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RESEARCH ARTICLE

DYNAMIC OPERATION AND ENERGY CONSUMPTION OF A MEDIUM-SCALE REVERSE OSMOSIS BRACKISH WATER DESALINATION PLANT WITH MEMBRANE FOULING

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ABSTRACT

Fouling of reverse osmosis (RO) membranes is one of the utmost significant issues that membrane manufacturers, the scientific community, and industry experts must address. The effects of this unavoidable phenomenon have a negative impact on the desalination system's performance. There are little published researches on fouling propensity on membranes from real operating desalination plants, which considered dynamic fouling in RO process. Indeed, these studies would help the plant operator to estimate the accurate time of membrane cleaning or replacing. For a practical application, this research introduces the brackish water RO system desalination plant of Arab Potash Company (APC) as a case study to investigate the fouling propensity in the membranes and instruct the operators towards the accurate time of membrane cleaning or replacement. The RO desalination plant is designed as a medium-sized (1200 m3 /day), multistage, two passes. To achieve this investigation, a previous original RO mathematical model equations produced by the same author has involved dynamic fouling analysis. Using a simulation-based model via Matlab, the consequences of membrane fouling accumulation for three continuous operational years on the performance indicators variations with time are studied. The simulation findings show that it is important to carry out an overall membrane cleaning within 92 continuous operational days as a consequence to a reduction of the water productivity by 10%. However, it is essential to replace the membranes within 2.99 operational years due to a reduction in water productivity by 25%, which deduces an increase of 17.5% in the specific energy consumption.

KEYWORDS

Reverse Osmosis (RO) process; Brackish water (BW) desalination; Dynamic fouling; Simulation; Arab Potash Company (APC).

1. INTRODUCTION

Exponential growth in population and enhanced standards of living together with aggressive increase of water contamination have not only increased the demand of freshwater, put made a severe stress on the capacity of natural water sources (Baggio et al., 2021). Specifically, Middle East is among several districts around the world where fresh water shortage has rigorously impacted public life and farming activities. Thus, specific efforts were made to advance superior processes for substitute water resources. In this occasion, the desalination technologies have been demonstrated as a reliable and sustainable solution (Jamaly et al., 2014; Al-Obaidi et al., 2024). Moreover, water recycling and successive wastewater treatment have minimised this concern to some level (Alsarayreh et al., 2020; Al-Obaidi et al., 2021).

The Reverse Osmosis (RO) technology has been emerged as a promising technology to meet freshwater demands due to its reliability and low consumption of energy (Alsarayreh et al., 2020; Al-Obaidi et al., 2022). RO is nowadays the number one desalination industry of seawater and brackish water with a progressive market shares (Ghernaout and El-Wakil, 2017). The study in a comparison to other thermal processes such as multi-effect distillation (MED) and multi-stage flash (MSF). In this aspect, RO process characterises by imposing a high-pressure to the feed water to suppress the osmotic pressure gradient between the two mediums, and therefore, water from the solution travels from high salinity side to the low salinity side (Kim et al., 2020)

Among the innovated RO modules, the spiral wound membrane module is the fundamental component of RO process technology (Burn et al., 2015). Despite the progress made in RO membranes, the fouling is a critical challenge that impacts the performance of desalination plants based on this technology (Al Aani et al., 2017). The pressure-driven membranes are generally distrusted to fouling, which is referred to the adsorption deposition or accumulation of particles, organic matter, or scaling agents (foulants) onto the membrane surface and inside the pores, that can weaken the performance indicators over purification time, including pressure drop across the membrane, water permeation, solute rejection, and specific energy consumption (Ibrahim et al., 2020; Jiang et al., 2017). This phenomenon not only impacts the efficacy of the RO system but also affects operational costs and the lifespan of the membranes. Specifically, the membrane surface fouling can substantially reduce the overall water flux, productivity, and product quality beside increasing energy demand (increasing inlet pressure), which necessitates frequent membrane cleaning that would raise the water product cost due to elevating overall treatment cost (Tong et al., 2019). In this aspect, reliant on the foulants

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nature, the membrane fouling can be categorized into biological fouling, scaling, and organic fouling. This specifically would limit the competitiveness of the RO process and its market share. Due to membrane damage, mostly, hasten membrane replacement is a mandatory option due to fouling that reduces membrane lifespan (Nthunya et al., 2022).

Due to the changing feed water features of brackish water, the membrane fouling of brackish water RO process is a little more difficult than in saltwater RO process as a resut to the extensive use of ground water (Ruiz-García et al., 2018). Thus, understanding of fouling propensity of brackish water RO membranes is the key to improving the overall operation and associated efficiency for a long operational term. More precisely, it is viable to understand the influential factors of membrane fouling in RO process and how to control it to assure the mitigation of fouling actions towards the overall performance. The study established that many parameters have positive and negative influences on membrane fouling (Najid et al., 2022). These parameters include the feed water properties of fluid temperature, feed velocity, operational pH, pump pressure. Also, the hydrophilic/hydrophobic surface characteristics of the membrane and the smoothness and roughness of the membrane have a clear contribution on membrane fouling. As a result, numerous studies investigated the problem of fouling in seawater and brackish water RO desalination systems and assessed the prosperity of different refurbishment techniques. This research focuses on membrane fouling of BWRO system. Some examples of relevant studies that concerned membrane fouling of BWRO desalination systems are outlined below.

To specifically demonstrate the decline of performance indicators over operational time of 500 days, (Abbas and Al-Bastaki, 2001). The analysed the long-term operational data of a medium-scale RO plant of FilmTec BW30-400 spiral wound membranes. The researchers investigated a number of operational parameters including the flow rates, pressures, salinities, pH, and temperatures of feed, permeate, and concentrate streams of 2:1:1 series configuration of brackish water RO process of 40 m3/day productivity. The associated results indicated a 25% decline in water permeability and a 1.9% decrease in salt rejection over 500 days. It was therefore ascertained that membrane fouling is the most reason to limit the performance of RO process.

conducted a complementary study to examine the long-term performance of the industrial spiral wound RO process of over a period of 1,500 continuous operational days (Al-Bastaki and Abbas, 2004). Using a theoretical model, the researchers analysed operational data of the plant and concluded a reduction of 39% of water transport coefficient over 4 years of continuous operation. Also, it was suggested that membrane interchange can further enhance efficiency.

The detrimental effects of membrane fouling on the reliability of water desalination systems are addressed by (Filloux et al., 2015). Researchers proved that a membrane fouling can lessen water productivity and permeate quality, which necessitates an increase in pump pressure. In turn, this has been thoroughly connected to poor performance metrics and high-costs of maintenance as a result to an increase in energy consumption, supplementary pre-treatment steps, repeated cleaning steps of the membranes, and compressed membrane lifespan.

The current research emphasis on studying the effect of membrane fouling on the performance indicators of RO system-based BW desalination for a long-operational time. Specifically, this research focuses on analysing the dynamic fouling of multi-stage multi-pass BWRO desalination system of Arab Potash Company (APC) located in Jordan. To systematically conduct this, an earlier model established by the same author is adjusted to characterize the dynamic behaviors of performance indicators of RO system under fouling while considering a fixed set of inlet conditions and three years of operational time. Indeed, the consequences of this research would help the plant operator to estimate the accurate time of membrane cleaning or replacing.

2. Modelling Of Bwro Process Considering Fouling

Constructed a detailed steady-state model to characterize the performance of a single spiral wound module of RO process headed for the treatment of brackish water and seawater (Al-Obaidi et al., 2018). Table 1 presents the full steady state model with clarifications of the associated parameters.

Table 1: Governing model equations of the BWRO system (Al-Obaidi et al., 2018)

No.	Equations	Unit	Descriptions
1	$Q_p = A_{w(T)}\, NDP_{fb}\, A_m$	[m^3/s]	Mass flow rate of permeate
2	$NDP_{fb} = P_{fb} - P_p - \pi_b + \pi_p$	[atm]	Driving pressure of water permeation
3	$Q_f = Q_p + Q_r$	[m^3/s]	Overall mass balance of water
4	$C_f Q_f = C_p Q_p + C_r Q_r$	[kg/s]	Mass balance of the salt
5	$Rec = \frac{Q_p}{Q_f}$	[-]	Recovery rate of freshwater
6	$Rej = \left(1 - \left(\frac{C_p}{C_f}\right)\right) x100\%;$ $Rej = \left(1 + \frac{B_{s(T)}}{J_w}\right)^{-1} x100\%$	[-]	Membrane salt rejection rate
7	$C_p = \frac{C_f}{Rec}\,[1-(1-Rec)]^{(1-Rej)}$	[kg/m^3]	Salt concentration of the permeate stream
8	$C_r = C_f\,[1-Rec]^{-Rej}$	[kg/m^3]	Salt concentration of the retentate stream
9	$J_w = \frac{B_{s(T)}\, Rej}{(1-Rej)}$	[m/s]	Water mass flux via the pores of the membrane
10	$Q_s = B_{s(T)}(C_w - C_p)$	[kg/m^2 s]	Salt mass flux via the pores of the membrane
11	$C_w = \left(\frac{C_f + C_r}{2} - C_p\right) e^{\frac{Q_p/A_m}{k}} + C_p$	[kg/m^3]	Salt concentration on the membrane surface
12	$k = 0.664\, k_{dc}\, Re_b^{0.5}\, Sc^{0.33} \left(\frac{D_b}{d_h}\right)\left(\frac{2d_h}{L_f}\right)^{0.5}$	[m/s]	Mass transfer coefficient
13	$Sc = \frac{\mu_b}{\rho_b\, D_b}$	[-]	Schmidt number
14	$P_{fb} = P_f - \frac{\Delta P_{drop,E}}{2}$	[atm]	Trans membrane pressure
15	$\Delta P_{drop,E} = \frac{9.8692x10^{-6}\, A^{*} \rho_b\, U_b^{2}\, L}{2 d_h\, Re_b^{n}}; Re_b = \frac{\rho_b\, d_h\, Q_b}{t_f\, W\, \mu_b}$	[atm]	Pressure drops across membrane channel

Table 1 (Cont.): Governing model equations of the BWRO system (Al-Obaidi et al., 2018)

16	$U_b = \frac{Q_b}{W\, t_f\, \epsilon}$	[m/s]	Bulk velocity
17	$Q_b = \frac{Q_f\ +\ Q_r}{2}$	[m³/s]	Bulk flow rate
18	$\pi_b = 0.7994\, C_b\ [1 + 0.003\ (T - 25)]$ $\pi_p = 0.7994\, C_p\ [1 + 0.003\ (T - 25)]$	[atm]	Osmosis pressure in feed and permeate channels
19	$C_b = \frac{C_f + C_r}{2}$	[kg/m^3]	Bulk salinity
20	$A_{w(T)} = A_{w(25\,°C)}\, TCF_p\, F_f$	[m/s atm]	Membrane water permeability
21	$B_{s(T)} = B_{s(25\,°C)}\, TCF_s$	[m/s]	Membrane solute permeability
22	$TCF_p = \exp[0.0343\ (T - 25)]\ at\ < 25\,°C$ $TCF_p = \exp[0.0307\ (T - 25)]\ at\ > 25\,°C$ $TCF_s = 1 + 0.05\ (T - 25)\ at\ < 25\,°C$ $TCF_s = 1 + 0.08\ (T - 25)\ at\ > 25\,°C$	[°C]	Temperature correction factor of permeate and solute
23	$SEC = \frac{\frac{Pfx101325xQf}{Qp\ \epsilon_{pump}}}{36x10^5}$	[kWh/m³]	Specific energy consumption

The model used to build a specific model for the BWRO desalination process of Arab Potash Company in Jordan, which was designed as multi RO stages of retentate and permeate reprocessing schemes. The model at that time has been built based on instilling new membranes in the pressure vessels. Consequently, the fouling factor was considered to equal one (new membranes). However, this is not actual case for a long – operational time. Basically, fouling has a noteworthy effect on the performance indicators of RO membranes and a dynamic evaluation of these indicators is required beside the necessity of fine-tuning of operational parameters if certain fresh water demand is required. Therefore, it has been decided to strengthen the model of by incorporating the influence of membrane fouling based dynamic operation (Al-Obaidi et al., 2018).

The analysis stated that the dynamic fouling factor (F_f) (Eq. 20 of (Table 1) of RO membranes based brackish water desalination along the operational time can be addressed using Eq. 24 (Al-Bastaki and Abbas, 2004). The fouling factor specifically representing the division of the membrane water permeability due to fouling to the original membrane water permeability.

$$F_f = 0.68 \exp\ \left(\frac{79}{t+201.1}\right) \tag{24}$$

t signifies the operational time in days.

3. A Case Study: BWRO Desalination Plant Of APC In Jordan

The BWRO desalination plant of APC and its operating have been described in previous works (Alsarayreh et al., 2020; Alsarayreh et al., 2020; Al-Obaidi, M., Alsarayreh, A. A., Al-Hroub, A., Alsadaie, S., & Mujtaba, I. M., 2018; Alsarayreh, et al., 2023; Alsarayreh et al., 2021; Alsarayreh, A. A., Al-Obaidi, M. A., Alrwashdeh, S. S., Patel, R., and Mujtaba, I. M., 2022). The feed raw water is taken from a groundwater well with a feed water salinity of 1098.62 ppm, 74 m^3/h of feed flowrate, 9.22 atm of feed pressure, pH of 7.59, and temperature of 25 °C. Fig. 1 depicts a representation of the BWRO plant of APC, which contains of 20 pressure vessels in two passes. In this aspect, each pass comprises two parallel stages of six pressure vessels with arrangement (4:2) for the 1st pass while two parallel stages of four pressure vessels with arrangement (2:1:1) for the 2nd pass. Each pressure vessel has six membrane elements in a series configuration and therefore the BWRO plant of APC has 120 membrane elements in total. The polyamide thin-film composite membrane element of a spiral wound ultra-low pressure BWRO membrane type TMG20D-400 manufactured by Toray Membrane USA Inc. of 37.2 m2 is used. The overall production capacity of BWRO plant of APC is 2034.3299 m3/day. The main features of the membrane element used in RO process and the water and solute transport coefficients are presented in Table 2.

Table 2: Characteristics of the RO membrane and water and solute transport coefficients (Al-Obaidi et al., 2018).

Membrane brand		**Transport parameters at 25 °C**	
Factor	Value	Factor	Value
Membrane supplier	Toray Membrane USA Inc.	Water $A_{w\ (T_o)}$	9.62x10^{-7} (m/atm s) at 25 °C
Membrane type and configuration	Ultra low-pressure BWRO of TMG20D-400, polyamide thin-film composite spiral wound	Solute $B_{s(T_o)}$	1.61x10^{-7} (m/s) at 25 °C
Measurements		**Features of feed spacer**	
Factor	Value	Factor	Value
Area of the membrane (A)	37.2 (m^2)	Spacer type	NALTEX-129
		length of filament in the spacer mesh L_f	2.77x10^{-3} m
		Feed and permeate spacer thickness t_f, t_p	8.6x10^{-4}, 5.5x10^{-4} (m)
Restrictions of inlet conditions		$A^{'}$	7.38 (dimensionless)
Maximum pump pressure	40.464 (atm)	n	0.34 (dimensionless)
		ε	0.9058 (dimensionless)
Maximum inlet water temperature	45 (°C)	k_{dc}	1.501 (dimensionless)
Maximum feed flow rate	432 (m³/day)		

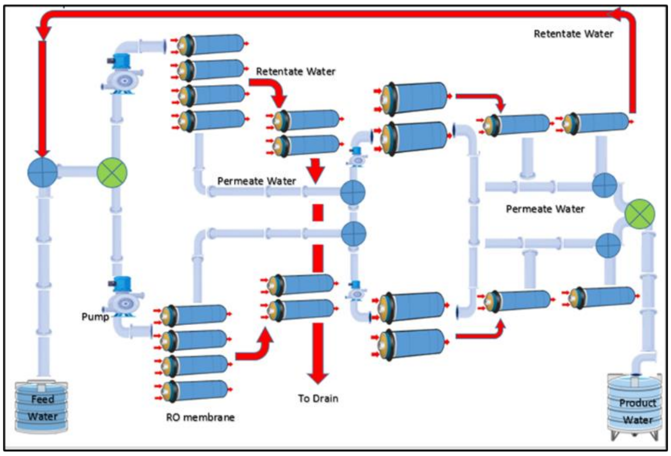

Figure 1: A representation of the BWRO plant of APC.

4. Dynamic Performance Of Bwro System Of Apc Under Fouling

This section focuses on presenting a critical analysis of long-term performance indicators of BWRO desalination plant of APC in the existence of fouling. The variations of performance metrics of the solute rejection, product salinity, water productivity, and specific energy consumption are evaluated. By understanding how these indexes change over time, operators can forecast the optimal timing for membrane cleaning or replacement. In turn, this would aid to upgrade the water productivity and process operation.

The model equations including the fouling factor presented in Table 1 is utilised to conduct a simulation study of BWRO plant of APC performance effected by fouling for three years while using a fixed set of inlet conditions of 74 m^3/h of feed flowrate, 1098.62 ppm of feed water salinity, 9.22 atm of feed pressure, and 25 °C of operating temperature. The simulation results show a sensitivity analysis of the performance indicators over three operational years as presented in Figs. 2 – 6.

Fig. 2 depicts the progress of solute rejection for cleaning membranes of BWRO process of APC and fouled membranes after three operational years. Specifically, Fig. 2 therefore depicts the influence of membrane fouling on the solute rejection at fixed inlet conditions. Clearly, the solute rejection decreases insignificantly from 99.79% to 99.71% after three operational years as a consequence to membrane fouling. The reduction of solute rejection can be attributed to a number of reasons such as the reduction of permeate flux via the membrane pores and reduced mass transfer coefficient with the effect of fouling accumulation on the membrane pores.

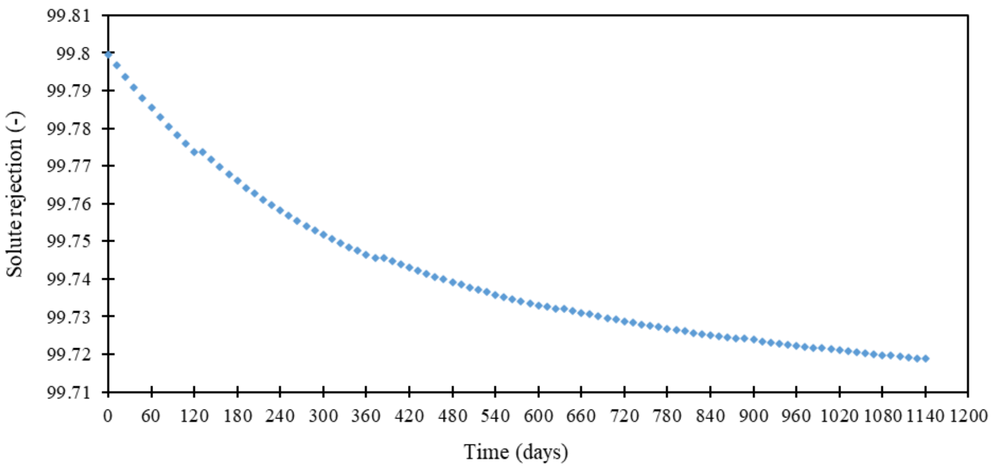

Figure 2: Variation of solute rejection against operational time

Fig. 3 shows the relationship between product water salinity against the operational three years. The results of Fig. 3 introduce a proof of deterioration in product salinity of around 40%. This can be endorsed to an upsurge of solute flux via the membrane pores with reduced water production as a response to growing the membrane fouling. The membrane fouling can specifically reduce the membrane's ability to efficiently reject salts, causing a higher salinity level in the permeate.

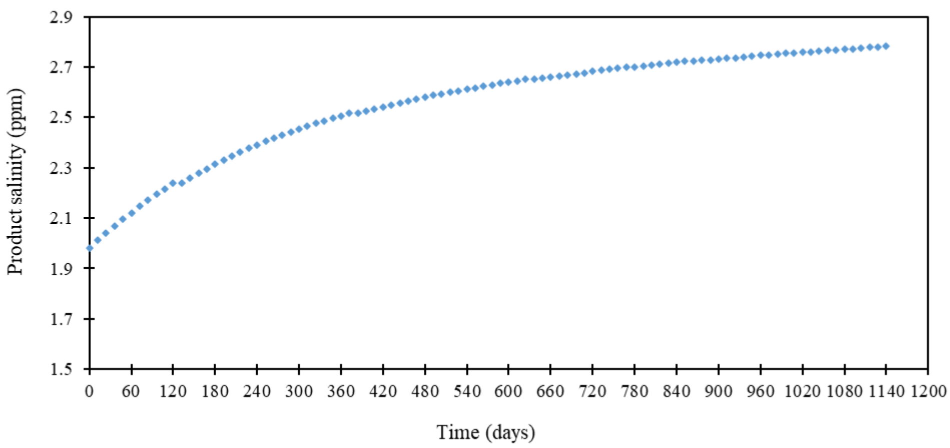

Figure 3: Variation of product salinity against operational time

Fig. 4 illustrates the behavior of water productivity of the BWRO system over three years due to fouling effects. This shows a decline in water productivity from approximately 1164.63 m^3/day to 874.43 m^3/day, a reduction of 24.9%. Occasionally, the simulation results deduced that operating the RO process for continuous operation of 1092 days (2.99 years) would introduce a reduction of 25% in the water productivity of 873.47 m^3/day. Exactly, this can specify the operational period of membrane replacement. However, 10% reduction of water productivity has been conducted after 92 days of continuous operation while attaining 1048.57 m^3/day. The trend of Fig. 4 delivers significant insights when considered alongside the discussion made of Fig. 3 of increased product salinity. First of all, the decline in water productivity correlates with the increase in product salinity along the operational three years. As the RO system's membranes become fouled or scaled over time, their efficiency diminishes by obstructing water flow through the membranes. Furthermore, the decline in permeate water flux, which is associated with water productivity, is related to a decline in the water transport coefficient at feed water temperature. Fig. 5 shows the reduction of water transport coefficient with operational time. Statistically, the water transport coefficient decreases by 28.23% over 1140 continuous operational days. The membrane fouling can essentially decrease the active membrane area and increasing the resistance across the membrane (Sim et al., 2018). Consequently, this not only has reduced the volume of water produced but also compromises the membrane's ability to reject salts efficiently, resulting in a greater product salinity.

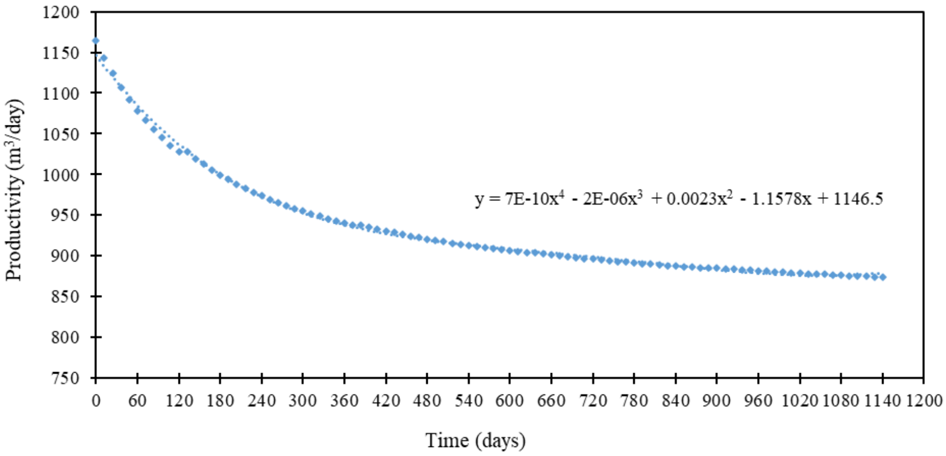

Figure 4: Variation of water productivity against operational time

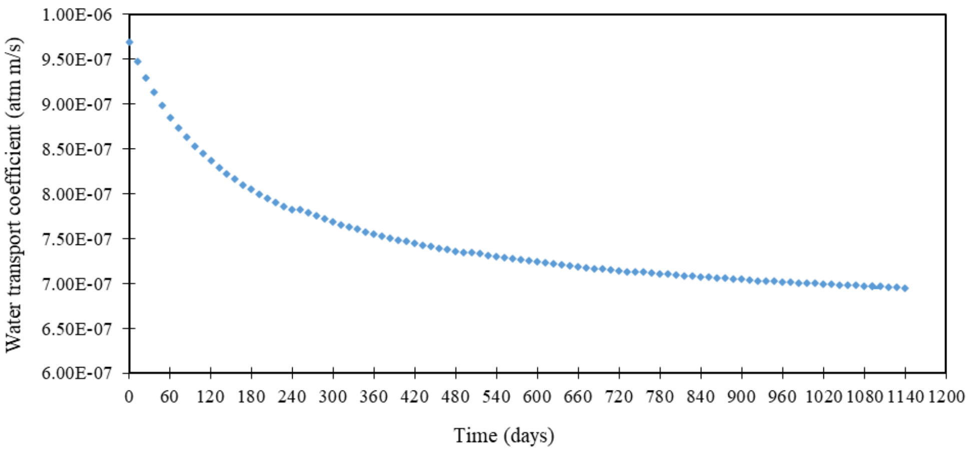

Figure 5: Variation of water transport coefficient against operational time

The specific energy consumption is defined as the amount of energy necessitated to generate a volume of water and is classically measured by kWh/m3. As depicted by Fig. 6, the BWRO process of APC requires only 0.834 kWh/m3 of specific energy consumption for the first time of plant's start. This is an indication of a low specific energy consumption, which is required as it reduces operational costs and permits more low-salinity water to be produced per unit volume of source water. However, the specific energy consumption increases to 0.98 kWh/m3 at the end of three years. Statistically, this is an increase of 17.5%, that can be ascribed to a reduction of water permeation while using a constant set of inlet conditions. Indeed, the membrane fouling is the main reason towards this deterioration of specific energy consumption, which clarifies an increase in energy demand, and reductions in membrane life expectancy.

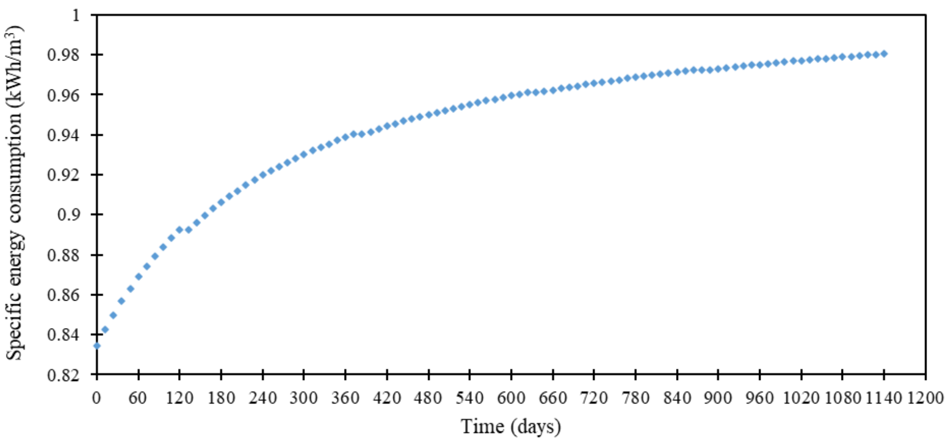

Figure 6: Variation of plant specific energy consumption against operational time

5. Techniques Of Membrane Restoration And Fouling Control For Bwro System Of Apc

To upgrade the overall performance of the BWRO system at APC and efficiently diminish membrane fouling, a number of possible restoration techniques can be applied as follows;

- The improvement of pretreatment equipment ahead of the RO membrane desalination by ensuring a set of ultrafiltration, microfiltration and Nano-filtration pre-filtration membranes is vital to maintain an excellent water productivity (Najid et al., 2022).

- Periodic membrane cleaning is important per 92 operational days to not exceed 10% reduction of water productivity. The membrane cleaning can be conducted by using chemical and physical cleaning techniques. The chemical cleaning uses aqueous solutions comprising chemical materials that would deteriorate the adhesion forces between the membrane surface and the foulants. Also, the physical cleaning applies mechanical forces greater than the forces connecting the RO membrane to the foulants. On top of this and referring to the cleaning frequency should be reduced as low as possible due to possible irreversible damages in membrane properties and performance (Regula et al., 2014). Otherwise, the membranes could be replaced after 2.99 operational years to not exceed 25% reduction of water production.

- Conducting an optimisation study is needed to preserve consistent water productivity and efficient fouling control. This would elaborate adjusted and optimal inlet conditions of feed pressure, feed flowrate, and operating temperature, which collectively aid to minimise fouling propensity.

6. Conclusions

In this research, the medium-sized industrial BWRO desalination plant of APC was theoretically taken as a case study for fouling detection besides analysing the dynamic behaviors of performance indicators along three years of operating time. One of the most effectual penalties of membrane fouling is the escalation of specific energy consumption, besides deteriorations of water productivity and product water. The obtained simulation results introduced the deterioration of 40% and 17.5% in product salinity and specific energy consumption, respectively, which are associated with a decline of 24.9% in water productivity for the three operational years. Towards the membrane restoration and fouling control, the dynamic simulation found that membrane cleaning can be achieved after 92 days of continuous operation, which mirrors a 10% reduction of water productivity. Also, the membrane replacement can be achieved after 1092 days of continuous operation, which mirrors a reduction of 25% in water productivity. The consequences of this research can have imperative associations for engineering efforts to lessen the fouling propensity of the membranes and diminish specific energy consumption in BWRO desalination plants.

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Conflict Of Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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