An Operational Study and Modeling of a Reverse Osmosis Desalination System

Marwa Asad Salih 1,* , Asmaa H. Dhiaa 2 and Zainab Hasan Abdulabbas 3

1Department of Chemical Engineering, Faculty of Engineering, University of Kufa, Najaf, Iraq - E-mail: marwa.salih@uokufa.edu.iq
2Department of Chemical Engineering, Faculty of Engineering, University of Kufa, Najaf, Iraq - E-mail: asmaah.alhusseini@uokufa.edu.iq
3Department of Civil Engineering, Faculty of Engineering, University of Kufa, Najaf, Iraq - E-mail: zainab.alhasnawi@uokufa.edu.iq
* Corresponding author: Chemical Engineering, University of Kufa, Najaf, Iraq.
Tel: +9647709751899.

Abstract. The desalination of brackish water is one of the common issues in the world and spiral wound membrane is mostly used in desalination systems in home and industrial level, in this study a spiral wound brackish water membrane element were used to study the reverse osmosis system practically with the effect of multiple operational parameters and by creating Matlab Simulink modeling to analyze the RO system performance depending on concentration polarization theory then compare both results. The parameters that studied were flow rate range (0.6, 1, 1.3, 1.6, and 2 cm3/s), concentration (100, 200, 300, 400 and 500 ppm), and temperature (15, 25 and 35 °C), of the feed and mass transfer coefficient for the permeate water, the salts that used (CaCl2 and KCl) and by the concentration polarization (a phenomenon of accumulation of solute) the salts will tangle up at the surface of the membrane and affect membrane efficiency. The results indicated that the membrane operation is response sensitively to variations in feed temperature. The modeling results indicated that the major effect on the membrane parameters is the feed temperature and concentration of the salt.

Keywords: Desalination; RO Simulation; Reverse Osmosis; mass transfer coefficient; Spiral Wound Membrane.

1. Introduction

Water covers about 70% of earth’s surface and it’s a vital element for all living beings. Despite that the major part of earth is covered by water, still there is a huge shortage of drinking water across the world in many countries. Desalination of sea water considers as one of the solutions of this problem. Applying desalination methods to seawater and brackish water can be depended as successful alternatives in many
situations, desalination is a technology where extra salts removed from brackish and seawater and it categorized into two processes thermal and membrane. (Thimmaraju et al., 2018). Water quality is usually improved with the use of reverse osmosis systems RO. This method was used to treat water on a large scale to convert salt water or sea water into drinking water, and is also used in cleaning sewage, and in industrial processes to recover salts and reuse them. These systems for water purification have become an essential part of many homes and are common in the market as well, where home owners always want to ensure that there are no chemicals to disturb the quality of drinking water (taste, color and smell) and pollutants that may affect their health. RO system is working to removes several inorganic impurities from drinking water, its performance depends on feed water, temperature, feed flow, and pressure in addition to the type of the membrane it’s differ in capacity and vary in their impurities rejection characteristics. (KNEEN et al., 2005). The polymer membrane affected in a sensitive way to any changes in the feed temperature. Its noticed that when feed temperature raised from 20°C to 40°C the permeate flux goes up to a 60 %, while it decreased when decreasing the feed flow rate from 17.8 to 9.0 L/min this happened under same temperature. Enhancing solute reinforcement at the surface of the membrane will increase the resistance to flux. There is a linear relationship between flux and pressure. A Spiegler-Kedem film theory model results match the experimental data that suggest the spiral wound type membrane is affected by smaller differences amount the feed flow rate and feed temperature. The modeling experiments showed that the salt concentration of the feed and the temperature are affect the mass transfer coefficient. (Goosen et al., 2004, cited by Santos et al., 2016).

RO model were built using Matlab and Thermolib to perform a numerical analysis for brackish water desalination production for several purposes found that all salts rejection could lowered by 9% to get high quantities water suitable for agricultural use, and physically by increasing the average pore size will reduce power consumption of the system (Sarai Atab et al., 2016). The comparison between model and practical results showed that these parameters matches with the practical data with comparatively high exactness. It found that at the temperature range from 0°C to 60°C the RO system operate in high stability (Jiang et al., 2014). A semi-rigorous mathematical model used to simulate an industrial brackish water RO plant, comparing the real data with model results showed a high accuracy in prediction the steady-state behavior of the RO were the general recovery value of water is 0.37 and rejection is 1.33%, a deterioration of the quality of the product noticed when increasing the pressure further than an assured value, water production could decreased if there a trans-membrane pressure difference reduced due to a drop in high frictional pressure. (Abbas, 2005, cited by Alsarayreh et al., 2020).

A drop in the permeate quality and a failing in product quality notice due to high flow feed rates and high operating pressures respectively (Abbas and Al-Bastaki, 2005, cited by Alsarayreh et al., 2020). Concentration polarization can be abandoned at higher feed flow rate. Increasing feed flow rate caused a decrease in the permeate concentration. the water flux with non-linear behavior increased by increasing operating pressure (Kaghazchi et al., 2010). It found that raising in the concentration level at the wall of the membrane caused by increasing module area, feed concentration, and feed pressure. Increasing feed flow rate and temperature would decrease concentration value of membrane wall (Kotb et al., 2015). The feed flow rate and feed pressure positively affected the salinity of permeate water (Al-Obaidi et al., 2018). It confirmed that the RO modeling showed a lower deviation after comparing its predicted data with the real data. In same subject, many simulation studies working to make assessment and prediction to the effect of variation in operating conditions of the RO system on the process indicators ( Alsarayreh et al.,2020).

2. Material and methods
2.1 Experimental Process

The spiral wound membrane is made of flat membrane sheets connected from all sides except one to connect the Collector channel materials permeate to be like a sheet, typically the polymer spiral wound module containing between 26 and 28 layers with about 40 m² of active membrane area and it is 9 cm in diameter and 15 cm in length.

Brine feed solutions were prepared in the glass vessels and fed to the Ro system by gravity of 9 m height (88.2 Kpa) to gives uniform feed of flow, it passes through three filters (5 microns) to remove
macromolecules and suspended solids then to the membrane by a high-pressure pump. The experiment was carried out for (KCl and CaCl₂) individually with different concentrations (100, 200, 300, 400 and 500ppm) to get brine feed, flow rate was varied (0.6 - 2 cm³/s) and for feed temperature (15 - 35 ºC).

2.2 Modeling Process

Solution diffusion model were used to describe our reverse osmosis mathematically. It assumes that the driving force of permeation is the gradient in chemical potential of the solute (Wijmans and Baker, 1995). the terms of solvent flux (J) were used to express the transport equation as below:

\[ Jv = A (\Delta P - \sigma \Delta \pi) \]  (1)

Aw: permeability of solvent (m s⁻¹ Pa⁻¹)
\( \Delta P \): pressure (Pa).
\( \Delta \pi \): difference in osmotic pressure (permeate - membrane surface) (Pa).
\( \sigma \): reflection coefficient.

Most of recent reverse osmosis and Nano filtration separations adopt equation (1) at the beginning of the design, it describes the behavior of the membrane where a layer of local concentrated (CP) will be created by high salt concentration at or close to the surface of membrane, this elevated salt concentration is a result of the rejection of ionic species, this layer shortly reaches a steady state, and the transverse solute flux through the CP layer is constant (Eric et al., 2002, Jeffrey et al., 2007).

The solvent flux (J) will be calculated by the below equation with steady state mass balance through CP:

\[ Jv \cdot Cp = Jv \cdot C - \left( D \frac{dc}{dx} \right) \]  (2)

Jv: permeate flux across the membrane L/m² h
Cp: concentration of permeate solute (kg/m³).
C: concentration of solute at the boundary layer (kg/m³).
D: coefficient of solute diffusion in water (m²/s) (Dharmesh, 2002).

Mixing the finite mass boundary layer thickness (δ), out to the convection diffusion mass balance, produces the relationship between CP and permeate flux:

\[ CP = \frac{Cm - Cp}{Cb - Cp} = \exp\left(Jv \right) \]  (3)

Cm: concentration at the membrane surface of the rejected salt (kg/m³).
Cb: solute concentration (bulk) (kg/m³).
K: Mass transfer coefficient (m s⁻¹)
Jv: permeate water flux (L/m² h) (Kim, S. Eric M.V. Hoek, 2005).

2.3 Simulation procedure

The Matlab/Simulink blocks software version R2017b (9.3.0.731579) were used to build a numerical model to analyze the design and examine the performance of any reverse osmosis system, this model designed based on theory of solution diffusion and the results obtained from the experimental work. The properties and mass transfer coefficient compared with the real data obtained from the experimental work, since the designed model affected by feed temperature and flow rate obviously.
3. Result and Discussion

3.1 Effect of feed flow rate on Mass transfer coefficient

Mass transfer coefficient increases with the increase in feed Flow Rate as shown in figures (1 and 2) for calcium chloride and potassium chloride respectively for comparison between both results experimental and modeling.

The figures show that increasing in feed Flow Rate leads to an increase in driving pressure for fluid flow and increase in turbulent flow respectively. This would prevent or decrease the concentration buildup in the solution at the surface membrane. In other words, the thickness of the concentration boundary solution will be less while the diffusivity of solute stays constant. Therefore, the mass transfer coefficient increases steadily relatively to the increase in the Feed Flow Rate.

![Figure 1. Effect of feed Flow Rate on K for CaCl₂](image-url)
3.2 Effect of feed temperature on Mass transfer coefficient

By increasing the feed temperature, the rate of water permeation increase through the membrane and then we obtained higher diffusion rate of water through the membrane due to the reduction in solution viscosity.

The real data show that the spiral wound polymer membrane is reflecting high sensitivity to feed temperature. The membrane productivity is very sensitive to deviation in feed water temperature. As water temperature increases, water flux linearly increases, mainly this because high level of diffusion rate of water through the membrane. Therefore, (K) increases with the increase in feed temperature as shows in figures (3 and 4) for calcium chloride and potassium chloride real and model respectively, while figure (5) illustrate the difference between the effects of feed flow rate on different salts with same concentration.

Figure 2. Effect of feed Flow Rate on K for KCl
Figure 3. Effect of feed Temperature on Mass Transfer Coefficient CaCl$_2$

Figure 4. Effect of feed Temperature on Mass Transfer Coefficient KCl
4. Conclusions

After making this comparison between the results showed that, the calculated values were consistent with experimental data. Evaluation of the operational data with model results presented that the model predicts the steady-state performance of the plant with respectable accuracy. Increasing the operating feed flow rate will reduce concentration polarization (CP) value and decreases the permeate concentration. The experiment data shows that when temperature of feed water is increased from 15 to 35 °C, the permeate salinity ppm TDS increases from 70 - 115 ppm TDS. Mass transfer coefficient increase with the increase in feed Flow Rate and feed temperature. For different salt feed is recognized that the selectivity of reverse osmosis is not to be based on a separating mechanism.

References

[1] Thimmaraju,M., Sreepada,D., Babu,G.S., Dasari,B.K, Velpula,S.K, & Vallepu,N.( 2018). Desalination of Water. 333-347.
[2] KNEEN, B., LEMLEY, A., & WAGENET, L. (2005). Reverse Osmosis treatment of Drinking Water. (November 2005).
https://docplayer.net/1739733-Water-treatment-notes-cornell-cooperative-extension-college-of-human-ecology-reverse-osmosis-treatment-of-drinking-water.html
[3] Goosen, M.F.A., Sablani, S.S., Al-Maskari, S.S., Al-Belushi, R.H. (2004). Effect of feed temperature and flow rate on permeate flux in spiral wound reverse osmosis systems. Second LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCEI'2004), Miami, USA).( B Santos, JG Crespo, MA Santos, S Velizarov, (2016). Oil refinery hazardous effluents minimization by membrane filtration: An on-site pilot plant study. Journal of Environmental Management).
[4] Sarai Atab, M., Smallbone, A.J., Roskilly, A.P. (2016). An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation. Desalination (174-184).

[5] Jiang A., Ding Q., Wang J., Jiangzhou S., Cheng W., Xing C., (2014). Mathematical modeling and simulation of SWRO process based on simultaneous method. Journal of Applied Mathematics.

[6] Abbas, A. (2005). Simulation and analysis of an industrial water desalination plant. Chemical Engineering and Processing. (44, 999–1004). (Alsarayreh A. A., Al-Obaidi M.A., Patel R., & Mujtaba I.M. (2020). Scope and Limitations of Modelling, Simulation, and Optimisation of a SpiralWound Reverse Osmosis Process-Based Water Desalination. MDPI. AG.)

[7] Abbas, A.; Al-Bastaki, N. (2005). Modeling of an RO water desalination unit using neural networks. Chemical Engineering and Processing. (114, 139–143). (Alsarayreh A. A., Al-Obaidi M.A., Patel R., & Mujtaba I.M. (2020). Scope and Limitations of Modelling, Simulation, and Optimisation of a SpiralWound Reverse Osmosis Process-Based Water Desalination. MDPI. AG.)

[8] Kaghazchi, T., Mehri, M., Ravanchi, M.T., & Kargari, A. (2010) A mathematical modeling of two industrial seawater desalination plants in the Persian Gulf region. (Desalination 2010, 252, 135–142).

[9] Kotb, H., Amer, E., & Ibrahim, K. (2015). Effect of operating conditions on salt concentration at the wall of RO membrane. (Desalination 2015, 357, 246–258).

[10] Al-Obaidi, M.A., Alsarayreh, A.A., Al-Hroub, A.M., Alsadaie, S., & Mujtaba, I.M. (2018). Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant. (Desalination 2018, 443, 272–284).

[11] Wijmans, J.G. & Baker, R.W. (1995). The Solution-Diffusion Model. (107(1-2) (1-21).

[12] Eric M.V. Hoek, Albert S. Kim, & Menachem Elimelech. (2002) Environmental Engineering Science 19(2002) 6.

[13] Jeffrey, R. McCutcheon, & Menachem Elimelech. (2007) American Institute of Chemical Engineers, 53, July (2007)7.

[14] Dharmesh S. Bhanushali. (2002). Solvent- Resistant Nanofiltration Membranes Separation Studies and Modeling. Ph.D Thesis, University of Kentucky, (2002).

[15] Kim, S. Eric M.V. Hoek. (2005). Modeling concentration polarization in reverse osmosis processes. Desalination 186 (2005) 111 128.