/m²/h and 15.1%, respectively.

Introducing two VHR elements in the lead position of the 8 MR element array as the Hybrid-1 design (2 VHR / 6 MR) with an average element flow of 26.8 m³/d resulted in a reduction in the projected lead element flux and recovery to approximately 30.5 L/m²/h and 13.1%, respectively. This array shows the highest feed pressure and lowest permeated TDS at the expense of energy, which were 70.6 bar, 295 mg/L and 4.93 kWh/m³, respectively, compared with the 8-MR element and 8-HF element arrays.

The Hybrid-2 design (2 HR / 6 HF) utilizing six higher flow elements in the back resulted in increasing the average element flow up to 31.7 m³/d compared with Hybrid-1 design value of 26.8 m³/d. This array led to a decrease in feed pressure and an increase in permeate TDS, which were 69.6 bar and 341 mg/L, respectively. Additionally, this array shows a significant reduction in the projected lead element flux and recovery to approximately 29.7 L/m²/h and 12.8%, respectively, compared with all 8-element arrays. Accordingly, Hybrid-2 design was investigated at 52% recovery and 15 L/m²/h flux rate. The operating feed pressure increased by approximately 2.5 bar with no change in permeate TDS and energy consumption as presented in Table 6. As in the previous discussion on four different 8-element SWRO configurations, Hybrid-2 design was selected and adopted in a split partial two-pass design for long-term operation and investigation at 52% recovery.

3.3. Performance evaluation of hybrid split partial two pass in long-term operation

3.3.1. NF feed

In reality, the physical and chemical properties of NF feed depend mainly on the NF membrane characteristics used in the trial. The existing NF membrane has a limited TDS rejection <20% and is affected sharply by the operating conditions, feed conductivity and temperature as shown in Fig. 5. NF product was used as RO feed. At the beginning of this trial, NF process was at 80% recovery, and then increased gradually up to 90% recovery. Accordingly, the NF feed conductivity was between 57,500 and 61,000 μS/cm, periodically reducing to 57,000–6,000 µS/cm due to mixing of second pass BWRO concentrate. As seen in Fig. 5, the NF feed SDI ranged from 0.5 to 2.6. The NF feed TOC averaged 0.15 mg/L. The NF feed boron concentrations were between 5.5 and 6.2 mg/L.

3.3.2. Hybrid split partial two pass

The hybrid design employs the SWRO array (2 HR / 6 HF). It has an average element flow of 31.7 m^3/d and is operated at 52% recovery with a flux and a flow rate of 15 L/m^2/h and 8.5 m^3/h, respectively as shown in Fig. 6. The RO feed pressure and temperature were in the range of 68–73.5 bar and 27°C–39.2°C, respectively. The operating feed pressure averaged 71.2 bar. The differential pressure across SWRO membranes was steady at 1.5–1.8 bar. For the first 700 operating hours, the permeate split ratio was 30% at feed temperature range of 30°C–32°C. The final permeate conductivity was in the range of 107–148, averaging 129 µS/cm. To maintain total permeate conductivity <100 µS/cm, based on feed temperature variations from 32°C to 38°C, the permeate split ratio decreased from 30–15 to 10%. At the end of the trial with decreasing feed temperature to 26.6°C, the permeate split ratio was increased to 35% and SWRO recovery increased to 53% owing to a decrease in NF feed conductivity. Based on the permeate split stream radios, the overall recoveries varied between 50% and 51.9% and averaged 50.4%.

The average recovery ratios of the 1st pass RO, BWRO and overall recovery were 52.2%, 92% and 50.4%, respectively, with corresponding permeate conductivities averaging 769, 50 and 78 µS/cm, respectively. The feed side permeate split stream conductivity was in the range of 134–314 µS/cm, compared with the rear side permeate conductivity of 611–1,342 µS/cm. The final permeate conductivity was between 39 and 140 µS/cm and averaged 78 µS/cm. The product flow rates for the 1st pass, 2nd pass (BWRO) and total product averaged 4.43, 3.53 and 4.13 m^3/h, respectively.

3.3.3. Second pass RO (BWRO)

BWRO was operated on the brine side permeate of the SWRO. The rear permeate ratios were increased from 65% to 90% due to feed temperature variations (27°C –39°C) to maintain total permeate conductivity below 100 µS/cm as per SWCC guidelines. Accordingly, the BWRO feed flow rates ranged from 2.8 to 4.0 m^3/h, with the flux rates varying between 25 and 36 L/m^2/h.

BWRO brine ranged from 6,500 to 11,500 µS and was mixed with SWRO feed. The BWRO was operated at approximately 92% recovery. BWRO showed stable performance in terms of product water recovery and permeate flow rates. Fig. 7 shows the recovery ratio, product flow rate and permeate conductivities for 6,000 h of operation. The BWRO feed pressure ranged between 7 and 9.8 bar and averaged 9 bar. The total differential pressure ranged 1.5–2.8 bar and averaged 2.6 bar. The BWRO feed conductivity ranged between 611 and 1,342 µS/cm, whereas final product ranged 20–105 µS/cm and averaged 50 µS/cm.

Fig. 8 shows the normalized flow and salt passage of SWRO. For the first 850 operating hours, the normalized permeate flow started with 4.44 m^3/h, then decreased and stabilized between 3.85 and 3.6 m^3/h. At the end of trial with decreasing NF feed conductivity due to a gradual decrease in feed temperature, normalized flow increased to approximately 4.12 m^3/h. There was no decrease in normalized salt passage. It is important to point out that during the entire operation there is no chemical cleaning performed on the SWRO process. Only membrane flushing with RO permeate was carried out on the SWRO process.

As shown in Fig. 8, it is observed that the normalized salt passage of SWRO is directly affected by NF feed conductivity. NF feed conductivity followed variations in seawater feed temperature and conductivity and was also affected by mixing NF feed with BWRO brine. Therefore, during the trial,

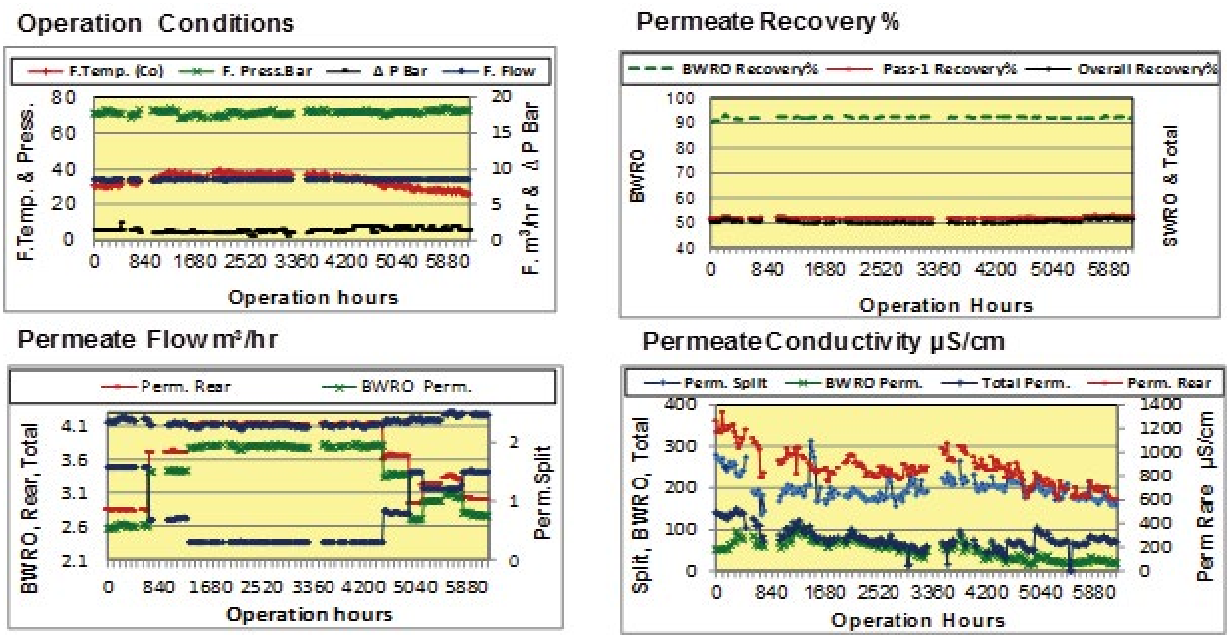

Fig. 6. Operation and performance parameters of hybrid split partial two-pass design for 6,000 h of operation.

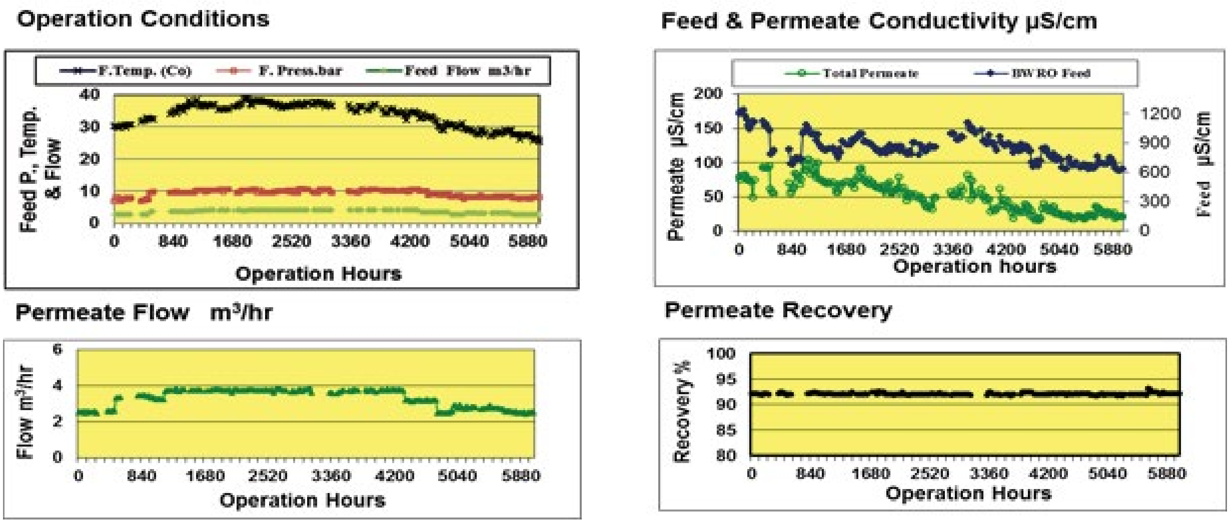

Fig. 7. Operation and performance parameters of second pass BWRO for 6,000 h of operation.

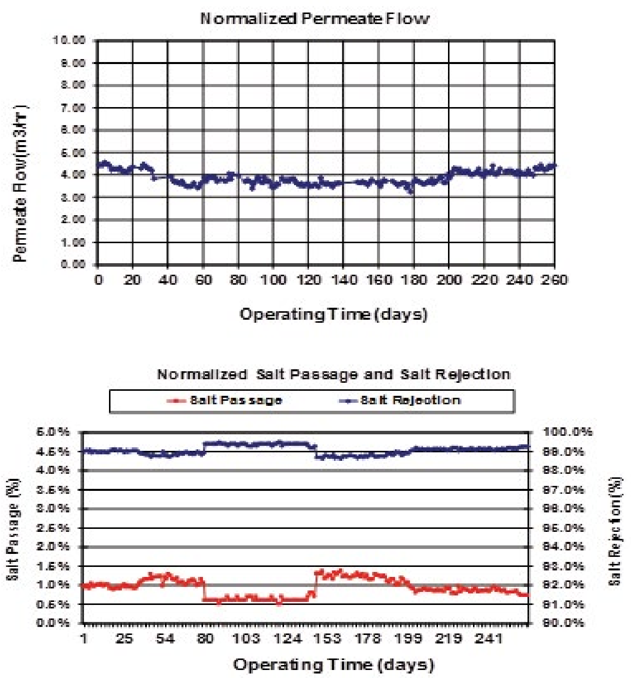

Fig. 8. Normalized flow and salt passage of SWRO process.

NF feed conductivity showed four different average ranges of conductivity, starting with 58,441, 57,650 and 58,920 µS/cm and ending with 57,100 µS/cm owing to a decrease in feed temperature. Accordingly, the normalized salt passage followed the same trend, starting with 1.06%, 0.62% and 1.21% and ending with 0.88%. There was no increase in normalized salt passage.

However, hybrid split partial two-pass design produced high quality permeate in terms of boron content and TDS. The final permeate conductivity averaged 78 µS/cm, which was below 100 µS/cm as recommended by SWCC regulations. Additionally, final permeate boron concentration ranged

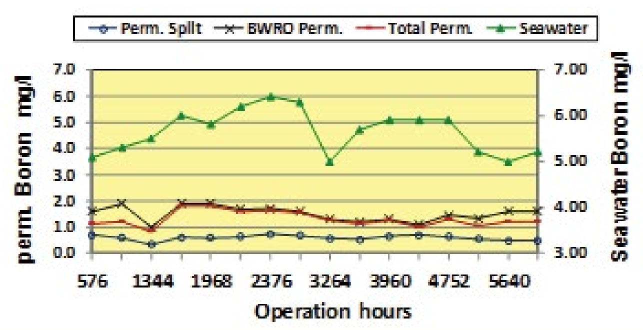

Fig. 9. Boron concentration in seawater feed and different permeates.

between 1 and 1.8 mg/L and averaged 1.35 mg/L, compared with the seawater feed boron concentration of 5–6 mg/L. By contrast, the boron concentration in the 1st pass RO ranged from 1.3 to 2.3 mg/L and averaged 1.9 mg/L. Fig. 9 shows the boron concentration in the seawater feed and different permeates.

Tables 7 and 8 present further confirmation of the actual and projected performance of hybrid split partial two-pass design after approximately 2,500 and 5,000 operating hours under two different conditions (10% permeate split ratio at 37.2°C) and (30% permeate split ratio at 31°C), respectively. The analysis results are presented in Tables 5 and 6 based on data taken on July 24, 2018 and November 5, 2018. From the comparison, it can be seen that the difference between the actual and projected feed pressures is approximately 1 bar. It is important to point out that during the entire operation, there is no chemical cleaning performed on the SWRO process as mentioned earlier. In addition, the actual permeate total TDS value is slightly higher than the projected values at different conditions whereas the actual and projected boron content are approximately similar. The 1st pass RO permeate and permeate rear TDS values are slightly better than the projected values.

Table 7
Actual and projected performance of hybrid split partial two-pass design after 2,500 h of operation (10% permeate split ratio and 37.2°C)

Data	July 24, 2018			
	SWRO		BWRO	
	Projected	Actual	Projected	Actual
Feed mg/L	41,002		409	380
Feed pH	7		5.07	5.3
Feed temp °C	37.2		37.2	37.1
Perm. flow m^3/h	4.41	4.44	3.7	3.72
Recovery %	52	52.1	92	92.3
Feed pressure bar	69	69.5	8.2	9.5
Press. drop bar	0.9	1.6	1.2	2.6
1st pass perm. TDS mg/L	379	360	20	28
Perm. split TDS mg/L	74	84	–	–
Perm. rear TDS mg/L	409	380	–	–
Perm. total boron mg/L	1.77	1.8	–	–
Perm. total TDS mg/L	24	35	–	–

Table 8
Actual and projected performance of hybrid split partial two-pass design after 5,000 h of operation (30% permeate split ratio and 31°C)

Data	November 5, 2018			
	SWRO		BWRO	
	Projected	Actual	Projected	Actual
Feed mg/L	40,738		436	390
Feed pH	7		5.1	5.3
Feed temp °C	31		31	30.9
Perm. flow m^3/h	4.41	4.45	2.7	2.72
Recovery %	52	52.1	92	92.2
Feed pressure bar	69	70	7	8.2
Press. drop bar	0.9	1.7	1	2
1st pass perm. TDS mg/L	317	300	25	21
Perm. split TDS mg/L	75	98	–	–
Perm. rear TDS mg/L	436	390	–	–
Perm. total boron mg/L	1.5	1.6	–	–
Perm. total TDS mg/L	42	48	–	–

The actual data were collected from pilot plant trials whereas the projected data were obtained from NF membrane projection software program obtained from membrane manufacturer.

Additionally, Tables 7 and 8 show the actual and projected performance of BWRO process at different conditions (feed TDS: 380 mg/L at 37°C and feed TDS: 420 mg/L at 31°C). The actual BWRO feed pressures are higher than the projected values by approximately 1.3 bar. There is no significant difference between the actual and projected BWRO permeate TDS. As seen in Tables 7 and 8, hybrid split partial two-pass design produces high quality permeate, as recommended by SWCC regulations (TDS < 50 mg/L and boron < 2.4 mg/L).

3.4. Biological count analysis

Seasonal distributions of non-disinfected intake feed seawater ranged from two orders of magnitude, in winter (0–1,440 h), peaking to three orders of magnitude in summer (4,080–7,440 h). Seasonal increase in bacterial content appears to increase over time with temperature. The product of the DMF decreases in bacterial concentration by an average of 87% (Fig. 10). This is unexpected as the pore size of the DMF is not small enough to impede microbial passage.

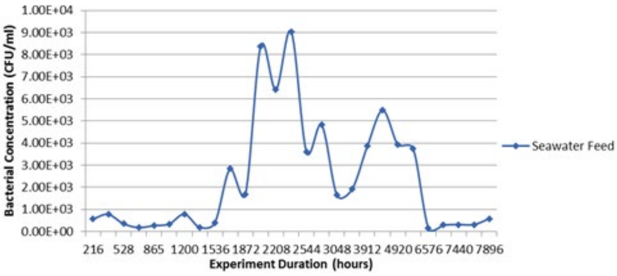

Fig. 10. Microbial CFU distribution of seawater feed vs. operation hours.

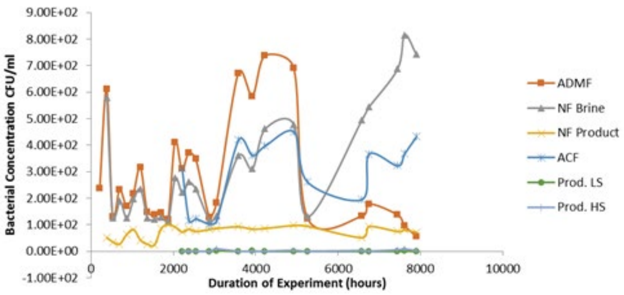

Fig. 11. Microbial CFU distribution over time at NF and SWRO processes.

The decrease may be attributed to bacteria intercalation within the DMF matrix that goes on to form biofilm enhancing bacterial removal [22]. In this way, the DMF behaves similar to a biological reactor, accounting an order of magnitude decrease in bacterial content between intake source feed and DMF filtrate.

In the NF product, a 77% reduction in bacterial content is observed from the DMF product. Up to the NF product, the system gives a 97% reduction in bacteria. A stabilized reduction in microbial content owing to the use of NF can be observed along seasonal concentration fluxions confirming NF's reduction in bacterial content (Fig. 11). Morphologically, bacteria appear larger in a CFU size in the product than in the NF brine.

The brine of the NF presents a smaller CFU size. There is a 7% increase in bacterial content from the DMF product. The increase does not reflect bacterial growth, but it may reflect an inability to grow in higher salinity conditions. For this reason, the increase in bacterial population is not reflective of the percentage of NF brine concentrate from the DMF product.

Bacterial content for RO product for both low salinity and high salinity permeates was at zero orders of magnitude. In the summer seasons, there is an increase in bacterial concentration after the cartridge filter and before the SWRO membrane (up to two orders of magnitude). This increase may be associated with growth impact factors resulting from the NF product storage tank. In both low and high salinity products of SWRO membranes, microbial concentrations were of zero orders of magnitude with over 99% reduction in bacterial content from the membrane feed stream.

The use of DMF as pre-treatment to NF and RO reduced bacterial content within the process feed stream and SWRO products for both low and high salinity.

4. Conclusions

- Successful long-term performance of about 8,000 h was achieved for a two-stage NF process; up to 88%–90% recovery on Gulf seawater with lower feed pressures (11–18 bar) and energy consumption (0.43–0.74 kWh/m^3) with very high sulfate rejection (96%) and low TDS rejection (13%–17%).
- NF pretreated split partial two-pass design was successfully operated for approximately 6,000 h, with SWRO and BWRO processes at 52–53 and 92% recovery, respectively, with an average overall recovery of 50.5%. The total permeate TDS and boron averaged 40 and 1.35 mg/L.
- The study concluded that hybrid split partial two-pass design with NF pretreated feed can be operated at about 50% overall recovery under two different operation modes, where very stringent permeate quality <50 mg/L TDS or normal potable water specification of 400 mg/L TDS can be achieved with and without a second pass BWRO system.

Recommendation

Based on results obtained from project Part-II, it was concluded that transition of Umm Lujj NF process from a single to a two-stage operation would result in an increase in recovery of NF and SWRO processes from 65% to 88% and from 50% to 52%, respectively, with an overall recovery of ≥44%. Accordingly, installation of a two-stage NF process at Umm Lujj SWRO plant (Train-100 and Train-200) is in progress and is expected to be commissioned during December 2019.

Acknowledgment

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