Performance evaluation of a brackish water reverse osmosis pilot-plant desalination process under different operating conditions:
Experimental study

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ABSTRACT

The Reverse Osmosis (RO) input parameters have key roles in mass transport and performance indicators. Several studies can be found in open literature. However, an experimental research on evaluating the brackish water RO input parameters influence on the performance metrics with justifying the interference between them via a robust model has not been addressed yet. This paper aims to design, construct, and experimentally evaluate the performance of a 50 m³/d RO pilot-plant to desalinate brackish water in Shahid Chamran University of Ahvaz, Iran. Water samples with various salinity ranging from 1000 to 5000 ppm were fed to a semi-permeable membrane under variable operating pressures from 5 to 13 bar. By evaluating permeate flux and brine flowrate, permeate and brine salinities, membrane water recovery, and salt rejection, some logical relations were derived. The results indicated that the performance of an RO unit is largely dependent on feed pressure and feed salinity. At a fixed feed concentration, an almost linear relationship was found to relate feed pressure and both permeate and brine flowrates. Statistically, it was found that 13 bar feed pressure results in a maximum salt rejection of 98.8% at a minimum permeate concentration of 12 ppm. Moreover, 73.3% reduction in permeate salinity and 30.8% increase in brine salinity are reported when feed pressure increases from 5 to 13 bar. Finally, it is concluded that the water transport coefficient is a function of feed pressure, salinity, and temperature, which is experimentally estimated to be 2.8552 L/(m² h bar).

1. Introduction

Water plays an important role in human generations continuance as well as economic development. The development of different industries and agriculture (Ruiz-García et al., 2018), the rapid growth of human population, tough and successive droughts, poor water management, irregular extraction of water resources and climate change have increased water demand in different countries (Pan et al., 2020). Water, as a significant element of human life, is consumed in drinking and different industries. Depending on consumption type, water should fulfill the minimum quality requirements.

At present, two-thirds of the world’s population faces water scarcity in at least one month of a year (Connor et al., 2017). Half of the world’s population will live in 88 developing countries with water scarcity by the year 2030 (UNWS, 2014). Moreover, global water consumption in agriculture and different industries is more than twice as rapidly as the population growth and is predicted to increase by 50% until 2030 (Connor et al., 2017). Surface and groundwater are the main resources of fresh water. Water crisis is a universal issue. Various methods, such as dam construction and cloud seeding, have been suggested to overcome water crisis. However, due to the greatness of oceans and seas on the earth, desalination is one of the vital strategies to resolve this issue (Gu et al., 2013). Although water covers 71% of the earth’s surface, only 3% is in fresh water’s form, including rivers, glaciers, lakes, and groundwater, or available in atmosphere and soil (Gökçek and Gökçek, 2016). Fresh water defines as water contains a permissible amount of total
dissolved solids. The water of oceans and seas is saline and requires advanced treatment and investment in construction of desalination facilities. Formerly, thermal desalination methods such as multi-stage flash evaporation (MSF), multiple-effect distillation (MED), and thermal vapor compression (TVC) were used (Al-Obaidi and Mujtaba, 2016a). However, membrane separation is one of the best seawater treatment methods (Arora et al., 2004) that has several benefits such as selective separation, low space requirement, process and plant compactness, low chemical requirement, operational simplicity, and ease of process automation (Al-Obaidi et al., 2018). It has been used for the treatment of very saline groundwater in comparison to other traditional treatment methods. More than 21% of the total desalination capacity has brackish water supplies globally (Jones et al., 2019). Amongst other desalination technologies, RO is the most reliable membrane method to desalinate seawater and brackish water, not only is more energy-sufficient but also is more economical than thermal desalination (Igobo and Davies, 2018). As membrane’s behavior examination and identification of effective parameters on its performance is essential to run RO units appropriately, it is vital to perceive the relationships between input parameters and performance metrics of the RO process by realizing the most affected parameters. In this regard, Ruiz-García et al. (2020) reported a linear and direct relationship between feed pressure and water flux. However, Shamal and Chung (2006) proved a nonlinear and direct relationship between feed pressure and salt rejection, and a proportional relationship between permeate flux and feed temperature. This effect was more sensitive at higher temperatures. Goosen et al. (2002) evaluated the feed temperature effect on permeate flux and mass transfer coefficient in spiral-wound RO membranes. They stated that there is more than 60% increase in water flux while the feed water temperature increases from 20 °C to 40 °C. Arora et al. (2004) made an effort to remove additional fluoride from groundwater using an RO membrane. This research represented that membrane performance is influenced by feed water pressure, pH, and feed concentration. Consequently, 95% of fluoride rejection was reported. Water and salt fluxes through RO membrane were examined by Zhou and Song (2005) under different operating conditions. They concluded that both feed pressure and feed salinity are the main reasons for salt passage through an RO membrane. Moreover, water flux is dependent on feed concentration. Djebeldjiana et al. (2009) analyzed the effects of operating variables on the performance of an RO unit. They reported that feed water pressure, temperature, and concentration are the most important variables affecting the performance of an RO system. Sassi and Mujtaba (2012) studied the influence of different feed salinities and temperatures on the design and operation of seawater RO desalination networks. The results affirmed the importance of those parameters. Barello et al. (2015) studied the RO process operation in a batch mode by modeling. They showed variation of permeate flux and salinity with feed salinity at 40 bar feed pressure. The results indicated a strong contribution of feed pressure and concentration on water permeability constant. A direct relationship was derived between salt passage and feed salinity at a fixed operating pressure. Atab et al. (2016) showed a direct relation between operating pressure and salt rejection. Haluch et al. (2017) assessed the performance of an RO system and indicated the negative effect of feed salinity on salt rejection. Al-Obaidi et al. (2017) developed a mathematical model to remove phenol from wastewater by an RO system. It was reported that the phenol rejection increases versus an increase in feed pressures of three feed concentrations. The largest amount of phenol rejection was about 91.4% at feed pressure of 14.99 bar. An increase in feed pressure causes an increase in water flux and a decrease in permeate concentration. Kazemian et al. (2018) worked on designing experiments method to realize the effect of operating parameters on energy consumption and permeate water salinity. They concluded that permeate water salinity increases due to an increase in feed water salinity and feed water temperature. Al-Obaidi et al. (2018) studied the performance of a medium-scale RO system (1200 m³/d) in Jordan, used to desalinate brackish water. They reported the influence of feed salinity increase, including reduction in total plant rejection, increase in permeate and brine water salinities. They stated that a 19% increase in feed pressure would cause 22% and 15% reductions in permeate and brine salinity, and 13.4% increase in total plant recovery. Boulaha et al. (2019) evaluated the effective operating parameters on an RO plant in Morocco for five years. They made a comparison among operating parameters and analytic results of the ROSA software and found 10% increase in permeate flux as a result of 4 °C increase in feed temperature. Ebrahim et al. (2019) investigated the influence of salt concentration on transport properties of different RO membranes in high pressure and high recovery units. That research indicated the effect of NaCl salinity on water and salt transport through a semi-permeable membrane. Du et al. (2020) studied high salinity brackish water desalination with different RO membranes. The results showed a constant pure water permeability coefficient in the range of applied feed pressure for each membrane. Moreover, it was shown that water flux is feed pressure dependent. Another conclusion of their study was that as feed salinity increases, salt rejection decreases.

The above literature review indicated the effect of feed salinity and feed pressure on the performance metrics of an RO system. However, a comprehensive experimental research on desalting brackish water via a constructed pilot-scale RO system to mathematically generate an explicit correlation for water transport parameter of the membrane type BW30-400 Filmtec was not fully addressed in the open literature. This research aims to design, construct, and evaluate the performance of an RO pilot-plant that produces 50 m³ of potable water per day and experimentally investigate the influence of operating parameters on the performance indicators of the RO process. The most important performance metrics of the RO system, water flux and salt rejection, depend on membrane recovery, feed water temperature, feed pressure, feed water salinity, and pH (Djebeldjiana et al., 2009). However, it should be noted that the impacts of feed salinity and feed pressure parameters could be apparently observed on the membrane performance. This research precisely focused on evaluating these parameters (feed salinity and pressure) on the process performance experimentally by measuring the interference between them. Water samples with various salinity ranging from 1000 to 5000 ppm were fed to a semi-permeable membrane under variable operating pressures from 5 to 13 bar (see section 4).

2. Theoretical background

Modeling of any industrial process is a vital task to specify the interrelationships between the inlet parameters and process performance (Hadadian et al., 2021).

The overall volumetric flow rate and solute mass flow rate through a semi-permeable membrane are represented in Equations (1) and (2).

\[
Q_f = Q_P + Q_C 
\]

\[
(Q_f \times C_f) = (Q_P \times C_P) + (Q_C \times C_C) 
\]

Where \(Q_f\), \(Q_P\), and \(Q_C\) are feed, permeate, and concentrate flow rates. In addition, \(C_f\), \(C_P\), and \(C_C\) are the feed, permeate, and concentrate salinity.

Membrane water recovery is a term that illustrates the ratio of permeate flow to feed flow in an RO system. Water recovery can be calculated by Equation (3):

\[
\%\text{Recovery} = \frac{Q_P}{Q_f} \times 100 \quad (3)
\]

The membrane recovery rate ranges between 50 and 85% in many RO plants (Kucera, 2015). Feed water characteristics, feed water salinity, pretreatment unit, and design configuration are the parameters that affect recovery rate (Greenlee et al., 2009).

Salt rejection is another important metrics of the RO system and defines as the percentage of removed salt from feed water by the membrane wall as described in Equation (4):

\[
\%\text{Rejection} = \frac{C_f - C_p}{C_f} \times 100 \quad (4)
\]
\[ \text{Rejection} = \frac{C_r - C_p}{C_r} \times 100 \quad (4) \]

Similarly, salt passage can be estimated using Equation (5):

\[ \text{Salt passage} = \%100 - \%\text{Rejection} \]

Water flux, the rate of water flow through 1 m² of membrane surface area, is obtained by Equation (6) for cross flows:

\[ J_w = K_w \times (TCF) \times (FF) \times \left( P_i - \frac{\Delta P_f}{2} - (\pi_f - \pi_i) \right) \times PF \quad (6) \]

\[ J_w \text{ and } K_w \text{ are water flux and water transport coefficients. } \pi_f \text{ and } \pi_p \text{ as the osmotic feed pressure and osmotic permeate pressure are calculated from the Van’t Hoff equation (Equation (7)) for ideal dilute solutions (Yokozeki, 2006), TCF is temperature correction factor (Equation (8)), FF is flow factor, } P_i \text{ is feed pressure, } P_p \text{ is permeate pressure, } \Delta P_f \text{ is concentrate-side pressure drop (Equation (9)), and PF as polarization factor is related to spacer feed geometries of the membrane and is proposed by membrane manufacturer (Ruiz-Garcia and de la Nuez-Pestana, 2018).} \]

\[ \pi = i \times \phi \times C_f \times R \times (T + 273.15) \quad (7) \]

\[ \pi \text{ is osmotic pressure, } i \text{ indicates the number of ions produced during the dissociation of solute, } \phi \text{ is the osmotic coefficient, } T \text{ is the temperature, and } R \text{ is universal gas constant. As an experimental observation, } 100 \text{ ppm of total dissolved solids in the solutions equal to 0.041–0.075 bar of osmotic pressure (Kucera, 2015).} \]

\[ FF \text{ (flow factor) is used to consider the operating time and fouling. As we used a new membrane, its value was assigned to be 1.} \]

\[ TCF = \exp\left(2640 \left(1 - \frac{1}{273.15 + T}\right)\right) \quad T \geq 25 \degree C \quad (8) \]

\[ TCF = \exp\left(3020 \left(1 - \frac{1}{273.15 + T}\right)\right) \quad T \leq 25 \degree C \quad (9) \]

\[ \Delta P_f = (0.068) \times (0.01) \times n \times (q_{fb})^{1.7} \]

\[ n \text{ is the number of elements, 0.068 is multiplied to this equation due to unit conversion, from psi to bar. } q_{fb} \text{ is the average feed-brine flow:} \]

\[ q_{fb} = \frac{Q_{feed} + Q_{brine}}{2} \times (0.264) \quad (10) \]

\[ q_{fb} \text{ is multiplied to 0.264 due to unit conversion, from L/min to gpm.} \]

3. Design and construction of the RO system

Based on the feed water quality, RO water desalination plants can be divided to three major parts: pretreatment, treatment, and post-treatment (Djebedjiana et al., 2009). Each part performs specified tasks.

3.1. Pretreatment unit

The pretreatment system is the first operating unit in which raw water enters as the feed. The most important aim of a pretreatment unit is to improve water quality and make it suitable for the membranes. In this regard, one of the most undesirable events that RO plants face is membrane fouling (Zhao et al., 2021). Fouling means stickiness of silt, clay, sand, and suspended solids on the membrane surface. Scaling, the sedimentation of salts on the membrane’s surface, is another critical reason that causes its destruction. This issue could play as a limiting factor regarding the flux recovery (Karabelas et al., 2020). An appropriate pretreatment unit would minimize membrane fouling and scaling, in addition to recovery and lifetime improvement.

This pretreatment unit of the constructed RO pilot-plant in Shahid Chamran University of Ahvaz (Iran) comprises of different parts: a storage raw water tank (TK-100), a 0.34 kW feed pump (P-100) to transfer the water through the unit, a cylindrical sand filter to remove the turbidity and suspended solids from the raw water, a cylindrical activated carbon filter to remove the organic compounds and chlorine, four microfilters to remove water suspended solids smaller than 5 μm.

3.2. RO unit

Osmosis phenomenon is a popular topic among scientists. If there is a semi-permeable membrane between two low and high-concentration solutions, the water will naturally flow to the higher concentration side due to the osmotic property. When the operating pressure equals the osmotic pressure of the more concentrated solution side, water flow stops. If the applied pressure is higher than the osmotic pressure, the water flow will be reversed. The feed water is pushed to the membrane by a high-pressure pump. In this process, the feed water divides to two parts of permeate and brine water. Brine flow contains viruses, bacteria, and suspended solids that do not pass the membrane. The membranes are known as the core of the treatment unit in RO systems. Figs. 1 and 2 show the photos and a schematic diagram of the constructed RO pilot-plant in Shahid Chamran University of Ahvaz, Iran.

The RO pilot-plant consists of different components: a 0.37 kW pump (P-101) that transfers the pretreatment water to the RO tank (TK-200), a mixer installed on the RO tank for salt mixing and preventing the particles from sedimentation, a 1.21 kW RO pump (P-200) located before the microfilters to provide pressure, four microfilters that remove not only water hardness but also remained turbidity and suspended solids smaller than 1 μm, a 3.06 kW high-pressure pump which is connected to a VFD to overcome the osmotic pressure in both sides of the membrane, a variable frequency drive (VFD) is used to adjust the feed pressure according to its input frequency, an 8-inch pressure vessel to protect the membrane, and a semi-permeable membrane. A FILMTEC™ BW30-400 membrane was used in this plant. Table 1 presents the characteristics of the membrane used. A valve at the end of the brine water pipe was used to adjust the membrane recovery ratio in each test.

3.3. Post-treatment unit

RO is an unsuitable method to remove CO₂ for it acidifies the permeate water and might cause corrosion in downstream pipes. In addition, RO is a non-selective process that totally removes all kinds of minerals in permeate water. The post-treatment unit is employed to adjust the pH of product water (control corrosion), improve the water quality (stabilization), and add ozone or UV rays as a disinfection treatment.

4. Methodology of the experimental tests

This section illustrates the evaluation of the effective operating parameters on the performance of the RO process. Feed pressure was adjusted by changing the VFD frequency connected to a high-pressure pump. An experimental curve (Fig. 3) was used to adjust the feed pressure. The experiments were conducted at a feed pressures of 5, 7, 9, 11, and 13 bar set. The feed water was adjusted at the salinity of 1,000, 2,000, 3,000, 4,000, and 5000 ppm, i.e., each feed water salinity was tested at the mentioned constant operating pressures. However, most of the experiments were carried out a fixed water recovery (about 30 ± 5%). For each experimental test, procedures were repeated three times and the average values were taken. Each set of data was recorded and showed in the form of figures to indicate the effect of different operating parameters including feed pressure and salinity. The water temperature and pH were fixed at 15 °C and 7.2, in all the experiments.

5. Results and discussion

Fig. 4 shows that an increase of feed pressure at a fixed feed salinity...
causes an almost linear rise in permeate flow. The trendline of each curve is plotted, where the maximum and minimum correlation coefficients are 0.9982 and 0.9896 for the feed salinity of 4000 ppm and 1000 ppm, respectively. Moreover, the increase of NaCl salinity of the feed water would negatively affect the water transport through the membrane. Specifically, increasing feed salinity would increase salt

Fig. 1. Photos of the constructed RO pilot-plant in Shahid Chamran University of Ahvaz, Iran. We have used only one spiral wound module. The second one is off.

Fig. 2. 3D schematic of the constructed RO pilot in Shahid Chamran University of Ahvaz, Iran.

1. Raw Water Tank (TK-100)
2. Feed Pump (P-100)
3. Sand Cartridge Filter
4. Activated Carbon Cartridge Filter
5. 5-Micron Cartridge Filter
6. Pretreatment Water Tank (TK-101)
7. Transfer Pump (P-101)
8. RO Tank (TK-200)
9. Mixer
10. High Pressure Pump
11. RO Membrane/Pressure Vessel
12. Backwash Tank
13. RO Pump (P-200)
14. 1-Micron Cartridge Filter
15. Backwash Pump
16. Electronic Board
17. VFD
18. Flow Meters and Pressure Gauges
accumulation on the membrane surface that retards the water permeation through the membrane pores. The same finding was affirmed by Al-Obaidi and Mujtaba (2016). Fig. 5 shows that the permeate flow decreases nonlinearly due to an increase in the feed salinity at a fixed feed pressure. Since the feed pressure directly affects the driving force applied to the feed water, an increase in the pressure causes an increase in the water flux through the membrane. This is only acceptable as the applied feed pressure is more than the osmotic pressure. It is important to realize that the osmotic pressure would rise by increasing the feed salinity. This matter means that the difference between the osmotic pressure and pump pressure decreases, which leads to a reduction in the permeate flux.

Fig. 6 depicts the changes of salt rejection versus the feed pressure at a fixed feed salinity. It is clear that feed pressure has a noticeable and positive effect on the salt rejection, i.e., when feed pressure increases from 5 to 13 bar, salt rejection increases from 95.5% to 98.8%. This can be attributed to the dilution of water on the permeate channel due to an increase in water flux. More importantly, Fig. 6 illustrates an exponential relationship relates to the variation of salt rejection and feed pressure at fixed feed salinity. A rapid increase of salt rejection at a low

Table 1  
Characteristics of FILMTEC™ BW30-400 membrane (DowChemical, 2017).

<table>
<thead>
<tr>
<th>The manufacturer</th>
<th>Membrane’s brand</th>
<th>Min and Max Salt Rejection (%)</th>
<th>pH range</th>
<th>Active Area (m²)</th>
<th>Maximum water temperature (°C)</th>
<th>Maximum operating pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FILMTEC™</td>
<td>BW30-400</td>
<td>99-99.5</td>
<td>2-11</td>
<td>37</td>
<td>45</td>
<td>41</td>
</tr>
</tbody>
</table>

Fig. 3. The experimental curve of the VFD frequency–operating pressure applied to feed water by the high pressure pump, pH and temperature of 7.2 and 15 °C.

Fig. 4. Effect of feed pressure on permeate flow rate at a fixed feed concentration, pH and temperature of 7.2 and 15 °C.

\[
y = 2.1452x - 3.4108 \\
R^2 = 0.9896 \\
y = 1.6503x - 2.6442 \\
R^2 = 0.9971 \\
y = 1.5053x - 3.1622 \\
R^2 = 0.9952 \\
y = 1.419x - 3.8452 \\
R^2 = 0.9982 \\
y = 1.387x - 4.6639 \\
R^2 = 0.9976 
\]
pressure of each feed salinity is noticed. However, a slower increase in salt rejection can be noticed as the feed pressure increases.

On the other hand, Fig. 7 presents that the salt rejection decreases nonlinearly by increasing the feed salinity at a fixed feed pressure. Again, increasing salt concentration in the feed solution would cause a reduction of the apparent diffusion coefficient of water and an increase in salt solubility. This issue in turn would increase the salt passage through the membrane pores and negatively affect the permeate concentration. In this regard, the maximum salt rejection is 98.8% at 13 bar feed pressure. Concerning Equation (4) and Fig. 4, this trend is justifiable. Besides, the feed pressure is more effective on the water flux compared to salt flux (Al-Obaidi et al., 2017).

The influence of operating pressure on the permeate salinity at fixed feed salinity is represented in Fig. 8. As feed pressure rises, the permeate water TDS concentration is consequently reduced (Alsarayreh et al., 2020). In addition, by increasing the feed salinity at a fixed feed pressure, the TDS concentration of permeate water grows, i.e., water becomes more saline than before. For instance, at a feed concentration of 1000 ppm, the TDS concentration of permeate water decreases from 45 ppm to 12 ppm due to increasing the feed pressure from 5 to 13 bar, i.e., about 73.3% reduction in permeate salinity is reported. It seems the reduction rate of permeate salinity as the pressure increases from 5 to 9 bar is more than that at higher pressures. In other words, at 9 bar, the reduction rate in permeate salinity is much slower. This matter can be understood more easily considering Equation (4). Concerning the direct relationship of salt rejection and feed pressure (Fig. 6) and based on Equation (4), at each fixed feed salinity, the TDS concentration of permeate water is reduced by increasing the feed pressure. More importantly, Fig. 8 discloses a bit linearity behavior between the permeate concentration and feed pressure within low salinity brackish water. However, this is not the case for high feed salinity of an exponential relationship.

Fig. 9 elaborates a linear relationship between the brine water flow rate and the operating pressure at fixed feed salinity. Obviously, a pressure increase would reduce brine flow rate exit the membrane. This is due to an increase in water permeation as a result of feed pressure rise that reduces the brine flow rate. This matter justifies by Equation (1), i.e., feed flow, permeate flow and concentrate flow rise by increasing the
feed pressure. The maximum and minimum correlation coefficients are obtained to be 0.9995 and 0.9622 for the feed salinity of 3000 ppm and 5000 ppm, respectively. It should be noted that at 13 bar feed pressure, the best water quality is obtained.

Fig. 10 shows the variation of brine salinity versus the feed pressure at a fixed feed salinity. It is obtained that feed pressure and brine salinity have a direct and linear relationship. Figs. 4, 8 and 9 and Equations (1) and (2) prove this trend, i.e., by increasing the feed pressure at a fixed feed salinity (or a fixed osmotic pressure), the water flux increases and consequently permeate salinity decreases and brine salinity increases. Besides, the brine salinity would increase according to Equation (2). Moreover, it should be mentioned that the correlation coefficient between the functions and their trendlines shows an almost linear relationship between the feed pressure and brine salinity.

Fig. 11 presents the rise of water recovery due to increasing the feed pressure at a fixed feed salinity. Table 2 shows the derived equations of $Q_P$ and $Q_C$ versus $P$ from Figs. 4 and 9. At a fixed feed salinity and temperature, if $\Delta R_i = R_i - R_{i-1}$, then every $\Delta R_i$ in these figures has a positive quantity, i.e., $R_i > R_{i-1}$.

Water transport coefficient ($K_w$) depends on membrane’s type (structure of the element), feed water temperature (Kucera, 2015) and flow factor ($FF$). The effects of fouling and operating time are reflected through $FF$ (Water, 2005). It is calculated exclusively for each membrane. The feed water temperature was fixed at 15°C during all the experiments. The slope of the trendline in Fig. 12 shows the value of the water transport coefficient ($K_w$). This coefficient is calculated using Equation (6). As can be seen in Fig. 12, as the operating pressure ranges from 1.19 to 12.23 bar, $K_w$ is obtained from the following equation:

$$Y = 2.8552X - 1.4837.$$  

The slope of this trendline is $2.8552$ L/(m².h.bar) equals to $7.93 \times 10^{-7}$ (m/(bar s)), as seen in the chart. This calculated coefficient, with an accuracy of about 92%, is close to the coefficient used by the other scientists, except the operating feed condition of our research is different from the others: feed salinity ranging from 1000 to 5000 ppm NaCl, feed pressure ranging from 5 to 13 bar, pH
7.2, the water temperature of 15 °C, and membrane recovery ranging from 19.53% to 49.58%. This different feed condition caused a little reduction in the quantity of the BW30-400 water transport condition of ours. For instance, it is about 10% less than the reported $K_w$ by the manufacturer or about 16% less than the calculated one by Sassi and Mujtaba (2010). In this regard, Sassi and Mujtaba (2010) stated that the water transport coefficient is $9.39 \times 10^{-7}$ m/(bar s) that corresponding to a set of operating conditions of feed salinity of 2540 ppm, feed pressure of 12.2 bar, the water temperature of 28.8 °C. Lastly, Ruiz-García and de la Nuez Pestana (2019) estimated the water transport coefficient as $9.63 \times 10^{-7}$ m/(bar s). The feed salinity ranged from 1000 to 15,000 ppm NaCl and feed pressure ranged from 1 to 42 bar.

6. Further implications of the developed set-up of RO system

The developed set-up of RO system results in a high productivity of freshwater of 50 m$^3$/d (50,000 L/d) with 12 ppm of salinity. Thus, the desalination system can be used to generate distilled water for labs of the Shahid Chamran University of Ahvaz, Iran. Furthermore, the instillation of this system in arid and semi arid areas in Iran would be an interesting
option to cope with water scarcity. Due to the high concern of boron in seawater, the developed RO system can be applied to desalinate seawater and reach the boron guideline of 0.5 ppm of WHO. However, a possible design modification might be necessary such as adapting the second pass design to gain this aim. Also, the production of irrigation water is possible if the inlet operating parameters are moderated under a separate study. To summarise, different grades of water can be deduced from the developed RO system to quantify different fields and requirements.

7. Conclusions

In this study, the performance of a brackish water RO system (with

Table 2

<table>
<thead>
<tr>
<th>C_f (ppm)</th>
<th>Q_p-P equation</th>
<th>Q_c-P equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>Q_p = 2.1452P-3.4108</td>
<td>Q_c = 1.0377P+10.846</td>
</tr>
<tr>
<td>2000</td>
<td>Q_p = 1.6503P-2.6442</td>
<td>Q_c = 0.9055P+9.4085</td>
</tr>
<tr>
<td>3000</td>
<td>Q_p = 1.5053P-3.1622</td>
<td>Q_c = 0.886P+8.137</td>
</tr>
<tr>
<td>4000</td>
<td>Q_p = 1.419P-3.8452</td>
<td>Q_c = 0.796P+7.548</td>
</tr>
<tr>
<td>5000</td>
<td>Q_p = 1.387P-4.6639</td>
<td>Q_c = 0.66P+7.24</td>
</tr>
</tbody>
</table>

Fig. 11. Effect of feed pressure and feed concentration on membrane water recovery, pH and temperature of 7.2 and 15 °C.

Fig. 12. Effect of operating pressure on water flux, pH and temperature of 7.2 and 15 °C.

\[
y = 2.8552x - 1.4837 \\
R^2 = 0.9259
\]
50 m³/d production capacity) of membrane type BW30-400 Filmtec under variable operating conditions of feed pressure and salinity was experimentally evaluated based on mathematical model. Feed pressure has an almost linear and direct relationship with permeate and brine flow. Permeate flux found to be non-linearly and negatively dependent on feed water salinity. Both feed pressure and feed salinity have important effects on salt rejection. The maximum salt rejection was reported 98.8% at 13 bar pressure. A 73.3% reduction in permeate salinity was reported when feed pressure increases from 5 to 13 bar. Moreover, the brine salinity of 1000 ppm. An almost linear and positive relationship was found to be among feed pressure to brine salinity and membrane water recovery. More importantly, it was found that water permeability constant is feed pressure, salinity, water recovery, and temperature-dependent. The water transport coefficient of this RO pilot-plant was found to be 2.8552 L/(m².h.bar) equals to 7.93 × 10⁻⁸ (m²/bar s) with 92% accuracy.

Declaration of competing interest
There is no conflict of interests.

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List of symbols

| TDS | Total dissolved solids (ppm) |
| RO | Reverse Osmosis |
| VFD | Variable frequency drive |
| TCF | Temperature Correction Factor (– ) |
| SWRO | Seawater Reverse Osmosis |
| BW | Brackish water |
| PF | Polarization factor (– ) |
| FF | Flow Factor (– ) |
| Qf | Feed flow (L/min) |
| Cf | Feed concentration (ppm) |
| Qp | Permeate flow (L/min) |
| Cp | Permeate concentration (ppm) |
| QC | Concentrate flow (L/min) |
| KW | Water transport coefficient (L/(m² h bar)) |
| Pf | Permeate pressure (bar) |
| Pf | Osmotic feed pressure (bar) |
| σp | Osmotic permeate pressure (bar) |
| Φ | Osmotic coefficient (– ) |
| R | Universal gas constant = 0.08314 (bar.L/moles.K) |
| T | Temperature (°C) |
| ηfe | Average feed-brine flow (L/min) |
| ΔPcs | Concentrate-side pressure drop (bar) |
| pH | Potential for hydrogen (– ) |
| JW | Water flux (L/m² h) |
| Δ | Brine recovery (%) |
| CC | Brine concentration (ppm) |

References


