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Process modeling and design of reverse osmosis membrane system for seawater desalination

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Abstract−Reverse osmosis desalination membranes can be utilized to purify seawater creating clean water. To meet purity requirements multiple membrane modules are typically required and the configuration should be chosen to minimize energy consumption and costs. Here a numerical model is proposed based on a tanks-in-series formulation of model equations. This model was validated against reverse osmosis system analysis (ROSA®) simulation software and used to investigate the performance of a number of different configurations. Systematic evaluation was made on how the performance of membrane systems is influenced by the arrangement of multiple vessels for the multi-module design of membranes systems.

Keywords: Reverse Osmosis, Process Modeling, Multi-module Design, Energy Recovery, Desalination

INTRODUCTION

Due to global population growth and increasing pollution generated by industrial development, securing clean water is becoming increasingly more important [1]. The most sustainable way to overcome the water supply imbalance is through seawater desalination processes which produce the majority of the produced clean water. Seawater desalination systems should be designed to remove salt in addition to other contaminants. Although desalination is possible through multi-stage flash evaporation methods, these consume fossil fuels and generate CO_2 emissions, which is unfavorable in terms of their effect on the environment, although research is still being carried out to improve their energy efficiency. Accordingly, in recent years there has been increased interest in water treatment technology using reverse osmosis membranes which offer a clean alternative method for desalination. However, electric power is required to generate the pressure difference which drives this separation. Therefore, it is necessary to design the optimal process for the most efficient operation cost in the seawater desalination process using the reverse osmosis membrane.

The seawater desalination process using reverse osmosis membrane is divided into water intake, pretreatment, reverse osmosis membrane system and post treatment. The water intake part consists of a screen device and a pump for intake of sea water to prevent the inflow of marine life and various floats, and the pretreatment system applies various water treatment methods, such as flocculation and filtration, to minimize fouling of the reverse osmosis membrane. The reverse osmosis membrane system is composed of a high-pressure pump, a reverse osmosis membrane, and an energy recovery device, with the high-pressure pump providing pressure to allow water to penetrate the reverse osmosis membrane. The pressure of the seawater supplied by the high-pressure pump varies depending on the salt concentration of the seawater, but it is generally about 60 to 80 bar. The concentrated water discharged in this process is under high pressure and is reused to pressurize the seawater using an energy recovery system. Finally, the post-treatment process is reached to supply minerals removed by the reverse osmosis membrane or chemicals to prevent corrosion of the pipe.

The standard of treatment in the seawater desalination process is the reduction of salts, boron and other chemicals in fresh water. The guideline limits of sodium, chlorine and boron are 50, 5 and 2.4 mg/L as specified by the WHO (World Health Organization) [2]. These WHO criteria have an impact on the design of the sea water reverse osmosis (SWRO) process. Thus, not only salt rejection but also boron separation membranes are selected. However, even SWRO membranes with good separation capability add a brackish water reverse osmosis (BWRO) process because it is difficult to meet WHO's freshwater total dissolved solids (TDS) standards.

Many studies have utilized modeling approaches to simulate the performance of reverse osmosis desalination modules. These approaches generally calculate water and salt flux based on the solution-diffusion model together with various assumptions. For example, Abbas developed a model where the solution-diffusion equations are solved by assuming an average value of salt concentration and volume flow rate on the feed/brine side of the membrane [3]. This model is then used to evaluate a number of different configurations, including multiple membrane modules [3]. This assumption was also made by Al-Obaidi et al., who used their model to optimize the configuration of a multi-stage membrane system [4]. Alternatively, finite-difference type methods have also been utilized which calculate the concentration of salt at set points along the length of the module, as implemented by studies such as that of Geraldes et al.

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[5]. Senthilmurugan et al. also proposed a finite-difference approach and they suggest that due to the nonlinear equations involved, solving them through an analytical approach would not be possible [6]. However, by assuming that mass transfer coefficients are constant Avlonitis et al. showed that an analytical solution could be obtained [7]. More recently, Sundaramoorthy et al. showed that by assuming negligible pressure drop on the permeate side, analytical solutions can even be found if the mass transfer coefficients vary along the length of the unit [8]. Analytical models have the potential to obtain solutions quickly compared to numerical finite-difference methods, but generally require some additional assumptions to make them possible. For this reason, numerical methods involving fewer assumptions should potentially be more accurate.

A number of studies have also developed models for predicting the removal of both salt and boron, including the study of Mane et al. [9] which utilizes the model equations proposed by Hyung and Kim [10] to predict the permeation of boron. More recently, Du et al. utilized the same boron permeation equations as part of superstructure optimization [11] and multi-objective optimization of desalination module configurations. In these studies, complex finite difference, or in the case of Mane et al. finite elements [9] methods, are used to solve and determine the salt and boron concentration at different points along the length of the module. It has also been shown that the analytical method proposed by Sundaramoorthy et al. [8] can be extended to predict the removal of both salt and boron [12].

An alternative numerical formulation to the finite-difference approach is the so-called "tanks-in-series" approach. This has previously been proposed for chemical reactors such that plug flow reactor performance can be approximated by multiple mixed flow tanks (fixed concentrations in each tank) connected in series [13]. This approach has also been utilized for the simulation of gas separation through membranes where the retentate and permeate sides of the membrane are divided into a number of tanks, and it is assumed the gas concentrations are fixed in each tank [14]. In particular Katoh et al. solved the resulting equations using a dynamic simulation [14]. Alternatively, Binns et al. suggested efficient strategies for solving the mass balance equations at steady-state using the Newton-Raphson method [15]. Regarding the number of tanks utilized, Lee et al. investigated differing numbers from 1 to 100 and found that 3 and 6 tank models gave the best fit for the TR and XTR membranes they tested [16]. Lee et al. suggest this is because the flow pattern is non-ideal: between perfect mixing (represented by a single tank) and plug flow (represented by a large number of tanks) [16].

In this study a tanks-in-series model was implemented for the simulation of seawater desalination through reverse osmosis. This extended the methodology of Abbas [3] by dividing the membrane length into a number of tanks where the salt concentration and volume flow rate are averaged for each tank such that the concentrations can be determined along the length of the module. This should be equivalent to the finite difference methods used by Geraldes et al. [5] and Du et al. [11], but is conceptually and visually simpler to understand. The number of tanks can also be used as a parameter when fitting a tanks-in-series model to account for non-ideal flow, as has been done before for chemical reactors [13] and for gas membrane separations [14]. The associated equations can be solved sequentially for each tank such that the calculated changes in salt concentration can be verified at each tank. The equations for boron permeation suggested by Hyung and Kim [10] are also implemented in this model and this is used to investigate the performance of a number of fundamentally different module configurations.

The prediction of boron concentration is important, as the overall economics of reverse osmosis systems are heavily influenced by the permeate boron concentration [17]. The use of generic and universal model parameters for the prediction of boron rejection would be straightforward and ideal. However, different behavior for the performance of membranes was observed, although membranes were operated at the same location [18]. As the behavior of desalination membrane systems is very site-specific and manufacturer-dependent, a tailor-made determination of model parameters for the membrane is necessary, which allows engineers to use the model in confidence. In this study, it is proposed to strategically integrate the process modeling of SWRO membrane with fitting of model parameters. The key model parameters are fitted from a number of data sets, with which membrane-specific parameters are obtained.

Also, a case study was carried out to illustrate the applicability of the model not only for a single module, but also for multi-vessel membrane systems. It is believed that the process model and simulation framework developed in this study provides a conceptual insight for the design of SWRO membrane systems as well as practical guidelines for the design of multi-vessel configuration, subject to energy recovery.

The paper is structured as the modeling of SWRO membrane systems developed in this study is, first, explained with accommodating boron rejection, which is the followed by model validation. Next section is then to investigate techno-economic impact of multi-vessel arrangement for membrane systems, with sensitivity analysis.

MODELING OF SWRO MEMBRANE WITH BORON REJECTION

Before analyzing the seawater desalination process using a membrane, a mathematical model of the membrane performance is very useful for the purpose of simulating and testing different configurations and different operating conditions. To simplify the modelling a number of assumptions can be made:

- The reverse osmosis membrane process system is in a steady state.
- No chemical reaction during reverse osmosis membrane process
- The membrane used in the reverse osmosis membrane process is not a porous membrane, and the process by which seawater permeates the membrane is dissolution diffusion.

1. Mathematical Model

The performance of the membrane process is predicted based on a mathematical model that considers the main variables, including the feed: flow rate, pressure and salt concentration in addition to the membrane type, size and geometry. The associated modeling equations can be solved assuming that the feed-side and per-

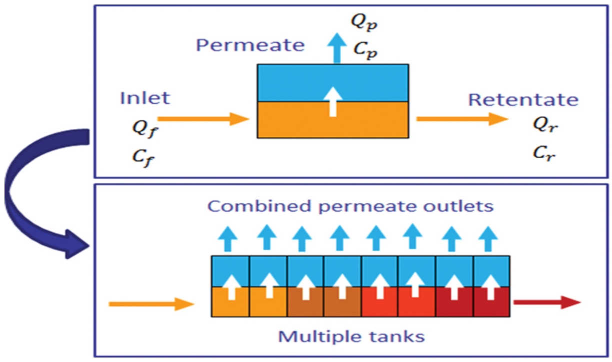

Fig. 1. Membrane modeling framework using multiple tanks concept.

meate-side are well-mixed tanks. However, this will only approximate the true performance of the module since in reality the concentration will change along the length of the membrane. A more accurate model can be realized by dividing the module length into multiple tanks-in-series where each tank is considered well-mixed, but the different tanks have different concentrations of salt and flow rates of water. This is shown in Fig. 1, which shows how a single tank model can be extended to multiple tanks.

In the case of seawater desalination membranes, boron removal should be considered as well as salt removal, generally considered. Thus, a membrane model is developed here in order to estimate water recovery (WR), salt rejection (SR), and boron rejection (BR).

The following equations are based on the model proposed by Abbas, who gave model equations for predicting salt and water flux through spiral wound desalination membrane modules [3]. To design the spiral-wound module membrane that we should predict in the program, the following mass balance equations and seawater flow rate equations were applied to the spaces in each membrane.

$$Q_f = Q_r + Q_p \quad (1)$$

$$Q_f C_f = Q_r C_r + Q_p C_p \quad (2)$$

$$Q_f C_{fB} = Q_r C_{rB} + Q_p C_{pB} \quad (3)$$

In addition, the following volumetric flow rates through the membrane were applied.

$$J_W = P_m(\Delta P - \Delta\pi) \quad (4)$$

$$J_S = P_S(C_m - C_p) \quad (5)$$

$$J_B = P_B(C_{mB} - C_{pB}) \quad (6)$$

In the above equations, Q and C are flowrate and concentration and subscripts f, r and p represent the feed, retentate (also known as the feed/brine side) and permeate, respectively. Where P_m is the water permeability, ΔP is the transmembrane pressure difference, $\Delta\pi$ is the transmembrane osmotic pressure, P_S is the salt permeability, C_m is the salt concentration at the membrane wall, and C_p is the permeate salt concentration. The subscript *B* refers to boron such that P_B is the boron permeability, C_{mB} is the boron concentration at the membrane wall and let of the membrane, and C_{pB} is the permeate concentration of boron.

The osmotic pressure is sometimes assumed to be a linear function of salt concentration, but here it is calculated through the following correlations [9,19]:

$$\pi = (0.6955 + 0.0025T) \times 10^8 \left(\frac{C}{\rho}\right) = e^{\frac{Jw}{k}} \quad (7)$$

$$\rho = 498.4M + \sqrt{248{,}400M^2 + 752.4MC} \quad (8)$$

$$M = 1.0069 - 2.757 \times 10^{-4}T \quad (9)$$

To determine the concentrations of salt and boron at the membrane wall the following equations can be used based on concentration polarization. If the average salt and boron concentrations are calculated $C_b = \frac{C_f + C_r}{2}$ and $C_{bB} = \frac{C_{fB} + C_{rB}}{2}$ and if the mass transfer coefficients k and k_2 are estimated, the wall concentrations can be estimated.

$$\varnothing_s = \frac{C_m - C_p}{C_b - C_p} = e^{\frac{Jw}{k}} \quad (10)$$

$$\varnothing_b = \frac{C_{mB} - C_{pB}}{C_{bB} - C_{pB}} = e^{\frac{Jw}{k_2}} \quad (11)$$

Additionally, it is necessary to calculate the mass transfer coefficient and retentate side pressure drop ΔP_s, which is calculated with the following equations [3].

$$Sh = \frac{kd_h}{D} = 0.664 k_{dc} Re^{0.5} Sc^{0.33} \left(\frac{2d_h}{l}\right)^{0.5} \quad (12)$$

$$\Delta P_s = \frac{\rho u^2 L C_{td}}{2d_h} \quad (13)$$

$$C_{td} = \frac{A'}{Re^n} \quad (14)$$

The mass transfer coefficient for boron can be considered related to the mass transfer coefficient for salt via a constant r, which was found by Taniguchi et al. to be equal to 0.97, but can also be a fitted parameter [19].

$$k_B = k_S \ r \quad (15)$$

2. Numerical Model Solution Algorithm

The equations described in Section 1 can be solved to calculate the retentate and permeate outlet conditions for a single tank. If that tank is labelled as *i* then the inputs and outputs of that tank can be described by the single tank shown in Fig. 2. A single membrane module is represented by multiple tanks, such that the output from each tank is passed to the subsequent downstream tanks and the permeate flows from each tank are combined as shown in Fig. 3. Although this figure shows 7 tanks from 2 up to 100 tanks have been tested, it was found that changing the number has only a minor effect on separator performance. This is presumably because the concentration and flow rate on the retentate side do not change significantly (compared to gas separation membrane processes). The numerical algorithm for calculating the outputs from a membrane module with multiple tanks is shown in Fig. 4.

3. Membrane Parameter Optimization

To create a membrane model that can express the performance of the membranes, it is necessary to know the values of parameters that characterize the membranes. However, while many parameters are typically provided by manufacturers, such as the module geometry and typical recommended operating conditions and performance, the water and salt permeability coefficients and pressure drop coefficients may not be provided. These missing parameters are required for modelling to predict the performance at conditions other than the single recommended operating conditions provided by manufacturers. There are many variables that can express the characteristics of each separator. Among the variables that can represent the characteristics of the membrane, water permeability (P_m), salt permeability (P_S), spacer parameters of total drag force (A′, n), and relation between salt and boron mass transfer coefficients (r) are the key variables which mainly affect the separation performance of the membrane. These parameters can be determined through fitting using experimental data or through fitting using pseudo-experimental data generated by simulation software. In this work, 25 sets of data were generated with the

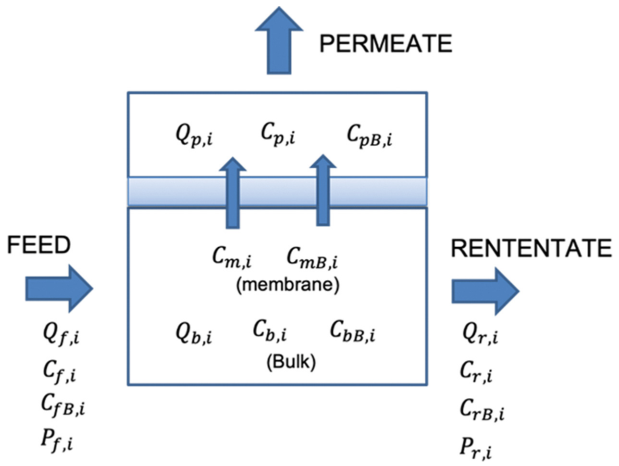

Fig. 2. Diagram of a single tank (i) used in the numerical model.

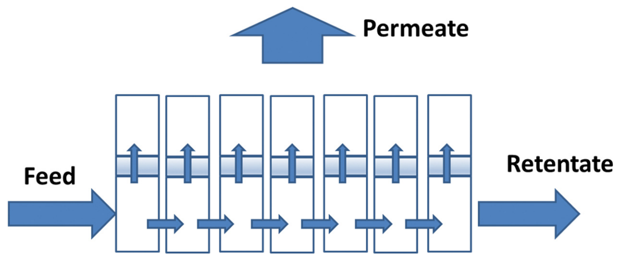

Fig. 3. Diagram of a membrane module containing multiple tanks.

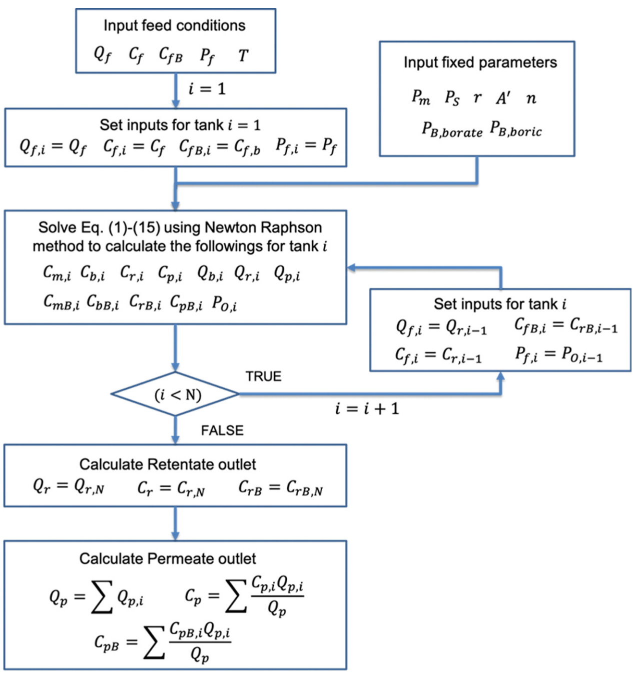

Fig. 4. Numerical algorithm for calculating the volume flowrate and concentration change along the length of a membrane module divided into N tanks-in-series.

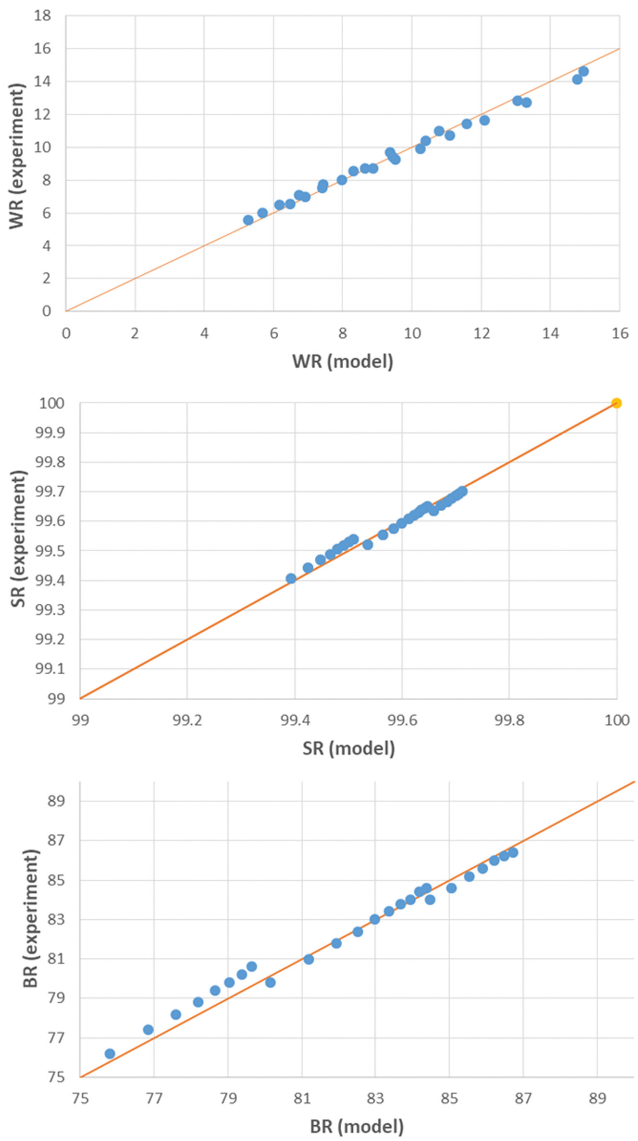

Fig. 5. Parity plots showing the fitting of the model against the 25 data points from Table 1 generated using ROSA [20].

Table 1. Pseudo-experimental data generated for parameter fitting [20]

Cases	Input variables		Output variables						
	Q_f (m^3/h)	P_f (bar)	P_r (bar)	Q_r (m^3/h)	$C_{,r}$ (kg/m^3)	Q_p (m^3/h)	$C_{,p}$ (kg/m^3)	$C_{B,r}$ (kg/m^3)	$C_{B,p}$ (kg/m^3)
Case 1	7	50	49.79	6.01	43.19	0.99	0.135	0.0060	0.0008
Case 2	8	50	49.74	6.98	42.53	1.02	0.129	0.0060	0.0008
Case 3	9	50	49.69	7.95	42.00	1.05	0.124	0.0059	0.0007
Case 4	11	50	49.59	9.91	41.20	1.09	0.116	0.0058	0.0007
Case 5	12	50	49.53	10.89	40.90	1.11	0.114	0.0058	0.0007
Case 6	13	50	49.47	11.87	40.63	1.13	0.111	0.0057	0.0007
Case 7	5	45	44.87	4.27	43.45	0.73	0.178	0.0060	0.0010
Case 8	6	45	44.83	5.23	42.57	0.77	0.166	0.0059	0.0010
Case 9	7	45	44.79	6.2	41.91	0.8	0.157	0.0059	0.0009
Case 10	8	45	44.74	7.17	41.39	0.83	0.151	0.0058	0.0009
Case 11	9	45	44.69	8.15	40.98	0.85	0.145	0.0058	0.0009
Case 12	10	45	44.64	9.13	40.64	0.87	0.141	0.0057	0.0008
Case 13	11	45	44.58	10.12	40.36	0.88	0.138	0.0057	0.0008
Case 14	12	45	44.53	11.1	40.12	0.9	0.134	0.0056	0.0008
Case 15	13	45	44.47	12.09	39.91	0.91	0.132	0.0056	0.0008
Case 16	14	45	44.41	13.08	39.73	0.92	0.130	0.0056	0.0008
Case 17	5	40	39.87	4.45	41.71	0.55	0.220	0.0058	0.0012
Case 18	6	40	39.83	5.42	41.08	0.58	0.207	0.0058	0.0011
Case 19	7	40	39.78	6.4	40.61	0.6	0.197	0.0057	0.0011
Case 20	8	40	39.73	7.38	40.24	0.62	0.190	0.0057	0.0011
Case 21	9	40	39.68	8.36	39.94	0.64	0.184	0.0056	0.0010
Case 22	11	40	39.58	10.34	39.49	0.66	0.175	0.0056	0.0010
Case 23	12	40	39.52	11.33	39.32	0.67	0.172	0.0056	0.0010
Case 24	13	40	39.46	12.32	39.16	0.68	0.169	0.0055	0.0010
Case 25	14	40	39.4	13.31	39.03	0.69	0.166	0.0055	0.0010

*Feed concentration of salt and boron are 37.125 kg/m^3 and 0.005 kg/m^3, respectively. Feed temperature is assumed to be 20 °C.

Table 2. Parameters fitted for the membrane model

$R_m=1/P_m$ (Pa·s/m)	$R_s=1/P_s$ (s/m)	A'	n	r	$P_{Bborate}$ (m/s)	P_{Bboric} (m/s)
3.84×10^{10}	8.65×10^{6}	1.01	0.991	0.655	2.06×10^{-10}	8.19×10^{-6}

range of feed flowrate and feed pressure generated from ROSA® software [20], as given in Table 1 and least-square method is used for fitting of these seven parameters, as shown in Table 2. Similar to the work of Lee et al. [16] we used only a small number of tanks (5 tanks in this case) for both the fitting of parameters and for simulation. The fitting of these parameters in the models can be shown in Fig. 5, which demonstrates through parity plots that the model fits well with this set of data.

4. Membrane Model Validation

To construct the membrane mathematical model using the above equations and to trust the results, it is necessary to judge the accuracy of the model. For this purpose, the performance verification factors are WR, SR and BR, so we compared the performance values of the ROSA® software and the mathematical model under various inlet pressure conditions. WR, SR and BR are obtained using the following equations.

$$WR(\%)=\frac{Q_p}{Q_f}\times 100 \quad (16)$$

$$SR(\%)=\frac{C_f-C_p}{C_f}\times 100 \quad (17)$$

$$BR(\%)=\frac{C_{fB}-C_{pB}}{C_{fB}}\times 100 \quad (18)$$

Calculations, as explained in Figs. 2 and 3, were applied to the MATLAB® program for mathematical modeling of the membrane model. To verify the effectiveness of the membrane model using the actual MATLAB® program, the results of the ROSA® software were compared with the model performance through influent with the following conditions.

For model validation, feed conditions used for model validation are 10 m^3/h for flowrate, 37.125 kg/m^3 for concentration and 20 °C for temperature. Membrane geometry for a single module is specified with 1.016 m for length (L), 6.8 m^2 for area (A), 5.93× 10^{-4} m for height of inflow space (h_{sp}), 8.126× 10^{-4} m for width of inflow space (d_h) and 1.501 for constant used for Reynolds number (k_{dc}).

As can be seen from the Table 3, the model follows the same trend as the results from ROSA® and gives similar values for the conditions tested. These two data points shown in Table 3 are not included in the data used for fitting and are shown here for validation of the fitting parameters and model. Hence, this model should be sufficient to estimate the performance of these types of membrane modules.

PROCESS DESIGN OF MULTI-VESSEL MEMBRANE SYSTEMS

Seawater desalination processes generally include only one single module, but instead utilize multiple membrane modules connected in various ways to generate clean water. For a fixed number of membrane modules, the manner in which they are connected will affect their performance in terms of water, salt and boron

Table 3. Comparison of model predictions with simulated values from ROSA® software [20]

Feed pressure (bar)	Model			ROSA®		
	WR (%) (percent error)	SR (%) (percent error)	BR (%) (percent error)	WR (%)	SR (%)	BR (%)
40	6.1756 (−5.009%)	99.4912 (−0.009%)	79.0516 (−0.938%)	6.50	99.5006	79.8000
50	11.0926 (+3.669%)	99.6929 (+0.016%)	85.9087 (+0.361%)	10.70	99.6774	85.6000

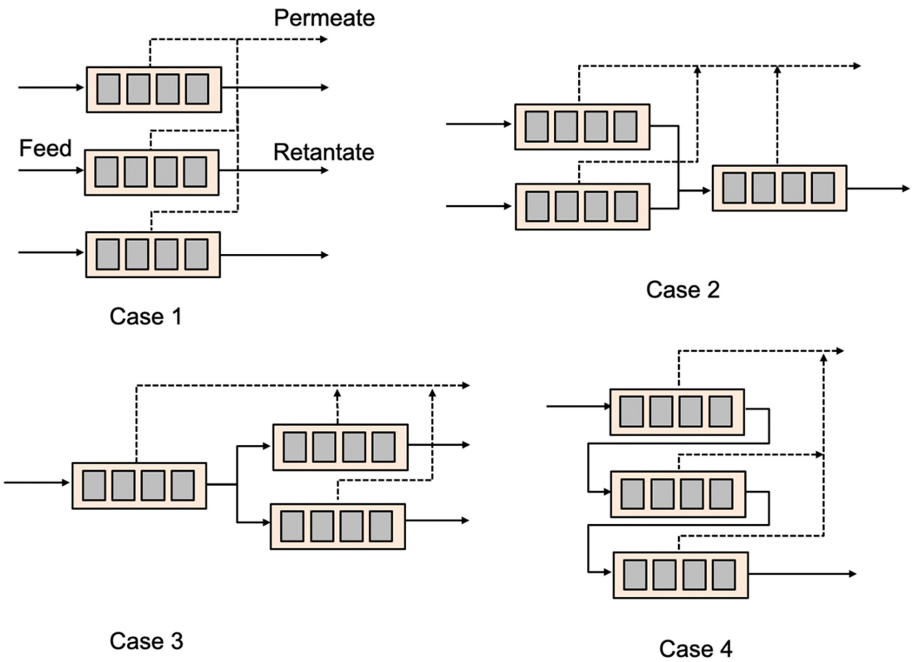

Fig. 6. Different configurations involving three vessels.

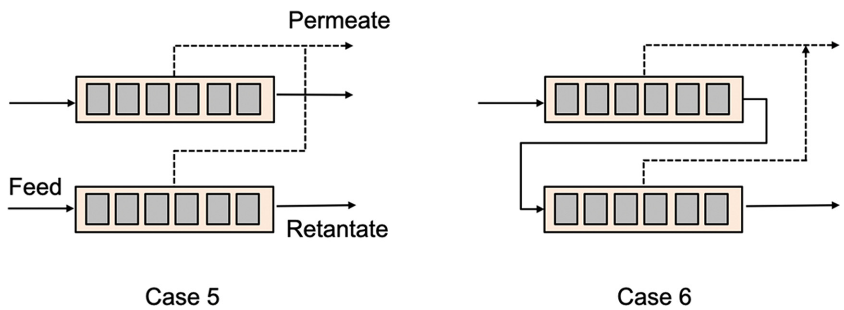

Fig. 7. Different configurations involving two vessels.

Table 4. Comparison of water and salt rejection for different vessel configurations against predictions from ROSA® software [20]

Cases	WR (%)			SR (%)		
	Model	ROSA®	Model error %	Model	ROSA®	Model error %
Case 1	46.47	43.95	+5.7	98.80	98.81	+0.01
Case 2	48.32	44.46	+8.7	98.85	98.84	+0.01
Case 3	48.47	43.62	+11.1	98.86	98.83	+0.03
Case 4	48.83	43.46	+12.4	99.87	98.84	+1.04
Case 5	42.83	44.34	−3.4	99.18	98.83	+0.35
Case 6	43.78	43.46	+0.7	99.20	98.84	+0.36

removal. In this study multiple membrane modules, namely, 12 modules are configured in various different ways to assess their performance with the following seawater feed.

Feed conditions to be considered in this section is given as:
- Salt concentration=37.125 kg/m^3
- Boron concentration=0.005 kg/m^3
- Temperature=20 °C
- Inlet flowrate=10 m^3/h
- Inlet pressure=50 bar

1. Multi-vessel Configurations of Membrane System

First, sets of four modules (each module represented by multiple tanks as shown in Fig. 3) are combined in each of three vessels (each small square in Fig. 6 represents a membrane module) so that the performance can then be evaluated using different configurations of the three vessels (a vessel contains four membrane modules). The different configurations are shown in Fig. 6. Case 1 has the three vessels in parallel, while Case 4 has the three vessels in series. Cases 2 and 3 are some combination of series and parallel vessels.

Alternatively, sets of six modules can be combined in each of two vessels so that the performance can then be evaluated using different configurations of the two vessels. There are only two possible configurations for this, as shown in Fig. 7. Case 5 is the configuration where the two vessels are in parallel, while Case 6 is based on two vessels connected in series. Since the modules inside each vessel are connected in series, Case 6 is equivalent to Case 4, as both arrange the 12 modules in series.

To simulate multi-vessel configuration, numerical procedures explained in Figs. 2, 3 and 4 are used to simulate the performance of each module with the retentate outlet pass to the next module inside the vessel. Additionally the vessels are connected as shown in Figs. 6 and 7. With these configurations, the resulting calculations are shown in Table 4, which is then validated with ROSA®. This shows that the process model developed in this work is accurate enough to be used in confidence for the design of multi-vessel arrangement.

2. Sensitivity Analysis

Numerous variables affect the performance of membrane-based seawater desalination: inlet conditions, including the inlet flow rate, concentration and pressure. Since the performance of the membrane process and the energy consumption change according to these values, it is useful to understand how these values influence the design. The sensitivity of performance with respect to these main design factors is further analyzed for Cases 1, 2 and 4 as representative membrane vessel configurations.

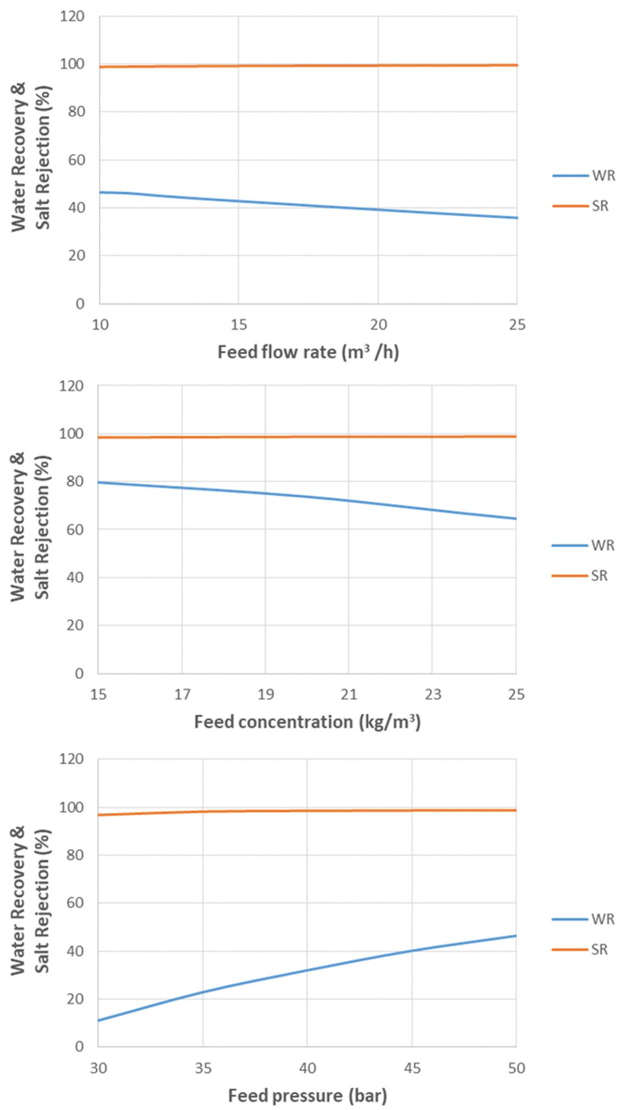

Fig. 8. Sensitivity analysis of key design variables for Case 1.

From these results in Figs. 8, 9, and 10 it can be seen that the water recovery rate tends to decrease as the inlet flow rate and inlet concentration increase, and the water recovery rate tends to increase as the inlet pressure increases. Furthermore, while the trends are the same there are minor differences where, for example, one con-

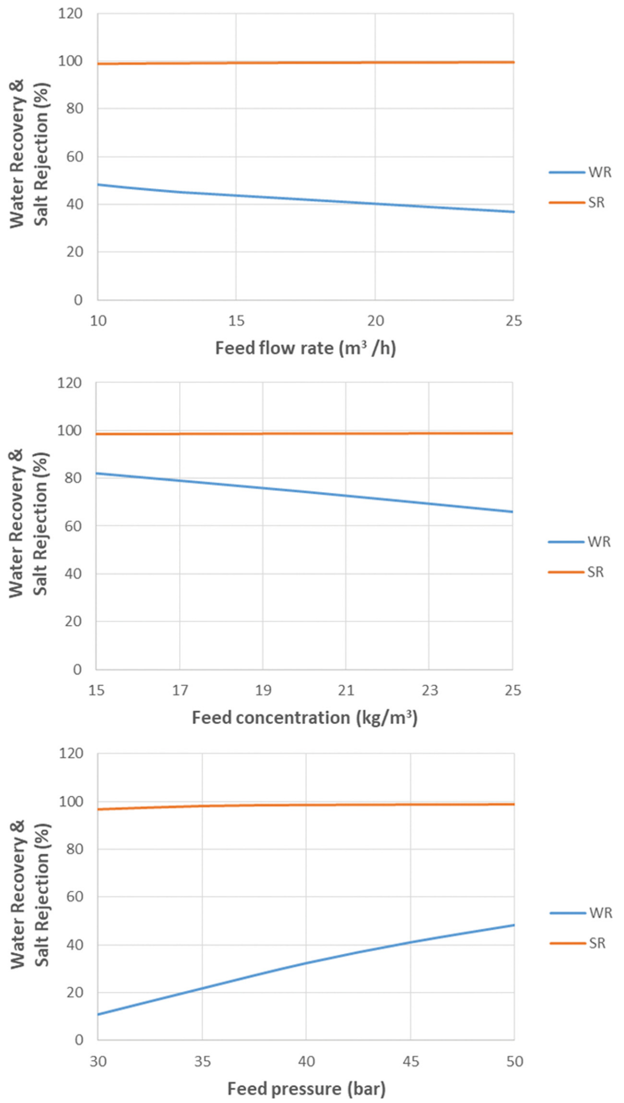

Fig. 9. Sensitivity analysis of key design variables for Case 2.

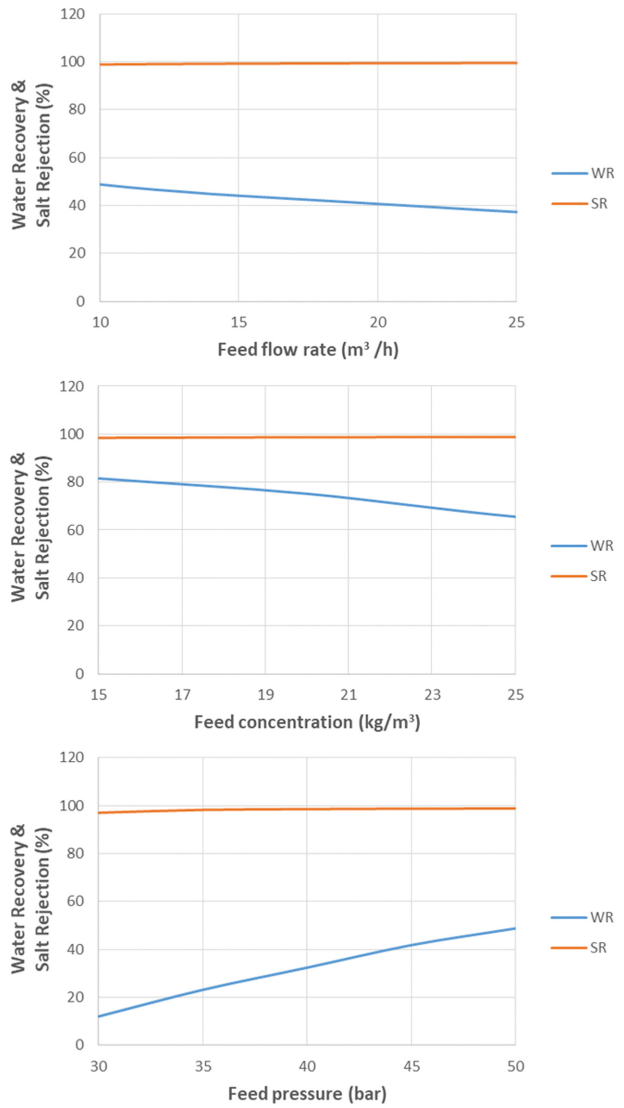

Fig. 10. Sensitivity analysis of key design variables for Case 4.

figuration performs better.

CONCLUSION

A mathematical model based on the tanks-in-series concept is proposed here for the design of reverse osmosis seawater desalination membranes. This should be more accurate than models which consider only an average value (or single tank) and numerically equivalent to finite-difference type approaches. This modelling approach was validated against simulation software developed by membrane module manufacturers and subsequently this model was used to evaluate different configurations of vessels. Separation performance differed according to the number of membrane modules inside each vessel, the number of vessels and the arrangement of the vessels. Given available experimental data, this method could be fitted to determine the performance at different operating conditions, leading to optimal configurations and designs.

This method could be extended in future work to consider different types of membrane modules (e.g., different membrane materials) and different combinations of membranes, which could potentially offer higher performance and lower costs when compared to designs using multiple identical membranes.

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NOMENCLATURE

C : concentration [kg m^{-3}]
d_h : hydraulic diameter [m]
D : diffusivity [m^2 s^{-1}]
i : index or tank number in tanks-in-series model
J_W : water flux [m s^{-1}]

J_S : salt flux [kg m^{-2} s^{-1}]
J_B : boron flux [kg m^{-2} s^{-1}]
k : mass transfer coefficient [m s^{-1}]
k_{dc} C_{td} A′ n : coefficients used in Eqs. (13) and (14) [dimensionless]
l : length of membrane mesh spacer [m]
L : length of membrane unit [m]
M : empirical parameter defined by Eq. (9)
N : number of tanks used in the tanks-in-series model
Q : volume flow rate [m^3h^{-1}]
P : pressure [Pa]
P_W : water permeability [m $s^{-1}Pa^{-1}$]
r : relation coefficient between salt and boron mass transfer [dimensionless]
Re : Reynolds number [dimensionless]
Sh : Sherwood number [dimensionless]
u : linear velocity [m s^{-1}]
T : temperature [C]
P_m : water permeability [m $s^{-1}Pa^{-1}$]
P_s : salt permeability [m s^{-1}]
$P_{Bborate}$: borate ion permeability [s m^{-1}]
P_{Bboric} : boric acid permeability [s m^{-1}]
R_m : membrane resistance to water [Pa s m^{-1}]
R_s : membrane resistance to salt [s m^{-1}]

Greek Letters
π : osmotic pressure [Pa]
ρ : density [kg m^{-3}]

Subscripts
f : feed
r : retentate
p : permeate
b : bulk (average value inside a tank)
B : boron
m : value at the membrane wall
W : water

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