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Optimum nanofiltration membrane arrangements in seawater pretreatment - Part-I

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ABSTRACT

NF membrane seawater pretreatment is an attractive technique that can provide unique permeate quality having negligible fouling and scaling potential and hence suitable for both membrane and thermal desalination processes. The technique was applied commercially in SWCC Umm-Lujj SWRO plant at 65% recovery. Operation at such recovery as pretreatment process is considered unattractive from the economic point of view. Accordingly, the aim of this study was to maximize NF product recovery and reduce operational cost while maintaining long membrane life. To achieve the target different investigation areas and techniques are considered. This paper presents Part-1 of this study which includes the performances of seven different NF arrangements in seawater pretreatment starting from 4 up to 20 NF elements in terms of recovery ratio, product quality, energy consumption and membrane hydraulic performance. The study revealed that 8-elements array at 65% recovery is the best choice for single stage NF process. Whereas, 14-, 18- and 20-elements arrays are optimal for two-stage NF process at 75%, 80% and 85% recovery, respectively with lower feed pressures and minimum fouling potential. Moreover, results indicated that transition of NF process from single stage operation at 65% recovery to two-stage at 85% recovery results in an increase in NF permeate TDS by 2000 mg/l which was compensated by major benefits such as higher productivity, higher recovery and lower energy consumption. Also, this paper describes results of successful long term performance of about 6048 h for 18-elements array at different recoveries of 65%, 75% and 80% in terms of SDI reduction, TDS rejection, and chemical composition of NF permeate.

Keywords: Seawater; Nanofiltration; Pretreatment; NF arrangements; Optimization; SWRO

1. Introduction

1.1. NF membrane seawater pretreatment

NF membrane seawater pretreatment is an attractive pretreatment technique initiated and developed by SWCC – SWRDI that removed most of the major problems in seawater desalination processes [1–7].

NF process was applied successfully for more than six years in Umm-Lujj SWRO plant at 65% recovery utilizing conventional array consists of six NF 8″ spiral wound elements connected in series. This conventional array was operated at 65% recovery with two different operation modes, initially with feed flow rate of 13.3 m^3/h and at higher flux average of 44.3 l/m^2-h which resulted in high fouling rates in lead elements coupled with repeated chemical cleaning. Later on, the number of pressure vessels were increased and feed flow rate

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dropped to 8 m^3/h resulting in reduction in array flux average to about 26 l/m^2-h coupled with steady operation [8,9]. But operating NF process at 65% recovery as pretreatment process is considered unattractive from economical point of view. In addition, NF operation at Umm-Lujj SWRO plant was accompanied by higher feed pressures where there is a gradual increase in feed pressure up to 37 bar which is restored by chemical cleaning. Moreover, sulfuric acid and SHMP are dosed to control scaling with higher chemical cost. Therefore, the existing study aims to maximize NF productivity and reduce operational cost, especially energy consumption which represents the highest cost component in NF process which reached about 1.82 kWh/m^3. On the other hand, NF seawater pretreatment deals with pretreated seawater having high TDS, high hardness content and also very fine turbidity and residual bacteria which can be accumulated on membrane surface with time. Moreover, Optimization of NF process at higher recoveries for cost effectiveness of NF permeate production would result in higher brine concentration accompanied by the effects of concentration polarization. Hence, NF process should be investigated and optimized at the maximum possible recovery under lower feed pressure and flux to reduce energy consumption and minimize fouling propensity while maintaining long membrane life.

Consequently, NF process requires additional investigation in order to obtain successful and economical long-term performance with a recovery of more than 85%. To accomplish this target, three investigation areas are considered to: (1) study and compare the performance of different NF arrays of one- and two- stage NF process to find out the optimal NF array, (2) optimize and evaluate the performance of optimum NF arrangement at the maximum possible recovery and (3) Introduce a simple flushing procedure employing seawater to keep NF membranes always in clean conditions.

1.2. Membrane arrangements

Membrane arrangements play an important role in the performance of RO/NF systems especially in recovery ratio, product quality, operation parameters as well as time dependent process such as fouling and scaling. There are different types of membrane arrangements, which can be used in RO or NF plants. Tapered brine staging system is usually recommended to increase plant product recovery. Here the velocities are boosted and the negative effects of concentration polarization as well as scaling and fouling problems are minimized. Also, based on recent advances in NF membrane technology, new NF membranes have been introduced in the market that can achieve higher TDS rejection at lower feed pressure. Accordingly, new NF arrangement called Dual-staged NF system has been employed for seawater desalting [10]. On the other hand, selecting optimum array design along with the optimization of process parameters is a crucial factor in fouling mitigation [11,12]. Therefore, this study aims to investigate and select the optimal NF array which could be operated at higher recoveries and lower energy consumption coupled with very low fouling propensity. Hence, Several trials were conducted under constant operating conditions to study and compare the performance of various NF membrane arrangements of one- and two- NF stage, starting from 4 up to 20 NF elements. Also, the study involved simulation of NF array which was applied commercially at Umm-Lujj SWRO plant in two different operation modes.

1.3. Flushing NF membranes with pretreated seawater

Several types of fouling (inorganic, organic, particulate and colloidal, and microbiological) can occur in a membrane system with obvious undesirable consequences starting from the adsorption or deposition of foulants on the membrane surface which leads to a drastic reduction in water flux, increase in pressure drop and degradation of membrane. Membrane performance can be restored by different procedures such as backwashing or flushing with water and various cleaning techniques depending on type of fouling (reversible or irreversible) and its constituents. Physical and chemical characteristics of feed water, concentration polarization, flux rate, brine velocity and membrane material have a pronounced effect on membrane fouling [13–15].

In view of all the above, NF membrane used in NF seawater pretreatment process, faces essential problems of pretreated seawater feed having high TDS, high hardness content and also very fine turbidity and residual bacteria which can be accumulated on membrane surface with time. Moreover, NF process when operated at higher recoveries result in high permeation rate leading to more fouling and also increased brine concentration accompanied by the effects of concentration polarization. Thus, previously mentioned factors lead to increase in fouling and scaling propensity in NF process. Flushing NF membranes with pretreated seawater was tried before and found to be beneficial and effective in NF process. Accordingly, flushing NF membranes with pretreated seawater was applied and its effects on the performance of NF process was investigated in this study.

2. Experimental work

Experimental work of this study can be divided into two parts. Part-1 has been completed and consists of preliminary tests to select the optimum NF arrangements as well as optimization and performance evaluation of 18-elements array in long term operation at different recoveries of 65%, 75% and 80%. Part-2 will involve optimization and performance evaluation of 20-elements array in long term operation at higher recoveries more than 85% followed by membrane autopsy at the end of the trial as well as life cycle cost analysis for three different NF arrangements.

2.1. Description of NF demonstration plant

2.1.1. Seawater supply and pretreatment system

Seawater is fed from a nonchlorinated seawater intake. Also, there is provision to use MSF pilot plant heat rejection section outlet as feed during winter season which can be blended with cold seawater to maintain constant feed temperature during preliminary tests of different NF arrays for accurate comparison. Pretreatment system consists of three pretreatment units with total capacity of 17 m^3/h. Each pretreatment unit comprises of dual media filter followed by fine sand filter. Ferric chloride was dosed as coagulant at a concentration of 0.6 ppm as Fe^{+3} while sulfuric acid was injected to maintain pretreated seawater at pH of 5.9. The pretreated seawater SDI values were maintained between 2.7–3.5.

2.1.2. NF 8″ skid

Fig. 1 shows schematic flow diagram of NF skid consists of booster pump (6 bar, 18 m^3/h), high pressure pump (30 bar and 18 m^3/h), 5 micron cartridge filter, seven pressure vessels of two elements and one pressure vessel of six elements. This test unit can accommodate any NF arrangement of one- or two-NF stage starting from 4 up to 20 spiral wound membrane elements of 8″×40″. Also this unit was provided with necessary piping and instrumentation to control all operating conditions as required and also to monitor performance parameters. Due to this higher flexibility, the effects of brine staging of different membrane arrangements on performance of NF process can be easily investigated and studied in terms of recovery ratio, permeate quality, energy consumption as well as membrane hydraulic performance.

In addition, the inter connecting piping between the two elements in the first and last two elements pressure vessels in all trials was replaced by a blind pipe to measure productivity of lead element and last element separately. Accordingly, lead element flux average and its recovery as well as Brine/Product ratio for the last element are calculated.

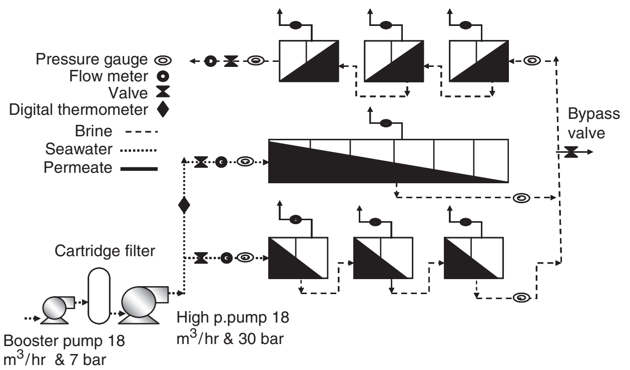

Fig. 1. NF Skid adopted in two-stage utilizing a total of 18 8″ × 40″ NF Elements.

2.1.3. NF membrane specifications

Earlier study which was conducted at SWCC-SWDRI classified NF membranes into three categories based on TDS rejection (13 NF membranes were investigated and classified into higher, lower and moderate rejection NF membranes). NF membrane of moderate TDS rejection (<30%) has been selected and employed in Umm-Lujj NF plant and existing trials. NF membrane specifications: productivity 30.2 m^2/d, active membrane area 32.5 m^2 and 98% $MgSO_4$ rejection (based on a 2000 mg/l $MgSO_4$ solution at 100 psig net pressure, 25°C, 15% recovery, B/P ratio for element 5:1).

2.2. Preliminary tests of different NF arrangements

The first part of the study was to investigate and select the optimum NF arrangements in seawater pretreatment. Trials focused on straight and tapered brine staging of one and two-stage utilizing commercial NF 8″ membrane elements of moderate rejection. Different NF arrays utilized in the trials are briefly described as follows:

(a) Straight brine staging arrangement: This arrangement usually adopted in single stage and its conventional array consists of six spiral wound elements connected in series. In addition to this 4-elements and 8-elements arrays have been investigated to study the effect of increasing or decreasing number of NF elements connected in series on the performance of single stage NF process.

(b) Tapered brine staging arrangement: Generally, this type of arrangement configured in two- or three-stage such as 2:1 or 3:2:1. This trial focused on two-stage of 2:1 and its conventional array consists of 12 or 18 NF elements. Also for comparison purposes 14-, 16- and 20-elements arrays were derived from the previous conventional arrays by adding or removing two elements from the second stage. For obtaining accurate comparison with realistic values different arrays of single-stage and two-stage were operated and compared at constant operating conditions specially feed temperature which was maintained at 28 ± 0.3°C as the moderate temperature between cold and hot seasons. Also, during the trials seawater feed conductivity was in the range of 61000–62000 µS/cm (feed TDS: 45000–46000 mg/l). Different NF arrays of single-stage were operated and compared at 65% recovery with 8 m^3/h feed flow and in some cases feed flow rate increased to 10 m^3/h. Whereas, different NF arrays of two-stage operated and compared at 75% recovery with 16 m^3/h feed flow and in few cases feed flow rates increased to 17 and 18 m^3/h while recovery ratios increased to 80 and 85% repectively. Operation and performance parameters were collected and averaged for each test. Chemical analyses for different NF arrays were performed including seawater, permeate and reject.

2.3. Operation and optimization of 18-elements NF array

18-elements array was operated for about 6048 h at ambient temperature, feed pH of 5.9, seawater feed conductivity ranged between 59900 and 62100 µS/cm while feed flow rate was maintained at 16 ± 0.1 m^3/h. Feed pressure was increased to maintain recovery ratio as required per each trial from 65% to 80%. Also based on the results obtained from the preliminary tests and commercial Umm-Lujj NF plant first stage recovery did not exceed 65% during entire operation as recommended recovery for 1st stage. Antiscalant was injected at dose rate of 4 ppm to prevent sulfate scaling. Operation and performance parameters were collected on daily basis. Chemical and biological analyses were performed for seawater, permeate and reject at various stages of the study. Flushing NF membranes with pretreated seawater was done on monthly basis for three hours. The flushing process is simple which is done by directing the most of pretreated seawater feed to the brine side of the NF membranes to flush any fouling materials accumulated on membrane surface. This process can be carried out in two different operation modes either by online and reducing first and second recoveries below 20% or with plant shutdown and utilizing booster pump. Inter stage bypass valve is employed to control second stage feed flow rate as required and also can assist in flushing first stage. Operation and performance parameters were monitored before, after and during flushing. In addition, during flushing SDI values were monitored for pretreated seawater inlet and outlet. Also, biological analyses for brine were determined before flushing and after three days from flushing date.

3. Results and discussion

3.1. Investigation and selection of optimum NF arrangements

3.1.1. Preliminary tests of one-stage NF arrangements

Fig. 2 and Table 1 show the effect of increasing number of NF membrane elements on the performance of single-stage NF process including membrane hydraulic performance, operation and performance parameters. Increasing number of NF membrane elements led to a sharp decrease in feed pressure accompanied by different effects on the performance of NF process as per the following:

(a) Feed pressure and energy consumption – At 65% recovery and feed flow of 8 m^3/h the highest operating pressure was 24.8 bar for 4-elements array (case# 1) which dropped to 17.6 and 14.8 bar with 6- and 8-element arrays respectively(case# 2 and case# 3). There was a decrease in operating feed pressure by about 10 bar due to increasing number of NF elements from 4 to 8 elements. The trial was repeated for 6- and 8-elements arrays with high feed flow rate of 10 m^3/h at 65% recovery. It was noticed that 8-elements array in both cases of 8 and 10 m^3/h feed flow rates showed the lowest feed pressures of 14.8 and 16.9 bar compared to 6-elements array of 17.6 and 20.1 bar respectively. Consequently, under the same operating conditions the energy consumption were 1.17, 0.9 and 0.79 kWh/m^3 for 4-, 6- and 8-elements arrays respectively. Also, it was observed that 8-elements array with feed flow rates of 8 and 10 m^3/h at 65% recovery showed the lowest energy consumption of 0.79 and 0.87 kWh/m^3 compared to 6-elements array of 0.90 and 1.0 kWh/m^3 respectively.

From Table 1, it was noticed that feed flow and productivity of 8-elements array (case# 4) increased by 25% compared to 6-elements array (case# 2) with no increase in feed pressure or energy consumption which showed the lowest values.

Energy consumption was calculated from the following equation:

$$\text{Energy } (kWh/m^3) = [Q_f \,.\, H_f \,\rho \;/\; 366\, Q_p.e]$$

where Q_f and Q_p the feed and product quantities in terms of m^3/h; H_f the pressure head in meter; ρ density of seawater (1.03); and e the pump efficiency normally about 0.85.

Also as shown in Fig. 2 and Table 1, TDS rejection following the same trend of feed pressure and decreased by increasing number of NF elements. TDS rejections by 4-, 6- and 8-elements arrays under the same operating conditions (65% recovery, 8 m^3/h feed flow and 28 ± 0.3°C feed temp.) were 31.1, 27.1 and 25% while their permeates conductivities were 48230, 50890 and 52120 µS/cm corresponding to TDS of 31350, 32890 and 33882 mg/l respectively.

In addition permeate conductivity of 8-elements array was significantly improved and dropped to 50780 µS/cm (33085 mg/l TDS) by increasing feed flow rate to 10 m^3/h corresponding to an increase in TDS rejection from 25 to 27.3%.

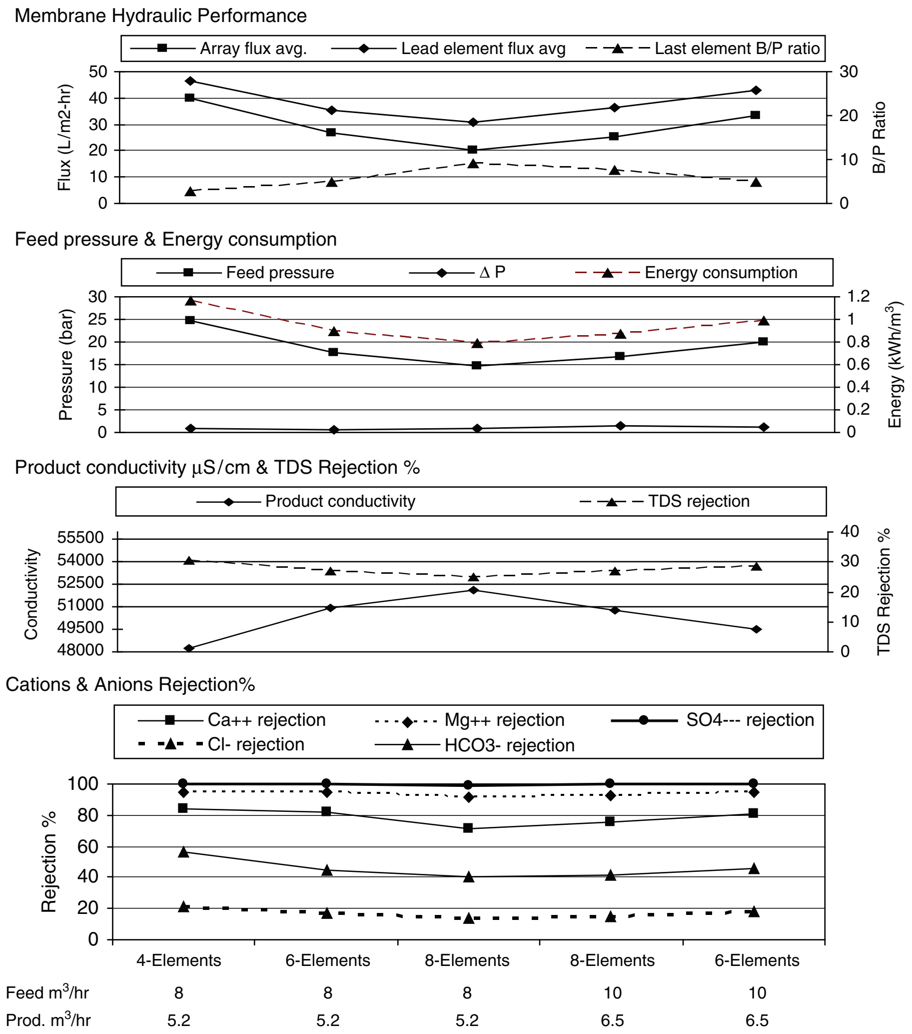

Fig. 2. The effect of increasing number of membrane elements on the performance of single-stage NF process at 65% recovery, feed flow rates of 8 and 10 m^3/h, feed temp. 28 ± 0.3°C and feed TDS of 45000–46000 mg/l.

Table 1
Operation and performance parameters of different arrays of single-stage NF process at constant operating conditions (65% recovery, feed temp. 28 ± 0.°C and feed TDS 45000–46000 mg/l)

Different arrays of single-stage NF process					Operation and performance parameters
Case# 5	Case# 4	Case# 3	Case# 2	Case# 1	
6	8	8	6	4	NF elements/array
10.03	10.05	8.05	8.05	7.97	Feed m^3/h
6.53	6.59	5.28	5.26	5.18	Permeate m^3/h
20.1	16.9	14.8	17.6	24.8	Feed pressure bar
1.03	1	1	0.69	0.7	ΔP bar
1	0.87	0.79	0.90	1.17	Energy Consumption kWh/m^3
32181	33085	33882	32890	31350	Permeate TDS mg/l
29.3	27.3	25	27.1	31.1	TDS rejection%
33.5	25.3	20.3	26.7	39.8	Array flux average l/m^2-h
45.5	37.8	30.9	37.2	46.6	Lead element flux l/m^2-h
15.5%	12%	12.5	15%	18.8	Lead element recovery%
4.9	7.5	9.1	5	2.6	Last element B/P ratio

(b) Membrane hydraulic performance - At 65% recovery and feed flow of 8 m^3/h, 4-elements array exhibited the highest values for both lead element flux average and lead element recovery% which were 46.6 l/m^2-h and 18.8% compared to nominal NF membrane performance of 38.7 l/m^2-h and 15% respectively. Lead element of 6-elements array showed values of 37.2 l/m^2-h and 15% recovery which were within nominal NF membrane performance. Whereas 8-elements array lead element showed the lowest values of 30.9 l/m^2-h and 12.5% recovery respectively indicating that feed flow could be increased from 8 to 10 m^3/h without any stress in lead element. Therefore, another trial was carried at 65% recovery with high feed flow of 10 m^3/h (case# 4 and case# 5) where 6-elements array showed higher values for both lead element flux average (45.5 l/m^2-h) and recovery (15.5%) compared to nominal NF membrane performance. Whereas lead element of 8-elements array exhibited values of 37.8 l/m^2-h and 12% recovery compared to nominal NF membrane performance of 38.7 l/m^2-h and 15% respectively. Also, last element B/P (Brine/ Product) ratio for 8-elements array showed significant improvement and increased to 7.5 compared to 6-elements array of 4.9. The key advantages of 8-elements array over 6-elements array is mainly due to increasing NF elements from 6 to 8-elements. That led to a decrease in both feed pressure and lead element recovery% which resulted in increasing feed flow and productivity by 25% without increasing energy consumption coupled with better membrane hydraulic performance and also without affecting permeate quality as seen in Table 1. In addition, case# 5 and case# 2 represent the first and second operation modes which applied commercially in Umm-Lujj SWRO plant. Initially, operation parameters of case# 5 were adopted and that led to higher membrane fouling coupled with repeated chemical cleaning. Later on Umm-Lujj NF plant was operated according to operation parameters of case# 2 by increasing number of pressure vessels and reducing feed flow rate/vessel from 10 to 8 m^3/h which resulted in a steady operation with lower fouling propensity.

(c) Comparison between 6-elements array which applied commercially in Umm-Lujj SWRO plant and 8- elements array - Based on the encouraging results which obtained from 8-elements array as seen in Table 1, additional investigation was carried out to confirm the same and presented in Fig. 3. Trial showed the individual performance of each two NF elements in 6-elements array (simulating two different operation modes of commercial NF plant) and 8-elements array. First operation mode exhibited high fouling propensity for the first two lead elements due to increasing its flux average up to 43.2 l/m^2-h compared to nominal NF membrane performance of 38.7 l/m^2-h coupled with higher individual

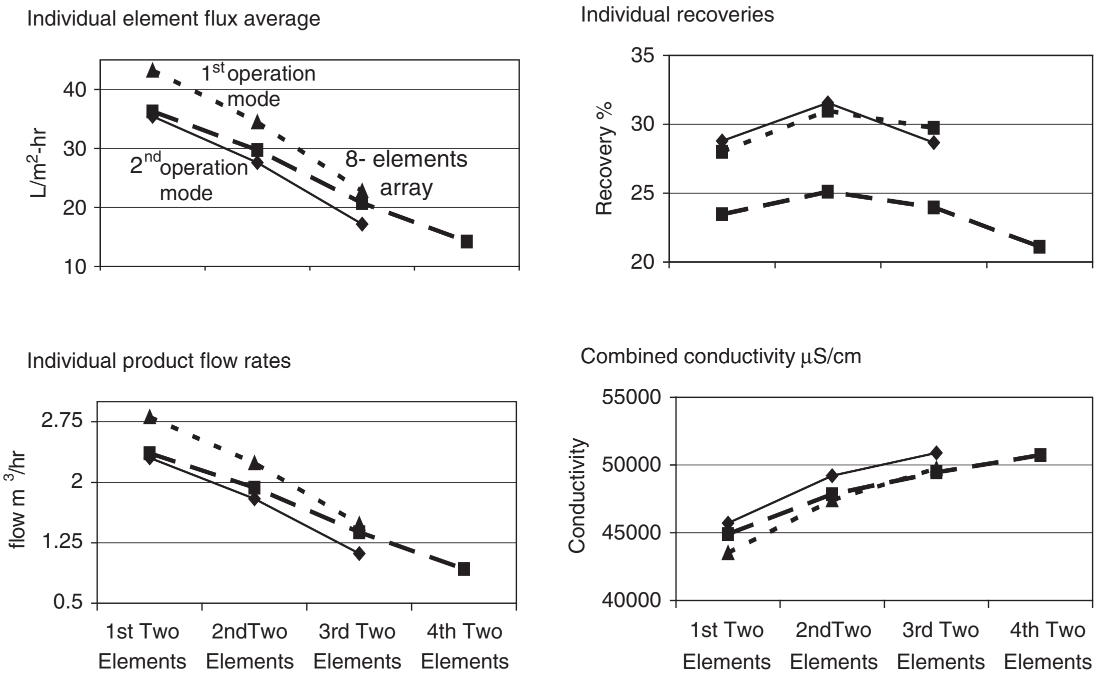

Fig. 3. Comparison between individual performance of each two elements in 6-elements array simulating two different operation modes of Umm-Lujj NF Plant and 8-elements array at 65% recovery.

recoveries of 28–31% and also lower B/P ratio for last element of 4.9. Whereas, second operation mode showed a decrease in the first two lead element flux average up to 35.4 l/m^2-h but still with same individual recoveries and last element B/P ratio.

On the other hand, although 8-elements array optimized with high feed flow rate of 10 m^3/h but showed the same trend of second operation mode of 8 m^3/h feed flow in terms of first two lead element flux average and individual product flow rates as shown in Fig. 3 with additional advantages. These advantages included lower individual recoveries of 21–23.5% and higher B/P ratio for last element which improved and increased significantly up to 7.5 as shown in Table 1 ensuring better membrane performance. Moreover, the trend of combined permeate conductivities, TDS rejection and permeate TDS for 8-elements array were approximately similar to the second operation mode as seen in Table 1 and Fig. 3. Accordingly, this trial again confirmed that 8-elements array exhibited the best performance compared to two different operation modes which was applied commercially in Umm-Lujj NF plant.

3.1.2. Preliminary tests of two-stage NF arrangements

Actually, NF seawater pretreatment deals with pretreated seawater having high TDS, high hardness content and also very fine turbidity and residual bacteria which can be accumulated on membrane surface with time. Moreover, NF process as pretreatment should be optimized at higher recoveries for cost effectiveness of NF permeate production and that would result in high brine concentration accompanied by the negative effects of concentration polarization. Therefore, this part of investigation aimed at optimizing operation and performance parameters of two-stage NF process at the maximum possible recovery with lower feed pressures. Therefore, 12-, 14-, 16-, 18- and 20-elements arrays were operated at constant operating conditions for accurate comparison and realistic values (75% recovery, feed flow rate of 16 m^3/h , feed temperature of 28 ± 0.3°C, and 45000–46000 mg/l feed TDS), taking into consideration that the recommended recovery for 1st stage NF process of 6 or 4 NF elements should not exceed 65% and 50% recovery respectively based on the results of single-stage trials. Operation and performance parameters of previously mentioned arrays are given in Fig. 4 and Table 2.

Similar to single-stage NF process, as the number of NF elements was increased from 12 to 20 elements, feed pressure decreased from 22.7 to 16.6 bar while ΔP increased from 1.5 to 3 bar. Energy consumption decreased from 0.91 to 0.74 kWh/m^3. TDS rejection also followed the same trend of feed pressure and decreased form 27.8 to 23.7%. Accordingly, 12-, 14- and 16-elements arrays showed the lowest permeates conductivities which ranged between 50400 and 51500 µS/cm (32778–33670 mg/l TDS) while 18- and 20-elements arrays exhibited the highest conductivity values of 52800 and 53100 µS/cm (34370 and 34710 mg/l TDS) respectively. Operation of 12-elements array at 75% recovery indicated that first stage was operated at high recovery of 56.5% which should not exceed 50% recovery as four elements connected in series coupled with the highest lead element recovery of 16.4% compared to nominal design value of 15%. Therefore, another trial was carried out at 72% recovery where 1st stage recovery dropped to the recommended limit of 50%, lead element recovery decreased to 13.8%, performance parameters of this trial was given in Table 3. Therefore the optimal recovery for 12-elements array was found to be 72%. Addition of two elements in second stage of 12-elements array to adopt 14-elements array resulted in significant improvement in array performance (case# 2). In comparison to 12-elements array as shown in Table 2, first stage recovery dropped from 56.5 to 51.6%, and second stage recovery increased from 45.6 to 48.5% with a decrease in both feed pressure and lead element recovery. Consequently, the optimal recovery for 14-elements array is found to be 75%.

The same result was observed for 18-elements array (case# 4). Addition of two elements in second stage to adopt 20-elements array (case# 5) resulted in a decrease in first stage recovery from 59.5 to 56%, and increase in second stage recovery from 39 to 46%. The difference between first and second stage recoveries for 20-elements array was about 10% compared to 18-elements array of 20%. Results in Table 2 indicated that 20-elements array (case # 5) exhibited the lowest values for feed pressure, lead element flux average and lead element recovery confirming that this array could achieve high recoveries up to 85%. With 20-elements array, 1st stage operated at lower recovery of 56% compared to the recommended recovery limit of 65% and also lead element flux average and its recovery showed lower values of 29 l/m^2-h and 12% compared to nominal design values of 37.8 l/m^2-h and 15% respectively. On the contrary, removal of two NF elements from the second stage of 18-elements array to adopt 16-elements array (case# 3) resulted in negative effects on the operation and performance parameters as seen in Table 2, the difference between first and second stage recoveries increased to about 30% which placing more stress on the first stage and operated at 63.3% close to the maximum recommended limit of 65% with the lowest feed flow to second stage of 5.86 m^3/h. Accordingly, there is no any safety margin to increase recovery above 75% or feed flow more than 16 m^3/h. Therefore this array was excluded from the comparison. But it is very interesting to point out that NF process is very

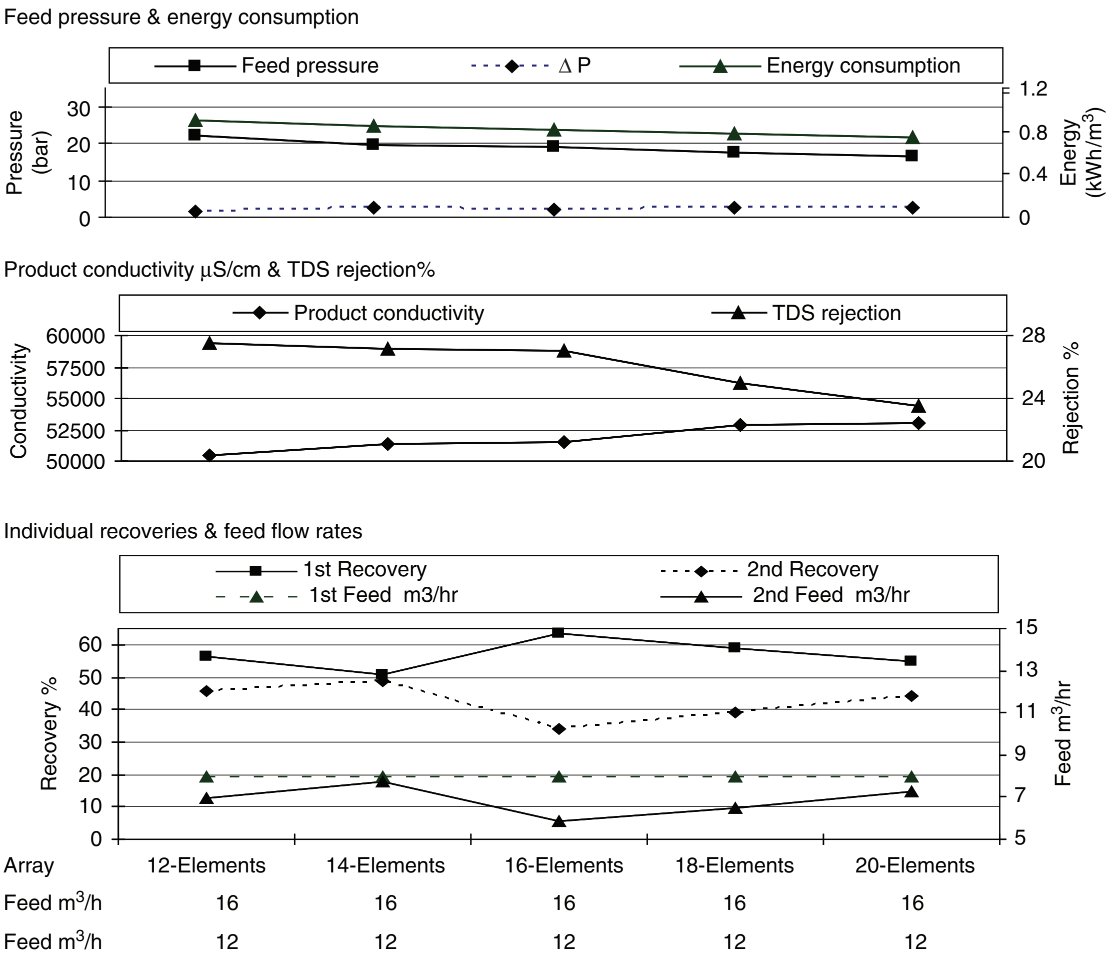

Fig. 4. The effect of increasing number of membrane elements on the performance of two-stage NF process at 75% recovery, 16 m^3/hr feed flow and feed temp. 28 ± 0.3°C.

Table 2
Operation and performance parameters of two-stage NF arrays at constant operating conditions (75% recovery, 28 ± 0.3°C feed Temp. and 45000–46000 mg/l feed TDS)

Different arrays of two-stage NF process					Operation and performance parameters
Case# 5	Case# 4	Case# 3	Case# 2	Case# 1	
20	18	16	14	12	NF elements/array
16.2	16.34	16.0	15.98	16.03	1st stage feed flow m^3/h
7.2	6.47	5.86	7.72	6.97	2nd stage feed flow m^3/h
56	59.5	63.3	51.6	56.5	1st stage recovery%
46	39	34.1	48.5	45.6	2nd stage recovery%
12.24	12.39	12.14	11.99	12.24	Permeate m^3/h
16.6	17.6	19	19.7	22.7	Feed pressure bar
3	2.4	2.2	2.5	1.52	ΔP bar
0.74	0.77	0.81	0.85	0.91	Energy consumption kWh/m^3
34710	34370	33670	33376	32778	Permeate TDS
23.7	24.5	26	26.6	27.8	TDS rejection%
18.8	21.1	23.3	26.4	31.4	Array flux average l/m^2-h
29	29.8	32.3	33.8	37.8	Lead element flux l/m^2-h
12	12.5	13.6	13.8	16.4	Lead element recovery%

Table 3
Operation and performance parameters of different NF arrays starting from 4 up to 20 elements at the recommended recovery for each NF array (Feed temp. 28 ± 0.3°C and Feed TDS 45000–46000 mg/l)

Different NF arrays							Operation and performance parameters
Two-stage NF process				Single-stage NF process			
20	18	14	12	8	6	4	NF elements/array
17	16.23	15.98	16.09	10.05	8.05	8	Feed flow m^3/h
14.45	13.02	11.99	11.6	6.59	5.26	4.02	Permeate m^3/h
85	80	75	72	65	65	50	Recovery %
19.5	19.7	19.7	21.4	16.9	17.6	18.3	Feed pressure bar
3.2	2.7	2.4	1.7	1.4	0.7	0.69	ΔP bar
0.74	0.79	0.85	0.93	0.87	0.90	1.2	Energy consumption kWh/m^3
35100	34640	33376	33150	32976	33080	32001	Permeate conductivity
22.9	23.9	26.6	27.1	27.5	27.3	29.7	TDS rejection%
22.3	22.2	26.4	29.7	25.3	26.7	30.9	Array flux average l/m^2-h
35.4	30.7	33.8	35.3	37.8	37.2	35.4	Lead element flux l/m^2-h
12.9	12.5	13.8	13.8	12.3	14.5	14.4	Lead element recovery %

sensitive towards any resistance to feed – concentrate flow, just addition or removal two elements from 2nd stage resulted in significant changes on the operation and performance parameters of two-stage NF array as seen in Table 2.

Based on these satisfying results18- and 20-elements array were tested at 80% and 85% recoveries and different feed flow rates of 16 and 17 m^3/h as shown in Table 3. The results indicated that 80% and 85% recoveries are considered the recommended limits for 18- and 20-elements arrays respectively. Although, 20-elements operated at the maximum recovery of 85% compared to 12-, 14-, and 18-elements arrays but showed the lowest feed pressure and energy consumption of 19.5 bar and 0.74 kWh/m^3 respectively. Moreover, no stress on the first stage elements which operated at 65% recovery with lower lead element flux average and recovery of 35.4 l/m^2-h and 12.9% respectively. Thus addition of two elements in the second stage of conventional arrays (12- and 18-elements) to adopt 14- and 20-element arrays offered several advantages including increasing second stage recovery and overall recovery coupled with reduction in feed pressure and energy consumption as shown in Tables 2 and 3.

3.1.3. Comparison of results for selecting the optimum NF arrangements

Fig. 5 and Table 3 showed a comparison between 7 different NF arrays starting from 4 up to 20 elements at the recommended recovery for each NF array. It is clear that the key advantages of increasing number of NF elements from 4 to 20 elements is mainly related to increasing recovery from 50% up to 85% with significant reduction in energy consumption from 1.2 to 0.74 kWh/m^3 as seen in Table 3. No increase in energy consumption occurred while switching from 75%, 80%, up to 85% recoveries and this mainly due to feed pressure increased only slightly by about 1.5 bar for each 5% increase in recovery and its effect was compensated by increasing productivity.

On the contrary as the number of NF elements was increased from 4 to 20 elements and recovery increased from 50 to 85%, TDS rejection decreased from 29.7 to 22.9% and total permeate conductivity increased from 49239 to 54000 μS/cm (32001 to 35100 mg/l TDS). Total permeate is a mixture of lead elements permeate of 46000 μS/cm and subsequent elements permeate which reached to 67000 μS/cm. The mixing ratio is affected by decreasing or increasing the number of NF elements, with 4-elements array at 50% recovery mixing ratio of first two elements to last two elements was 0.55:0.45 and both produced high quality permeate while with 20-elements array at 85% recovery ratio became 0.15:0.85 which reflected directly on TDS rejection and total permeate conductivity.

In brief, with exception of 4-elements array which was operated at low recovery of 50%, it is concluded that increasing recovery from 65 to 85% resulted in a decrease in TDS rejection from 27.3 to 22.9 and an increase in permeate conductivity from 50800 to 54000 μS/cm corresponding to increase in permeate TDS by about 2000 mg/l from 33080 to 35100 mg/l. However, this drawback was compensated by major benefits such as higher productivity, higher recovery, lower feed pressure and lower energy consumption. On the other hand all NF arrays produced high quality permeates with SDI values between 0.4 and 0.80.

Cations and anions rejections of Ca^{++}, Mg^{++}, SO_4^-, HCO_3^- and Cl^- are given in Figs. 2 and 5 and showed

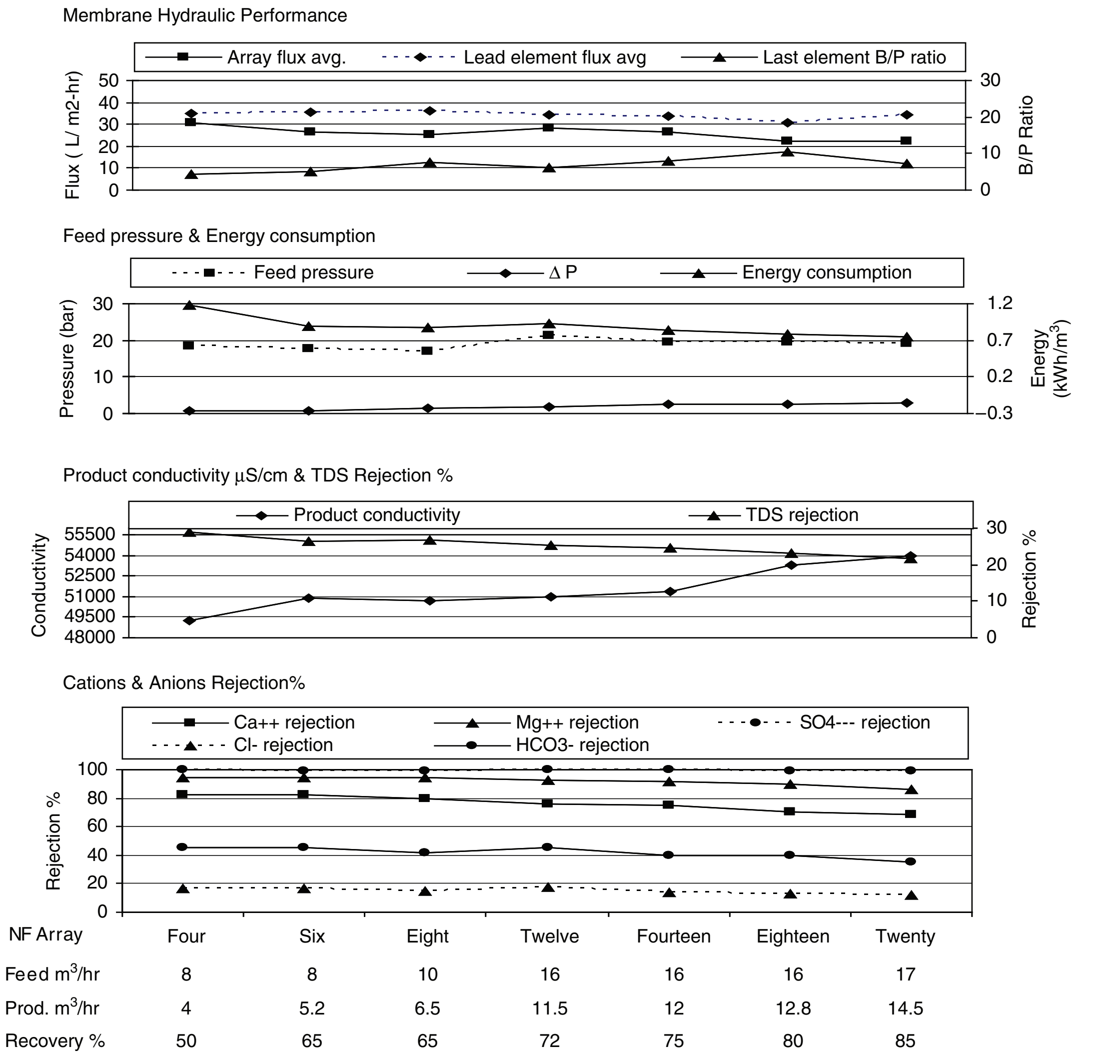

Fig. 5. Comparison between different NF arrays starting from 4 up to 20 elements at the recommended recovery for each NF array.

5 different rejection levels following mainly membrane selectivity towards different ions which affected to some extent by increasing number of elements and recovery ratio. Sulfate rejection was ≥99.3% regardless of recovery or number of elements present in NF array. Whereas, Mg^{++}, Ca^{++}, HCO_{3^-} and Cl^- rejection levels started with 94.8, 82.3, 45.1 and 16.7% at 50% recovery and decreased to 85.9, 68.8, 35 and 12.2% at 85% recovery, respectively.

Consequently, four optimum arrangements can be extracted for NF membrane seawater pretreatment process. The first one is 8-elements array which is considered the best choice for single stage NF process and operated at 65% recovery. Whereas 14-,18- and 20-elements arrays are optimal for two-stage NF process and could be operated at 75%, 80% and 85% recovery respectively. The main difference between these arrays is related to TDS rejection which dropped gradually from 27.5, 26.6 and 23.9 up to 22.9% respectively.

Also, Fig. 6 shows another comparison between three optimum NF arrangements operated at different recoveries of 65%, 75% and 85% and different feed flow rates of 8, 16 and 17 m^3/h confirming the same.

From the previous discussion it is concluded that 8-elements array at 65% recovery is found to be the best choice for single-stage NF process compared to the conventional array of six elements, its productivity and feed flow increased by 25% with no increase in feed pressure or energy consumption and also no drop in product quality coupled with better membrane hydraulic performance. Actually these results are in conformity with employing 8-elements SWRO array in Larnaca and Ashkelon SWRO plants instead of conventional 6-elements array which resulted in operating at higher

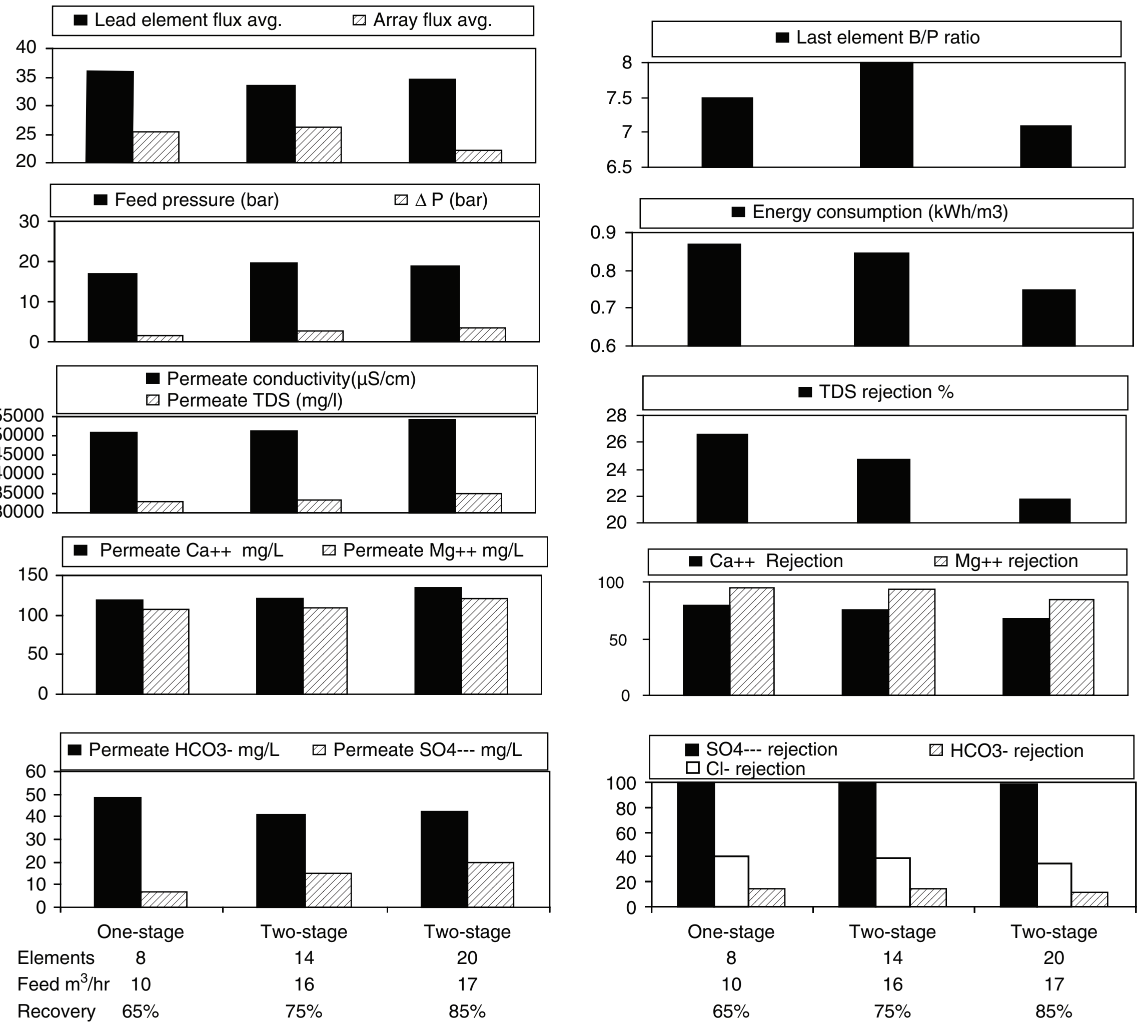

Fig. 6. Comparison between three optimum NF arrangements in seawater pretreatment at different recoveries 65%, 75% & 85% and different feed flow rates.

feed flow and recovery coupled decreased capital cost due to decreasing number of pressure vessels [17–20].

Whereas, 20-elements array is recommended for two-stage NF process and could be operated at 85% recovery with lower energy consumption. Moreover, 20-elements array gives higher flexibility and benefits to system operation such as: (1) additional reduction in capital cost could be achieved when taking the advantages of 8-elements/PV in first stage instead of 6-elements/PV to adopt 24 NF elements in 2:1 array resulting in increasing feed flow from 16 up to 20 m^3/h and productivity from 13.6 to 18 m^3/h with reduced investment cost due to decreasing number of pressure vessels as confirmed from the existing trial and 8-elements SWRO array [17–20], (2) implementation of internally staged membrane design involving a proper combination of moderate and lower rejection NF membranes for additional reduction in energy cost with better membrane hydraulics [21] and (3) no increase in energy consumption occurred while switching from 75%, 80%, up to 85% recoveries. Accordingly Life cycle cost analysis for three NF arrangements was given in Part-II of this study to estimate the real benefits due to increasing membrane elements and transition of NF process from single-stage at 65% recovery to two-stage at 90% recovery [22].

3.2. Performance evaluation of 18-elements array in long term operation

The performance test consisted of 3 phases operations: (1) Two months operation at 65% recovery, (2) Four months operation at 75% recovery and (3) Two months operation at 80% recovery. Performance evaluation started with 65% recovery which is considered as intermediate step between one- and two-stage NF processes and also expected to provide the initial guidelines

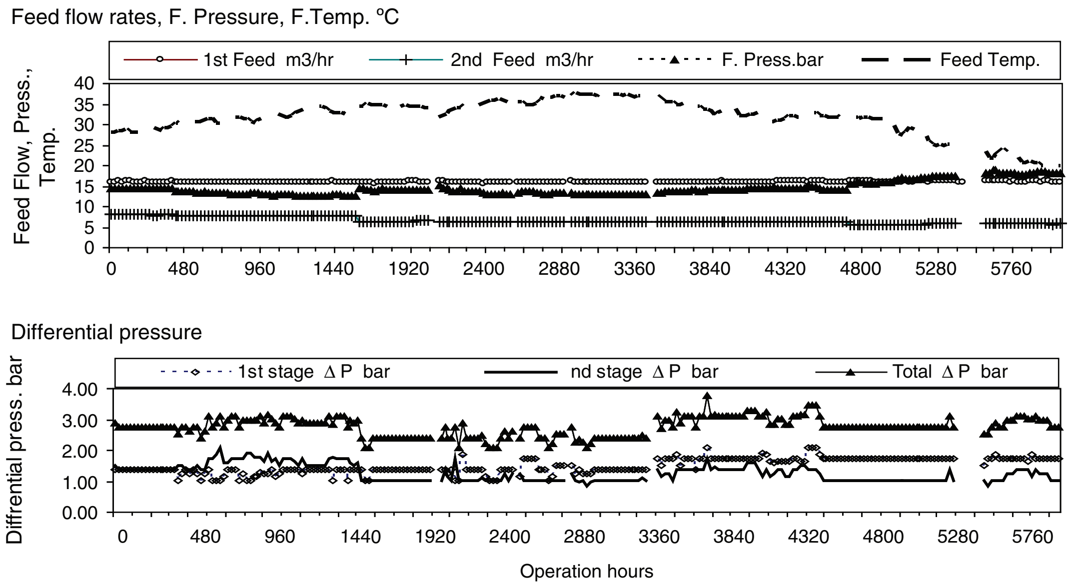

Fig. 7. Operation parameters of two-stage NF process vs. operation time.

for the higher recoveries tests. Figs. 7 and 8 show operation and performance parameters of two-stage NF process at different recoveries vs. operation time.

3.2.1. Performance evaluation of 18-elements array at 65% recovery

18-elements array was operated for 1560 h at 65% recovery and stable operation was confirmed. During this test period feed pressure showed the lowest values and ranged from 12.5 to14.5 bar corresponds to feed temperature of 28–34.8°C. Feed flow rate was maintained at about 15.9–16.1 m^3/h. Differential pressure across membranes of first and second stage were steady at 1.4 and 1.7 bar respectively while total ΔP during test period remained at about 3.1 bar. As can be seen in Fig. 8 stable membrane performance was obtained in terms of product flow rates and product recoveries. The product flow rates for first, second stage and total averaged at 8.1, 2.3 and 10.4 m^3/h corresponds to average recoveries of 50.7%, 29.7% and 65.5% while their corresponding conductivities averaged at 51700, 58500 and 53500 µS/cm respectively. Results obtained from 65% recovery test indicated that 1st stage membranes operated at 50% recovery compared to the recommended 1st stage recovery of 65% and therefore is capable to meet the requirements of higher recoveries without any trouble.

3.2.2. Performance evaluation of 18-elements array at 75% recovery

18-elements array was operated successfully at 75% recovery for 3144 h and steady operation with satisfying results was achieved. At the beginning of this trial and during changeover from 65% to 75% recovery operation and performance parameters were carefully checked to evaluate exactly the variations in feed pressure and energy consumption, productivity and permeate conductivity which were 12.76 bar, 0.72 kWh/m^3, 10.4 m^3/h and 53850 µs/cm at 65% recovery while at 75%, they were 14.48 bar, 0.72 kWh/m^3, 12 m^3/h and 54250 µs/cm respectively. Increasing recovery from 65% to 75% resulted in an increase in permeate conductivity by 400 µs/cm while energy consumption remained steady due to low increase in feed pressure by 1.72 bar and its effect was compensated by increasing productivity. During test period feed pressure varied between 13 and 15.2 bar corresponds to feed temperature of 31–37.8°C. First stage feed flow rate was maintained at average value of 15.9 ± 0.1 m^3/h whereas second stage feed flow rate was about 6.3 ± 0.1 m^3/h.

Fig. 8 represents the plots of recovery ratios and products flow rates. First stage recovery was remarkably constant with average value of 60% ± 0.5 while the average recovery for the second stage was 37% ± 1 and overall recovery was kept at 75% ± 0.3. Consequently first and second stage showed stable product flow rates of 9.6 ± 0.1 and 2.4 ± 0.1 m^3/h respectively while total product was kept at average value of 12 ± 0.1 m^3/h. In addition, average permeates conductivities for first stage, second stage and total were 52730, 60350 and 54240 µS/cm respectively. As shown in Fig. 7, during test period of 3144 h differential pressure for first stage and second stage remained steady between 1.4–1.7 and 1–1.4 bar respectively and total ΔP reached about 3.1 bar.

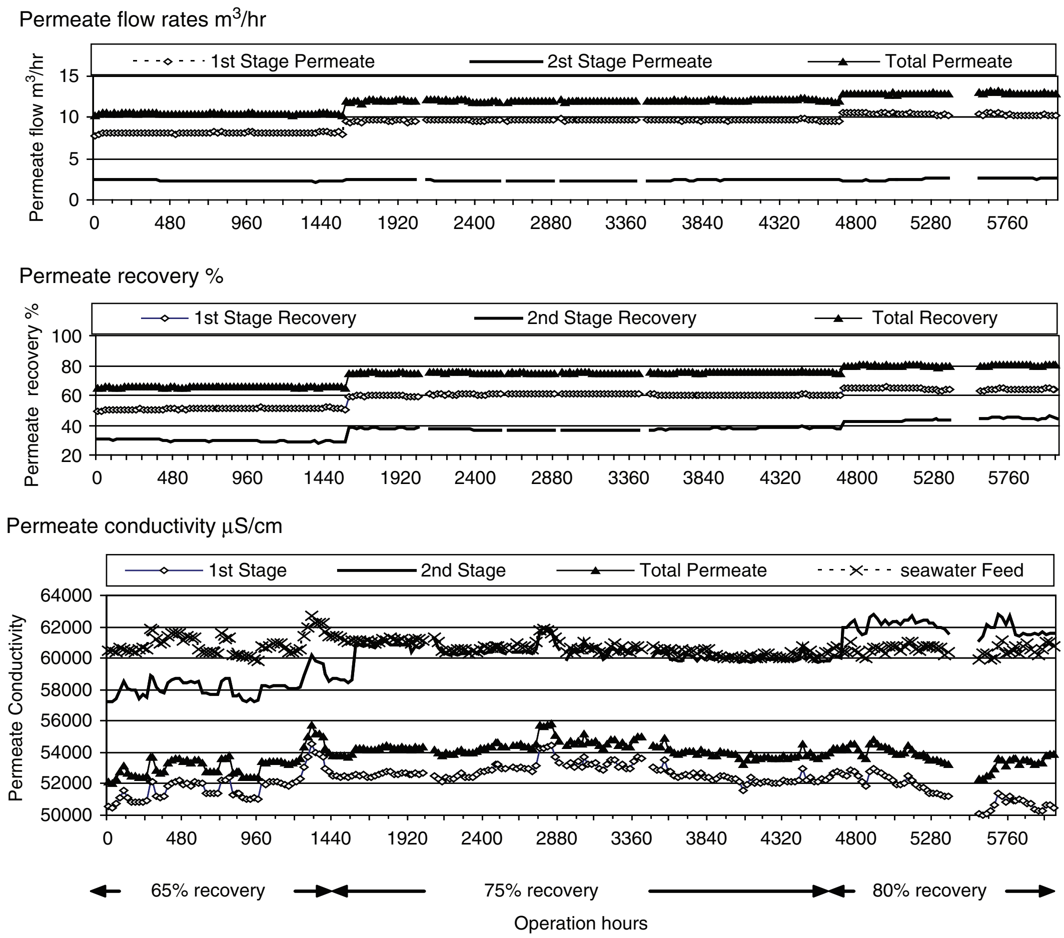

Fig. 8. Performance parameters of two-stage NF process utilizing 18 8″ × 40″ NF elements in seawater pretreatment up to 80% recovery vs. operation time.

3.2.3. Performance evaluation of 18-elements array at 80% recovery

This investigation describes performance of 18-elements array for 1344 operation hours at 80% recovery while the remaining 888 h will be presented in Part 2 of this study. Similar to 75% recovery test, switching from 75% to 80% recovery was accompanied by a slight increase in feed pressure from 14.1 to 15.5 bar and also slight increase in total permeate conductivity from 54150 to 54500 µS/cm. Moreover, no increase in energy consumption occurred which remained stable at 0.67 kWh/m^3 due to the same reason as mentioned previously. During 80% recovery test, NF membranes were exposed to a gradual decrease in feed temperature from 32 to 20.7°C due to seasonal variations. Accordingly, feed pressure increased from 15.5 to 19 bar to maintain recovery at 80%. First and second stage feed flow rates were controlled at average values of 16.2 and 5.7 m^3/h respectively.

First stage recovery was stable at average value of 64% ± 0.5 whereas the average recovery for the second stage was 43.5% ± 0.5 and overall recovery was kept at 79.5% ± 0.5. Consequently, first and second stages showed stable product flow rates of 10.4 ± 0.1 and 2.5 ± 0.1 m^3/h respectively while total product was kept at average value of 12.9 ± 0.1 m^3/h In addition, a significant improvement was observed in permeates conductivities due to a sharp decrease in feed temperature. Total permeate conductivity dropped from 54400 to 53500 µs/cm and in few occasions decreased to 52900 µs/cm due to a decrease in seawater feed conductivity which reached to about 59900 µs/cm. Permeate conductivities of first and second stages averaged 51700 and 62040 µs/cm respectively.

In addition, during the test period of 1344 h differential pressure for first stage and second stage remained steady at 1.7–1.9 and 1.0–1.2 bar respectively and total ΔP reached about 2.7–3.1 bar. Moreover, during entire operation of 6048 h differential pressure values for first and second stage were stable while total ΔP did not exceed 3.1 bar and was close to the initial value of 2.8 bar as shown in Fig. 7. To date no chemical cleaning was performed but only membrane flushing with pretreated seawater was done on monthly basis for three hours. The existing trial has been in continues operation all the time with exception of few days for maintenance activities.

On the other hand, normalization of NF performance data is not possible with the existing NF projection software programs due to two important issues: (1) the existing NF programs are designed for low salinity feeds not for seawater feed and (2) NF membranes in long term operation with seawater converted gradually from tight to loose membrane structure resulting in decreased TDS rejection along with decreased feed pressure and increased flux rate, which is completely different compared to RO membrane behavior.

Therefore based on long operational experience with NF seawater pretreatment process, lead element flux rate and recovery, operation and performance parameters as well as tools such as periodic membrane weights and membrane autopsy are used to verify sable NF process performance.

3.2.4. Permeate SDI and SDI reduction

Fig. 9 shows seawater feed SDI, permeate SDI and SDI reduction at different recoveries vs. operation time. For the first 4680 operation hours automatic filter plugging analyzer was used to measure SDI values and for the remaining 1368 h manual apparatus was used due to malfunction of automated analyzer. Automated SDI analyzer showed permeate SDI values ranged from 0.5 to 0.8 while with manual SDI analyzer lower values were obtained and varied between 0.4 and 0.6. However, high NF permeate quality was achieved all the time at different recovery ratios with 67–87% reduction in SDI values.

3.2.5. Permeate TDS and TDS rejection

During test period of 6048 operation hours TDS rejection by NF membranes was affected by many different variables including increasing recovery ratio from 65 to 80% as well as operating conditions such as feed pressure, feed temperature and feed TDS. NF membranes used in this trial has a limited TDS rejection <30% unlike RO membranes of more than 99.5% TDS rejection and therefore any slight increase or decrease in feed TDS or feed temperature reflected directly on total permeate conductivity. Results of preliminary tests indicated that conversion of NF process from single-stage of 6-elements to two-stage of 18-elements at 65% recovery resulted in an increase in total permeate conductivity by 1600 µS/cm. During operation and optimization of 18-elements array, the effect of increasing recovery from 65, 75% up to 80% on permeate conductivity was recorded when switching from one recovery test to another. Permeate conductivity increased by 400 and 350 µS/cm when recovery ratio increased to 75% and 80% respectively. Actually the effect of increasing recovery ratio on permeate conductivity was relatively insignificant compared to the effects of feed conductivity and feed temperature as can be seen from their trends in Fig. 8.

Operation at 65% recovery was accompanied by a wide range of temperature variations which ranged from 28 to 34.6°C. Accordingly, total permeate conductivity followed the same trend and showed a wide

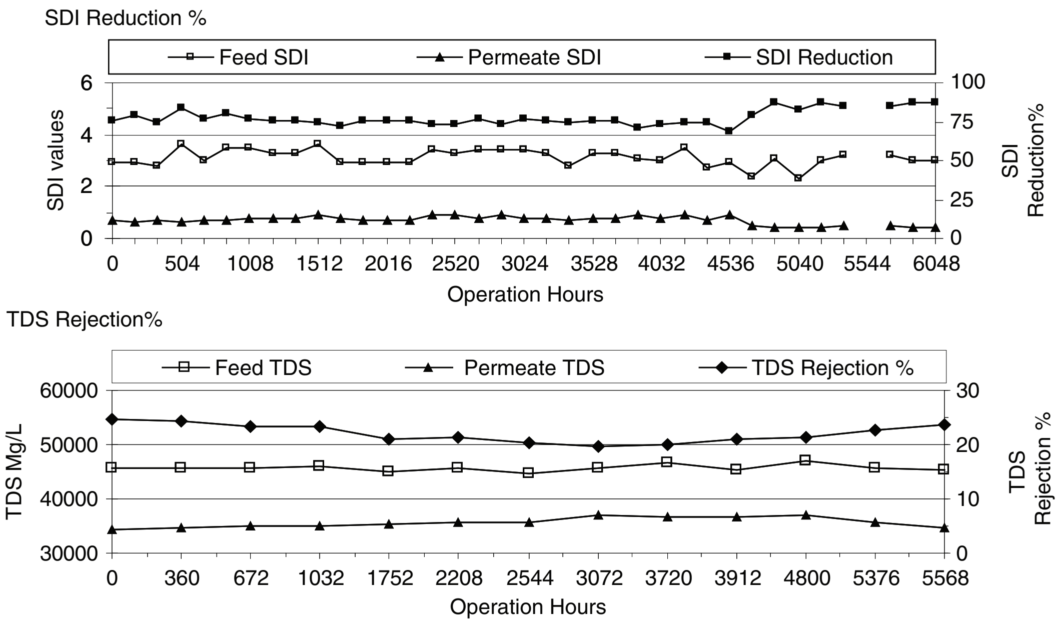

Fig. 9. SDI reduction and TDS rejection vs. operation time.

range of conductivity values which ranged from 52100 to 54200 µS/cm. Whereas at the end of 65% recovery test and within few days permeate conductivity increased by 1600 µS/cm and reached about 55750 µS/cm due to an increase in feed conductivity by the same ratio.

At 75% recovery test, feed temperature showed a narrow range of 33.2–37.5°C. Therefore permeate conductivity exhibited a narrow range of 54200–54900 µS/cm with exception of few days permeate conductivity reached about 55800 µS/cm due to an increase in feed conductivity. At 80% recovery test feed temperature showed a gradual decrease from 32 to 20.7°C. Therefore a significant improvement in permeate quality was observed and conductivity dropped gradually from 54400 to 53500 µS/cm and in few occasions reached about 52900 µS/cm due to a decrease in feed conductivity.

It is clear that total permeate conductivity affected sharply by feed temperature which followed seasonal variations. Moreover, any slight increase or decrease in feed conductivity reflected directly on permeate conductivity which increased or decreased by the same ratio.

Fig. 9 exhibits the trend of permeate TDS and TDS rejection along with seawater feed TDS versus operation time at different recovery ratios. The initial values of permeate TDS and TDS rejection at the beginning of the trial at 65% recovery were 34360 mg/l and 24.8% respectively. TDS rejection showed a decline trend which reached to about 19.7% and then improved and increased to 22.7% during 80% recovery test due to decreasing seawater temperature. The highest permeate TDS value was 37200 mg/l at the maximum feed temperature of 37.8°C.

3.2.6. Seawater ions rejection

Fig. 10 shows the effect of two-stage NF process which operated at different recoveries ratios starting from 65% up to 80% on the chemical composition of permeate as well as rejection of seawater feed ions with operation time. Chemical analysis was performed occasionally. It can be seen five different rejection levels for SO_4^-, Mg^{++}, Ca^{++}, HCO_3^- and Cl^- according to NF membrane selectivity towards different ions. Sulfate ion rejection was steady with operation time and showed a remarkable rejection level of ≥99.3% all the time although sulfate concentration in second stage feed and brine reject reached about 10200 and 17000 mg/l respectively. Consequently, the sulfate ion concentration in permeate ranged from 7.7 to 24.9 mg/l.

Rejection levels of Ca^{++}, Mg^{++}, and Cl^- were 70.0, 90.6 and 12.9% at the beginning of 65% recovery test and exhibited a decline trend with operation time and reached about 51%, 79.4% and 9% respectively due to an increase in feed temperature from 28 to 37.5°C. Whereas at the end of 80% recovery test there was improvement in rejection values which became 57.8, 84.9% and 9.3 respectively due to a decrease in feed temperature up to 20.7°C. Consequently, the concentration of Ca^{++}, Mg^{++}, and Cl^- ions in NF permeate ranged between (144–240 mg/l),

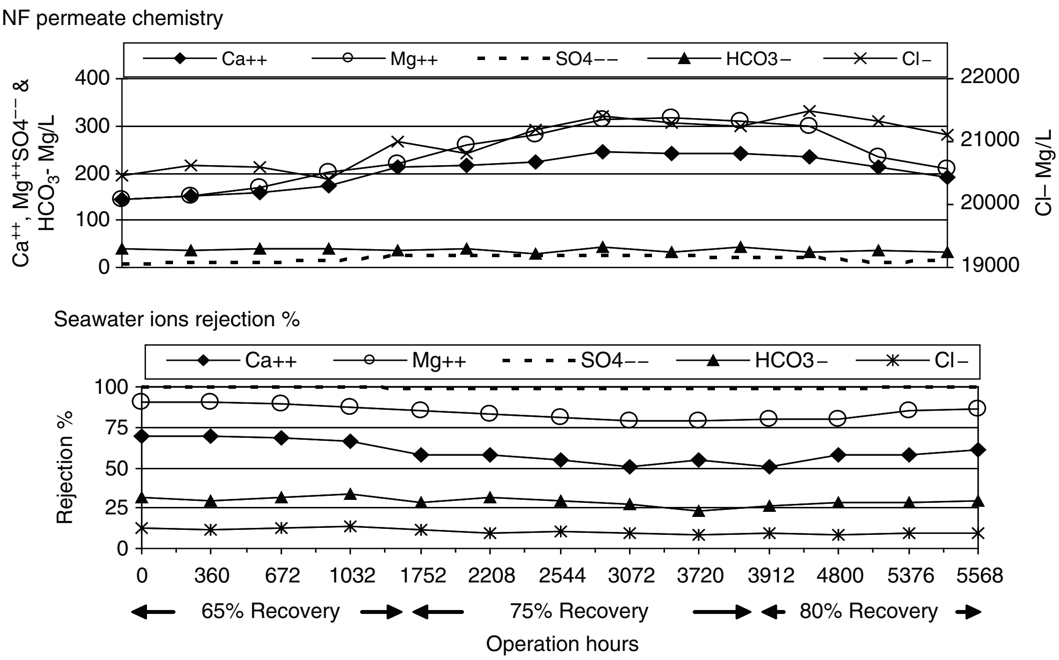

Fig. 10. NF Permeate chemistry & seawater ions rejection % vs. operation time.

(143–315 mg/l) and (20470–21292 mg/l) respectively. On the other hand bicarbonate rejection with operation time varied in a narrow range of (30.5–40%). Decline trend in rejection values of Ca^{++}, Mg^{++}, and Cl^{-} is mainly due to the effects of NF membrane performance and increasing feed temperature.

3.2.7. The effect of membrane flushing on NF process

Membrane flushing was performed on monthly basis for three hours. Operation and performance parameters were monitored before and after flushing and no variations were observed specially for feed pressure and differential pressure indicating that NF membranes in clean conditions. This is mainly due to three important factors: (1) high quality pretreated seawater, (2) optimization of process parameters under lower feed pressures, lower lead element flux average of 34 l/m^2-h, (3) regular flushing of NF membranes with pretreated seawater. The effectiveness of flushing process was evaluated by measuring SDI values for pretreated seawater inlet and outlet every 15 min during flushing. SDI values of seawater outlet for the first 30 min increased by 0.5–1 compared to seawater inlet while for the remaining 150 min no significant increase in SDI value was found. It is observed that effective flushing was obtained at the first hour and therefore it is recommended to perform membrane flushing for one hour and in short intervals. Optimization of flushing cycle and its duration is mainly dependent on pretreated seawater feed quality, operation time and recovery (%) as well as optimization of process parameters which considered crucial factor in fouling mitigation. The net outcome of all the previously mentioned factors can be observed by monitoring SDI values during flushing beside other operation and performance parameters. It was noticed that operation at 40% recovery was sufficient to flush second stage and reduce its recovery below 20% while employing inter-stage bypass valve can assist in flushing first stage and reduce its recovery. Moreover, flushing of first and second stages can be done at the same time by increasing feed flow rate. On the other hand during entire operation of 6048 h differential pressure values for first and second stage were stable while total ΔP did not exceed 3.2 bar. Also, to date no chemical cleaning was performed but only membranes flushed with pretreated seawater. It is important to point out that, during membrane flushing, quality of produced permeate was not affected and both SDI and conductivity values were within the acceptable limits of less than 1 and 54000 μS/cm respectively. Accordingly, the produced permeate can be normally used and no need to be discarded.

3.2.8. Biological analyses

The density of bacteria in non-chlorinated seawater feed before and after cartridge filter showed average values of 1.7×10^3 and 4.2×10^3 CFU/ml respectively. Bacterial counts and growth rates indicate no significant differences in the 18-elements array at recovery ratios of 65, 75 and 80%. The density of bacteria in brine without antiscalant recorded values of 2.57×10^3 and 1.23×10^4 while with antiscalant were 1.27×10^4 and 1.85×10^4 in terms of CFU/ml. The results indicated that antiscalant has no effect on bacterial growth rates. Brine bacterial counts before flushing (2.27×10^4, 1.73×10^4) was found to be slightly higher than after flushing (1.85×10^4, 2.4×10^3) indicating beneficial effect of membrane flushing. Moreover, operation of NF demonstration plant without application of disinfection did not cause any biofouling for NF membranes in conformity with earlier findings.

4. Conclusions

1. 8-elements array at 65% recovery is the best choice for single stage NF process compared to conventional array of six elements.
2. Addition of two elements in second stage of 2:1 array resulted in significant improvement in array performance with better membrane hydraulics.
3. 14-,18- and 20-elements arrays are optimal for two-stage NF process and could be operated at 75%, 80% and 85% recovery respectively.
4. Increasing NF product recovery from 65 to 85% results in an increase in NF permeate TDS by 2000 mg/l which was compensated by major benefits including higher productivity, higher recovery, operating with minimum feed pressure and energy consumption.
5. There is no increase in energy consumption occurred while increasing recovery from 65%, 75% up to 80%. This is one of main advantages of long NF array which allowed for obtaininIg higher recoveries with only slight increase in operating feed pressure.
6. NF product quality affected sharply by feed temperature and following seasonal variations. Moreover, any slight increase or decrease in feed conductivity reflected directly on permeate conductivity which increased or decreased by the same ratio.
7. Cations and anions rejections of Ca^{++}, Mg^{++}, SO_4^{-}, HCO_3^{-} and Cl^{-} by NF membranes showed 5 different rejection levels following mainly membrane selectivity towards different ions which affected by some extent by increasing number of elements, recovery ratio and operation time with exception of sulfate rejection which exhibited steady rejection of 99% in all cases.
8. Successful long term performance of 6048 h was achieved for 18-elements array up to 80% recovery with lower feed pressures (12–19 bar). High quality permeate was obtained all the time with SDI values ranged between 0.4 and 0.8.

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