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

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11
12 **Abstract**

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

24
25 **Keywords:** Reverse Osmosis; Brackish Water Desalination, Simulation, Retentate Recycle,
26 Energy Consumption.

1 **1. Introduction**

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

8 The RO process has stated its robustness as a foremost technology for desalting brackish water
9 as a response to its high performance of salt rejection and water permeation (Ghaffour et al.,
10 2015). Moreover, the application of RO process compared to other conventional thermal
11 technologies is remarkably increased due to its high purification production with low cost and
12 energy consumption (Al-Karaghoul and Kazmerski, 2013). The multistage RO process is
13 eventually designed in several configurations to satisfy the qualifications of the produced water.
14 In this respect, the Arab Potash Company (APC) employed a multistage multi-pass RO plant of
15 brackish water desalination with a capacity of 1200 m³/day to produce low-salinity water is
16 around 2 ppm (Al-Obaidi et al., 2018).

17 Precisely, the permeate and retentate recycling designs were employed by several researchers to
18 improve the RO process performance and their influences on the response indicators were
19 investigated. For instance, Al-Bastaki and Abbas (1999) utilised a retentate cyclic mode in a
20 small-scale spiral wound RO water desalination plant to explore its contribution on the permeate
21 flow rate and salt rejection. They demonstrated that implementing the cyclic mode would
22 significantly reduce the concentration polarisation and enhance the permeate flux. Al-Bastaki
23 and Abbas (2003) studied the impact of permeate recycling design on the performance of a

1 small-scale spiral wound RO desalination plant. The permeate recycle **percentage** between 0% to
2 25% has limited the concentration polarisation that completely enhanced the product quality
3 despite a reduction of the production rate. Definitely, the product concentration was reduced by
4 15% at 25% of permeate recycling **percentage** compared to the case of no recycle mode.
5 Whereas, the production rate was reduced by 22% compared to the case of no recycle mode.

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

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

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

19 **Al-Obaidi et al. (2018)** achieved an extensive study to estimate the performance of brackish
20 water desalination plant of APC located in Jordan and based on multistage RO process via
21 modelling and simulation. The model developed was validated against an actual data collected
22 from APC and used to carry out a sensitivity analysis to predict the plant performance against the
23 variation of operating conditions. However, up to the authors' knowledge, the influence of

1 different flow rate percentages of recycling the high salinity retentate stream of the 1st pass on
2 the process performance indicators has not yet been explored. Therefore, this research comes to
3 resolve this challenge by presuming the recycling of the high salinity retentate stream of the 1st
4 pass (that is originally disposed into the drain system) at different ratios between 10% to 100% to
5 the feed water stream and explore its influence on the process operation. Consequently, the
6 process performance indicators would be compared against the original experimental data of no
7 recycle mode that carried out at specified operating conditions to assess its feasibility.

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

11

12 **2. Description of BWRO desalination plant of APC**

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

18 The low-pressure permeates of the 1st pass (position 1) are combined and pumped to the 2nd pass
19 for further filtration. Therefore, two forwarding high pumps are used to drive the water through
20 the membranes in the 2nd pass. However, the high salinity retentate from the 1st pass is
21 discharged into the drain system (position 4). The permeate streams of 2nd pass are grouped to
22 form the plant product stream, which is collected in product tank with salinity around 2 ppm
23 (position 3). However, the low salinity retentate stream from the 2nd pass (position 2) is totally

1 recycled back (100%) to be coupled with the main stream of raw water (with salinity 1098.62
2 ppm). [Table 1](#) shows the transport parameters and membranes specification. Also, the operating
3 parameters of BWRO plant of APC are listed in [Table 2](#). More importantly, the suggested
4 modified design of this study is to recycle the high-concentration stream (position 4) at different
5 flow rate percentages to the main feed stream as presented in [Fig. 1](#), and explore its influence on
6 the process performance indicators.

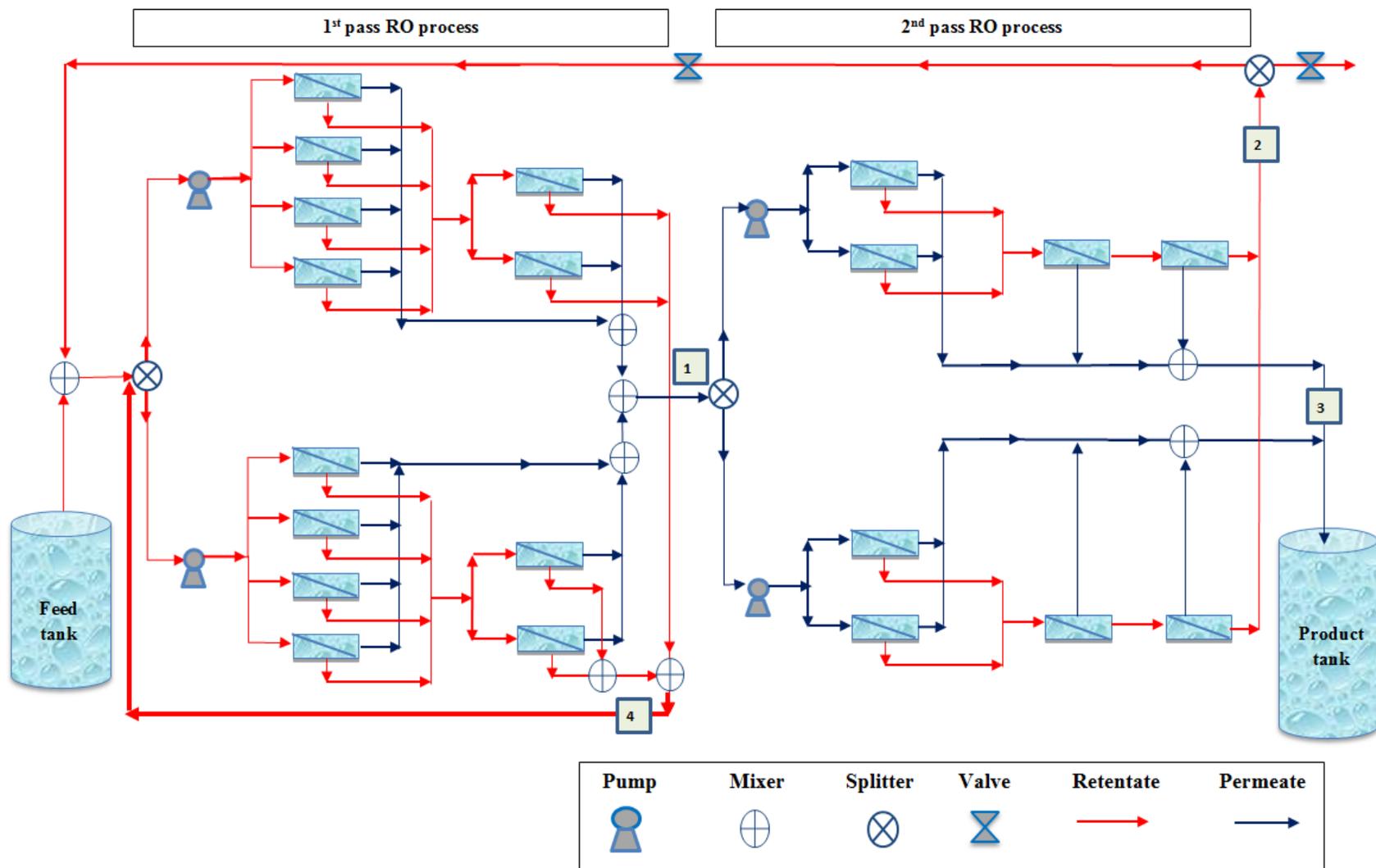


Fig. 1. Schematic diagram of BWRO desalination plant of APC (Adapted from Al-Obaidi et al., 2018).

1 **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)

2
3 **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 configuration	TMG20D-400, spiral wound
Spacer type	NALTEX-129	Length of filament in the spacer mesh L_f (m)	2.77×10^{-3}
Feed spacer thickness (t_f) (m)	8.6×10^{-4} (34 mils)	Permeate spacer thickness (t_p) (m)	5.5×10^{-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)	9.6203×10^{-7}	$B_s(T_o)$ (NDMA) (m/s) at 25 (°C)	1.61277×10^{-7}
Hydraulic diameter of the feed spacer channel d_h (m)	8.126×10^{-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%		

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5
6 **3. RO process modelling**

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

1 obtained and leading to the maximum performance.

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

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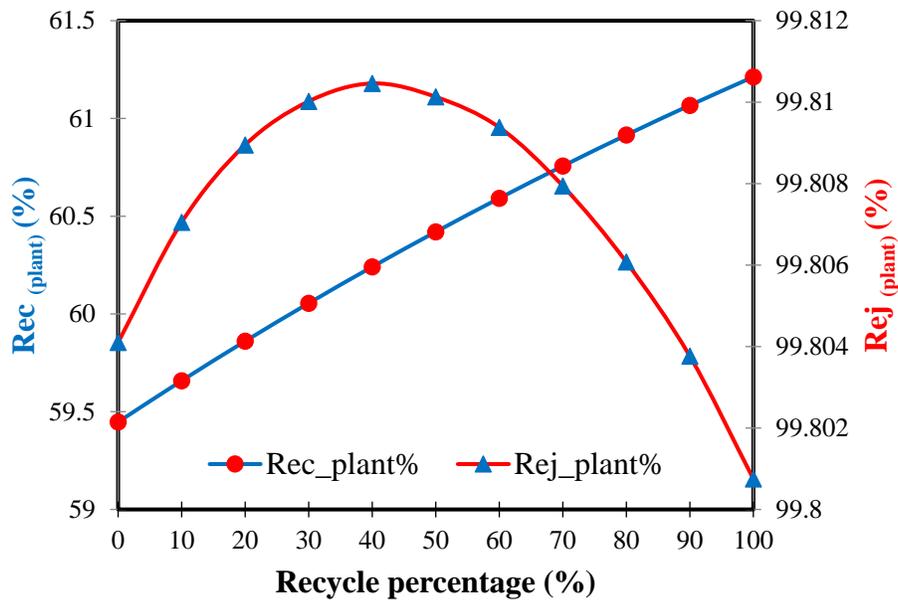
9 **4. RO process simulation: Impact of recycling the retentate of 1st pass on the process** 10 **performance**

11 The RO process performance can be analysed based on simulation in order to understand the
12 process behaviour at an open range of operating conditions. This would entirely aid to obtain
13 high efficiency **including quality and quantity of the produced water**. In this section, the
14 performance of the BWRO process of APC plant is examined by varying the 1st pass retentate
15 stream recycle **percentage** from 10% to 100% in a step change of 10%. In other words, this
16 section focuses on studying the process performance against a step change of a spontaneous
17 retentate recycle of the high salinity 1st pass stream for once time of operation. This is quite
18 different than applying a continuous operation of recycling the retentate stream of the 1st pass
19 that would deteriorate the process performance due to working in a partial closed-loop, which is
20 not the aim of this study. Consequently, this paper **would** investigate whether this spontaneous
21 retentate recycle design has feasible advantages or not. It is **important** to confirm that the RO
22 plant is **currently** working at no recycle mode of the 1st pass retentate stream. The process
23 performance indicators include the total plant recovery (Rec), total plant rejection (Rej), product
24 flow rate and concentration (Q_p , C_p), retentate flow rate and concentration (Q_r , C_r), 1st and 2nd

1 **passes** recovery, 1st and 2nd **passes** mass transfer coefficient, total energy consumption, and 1st
2 pass permeate flow rate. Also, the current simulation is carried out at fixed values of 1098.62
3 ppm, 74 m³/h, 9.22 atm, and 25°C of raw water concentration, feed flow rate, operating pressure,
4 and temperature, respectively.

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

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

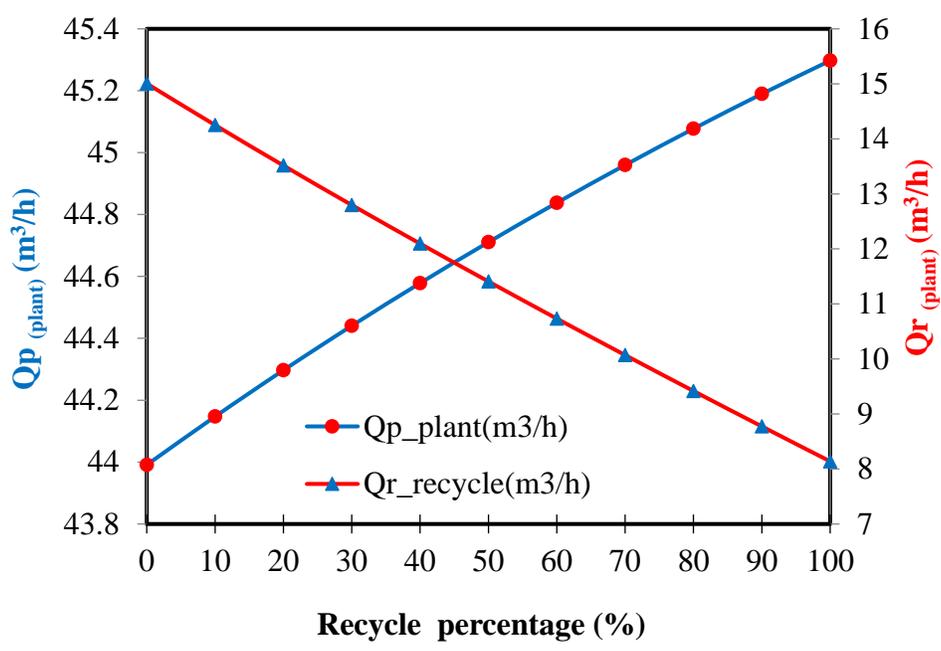


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 7 **Fig. 2.** Effect of different recycle percentage of the 1st pass retentate stream on overall plant recovery and solute
 8 rejection

9
 10 The impact of increasing the 1st pass retentate recycle percentage from 0 to 100% on the total
 11 plant product and retentate flow rates is shown in Fig. 3. It is clear that the product flow rate and
 12 retentate flow rate are considerably increased and decreased, respectively. Statistically, this is
 13 corresponding to an increase of 2.96% in the product flow rate and a decrease of 45.7% in the
 14 retentate flow rate. Increasing of product flow rate is ascribed to the variation of product flow
 15 rate of the 1st pass. As illustrated above, increasing the recycle percentage of retentate stream of

1 the 1st pass would decrease the total permeate flow rate of the 1st pass, which represents the feed
 2 flow rate of the 2nd pass. This means a lower velocity inside all the modules of the 2nd pass that
 3 resulted from decreasing the inlet feed flow rate of the 2nd pass with increasing the retentate
 4 recycled **percentage** of the 1st pass. Therefore, **it can be said that** an increase in the total permeate
 5 flow rate of the 2nd pass **is expected due** to increasing the residence time of water inside the 2nd
 6 pass RO process. Relying on this point, this would also be related with a reduced retentate flow
 7 rate as noticed in Fig. 3 and an increased water recovery of the 2nd pass. However, the overall
 8 water plant recovery keeps **a marginal increase** due to a high proceed of feed flow rate compared
 9 to **an equivalent promotion of total product flow rate of the plant** as illustrated in Fig. 2 and
 10 Table 3.

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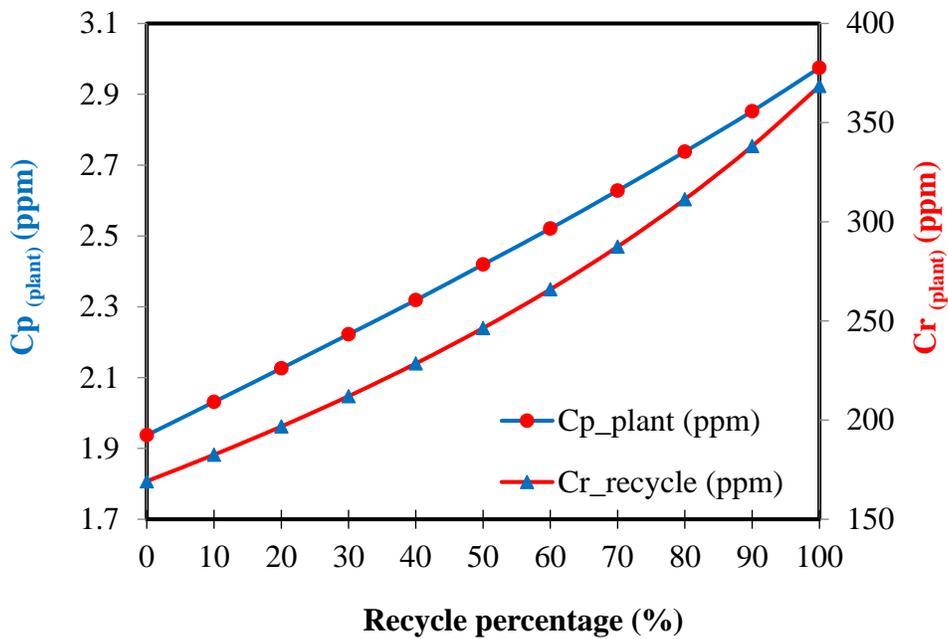
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13 **Fig. 3.** Effect of different recycle **percentage** of the 1st pass retentate stream on product and retentate plant flowrate.

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

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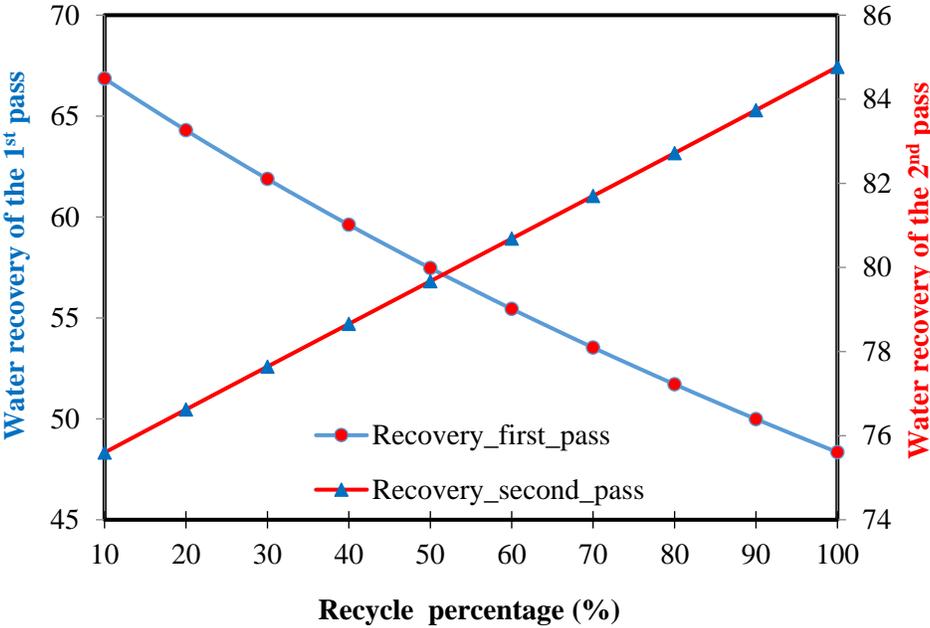
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11 **Fig. 4.** Effect of different recycle percentage of the 1st pass retentate stream on product and retentate plant
 12 concentration

13

14 The models predictions for the impact of changing the recycle percentage of the 1st pass from 0
 15 to 100% on the water recovery is depicted in Fig. 5. This in turn confirmed a reduction of water

1 recovery ratio of the 1st pass of around 27.7%. An increase in the plant feed flow rate would
 2 possibly explain this. Basically, Eq. 17 in Table A.1 of Appendix A reflects this fact.
 3 Furthermore, increasing the feed concentration can raise the concentration polarisation that
 4 completely reduces the permeated water of each membrane. This also supports the reduction of
 5 total water recovery of the 1st pass. Consequently, the 1st pass permeate flow rate and water
 6 recover are dropped as a result to increasing the recycle retentate percentage. In the same aspect,
 7 increasing the recycle percentage of the 1st pass would increase the water recovery of the 2nd pass
 8 by about 12%. This is mainly attributed to a reduction of total feed flow rate of the 2nd pass as a
 9 result to the growth of the recycle percentage of the 1st pass, which causes an insignificant
 10 increase of plant water recovery as a result to increasing the permeate flow rate of the 2nd pass
 11 (Table 3).



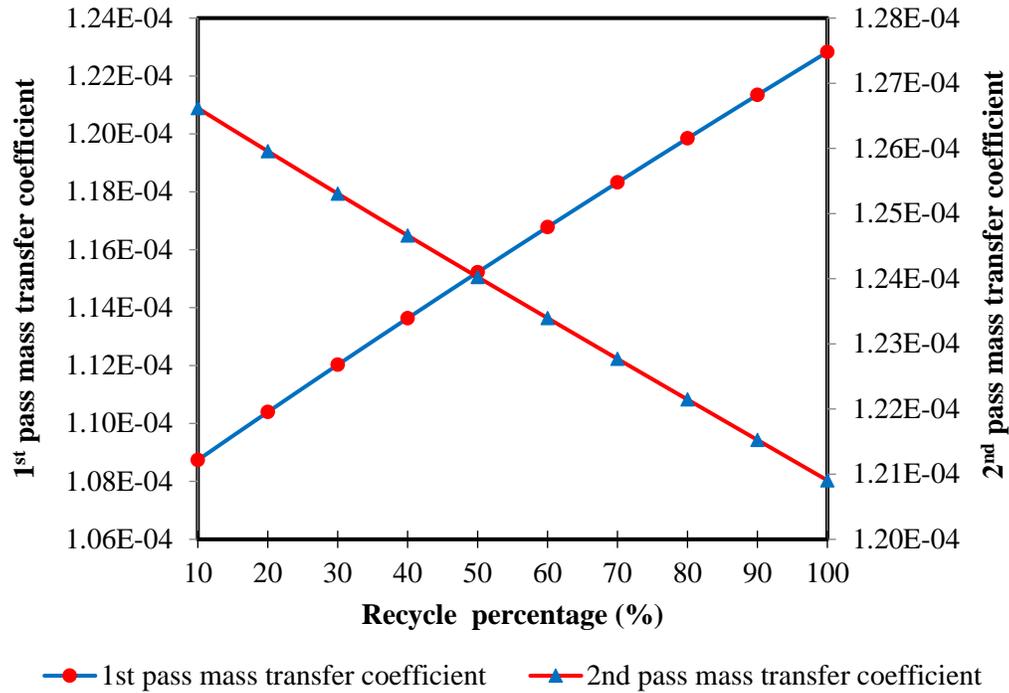
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 14 **Fig. 5.** Effect of different recycle percentage of the 1st pass retentate stream on the 1st and 2nd passes water recovery
 15

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

8 It can be seen from [Fig. 6](#) that increasing the 1st pass retentate recycle **percentage** from 0 to 100%
9 has a positive impact on the 1st pass mass transfer coefficient. Statistically, this is associated with
10 an increase of 13%. This is ascribed to a significant increase of bulk velocity associated with
11 increasing the solute diffusivity as a result to increasing feed concentration. In other words, the
12 mass transfer coefficient is enhanced due to a higher turbulence in feed channel as a result **to**
13 **increasing the cross-flow velocity. However, the quantity of water permeation through the**
14 **membrane pores of the 1st pass has been decreased** as a result to increasing the level of
15 concentration polarisation. The **retardation** of permeate flow rate of the 1st pass has already
16 presented in [Table 3](#) due to **an increase in the** recycle **percentage**. However, increasing the
17 retentate recycle **percentage** from 0% to 100% has decreased the mass transfer coefficient of the
18 2nd pass as given in [Fig. 6](#). This is specifically comes with a reduction of 4.73% in **the** mass
19 transfer coefficient. Interestingly, the reduction of mass transfer coefficient in the 2nd pass can be
20 attributed to a noticeable reduction of permeate flow rate of the 1st pass that specifies the feed
21 flow rate of the 2nd pass. Therefore, the bulk flow rate of each module in the 2nd pass will be
22 decreased that **accompany** with a reduction of mass transfer coefficient ([Fig. 6](#)). However, the

1 fluid would have more residence time inside each module of the 2nd pass that would interpret the
 2 increase of permeate flow rate of the 2nd pass as illustrated in Table 3.

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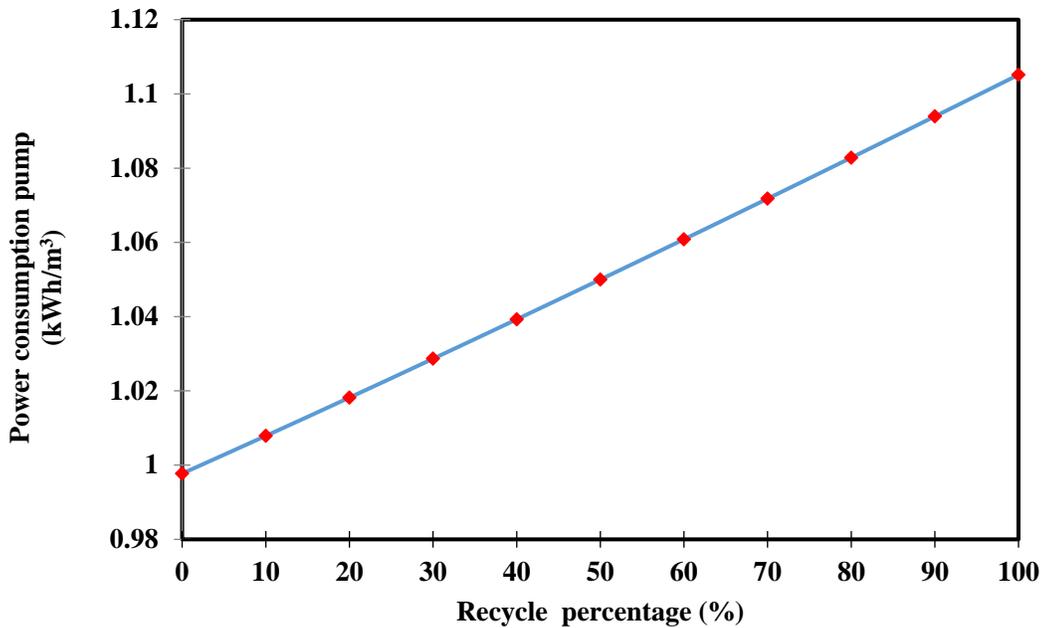
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5 **Fig. 6.** Effect of different recycle percentage of the 1st pass retentate stream on the 1st and 2nd passes mass transfer
 6 coefficient

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8 It is important to mention that the current simulation is conducted at fixed raw water flow rate,
 9 pressure, temperature, and pump efficiency (Table 1). Fig. 7 and Table 4 depict that the total
 10 energy consumption of the plant is increased by 10.7% as a response to an increase in the
 11 retentate recycle percentage of the 1st pass from 0% to 100%. Basically, the calculation of energy
 12 consumption of RO process of APC of power per cubic meter of fresh water (see Eq. 25 in Table
 13 A.1 in Appendix A) is carried out for the 1st pass and 2nd pass where the pumps are located.
 14 Therefore, it is plausible to expect an increase of energy consumption as a response to an

1 increase in the feed flow rate of the 1st pass ($Q_f(Raw\ water) + Q_r(1st\ pass) + Q_r(2nd\ pass)$) despite
 2 the reduction of feed flow rate of the 2nd pass ($Q_f(Block\ 3)$) as percentage of recycled stream of
 3 the 1st pass increases. Seemingly, the increase of total permeate flow rate ($Q_p(plant)$) is not
 4 comparable with the increase of feed flow rate of the 1st pass that would explain the growth of
 5 energy consumption. Occasionally, a marginal enhancement of the product flow rate was noticed
 6 due to increasing the retentate recycled percentage of the 1st pass (Table 3). On the other hand, a
 7 continuous increase of feed flow rate of the 1st pass has dominated the energy consumption.
 8 Statistical results of total energy consumption are embedded in Table 4.



10
 11 **Fig. 7.** Effect of different recycle percentage of the 1st pass retentate stream on the total energy consumption

12
 13 Table 3 summarises all the simulation results that associated with the influence of varying the 1st
 14 pass retentate recycle percentage from 10 to 100% at fixed operating pressure and raw water
 15 concentration, raw feed flow rate, and temperature of raw water of 9.22 atm, 1098.62 ppm, 74

1 m³/h, and 25°C, respectively on several operating parameters including the 1st pass permeate
 2 flow rate, 2nd pass permeate flow rate, overall solute rejection and water recovery of the plant,
 3 mass transfer coefficient of the 1st pass, and mass transfer coefficient of the 2nd pass.
 4 Essentially, the 1st pass permeate flow rate fed to the 2nd pass is significantly decreased by about
 5 9.4% as a response to this variation. This can be attributed to an increase in the retentate
 6 concentration with increasing the 1st pass retentate recycle percentage. Furthermore, increasing
 7 the feed concentration has entirely impacted the concentration polarisation which reduces the
 8 permeated water through the membranes. Therefore, the total permeate flow rate of 1st pass is
 9 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 1 st pass (m ³ /h)	58.39	57.81	57.23	56.67	56.11
Total Qp of the 2 nd 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 1 st 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 2 nd 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 1 st pass (m ³ /h)	55.57	55.03	54.49	53.96	53.44
Total Qp of the 2 nd 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 1 st 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 2 nd pass (-)	1.23×10^{-4}	1.23×10^{-4}	1.22×10^{-4}	1.22×10^{-4}	1.21×10^{-4}

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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%.

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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 1 st pass = 0 %		Indicators of process performance at recycle percentage from 1 st pass = 40 %		Indicators of process performance at recycle percentage from 1 st 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
Q _{r_recycle} from the 2 nd pass (m ³ /h)	15.005	Q _{r_recycle} from the 2 nd pass (m ³ /h)	12.095	Q _{r_recycle} from the 2 nd pass (m ³ /h)	8.139
C _{p_plant} (ppm)	1.937	C _{p_plant} (ppm)	2.319	C _{p_plant} (ppm)	2.975
Cr_recycle of the 2 nd pass (ppm)	169.159	Cr_recycle of the 2 nd pass (ppm)	228.545	Cr_recycle of the 2 nd 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

1 process of APC plant. Interestingly, increasing the 1st pass recycle percentage from 0% to 100%
2 has increased the 1st pass mass transfer coefficient of 13%, which has a positive impact on the
3 quantity of permeated water. Also, an increase of permeate flow rate of the 2nd pass by 3% has
4 been deduced as a result to increase the residence time of water inside the 2nd pass RO modules.
5 This also associated with inconsiderable increase of the product water salinity of 2.975 ppm,
6 which is still much below the recommended drinking water salinity limit of ~200 ppm set by
7 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	$A_{w(T)} = A_{w(25\text{ }^\circ\text{C})} TCF_p F_f$	Water permeability constant at operating temperature at (25 °C) (m/s atm)
3	$TCF_p = \exp[0.0343 (T - 25)] < 25\text{ }^\circ\text{C}$	Temperature correction factor of permeate at standard conditions which are proposed by the membrane manufacturer Toray Membrane USA Inc. 2015
	$TCF_p = \exp[0.0307 (T - 25)] > 25\text{ }^\circ\text{C}$	
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	$\Delta P_{drop,E} = \frac{9.8692 \times 10^{-6} A^* \rho_b U_b^2 L}{2 d_h Re_b^n}$	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	$Q_s = B_{s(T)} (C_w - C_p)$	Solute flux through the membrane (kg/m ² s)
11	$B_{s(T)} = B_{s(25\text{ }^\circ\text{C})} TCF_s$	Solute transport parameter at operating temperature (m/s)
12	$TCF_s = 1 + 0.05 (T - 25) < 25\text{ }^\circ\text{C}$ $TCF_s = 1 + 0.08 (T - 25) > 25\text{ }^\circ\text{C}$	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	$Re = \frac{\rho d_e v_w}{\mu}$	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	$Rej = \left(1 + \frac{B_{s(T)}}{J_w}\right)^{-1}$	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	$E1 = \frac{Pf^{(in)}(plant) * 101325 * Qf(Raw\ water)}{\frac{QP(plant) * \epsilon\ pump}{36 * 10^5}} + \frac{Pf(Block\ 3) * 101325 * Qf(Block\ 3)}{\frac{QP(plant) * \epsilon\ pump}{36 * 10^5}}$	Total plant energy consumption