APPLICATION OF THE SOLUTION-DIFFUSION MODEL TO OPTIMIZE WATER FLUX IN REVERSE OSMOSIS DESALINATION PLANTS

Hisham A. Maddah [1, 3] ; Mohammed A. Almugahwi [2, 3]
(1) Department of Chemical Engineering, King Abdulaziz University, Rabigh, 21911, PO Box 344, Saudi Arabia, Email: hmaddah@kau.edu.sa; (2) Department of Abqaiq Plant Operation Engineering, Saudi Aramco Company; (3) Department of Chemical Engineering, University of Southern California, Los Angeles, United States

Abstract - This paper suggests a new method of predicting flux values at reverse osmosis (RO) desalination plants. The study is initiated by using the solution-diffusion model that is applied to the groundwater source at Abqaiq plant (500 RO plant) at Saudi Aramco, Dhahran, Saudi Arabia in order to calculate the osmotic pressure of the treated water for Shedgum/Abqaiq groundwater. For modelling purposes, the same technique is used to determine the osmotic pressure drops at the same plant configuration and operating conditions when using seawater sources such that of Arabian Gulf and Red Sea waters. High rejection brackish water RO (BWRO) element Toray TM720D-400 with 8” is the RO membrane type that is used at Abqaiq plant. The calculated osmotic pressures of the three water sources, assuming that they are all treated at Abqaiq plant, are utilized to determine the appropriate flux values as well as membrane resistances of different BWRO Toray membranes. Values of numerous parameters such as water permeability constant, applied pressure, gas constant, water temperature, water molar volume and membrane thickness, water salinity/TDS are taken into account to develop our calculations through the solution-diffusion model. A comparison between low-pressure, standard and high-pressure BWRO Toray membranes performance have been established to select the ideal membrane type for the treatment of water from various sources at Abqaiq plant. The model results confirm an inverse relationship between the membrane thickness and the water flux rate. Also, a proportional linear relation between the overall water flux and the applied pressure across the membrane is identified. Higher flux rates and lower salinity indicate lower membrane resistance which yield to higher water production. Modelled data predict that BWRO Toray TM720D-440 with 8”membrane is the optimal BWRO membrane choice for the three water sources at Abqaiq plant.

Keywords - Reverse Osmosis, Flux, Treatment, Desalination, Modelling, Solution-Diffusion

1. INTRODUCTION

The solution-diffusion model is popular technique that is used to explain the transport in dialysis, reverse osmosis, gas permeation and pervaporation. Previous experimental data and modelling results verified that flux rate is proportional to a gradient in the chemical potential [1].

There are two different models to describe and control the permeation in membranes for better separation. The first model is the solution-diffusion model where permeants dissolve (sorption) in the membrane material at the upstream interface in the presence of a concentration gradient that allows permeants to diffuse through the membrane and desorbed on the downstream interface side. Separation between different permeants occurs because each material has a different diffusion rate in the membrane. The solution-diffusion model has been used since 1940 to explain the transport of gases across polymeric membranes. A second model called the pore-flow model depends on the presence of a pressure gradient which yields to a convection flow of permeants through

membrane's tiny pores is more limited compared to the first model. Exclusion or filtration of larger permeant's pores is the separation technique which explains the pore-flow model [1, 2].
There is a major difference between the solution-diffusion model and the pore-flow model in expressing the chemical potential. In the solution-diffusion model, the pressure within a membrane is uniform and that the chemical potential gradient is expressed only as a concentration gradient. Solution-diffusion membranes transmit pressure in the same way as liquids that is the reason for expressing the pressure difference across the membrane as a concentration gradient only. On the other hand, the chemical potential gradient in the pore-flow model is expressed only as a pressure gradient since that the concentrations of both solvent and solute within a membrane are uniform. Figure 1 shows a comparison between both models for one-component solution in a pressure-driven permeation system [1, 2].

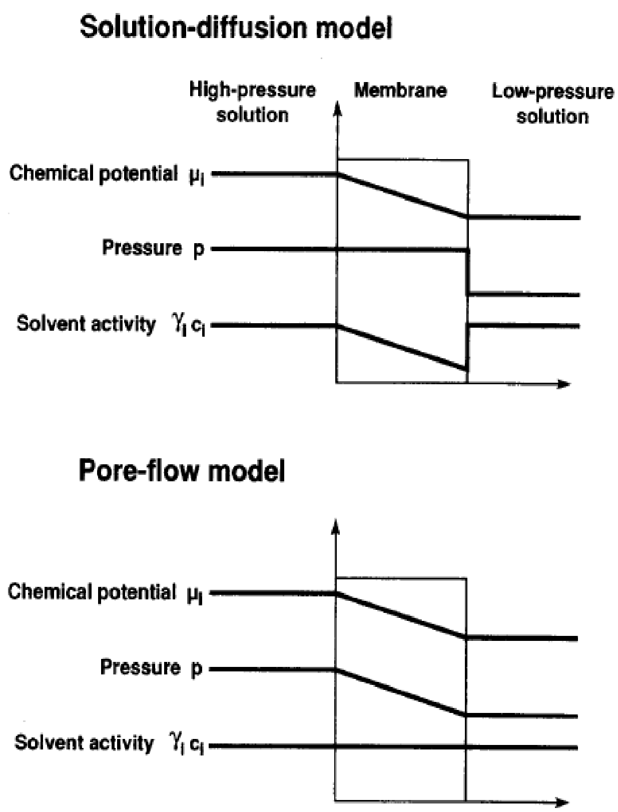

Figure 1. Pressure-driven permeation of a one-component solution across a membrane according to the solution-diffusion and the pore-flow models

The objective of this work is to estimate the osmotic pressure drop value of the high rejection brackish water RO membrane (Toray TM720D-400 with 8") by using the solution-diffusion model that is applied to Abqaiq plant (500 RO plant) for Shedgum/Abqaiq groundwater at Saudi Aramco, Dhahran, Saudi Arabia. Osmotic pressure drops has been calculated for the groundwater, Arabian Gulf and Red Sea waters at the same plant configuration and operating conditions of Abqaiq plant in Aramco.
The calculated osmotic pressures are utilized to determine the applied pressure drop across the membrane and the applicability of using different BWRO Toray membrane types for the treatment of seawaters. The maximum achievable water flux values are determined for the various suggested

BWRO membranes for the three water sources. Also, the membrane resistance values has been investigated for comparison purposes. The ideal membrane for the treatment of various water sources at a RO plant with the same configuration of Abqaiq plant has been selected.
The feasibility of using BWRO membranes in desalination of Red Sea water in Jeddah, Saudi Arabia is studied at the same flux rate of Arabian Gulf water source and same plant conditions of Abqaiq plant. The osmotic pressure drop, applied pressure drop, flux rates and membrane resistance values for Red Sea water source are compared with those of Shedgum/Abqaiq groundwater and Arabian Gulf water.

2. REVERSE OSMOSIS

In reverse osmosis, water flows from the salt solution to the pure waterside by applying pressure (Δp) that is greater than the osmotic pressure $(\Delta\pi)$ [1]. Generally, in reverse osmosis, we must satisfy this condition $(\Delta p > \Delta\pi)$ all the time to allow water to pass through the membrane and reach the permeate side [1, 2]. Reverse osmosis membranes are preferred over Ultrafiltration and Nanofiltration since they are capable of removing 90 to 99% of TDS in water [3].
Osmotic pressure $(\Delta\pi)$ is defined as the pressure difference $(p_o - p_\ell)$ across the membrane. If a pressure higher than the osmotic pressure is applied to the feed side (left side in Figure 2) of the membrane, the process is called reverse osmosis. Figure 2 shows the driving forces in a reverse osmosis membrane according to the solution-diffusion and the pore-flow models. μ_i and γ_i are the chemical potential and activity coefficient, respectively, of component i [1].

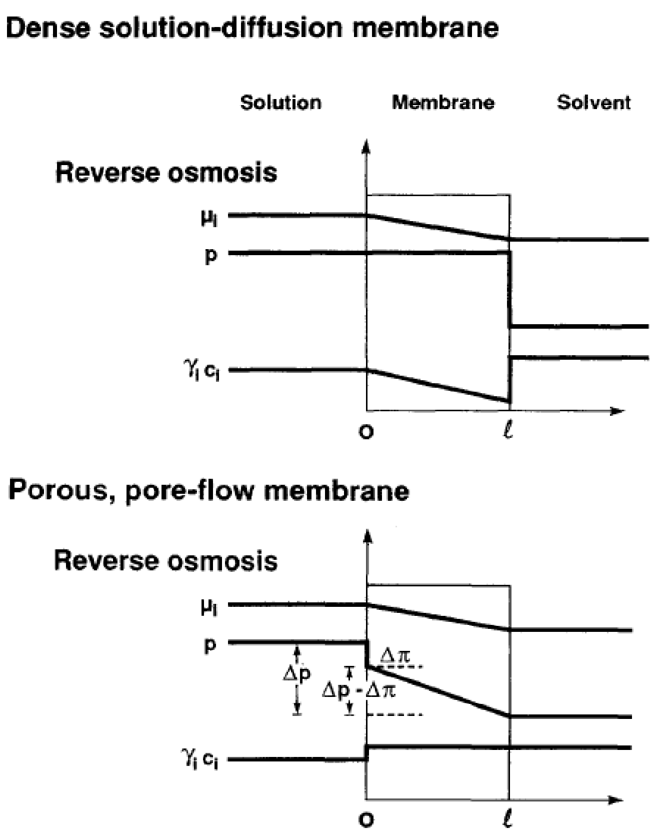

Figure 2. Chemical potential, pressure, and solvent activity profiles in a reverse osmosis membrane according to the solution-diffusion and the pore-flow models

3. METHODOLOGY AND DATA

Abqaiq 500 RO plant data (Table 1) has been used to determine osmotic pressure drop values for the RO membrane (Toray TM720D-400 with 8”) from Equations (1) and (2). However, in order to calculate the osmotic pressure for seawater sources, we applied the same information of Shedgum/Abqaiq groundwater at Abqaiq 500 RO plant, except for the flux and salinity values, for the treatment of either Arabian Gulf or Red Sea waters as listed in Table 1 [1, 4].
Water permeability is approximately determined to be $9.5 \times 10^{-7}\ cm^2/s$ [8]. For water-salt solution, reverse osmosis permeation expression can be simplified as the following [1, 5]:

$$\boldsymbol{J_i} = \boldsymbol{A}(\boldsymbol{\Delta p} - \boldsymbol{\Delta \pi}) \qquad (1)$$

$$\boldsymbol{A} = \frac{\boldsymbol{P_i c_{io} \nu_i}}{\boldsymbol{RT\ell}} \qquad (2)$$

Where;
$\boldsymbol{J_i}$ = Membrane flux of component i, water, gfd
$\boldsymbol{\Delta p}$ = Applied pressure drop across the membrane, psi
$\boldsymbol{\Delta \pi}$ = Osmotic pressure drop across the membrane, psi
$\boldsymbol{A}$ = Water permeability constant, cm/atm s
$\boldsymbol{P_i}$ =Permeability of component i, water, cm^2/s
$\boldsymbol{c_{io}}$ = Initial mole concentration of water, ppm
$\boldsymbol{\nu_i}$ = Water molar volume, cm^3/mol
T = Water tempreture, K
$\boldsymbol{R}$ = Gas constant, $m^3 atm/mol\ K$
$\boldsymbol{\ell}$ = Membrane thickness which is assumed to be similar to spacer thickness, mil

Table 1. Data of RO Membrane Process at Abqaiq 500 RO Plant (Shedgum/Abqaiq groundwater) and the Two Seawaters Studied Scenarios [1, 4, 6, 7]

Parameter	Shedgum/Abqaiq Groundwater	Arabian Gulf Water Scenario	Red Sea Water Scenario
Membrane type	Toray TM720D-400 with 8”		
RO module	72 parallel membranes × 8 units		
Membrane thickness (ℓ) [3]	Assumed to be similar to spacer thickness of 34 mil		
Membrane area ($Area$) [3]	400 ft^2		
Max pressure drop per vessel (Δp)	~ 60 psi		
Max pressure drop per membrane (Δp)	~ 20 psi		
Water salinity ($\boldsymbol{c_{io}}$)*	~ 2800 ppm [4]	~ 41070 ppm [6]	~ 42070 ppm [7]
Membrane water flux (J_i)*	~ 18 gfd	~ 12 gfd	~ 12 gfd
Water temperature (T)	~ 25°C		
Water permeability constant (P_i)**	$9.5 \times 10^{-7}\ cm^2/s$		
Water molar volume (ν_i)	18 cm^3/mol		
Gas constant (R)	$8.2057 \times 10^{-5}\ m^3 atm/mol\ K$		

*Averaged values
** Taken from Paul (2004), regardless of the temperature effect on permeability; can be calculated at different temperatures from Maddah (2016).

Membrane resistance [8] constants for each BWRO Toray membrane has been calculated by using Equation (3).

$$\boldsymbol{J_i} = \frac{\boldsymbol{\Delta p}}{\boldsymbol{\kappa\, \mathcal{R}_m}} \qquad (3)$$

Where;
$\boldsymbol{J_i}$ = Membrane flux of component i, water, gfd
$\boldsymbol{\Delta p}$ = Applied pressure difference across the membrane, psi
$\boldsymbol{\kappa}$ = Dynamic viscosity of water, $Ib\ s/ft^2$
$\boldsymbol{\mathcal{R}_m}$ = Membrane resistance , ft^{-1}

Van't Hoff [9] osmotic pressure (π) formula can estimate the osmotic pressure of an aqueous solution from its molar concentrations of dissolved species. The overall required osmotic pressure drop $(\Delta\pi)$ for a water treatment plant has been investigated for the three various water sources from Equation (4).

$$\boldsymbol{\pi} = \boldsymbol{\mathcal{M}}\mathbb{R}\boldsymbol{T} \qquad (4)$$

Where;
$\boldsymbol{\mathcal{M}}$ = Molar concentration of dissolved species, mol/L
$\mathbb{R}$ = Ideal gas constant, 0.08206 $L\ atm/mol\ K$
$\boldsymbol{T}$ =Water tempreture, K

Equation (5) defines the ability of a membrane to separate salt from the feed solution which is known as membrane removal percentage (χ) and it increases with the applied pressure. The feed TDS concentration is taken from the three studied various sources, as shown in Table 1, while the outlet TDS concentration is determined by using Equation (5) at a similar removal percentage of Toray TM720D-400 with 8'' membrane that is 99.8%, Table 4. The water molecular weight $(18\ g/mol)$ should be used to convert our ppm values to molar concentrations of TDS.

$$\chi = \left(\frac{\boldsymbol{c_{jo}} - \boldsymbol{c_{j\ell}}}{\boldsymbol{c_{jo}}}\right) \times \mathbf{100} \qquad (5)$$

Where;
χ = Membrane removal percentage, %
$\boldsymbol{c_{jo}}$ = Initial mole concentration of component j, salt, ppm
$\boldsymbol{c_{j\ell}}$ = Final mole concentration of component j, salt, ppm

Table 2 shows the applied pressure drop per element (RO module) must be at 20 psi or below and must be 60 psi or below per vessel [4, 6]. The assumption of having an equal pressure on membranes per vessel would simplify our calculations. Altaee's study showed that permeate flow, pressure and recovery rate are distributed almost equally to membranes per RO vessel [10]. A field study confirmed an improved performance by rearranging the elements in pressure vessels in order to reduce the pressure drop and permeate conductivity across the vessel [11]. Typical flux rates and maximum recovery values for the groundwater and the two studied water source scenarios (Arabian Gulf and Red Sea waters) at Abqaiq 500 RO plant are given in Table 3.

Table 2. Operating Design Limits of the Overall RO Module at Abqaiq 500 RO Plant for Shedgum/Abqaiq groundwater [4, 12, 13]

Operating Limits	
Maximum Operating Pressure	600psi (4.1 MPa)
Maximum Feed Water Temperature	113°F (45 °C)
Maximum Feed Water SDI_{15}	5
Feed Water Chlorine Concentration	Not Detectable
Feed Water pH Range, Continuous Operation	2-11
Feed Water pH Range, Chemical Cleaning	1-12
Maximum Pressure Drop per Element	20psi (0.14 MPa)
Maximum Pressure Drop per Vessel	60psi (0.4 MPa)

Table 3. Characteristics of Groundwater Source and the Studied Water Sources at Abqaiq 500 RO Plant [4]

Water Source	Shedgum/Abqaiq Groundwater	Arabian Gulf	Red Sea
Feed silt density index	$SDI < 3$	$SDI < 4$	$SDI < 4$
Typical target flux, gfd	18	12	12
Max. element recovery, %	19	14	14

The determined osmotic pressure values for the RO membrane (Toray TM720D-400 with 8") of the groundwater and the two studied water source scenarios are used again in Equation (1) to calculate the applied pressure drop and suggested flux values. The same osmotic pressure drop for each case is utilized to determine the results of different Toray BWRO membrane types at high, low and standard operating pressure as shown in Table 4. It is worth mentioning that our applied pressure drop must be higher than the calculated osmotic pressure in order to have a positive flux.

Table 4. Various Toray Brackish Water RO 8″ Diameter Membranes [13, 14]

Category	Type	Rejection (%)	Thickness (mil)*
Standard BWRO	TM720-370	99.7	31
	TM720-440	99.7	28
High-pressure BWRO	TM720DA400	99.8	31
	TM720D-400	99.8	34
	TM720D-440	99.8	28
Low-pressure BWRO	TM720C-440	99.2	28
	TM720L-400	99.5	31
	TM720L-440	99.5	28

* Since enough data are not available, membrane thickness is assumed to be the same as spacer thickness to ease our calculations

TS-diagrams [7] are used to determine the exact value of water densities at different feed sources from the average water temperature and water salinity, Table 5. Exact water densities would allow us to convert gas constant values from $m^3 atm/mol\,K$ to kg $atm/mol\,K$ and advance our calculations.

Table 5. Water Densities at Different Sources from TS-diagrams [4, 6, 7, 15]

Water Source	Temperature (°C)	Salinity (ppm)	Density (kg/m^3)
Shedgum/Abqaiq Groundwater	25	2800 [2]	999.19
Arabian Gulf	25	41070 [4]	1027.97
Red Sea	25	42070 [6]	1028.67

4. RESULTS AND DISCUSSIONS

TM-720-370 and TM720-440 are standard BWRO membranes and TM720C-440, TM720L-400 and TM720L-440 are low-pressure BWRO membranes whereas TM720DA400, TM720D-400 and TM720D-440 are high-pressure BWRO membranes, Table 4.

Equations (1) and (2) allowed us to calculated osmotic pressure drop ($\Delta\pi$) for each water source; calculations are reported in Table 6. It is shown that the osmotic pressure of the groundwater source is less than Arabian Gulf and Red Sea water sources which is related to the flux rates and water salinity. Flux rate for Arabian Gulf and Red Sea waters are approximately half of the groundwater source. However, water salinity of the groundwater source is much lower than the other sources. Therefore, the required applied pressure drop must be larger in case of seawater sources due to the higher determined osmotic pressure values of these sources. Since the plant configuration has 8 elements per vessel, we should have a maximum osmotic pressure of 60 psi or less per vessel which is equivalent to a max pressure of 7.5 psi per membrane; assuming that the pressure is distributed equally on membranes per vessel. The selected applied pressure range for our study is 6.5 to 7.5 psi; maximum pressure values are assigned to the different membranes based on their category as illustrated in Table 7.

Table 6. Calculated Osmotic Pressure Drop ($\Delta\pi$) for Each Water Source from Equation (1) and (2)

Water Source	A (cm/ atm s)	J_i (cm/s)	J_i/A (atm)	Δπ (atm)	**Δπ (psi)**	Δπ per vessel < 60 (psi)
Shedgum/Abqaiq groundwater	0.00808	0.00083	0.10288	0.441	**6.48**	51.84
Arabian Gulf water	0.00755	0.00056	0.07417	0.470	**6.90**	55.21
Red Sea water	0.00754	0.00056	0.07430	0.470	**6.90**	55.20

Table 7. Assigned Pressure Values for Toray BWRO Membranes

Category	Type	Δp Range (psi)*
Standard BWRO	TM720-370	6.50 - 7.25
	TM720-440	6.50 - 7.25
High-pressure BWRO	TM720DA400	6.50 - 7.50
	TM720D-400	6.50 - 7.50
	TM720D-440	6.50 - 7.50
Low-pressure BWRO	TM720C-440	6.50 - 7.00
	TM720L-400	6.50 - 7.00
	TM720L-440	6.50 - 7.00

*High and low pressure values area taken relative to the standard pressure

The relation between the applied pressure drops and the overall water flux rates for the groundwater source are obtained in Figures 3, 4 and 5 for standard, high-pressure and low-pressure Toray BWRO membranes, respectively. Figure 3 shows that the maximum possible flux for the groundwater in the standard membranes is around 11 gfd for TM720-440 membrane, where in Figures 4 and 5 the highest observed groundwater flux in the high-pressure and low-pressure membranes are 14.7 gfd for TM720D-440 and 7.5 gfd for TM720C-440 and TM720L-440, respectively (blue and green lines overlap in Figure 5). This observation is associated with the membrane thickness in which the least membrane thickness (28 mil) has been capable to achieve the highest flux. This confirms an inverse relationship between the membrane thickness and the water flux rate. Further, there is a linear relation between the applied pressure drop and the overall water flux.

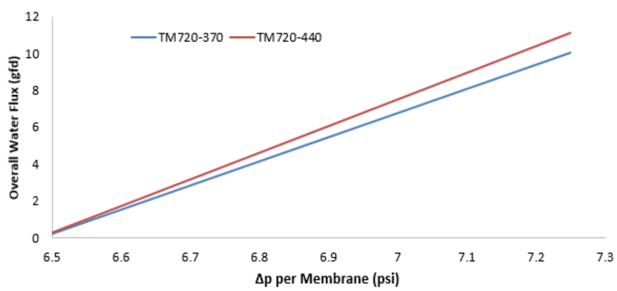

Figure 3. Effect of different applied pressures on the groundwater flux for Toray standard BWRO membranes

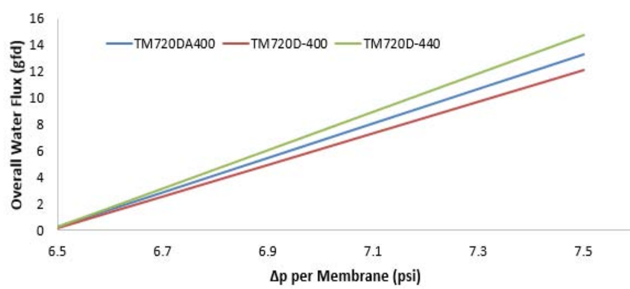

Figure 4. Effect of different applied pressures on the groundwater flux for Toray high-pressure BWRO membranes

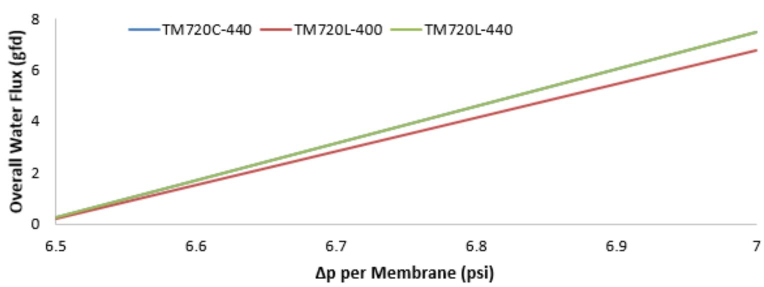

Figure 5. Effect of different applied pressures on the groundwater flux for Toray low-pressure BWRO membranes

Figure 6 identifies a proportional relation between the water flux and the applied pressure across the membrane. The highest recorded flux is accounted for TM720D-440 for Shedgum/Abqaiq groundwater because water TDS is low for groundwater and TM720D-440 has the lowest thickness and the highest pressure range. The Arabian Gulf and Red Sea water sources almost have similar flux rates at same applied pressures due to the similarities in their water salinity levels. TM720C-440, TM720L-400 and TM720L-440 membranes reserved the lowest flux values since they are categorized as a low-pressure BWRO membranes.

Figure 7 demonstrates the membrane resistance for the three studied water sources. Seawater sources have higher membranes resistances than the groundwater source because of having lower flux and higher TDS. TM720L-400 has the highest membrane resistance since it is in the low-pressure category and has the highest membrane thickness of 31 mil.

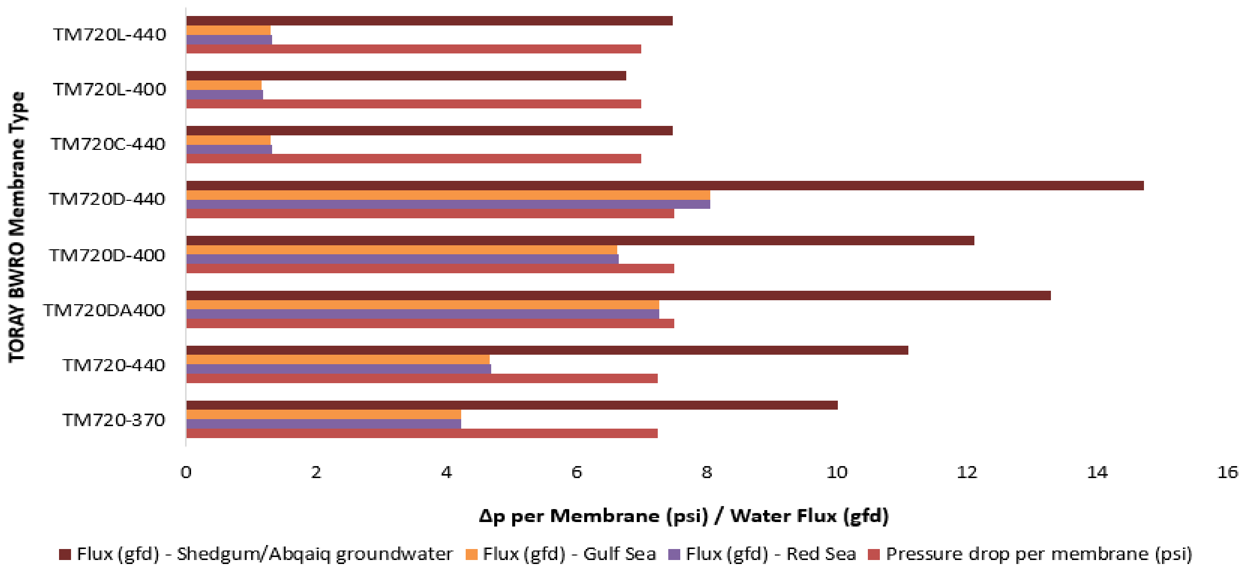

Figure 6. Observed water flux for various water sources at different applied pressures and Toray BWRO membranes

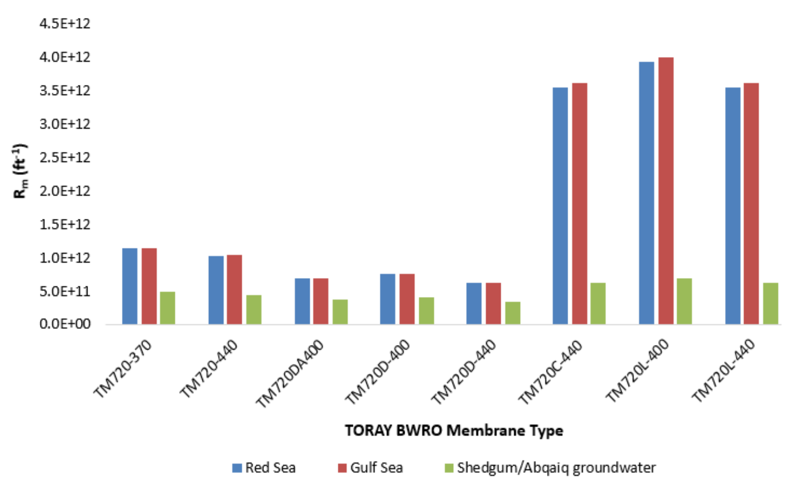

Figure 7. Observed membranes resistance of various water sources for Toray BWRO membranes

Equation (4) calculations are shown in Table 8. The study predictions estimated that the overall osmotic pressure drops required for seawater and groundwater treatment plants are approximately 55 psi and 830 psi, respectively. The higher the salinity difference between the fed and the produced water, the more the osmotic pressure drop we need to overcome in order to produce treated water (positive flux).

Table 8. Van't Hoff Calculations for the Required Osmotic Pressures for Water Sources

Water Source	Concenctrations (mol/L)		Mmebrane Removal (%)	Osmotic Pressure (atm)			$\lvert\Delta\pi\rvert$ (psi)
	TDS_{in}	TDS_{out}		π_{in}	π_{out}	$\lvert\Delta\pi\rvert$	
Shedgum/Abqaiq groundwater	0.156	0.00031	99.8	3.81	0.01	3.80	55.80
Arabian Gulf water	2.282	0.005	99.8	55.82	0.11	55.71	818.41
Red Sea water	2.337	0.005	99.8	57.18	0.11	57.07	838.34

5. CONCLUSIONS

The application of the solution-diffusion model to Abqaiq plant (500 RO plant) is initiated by using various parameters to calculate the osmotic pressure of Toray TM720D-400 with 8" membrane for Shedgum/Abqaiq groundwater treatment. For the same membrane, the osmotic pressure values are determined for Arabian Gulf and Red Sea waters to predict flux rates in other membranes for seawater situations. Low-pressure, standard and high-pressure BWRO Toray membranes performance have been compared to identify the optimal membrane kind for the treatment of the three studied water sources at Abqaiq 500 RO plant.

The assumption of having a membrane thickness that is similar to its spacer thickness may not seem very accurate. However, it is true that we should have a proportional relation between both thicknesses which suggests that our results are still valid. A linear relationship has been observed between the water flux and the applied pressure drops. It is proved that membrane flux decreases with the increase in membrane thickness at constant pressure drop. Modelling results endorse that BWRO Toray TM720D-440 with 8"membrane is the optimum membrane choice for the three water sources at Abqaiq 500 RO plant since it has the lowest membrane resistance and the highest overall water flux.

6. ACKNOWLEDGEMENTS

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Hisham A. Maddah [1] ; Mohammed A. Almugahwi [2]

(1) Department of Chemical Engineering, King Abdulaziz University, Rabigh, Saudi Arabia, (2) Department of Abqaiq Plant Operation Engineering, Saudi Aramco Company

Introduction

The solution-diffusion model is popular technique that is used to explain the transport in dialysis, reverse osmosis, gas permeation and pervaporation. In the solution-diffusion model, the pressure within a membrane is uniform and that the chemical potential gradient is expressed only as a concentration gradient.

Purpose

This paper suggests a new method of predicting flux values at reverse osmosis (RO) desalination plants. The study is initiated by using the solution-diffusion model that is applied to the groundwater source at Abqaiq plant (500 RO plant) at Saudi Aramco, Dhahran, Saudi Arabia in order to calculate the osmotic pressure of the treated water for Shedgum/Abqaiq groundwater.

Methodology & Data

Values of numerous parameters such as water permeability constant, applied pressure, gas constant, water temperature, water molar volume and membrane thickness, water salinity/TDS are taken into account to develop our calculations through the solution-diffusion model. A comparison between low-pressure, standard and high-pressure BWRO Toray membranes performance have been established to select the ideal membrane type for the treatment of water from various sources at Abqaiq plant.

Abqaiq 500 RO plant data has been used to determine osmotic pressure drops for the RO membrane (Toray TM720D-400 with 8") from Eq. (1) and (2).

However, in order to calculate the osmotic pressure for seawater sources, we applied the same information of Shedgum/Abqaiq groundwater at Abqaiq 500 RO plant, except for the flux and salinity values, for the treatment of either Arabian Gulf or Red Sea waters. Water permeability is approximately determined to be $9.5 \times 10^{-7}\ cm^2/s$. For water-salt solution, reverse osmosis permeation expression is simplified in Eq. (1) and (2); where membrane resistance constants are calculated by using Eq. (3).

$$J_i = A(\Delta p - \Delta \pi) \qquad (1)$$

$$A = \frac{P_i c_{io} \nu_i}{RT\ell} \qquad (2)$$

$$J_i = \frac{\Delta p}{\kappa \mathcal{R}_m} \qquad (3)$$

Where;

J_i = Membrane flux of component i, water, gfd

Δp = Applied pressure drop, psi

$\Delta \pi$ = Osmotic pressure drop, psi

A = Water permeability constant, cm/atm s

P_i = Permeability of component i, water, cm^2/s

c_{io} = Initial mole concentration of water, ppm

ν_i = Water molar volume, cm^3/mol

T = Water tempreture, K

R = Gas constant, $m^3 atm/mol\ K$

ℓ = Membrane or spacer thickness, mil

κ = Dynamic viscosity of water, $Ib\ s/ft^2$

$\mathcal{R}_m$ = Membrane resistance , ft^{-1}

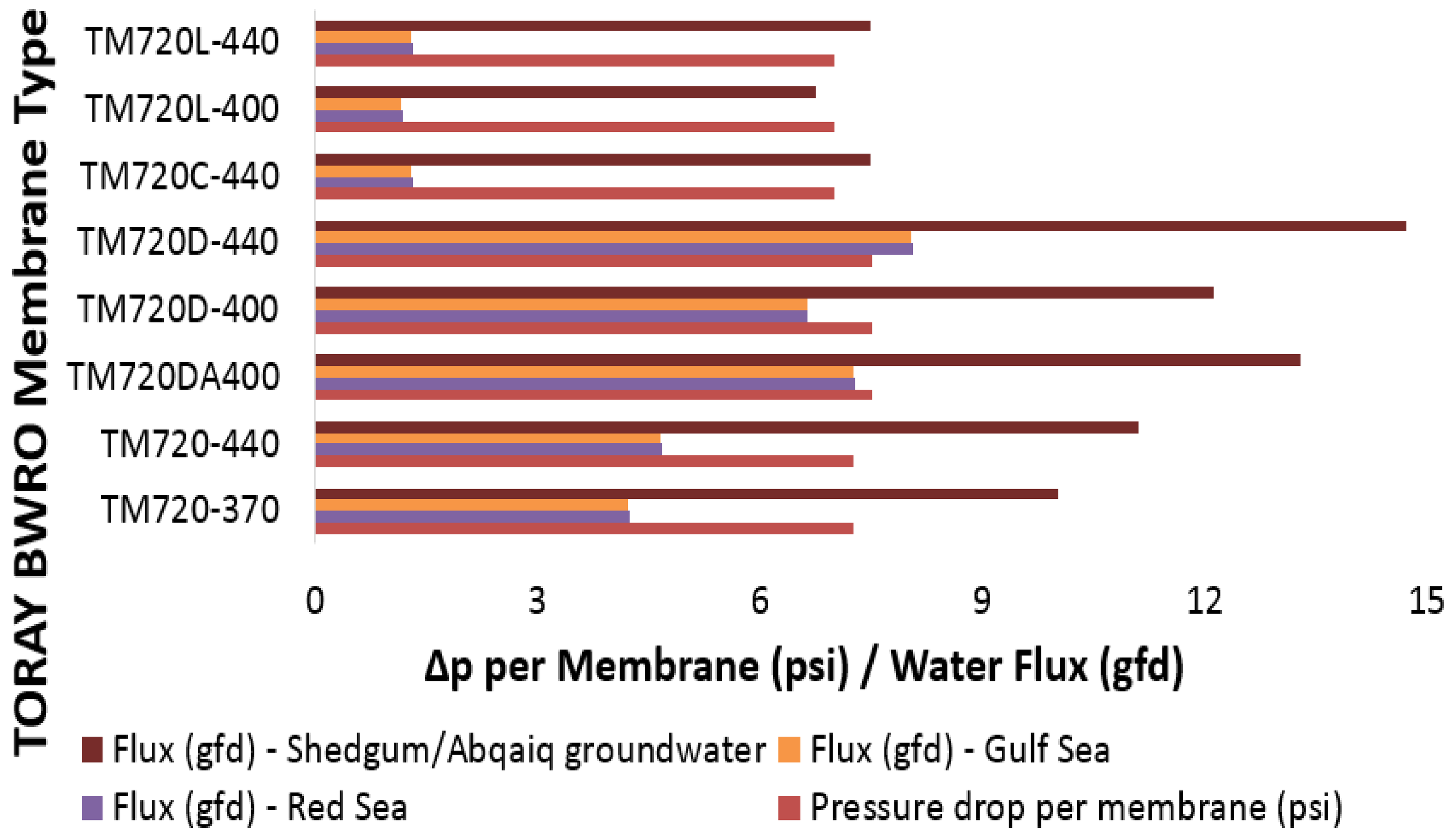
Above equations are used to calculate osmotic pressures of the three water sources and then utilized to determine the appropriate flux and resistance of different BWRO Toray membranes.

Results

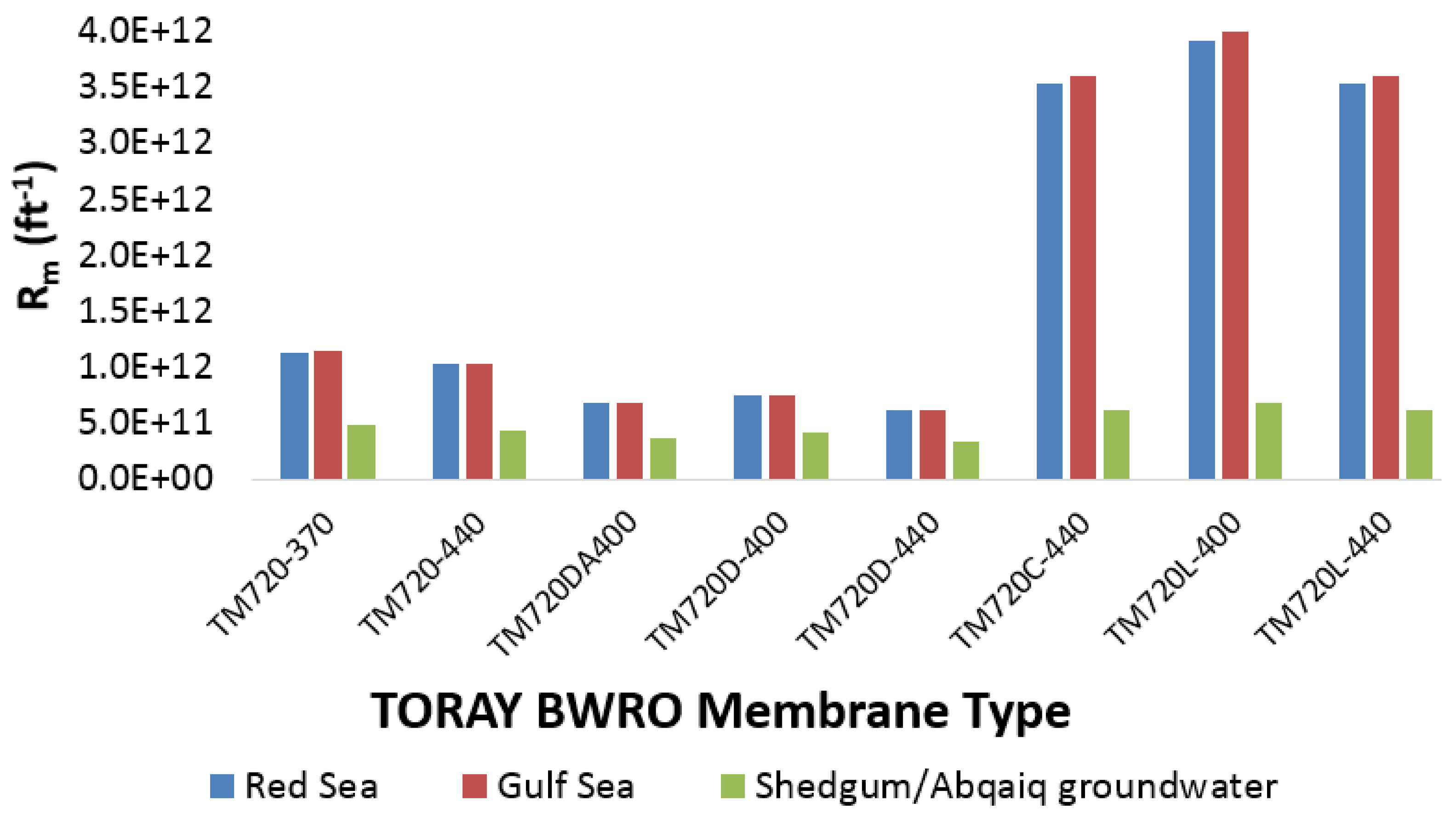
A proportional relation between the water flux and the applied pressure is identified. The highest recorded flux is accounted for TM720D-440 for Shedgum/Abqaiq groundwater because of low water TDS, low membrane thickness and the highest pressure operating range. Seawater sources have higher membranes resistances than the groundwater source because of having lower flux and higher TDS.

Calculated Osmotic Pressure Drop ($\Delta\pi$)

Water Source	Δπ (psi)	Δπ per vessel < 60 (psi)
Shedgum/Abqaiq groundwater	6.48	51.84
Arabian Gulf water	6.90	55.21
Red Sea water	6.90	55.20



Observed water flux for various water sources at different applied pressures and Toray BWRO membranes



Observed membranes resistance of various water sources for Toray BWRO membranes

Conclusion

The model results confirm an inverse relationship between the membrane thickness and the water flux rate. Also, a proportional linear relation between the overall water flux and the applied pressure across the membrane is identified. Higher flux rates and lower salinity indicate lower membrane resistance which yield to higher water production. Modelled data predict that BWRO Toray TM720D-440 with 8"membrane is the optimal BWRO membrane choice for the three water sources at Abqaiq 500 RO plant since it has the lowest membrane resistance and the highest overall water flux.

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