Journal of Techniques, ISSN: 2708-8383, Vol. 5, No. 1, 2023, Pages 1-7
DOI: https://doi.org/10.51173/jt.v5i1.1166

JOURNAL OF TECHNIQUES

Journal homepage*: http://journal.mtu.edu.iq*

RESEARCH ARTICLE - ENGINEERING

Reduction of Energy Consumption of Brackish Water Reverse Osmosis Desalination System Via Model Based Optimisation

Mudhar A. Al-Obaidi[1,2*], Alanood A. Alsarayreh[3], and I. M. Mujtaba [4]

[1] Technical Institute / Baquba, Middle Technical University, Baghdad, Iraq

[2] Technical Instructors Training Institute, Middle Technical University, Baghdad, Iraq

[3] Chemical Engineering Department, Faculty of Engineering, Mutah University, P.O. Box 7, Karak 61710 – Jordan

[4] Department of Chemical of Engineering, Faculty of Engineering and Informatics, University of Bradford, Bradford BD7 1DP, UK

[*] Corresponding author E-mail: dr.mudhar.alubedy@mtu.edu.iq

Article Info.

Article history:

Received
09 January 2023

Accepted
05 March 2023

Publishing
31 March 2023

Abstract

Reverse Osmosis (RO) process is being engaged to yield fresh water from brackish water sources. However, the RO process is characterized by its high specific energy consumption (SEC) owing to high-pressure pumps. The current study focuses on reducing the SEC of the brackish water RO desalination plant using model-based optimization practice. The inlet conditions of RO process such as the feed pressure, flow rate (individual membrane module and total plant) and temperature, have a substantial influence on the performance indicators namely, water productivity, product concentration and SEC. Therefore, the optimisation of this study has been directed to determine optimal inlet conditions within feasible limits to minimise SEC. Arab Potash Company (APC) brackish water RO desalination plant has been considered as the case study. The optimal inlet conditions have resulted in a significant energy saving of 27.97% depending on the set of decision variables being considered at a fixed brackish water feed concentration.

Publisher : Middle Technical University

Keywords: Brackish Water Desalination; Reverse Osmosis; Optimisation-Based Model; Performance Metrics; Specific Energy Consumption (SEC).

1. Introduction

Due to population growth and lifestyle changes, freshwater is becoming increasingly scarce in many regions of the world. To solve this issue, many techniques including reverse osmosis (RO) were developed and applied to seawater, brackish water and industrial effluents [1,2].

In RO process, operational pressure higher than osmotic pressure allows permeation of potable water through the membrane while discarding the salts or other toxic compounds. The inlet pump pressure, water concentration, feed flow rate, and water temperature, as well as the design of the membrane module, have a considerable influence on the performance metrics. The most often utilised performance parameters are typically water productivity, product concentration, and overall specific energy consumption (SEC). Note, RO process uses a lot of energy, which needs to be greatly decreased to make it an energy efficient process as energy consumption is directly linked to the cost of producing water. Also, note that osmotic pressure, friction losses in the retentate and permeate channels, and resistance to fluid permeation across the membrane all contribute to SEC [3]. The following literatures discuss recent examples from the open literature that made improvements of RO desalination systems via the reduction of SEC.

Wei and McGovern [4] used a simple model to evaluate the performance indicators of a two-stage RO system compared to a single-stage RO process. The model was embedded in an optimisation to find the optimal system design and operation that guarantees the highest saving of energy. The results showed the propensity to minimise the spatial variance in flux using an optimised pressure. The authors recommended the utilisation of a two-stage RO system that has optimal element arrangement and pump pressures will result in the biggest energy savings.

For steady state operation of both brackish water and seawater RO desalination systems, Karabelas et al. [3] assessed the impact of basic design parameters including the osmotic pressure, the resistance against fluid flux through the membrane’s pores, and friction losses and several defined factors including high pressure pumps and energy recovery device on SEC of a seven membrane-elements pressure vessel. Their findings showed the importance of improving the membrane structure to gain a higher productivity besides enhancing the efficiency of pumps

Nomenclature

A_m	Membrane area (m²)	k_{dc}	Dimensional parameter in Eq. 12 of Table 2 (-)
$A_{w(T)}$	Water transport parameter at water temperature (m/atm s)	k	Mass transfer coefficient (m/s)
$A_{w(To)}$	Water transport parameter at 25 ºC (m/atm s)	L	Length of membrane (m)
A^*	Spacer features (dimensionless)	n	Dimensional spacer specification (-)
$B_{s(T)}$	Solute transport parameter at water temperature (m/s)	P_f	Pump pressure (atm)
$B_{s(To)}$	Solute transport parameter at 25 ºC (m/s)	P_r	Brine pressure (atm)
C_b	Bulk solute concentration (kg/m³)	P_p	Product water pressure (atm)
C_f	Water solute concentration (kg/m³)	Q_f	Water feed flow rate (m³/s)
C_m	Membrane solute concentration (kg/m³)	Q_p	Product water flow rate (m³/s)
C_p	Product water solute concentration (kg/m³)	Re	Reynolds number (-)
C_r	Retentate solute concentration (kg/m³)	Rej	Solute rejection (-)
D_b	Solute diffusion coefficient (m²/s)	Rec	Water recovery (-)
d_h	Membrane hydraulic diameter (m)	SEC	Specific energy consumption (kWh/m³)
Q_s	Solute permeation flux (kg/m² s)	T	Water temperature (°C)
J_w	Water permeation flux (m/s)	t_f	Height of feed channel (m)
W	Width of membrane (m)	π_b	Bulk osmotic pressure (atm)
ρ_b	Water density (kg/m³)	π_p	Product water osmotic pressure (atm)
μ_b	Water viscosity (kg/m s)	ϵ	Void fraction of the spacer (-)
$\Delta P_{drop,E}$	Pressure drop (atm)		

and energy recovery devices. Also, it has been noticed that the feed spacers and membrane envelope number/width have insignificant effect on SEC. Due to its high concentration, the SEC of seawater desalination is greater than brackish water desalination.

Koutsou et al. [5] investigated the influence of operating temperature on the performance of a typical RO unit based on brackish water and seawater RO desalination systems. It was observed that an increase in feed temperature from 15 ºC to 40 ºC has caused in a reduction in SEC for a brackish water RO desalination system. But, the positive influence of water temperature on SEC was not significant for a seawater desalination RO system due to its high osmotic pressure.

To mitigate the SEC, Alsarayreh et al. [6] analysed the effectiveness of adding an energy recovery device to the medium-scale brackish water RO desalination system of Arab Potash Company (APC) in Jordan. The simulation was carried out based a comprehensive model for the RO system. The simulation results of RO system with and without an Energy Recovery Device (ERD) were compared. According to the simulation results, the calculated total energy consumption can be reduced between 47% to 63% with the addition of an energy recovery device (ERD) compared to the original RO design system of no ERD.

Alsarayreh et al. [7] evaluated the influence of both pump pressure and feed flow rate on the SEC of brackish water RO desalination system of APC using model based optimisation technique. The feed concentration and temperature of brackish water were considered fixed throughout the optimisation. The optimisation results showed a decline of SEC by 22.5% compared to the actual SEC.

Lim et al. [8] studied the reduction of SEC of ultra-permeable membranes stuffed in hollow fiber and spiral wound modules of RO seawater desalination system. The outcomes presented that tripling of water permeability in a spiral wound module would reduce SEC by 16%. This is basically experienced via changing the membrane module type. Furthermore, the quadrupling of water permeability in a hollow fiber module would causes a drop of 23% of SEC.

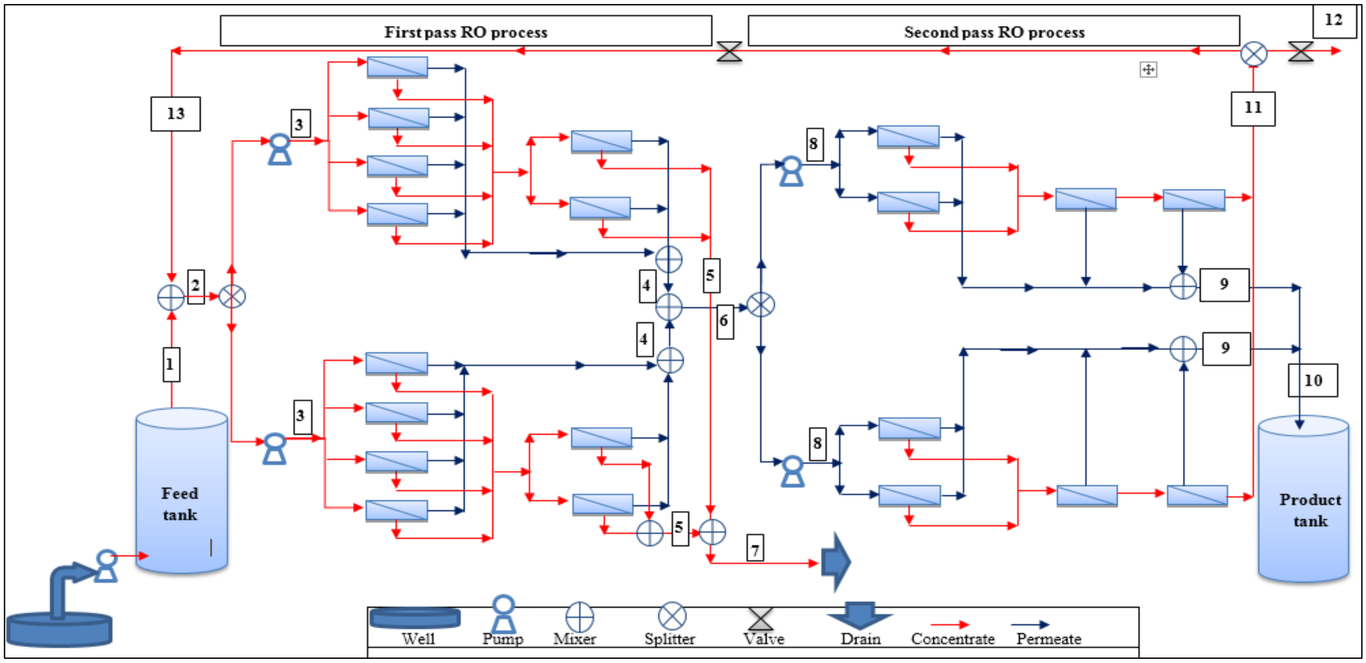
Based on the above literature review, the saving of SEC can be achieved via adapting the RO process design, optimising the inlet feed conditions, adding an ERD, and improving the membrane structure to promote water permeation, etc. To the best of the authors' knowledge, there is no accessible literature that discusses the reduction of the total energy consumption of the RO system of APC through optimisation while taking into account simultaneous influence of input conditions (pump pressure, feed flow rate, and water temperature). The objectives of this study would therefore go beyond those of Alsarayreh et al. [7] which neglected the effect of temperature and focused on feed pressure and flow rate as the key inlet conditions at a constant brackish water concentration of 1089.62 ppm and temperature of 25 ºC. To explore the contribution of feed temperature as a control variable, the current study endeavors to optimise the decision variables at fixed brackish water concentration 1089.62 ppm and explore the lowest SEC and make a comparison of the results reported by Alsarayreh et al. [7]. To accomplish this aim, a comprehensive mathematical model of RO system of APC will be used to carry out the optimisation study, which entails the reduction of SEC via finding the optimal values of pump pressure, brackish water flow rate and temperature.

2. Explanation of RO Desalination Plant of APC: A Case Study

The brackish water RO system setup for the APC plant (with a 1200 m3/day of designed capacity) is depicted in Fig. 1 along with the feed characteristics. The RO plant has two passes with reprocessing designs for permeate and retentate. Pressure vessels are arranged in two stages of 4:2 in the first pass. Two stages of a 2:1:1 arrangement of pressure vessels make up the second pass' design. The second pass is in charge of further desalinating the permeate from the first pass. In order to increase the total water production, the RO system has also thought about recirculating the retentate from the second pass and connecting it to the intake supply. Table 1 introduces the specifications delivered by the manufacturer of the membrane module of the RO process, membrane transport parameter, and the recommended maximum and minimum limits of inlet feed conditions.

Table 1. Membrane type, membrane transport parameters and maximum and minimum recommended inlet variables [7]

Parameter	Value
Membrane type	TMG20D-400, Ultra low pressure BWRO, spiral wound, polyamide thin-film Composite
Water transport parameter $A_{w\,(T_o)}$ (m/atm s)	$9.62\text{x}10^{-7}$
Solute transport parameter $B_{s(T_o)}$	$1.61\text{x}10^{-7}$
Max. feed pressure (atm)	40.46
Max. feed temperature (°C)	45
Max. feed flowrate (m^3/day)	432



Characteristics of brackish water and inlet feed water of RO system: Brackish water salinity: 1098.62 ppm; Inlet water salinity of RO process: 988.99 ppm; Recycled water salinity: 223.5 ppm; Feed flow rate of brackish water: 1776 m^3/day; Recycled water flow rate: 276.83 m^3/day; Inlet feed flow rate of RO process: 2052.82 m^3/day; 1st pass pressure: 9.22 atm; 2nd pass pressure: 9.90 atm; Temperature: 25 °C; Product salinity: 1.98 ppm; Productivity: 1163.54 m^3/day; SEC: 0.84 kWh/m^3

Fig. 1. Schematic diagram of the brackish water RO plant of APC system _ Jordan (Adapted from Al-Obaidi et al. [9])

3. Modeling of RO System of APC

Al-Obaidi et al. [9] settled a comprehensive model for the single spiral wound module of the RO process that includes various mathematical equations to explain the linkages between the inlet and outlet variables in addition to providing performance indicators of the process. The model equations from Al-Obaidi et al. [9] are shown in Table 2. This model was employed to create a comprehensive model for the brackish water RO desalination plant that included the capability to forecast key performance indicators in addition to providing comprehensive data for each module, pressure vessel, stage, and pass. A comparison between the actual data and the model predictions has been included in Table 3 to ensure the accuracy of the model. Table 3 shows the high accuracy of the model, which can be utilised for further simulation and optimisation studies.

Table 2. Modeling of a spiral wound module of RO process (Al-Obaidi et al. [9])

No.	Model equations	Specifications
1	$Q_p = A_{w(T)}\, NDP_{fb}\, A_m$	Water permeation (m^3/s)
2	$A_{w(T)} = A_{w(25\,C)}\, TCF_p\, F_f$	Water permeability parameter at any operational temperature relative to the one at 25 °C (m/s atm)
3	$TCF_p = \exp[0.0343\,(T-25)] \quad < 25\,°C$ $TCF_p = \exp[0.0307\,(T-25)] \quad > 25\,°C$	Temperature correction factor of permeate
4	$NDP_{fb} = P_{fb} - P_p - \pi_b + \pi_p$	Net driving pressure on the feed side (atm)
5	$P_{fb} = P_f - \frac{\Delta P_{drop,E}}{2}$	Pressure of feed brine (atm)
6	$\Delta P_{drop,E} = \frac{9.8692x10^{-6}\, A^{*} \rho_b\, {U_b}^2\, L}{2 d_h\, Re_b^n}$	Pressure drop throughout the length of membrane (atm)

7	$C_b = \frac{C_f + C_r}{2}$	Bulk concentration (kg/m³)
8	$Q_s = B_{s(T)}\left(C_w - C_p\right)$	Solute permeation (kg/m² s)
9	$B_{s(T)} = B_{s(25\,C)}\,TCF_s$	Solute transport parameter at inlet water temperature relative to the one at 25 ºC (m/s)
10	$C_m = \left(\frac{C_f + C_r}{2} - C_p\right) exp\left(\frac{Q_p/A_m}{k}\right) + C_p$	Salt concentration on the membrane wall (kg/m³)
11	$k = 0.664\,k_{dc}\,Re_b^{0.5}\,Sc^{0.33}\left(\frac{D_b}{d_h}\right)\left(\frac{2d_h}{L_f}\right)^{0.5}$	Mass transfer coefficient (m/s)
12	$Sc = \frac{\mu_b}{\rho_b\,D_b}, \quad \mathrm{Re} = \frac{\rho\,d_e\,J_w}{\mu}$	Schmidt and Reynolds numbers (-)
13	$J_w = \frac{B_{s(T)}\,Rej}{(1 - Rej)}$	Water flux (m/s)
14	$C_p = \frac{C_f}{Rec}\,[1 - (1 - Rec)]^{(1-Rej)}$	Average product concentration (kg/m³)
15	$C_r = C_f\,[1 - Rec]^{-Rej}$	Average brine concentration (kg/m³)
16	$Rec = \frac{Q_p}{Q_f}$	Water recovery (-)
17	$Rej = \frac{C_f - C_p}{C_f}$	Solute rejection (-)
18	$SEC = \frac{Pf\ \ Qf * 101325}{\frac{Qp_{(plant)}\ \boldsymbol{\varepsilon}\ pump}{36x10^5}}$	Specific energy consumption (kWh/m³)

Table 3. Comparison of model's predictions and actual data of RO model of APC (Adapted from Al-Obaidi et al. [9])

Parameter	Unit	Actual data	Model predictions	Percentage of error
1st pass RO process				
Productivity	(m³/day)	701.592	706.152	0.65
Disposed brine flow rate of the 1st pass	m³/day	603.36	612.37	1.49
Solute rejection	(-)	95.466	95.460	0.00
Water recovery	(-)	70.08	70.056	0.03
2nd pass RO process				
Productivity	(m³/day)	589.68	579.144	1.78
Solute rejection	(-)	95.5	95.501	1.59
Water recovery	(-)	83.5	82.012	1.78
Overall RO plant				
Product concentration	(ppm)	1.96	1.98	1.02
Productivity	(m³/day)	1179.36	1163.537	1.34

To account the SEC of brackish water RO desalination of APC, the following equation is used due to having two pumps in both the 1st and 2nd passes,

$$SEC_{RO-APC} = \frac{Pf(in)_{(plant)} * 101325 * Qf_{(Raw\ water)}}{\frac{Qp_{(plant)} * \boldsymbol{\varepsilon}\ pump}{36x10^5}} + \frac{Pf_{(Block\ 3)} * 101325 * Qf_{(Block\ 3)}}{\frac{Qp_{(plant)} * \boldsymbol{\varepsilon}\ pump}{36x10^5}} \qquad (19)$$

The overall model of RO plant of APC was coded and solved using MATLAB software. This model has been embedded in the optimisation problem to minimise the SEC of the RO plant.

4. Description of Optimisation Problem

The primary objective of the optimisation was to obtain the minimum SEC of the RO process of the APC. The pump pressure, brackish water flow rate, and water temperature have been regarded as the control variables to be optimised, which would ensure that the objective function is achieved. For the optimisation study, the inlet brackish water concentration of 1098.62 ppm was fixed. It should be mentioned that Alsarayreh et al. [7] were able to optimise the same RO plant at constant brackish water feed concentration (1098.62 ppm) and water temperature (25 ºC) and achieved a reduction of SEC of 22.5%. Consequently, this study is seeking to further reduce the SEC by optimising the water temperature in addition to other parameters. The Non-Linear Programming (NLP) optimisation framework of Optimisation Toolbox provided in MATLAB has enabled to carry out the optimisation study.

The optimisation problem has therefore constructed as follows;

Min $\qquad SEC_{RO-APC}$

$Q_{f(plant)}, P_{f(plant)}, T_{(plant)}$

Subject to: Equality constraints: RO process model

Inequality constraints:

a) Maximum and minimum bounds of brackish water flow rate, pump pressure, and water temperature of the RO system

$$(696.96\ \text{m}^3/\text{day})\ \ Q_{f(plant)}{}^{L} \leq Q_{f(plant)} \leq Q_{f(plant)}{}^{U}\ (3707.52\ \text{m}^3/\text{day})$$

$$(5\ \text{atm})\ P_{f(plant)}{}^{L} \leq P_{f(plant)} \leq P_{f(plant)}{}^{U}\ \ (20\ \text{atm})$$

$$(15\ ^\circ\text{C})\ T_{(plant)}{}^{L} \leq T_{(plant)} \leq T_{(plant)}{}^{U}\ \ (45\ ^\circ\text{C})$$

b) Maximum and minimum bounds of brackish water flow rate of each membrane module

$$(87.12\ \text{m}^3/\text{day})\ \ Q_{f(membrane)}{}^{L} \leq Q_{f(membrane)} \leq Q_{f(membrane)}{}^{U}\ (463.44\ \text{m}^3/\text{day})$$

Please note that the upper and lower limits of a single membrane are brought from the manufacturer of the membrane selected (https://www.water.toray/products/ro/). Based on this, the upper and lower limits of the RO system are calculated.

4.1. Optimisation results

Using the inlet conditions shown in Fig. 1, Table 4 displays the initial performance metrics of the brackish water RO desalination plant of APC. Additionally, Table 4 shows the optimisation results of Alsarayreh et al. [7], including the best control variables, the pump pressure and feed flow rate at constant brackish water concentration and water temperature of 1098.62 ppm and 25 ºC, respectively, and the least amount of specific energy that can be used in accordance. Table 4 also includes the optimisation results from the current study and presents the ideal pump pressure, feed flow rate, and water temperature as well as the lowest upgraded SEC.

Referring to the original simulation data and the optimisation results of Table 4, it should be noted that the reduction of pump pressure and feed flow rate is important to gain the lowest SEC. Specifically, this has been clearly demonstrated for both the optimisation results of Alsarayreh et al. [7] and the current study.

For fixed brackish water concentration and water temperature of 1098.62 ppm and 25 ºC, respectively, the optimisation results Alsarayreh et al. [7] shows an energy saving of 22.97% compared to that in the original simulation results at an optimal water flow rate entering the RO system and pump's pressure of 1479.94 m³/day and 7.57 atm, respectively. For the same brackish water concentration of 1098.62 ppm and 25 ºC, this work resulted in an energy saving of 27.97% compared to that in the original simulation results but at an optimal water flow rate entering the RO system of 1883.15 m³/day, pump's pressure of 6.35 atm, and feed water temperature of 34.08 ºC. Note, the optimised SEC of the current study is basically lower than the optimised SEC of Alsarayreh et al. [7] by around 6.49%. This improvement is due to optimising the feed temperature together with other parameters.

Further analysis of the associated optimisation results of Table 4 would confirm that Alsarayreh et al. [7] and the current study have achieved lower water productivities (compared to the original RO system) and higher brine flow rate with increased product concentration if compared to the original simulation data. In other words, these are the penalties to ensure a lower SEC.

The reduction of water productivity in the optimisation results of Alsarayreh et al. [7] and the current study can be endorsed to the utilisation of lower values of pump pressure and water feed flow rate entering the RO system. In this regard, it can be noticed that the implementation of water temperature as a control variable in the optimisation of current study has led to a higher productivity compared to the one presented by Alsarayreh et al. [7]. However, the product salinity has been increased to 8 ppm, compared to the optimal value of 3.73 ppm of Alsarayreh et al. [7], which is still within the level of an industrial distilled water. This increase of product concentration can be ascribed to the increase of feed temperature from 25 ºC to 34.08 ºC, which enhances the permeation of solute throughout the membrane pores as a result to enhancing the mobility of the membrane context. Here, it is viable to notice that increasing feed temperature from 25 ºC to 34.08 ºC is within the membrane manufacturer's specification. The RO plant of APC is a part of the potash industry of APC, which can have advantages from the other industrial units. In other words, the increase of water temperature from 25 ºC to 34.08 ºC can be guaranteed in summer or using a heat exchanger existed in the project. Finally, the salt rejection has not been significantly changed after attaining the maximum energy saving of the RO system.

The optimum bracksih water temperature of the current study is 34.08 ºC, which requires the instillation of a heat exchanger. This in turn would increase the fresh water production cost due to increasing the capital cost. Thus, it is useful to carry out a specific study to optimise the fresh water production cost and specific energy consumption taken into account the simultaneous reduction of both of them with introducing a modified design of RO system of APC via a superstructure optimisation. Superstructure optimisation entails determining the optimal superstructure design that achieves specified performance targets while also taking into account issues like cost, safety, and reliability. Often, the optimisation process entails creating a mathematical model of the system or process that can be used to compare the performance of various superstructure designs [10]. This also should consider maintaining the original water productivity of RO system to resolve the shortcoming of the current study (reduction of water roductivity).

Table 4. Characteristics of feed water, simulation results, optimisation results of Alsarayreh et al. [7] and optimisation results of this study

Characteristics of brackish water and water entering the RO system		
Parameter	**Unit**	**Value**
Brackish water feed concentration	ppm	1098.62
Brackish water feed flow rate	m³/day	1776
Concentration of water entering the RO system	ppm	988.9
Flow rate of water entering the RO system	m³/day	2052.82
Pump pressure	atm	9.22
Water temperature	°C	25
Simulation results		
Water recovery	%	56.68

Salt rejection	%	99.79
Productivity	m^3/day	1163.53
Product concentration	ppm	1.98
Brine flow rate (disposed of the 1st pass)	m^3/day	276.83
SEC	kWh/m^3	0.84
Optimal feed conditions of Alsarayreh et al. [7] at constant brackish water concentration and water temperature of 1098.62 ppm and 25 ºC		
Pump pressure	atm	7.57
Water flow rate entering the RO system	m^3/day	1479.94
Optimised performance indicators of Alsarayreh et al. [7]		
Water recovery	%	64.53
Salt rejection	%	99.62
Productivity	m^3/day	954.996
Product concentration	ppm	3.73
Brine flow rate (disposed of the 1st pass)	m^3/day	385.678
SEC	kWh/m^3	0.647
Energy saving compared to original simulation= 22.97%		
Optimal feed conditions of the current study at a constant brackish water concentration of 1098.62 ppm		
Pump pressure	atm	6.35
Water flow rate entering the RO system	m^3/day	1883.15
Water temperature	ºC	34.08
Optimised performance indicators of the current study at a constant brackish water concentration of 1098.62 ppm		
Water recovery	%	53.11
Salt rejection	%	99.18
Productivity	m^3/day	1000.308
Product concentration	ppm	8.0
Brine flow rate (disposed of the 1st pass)	m^3/day	743.48
SEC	kWh/m^3	0.605
Energy saving compared to original simulation = 27.97%		

5. Conclusions

A single optimisation framework was created in this study to alleviate the overall energy consumption of the medium-scale RO brackish water desalination system of Arab Potash Company in Jordan. This is basically conducted within a comprehensive optimisation designed problem that considered the overall inlet characteristics of feed water including pump pressure, brackish water flow rate and water temperature at a fixed brackish water concentration. The optimisation problem was utilised with the allowable operational limits of the inlet feed variables to assure a safe desalination practice. To systematically represent the importance of this research, the optimisation results of the current study were compared against the simulation data and the optimisation results of an earlier authors' study that ignored the influence of water temperature. The optimisation results of this study introduced the possibility of having a gain of energy saving of 27.97%, which is in advance of 22% reduction of SEC compared to the one presented in the open literature.

Acknowledgment

The researchers would like to extend their sincerest gratitude to the staff at the Arab Potash Company, Jordan.

References

[1] M. Al-Obaidi, C. Kara-Zaitri, I.M. Mujtaba "Wastewater treatment by reverse osmosis process" CRC Press, 2020.

[2] I.M. Mujtaba, M.T. Sowgath "Desalination Technologies: Design and Operation" Elsevier, 2022.

[3] A.J. Karabelas, C.P. Koutsou, M. Kostoglou, D.C. Sioutopoulos "Analysis of specific energy consumption in reverse osmosis desalination processes" Desalination, vol. 431, pp.15-21, 2018.

[4] Q.J. Wei, R.K. McGovern "Saving energy with an optimized two-stage reverse osmosis system" Environmental Science: Water Research & Technology, vol. 3, No.4, pp.659-670, 2017, https://doi.org/10.1039/C7EW00069C.

[5] C.P. Koutsou, E. Kritikos, A.J. Karabelas, M. Kostoglou. "Analysis of temperature effects on the specific energy consumption in reverse osmosis desalination processes" Desalination, vol. 476, p.114213, 2020, https://doi.org/10.1016/j.desal.2019.114213.

[6] A.A. Alsarayreh, M.A. Al-Obaidi, A.M. Al-Hroub, R. Patel, I.M. Mujtaba "Evaluation and minimisation of energy consumption in a medium-scale reverse osmosis brackish water desalination plant" Journal of Cleaner Production, vol. 248, pp.119220, 2020a, https://doi.org/10.1016/j.jclepro.2019.119220.

[7] A.A. Alsarayreh, M.A. Al-Obaidi, A.M. Al-Hroub, R. Patel, I.M. Mujtaba "Optimisation of Energy Consumption in a Medium-scale Reverse Osmosis Brackish Water Desalination Plant" In Computer Aided Chemical Engineering (Vol. 48, pp. 373-378). Elsevier, 2020, https://doi.org/10.1016/B978-0-12-823377-1.50063-X.

[8] Y.J. Lim, Y. Ma, J.W. Chew, R. Wang "Assessing the potential of highly permeable reverse osmosis membranes for desalination: Specific energy and footprint analysis" Desalination, vol. 533, pp.115771, 2022. https://doi.org/10.1016/j.desal.2022.115771.

[9] M.A. Al-Obaidi, A.A. Alsarayreh, A.M. Al-Hroub, S. Alsadaie, I.M. Mujtaba "Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant" Desalination, vol. 443, pp. 272-284, 2018, https://doi.org/10.1016/j.desal.2018.06.010.

[10] M. Di Martino, S. Avraamidou, E.N. Pistikopoulos "A neural network based superstructure optimization approach to reverse osmosis desalination plants" Membranes, vol. 12, No. 2, pp.199, 2022.