Humidification-dehumidification desalination process: Performance evaluation and improvement through experimental and numerical methods

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Evaluation and minimisation of energy consumption in a medium-scale reverse osmosis brackish water desalination plant

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Abstract

The Reverse Osmosis (RO) process has been expansively used in water treatment as a result of its low energy consumption compared to thermal distillation processes, leading to reduced overall water production cost. Evaluation and minimisation of energy consumption (expressed in kWh/m^3 of fresh water production) in a medium-scale spiral wound brackish water RO (BWRO) desalination plant of the Arab Potash Company (APC) are the main aims of this research. The model developed earlier by the authors has been integrated to simulate the process and achieve the main aims. Energy consumption calculations of low salinity BWRO desalination plant, with and without an energy recovery device, have been carried out using the gPROMS software suite. In other words, this research evaluated the impact of adding an energy recovery device on the RO process energy consumption of the APC, which is introduced for the first time. Also, the effects of several operating conditions of BWRO process include the feed flow rate, pressure and temperature on the performance indicators, which include the energy consumption and total plant recovery at different energy recovery device efficiencies, were studied. The simulation results showed that the total energy consumption could be reduced at low values of feed flow rates and pressures and high values of temperatures. More importantly, there is an opportunity to

reduce the total energy consumption between 47% - 53.8% compared to the one calculated for the original design without an energy recovery device.

1. Introduction

Brackish water desalination is a well-known technology used to separate feed salinity water into low salinity water and concentrated brine. Basically, this technology requires vast quantities of energy, which is a function of incoming saline water parameters including the salinity, flow rate, pressure, and temperature (Wei and McGovern, 2017). In this respect, The RO process is one of the most common industrial applications deployed to produce reuse water from wastewater (Al-Obaidi et al., 2017a) and fresh water from brackish water resource (Anqi et al., 2015). This is economically and technically feasible due to recent improvements of RO membranes (Zhu et al., 2010). This in turn has resulted in a distinctive decrease in the total energy consumption compared to the other common technologies (e.g., thermal process of Multi Stage Flash) (Oh et al., 2009). It is noteworthy to know that the seawater RO process entails between 2 to 5 kWh/m^3 of power consumption based on the feed characteristics (Xevgenos et al., 2016). However, the total energy consumption of the BWRO process, which comprises the electrical energy consumption, ranges between 1.5 and 2.5 kWh/m^3 (Azevedo, 2014). In general, The downgrading in energy consumption of RO water desalination plants has been ongoing since the 1960s due to the development of energy recovery devices (ERDs). However, the research of mitigating the total energy consumption of RO desalination is still valid by investigating other feasible options especially for medium and large size RO desalination plants (Pérez-González et al., 2012). In this regard, there are several process designs that have been considered to decrease the energy consumption of water desalination plants besides suggesting further process improvements. For instance, Sassi and Mujtaba (2011) utilised a non-linear optimisation problem to minimise the specific energy consumption (SEC) of three-stages RO process at a fixed high-quality fresh water flow rate based on optimising the operating and design parameters. This in turn entailed a reduction of 20% in total energy consumption compared to the original process design. Also, Koutsou et al. (2015) investigated the effect of alternative designs of RO process including membrane sheet number/width and feed-spacer geometry on the SEC at fixed recovery ratio. More importantly, the addition of ERD to the RO process has been conveyed by several researchers such as Al-Zahrani et al. (2012). This is evidenced by investigating the impact of different ERD efficiencies on energy consumption of seawater and brackish water RO desalination processes. However, it is necessary to run the RO process at high operating pressures to overcome the trans-membrane osmotic pressure that would significantly increase the pumping power. Moreover, the RO process performance in term of the water recovery and consuming energy is highly sensitive to several operating parameters as presented in many of steady-state and dynamic RO simulation and optimisation attempts (Villafafila and Mujtaba, 2003; Qi et al., 2012; Zhao et al., 2013; Al-Obaidi et al., 2017b, 2018a). For instance, Villafafila and Mujtaba (2003) implemented ERDs, and pressure exchangers in the optimisation target. Overall, they confirmed that the energy consumption could be dropped by more than half by implementing these devices on the plants. This improvement is mainly due to the fact that the energy can be absorbed from the high-pressure high-concentration retentate stream and deliver it efficiently to the raw water (Anderson et al., 2009). Accordingly, the energy consumption can be considered as the most effective contributor to the total fresh water production cost of RO system (Geraldes et al., 2005; Qi et al., 2012; Mazlan et al., 2016). Therefore, any reduction of energy consumption would afford a primitive effect on reducing the total fresh water production cost of RO process (Koroneos et al., 2007).

Several successful examples of reducing the total energy consumption in seawater and brackish water RO desalination process can be found in the open literature. To systematically realised the progress of reducing the energy consumption of the RO system, Table 1 demonstrates sevral examples of published studies that covered the mitigation of total energy consumption with explicitly highlighting the most advantages and disadvantages.

Table 1. Summary of studies on the energy consumption of RO process

No.	Author and year	Principle of the study	Features and advantages	Results	Shortcoming
1	Farooque (2008)	The specific energy consumption, percentage of energy saving, the efficiency of ERD and percentage of throttle loss are estimated using fundematal equations	The influence of ERDs on the energy consumption of several seawater RO plants was investigated	A maximum energy saving of 27% can be achieved based on the maximum power consumption of the high-pressure pump of 7.93 kWh/m^3.	The influence of feed flow rate on the total energy consumption was not specifically analysed
2	Sharif et al. (2009)	Presented an analytical method to estimate the specific energy consumption	The influence of operating conditions and membrane area and water transport parameter on the energy consumption of seawater RO process was analysed	The minimum specific energy consumption can be achieved at water recovery of 70% for a given feed salinity and membrane permeate flow rate of less than 2 m^3/h.	The impact of several operating conditions on the energy consumption was not critically studied
3	Li (2010)	Development of a constrained nonlinear optimisation framework	Analyse the energy consumptions of three RO modules; a single stage, two stages, and a single stage with an ERD were optimised	Increasing the number of stages as well as applying an ERD would enhance the reduction of energy consumption	The calculations were specifically carried out at fixed retentate pressure.
4	Qi et al. (2012)	Development of a model for both single and two-stages RO process considering the concentration polarisation issue	The influence of operating conditions, ERD and pump efficiencies on the specific energy consumption was studied	The optimised water recovery shifts to lower values as a result of the existence of ERDs.	The impact of operating conditions such as feed flow rate and temperature on the total energy consumption was not investigated
5	El-Ghonemy (2012)	A primitive model equations were used to estimate the specific power consumption and total water recovery	The performance of two-stage RO seawater desalination plant with two different ERDs on the energy consumption was analysed	An energy saving between 41% to 42% was achievable for all the trains in the first stage due to the use of an ERD	The impact of several operating conditions on the specific energy consumption was not analysed
6	Kim et al.	Simple model	One centrifugal ERD and	isobaric ERDs have	Short-term experiments

	(2013)	equations were used to calculate the energy transfer efficiency, and specific energy consumption,	two isobaric ERDs (pressure exchanger and presssure exchanger for energy recovery were installed to an actual seawater RO plant of 1000 m^3/day and the energy consumption was assessed under various conditions	higher efficiency than the centrifugal ERD	were carried out to recognise the performance of ERD system
7	Wei et al. (2017)	A mass-balance model was presented to calculate the performance of RO system	An optimal design and operation of a two-stage RO system was achieved and compared to a single-stage system with attaining a lower bound for the energy savings	The highest energy savings are achieved with a two-stage RO system that has optimal configuration and pressure	The model assumed perfect salt rejection. Also, the pressure dependence of density and osmotic pressure were ignored.

Up to this point, it is plausible to confirm that the implementation of an ERD in the RO process at any operating condition can meaningfully decrease the specific energy consumption (Manth et al., 2003). Basically, this is attributed to the surplus energy that can be regained by the ERD from the high salinity stream (brine stream) (Anderson et al., 2009; Al-Zahrani et al., 2012). Therefore, the idea of employing an ERD at different efficiencies in the original design of RO system of Arab Potash Company (APC) constitutes the main target of this research. Also, it is fair to expect that the drop in energy consumption can be improved at high-efficiencies of the ERD. To the best of the authors' knowledge, the sensitivity analysis of the energy consumption with and without an ERD and also towards the variation of operating conditions of a medium-sized industrial BWRO desalination plant of the APC has not been carried out. Mostly, it is hard to find comprehensive research in the open literature that discussed the influence of operating condition on the specific energy consumption of multistage multi-pass RO process. This is particularly for the impact of operating flow rate and temperature on the specific energy consumption. Therefore, in this research, a thorough analysis of the energy consumption and total plant recovery ratio of the RO process via simulation is carried out. To attain this aim, a comprehensive earlier model developed by the same authors (Al-Obaidi et al., 2018b) has been utilised and integrated by including the calculation of energy consumption with and without an ERD. The impacts of several operating parameters on the performance indicators represented by the energy consumption and total plant recovery are presented in detail. The direction of travel of this research was to conduct a major advance in the original multistage RO design of APC (without an ERD), to elucidate an economically viable separation process.

2. Model development

Al-Obaidi et al. (2018b) have improved a comprehensive mathematical model for the multistage, multi-pass spiral wound RO process based on the philosophies of solution diffusion model. The model was already developed based on some common assumptions of a) steady state operation, b) constant membrane characteristics (solvent and solute transport parameters and friction factor), c) one atmospheric pressure at the permeate channel, d) film-theory model used to calculate the concentration at the membrane wall, and e) isothermal process. Interestingly, the model developed considered the existence of concentration polarisation and signifies the impact of feed spacer on the pressure drop along the feed channel. The detailed equations of the model developed by Al-Obaidi et al. (2018b) are given in Table A.1 of Appendix A. The theoretical model has been applied to investigate the performance of BWRO desalination plant operated by the Arab Potash Company (APC). Interestingly, this model is currently modified by including energy consumption correlations. It is highly-recommended to quantify the consequence of the variation of operating parameters on the total energy consumption and plant recovery ratio with and without the presence of an ERD. Therefore, the interest of this research has been directed to weight the possibility of decreasing the total energy consumption by investigating the impact of adding an ERD at different efficiencies and simulating the multistage RO process of APC at a wide range of operating conditions. Generally, the ERD and pump efficiencies are addressed as the two particular areas that can be employed to decrease the specific energy consumption for any RO desalination plant. Table 2 shows the recent used operating conditions of the feed (brackish water at low salinity of 1098.62 ppm) to the RO plant of APC.

Table 2. Feed water details of brackish water RO plant of APC.

Parameter	Values
Salinity (ppm)	1098
Volumetric flow rate (m^3/h)	7.45 – 7.55
Temperature (°C)	25
Pressure of 1st pass (atm)	9.22
Pressure of 2nd pass (atm)	9.832

In this respect, the performance of any desalination process can be characterised based on evaluating one of the most significant parameters, i.e. the specific energy consumption (Semiat, 2008). Therefore, the multistage multi-pass RO process of APC model equations of Al-Obaidi et al. (2018b) has been currently strengthened by considering three new equations that specifically used to evaluate the total energy consumption of the whole plant. This is described in the following;

The specific energy consumption of the high-pressure pump E_{HPP} (kWh/m^3) is evaluated using Eq. (1) developed by Qi et al. (2012).

$$E_{HPP} = \frac{\frac{\left(\left(Pf_{(in\_plant)}\right)\times 101325\right)\left(Qf_{(in\_plant)}\right)}{\left(Qp_{(total\ plant)}\ \varepsilon_{HP\ pump}\right)}}{36\times 10^5} \quad (1)$$

$Pf_{(in\_plant)}$ is the operating feed pressure (atm), $Qf_{(in\_plant)}$ is the applied feed flow rate (m^3/s), $Qp_{(total\ plant)}$ is the total flow rate (m^3/s), and $\boldsymbol{\varepsilon}_{HP\ pump}$ is the high-pressure pump efficiency (dimensionless). However, the specific energy consumption of RO system with the existence of an ERD (consists of a high-pressure pump (HPP), an ERD and booster pump (BP)) (E_{plant}) (kWh/m^3) is calculated using Eq. (2). It should be noted that one of the most important characteristic of an ERD is the recovery of energy from the high-concentrtaion stream (retentate) to the inlet feed stream via the pressure exchangers. In this regard, the substraction of the consumed energy of the pumps and the recovered energy by the ERD presents the net energy consumption per m^3 of permeate of the RO process using an ERD.

$$\mathrm{E_{plant}} = \frac{\frac{\left(\left(\mathrm{Pf_{(in\_plant)}}\right)\times 101325\times\right)\left(\mathrm{Qf_{(in\_plant)}}\right)}{\left(\mathrm{Qp_{(total\ plant)}}\ \varepsilon_{\mathrm{HP\ pump}}\right)} + \frac{\left(\left(\mathrm{Pf_{(B\ pump)}}\right)\times 101325\times\right)\left(\mathrm{Qf_{(pass\ 2)}}\right)}{\left(\mathrm{Qp_{(total\ plant)}}\ \varepsilon_{\mathrm{B\ pump}}\right)} - \frac{\left(\left(\mathrm{Pf_{pass\ 1}}\right)\times 101325\times\right)\left(\mathrm{Qr_{(pass\ 1)}}\right)\left(\varepsilon_{\mathrm{ERD}}\right)}{\left(\mathrm{Qp_{(total\ plant)}}\right)}}{36\times 10^5} \quad (2)$$

$\mathrm{Pf_{(B\ pump)}}$ is the outlet booster pump pressure (atm), $\mathrm{Qf_{(pass\ 2)}}$ is the second pass inlet feed flow rate (m^3/s), $\boldsymbol{\varepsilon}_{\mathrm{B\ pump}}$ is the booster pump efficiency (dimensionless), $\mathrm{Pf_{(pass1)}}$ is the first pass inlet feed pressure (atm), $\mathrm{Qr_{(pass\ 1)}}$ is the retentate flow rate for the first pass (m^3/s), and $\boldsymbol{\varepsilon}_{\mathrm{ERD}}$ is the energy recovery device efficiency (dimensionless).

Hence, the outlet pressure of the ERD can be estimated based on the retentate pressure and the ERD efficiency, as highlighted in Eq. (3).

$$\varepsilon_{\mathrm{ERD}} = \frac{\mathrm{P_{out(ERD)}}}{\mathrm{P_{out\ (Module)}}}$$

(3)

$\mathrm{P_{out(ERD)}}$ (atm) is the outlet pressure of the ERD and $\mathrm{P_{out\ (MODULE)}}$ (atm) is the retentate pressure of the membrane module. However, the booster pump pressure ($\mathrm{Pf_{(BP)}}$) (atm) can be obtained by Eq. (4).

$$\mathrm{Pf_{(BP)}} = \mathrm{Pf_{(in\_plant)}} - \left(\mathrm{Pf_{pass\ 1}}\ \boldsymbol{\varepsilon}_{\mathrm{ERD}}\right) \quad (4)$$

3. Description of the proposed medium-scale brackish water RO desalination plant of APC

The brackish water RO desalination plant of APC (capacity of 1200 m³/day) located in in the region of Dead Sea in the Hashemite Kingdom of Jordan is used to produce pure low-salinity water with a conductivity less than 1 µs. The raw water is pumped to the water desalination unit from groundwater salt wells at pH=7.45–7.59 and low salinity around 1100 ppm. The whole desalination plant comprises different units of pre-treatment, high-pressure pumps (type: Goulds pumps, ITT), multistage RO process, post-treatment permeate re-mineralisation treatment, and brine discharge. Fig. 1 shows a flowsheet of the industrial multistage RO plant presented by Al-Obaidi et al. (2018b), which consists of 20 pressure vessels and 120 membranes. Spiral wound membranes of 37.2 m^2 type TMG20D-400 synthesised by Toray Membrane USA Inc., was stuffed in the pressure vessels. The RO configuration used both retentate and permeate reprocessing strategies to quantify the requirements of very low concentration of the produced water. Moreover, 1st and 2nd passes were used in the RO configuration with arrangements (4:2) and (2:1:1), respectively. In other words, the permeate of the 1st pass is reprocessed in the 2nd pass for extra-filtration, which produces very low-salinity of produced water around 2 ppm. In this regard, the feed water of the first pass of RO system consists of the blending of two streans, i.e., the raw water stream and the low salinity retentate stream of the 2nd pass. It is noteworthy to mention that a new design modification is employed in the current study by adding an ERD and booster pump after the first pass, as shown in the subfigure (Fig. 1). This also excluded the second high-pressure pump of the 2nd pass. The addition of an ERD is attributed to the possibility of reusing the hydraulic energy in the brine stream of the 1st pass of multistage RO plant, which has been already sent to the drainage system. This stream has a relative medium pressure of around 8.6 atm, that can be successfully transferred to low-pressure permeate stream of the 1st pass (1 atm). In other words, this research intends to recover the energy from the high-pressure retentate stream and deliver it to the next pass low-pressure stream by employing an ERD at different efficiencies. For instance, the 1 atm pressure can be converted into 7.9 atm when an ERD of 90% efficiency is deployed. Furthermore, the permeate pressure can be further increased into 9.2 atm by applying a booster pump (Fig. 1). Accordingly, the booster pump is used to elevate the feed stream pressure of the 2nd pass to the same value of the operating plant pressure (9.2 atm). In this respect, the high-concentration stream of the 1st pass will be discharged out at atmospheric pressure (1 atm).

The next section will explore the contribution of the recent modification in the design of multistage multi-pass RO plant of APC by applying an ERD and booster pump at different efficiencies. The energy consumption of this set-up will be compared against the energy usage in the unmodified RO plant of APC. Also, the calculations of energy consumption would be estimated for an extensive range of variations in the main operating conditions.

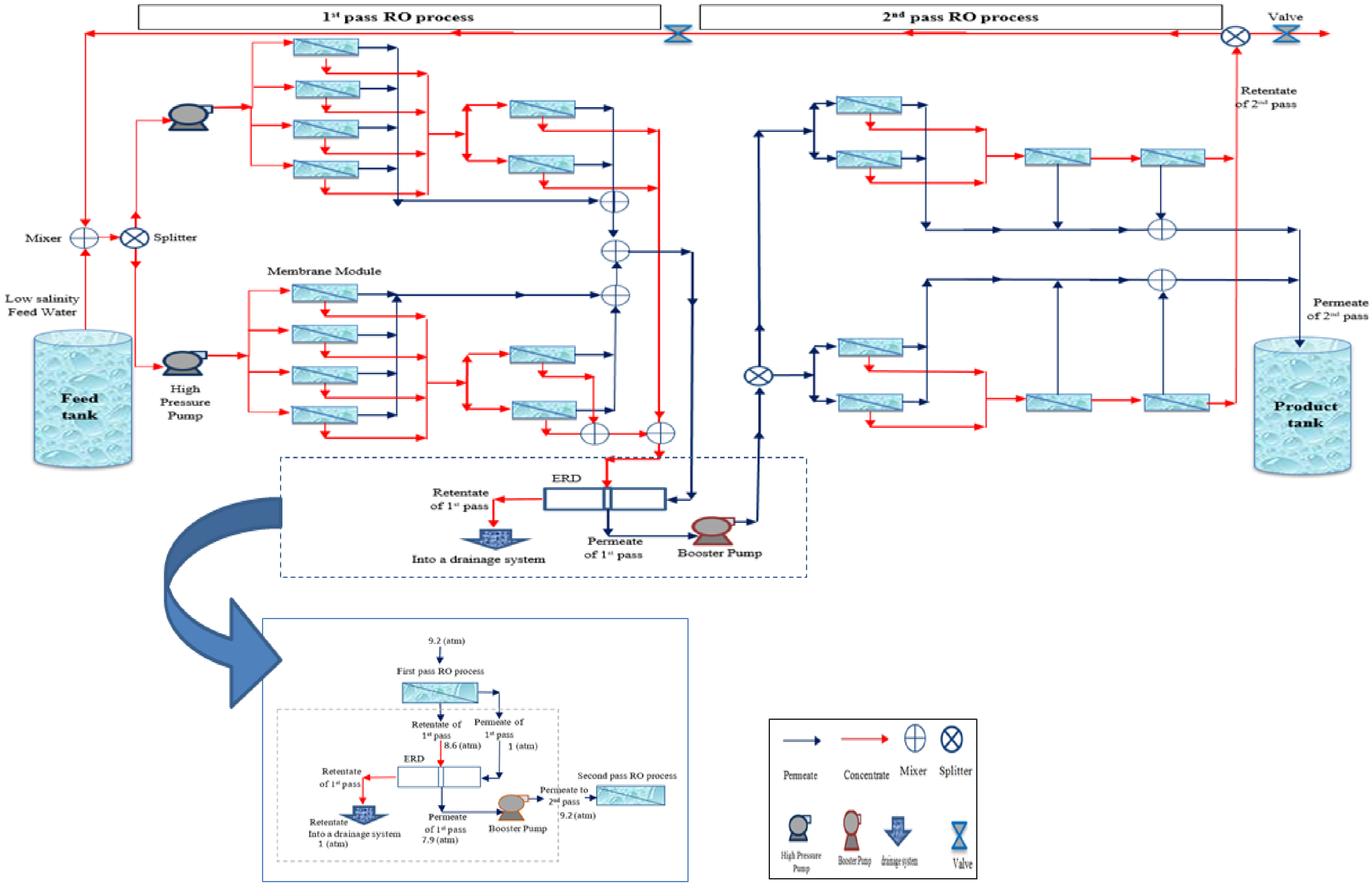

Fig. 1. Schematic diagram of multistage, multi-pass BWRO desalination plant of APC with adding of an ERD and booster pump

4. Methodology

gPROMS is a potent modelling platform mainely used to carry out steady state and dynamic simulation, and primitive optimisation. However, a successful processs simulation requires an accurate model with applicable degree of freedom. gPROMS has several advantages of using its simple interface and its ability of handling steady satte and dynamic processes of many algebraic, differential, and partial differential equations, sensitivity analysis and design of expriments. Moreover, the parameter estimation tool can be used to forecast the model parameters bsased on actual data. More importantly, the model equations of any studied model can be written in a random way without considering hierarchy model structures as the case of Matlab. In this regards, gPROMS suits has been used to simulate the RO system of APC based on the model developed by Al-Obaidi et al. (2018b) linked to Eqs. 1 to 4 presented in section 2.

5. Results and discussion

5.1 Process simulation: Impact of operating parameters

In this research, the specific energy consumption and plant water recovery are identified as the most crucial performance indicators, which are evaluated for the RO system of APC considering a wide range of operating feed flow rate, pressure, and temperature at three different ERD efficiencies of 80%, 85%, and 90%. In other words, the impact of different operating conditions on the performance of RO desalination plant of APC has been judged by conducting a sensitivity analysis using gPROMS software suits. It is broadly speaking that the specific energy consumption is at least to some extent controlled by the feed fluid characteristics and operating conditions. Therefore, it is vital to comparatively analyse the contribution of these parameters on relevant water recovery and energy consumption. More importantly, the evaluation of these indicators is carried out at a fixed inlet feed concentration of 1098.62 ppm (actual concentration of brackish groundwater). However, it is decided to examine the effect of 20% variation of operating parameters of feed flow rate and pressure against the specific energy consumption and water recovery. Also, 20% variation of operating temperature from 25 ºC to 30 ºC is selected to represent the temperature variation of stored water in the feed tanks along summer and winter in the region of Dead Sea (Jordan). It is worth noting that high recoveries of freshwater can be produced as a result of using low feed concentration due to low osmotic pressure that exists in the RO modules (Al-Bastaki and Abbas, 2003).

5.1.1 *Impact of operating feed flow rate*

This section demonstrates the effect of operating feed flow rate ($Qf_{(in\text{-}plant)}$) variation from 74 to 88.8 m^3/h (20% increase), at constant feed concentration, pressure, and temperature of 1098.62 ppm, 9.22 atm, and 25 °C, respectively, on the total energy consumption and plant water recovery with and without the application of an ERD at different efficiencies.

Fig. 2 shows a maximum water recovery of 65.84% that can be attained at the lowest feed flow rate of 74 m^3/h and commensurate with the lowest energy consumption of 0.837 kWh/m^3 without an ERD inclusion. This is attributed to a lower pressure drop inside each RO module due to the practice of low feed flow rate, which elevates the water permeation through the membranes. In other words, the loss of pressure increases with increasing feed flow rate due to the growth in friction along the membrane length, which limits the resultant water driving force. This played a weighty role in reducing the water permeation through the membranes despite the advantages of lowering the concentration polarisation and osmotic pressure due to increasing the feed flow rate (Villafafila and Mujtaba, 2003). In this regard, higher turbulence in the high concentration channel is an anticipated statement as a result to increasing the feed velocity in all the membranes situated in the 1st pass of the RO plant, which in turn increases the total retentate flow rate, decreases the retentate pressure and decreases the total permeate flow rate of the same pass. This can explain the noted reduction of total plant permeate flow rate and water recovery as a response to growing plant feed flow rate.

Fig. 2 also depicts an increase in the specific energy consumption due to increasing the feed flow rate, while keeping all the other operating conditions constant, due to a lower gain of fresh water penetrated the membranes (see Eq. (1)). This is basically true due to an apparent reduction of water recovery and water permeation as a consequence of increasing the feed flow rate. Consequently, it is recommended to run the RO process at low values of feed flow rate to guarantee high values of water recovery at low values of energy consumption. In this respect, Al-Shayji (1998) provided a neural network model for simulation of a large-scale commercial Jeddah1 seawater RO Plant Phase II (the Kingdom of Saudi Arabia). The model used to appraise the influence of several operating conditions on the total consumption energy including water recovery. The simulation results showed an increase in the rate of production would reduce the energy consumption.

Also, Fig. 2 affirmed that increasing the ERD efficiency from 80% to 85% and then to 90% can result in a reduction of specific energy consumption by around 48.3%, 50.5%, and 53.8%, respectively. Therefore, it is concluded that an increase in ERD efficiencies would decrease the specific energy consumption of the RO process. More precisely, the energy consumption falls by a constant value of 6.6% for all feed flow rates when increasing the ERD efficiency from 80% to 85%. However, a reduction of a fixed value of 6.9% in energy consumption is noticed for all feed flow rates by elevating the ERD efficiency from 85% to 90%. Thus, it is suggested to implement a low feed flow rate with the presence of an ERD at the highest possible efficiency at fixed pressure and temperature to guarantee lower energy consumption. Moreover, running the RO system at the highest feed flow rate requires a maximum specific energy consumption due to diminishing the water permeation through the membrane pores. It is noteworthy to mention that increasing the feed flow rate inside the membrane feed channel would increase the axial pressure drop that entirely reduces the water recovery. In this respect, Fig. 2 confirmed the highest energy consumption for the case of without ERD, which stimulates the original design of multistage multi-pass RO system of APC.

The presented results of Fig. 2 are in a good agreement with the findings of Al-Obaidi et al. (2018c) over er the range of feed flow rate for the removal of N-nitrosamine at a very low concentration from wastewater using multistage RO system.

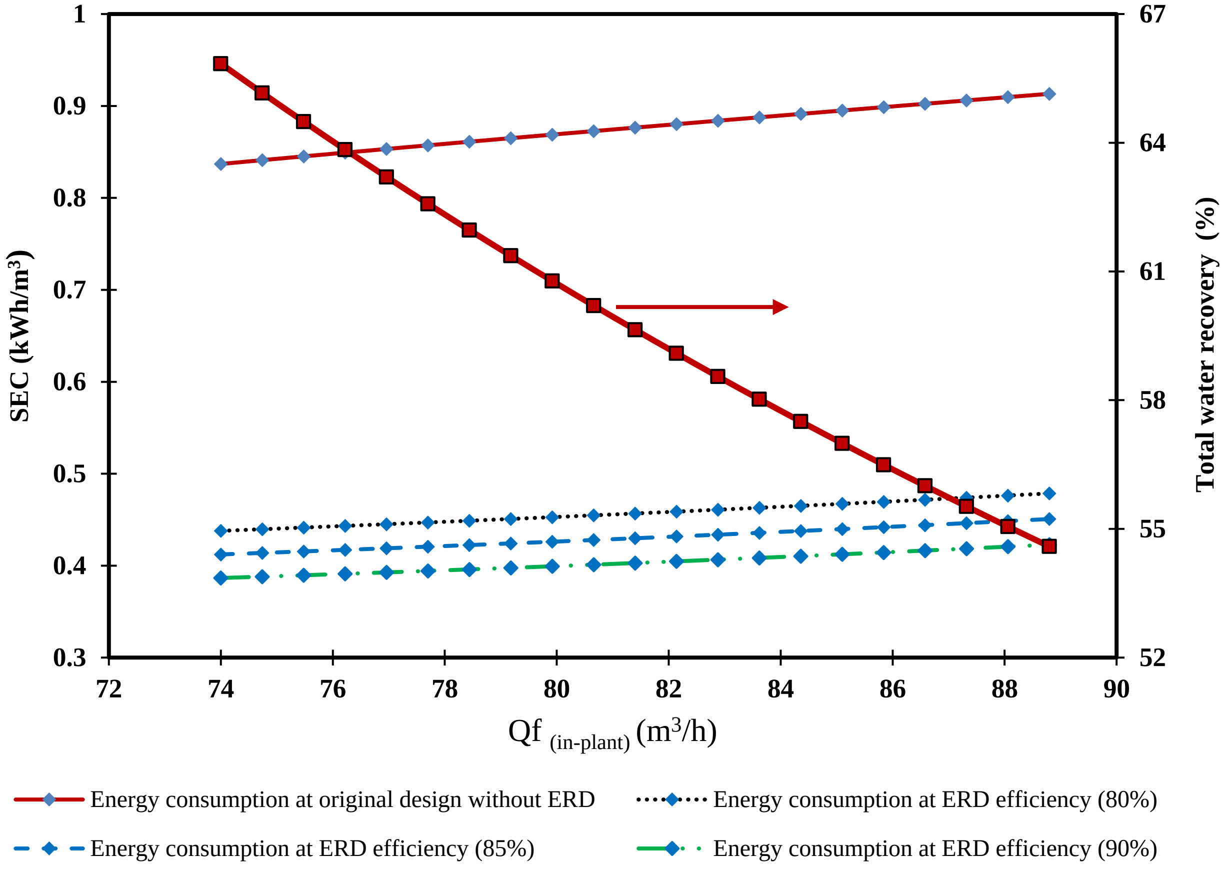

Fig. 2. Specific energy consumption and total water recovery of BWRO desalination plant of APC with and without an ERD (at different efficiencies) against plant feed flow rate.

5.1.2 Impact of operating feed pressure

The influence of feed pressure ($Pf_{(in\_plant)}$) on the performance indicators including the total water recovery and energy consumption of RO system has been studied by several researchers such as Avlonitis et al. (2003) and Dimitriou et al. (2015). Basically, the pressure is one of the most affected parameters on delivering high water permeation rate and high-quality water (Wei and McGovern, 2017; Karabelas et al., 2018). Thus, this section aims to investigate the impact of increasing the plant pressure by 20% on the nominated performance indicators of total water recovery and energy consumption.

A linear correlation between the feed pressure and both energy consumption and water recovery is illustrated in Fig. 3 for the selected variation of operating pressure from 9.22 atm to 11.06 atm at fixed feed concentration, flow rate, and temperature of 1098.62 ppm, 74 m^3/h, and 25 °C, respectively. However, an insignificant jump of water recovery is noticed close to 10.4 atm, which can be attributed to an insignificant increase of water permeation through the membrane texture. Specifically, any variation of feed pressure would directly affect both the water and solute flow rates through the membranes, which in turn alter the total water recovery (Thomson et al., 2003; Greenlee et al., 2009). More specifically, an increase in the applied pressure far away from osmotic pressure would enhance the driving force and hence water permeation through the membrane.

Fig. 3 presents that total water recovery with and without an ERD is significantly increased by increasing the operating pressure. This is agreed with a continuous reduction of the retentate flow rate of the 1st pass, increase of fresh water flow rate of the 1st and 2nd passes of the RO plant, that guarantees the evolution of total plant permeation flow rate. Also, it is fair to expect the production of high-quality water as a result of increasing operating pressure. It should also be noted that a maximum selected operating pressure of 11.06 atm would attain a maximum water recovery of 81.42% at a maximum energy consumption of 0.943 kWh/m^3 without an ERD (Fig. 3). This is comparable with the maximum water recovery achieved at the lowest feed flow rate (Fig. 2), which affirmed the superiority of feed pressure in the RO process. Also, this would reflect the advantages of the two pass multistage of RO process of APC, which is critically designed to operate at high water recoveries that commensurate with low feed salinity. In this respect, Mazlan et al. (2016) confirmed the feasibility of the RO process configuration to maintain the process at high water recoveries. This is specifically characterised by selecting a single stage (2:1) configuration of seawater RO system running at 50% of water recovery and a two-stage (3:2) configuration was nominated for running at 75% of water recovery.

In contrast, increasing of feed pressure has a considerable passive impact on the specific energy consumption, which is dramatically increased (Fig. 3). In other words, the RO system operating at high recoveries (high operating pressures) would require higher energy than those working at low recoveries and low water permeation (low operating pressures). The simulation results of this case confirm the authority of feed pressure to control the energy consumption compared to the incomparable impact of total permeate flow rate ($\mathrm{Qp}_{(\mathrm{total\ plant})}$) (see Eqs. 1 and 2). In other words, the progress of permeate flow rate due to an increased pressure was not sufficient to reduce the energy consumption. Therefore, the simulation results of Fig. 3 indicate that at the fixed feed flow rate, concentration, and temperature, the lower feed pressure results in lower water recovery and permeate flow rate, which generally sustain with lower specific energy consumption. The results obtained are also commensurate with the results of Stover (2007) and Sharif et al. (2009).

The specific energy consumption decreases, as expected when an ERD is used. As shown in Fig. 3, the lower energy consumption can be obtained by increasing the ERD efficiency from 80% to 85% and then to 90%. Apparently, the energy consumption dropped by a fixed value of 6% of all pressures with increasing the ERD efficiency from 80% to 85%. This is compared to 6.4% of energy reduction at all pressures, which is detected by increasing the ERD efficiency from 85% to 90%. Consequently, the specific energy consumption can be significantly decreased by around 47 %, 50.5%, and, 53.8% in the case of adding an ERD in the original RO system of APC at the ERD efficiencies of 80%, 85%, and 90%, respectively. The recovery of the surplus energy of the high-pressure retentate stream of the 1st pass has quietly represented a substantial amount of hydraulic energy that can be saved for the studied RO system of APC. Furthermore, the maximum specific energy consumption is registered for the case of original design of RO system of APC where only pumps are used (Fig. 3). The aforementioned results agree with the findings of Farooque (2008). Farooque (2008) investigated the influence of various ERDs of different efficiencies on the performance of seawater desalination RO plant in Saudi Arabia. This is originally confirmed the possibility of 27% as a maximum energy saving based on the maximum power consumption of the high-pressure pump of 7.93 kWh/m^3.

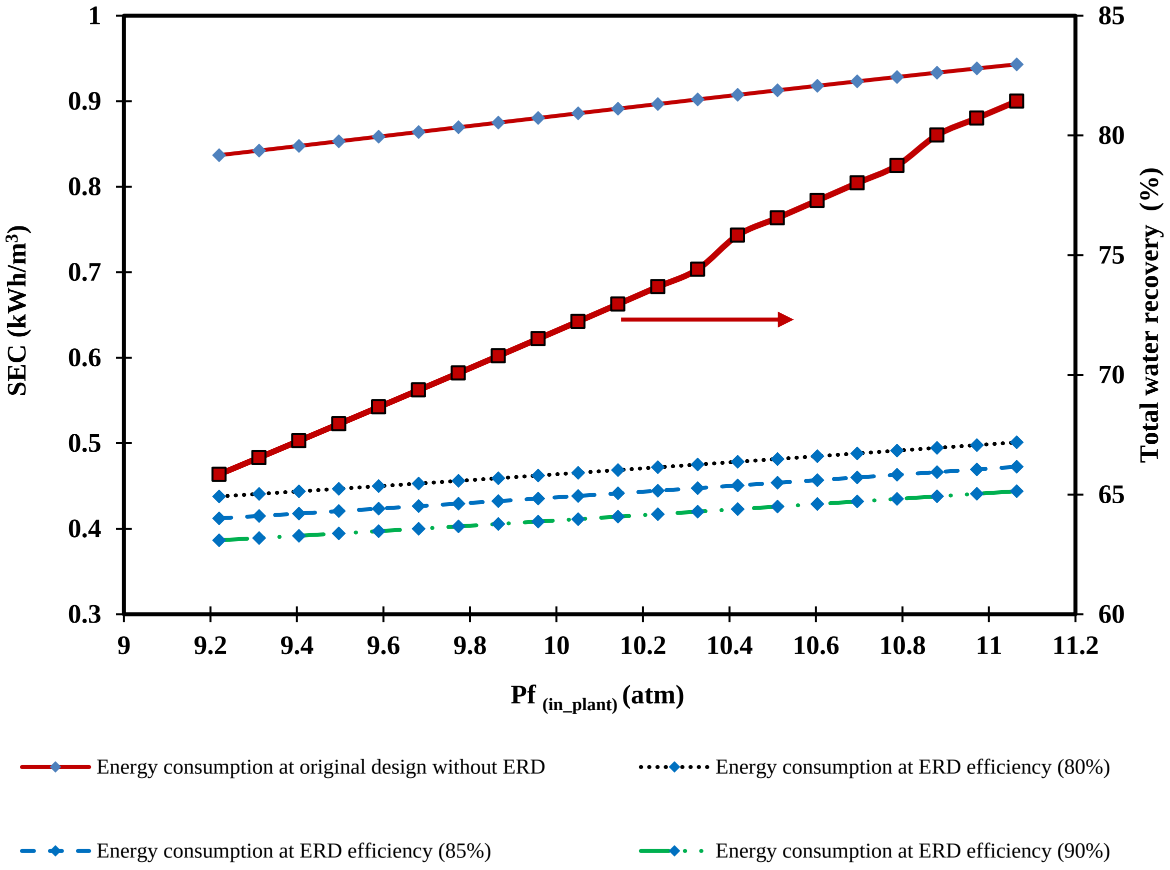

Fig. 3. Specific energy consumption and total water recovery of BWRO desalination plant of APC with and without an ERD (at different efficiencies) against operating feed pressure.

5.1.3 Impact of feed temperature

Jiang et al. (2015) reported that the feed temperature ($T_{(plant)}$) (°C) has a considerable contribution on energy consumption and water recovery for any RO system. In this regard, the performance indicators of the brackish water RO desalination plant of APC (the total energy consumption and water recovery) are assessed in this section by imposing an increase in the applied temperature from 23 °C to 30 °C (within the feed water temperature variation due to seasonal variation in the plant area). Fig. 4 shows a growth in the water recovery with the increased operating temperature at fixed feed concentration, flow rate, and pressure of 1098.62 ppm, 74 m^3/h, and 9.220 atm, respectively. These results are in a good agreement with Agashichev and Lootahb (2003) and Saasi and Mujtaba (2012). It is well known that any increase in the applied temperature would enhance the water penetration through the membrane matrix as a result to affecting the membrane pore size (Malaeb and Ayoub, 2011). This is specifically attributed to enlarging the membrane pore size due to to the thermal expansion of the membrane material, which would increase the water flux through the membrane texture. In this regard, Morin et al. (2004) deduced that increasing the pore size during buttermilk Microfiltration process causes an increase in the permeation fluxe. Moreover, Dang et al. (2014) experimentally affirmed an increase in the effective pore radius of NF membrane from 0.39 to 0.44 nm as a result to increasing the feed temperature from 20 to 40 °C. Apparently, increasing operating temperature would decrease the water viscosity and density in addition to increase the water transport parameter. Consequently, this would increase the water permeation through the membrane pores. Therefore, it is fair to expect an improvement of water permeation and water recovery as a consequence of increasing temperature (Gude, 2011). Simulation carried out in this study show an increase in water recovery by around 12.7% due to increasing temperature from 25 °C to 30 °C. However, it is noteworthy to mention that increasing temperature would increases the solute diffusion through the membrane as a consequence of enlarging the membrane pore size. Therefore, it is also fair to expect that increasing temperature would slightly reduce the quality of permeated water at the permeate channel and reduce solute rejection. The simulation results affirmed an increase of fresh water concentration from 1.99 ppm at 25 °C to 3.58 ppm at 30 °C. This in an agreement with the findings of Jin et al. (2009) who studied the effect of feed temperature of the RO process on both energy consumption and salt rejection. The results confirmed that increasing temperature could limit the concentration polarisation, which increases water and salt permeabilities. This in turn reduces the relevant salt rejection and specific energy consumption.

Fig. 4 approves a maximum water recovery of 75.45% has been achieved at the maximum tested temperature of 30 ºC, which associated with the lowest energy consumption of 0.786 kWh/m^3. Basically, Fig. 4 depicts that the specific energy consumption significantly decreases due to increasing temperature from 23 °C to 30 °C with approximately 4.9% without an ERD (original design) and 2.3%, 4.8%, and 2.6% with an ERD efficiency of 80%, 85%, and, 90%, respectively. Specifically, the specific energy consumption decreases by 47%, 50.6%, and 51.8% for the employment of 80%, 85%, and, 90% of the ERD efficiency, respectively, compared to the original design of APC (without an ERD).

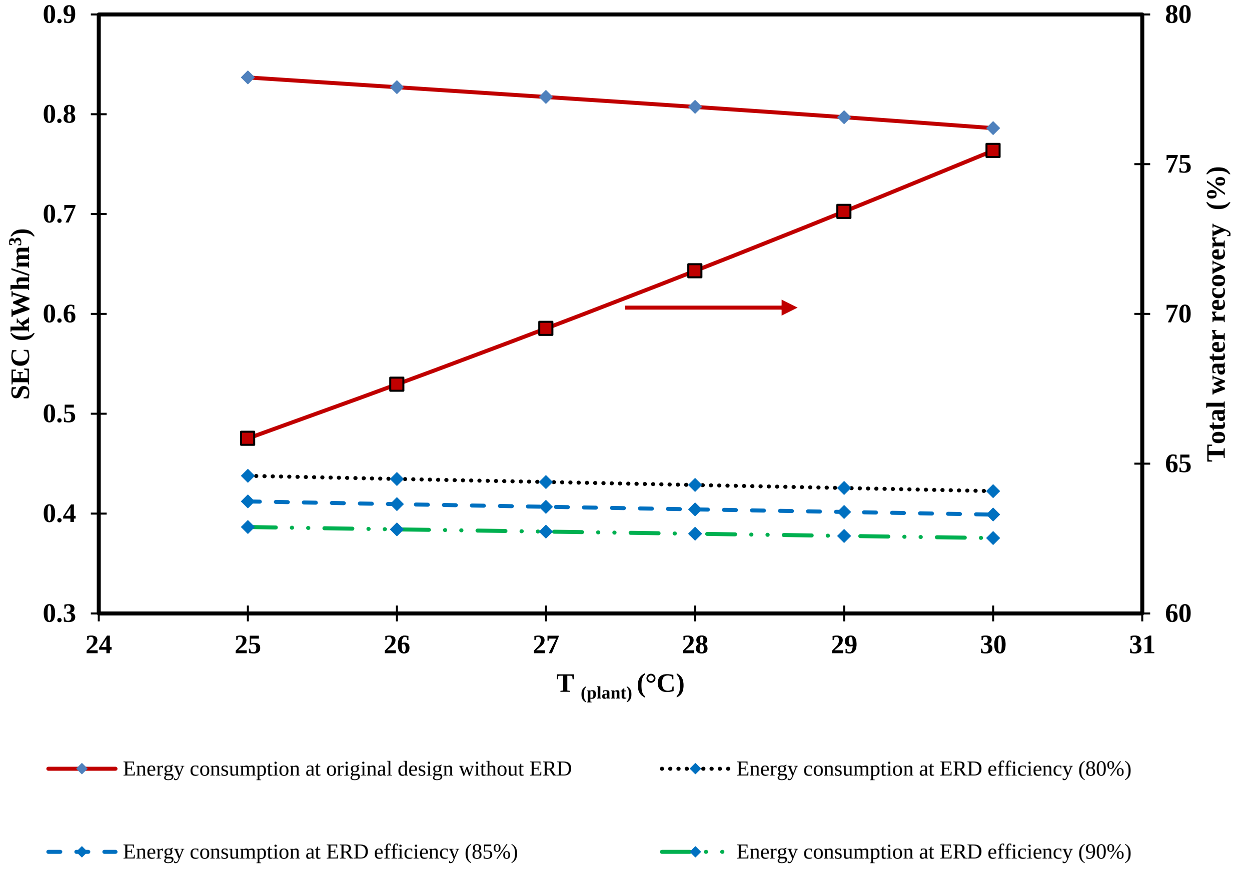

Fig. 4. Specific energy consumption and total recovery of BWRO desalination plant of APC without and with an ERD (at different efficiencies) against feed temperature.

To summarise, the simulation results confirm that low values of feed flow rate and operating pressure reduces the energy consumption. Moreover, increasing operating temperatures would reduce the energy consumption. It is also concluded that any increase of water permeation of the RO process would serve the minimisation of total energy consumption. The same trend of these simulation results are in consistent with the simulation results of Stover et al. (2005) who presented the reduction of energy consumption of SWRO plant in Ghalilah (United Arab Emirates) as a response to increasing permeate flow rate.

This study has also affirmed the positive impact of employing an ERD in the actual design of the RO process of APC. Precisely, the implementation of an ERD plays a considerable role in mitigating the energy consumption over the range of operating conditions. Increased the ERD efficiency also results in higher energy savings. There is also a noticeable positive impact of increasing feed pressure and temperature on the water recovery rate. However, it is important to note that the outputs of this study are based on the assumption of 'high-performance' RO membranes of APC, which corresponds with the current upgraded membranes of infinite water permeation (Al-Obaidi et al., 2018b). This is originally proposed in the model developed by Al-Obaidi et al., (2018b) who ignored the impact of membrane fouling. Therefore, it is fair to expect that the simulation results of the current study would not accurately stimulate the process performance of a multistage multi-pass RO system of APC after a long time of operation. In other words, the evaluation of specific energy consumption and water recovery has been carried out based on fixed membrane permeability that would definitely vary (a prime concern) and affect the process performance due to fouling propensity. This in turn would result in a greater energy loss during the filtration process.

6. Expected merits of the advanced design of APC

On the basis of simulation consideration, several expected merits of the implementation of an ERD in the multistage multi-pass RO system of APC can be drawn as follows:

- Installing an ERD in the multistage multi-pass RO design of APC would result in a decrease in the total energy consumption between 47% - 53.8% compared to the original design without an ERD. In this regard, Khawaji et al. (2007) presented a reduction of energy consumption from 6-8 kWh/m^3 without an ERD to 4-5 kWh/m^3 with an ERD for seawater RO desalination plant with capacity of 13.3 million gallons per day (MGD) located in the Kingdom of Saudi Arabia. Moreover, Stover (2007) affirmed the possibility of a dramatic improvement of seawater RO system as a result to use isobaric ERDs, which can diminish the energy consumption by as much as 60% compared to RO systems operating without ERD.

- Although the addition of an ERD and a booster pump is relatively expensive compared to the original design of RO system and would increase the fresh water production cost, it is expected that the benefit of this design will recover the capital cost of purchasing the ERD and booster pump. This is due to lower energy consumption over a prolonged operation time.
- Reducing the total energy consumption would aid to reduce the CO_2 gas emissions in the atmosphere. This is basically true since increasing the energy consumption means a higher necessity of fossil fuel combustion for electricity generation. In this aspect, the casual nexus between different sources of energy consumption and CO_2 gas emissions was explored by Palamalai et al. (2015). This in turn showed a statistical positive correlation that illustrates a high-level of energy consumption from the electricity sector would lead to high-gas emissions that passively impact the environment. Therefore, there are numerous publications that emphysised on energy saving.

Therefore, it is recommended to fine-tuning the original design of RO system of APC to comprise an ERD where a subsequent power saving can be achieved.

Some attempts were made considering different aspects to minimise the total energy consumption of RO system that would be in meaningful relationship with the recent study. For instance, Karabelas et al. (2018) analysed the contribution of several key design parameters to reduce the specific energy consumption of seven spiral wound modules in the pressure vessel for typical seawater and brackish water RO desalination processes. The assessed parameters were the retentate osmotic pressure, membrane permeability, friction losses in the feed and permeate channels, and the efficiency of ERD and high-pressure pumps. They demonstrated the importance of water permeability and efficiency of ERD and pumps to attain marginal reduction of specific energy consumption. Moreover, a superstructure optimisation methodology was used by Du et al. (2019), which include all possible stream configurations in an RO network. In this regard, the optimal blending of different salinity streams could cause insignificant exergy destruction and lower total energy requirements. The effect of applying different membrane types of the original design of APC on the specific energy consumption will be investigated in the future research.

7. Conclusions

The effects of the performance indicators of specific energy consumption and water recovery of the Brackish Water Reverse Osmosis (BWRO) process of the Arab Potash Company (APC) have been evaluated in this study. This includes the possibility of adding an Energy Recovery Device (ERD) to the original multistage multi-pass RO design and investigate the possibility of saving energy. To attain this goal, an earlier model developed by the same authors has been upgraded to estimate the specific energy consumption for with and without an ERD. The simulation studies covered the evaluation of the applied conditions of BWRO process, including feed flow rate, pressure, and temperature, on the plant performance indicators at different efficiencies of an ERD. The results show that water recovery improves with increasing feed pressure and temperature, but reduces with increasing feed flow rate. More importantly, lower energy consumption can be attained at lower values of feed flow rates and pressures and higher values of operating temperatures. Also, implementing an ERD would entirely significantly reduce the energy consumption of the RO system when compared to the original design (without an ERD) for all the tested operating parameters. Specifically, this showed maximum reductions in energy consumption of 48.3%, 50.6 %, and, 53.8% in line with 80%, 85%, and, 90% of ERD efficiency, respectively. This in turn confirmed the feasibility of installing an ERD in the original design of APC.

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