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# Characterization of reverse osmosis and nanofiltration membranes: effects of operating conditions and specific ion rejection

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## ABSTRACT

Reverse osmosis (RO) and nanofiltration (NF) are two of the most commonly used technologies for desalinating brackish and saline waters to provide potable water. However, there is still lack of a thorough comparison between these two methods providing the better option in different conditions. Therefore, in this paper, salt rejection and the effects of operation conditions on the performance of RO and NF systems are compared. Inlet water conductivity, inlet pH, permeate flow rate, temperature, and recovery rate are used as variable operating conditions, and permeate conductivity is considered as the target of comparison as it reflects the level of salts in product water. Five combinations of inland brackish water, drawn from wells located at the experimental site, were applied as different feed waters and five distinct types of membranes, three RO and two NF, were studied using pilot-scale equipment. To allow meaningful comparison among RO and NF membrane performances, identical hydrodynamic operating conditions and feed water chemistries were employed during tests. In both systems, negative rejection occurred for specific ions. The results suggest that the performances of RO and NF membranes (i.e. the amount of total dissolved salts remaining in produced water) are quite different. Based on the experimental data, new insights can be reached regarding the best choice of membrane, based on the minimization of electrical conductivity and the ability to reject specific ions in different operating conditions.

*Keywords:* Desalination; Water treatment; Membrane; Reverse osmosis; Nanofiltration; Characterization

## 1. Introduction

Half of the world's population, spread across 88 developing countries, can be affected severely by water scarcity. Poor water quality causes 80–90% of all diseases and 30% of all deaths in such countries [1]. As a result, governments all over the world are beginning to pay special attention to the crisis of water shortage, which is projected to worsen significantly as a result of population growth, pollution, and increased industrialization. Freshwater supplies constitute only about 2.5% of the water on earth, but earth's vast saltwater sources, including oceans and brackish waters, can be desalinated to produce usable freshwater [2].

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Membrane-based desalination processes are widely considered to be promising solutions for augmenting water supplies and alleviating water scarcity. In inland desalination plants, which mainly draw on brackish water sources, the most common water quality problems are caused by suspended solids and hardness [3,4]. Both problems respond to inexpensive treatment methods.

At present, one of the most effective and robust technologies for desalinating brackish and saline waters to provide drinking water is (reverse osmosis) RO. RO systems typically use less energy than thermal distillation, leading to a reduction in overall desalination costs, and allowing new brackish groundwater desalination facilities to use RO technology much more economically than distillation technologies. As a result, about 70% of the desalination plants in the United States use RO systems [5,6]. However, RO uses an average of 4 kW prime (electric) energy to produce one cubic meter of product water [7,8], which results in emissions of 1.8 kg $CO_2$ per cubic meter of product water [9]. In addition, fouling is inevitable in RO systems; the filters clog and require cleaning with chemical agents, increasing the cost of producing freshwater with RO systems [10–13].

One membrane-based process shows a great interest as RO is NF, a technology in which there has been growing interest in recent years. Based on recent studies, NF could be of strategic importance in several applications where RO has dominated for several decades [14,15]—for instance, in the removal of hardness ($CaCO_3$, $MgCO_3$), and natural organic matter, and as pretreatment (usually for seawater distillation or in a zero-liquid discharge process). NF membranes' advantages in these areas come from their larger pore sizes, which result in a higher permeability for monovalent ions such as sodium, potassium, and chloride. This higher permeability, in turn, gives NF systems a lower driving pressure, lower cost, and higher flow rate than RO. However, NF produces lower quality water than RO [6,16,17]. Therefore, there is an interest in knowing which technology gives superior performance in particular applications.

To date, although there are many valuable research in the area of membranes, no work has been done to directly compare RO and NF performance under identical physicochemical conditions in order to develop a wide approach that considers various aspects, compares different methods, arrives at optimum conditions for RO/NF processes, and recommends the best choice of membrane in each case. A comprehensive table that details the best membrane choice for specific conditions could reduce the costs of treatment plants, saving time, effort, and energy. Additionally, most of the works in this area have been done using lab-scale experiments, while the industrial use of these types of membranes needs the results and conclusions of full-scale experiments to make sure that the test conditions were very close to those of real plants.

Hence, the objective of this study was to systematically compare the product water from RO and NF pilot systems using real brackish water with various chemistries and commercial membranes. To accomplish this goal, identical hydrodynamic operating conditions and feed water chemistries were employed for both systems, and the effects of inlet water conductivity, inlet pH, inlet flow rate, temperature, and recovery were studied. The salt rejection from each set of membranes was also calculated. Observations provide new insights into the best choice of membranes for different operating conditions, based on the factors of minimized electrical conductance and the ability to reject specific ions.

## 2. Materials and methods

### 2.1. Operating parameters

To accomplish the experiment design, three different levels were considered for input parameters: the lowest possible value and the highest acceptable value as well as one center point closely reflecting the average of low and high levels. Since the experimental setup was pilot scale, the single center point was used to check the validity of results from low and high levels. Inlet water conductivity 1,700–6,500 μS/cm equivalent to total dissolved solids of 1,240–6,674 mg/L, inlet pH 5–8, permeate flow rate 2.7–5.5 $m^3/h$, temperature 15.6–37.8℃, and recovery rate 70–80% were used as input or variable operating conditions, and permeate conductivity was considered as the target of comparison as it reflects the level of salts in product water. In each test, input parameters were defined for the experiment and set to the equipment. All other operating conditions were recorded. The experimental design was based on a factorial design with one middle point, which resulted in eight high and eight low levels for each parameter, including interactions. The order of the 17 tests was randomized to raise the level of quality assurance. The same set of 17 tests was run for each set of membranes and for each feedwater type.

### 2.2. Membrane elements

Five different sets of hollow fiber membranes, two of which were NF and three of which were RO, were used in the experiments. The two NF membranes were: (1) industrial high-rejection nanofiltration elements (DK series), with an approximate molecular weight cut-off of 150–300 Dalton for uncharged organic molecules, an active area of 98 $ft^2$, and fiberglass outer wrap and (2) the water-softening NF elements (HL series), with an approximate molecular weight cut-off of 150–300 Daltons for uncharged organic molecules, an active area of 89 $ft^2$, and fiberglass outer wrap. The three RO membranes were: (1) the low energy brackish water RO elements (AK series), with an operating pressure of 100 psi (689 kPa), an active area of 85 $ft^2$, and fiberglass outer wrap, (2) the extreme low pressure brackish water RO elements (AP series), with a typical operating pressure of 70 psi (483 kPa), a feed channel spacer of 34 mil (0.86 mm) thick, an active area of 80 $ft^2$, and fiberglass outer wrap, and (3) the Standard Brackish Water RO Elements (AG series), with an operating pressure of 200 psi (1,379 kPa), an active area of 90 $ft^2$, and fiberglass outer wrap. All of the membranes, both RO and NF, were brand new and were manufactured by and purchased from General Electric (GE) Company [18]. Use of commercial membranes helped the results of this study being more reliable for industry.

### 2.3. Source waters

The experiment drew on a total of five different brackish waters as feed. Two of the feedwaters came directly from wells at the the US Bureau of Reclamation's (Reclamation) Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, NM, where the experiments were conducted, and three of the feedwaters were made by modifying the water from the two chosen wells.

There are four different wells available at the BGNDRF, and each of these four well waters has a specific water chemistry that affects their characteristics such as pH and TDS, resulting in different conductivities. The wells chosen for the first two feedwater sources were Well 1 and Well 2, which have considerably different ion concentrations. The remaining feedwater sources were derived from the waters of Well 1 and Well 2: the third feedwater source, "Well 1 Warm", was the same as Well 1, but was raised to a much higher temperature; the fourth feedwater source, "Salt Added Well 1", was made by adding significant amounts of sodium chloride to the water from Well 1, resulting in higher conductivity and providing more data points to study the effect of inlet water conductivity on product water; and the fifth and final feedwater source, "Blend", was a 50–50 mix of Well 1 and Well 2 [18]. Baseline water quality analyses for Well 1 and Well 2, as reported by Reclamation, are listed in Table 1.

### 2.4. Antiscalant

To prevent the precipitation of low-solubility salts, GE's Hypersperse MDC-706 antiscalant was added to the system (feedwater) at the recommended concentration. Hypersperse MDC-706 is a proprietary blend targeting calcium sulfate scaling, and its ingredients are listed in Table 2.

### 2.5. Pilot plant equipment

As mentioned earlier, this research utilized pilot plant experiments. The RO/NF pilot that was used located at bay #5 of a the central research building at BGNDRF. At the facility, well water was first pumped from the aquifer to a large outside storage tank, and then to a smaller hydrostatic tank which pressurized the water to 350 kPa before it entered the facility. The source water then entered the pretreatment system, a multimedia filter (MMF), which reduced the level of suspended solids (turbidity, or small particles such as silt, clay, grit, organic matter, algae, and other microorganisms) in incoming feedwater. Although groundwater sources are typically free of organic and/or suspended turbidity particles [19], the MMF was added as precautionary measure to ensure that experimental results were not compromised by possible unexpected contaminants from the BGNDRF well waters [16,18,20]. After the multimedia filtration, the water was fed to the system, where it was chemically treated to meet the operating conditions for each test. There were five chemical pumps at the back of the equipment. One of them, which was always turned on, was used to add antiscalant to the system. The other four pumps were used to add hydrochloric acid, bisulfate, chlorine, and sodium chloride to the feedwater as needed (the pumps were turned on or off based on the desired operating conditions for each test). After chemicals were added to the feedwater, it was named as the inlet stream and was fed to the membranes. The inlet passed through two 5-μm cartridge filters that protected the membranes from fine suspended particles, particularly iron ($Fe^{2+}$). The filters also prevented the possible oxidation of the phosphonate antiscalant [16]. After leaving this stage, the inlet stream entered a positive displacement pump, which pumped the feedwater to the first set of pressure vessels. There were six pressure vessels divided into four sets; set one contained vessels number 1 and 2, set two contained vessels 3 and 4, set three was number 5

Table 1
Well water report

| Source | Conductivity ($\mu$S/cm) | $Ca^{2+}$ (mg/L) | $Mg^{2+}$ (mg/L) | $Na^{+}$ (mg/L) | $Cl^{-}$ (mg/L) | $SO_4^{2-}$ (mg/L) | $HCO_3^{-}$ (mg/L) | $SiO_2$ (mg/L) | SI ($CaSO_4$) |
|---|---|---|---|---|---|---|---|---|---|
| Well 1 | 1,700 | 57 | 15 | 342 | 36 | 650 | 182 | 27 | 0.07 |
| Well 2 | 5,800 | 544 | 357 | 835 | 550 | 3,229 | 297 | 22 | 0.96 |

Table 2
Hypersperse MDC-706 ingredients

| Name | CAS | Proportion (%) |
|---|---|---|
| Potassium hydroxide | 1,310-58-3 | 1–5 |
| Organic derivative of phosphoric acid, HDTMP | 38,820-59-6 | 20–40 |
| Water | 7,732-18-5 | 50–70 |

and set four was number 6. Each pressure vessel was holding three membrane elements inside. The total concentrate coming out of the first set was routed as a feed to the pressure vessels of the second set. The concentrate from set two was collected and fed to the fifth membrane, and finally the retentate stream of vessel number five was routed to vessel 6 as feed. The concentrate leaving the last membrane element housing flowed to the concentrate outlet. The permeate stream also left each of the housings, and was collected into a common manifold. Both permeate and concentrate streams flowed through the flow meter and the conductivity analyzer before they exited the experimental setup. The detailed process flow is shown in Fig. 1.

## 3. Results and discussion

### 3.1. Effects of operating conditions

Using SAS programming, the data were analyzed for the effect of different operating conditions on the quality of produced water. The Shapiro–Wilk test was used to investigate the normality of the data, and correlations between independent parameters (not including covariated parameters), were identified through the use of regression analysis. While the data from all the experiments did not lead to a definitive regression relation between input factors and permeate conductivity, it did acquire the coefficients for each parameter that affects the product water conductivity.

The experimental results showed that inlet conductivity and primary pressure are the two most important parameters that have great influences on the performance of both RO and NF systems. Inlet conductivity was the primary factor, and although its coefficient was not especially high, inlet conductivity always showed an influence. Primary pressure was a secondary factor: any increase in the primary pressure resulted in decreases in the permeate conductivity, which implied lower amount of salts in produced water. Although this effect was observed for both RO and NF membranes, the same pressure increase led to greater results for the NF membranes than it did for the RO membranes. Therefore, if lower pressure is desirable in an operation, it would be better to use NF membranes and obtain the same results as using RO with higher pressure.

Another impactful factor was pH, which changes the equilibrium of weak acids. If equilibrium is shifted toward charged species, then these components of the weak acid will be retained in the concentrate, while uncharged components go through the membrane with the water molecules and then re-establish equilibrium in the permeate. Interestingly, despite the fact that hypothetical regressions posit a high coefficient between pH and permeate conductivity, pH showed only slight effects in comparison with the first two parameters. Nevertheless, pH was inversely related to product TDS, and higher pH resulted in lower ion concentration in the product stream, which is a desirable effect.

Permeate conductivity was also affected by the recovery rate, which was defined as the percentage volume of feedwater that is produced as a freshwater. For both RO and NF systems, as the recovery rate increased, the permeate stream had an increased conductivity as well. However, greater influence of recovery rate is observed on RO compared to NF.

Temperature was tested and analyzed differently than the other factors. To identify the impact of temperature, experiments with Well 1 Warm water were conducted under the same operating conditions as

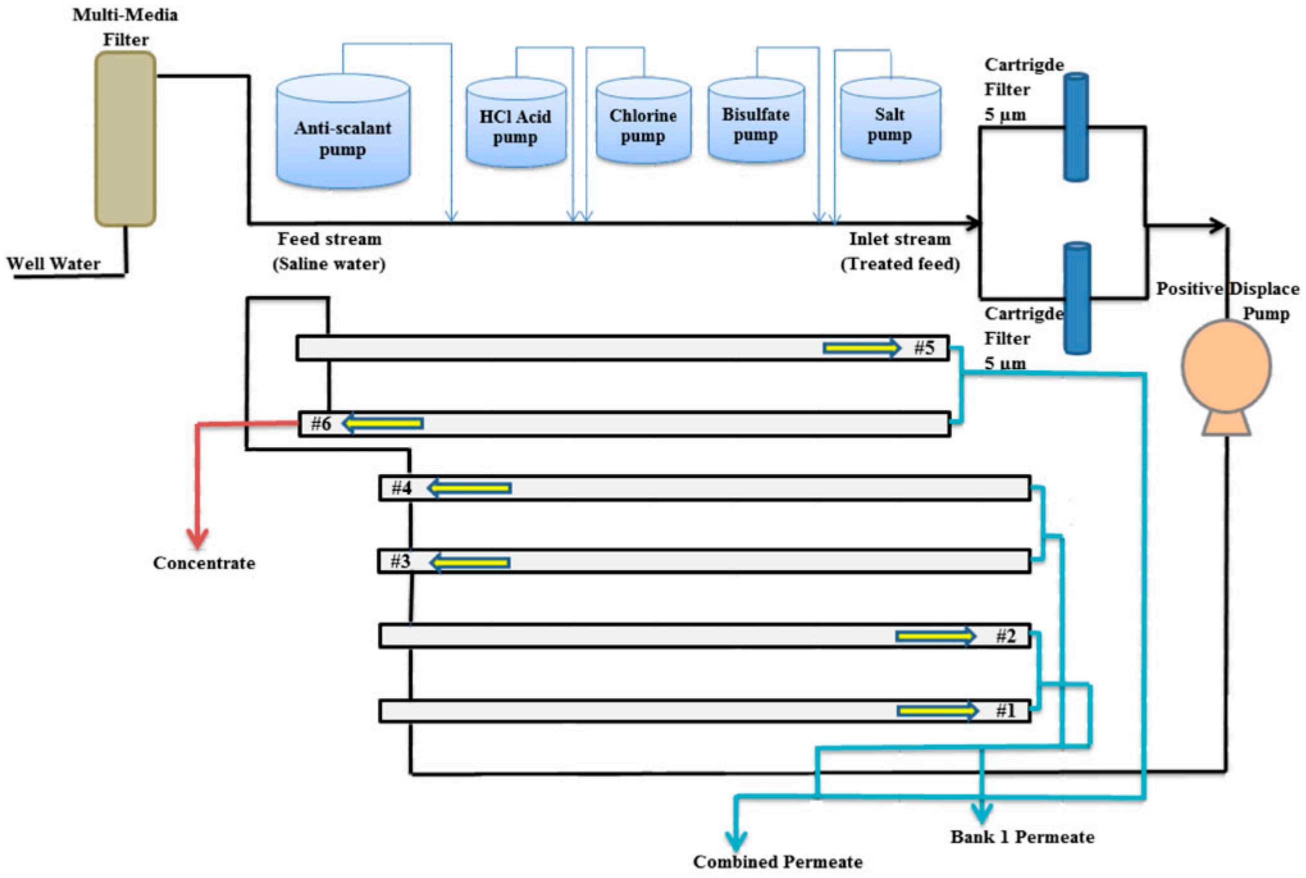

Fig. 1. Process flow diagram of RO/NF pilot plant equipment [18].

Well 1 Cold (with the exception of higher temperature). The highest temperature that been used for the experiments was 100°F, which was not too high to affect the viscosity of water or to soften the membrane polymers. Therefore, there was no need to use any correction factor and normalization of data. Similar to inlet conductivity and recovery, temperature increase had an aggregative effect on permeate conductivity in both RO and NF systems, but the average temperature ratio for NF membranes was lower than that of RO membranes, meaning that temperature affected the operation of RO membranes more than it affected NF membranes.

As expected, the statistical analysis with SAS programming identified a significant degree of covariance between flow rate and primary pressure. This means that higher flow rates increased the primary pressure; therefore, increasing the flow rate will have the same effect on the output as increasing the primary pressure. Hence, increases in the flow rate will result in lower system performance, and higher permeate conductivity. Since flow rate and primary pressure have high covariance, the impact of flow rate can be omitted. This covariance is explained by Bernoulli’s equation (Eq. (1)):

Table 3
Effect of operating factors on the product of RO/NF

| Input parameters | Ave. coefficient in RO | Ave. coefficient in NF | Change in parameter | Permeate conductivity |
|---|---|---|---|---|
| Inlet conductivity | 0.15 | 0.99 | ↑ | ↑ |
| Primary pressure | −1.33 | −1.80 | ↑ | ↓ |
| pH | −17.49 | −49.80 | ↑ | ↓ |
| Recovery | 6.57 | 6.52 | ↑ | ↑ |

Table 4
Rejection of sodium and potassium

| Membrane rejection | Membrane rejection rate | |
|---|---|---|
| | Sodium [Min, Max] (%) | Potassium [Min, Max] (%) |
| NF-DK | [33, 74] | [14, 72] |
| NF-HL | [14, 64] | [19, 68] |
| RO-AK | [83, 97] | [81, 93] |
| RO-AP | [75, 94] | [79, 94] |
| RO-AG | [97, 99] | [84, 93] |

Table 5
Rejection of chloride and fluoride

| Membrane rejection | Membrane rejection rate | |
|---|---|---|
| | Chloride [Min, Max] (%) | Fluoride [Min, Max] (%) |
| NF-DK | [–350, −3] | [29, 90] |
| NF-HL | [–745, −18] | [–15, 80] |
| RO-AK | [6, 92] | [20, 94] |
| RO-AP | [11, 82] | [35, 93] |
| RO-AG | [79, 99] | [67, 96] |

Table 6
Rejection of calcium and magnesium

| Membrane rejection | Membrane rejection rate | |
|---|---|---|
| | Calcium [Min, Max] (%) | Magnesium [Min, Max] (%) |
| NF-DK | [95, 98] | [97, 99] |
| NF-HL | [93, 97] | [94, 98] |
| RO-AK | [99, 100] | [99, 100] |
| RO-AP | [98, 100] | [98, 100] |
| RO-AG | [100, 100] | [99, 100] |

Table 7
Rejection of sulfate and bicarbonate

| Membrane rejection | Membrane rejection rate | |
|---|---|---|
| | Sulfate [Min, Max] (%) | Bicarbonate [Min, Max] (%) |
| NF-DK | [99, 100] | [19, 77] |
| NF-HL | [95, 99] | [13, 60] |
| RO-AK | [98, 99] | [83, 97] |
| RO-AP | [98, 100] | [86, 95] |
| RO-AG | [87, 100] | [86, 99] |

$$P + \frac{1}{2}\rho V^2 + \rho g h = \text{constant} \tag{1}$$

where $P$ is the pressure, $\rho$ is the density, $V$ is the velocity, $h$ is elevation, and $g$ is the gravitational acceleration. The relationship between velocity and dynamic pressure is given by:

$$V \sim \sqrt{\frac{2P}{\rho}} \tag{2}$$

Besides, flow rate and velocity are related using the following relation:

$$Q = VA \tag{3}$$

where $A$ is the cross-sectional area of the flow and $V$ is its average velocity. Therefore, based on Eqs. (2) and (3), flow rate and pressure are directly related to each other, meaning that any increase in flow rate would cause increased pressure, and consequently have the same effect as increased pressure on the product of RO/NF systems. Table 3 summarizes and displays the effect of each factor.

### 3.2. Specific ion rejection

The rate of rejection for each ion in a solution is calculated by the following equation:

Table 8
Rejection of nitrate

| Membrane rejection | Membrane rejection rate Nitrate [Min, Max] (%) |
|---|---|
| NF-DK | [–16, −3] |
| NF-HL | [–14, −9] |
| RO-AK | [42, 66] |
| RO-AP | [10, 46] |
| RO-AG | [88, 92] |

Table 9
Rejection of silica

| Membrane rejection | Membrane rejection rate Silica [Min, Max] (%) |
|---|---|
| NF-DK | [–20, −18] |
| NF-HL | [–58, 14] |
| RO-AK | [81, 94] |
| RO-AP | [58, 89] |
| RO-AG | [96, 98] |

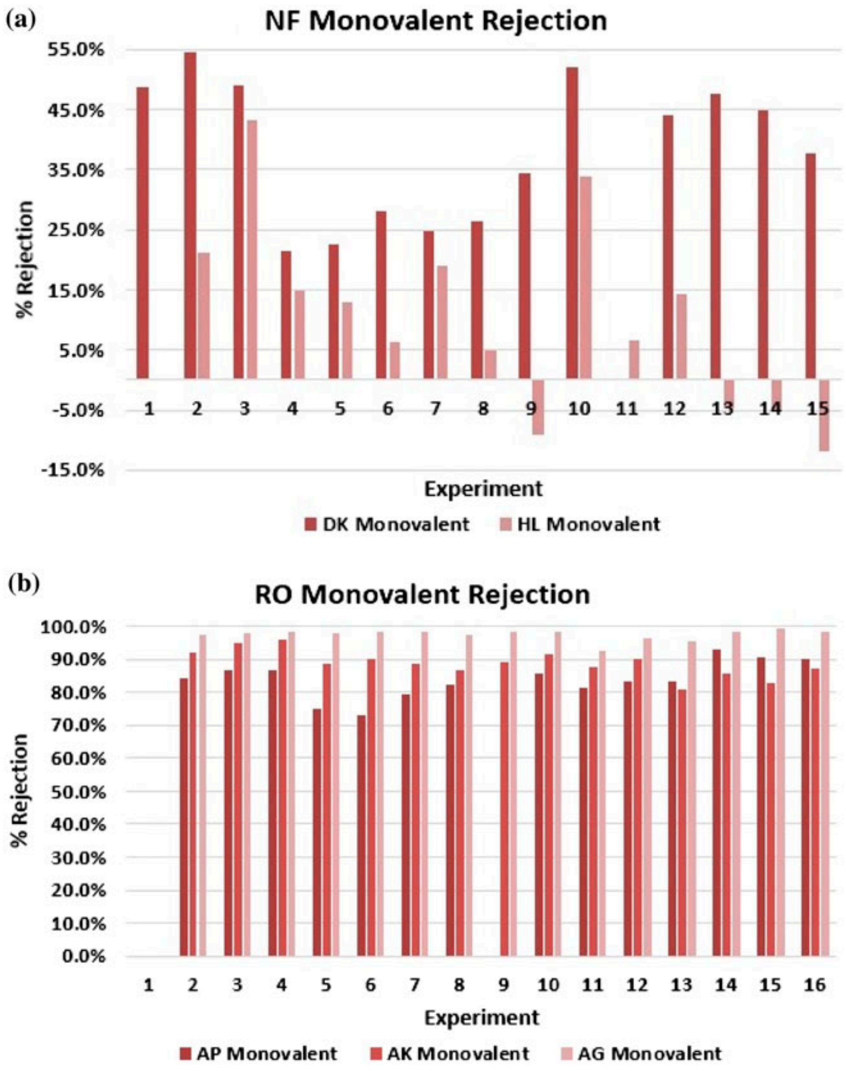

Fig. 2 Rejection of monovalent ions via RO and NF membranes [18]: (a) NF rejection of monovalent ions: DK (min 21%–max 54%), and HL (min −12%–max 43%) and (b) RO rejection of monovalent ions: AP (min 73%–max 93%), AK (min 81%–max 96%), and AG (min 92%–max 99%).

$$R = \left(1 - \frac{C_{\mathrm{p}}}{C_{\mathrm{f}}}\right) \tag{4}$$

Applying a data-set to Eq. (4) provides specific ion rejections for each set of membranes. Results are discussed below.

### 3.2.1. Sodium and potassium rejections

Sodium and potassium are moderately rejected via NF membranes. The experimental results showed that both ions were removed better when the feed water (such as that from Well 1, Well 1 Warm, and Salt-Added Well 1) had lower levels of TDS, rather than in conditions when the feed contained more ions, such as in feed from Well 2 and Blend. RO membranes showed much better rejections of sodium than NF membranes, while the rejection difference between RO and NF was much lower for potassium. Table 4 shows this comparison numerically.

### 3.2.2. Chloride and fluoride rejections

Nanofiltration and reverse osmosis membranes showed significantly different performances in regard to chloride and fluoride ion rejections. In addition to a very poor rejection of fluoride, NF membranes interestingly showed negative rejection of chloride. Negative rejection is defined as having greater

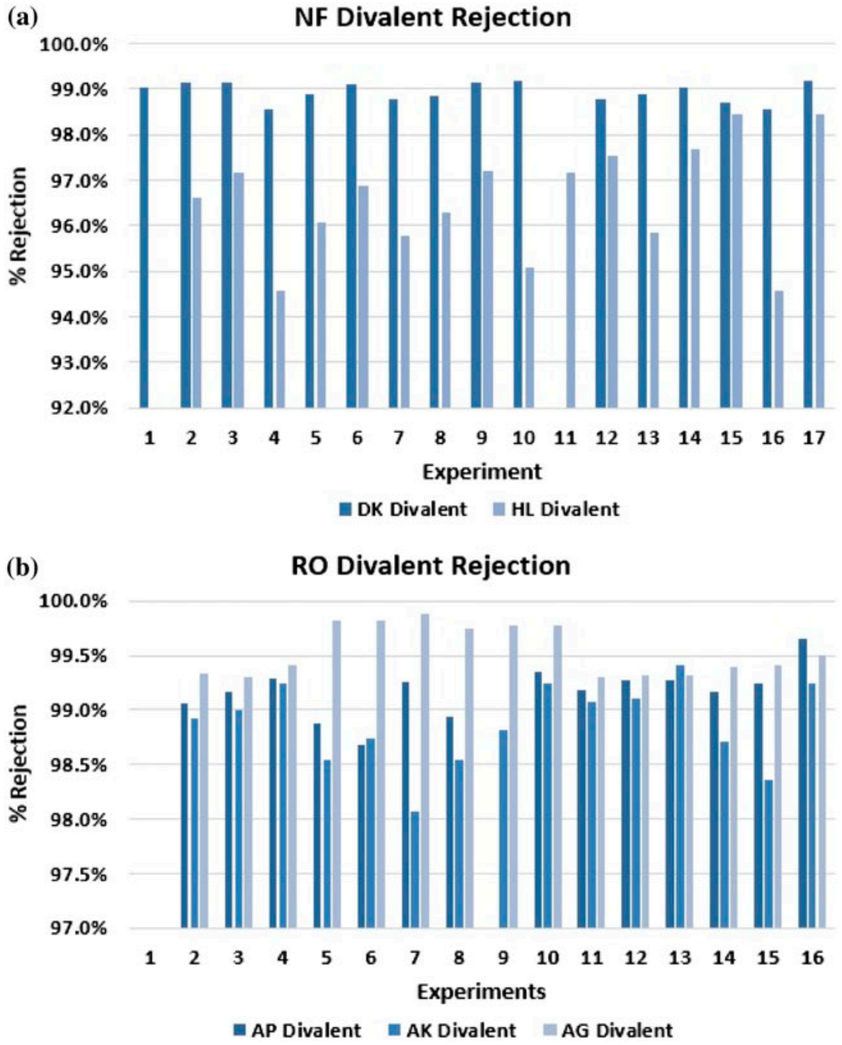

Fig. 3 Rejection of divalent ions via RO and NF membranes [18]: (a) NF rejection of divalent ions: DK (min 99%–max 99%), and HL (min 95%–max 98%) and (b) RO rejection of divalent ions: AP (min 99%–max 100%), AK (min 98%–max 99%), and AG (min 99%–max 100%).

amounts of a solute in product water rather than its initial amounts in feedwater. This negative removal of ions can be explained by several different mechanisms. However, in most cases, the phenomenon is caused by increased concentration of an ion in the membrane phase. The increased concentration occurs with weakening of electric field of filtration potential, which retards counter-ions and prevent the increased concentration by demonstrating themselves in negative rejections. Yaroshchuk and Gilron et al. [21,22] broadly elaborate on this phenomenon. However, RO membranes showed different results in the removal of chloride and fluoride. In the RO systems, none of chloride and fluoride had negative rejections. Chloride was mostly rejected at levels higher than 60%. There were some exceptions as in tests of Well 1 Warm and Well 1 Cold that showed lower levels of chloride rejection, such as 6 and 11%. This could be explained by very low amounts of sodium chloride in feedwater. Fluoride also was rejected much more through RO systems than trough NF systems. Consequently, the application of RO membranes is highly recommended for cases in which the removal of chloride or fluoride is of great concern. Table 5 demonstrates the results.

### 3.2.3. Calcium and magnesium rejections

RO and NF systems operated similarly with regard to the removal of calcium and magnesium; however, NF membranes had a lower average rejection percentage than RO membranes for calcium and magnesium. Table 6 demonstrates these findings numerically.

### 3.2.4. Sulfate and bicarbonate rejections

Results from RO and NF data showed significant difference in the membranes' effectiveness in removing bicarbonate from feedwater; however, both RO and NF had similar outcomes in sulfate rejections. For bicarbonate, RO systems had a much better rejection rate, up to 99%. In NF membranes, the bicarbonate rejection rate was 75%. Both RO and NF systems had almost complete rejection of sulfate, mostly higher than 99%, with an uncommon minimum of 87%. Therefore, when it comes to the rejection of sulfate, the choice between RO and NF depends on other objectives, as shown in Table 7.

### 3.2.5. Nitrate rejection

In the case of nitrate rejection, NF membranes again exhibited negative rejection rates, while RO membranes provided moderate rejection rates. Results are shown in Table 8.

### 3.2.6. Silica rejection

Analysis of data showed that silica passed through NF membranes almost completely, whereas it was mostly rejected by RO membranes (Table 9).

### 3.2.7. Rejection of monovalent and divalent ions

The rejection rates for two groups of monovalent and divalent ions, compared between RO and NF membranes, are presented in Figs. 2(a) and (b), 3(a) and (b), respectively. Monovalent ions include $Na^+$, $K^+$, $Cl^-$, $F^-$, $NO_3^-$, and $HCO_3^-$, and divalent ions include $Ca^{2+}$, $Mg^{2+}$, and $SO_4^2-$. The determination of monovalent and divalent ion removal was carried out by adding the sums of the mass of monovalent and divalent ions in the feed and permeate streams, followed by the use of Eq. (4) to determine specific ion rejection. The legend for both Figs. 2(a) and (b), 3(a) and (b) are shown in Table 10.

As the outcomes show, RO systems performed better than NF systems in the rejection of monovalent ions, but the difference was lower for the rejection of divalent ions. Therefore, if the goal is to reject high amounts of divalent ions without any concern about monovalent ions, either NF or RO systems would be appropriate, and the final choice would depend on parameters such as energy consumption or cost of operation.

In conclusion, the ultimate choice of RO or NF membranes for the treatment process directly depends on operating conditions as well as which specific ion is the target for removal. For ideal performance, the rejection of a specific ion has higher priority than the operating conditions. However, both factors should be coupled to arrive at the best decision. Tables 11 and 12(a)–(c) represent the top choice in regard to both ion rejection and operating factors. Plus and minus signs in Table 12 show high and low levels, respectively. In both Tables 11 and 12, there are some cases in which both RO and NF membranes have the same output. For such cases, the best choice is mentioned as "RO/NF" where the final decision should be made based on operating conditions (for Table 11) or rejection targets (for Table 12).

Table 10
Legend of experiments

| Experiment # | Name |
|---|---|
| 1 | Well 1 Cold-Run 1 |
| 2 | Well 1 Cold-Run 5 |
| 3 | Well 1 Cold-Run 14 |
| 4 | Well 2-Run 1 |
| 5 | Well 2-Run 5 |
| 6 | Well 2-Run 14 |
| 7 | Blend-Run 1 |
| 8 | Blend-Run 5 |
| 9 | Blend-Run 14 |
| 10 | Well 1 Warm-Run 1 |
| 11 | Well 1 Warm-Run 5 |
| 12 | Well 1 Warm-Run 14 |
| 13 | Salt Added Well 1-Run 1 |
| 14 | Salt Added Well 1-Run 5 |
| 15 | Salt Added Well 1-Run 14 |

Table 11
Best choice of membrane in regard to specific ion rejections

| Rejection target | Best choice of membrane |
|---|---|
| Sodium ($Na^+$) | RO |
| Potassium ($K^+$) | RO/NF |
| Chloride ($Cl^-$) | RO |
| Fluoride ($F^-$) | RO |
| Nitrate ($NO_3^-$) | RO |
| Bicarbonate ($HCO_3^-$) | RO |
| Sulfate ($SO_4^{2-}$) | RO/NF |
| Calcium ($Ca^{2+}$) | RO/NF |
| Magnesium ($Mg^{2+}$) | RO/NF |
| Silica | RO |
| Monovalent | RO |
| Divalent | RO/NF |

Table 12
Best choice of membrane in regard to the operating conditions

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | >9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *(a) Operating conditions in which NF is the best option* | | | | | | | | | | | | | |
| Conductivity | + | + | + | + | + | + | − | − | − | − | − | − | − |
| Pressure | + | + | − | − | − | − | + | + | + | − | − | − | − |
| pH | + | − | + | + | − | − | + | + | − | + | + | − | − |
| Recovery | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Temperature | + | + | + | − | + | − | + | − | + | + | − | + | − |
| Membrane | Nanofiltration | | | | | | | | | | | | |
| *(b) Operating conditions in which RO is the best option* | | | | | | | | | | | | | |
| Conductivity | + | + | + | + | + | + | − | − | − | − | − | − | − |
| Pressure | + | + | − | − | − | − | + | + | + | − | − | − | − |
| pH | − | − | + | + | − | − | + | − | − | + | + | − | − |
| Recovery | − | − | − | − | − | − | − | − | − | − | − | − | − |
| Temperature | + | − | + | − | + | − | − | + | − | + | − | + | − |
| Membrane | Reverse osmosis | | | | | | | | | | | | |

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| *(c) Operating conditions in which either RO/NF can be used* | | | | | | |
| Conductivity | + | + | + | + | − | − |
| Pressure | + | + | + | + | + | + |
| pH | + | + | + | − | + | − |
| Recovery | + | − | − | + | − | + |
| Temperature | − | + | − | − | + | − |
| Membrane | RO/NF | | | | | |

## 4. Conclusions

In this study, we systematically compared the effects of operating conditions on the water produced by RO and NF membranes, and made a table displaying the best choice of membranes in particular conditions. The novelty and value of this work is that all the experiments have been done under conditions very similar to those of industrial plants. While most previous studies did the tests in labs and tried to simulate the water chemistries of brackish and/or seawaters in their feeds, here we used real brackish waters from two wells located in the southwestern region of the United States. Moreover, the use of commercial membranes and pilot-scale equipment provided more reliable insights into the application of RO and NF techniques. Observations showed that inlet conductivity, primary pressure, pH, temperature, and recovery rate were the key parameters affecting the quality of produced water in both systems. The important point is that the parameters impacted RO and NF systems differently, implying the necessity of finding the optimal option.

In particular applications where the main goal of the treatment is to remove specific ions, ion rejection plays a significant rule in finding the best choice of membranes. Therefore, the effects of operating parameters should be coupled with the ion rejection capability of RO and NF membranes in order to provide the most favorable option. Interestingly, the concentration of some ions in the permeate stream was higher than that in the feed, after being treated by RO or NF desalination. This phenomenon has been referred to as negative rejection. NF membranes showed negative rejections of chloride, fluoride, nitrate, and silica. Studying the origin of negative rejections and finding a solution for this problem would be one of the major interests in our future work.

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