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Performance evaluation of reverse osmosis brackish water desalination plant with different recycled ratios of retentate

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Abstract

Reverse Osmosis (RO) process has become one of the most widely utilised technologies for brackish water desalination for its capabilities of producing high-quality water. This paper emphasis on investigating the feasibility of implementing the retentate recycle design on the original design of an industrial medium-sized multistage and multi-pass spiral wound brackish water RO desalination plant (1200 m³/day) of Arab Potash Company (APC) located in Jordan. Specifically, this research explores the impact of recycling the high salinity stream of the 1st pass (at different recycled percentages) to the feed stream on the process performance indicators include, the fresh water salinity, overall recovery rate, and specific energy consumption. The simulation is carried out using an earlier model developed by the same authors for the specified RO plant using gPROMS suits. This confirmed the possibility of increasing the product capacity by around 3% with 100% recycle percentage of the high salinity retentate stream.

Keywords: Reverse Osmosis; Brackish Water Desalination, Simulation, Retentate Recycle, Energy Consumption.

1. Introduction

Generally, water scarcity is a major environmental challenge facing Jordan since the early 1960s until these days. In fact, Jordan occupies the 10th rank in the world in terms of the shortage and insufficient of water resources (Hadadin et al., 2010). Consequently, it is important to exploit the brackish water besides seawater to be used as a main source of drinking water, agriculture and industrial requirements. This in turn would aid to resolve the challenge of water shortage in those countries located in the Middle East and Africa.

The RO process has stated its robustness as a foremost technology for desalting brackish water as a response to its high performance of salt rejection and water permeation (Ghaffour et al., 2015). Moreover, the application of RO process compared to other conventional thermal technologies is remarkably increased due to its high purification production with low cost and energy consumption (Al-Karaghouli and Kazmerski, 2013). The multistage RO process is eventually designed in several configurations to satisfy the qualifications of the produced water. In this respect, the Arab Potash Company (APC) employed a multistage multi-pass RO plant of brackish water desalination with a capacity of 1200 m^3/day to produce low-salinity water is around 2 ppm (Al-Obaidi et al., 2018).

Precisely, the permeate and retentate recycling designs were employed by several researchers to improve the RO process performance and their influences on the response indicators were investigated. For instance, Al-Bastaki and Abbas (1999) utilised a retentate cyclic mode in a small-scale spiral wound RO water desalination plant to explore its contribution on the permeate flow rate and salt rejection. They demonstrated that implementing the cyclic mode would significantly reduce the concentration polarisation and enhance the permeate flux. Al-Bastaki and Abbas (2003) studied the impact of permeate recycling design on the performance of a small-scale spiral wound RO desalination plant. The permeate recycle percentage between 0% to 25% has limited the concentration polarisation that completely enhanced the product quality despite a reduction of the production rate. Definitely, the product concentration was reduced by 15% at 25% of permeate recycling percentage compared to the case of no recycle mode. Whereas, the production rate was reduced by 22% compared to the case of no recycle mode.

A scenario of partial retentate recycle was tested on a small pilot-scale brackish water RO process by Sarkar et al. (2008). Increased retentate recycle requires an increase in the operating temperature to steadily maintain the performance at fixed product flow rate.

Sharma et al. (2017) studied the performance of a batch closed-loop design RO membrane process with partial retentate recirculation and opened-loop design process without recirculation. The simulation results affirmed that the closed-loop design with recirculation of retentate consumes between 70-95% less power energy compared with open-loop design. Moreover, implementing recirculation with optimal ratio (maximum recirculation) can save up to 95% of energy power consumption.

Al-Obaidi et al. (2019) explored the influence of permeate, retentate and permeate-retentate streams recycling schemes on the rejection of chlorophenol from wastewater using model-based simulation. This in turn affirmed that the permeate recycling scheme has a considerable influence on the RO process performance compared to other schemes.

Al-Obaidi et al. (2018) achieved an extensive study to estimate the performance of brackish water desalination plant of APC located in Jordan and based on multistage RO process via modelling and simulation. The model developed was validated against an actual data collected from APC and used to carry out a sensitivity analysis to predict the plant performance against the variation of operating conditions. However, up to the authors' knowledge, the influence of different flow rate percentages of recycling the high salinity retentate stream of the 1st pass on the process performance indicators has not yet been explored. Therefore, this research comes to resolve this challenge by presuming the recycling of the high salinity retentate stream of the 1st pass (that is originally disposed into the drain system) at different ratios between 10% to 100% to the feed water stream and explore its influence on the process operation. Consequently, the process performance indicators would be compared against the original experimental data of no recycle mode that carried out at specified operating conditions to assess its feasibility.

It is important to mention that the recent paper is basically an extended version of the presented paper at the conference on Proceedings of the 29th European Symposium on Computer Aided Process Engineering (Alsarayreh et al., 2019).

2. Description of BWRO desalination plant of APC

Fig. 1 represents the actual BWRO plant configuration which contains 120 membranes, 20 pressure vessels (6 membranes in each) and comprises of two passes with retentate reprocessing design of the 2nd pass. The 1st pass comprises 2 stages arranged in parallel of 6 pressure vessels with configuration (4:2) and the 2nd pass comprises 3 stages arranged in parallel of 4 pressure vessels with configuration (2:1:1).

The low-pressure permeates of the 1st pass (position 1) are combined and pumped to the 2nd pass for further filtration. Therefore, two forwarding high pumps are used to drive the water through the membranes in the 2nd pass. However, the high salinity retentate from the 1st pass is discharged into the drain system (position 4). The permeate streams of 2nd pass are grouped to form the plant product stream, which is collected in product tank with salinity around 2 ppm (position 3). However, the low salinity retentate stream from the 2nd pass (position 2) is totally recycled back (100%) to be coupled with the main stream of raw water (with salinity 1098.62 ppm). Table 1 shows the transport parameters and membranes specification. Also, the operating parameters of BWRO plant of APC are listed in Table 2. More importantly, the suggested modified design of this study is to recycle the high-concentration stream (position 4) at different flow rate percentages to the main feed stream as presented in Fig. 1, and explore its influence on the process performance indicators.

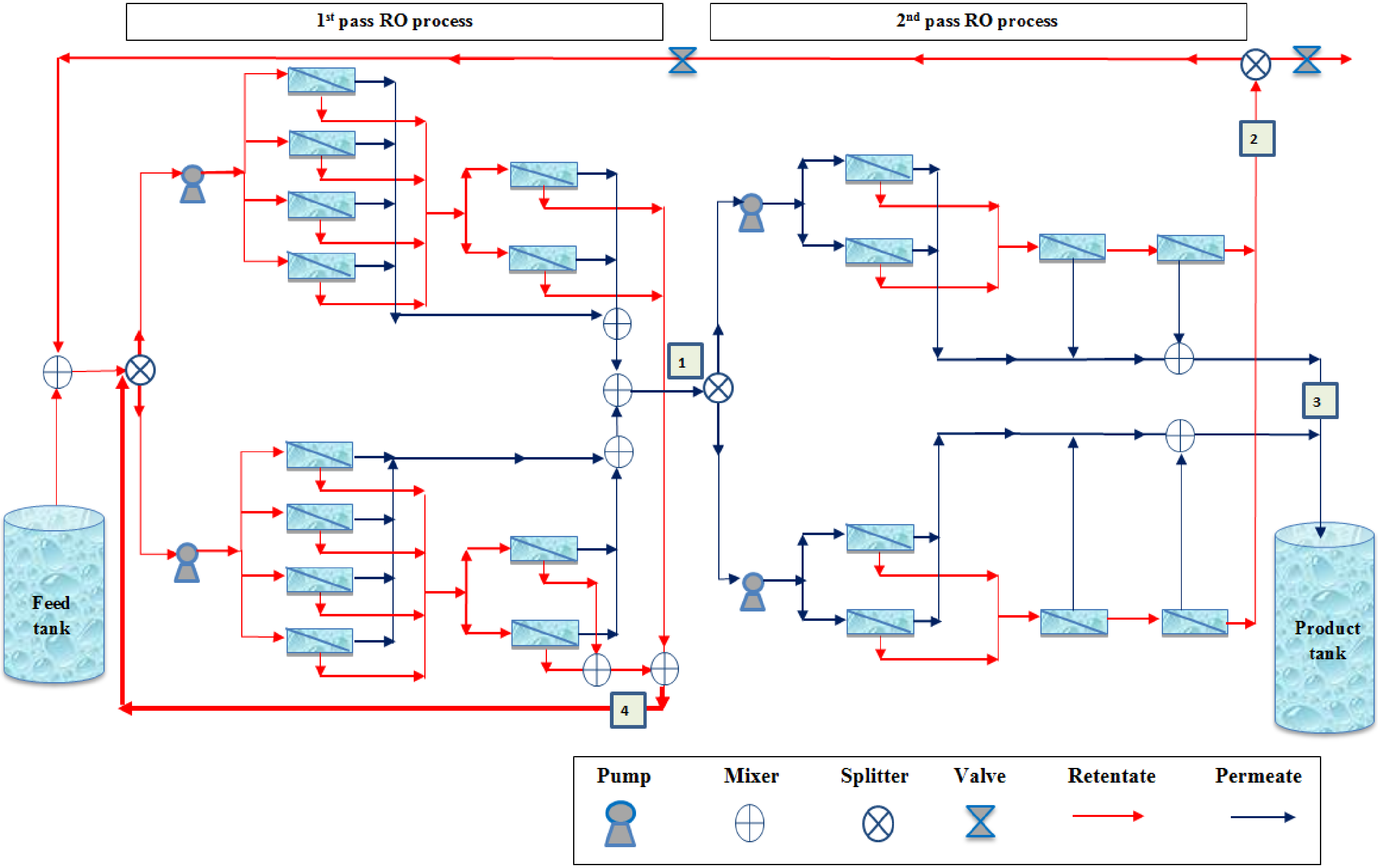

Fig. 1. Schematic diagram of BWRO desalination plant of APC (Adapted from Al-Obaidi et al., 2018).

Table 1. Operating parameters for an industrial BWRO plant of APC (Adapted from Al-Obaidi et al., 2018)

Parameter	Feed water salinity (ppm)	Feed water flow rate (m^3/h)	Feed pressure (atm)	Feed temperature (°C)	Daily production capacity (m^3/day)	Average product salinity (ppm)	Conductivity (μs/cm)	Total system rejection (%)
Value	(1098.62)	(74)	9.22	(25)	(1200)	(1.96)	(1983.06)	(99.80)

Table 2. Specifications of the spiral wound membrane element (Adapted from Al-Obaidi et al., 2018)

Parameter	Value	Parameter	Value
Membrane supplier	Toray Membrane USA Inc.	Membrane type and configuration	TMG20D-400, spiral wound
Spacer type	NALTEX-129	Length of filament in the spacer mesh L_f (m)	$2.77\text{x}10^{-3}$
Feed spacer thickness (t_f) (m)	$8.6\text{x}10^{-4}$ (34 mils)	Permeate spacer thickness (t_p) (m)	$5.5\text{x}10^{-4}$
Membrane length L (m)	1	Membrane width W (m)	37.2
Effective membrane area A (m^2)	37.2	Minimum salt rejection (%)	99.5
$A_{w\,(T_o)}$(m/atm s) at 25 (°C)	$9.6203\text{x}10^{-7}$	$B_{s(T_o)}$ (NDMA) (m/s) at 25 (°C)	$1.61277\text{x}10^{-7}$
Hydraulic diameter of the feed spacer channel d_h (m)	$8.126\text{x}10^{-4}$	Maximum pressure drop per element (atm)	0.987
$A^{'}$ (dimensionless)	7.38	n (dimensionless)	0.34
k_{dc} (dimensionless)	1.501	ε (dimensionless)	0.9058
Maximum operating pressure (atm)	40.464	Maximum feed temperature (°C)	45
Pump efficiency (-)	0.85%		

3. RO process modelling

Modelling of any RO process has a vital role to understand the transport phenomenon inside the module which helps to implement an optimum process design. Moreover, it aids to carry out a comprehensive simulation to specify the influence of each operating variable on the process outputs. Therefore, the operator can determine the best operating conditions to guarantee the optimum operation of RO process. In other words, the practical controlling variables can be obtained and leading to the maximum performance.

The steady state model for an individual spiral wound RO process was developed by Al-Obaidi et al. (2018) and successfully used to characterise the transport phenomena for each membrane and multistage brackish water RO plant of Arab Potash Company (APC) as given in Table A.1 of Appendix. A. The complete mathematical model has been coded and solved within the gPROMS software suite. The model developed is validated with the actual data collected from APC and showed a good agreement.

4. RO process simulation: Impact of recycling the retentate of 1st pass on the process performance

The RO process performance can be analysed based on simulation in order to understand the process behaviour at an open range of operating conditions. This would entirely aid to obtain high efficiency including quality and quantity of the produced water. In this section, the performance of the BWRO process of APC plant is examined by varying the 1st pass retentate stream recycle percentage from 10% to 100% in a step change of 10%. In other words, this section focuses on studying the process performance against a step change of a spontaneous retentate recycle of the high salinity 1st pass stream for once time of operation. This is quite different than applying a continuous operation of recycling the retentate stream of the 1st pass that would deteriorate the process performance due to working in a partial closed-loop, which is not the aim of this study. Consequently, this paper would investigate whether this spontaneous retentate recycle design has feasible advantages or not. It is important to confirm that the RO plant is currently working at no recycle mode of the 1st pass retentate stream. The process performance indicators include the total plant recovery (Rec), total plant rejection (Rej), product flow rate and concentration (Qp, Cp), retentate flow rate and concentration (Qr, Cr), 1st and 2nd passes recovery, 1st and 2nd passes mass transfer coefficient, total energy consumption, and 1st pass permeate flow rate. Also, the current simulation is carried out at fixed values of 1098.62 ppm, 74 m^3/h, 9.22 atm, and 25°C of raw water concentration, feed flow rate, operating pressure, and temperature, respectively.

Fig. 2. shows the influence of recycle percentage of the 1st pass retentate stream from 0 to 100% on the plant rejection and water recovery. An exponential relationship and a continuous increase of a linear relationship can be noticed for the solute rejection and total plant recovery, respectively, as a result to an increase in the 1st pass retentate stream. Statistically, this is corresponding to a decrease of 0.003%, and an increase of around 3% for solute rejection and plant water recovery, respectively. In this regard, it can be said that the optimal value of solute rejection can be attained at 40% of retentate recycled percentage. More essentially, the insignificant increase of plant water recovery can be attributed to an insignificant increase in the total plant permeate flow rate (at fixed raw water flow rate) due to an increase in the retentate recycle percentage of the 1st pass. As a result of this, the bulk velocity of all the membrane stages increases that accompanied with a reduction in the residence time of solution inside the feed channel. As a result of this, the bulk velocity of all the membrane stages in the 1st pass increases that corresponding to an increase in the concentration polarisation and entirely retard the permeated water through the membranes. Hence, the overall 1st pass permeate flow rate is decreased as a response to increasing the retentate recycle percentage of the 1st pass of high salinity stream (Table 3). However, an incremental increase of water recovery (around 3%) has been occurred due to a continual increase of total permeate flow rate of the 2nd pass (around 3%) as the percentage of retentate recycle increases (Table 3). This in turn has insignificantly increased the overall water recovery as noticed in Fig. 2. Thus, it is fair to expect a reduction in

the total energy consumption of the RO plant as a result to increasing the recycle percentage as shown in Fig.7. It is worth noting that any increase in the overall permeate flow rate $Qp_{(plant)}$ means a lower necessity of energy consumption. This is originally highlighted in Eq. 25 in Table A.1 of Appendix A.

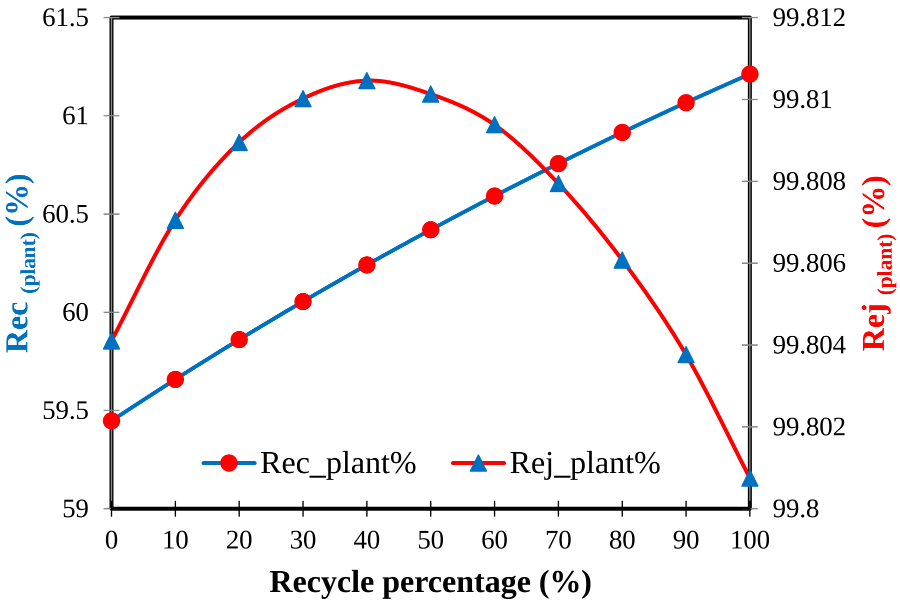

Fig. 2. Effect of different recycle percentage of the 1st pass retentate stream on overall plant recovery and solute rejection

The impact of increasing the 1st pass retentate recycle percentage from 0 to 100% on the total plant product and retentate flow rates is shown in Fig. 3. It is clear that the product flow rate and retentate flow rate are considerably increased and decreased, respectively. Statistically, this is corresponding to an increase of 2.96% in the product flow rate and a decrease of 45.7% in the retentate flow rate. Increasing of product flow rate is ascribed to the variation of product flow rate of the 1st pass. As illustrated above, increasing the recycle percentage of retentate stream of the 1st pass would decrease the total permeate flow rate of the 1st pass, which represents the feed flow rate of the 2nd pass. This means a lower velocity inside all the modules of the 2nd pass that resulted from decreasing the inlet feed flow rate of the 2nd pass with increasing the retentate recycled percentage of the 1st pass. Therefore, it can be said that an increase in the total permeate flow rate of the 2nd pass is expected due to increasing the residence time of water inside the 2nd pass RO process. Relying on this point, this would also be related with a reduced retentate flow rate as noticed in Fig. 3 and an increased water recovery of the 2nd pass. However, the overall water plant recovery keeps a marginal increase due to a high proceed of feed flow rate compared to an equivalent promotion of total product flow rate of the plant as illustrated in Fig. 2 and Table 3.

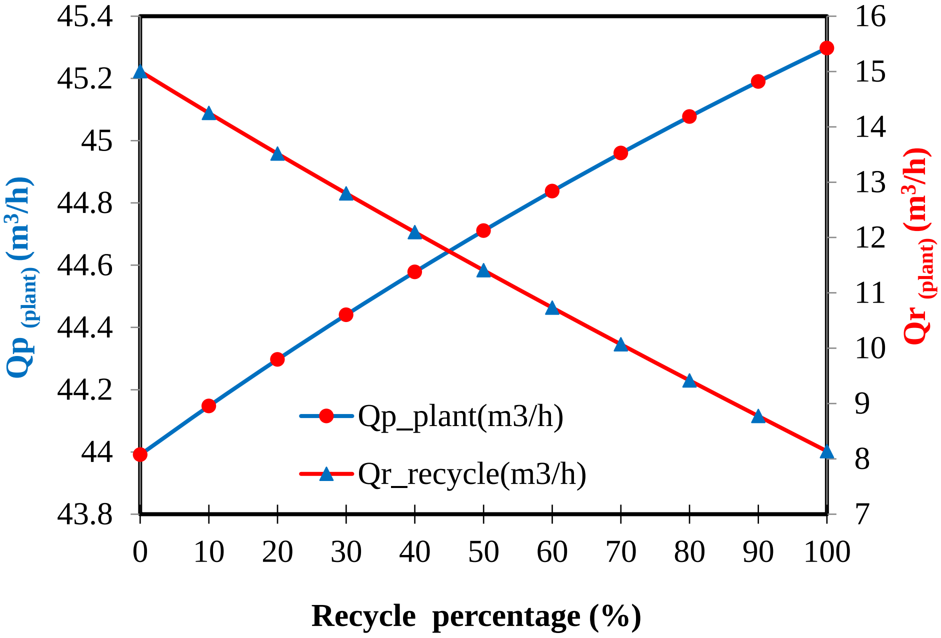

Fig. 3. Effect of different recycle percentage of the 1st pass retentate stream on product and retentate plant flowrate.

The simulation results of Fig. 4 confirm that increasing of the 1st pass recycled retentate percentage from 0 to 100% causes an increase in the product concentration and a significant increase in the retentate concentration. This is specifically comes with 53.5%, and 117.8% of increasing in the product salinity and retentate salinity, respectively. This is attributed to increasing the plant feed water concentration due to increasing the recycle percentage of high-salinity retentate stream. Furthermore, these results support the findings of Table 3 and Fig. 2 that associated with a continuous increase of permeate flow rate of the 2nd pass and total water recovery, respectively

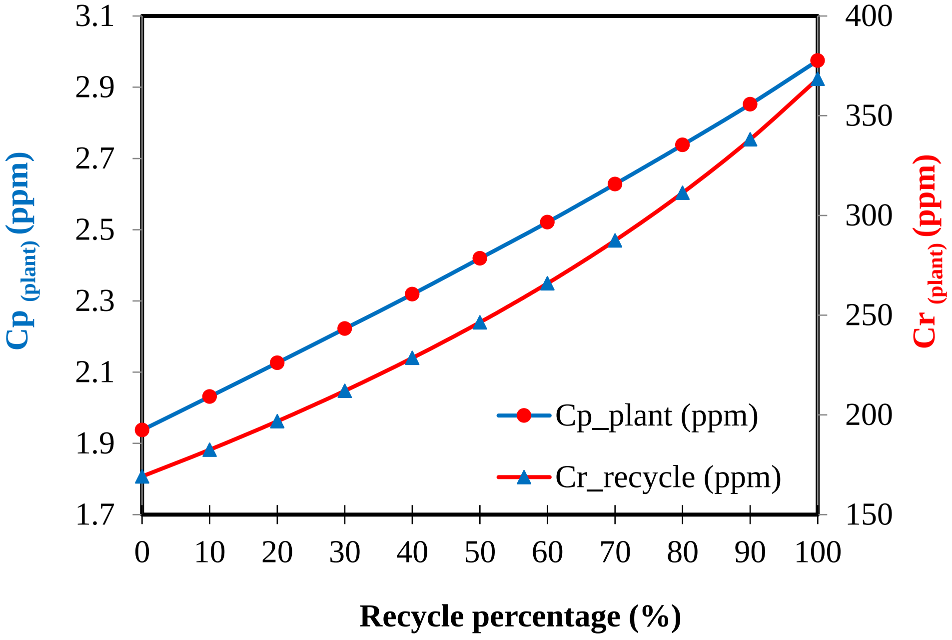

Fig. 4. Effect of different recycle percentage of the 1st pass retentate stream on product and retentate plant concentration

The models predictions for the impact of changing the recycle percentage of the 1st pass from 0 to 100% on the water recovery is depicted in Fig. 5. This in turn confirmed a reduction of water recovery ratio of the 1st pass of around 27.7%. An increase in the plant feed flow rate would possibly explain this. Basically, Eq. 17 in Table A.1 of Appendix A reflects this fact. Furthermore, increasing the feed concentration can raise the concentration polarisation that completely reduces the permeated water of each membrane. This also supports the reduction of total water recovery of the 1st pass. Consequently, the 1st pass permeate flow rate and water recover are dropped as a result to increasing the recycle retentate percentage. In the same aspect, increasing the recycle percentage of the 1st pass would increase the water recovery of the 2nd pass by about 12%. This is mainly attributed to a reduction of total feed flow rate of the 2nd pass as a result to the growth of the recycle percentage of the 1st pass, which causes an insignificant increase of plant water recovery as a result to increasing the permeate flow rate of the 2nd pass (Table 3).

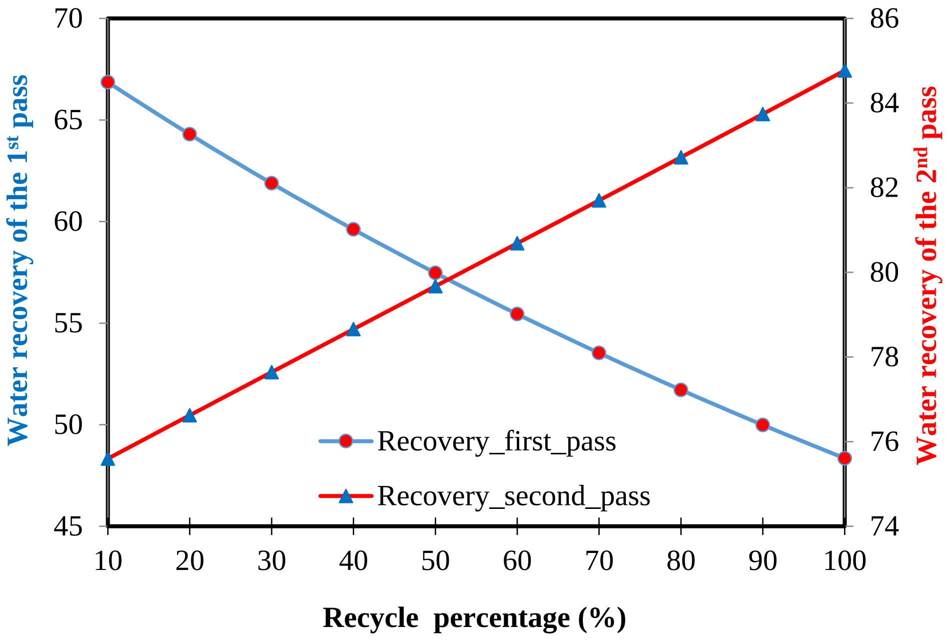

Fig. 5. Effect of different recycle percentage of the 1st pass retentate stream on the 1st and 2nd passes water recovery

To systematically understand, the transport phenomena inside each membrane in both the 1st and 2nd passes, it is vital to explore the variation of mass transfer coefficient as a result to increasing the retentate recycle percentage of the 1st pass. Basically, the mass transfer coefficient is a measure of water permeation that related to the fluid physical properties such as diffusivity and fluid velocity inside the module. The concentration polarisation can be significantly determined by determining the mass transfer coefficient. The mass transfer coefficient is already modelled in Eq. 14 in Table A.1 of Appendix A.

It can be seen from Fig. 6 that increasing the 1st pass retentate recycle percentage from 0 to 100% has a positive impact on the 1st pass mass transfer coefficient. Statistically, this is associated with an increase of 13%. This is ascribed to a significant increase of bulk velocity associated with increasing the solute diffusivity as a result to increasing feed concentration. In other words, the mass transfer coefficient is enhanced due to a higher turbulence in feed channel as a result to increasing the cross-flow velocity. However, the quantity of water permeation through the membrane pores of the 1st pass has been decreased as a result to increasing the level of concentration polarisation. The retardation of permeate flow rate of the 1st pass has already presented in Table 3 due to an increase in the recycle percentage. However, increasing the retentate recycle percentage from 0% to 100% has decreased the mass transfer coefficient of the 2nd pass as given in Fig. 6. This is specifically comes with a reduction of 4.73% in the mass transfer coefficient. Interestingly, the reduction of mass transfer coefficient in the 2nd pass can be attributed to a noticeable reduction of permeate flow rate of the 1st pass that specifies the feed flow rate of the 2nd pass. Therefore, the bulk flow rate of each module in the 2nd pass will be decreased that accompany with a reduction of mass transfer coefficient (Fig. 6). However, the fluid would have more residence time inside each module of the 2nd pass that would interpret the increase of permeate flow rate of the 2nd pass as illustrated in Table 3.

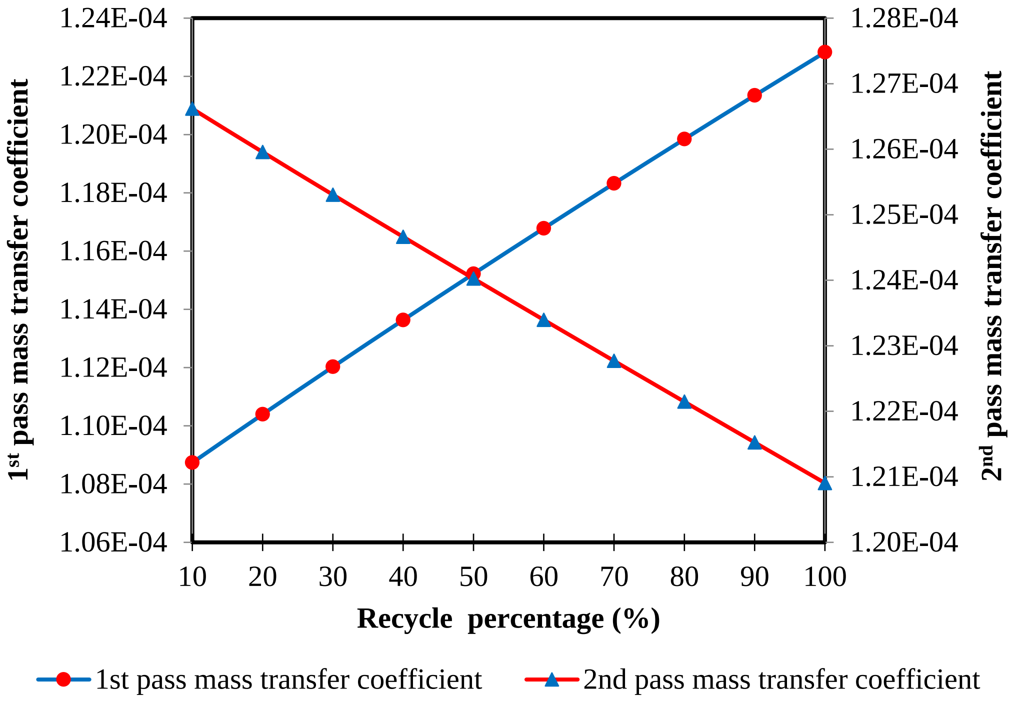

Fig. 6. Effect of different recycle percentage of the 1st pass retentate stream on the 1st and 2nd passes mass transfer coefficient

It is important to mention that the current simulation is conducted at fixed raw water flow rate, pressure, temperature, and pump efficiency (Table 1). Fig. 7 and Table 4 depict that the total energy consumption of the plant is increased by 10.7% as a response to an increase in the retentate recycle percentage of the 1st pass from 0% to 100%. Basically, the calculation of energy consumption of RO process of APC of power per cubic meter of fresh water (see Eq. 25 in Table A.1 in Appendix A) is carried out for the 1st pass and 2nd pass where the pumps are located. Therefore, it is plausible to expect an increase of energy consumption as a response to an increase in the feed flow rate of the 1st pass ($Q_{f\,(Raw\,water)} + Q_{r(1st\,pass)} + Q_{r(2nd\,pass)}$) despite the reduction of feed flow rate of the 2nd pass ($Q_{f(Block\,3)}$) as percentage of recycled stream of the 1st pass increases. Seemingly, the increase of total permeate flow rate ($Q_{p(plant)}$) is not comparable with the increase of feed flow rate of the 1st pass that would explain the growth of energy consumption. Occasionally, a marginal enhancement of the product flow rate was noticed due to increasing the retentate recycled percentage of the 1st pass (Table 3). On the other hand, a continuous increase of feed flow rate of the 1st pass has dominated the energy consumption. Statistical results of total energy consumption are embedded in Table 4.

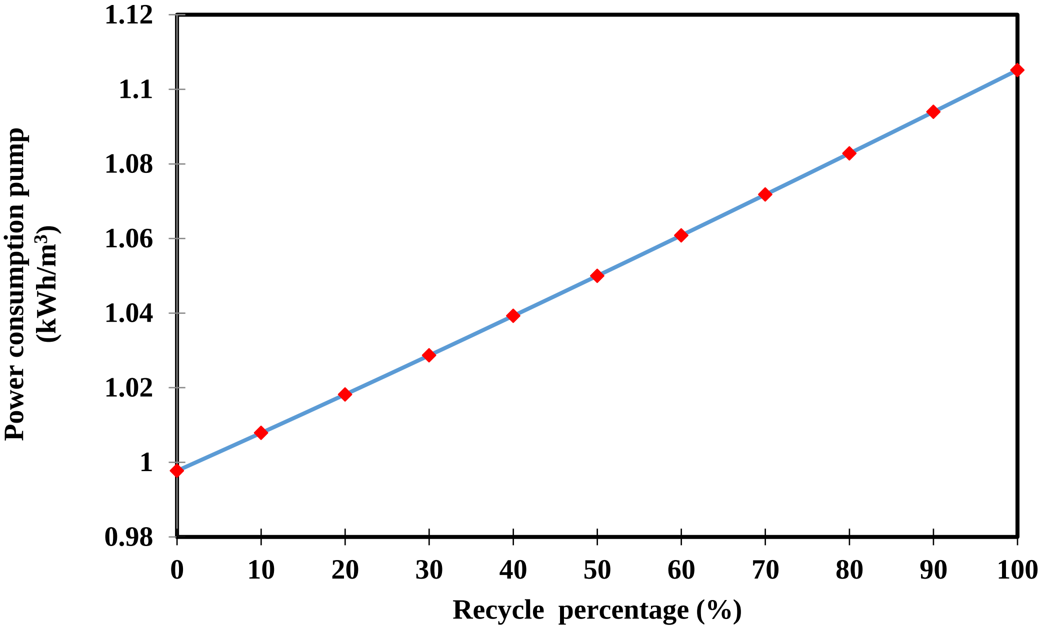

Fig. 7. Effect of different recycle percentage of the 1st pass retentate stream on the total energy consumption

Table 3 summarises all the simulation results that associated with the influence of varying the 1st pass retentate recycle percentage from 10 to 100% at fixed operating pressure and raw water concentration, raw feed flow rate, and temperature of raw water of 9.22 atm, 1098.62 ppm, 74 m^3/h, and 25°C, respectively on several operating parameters including the 1st pass permeate flow rate, 2nd pass permeate flow rate, overall solute rejection and water recovery of the plant, mass transfer coefficient of the 1st pass, and mass transfer coefficient of the 2nd pass. Essentially, the 1st pass permeate flow rate fed to the 2nd pass is significantly decreased by about 9.4% as a response to this variation. This can be attributed to an increase in the retentate concentration with increasing the 1st pass retentate recycle percentage. Furthermore, increasing the feed concentration has entirely impacted the concentration polarisation which reduces the permeated water through the membranes. Therefore, the total permeate flow rate of 1st pass is decreased dramatically as a result to increasing the retentate percentage.

Table 3. The simulation results of several operating conditions and process performance indicators with varied recycle ratio of the 1st pass retentate stream

Recycle percentage	**10%**	**20%**	**30%**	**40%**	**50%**
Total Qp of the 1st pass (m^3/h)	58.39	57.81	57.23	56.67	56.11
Total Qp of the 2nd pass (m^3/h), which represents the total plant permeate flow rate ($Q_{p(plant)}$)	44.147	44.296	44.440	44.578	44.7106
Total solute rejection of the plant (%)	99.80	99.80	99.81	99.82	99.80
Total water recovery of the plant (%)	59.65	56.86	60.05	60.24	60.41
Mass transfer coefficient of the 1st pass (-)	1.09×10^{-4}	1.10×10^{-4}	1.12×10^{-4}	1.14×10^{-4}	1.15×10^{-4}
Mass transfer coefficient of the 2nd pass (-)	1.27×10^{-4}	1.26×10^{-4}	1.25×10^{-4}	1.25×10^{-4}	1.24×10^{-4}
Recycle percentage	**60%**	**70%**	**80%**	**90%**	**100%**
Total Qp of the 1st pass (m^3/h)	55.57	55.03	54.49	53.96	53.44
Total Qp of the 2nd pass (m^3/h) which represents	44.837	44.959	45.077	45.189	45.297

the total plant permeate flow rate ($Q_{p(plant)}$)					
Total solute rejection of the plant (%)	99.80	99.80	99.80	99.80	99.80
Total water recovery of the plant (%)	60.591	60.756	60.915	61.07	61.21
Mass transfer coefficient of the 1st pass (-)	1.17×10^{-4}	1.18×10^{-4}	1.20×10^{-4}	1.21×10^{-4}	1.23×10^{-4}
Mass transfer coefficient of the 2nd pass (-)	1.23×10^{-4}	1.23×10^{-4}	1.22×10^{-4}	1.22×10^{-4}	1.21×10^{-4}

To comprehend the performance of multistage RO process with no recycle mode (0% retentate percentage), Table.4 presents the simulation results of several performance indicators with 40%, 100%, and without recycling mode for comparison purposes. Precisely, it can be noticed that no recycle mode (0%) can keep the process at the lowest product concentration and lowest water recovery that corresponding with the lowest energy consumption. However, the highest overall product flow rate has been attained at 100% retentate recycle of the 1st pass, which involved a slight increase in product concentration from 1.937 to 2.974 ppm at the same operating conditions. Interestingly, the enhancement of the productivity of fresh water accompanied an increase of energy consumption by around 11% within almost fixed solute rejection. Up to the authors' knowledge, increasing the product flow rate for such Reverse Osmosis desalination plant by 3% will be profitable for the long-time of operation that need to be applied in the original RO process design. Moreover, the improvement of energy consumption can be enlarged via the use of more-efficient pumps as the current pump efficiency was 85%.

Table 4. Simulation results of process performance indicators with 0% (without recycle mode), 40% and 100% percentages of retentate recycle

Without recycle mode (APC plant)		With recycle mode		With recycle mode	
Indicators of process performance at recycle percentage from 1st pass = 0 %		Indicators of process performance at recycle percentage from 1st pass = 40 %		Indicators of process performance at recycle percentage from 1st pass = 100 %	
Rej_plant (%)	99.804	Rej_plant (%)	99.811	Rej_plant (%)	99.801
Rec_plant (%)	59.44733	Rec_plant (%)	60.24091	Rec_plant (%)	61.21247
$Q_{p(plant)}$ (m^3/h)	43.991	$Q_{p(plant)}$ (m^3/h)	44.578	$Q_{p(plant)}$ (m^3/h)	45.297
Qr_recycle from the 2nd pass (m^3/h)	15.005	Qr_recycle from the 2nd pass (m^3/h)	12.095	Qr_recycle from the 2nd pass (m^3/h)	8.139
Cp_plant (ppm)	1.937	Cp_plant (ppm)	2.319	Cp_plant (ppm)	2.975
Cr_recycle of the 2nd pass (ppm)	169.159	Cr_recycle of the 2nd pass (ppm)	228.545	Cr_recycle of the 2nd pass (ppm)	368.465
Power consumption: pump (kWh/m^3)	0.997	Power consumption: pump (kWh/m^3)	1.039	Power consumption: pump (kWh/m^3)	1.105

5. Conclusions

The performance of multistage and multi-pass RO brackish water desalination plant of Arab Potash Company (APC) with a new design of different recycled percentages of 1st pass retentate is investigated via simulation. The simulation is carried out at fixed raw water flow rate, concentration, pressure, and temperature. This explored that an implementing of a 100% recycle percentage can result in an increase in the production capacity (although with increased salinity of the product water) compared to 0% of no recycle mode that is currently used in the RO process of APC plant. Interestingly, increasing the 1st pass recycle percentage from 0% to 100% has increased the 1st pass mass transfer coefficient of 13%, which has a positive impact on the quantity of permeated water. Also, an increase of permeate flow rate of the 2nd pass by 3% has been deduced as a result to increase the residence time of water inside the 2nd pass RO modules. This also associated with inconsiderable increase of the product water salinity of 2.975 ppm, which is still much below the recommended drinking water salinity limit of ~200 ppm set by various countries of the world.

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Table. A.1. Mathematical model of RO system of APC

No.	Model equations	Specifications
1	$Q_p = A_{w(T)} \, NDP_{fb} \, A_m$	Total water flux (m^3/s)
2	$A_{w(T)} = A_{w(25\,C)} \, TCF_p \, F_f$	Water permeability constant at operating temperature 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 at standard conditions which are proposed by the membrane manufacturer (Toray Membrane USA Inc., 2015)
4	$NDP_{fb} = P_{fb} - P_p - \pi_b + \pi_p$	The driving pressure (atm)
5	$P_{fb} = P_f - \frac{\Delta P_{drop,E}}{2}$	Feed brine pressure (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 along the membrane element (atm)
7	$Q_b = \frac{Q_f + Q_r}{2}$	Bulk flow rate (m^3/s)
8	$\pi_b = 0.7994 \, C_b \, [1 + 0.003\,(T-25)]$ $\pi_p = 0.7994 \, C_p \, [1 + 0.003\,(T-25)]$	Bulk and permeate osmotic pressures are proposed by the membrane manufacturer (Toray Membrane USA Inc.)
9	$C_b = \frac{C_f + C_r}{2}$	Bulk salinity (kg/m^3)
10	$Q_s = B_{s(T)} \left(C_w - C_p\right)$	Solute flux through the membrane (kg/m^2 s)
11	$B_{s(T)} = B_{s(25\,C)} \, TCF_s$	Solute transport parameter at operating temperature (m/s)
12	$TCF_s = 1 + 0.05\,(T-25) < 25\,°C$ $TCF_s = 1 + 0.08\,(T-25) > 25\,°C$	Temperature correction factor of solute at standard conditions which are proposed by the membrane manufacturer (Toray Membrane USA Inc.).
13	$C_w = C_p + \left(\frac{C_f + C_r}{2} - C_p\right) exp\left(\frac{Q_p/A_m}{k}\right)$	Concentration at the membrane surface (kg/m^3)
14	$k = 0.664 \, k_{dc} \, Re_b^{0.5} \, Sc^{0.33} \left(\frac{D_b}{d_h}\right)\left(\frac{2d_h}{L_f}\right)^{0.5}$	Mass transfer coefficient (dimensionless) (Da Costa et al. (1994)
15	$Sc = \frac{\mu_b}{\rho_b \, D_b}$	Schmidt number (dimensionless)
16	$Re = \frac{\rho \, d_e J_w}{\mu}$	Reynolds number (dimensionless)
17	$Rec = \frac{Q_p}{Q_f} = \frac{(C_r - C_f)}{(C_r - C_p)}$	Total water recovery (dimensionless)
18	$Q_s = \frac{Q_p \, C_p}{A_m}$	Solute flux
19	$Rej_{real} = \frac{Q_p\,(1 - Rej)}{A_m \, B_{s(T)}} \; Rej_{real} = \frac{C_w - C_p}{C_w}$	Real solute rejection (dimensionless)
20	$Rej = \frac{C_f - C_p}{C_f}$	Observed rejection (dimensionless)

21	$J_w = \frac{B_{s(T)}\ Rej_{real}}{(1 - Rej)}$	Water flux J_w (m/s)
22	$\mathrm{Rej} = \left(1 + \frac{\mathrm{B_{s(T)}}}{\mathrm{J_w}}\right)^{-1}$	Solute rejection by assuming that Rej equals Rej_{real}
23	$C_p = \frac{C_f}{Rec}\ [1 - (1 - Rec)]^{(1-Rej)}$	Average permeate salinity at the permeate channel
24	$C_r = C_f\ [1 - Rec]^{-Rej}$	Average retentate salinity at the permeate channel
25	$E1 = \frac{Pf(in)_{(plant)}*101325*Qf_{(Raw\ water)}}{\frac{Qp_{(plant)}*\varepsilon\ punp}{36x10^5}} + \frac{Pf_{(Block\ 3)}*101325*Qf_{(Block\ 3)}}{\frac{Qp_{(plant)}*\varepsilon\ punp}{36x10^5}}$	Total plant energy consumption