Effects of Different Designs of Pressure Vessels on Efficiency and Energy Consumption of Reverse Osmosis Systems

Shamsedin Ghourejili [a], Sina Yaghoubi [a], Farrokhfar Valizadeh Harzand [a], Aziz Babapoor [*a]

[a] Department of Chemical Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

Abstract

One of the cost-effective methods of water purification is reverse osmosis. In the present work, the effect of pressure vessels with different numbers of membranes in two types of reverse osmosis system design is investigated. Simulation results showed that pressure vessels with more membranes have lower energy consumption and higher efficiency in different simple and hybrid designs of reverse osmosis systems. Findings showed that the first design performs better in terms of energy consumption and efficiency than the second design. The study also showed that maximum efficiency was achieved using the first design of the hybrid two-stage brackish water reverse osmosis system. The least efficient system was the hybrid single-stage seawater reverse osmosis system.

Keywords: Pressure vessel; Reverse osmosis; Energy consumption; Efficiency; Seawater reverse osmosis; Brackish water reverse osmosis

[*] Corresponding author: Department of Chemical Engineering, University of Mohaghegh Ardabili, P.O. Box 179, Ardabil, Iran

E-mail address: babapoor@uma.ac.ir, babapoor2006@yahoo.com

Tel/Fax Number: +98-45-31505757

1. Introduction

In recent years, the use of membranes and membrane processes has constantly been increasing [1]. One of the main applications of membranes is desalination, one of the main methods of producing freshwater [2]. In addition, membranes are used in many fields, such as electrodialysis, electroosmosis processes, and drug purification [3-5]. Simulation techniques have been used directly and indirectly in most areas of membrane processes [6-8]. Simulations of membrane-based processes are useful in predicting processes and enable fast and cheap optimization [9]. Saltwater desalination has become an important method to overcome the global shortage of fresh water. Thanks to the development of water desalination methods, fresh water supply can be increased beyond what the hydrological cycle can provide [10]. The processes involved in reverse osmosis (RO) systems are well-developed and unparalleled in case of reliability and energy efficiency. Due to these reasons, they have become the most popular method of purifying water among other available technologies. Thus, many researchers are putting efforts into developing RO systems to make utilization of these systems as a reliable source of supplying freshwater feasible [11, 12]. Currently, multi-stage flash distillation (MSF), multi-effect distillation, vapor compression (VC), RO, and electrodialysis (ED) are the most popular commercially available methods of desalination [13, 14]. Most popular desalination processes rely on fossil fuels for energy [13-17].

Ludwig [18] investigated the energy usage of seawater RO (SWRO) systems and analyzed the possibility of bettering their layout and function with Energy Recovery Instruments (ERIs). Data revealed that for purifying a seawater sample having a total dissolved solids (TDS) equal to 35,000 ppm, approximately 3.5 W.h/m^3 of energy is typically used. Park *et al.* [19] theoretically analyzed low-energy SWRO plants. Methods of improving the energy efficiency of RO units have been divided into two groups: direct and indirect. An example of a direct method is diluting the feedwater, while an example of an indirect method is reducing the difference in osmotic pressure. Unlike thermal desalination methods, the amount of TDS in seawater predominantly affects SWRO desalination systems. Feed water salinity determines the osmotic pressure and pumps' workload. Thus, it affects the amount of energy consumption in SWRO plants. Based on prior studies, water with the highest quality can be produced using different internally staged designs (ISD) with the full flow to the second pass. The cost of producing water using a system with permeate splitting mechanisms is estimated to be 8% lower than when a system with a full two-pass configuration is used. In addition, also by integrating permeate bypass mechanisms, the costs of water production can be lowered by 6% [20]. Research by Altaee *et al.* [21] demonstrated that for desalinating seawater, systems that utilize forward osmosis (FO) and RO have a higher recovery rate than conventional RO systems. Studies showed that the recovery rate does not exceed 50% by using less saline feed water due to scaling issues. However, since the draw solution in FO systems gets highly concentrated, these issues do not affect such systems, indicating that the recovery rate in FO-RO units can be increased beyond 50%. For purifying feeds like seawater, which contain high levels of TDS, high hydraulic pressures must be applied, increasing the amount of energy desalination plants consume. In such scenarios, lower levels of energy consumption can be achieved by lowering the feed's osmotic pressure.

In recent studies, researchers suggested several osmotic pressure reduction methods. Studies by Mustaqimah *et al.* [22], where ROSA was employed, demonstrated that applying higher feed water pressures yields permeate water containing more TDS. Based on results obtained using ROSA, it was found that the recovery rate and permeate TDS are higher in two-stage systems compared to single-stage ones. Joseph and Damodaran [23] dynamically simulated the SWRO process using LabVIEW to help understand the dynamics of processes involved in SWRO plants. Simplified functional-decomposition approach modelings were employed to perform RO desalination process simulations to understand the dynamics of the processes. Comparing the results of dynamic simulations with transient ones and using operational data of real-world desalination plants, it was found that reasonably raising the feed's temperature reduces specific energy consumption (SEC) for various recovery rates within RO systems. According to investigations by Al-Obaidi *et al.* [24], parameters such as feed flow rate and pressure could be adjusted to lower the permeate in brackishwater RO (BWRO) plants. The costs of desalinating highly saline feeds using BWRO plants can be lowered using energy recovery devices (ERDs), as shown by Pearson *et al.* [25]. Through ROSA simulations, Oh *et al.* [26] validated that higher flow flux in RO plats increases permeate quality. However, doing so increases the overall energy consumption of RO plants. According to comprehensive pieces of information collected by Kim *et al.* [27] on factors affecting the energy consumption of SWRO plants, high SEC is the main issue of RO systems. Wilf *et al.* [28] demonstrated that upping the amount of high-rejection membranes and ERDs could be employed to cut the operational cost of RO systems. Fig. 1 shows the processes that are involved in an SWRO plant.

Seawater desalination can be summarized in four steps: pumping seawater to the plant, pretreatment of water, desalination in the RO system, and post-treatment of permeate. Seawater gets pressurized and pumped into the pressure vessel (PV) of the RO unit containing several RO membranes. For increasing the recovery rate of RO units, up to 8 RO elements are often placed inside PVs [29-32]. Technically, PVs are tanks, vessels, and pipelines that receive, carry, or store fluids, and their internal pressure differs from the outside pressure. Unlike tanks, PVs are not limited to atmospheric pressure [33].

As seawater moves through the PV, the desalination rate gradually decreases, leading to a steady increase in salinity, creating a highly saline solution at the PV outlet, causing scale formation on membranes located near membranes and consequently lowering the recovery rate. As a result, antiscalants, chemical softening of feed water, and membrane treatment typically must be employed in RO plants [31, 32, 34-36]. Scale removal solutions are not always cost-effective. Thus, central feeding was proposed as a substitute for conventional anti-scaling measurements in SWRO units [37]. In central feeding, a central port distributes feedwater evenly on both sides of the PV. Central feeding in SWRO plants reduces the likelihood of scale formation on the last membrane elements, but this design demands higher feed flow rates. Another method for controlling scale formation and fouling is using membranes modified using nanomaterials that prevent fouling [38]. Simulation performed by Altaee [32] showed that as the desalination capacity and feed's silt density index (SDI) increase, using PVs with central feeding becomes more economical than using other designs. Investigations by Kim *et al.* [39] showed that mixing the rejected brine of the last membranes with the feed water and returning it to the system improves the quality of permeate by 15%.

Despite the abundance of research on RO systems and the recent surge of publications, there remain essential deficiencies in studies of how different PV designs influence crucial factors such as RO plants' efficiency and energy consumption. Thus, in this paper, how two different PVs, each containing a different number of membranes, affect the energy consumption and efficiency of different RO systems is evaluated.

2. Materials and methods

In this paper, SWRO and BWRO plants having desalination capacities equal to 700 m^3⁄day and 300 m^3⁄day, respectively, were assumed. Different hybrid and simple SWRO and BWRO systems, each having PVs with different numbers of membranes, were designed. Feeds used for BWRO systems were assumed to have a TDS ranging from 700 to 1450 ppm. SWRO systems were assumed to use feeds with a TDS ranging from 21500 to 42000 ppm.

Commercially available BW400ES and BW400R were used in BWRO systems, and SW400GR and SW400R membranes were used in SWRO systems. For hybrid and simple single-stage BWRO systems, 3-element and 4-element PVs were used. BW400R membranes were used in 3-element PVs, and BW400ES membranes were used in 4-element PVs. In hybrid and simple two-stage BWRO systems, 4-element, 2-element, and single-element PVs were used. In SWRO systems, 8-element and 7-element PVs were used. The model was validated under a frame of recommended guidelines. PVs with 4 membranes were used to save money and energy. The membranes' specifications are provided along with flow rate, inlet flux, and produced water in Table 1.

The number of required membranes was calculated using Equation 1, which is provided in the following:

$$N = \frac{\text{Produced water} \times 1440\ ({}^{gpm}\!/\!_{gpd})}{\text{Inlet flux}\ (gfd) \times \text{membrane surface area}\ (ft^2)} \tag{1}$$

BWRO and SWRO unit simulations were performed assuming a well water sample with an SDI<3 is about to be desalinated. According to design guidelines, in such operating conditions, the value of inlet flux must be 16 to 20 GFD and 8 to 12 GFD for BWRO and SWRO systems, respectively [40]. Specifications of the investigated designs of simple and hybrid two-stage RO units are given in Tables 2 and 3.

3. Results and discussion

3.1. Effects of different designs of PVs on energy consumption in simple and hybrid designs of RO systems

Fig. 2 shows that a rise in the amount of TDS in feed water increases the amount of consumed energy in simple and hybrid single-stage SWRO systems. From Fig. 2, it can be deduced that using feeds containing high amounts of TDS increases the osmotic pressure, ultimately increasing the pumps' workload and energy consumption [41-43]. Fig. 2 also shows that there is not much difference in the amount of consumed energy in simple and hybrid single-stage SWRO systems.

Fig. 3 shows the energy consumption in simple and hybrid two-stage BWRO systems. Based on Fig. 3, highly saline feeds, due to having higher osmotic pressures, increase the workload of pumps and, as a result, the system's energy consumption [41, 42, 44, 45]. Fig. 3 also shows that among the investigated designs, the first design consumes less energy than the second design. Based on Fig. 3, the first design requires fewer PVs if the number of membranes does not change. Therefore, the first design is more economical than the second design.

Fig. 4 demonstrates that as the TDS of the feedwater increases, the energy consumption of simple and hybrid single-stage BWRO systems increases. Additionally, hybrid single-stage systems consume less energy than simple ones due to the placement of membranes with the highest removal percentage upstream of the PV and membranes with the highest flux percentage (FP) downstream of the PV [41, 42]. Fig. 4 shows that simple two-stage configurations consume less energy than hybrid two-stage configurations.

3.2. Effects of different designs of PVs on efficiency in simple and hybrid designs of RO systems

Fig. 5 demonstrates that highly concentrated saline feeds diminish the effectiveness of simple and hybrid single-stage SWRO units [41, 42, 46]. Based on Fig. 5, it is clear that the performance of single-stage hybrid SWRO systems is negligibly affected by the TDS of the feed. The efficiency of simple single-stage designs in SWRO systems is higher than in BWRO systems. The general deduction is that simple single-stage configuration of SWRO systems is more efficient than hybrid single-stage ones. Therefore, if the number of membranes used does not change, using a simple single-stage design not only increases the system's efficiency but also reduces the number of PVs required, lowering the construction costs of the SWRO plant.

Fig. 6 demonstrates that in specific ranges, the TDS of feed does not majorly impact the efficiency of simple and hybrid two-stage BWRO units. Simple two-stage designs' efficiency is higher than hybrid two-stage ones. Consequently, simple two-stage designs are more economical regarding construction and operating costs in similar conditions than their hybrid two-stage counterparts.

Fig. 7 displays how the feed's TDS affects the efficiency of both simple and hybrid configurations of single-stage BWRO plants. It is evident that, in specific ranges, increasing the TDS of the feedwater does not impact the efficiency of RO systems. Furthermore, simple single-stage configurations seem more efficient than hybrid single-stage ones.

The efficiency of different RO systems investigated in this study is summarized in Table 4. The highest efficiency is seen in two-stage hybrid BWRO systems. The least efficient systems were single-stage hybrid SWRO units.

4. Conclusion

RO technology is an emerging method of water treatment. The effects of different designs of PVs on the efficiency and energy consumption in simple and hybrid designs of RO units were investigated in this paper. Simulation of simple and hybrid single-stage systems for seawater desalination showed that there was not much difference between the amount of consumed energy in such designs of SWRO systems. The results showed that in simple and hybrid two-stage and single-stage BWRO plants, energy consumption in the first design was much less than in the second design. For seawater desalination, the first design of the simple single-stage system has higher efficiency than the second design. However, the first design of the hybrid single-stage system is no more efficient than the second design. For brackish water desalination, simulations showed that the RO system designs with a lower number of PVs and more membranes have higher efficiency and lower energy consumption than designs with a high number of PVs and a lower number of membranes. Furthermore, for seawater desalination, simple single-stage designs with fewer PVs and more membranes have higher efficiency than designs with a high number of PVs and a lower number of membranes.

References

1. Guo, Y., C. Liu, H. Liu, et al., "Contemporary antibiofouling modifications of reverse osmosis membranes: State-of-the-art insights on mechanisms and strategies". *Chemical Engineering Journal*, **429**, pp. 132400 (2022).
2. Tawalbeh, M., L. Qalyoubi, A. Al-Othman, et al., "Insights on the development of enhanced antifouling reverse osmosis membranes: Industrial applications and challenges". *Desalination*, **553**, pp. 116460 (2023).
3. Khosravikia, M., "Quantitative model for predicting the electroosmotic flow in dual- pole nanochannels". *Electrophoresis*, **44**(7-8), pp. 733-743 (2023).
4. Zhang, K., H.-H. Wu, H.-Q. Huo, et al., "Recent advances in nanofiltration, reverse osmosis membranes and their applications in biomedical separation field". *Chinese Journal of Chemical Engineering*, (2022).
5. Luo, Y., Y. Liu, J. Shen, et al., "Application of bipolar membrane electrodialysis in environmental protection and resource recovery: A review". *Membranes*, **12**(9), pp. 829 (2022).
6. Khosravikia, M. and A. Rahbar-Kelishami, "A simulation study of an applied approach to enhance drug recovery through electromembrane extraction". *Journal of Molecular Liquids*, **358**, pp. 119210 (2022).
7. Viet, N.D., D. Jang, Y. Yoon, et al., "Enhancement of membrane system performance using artificial intelligence technologies for sustainable water and wastewater treatment: A critical review". *Critical Reviews in Environmental Science and Technology*, **52**(20), pp. 3689-3719 (2022).
8. Saabas, D. and J. Lee, "Recovery of ammonia from simulated membrane contactor effluent using bipolar membrane electrodialysis". *Journal of Membrane Science*, **644**, pp. 120081 (2022).
9. Nadeem, K., M. Alliet, Q. Plana, et al., "Modeling, simulation and control of biological and chemical P-removal processes for membrane bioreactors (MBRs) from lab to full-scale applications: State of the art". *Science of the Total Environment*, **809**, pp. 151109 (2022).
10. McGinnis, R.L. and M. Elimelech, "Global challenges in energy and water supply: the promise of engineered osmosis". *Environ Sci Technol*, **42**(23), pp. 8625-8629 (2008).
11. Altaee, A., "Computational model for estimating reverse osmosis system design and performance: Part-one binary feed solution". *Desalination, 291*, pp. 101-105 (2012).
12. Koutsou, C., E. Kritikos, A. Karabelas, et al., "Analysis of temperature effects on the specific energy consumption in reverse osmosis desalination processes". *Desalination*, **476**, pp. 114213 (2020).
13. Zaidi, S.J., F. Fadhillah, Z. Khan, et al., "Salt and water transport in reverse osmosis thin film composite seawater desalination membranes". *Desalination*, **368**, pp. 202-213 (2015).
14. Chen, J. and G. Li, "Marine reverse osmosis desalination plant—a case study". *Desalination*, **174**(3), pp. 299-303 (2005).
15. Sayyaadi, H. and A. Saffari, "Thermoeconomic optimization of multi effect distillation desalination systems". *Applied Energy*, **87**(4), pp. 1122-1133 (2010).
16. Lee, K.P., T.C. Arnot, and D. Mattia, "A review of reverse osmosis membrane materials for desalination—Development to date and future potential". *Journal of Membrane Science*, **370**(1-2), pp. 1-22 (2011).
17. Schiffler, M., "Perspectives and challenges for desalination in the 21st century". *Desalination*, **165**, pp. 1-9 (2004).
18. Ludwig, H., "Energy consumption of reverse osmosis seawater desalination-possibilities for its optimisation in design and operation of SWRO plants". *Desalination and Water Treatment, 13(1-3)*, pp. 13-25 (2010).
19. Park, K., J. Kim, Y.D. Ryook, et al., "Towards a low-energy seawater reverse osmosis desalination plant: A review and theoretical analysis for future directions". *Journal of Membrane Science, 595*, pp. 117607 (2020).

20. Alabduljalil, S., S. Alotaibi, and H. Abdulrahim, "Techno-economic evaluation of different seawater reverse osmosis configurations for efficient boron removal". *Desalination and Water Treatment, 168*, pp. 65-76 (2019).
21. Altaee, A., G. Zaragoza, and H.R. van Tonningen, "Comparison between forward osmosis-reverse osmosis and reverse osmosis processes for seawater desalination". *Desalination, 336*, pp. 50-57 (2014).
22. Mustaqimah, M., M. Alghoul, P. Poovanaesvaran, et al., "Comparison of One Stage and Two Stage-Brackish Water Reverse Osmosis System: A Simulation study". *Computational Methods in Science and Engineering*, (2013).
23. Joseph, A. and V. Damodaran, "Dynamic simulation of the reverse osmosis process for seawater using LabVIEW and an analysis of the process performance". *Computers & Chemical Engineering, 121*, pp. 294-305 (2019).
24. Al-Obaidi, M.A., A.A. Alsarayreh, A.M. Al-Hroub, et al., "Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant". *Desalination, 443*, pp. 272-284 (2018).
25. Pearson, J.L., P.R. Michael, N. Ghaffour, et al., "Economics and Energy Consumption of Brackish Water Reverse Osmosis Desalination: Innovations and Impacts of Feedwater Quality". *Membranes (Basel)*, **11**(8), pp. 616 (2021).
26. Oh, H.-J., T.-M. Hwang, and S. Lee, "A simplified simulation model of RO systems for seawater desalination". *Desalination, 238(1-3)*, pp. 128-139 (2009).
27. Kim, J., K. Park, D.R. Yang, et al., "A comprehensive review of energy consumption of seawater reverse osmosis desalination plants". *Applied Energy*, **254**, pp. 113652 (2019).
28. Wilf, M. and K. Klinko, "Optimization of seawater RO systems design". *Desalination*, **138**(1-3), pp. 299-306 (2001).
29. Kim, Y.M., S.J. Kim, Y.S. Kim, et al., "Overview of systems engineering approaches for a large-scale seawater desalination plant with a reverse osmosis network". *Desalination*, **238**(1-3), pp. 312-332 (2009).
30. Kamal, A., T. El-Sayed, A. El-Butch, et al., "Analytical and finite element modeling of pressure vessels for seawater reverse osmosis desalination plants". *Desalination*, **397**, pp. 126-139 (2016).
31. Solutions, D.W., "Filmtec™ Reverse Osmosis Membranes". *Technical Manual*, *Form*, **399**(609-00071), pp. 1-180 (2010).
32. Altaee, A., "Theoretical study on feed water designs to reverse osmosis pressure vessel". *Desalination*, **326**, pp. 1-9 (2013).
33. Chattopadhyay, S., "Pressure vessels: design and practice", CRC press, (2004).
34. Fritzmann, C., J. Löwenberg, T. Wintgens, et al., "State-of-the-art of reverse osmosis desalination". *Desalination*, **216**(1-3), pp. 1-76 (2007).
35. Hamed, O.A., "Overview of hybrid desalination systems—current status and future prospects". *Desalination*, **186**(1-3), pp. 207-214 (2005).
36. Gullinkala, T., B. Digman, C. Gorey, et al., "Desalination: reverse osmosis and membrane distillation". *Sustainability science and engineering*, **2**, pp. 65-93 (2010).
37. Hoek, E.M., J. Allred, T. Knoell, et al., "Modeling the effects of fouling on full-scale reverse osmosis processes". *Journal of Membrane Science*, **314**(1-2), pp. 33-49 (2008).
38. Yaghoubi, S., A. Babapoor, S.M. Mousavi, et al., "Recent Advances in Plasmonic Chemically Modified Bioactive Membrane Applications for the Removal of Water Pollution". *Water*, **14**(22), pp. 3616 (2022).
39. Kim, J. and S. Hong, "A novel single-pass reverse osmosis configuration for high-purity water production and low energy consumption in seawater desalination". *Desalination*, **429**, pp. 142-154 (2018).
40. Lenntech. *Reverse Osmosis Demineralization*. 2022 [cited 2022]; Available from: https://www.lenntech.com.
41. Jeong, K., M. Park, S.J. Ki, et al., "A systematic optimization of Internally Staged Design (ISD) for a full-scale reverse osmosis process". *Journal of Membrane Science*, **540**, pp. 285-296 (2017).

42. Kim, J. and S. Hong, "Optimizing seawater reverse osmosis with internally staged design to improve product water quality and energy efficiency". *Journal of membrane science*, **568**, pp. 76-86 (2018).
43. Du, Y., H. Gu, X. Sun, et al., "Simultaneous optimization of size and operation for seawater reverse osmosis network with permeate split and interstage permeate split designs". *Industrial & Engineering Chemistry Research*, **60**(10), pp. 4041-4059 (2021).
44. Ghourejili, S., S. Yaghoubi, F. Valizadeh Harzand, et al., "Effects of Total Dissolved Solids on Pressure Drop and Net Driving Pressure in Different Designs of Brackish and Seawater Reverse Osmosis Systems". *Arabian Journal for Science and Engineering*, **48**(7), pp. 8785-8799 (2022).
45. Ghourejili, S., F. Valizadeh Harzand, S. Yaghoubi, et al., "Investigation of the Effects of Temperature on Net Driving Pressure and Pressure Drop in Different Configurations of the Reverse Osmosis System Using Computer Simulations". *Arabian Journal for Science and Engineering*, pp. 1-11 (2023).
46. Al-Hotmani, O., M. Al-Obaidi, R. Patel, et al., "Performance analysis of a hybrid system of multi effect distillation and permeate reprocessing reverse osmosis processes for seawater desalination". *Desalination*, **470**, pp. 114066 (2019).

List of Figures

Fig. 1. Processes involved in an SWRO desalination plant. Redrawn with permission from Ref. [29]. Copyright © 2009, Elsevier.

Fig. 2. Effects of feed's TDS on energy consumption in simple and hybrid single-stage SWRO systems.

Fig. 3. Effects of feed's TDS on energy consumption in simple and hybrid two-stage BWRO systems.

Fig. 4. Effects of feed's TDS on energy consumption in simple and single-stage hybrid BWRO systems.

Fig. 5. Effects of feed's TDS on efficiency in simple and hybrid single-stage SWRO systems.

Fig. 6. Effects of feed's TDS on efficiency in simple and hybrid two-stage BWRO systems.

Fig. 7. Effects of feed's TDS on efficiency in simple and hybrid single-stage BWRO systems.

Shamsedin Ghourejili received his MSc degree in Chemical Engineering from the University of Mohaghegh Ardabili. His research interests include the optimization of energy consumption in membrane processes and the simulation of processes using computational fluid dynamics. He has presented several articles in this field.

Sina Yaghoubi is a Master's Student at the University of Mohaghegh Ardabili studying Chemical Engineering (Process design). He received his B.Eng. in Hydraulic Engineering from the University of Guilan. He is currently working on advanced chemical engineering technologies, applications of computer simulations in chemical engineering, and renewable energy production and water purification under the supervision of Dr. Aziz Babapoor. His research interests are advanced chemical engineering, chemical process design, hydraulic structure design, computational fluid dynamics (CFD), computer simulation and modeling, CAD modeling, GIS analysis, GIS mapping, water and wastewater treatment, water purification technologies, and renewable energies.

Farrokhfar Valizadeh Harzand received his bachelor's degree from Mohaghegh Ardabili University in the field of Chemical Engineering and is a Master's student in the field of Chemical Engineering (separation processes) at Mohaghegh Ardabili University. His interests include drug delivery, nanotechnology, membranes, and membrane processes, and he has published articles in these fields. He is currently studying the field of drug delivery with advanced materials.

Aziz Babapoor is working as an Associate Professor at the Department of Chemical Engineering, University of Mohaghegh Ardabili. He obtained his Ph.D. degree with honors from Shiraz University in Chemical Engineering in 2015. He obtained his MSc and BSc degrees from the Sharif University of Technology in Chemical Engineering. Professor Babapoor has authored 25 books in domestic and international publications and presented more than 250 papers in international journals and conferences. He was selected as a top researcher of the university and achieved the first rank in Ardabil province in the festival of top researchers in 2020. He was selected as the top two-percent scientists in the world in 2020, 2021, 2022, and 2023.

List of Tables

Table 1. Specifications of flow rate, flux inlet and produced water, and Required membrane.

Table 2. Investigated designs of the BWRO system.

Table 3. Investigated designs of the SWRO system.

Table 4. Minimum and maximum recovery ratio in investigated RO systems.

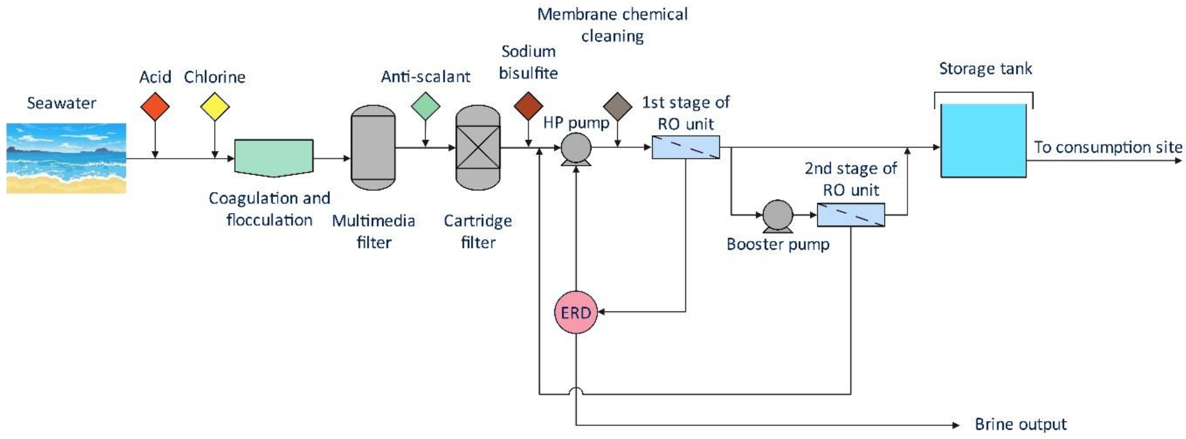

Membrane chemical cleaning
Sodium bisulfite
Acid
Chlorine
Anti-scalant
Storage tank
Seawater
1st stage of RO unit
HP pump
To consumption site
2nd stage of RO unit
Coagulation and flocculation
Multimedia filter
Cartridge filter
Booster pump
ERD
Brine output

Fig. 1.

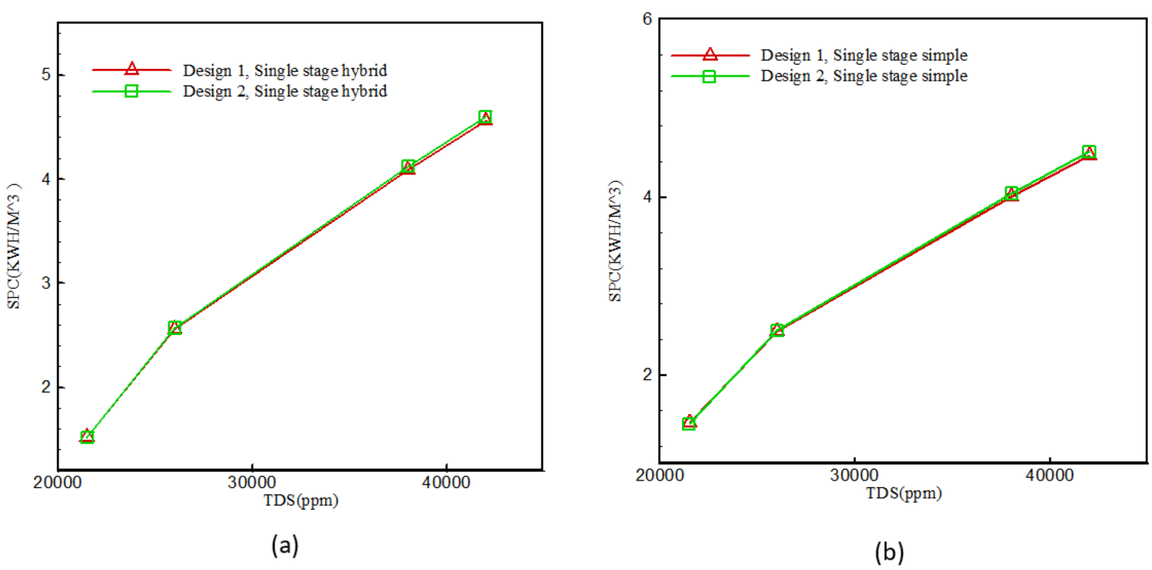
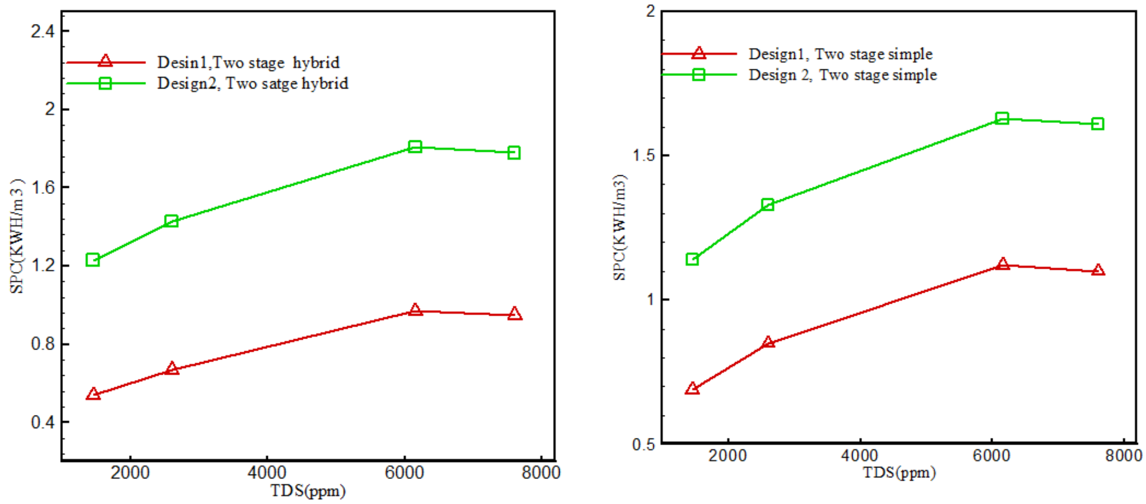
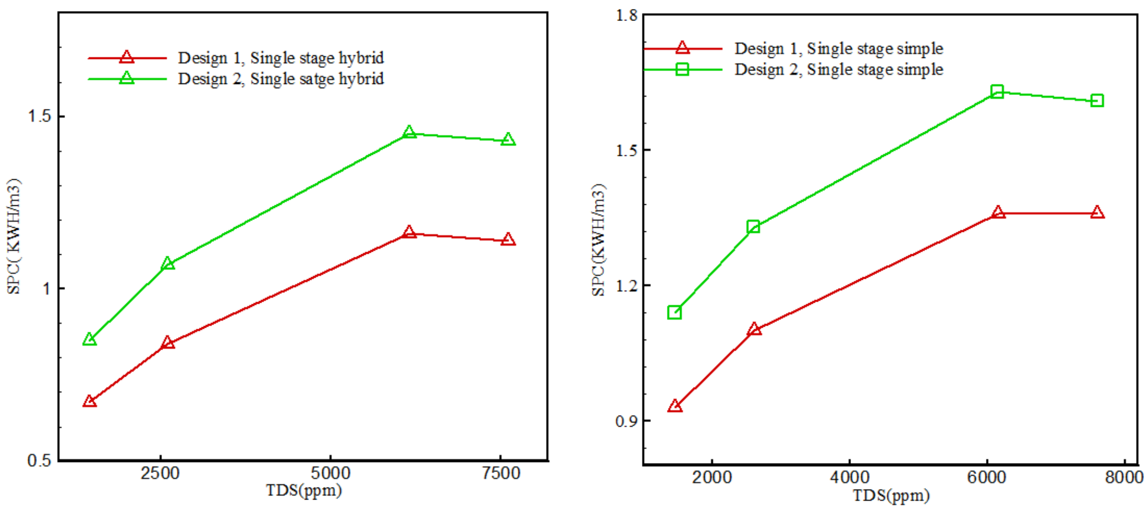

Design 1, Single stage hybrid
Design 2, Single stage hybrid
SPC(KWH/M^3)
TDS(ppm)
(a)
Design 1, Single stage simple
Design 2, Single stage simple
SPC(KWH/M^3)
TDS(ppm)
(b)

Fig. 2.



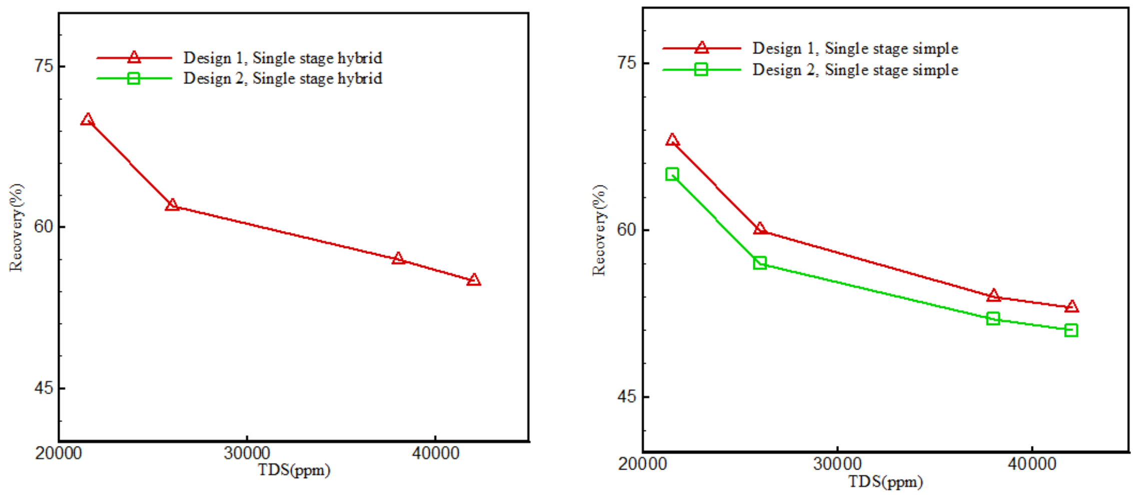
(a) (b)

Fig. 3.



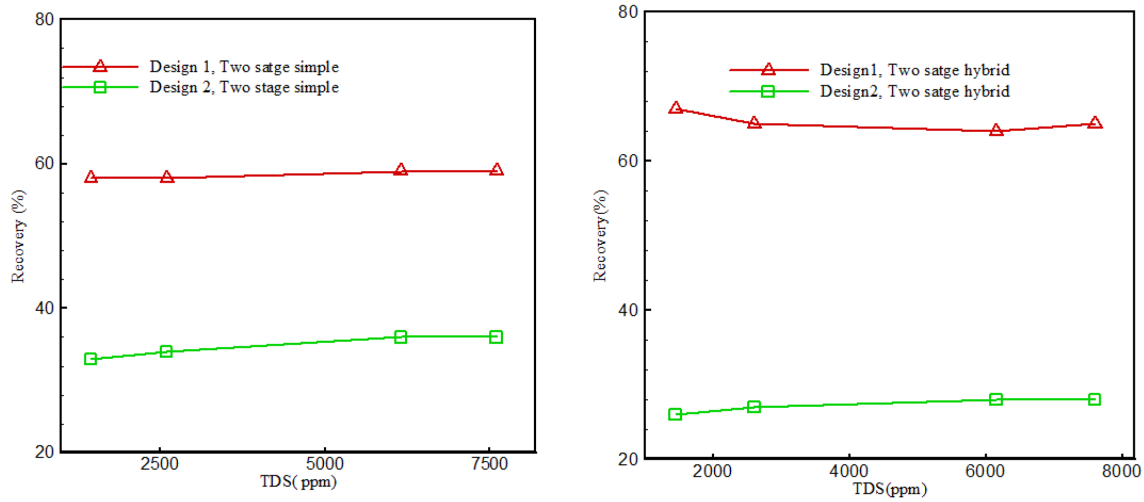
(a) (b)

Fig. 4.



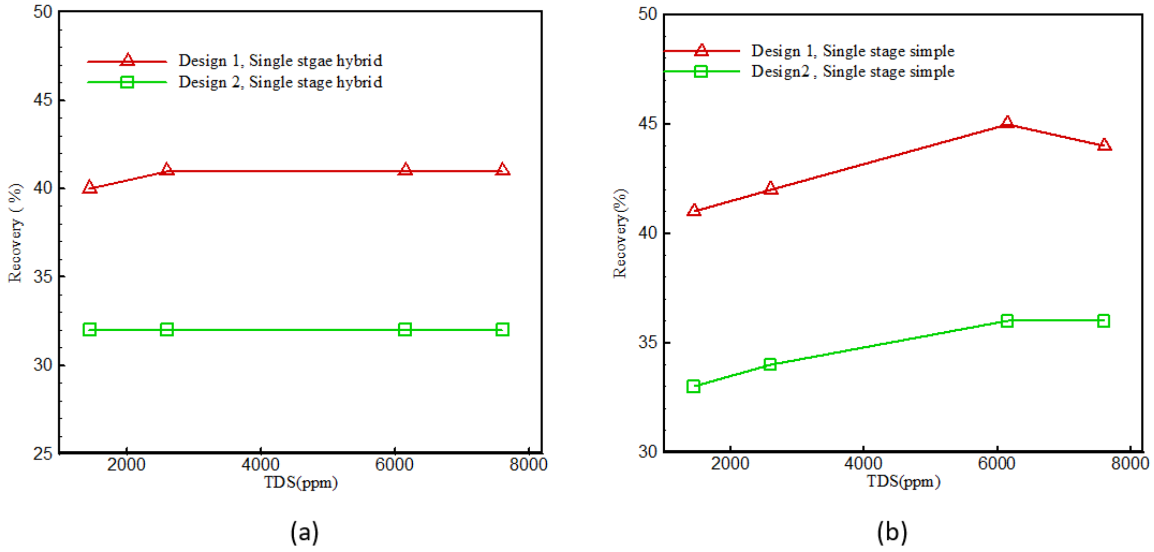
(a) (b)

Fig. 5.



(a) (b)

Fig. 6.



Design 1, Single stgae hybrid
Design 2, Single stage hybrid
Recovery (%)
TDS(ppm)
(a)
Design 1, Single stage simple
Design2 , Single stage simple
Recovery(%)
TDS(ppm)
(b)

Fig. 7.

Table 1.

Type	Inlet flux (gfd)	Produced water (gpm)	Membrane surface area (ft^2)	Required number of membranes
SWRO	8.26	128.5	400	56
BWRO	16.51	55	400	12

Table 2.

Type of design	Design 1	Design 2	No. membranes	No. PVs
Hybrid single-stage	*	---	12	3
Hybrid single-stage	---	*	12	4
Simple single-stage	*	---	12	3
Simple single-stage	---	*	12	4
Hybrid two-stage	*	---	12	3
Hybrid two-stage	---	*	12	8
Simple two-stage	*	---	12	3
simple two-stage	---	*	12	8

Table 3.

Type of design	Design 1	Design 2	No. membranes	No. PVs
Hybrid single-stage	*	---	56	7
Hybrid single-stage	---	*	56	7
Simple single-stage	*	---	56	7

Table 4.

Type of design	Minimum recovery ratio	Maximum recover ratio
Hybrid single-stage (BWRO)	25	28
Simple single-stage (BWRO)	24	25
Hybrid two-stage (BWRO)	128	158
Simple two-stage (BWRO)	64	76
Simple single-stage (SWRO)	4	5
Hybrid single-stage (SWRO)	3	4