A Computational Model to Estimate the Performance of 8 inches RO Membranes in Pressure Vessel

Ali Altaee*

School of Engineering University of the West of Scotland Paisley PA1 2BE, UK

Abstract: A computational model for estimating RO system performance was developed in this study. Wide range of seawater concentrations 32000 mg/L, 35000 mg/L, 38000 mg/L, and 43000 mg/L were used as feed solution. Two different types of Filmtec RO membranes were investigated; SW30HRLE-440i and SW30HR-380. A pressure vessel of four RO elements was simulated in this paper. The recovery rate, ions rejection rate, flow arte, and permeate concentration was simulated for each element in the pressure vessel. The results from this study were compared with Reverse Osmosis System Analysis (ROSA) software assuming that the simulation results from ROSA are reasonably accurate. It was found that the results from this study were in a good agreement with ROSA. The model was also validated against a commercial RO system for seawater desalination, feed concentration 43000 mg/L. An agreement more than 85% was achieved between the model and the experimental data.

Keywords: Reverse osmosis, desalination, RO modeling, pressure vessel.

1. INTRODUCTION

Increasing demands on fresh water and depleting natural water resources is one of the major problems which affected most parts of the world [1-3]. Ground and surface water contamination contributed to water shortage problems. Tapping seawater is one way to meet the increasing demands on fresh water [1, 5-6]. Seawater desalination is widely practiced in arid and water shortage areas for fresh water supply [1, 5-7]. Thermal and RO technologies are the most common desalination technologies albeit the number of RO plants exceeded thermal plants worldwide [8-9]. RO process, in fact, requires lower energy than thermal processes and efficiently reliable. 8 inches RO is the most popular membrane for seawater desalination. Nowadays, most of the large RO desalination plants use 8 inches spiral wound elements in their design. Similarly, the 8 inches low pressure RO is widely used in water reclamation plants.

The objective of present work is to study and estimate the performance RO membranes in the high pressure vessel. This is particularly important in the early stage of RO system design to estimate the permeate flow rate, recovery rate, permeate concentration, and feed pressure of each pressure vessel. A wealth of literature was published in modeling RO membranes but most of it was in studying the performance of a single RO element [10-12]. Many studies investigated the performance of RO system without investigating the performance of each element in the high pressure vessel [13, 14]. As explained in the part-one of this study, the performance of RO system has to be evaluated to estimate the number and type of RO elements required for any new RO desalination plant. This is particularly important in estimating the initial cost of the RO plant. There is a number of software was developed by membrane manufacturing companies for estimating the performance of RO system such as ROSA and IMS programme. Unfortunately, such software has a limited applicability as it can only be used with RO membranes made by the manufacturing company. In the part-one of this study, a model was developed for estimating the performance of RO membrane system which can accommodate any type of RO membranes. NaCl was used as a feed solution in part one on the study. The model showed a good agreement with ROSA simulation results [15]. However, in addition to sodium and chloride ions seawater contains other ions such as magnesium, calcium, potassium, sulfate, carbonate in fairly high concentrations [16, 17]. These ions although exist in lower concentrations than sodium and chloride but they have significant impact on the RO membrane performance [1]. For instance calcium and sulfate ions contribute to the scale problems in the RO membranes [1, 14]. On the other hand, boron exists in a very low concentration but it has especial importance due to its potential risk on the human health and environment [18]. Further more, it should be noted here that the osmotic pressure of NaCl solution is different to that of seawater even if the TDS concentration is equal. Finally, it is important to know the concentrations of different ions in the permeate water and how may the concentrations of these ions effect the quality of desalinated water. In this paper the effect of different

*Address corresponding to this author at the School of Engineering University of the West of Scotland Paisley PA1 2BE, UK; Tel: +971507356657; E-mail: alialtaee@hotmail.com

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ions in seawater are evaluated. In addition to sodium and chloride ions, sulfate, calcium, potassium, and magnesium ions were considered in the simulation because of their relatively high concentrations in seawater [16, 17]. Four Filmtec RO membranes type SW30HRLE-400i and SW30HR-380 were investigated. The recovery rate, permeate concentration, feed pressure and rejection rate of each element in the pressure vessel was evaluated. Then, the simulation results were compared with ROSA software assuming that ROSA has acceptable marginal errors [15]. The model was also validated against a pilot plant RO system for seawater desalination, feed concentration 43000 mg/L [19].

2. MODEL DEVELOPMENT

A computational model was developed in this study to estimate the performance of RO membranes in a high pressure vessel. In the present work, seawater was used as a feed solution and the performance of RO membrane system was evaluated accordingly. The concentrations of sodium, chloride, calcium, sulfate, magnesium, and potassium ions in seawater were accounted for in calculating the rejection rate, osmotic pressure, and permeate concentration of the RO system.

The mathematical equations used this study are listed in Table **1**. Additional details about these equations are shown in Figure **1** [15]. Table **1** equations were used throughout this study in estimating the performance of RO elements in a high pressure vessel. Pressure drop along the concentrate side of the RO membrane was estimated from the following equation [16]:

$$P_{cd} = 0.01 * n * q_{cave}^{1.7}$$

Typically, pressure drop in the concentrate side of seawater RO membranes is about 0.1 bar. The aforementioned equation was developed by Filmtec to estimate the pressure drop in 8 inch diameter seawater RO membrane but it can also be applied to different 8 inch seawater RO membranes since; first membrane companies using almost the same technologies in the manufacturing process. Secondly pressure drop in the concentrate side of RO is insignificant.

The method of computing the performance of RO elements in the pressure vessel requires iterative calculations of feed osmotic pressure, recovery rate, and feed pressure of each RO membrane in the vessel. Up to 8 RO elements can be loaded in a signal pressure vessel. However, in small plants a pressure vessel of 6 to 8 elements is used. 4-6 RO elements per pressure vessel was investigated in the current study. Bearing in mind this procedure can be adopted for extended numbers RO element in the pressure vessel.

3. RESULTS AND DISCUSSION

Two different types of seawater Filmtec membranes were investigated in this study, SW30HRLE-400i and

Table 1: Mathematical Equations Applied in The Model Building

Equation	Application
$Q_p = A_m * A_w * FF * (P_f - \frac{P_{cd}}{2} - P_p - \pi_{cave} + \pi_p)$	Calculate initial flow in RO system
$\pi = n_i * C * R_g * T$	Calculate osmotic pressure of seawater
$C_{fc} = C_f * \frac{\ln \frac{1}{1-R}}{R}$	Calculate average concentrate side feed concentration
$CP = EXP(0.7R)$	Calculate concentration polarization factor
$C_p = B * C_{fc} * CP * Rj * \frac{A_m}{Q_p}$	Calculate permeate concentration
$\pi_p = \pi_f * (1 - R_j)$	Calculate permeate feed pressure
$\pi_{cave} = \pi_f * \frac{C_{fc}}{C_f} * CP$	Calculate average concentrate side osmotic pressure
$B = \frac{(1-Rj) * J}{Rj}$	Calculate slat diffusion coefficient

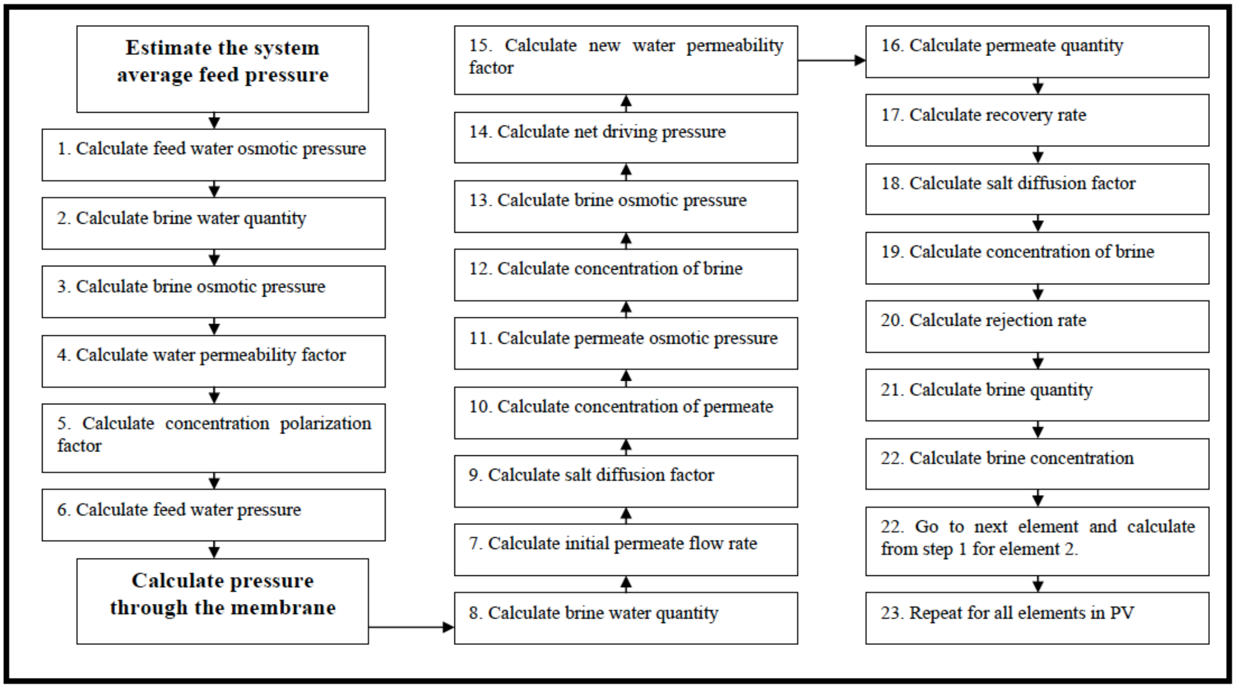


Figure 1: Diagram showing steps followed to compute the membrane performance.

SW30HR-380. The characteristics of these membranes are described in the following sections of this paper. Three different feed concentrations were examined here, 32000 mg/L, 35000 mg/L and 38000 mg/L. Then, data from an RO pilot plant were used to validate the model in this study.

3.1. Filmtec RO Membrane SW30HRLE-440i

Filmtec membrane type SWHRLE-400i was considered in this study for RO system analysis. A pressure vessel contains four RO membrane was under investigation. Dow™ Filmtec SWHRLE-400i is a high rejection rate and productivity RO membrane which is suitable for seawater desalination at reasonable cost [16]. The membrane properties can be found on the manufacturing website as well as in the part one of this study [15]. The membrane permeability and salt diffusion were 1.056 L/m^2.h.bar and 0.00189 m/d respectively. The total active area of SWHRLE-400i module is 37.2 m^2 and salt rejection rate is 99.75% [16].

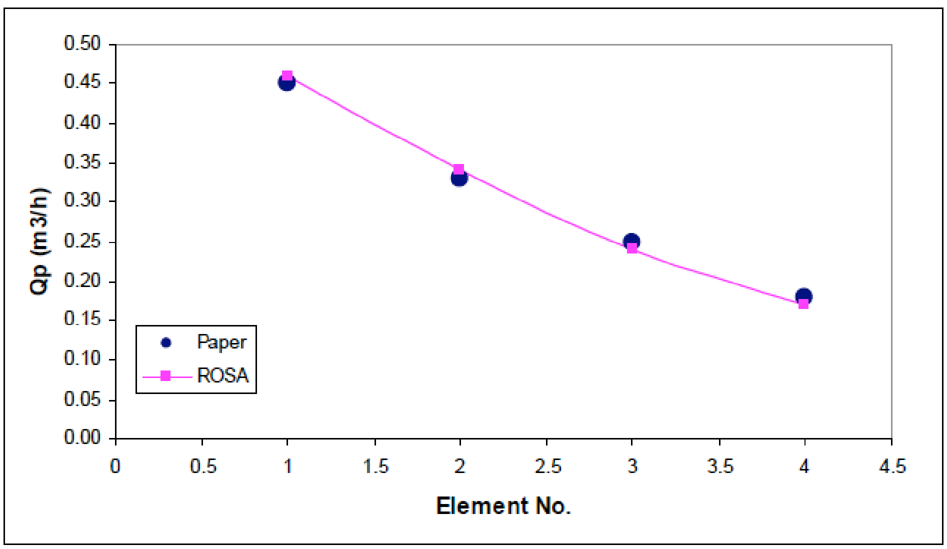
In the current study seawater was used as a feed solution. Two different concentrations were applied to evaluate the performance of RO system [16, 17]. In

Table 2: Seawater Composition [16]

Ions	Eastern Mediterranean (38000 mg/L)	Standard Seawater (35000 mg/L)	Standard Seawater (32000 mg/L)
Cl^-	21200	19406	17737
Na+	11800	9854	9856
SO_4^{2-}	2950	2710	2477
Mg^{2+}	1403	1182	1182
K^+	463	387	354
Ca^{2+}	423	421	385
Br-	155	-	
BO_3^{3-}	72	-	
I^-	2	-	
HCO_3^-		142	130
SiO_3^{2-}		1	0.9

case one, seawater concentration was 35000 mg/L which represents typical seawater. Whilst in case two, the concentration of feed water was increased to 38000 mg/L to represents Eastern Mediterranean seawater [17]. The composition of seawater in both concentrations is listed in Table **2**. In addition to the sodium and chloride ions, seawater contains calcium, magnesium, potassium, sulfate, boron, silicon, bicarbonate, bromide and carbonate. Also there are other ions which exist in a trace concentration such as nitrate, fluoride, ion and manganese and will not be considered in this study [16, 17]. The major ions of concern in this study are Na, Cl, Mg, Ca, and SO_4 due to their high concentration in seawater and impact on the RO desalination process [18]. The simulation conditions of both seawater salinities (i.e. 35000 mg/L and 38000 mg/L) were as following; feed water flow rate 4 m^3/h, recovery rate 30%, feed temperature 25 ^oC and feed water pH 7.6.

The simulation results from the model in this paper were compared with ROSA. Recovery rate, permeate concentration, permeate flow rate, and feed pressure of each element in the pressure vessel were calculated. The simulation results showed that the elements flow rates from this study were very close to those from ROSA (Figure **2**). The flow rate decreased from the head to the tail element which was due to the higher osmotic pressure of the feed solution. Similarly, the recovery rates from both models were very close (Figure **3**). The total recovery rates of the RO system from ROSA and this study were equal; 1.2 m^3/h. In



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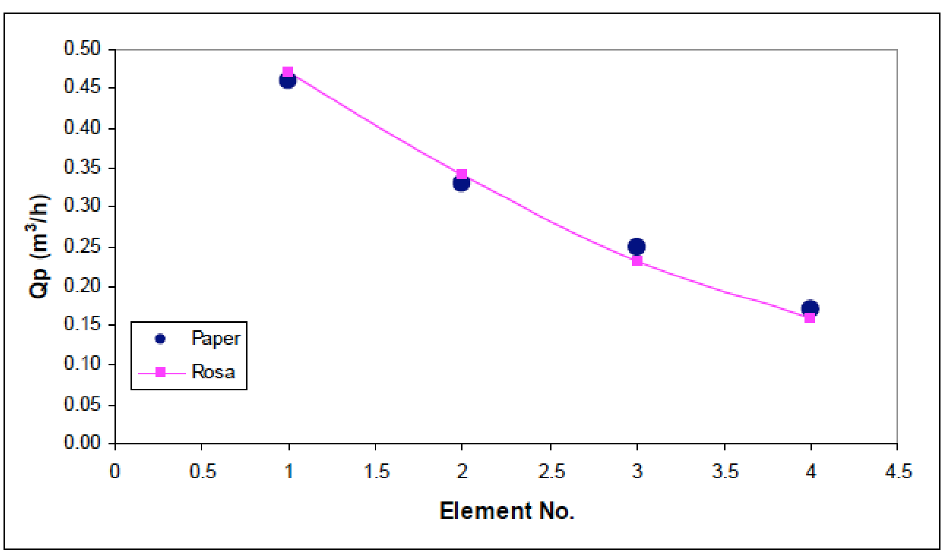

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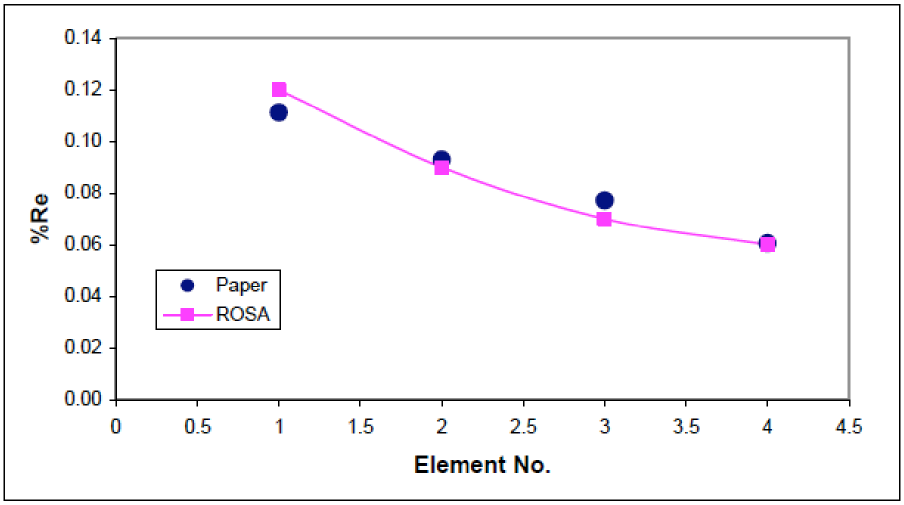
Figure 2: Permeate flow of each element in the RO system. **a**) feed water 35000 mg/L. **b**) Feed water 38000 mg/L.



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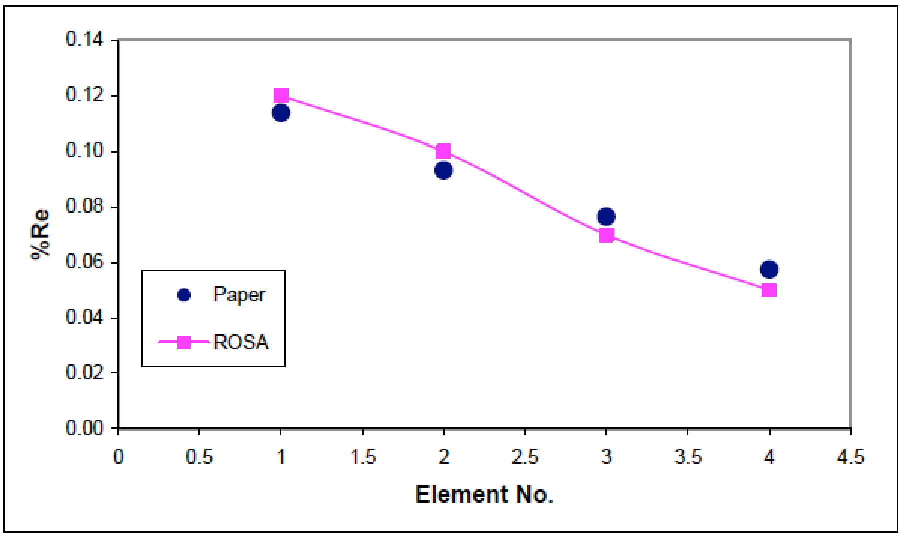

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Figure 3: Recovery rate of each element in the RO system. **a**) Feed water TDS 35000 mg/L. **b**) Feed water TDS 38000 mg/L.

case of feed pressure, although there was more than 98% agreement between the two models, the feed pressure in this study was slightly higher than ROSA (Figure **4**). This was probably due to the slightly higher osmotic pressure calculated in the present work. However, the differences in feed pressure between the two models were insignificant. On the other hand, the concentrations of permeate from both models were also compared. As illustrated in Figure **5**, there was a good agreement between the two models and for both feed water concentrations, i.e. 35000 mg/L and 38000 mg/L. The overall agreement between this study and ROSA was more than 90%.

3.2. Filmtec RO Membrane SW30HR-380

A pressure vessel consists of four RO membranes type SW30 HR-380 was investigated here. Dow™ Filmtec SW30HR-380 exhibits a high performance and salt rejection which makes it suitable for seawater desalination [16]. The membrane properties can be found on the manufacturing website [16]. The membrane permeability and salt diffusion were 0.917 L/m^2.h.bar and 0.00197 m/d respectively. The total active area of SW30HR-380 module is 35 m^2 and salt rejection rate is 99.7%.

A feed water concentration equal to 32000 mg/L was investigated here to estimate the performance of RO membrane system. The composition of seawater is shown in Table **2**. The main ions in feed water are sodium, chloride, calcium, magnesium, potassium, sulfate, silicon, bicarbonate, bromide and carbonate. The simulation conditions were as following: 4 m^3/h feed water flow rate, 30% recovery rate, feed temperature 25 ^{o}C and feed water pH 7.6.

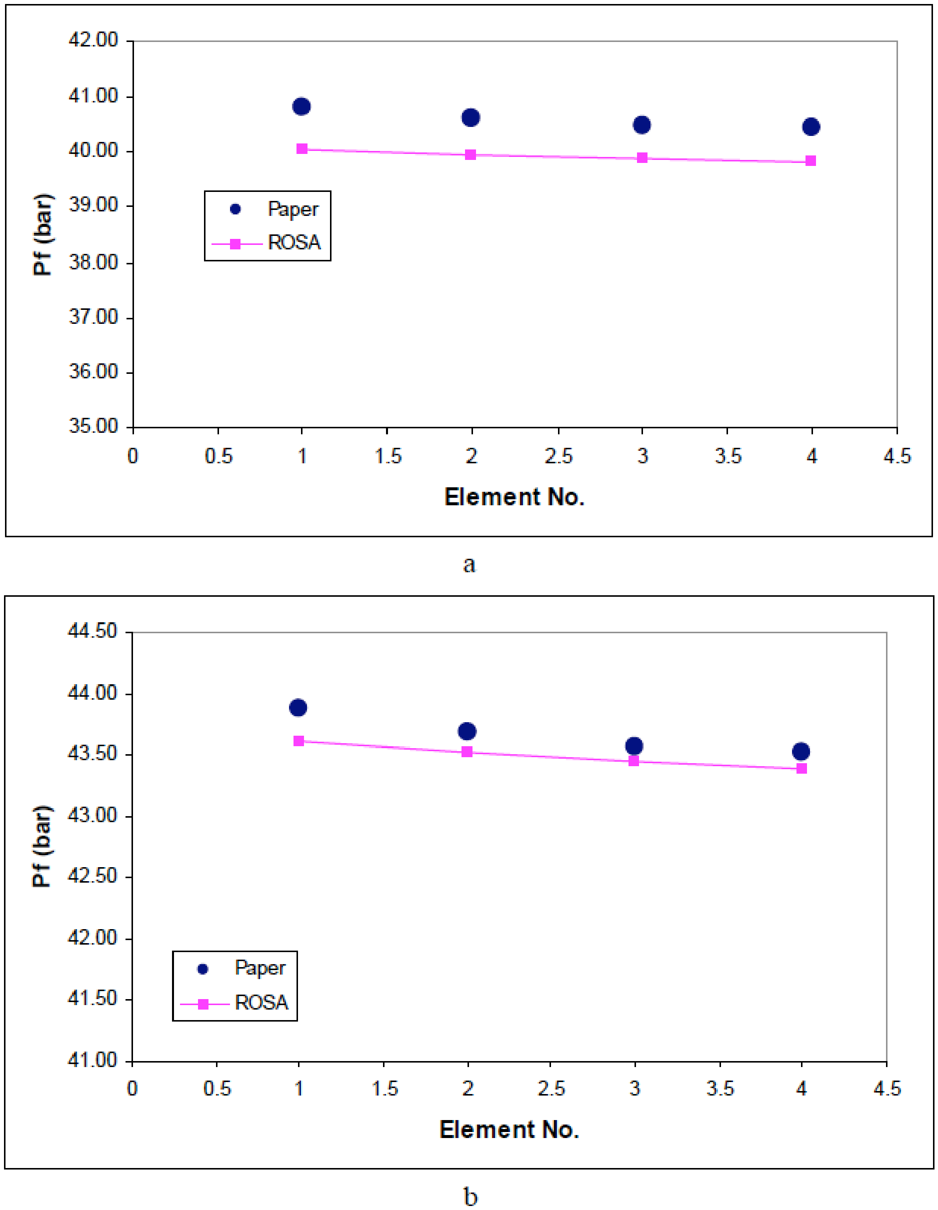
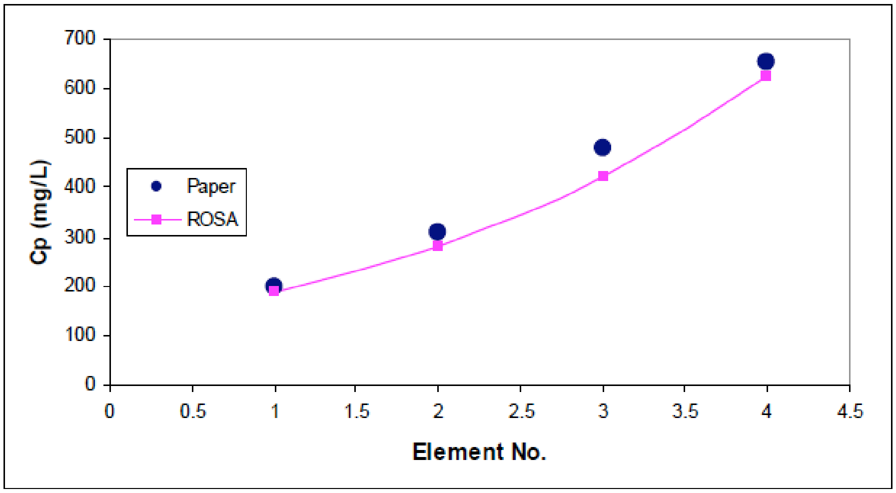


Figure 4: Feed pressure of each element in the RO system. **a**) Feed water TDS 35000 mg/L. **b**) Feed water TDS 38000 mg/L.

Recovery rate, permeate concentration, permeate flow rate, and feed pressure of each element in the pressure vessel was compared with ROSA. A good agreement was identified between the two models. More than 95% of the permeate flow rates from this study agreed with ROSA results (Figure **6**). Similarly, a good agreement was observed between the recovery rates of this study and ROSA (Figure **7**). In both models, the recovery and flow rates decreased from first to last RO element in the high pressure vessel due to increasing the osmotic pressure of feed solution. Regarding feed pressure, it was noticed to be slightly higher in this study compared to ROSA (Figure **8**). This insignificant difference was due to the slightly higher feed osmotic pressure in this study compared to ROSA; 23.52 bar compared to 22.67 bar respectively. Finally, the permeate concentration from this study was compared with ROSA (Figure **9**). The results showed a insignificant difference between the study and ROSA; 534 mg/L and 490 mg/L respectively. An average agreement over 95% was achieved between ROSA and this paper which indicated the reliability of the model here in estimating the performance of RO system.

3.3. Experimental Data from SWRO Plant

The model was also validated against experimental data from SWRO membrane system for seawater desalination in the Red Sea. More information about the SWRO plant can be found in the literature [19].



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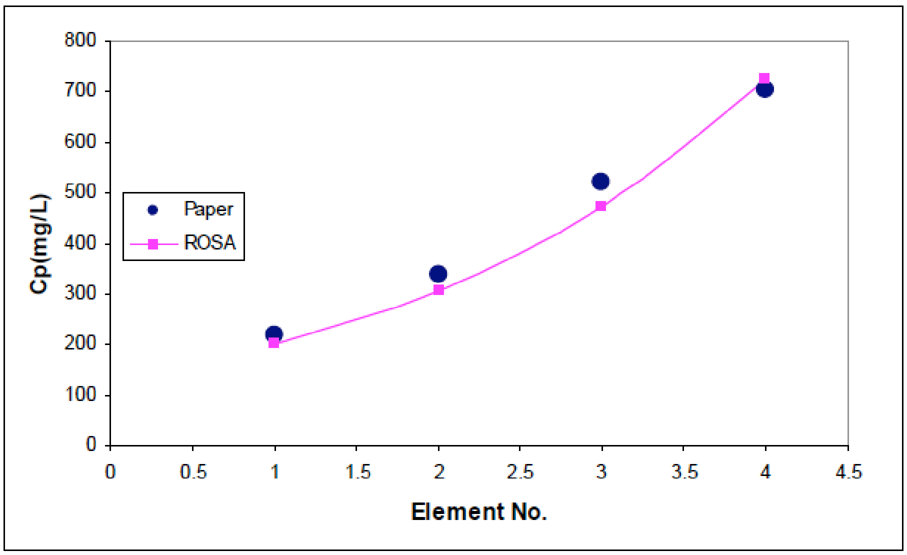

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Figure 5: Permeate concentration of each element in the RO system. **a**) Feed water TDS 35000 mg/L. **b**) Feed water TDS 38000 mg/L.

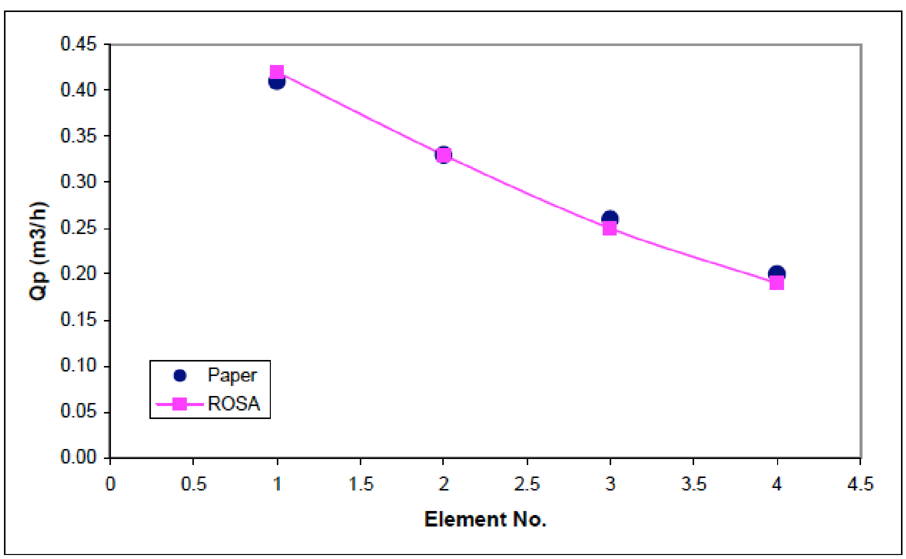

Figure 6: Permeate flow of each element in the RO system.

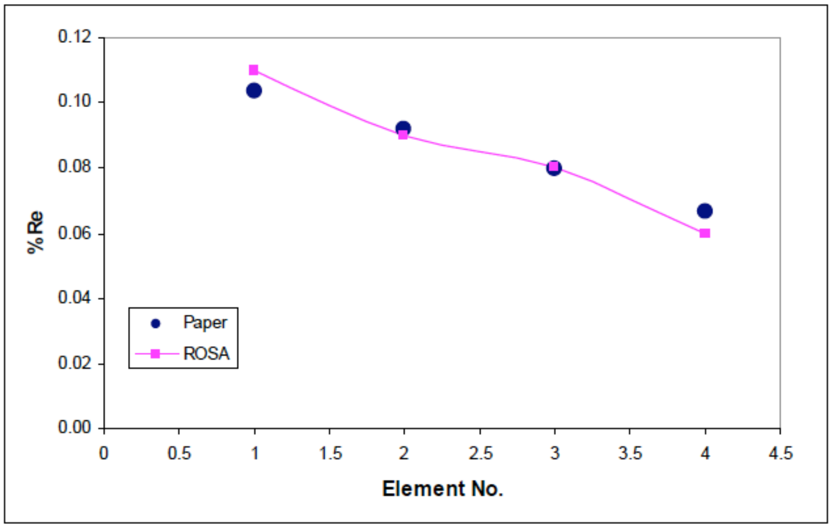

Figure 7: Recovery rate of each element in the RO system.

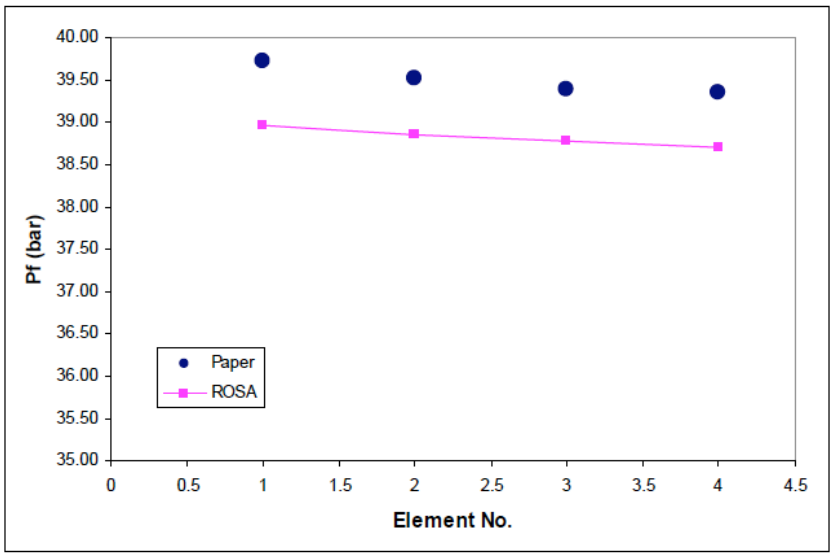

Figure 8: Feed pressure of each element in the RO system.

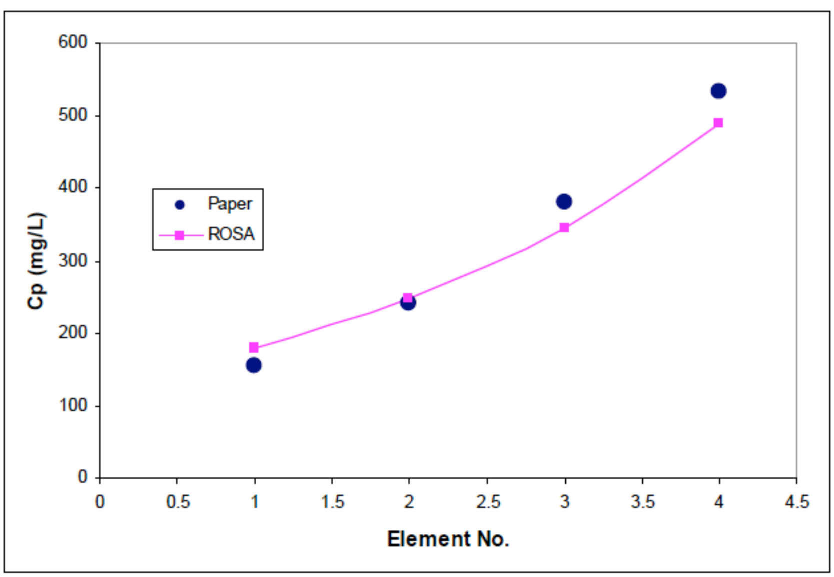

Figure 9: Permeate concentration of each element in the RO system.

Table 3: SWRO Membrane Specifications [17]

Parameter	Value
Membrane length	40 inch (101.6 cm)
Membrane width	8 inch (20.32 cm)
Membrane area	300 ft^2 (27.9 m^2)
Design rejection	99.4%
Design permeate flow rate	5000 US gpm (19.0 m^3/d)
Maximum operating pressure	1000 psi (69 bar)
Allowable operating-cleaning pH range	4-11, 2.5-11
Allowable feed water temperature	1 to 45 ^oC

Testing condition: 32800 mg/L NaCl, 55.2 bar, 7% recovery, 25 ^oC and pH 5.7.

Each pressure vessel in the plant contains 6 spiral wound SWRO membranes. The specifications of RO membranes are shown in Table **3**.

From the experimental data, water permeability and salt diffusion coefficient were calculated as following:

$$A_w = 0.964 \text{ L/m}^2\text{.h.bar}$$

$$B = 0.0041 \text{ m/d}$$

The feed flow and recovery rate of the RO system were, respectively, 9.6 m^3/h and 30%. These data were used in this study to investigate its efficiency in predicting the performance of RO membrane system. A strong agreement was found between this study and the experimental data (Table **4**). For permeate TDS, an agreement over 80% was achieved between the experimental data and this study; 451 mg/L compared to 506 mg/L respectively. The permeate TDS increased from the head to the tail element in the pressure vessel as shown in Table **5**. Additionally, permeate flow, recovery rate and permeate concentration of each RO elements in the pressure vessel were calculated and the total values of these parameters were compared with the pilot plant data (Table **5**). Once again, a good agreement was found between the two them (Figure **10**). As expected the permeate TDS increased from head to tail element while the recover rate and permeate flow decreased from the head to the tail RO element. A comparison between the pilot plant data and the results from this study shows the reliability of the model in estimating the performance of the RO system.

4. CONCLUSION

The performance of RO system was estimated using a computational model. The model was

Table 4: Comparison Between the Results from SWRO Plant and the Study

Parameter	Experimental Data		Model
	Feed	Product	Product
Ca	550	4	5
Mg	1570	12	15
Na	13000	140	179
K	800	10	12
CO_3	1	3	-
HCO_3	135	40	-
SO_4	3700	2	3.4
Cl	23370	240	291
NO_3	1.6	-	-
F	2.5	-	-
TDS	43130	451	506
Recovery rate	-	30%	30%
Permeate flow rate m^3/h	-	2.88	2.88
No of elements/vessel		6	6

Table 5: Distribution of Permeate Flow, Recovery Rate and Permeate TDS Through the Pressure Vessel

Parameter	Feed	Element Number						Model Total	Exp. Data
		1	2	3	4	5	6		
Qp m3/h	9.6	0.63	0.54	0.5	0.45	0.4	0.36	2.88	2.88
%Re	30	0.07	0.06	0.06	0.06	0.05	0.05	0.3	0.3
Cp mg/L	43130	173	264	412	605	836	1091	506	451

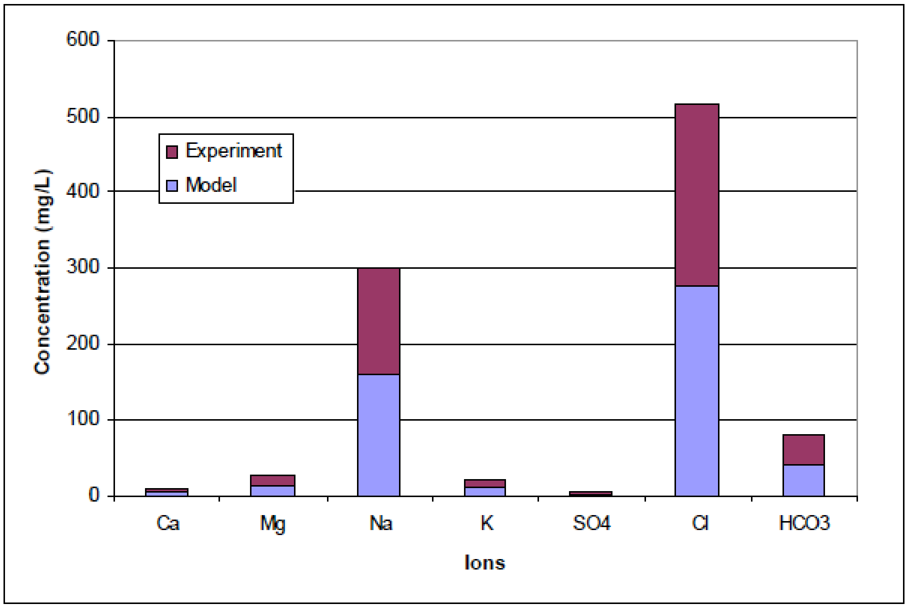

Figure 10: Comparison between experimental and the model seawater ions concentration.

developed to predict the performance of RO membrane using different seawater concentrations. The results from the study were compared with ROSA assuming that ROSA results are fairly accurate [15]. In this study, two types of Filmtec RO membranes were investigated using wide rage of seawater concentrations; 32000 mg/L, 35000 mg/L, 38000 mg/L, and 43000 mg/L. Recovery rate, permeate flow, permeate flow, and permeate concentration of each element in the pressure vessel was compared with ROSA (Figures **1** to **9**). The simulation results showed a good agreement between this study and ROSA. For all feed concentrations, the results from this study were consistently comparable to ROSA. Then, the model was tested against pilot plant data for seawater desalination; feed salinity 43000 mg/L. There was a good agreement between the study and the pilot plant results as shown in Tables **4** and **5**. In conclusion, the study presented a computational model which was able to generate a reproducible data and can reliably be used for estimating the performance of RO system regardless the type of RO membrane or feed water salinity.

In contrast to the commercial RO models, the model in this study is open source and can readily be coupled with any other software used in the design of post-treatment and/or pretreatment processes of RO desalination plant. It should be noted here that results obtained from the model here would be slightly different to the experimental data due to errors from calculating the actual solution concentration at the membrane surface, membrane compaction, and membrane fouling. However, the expected uncertainties of the model is quiet reasonable and within acceptable range.

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NOMENCLATURE

ACF = average concentration factor

Am = membrane area m^2

A_w = water permeability constant L/ m^2.h.bar

B = salt permeability constant m/day

C = concentration mg/L

C_b = bulk concentration mg/L

C_f = feed concentration mg/L

C_{fc} = concentrate feed concentration mg/L

CP = concentration polarization factor

C_p = permeate concentration mg/L

C_w = concentration at the membrane surface mg/L

FF = fouling factor average concentrate side flow rate

J = water flux L/ m^2.h

n_i = number of moles of species i

n = number of RO elements in series

P_{cd} = concentrate side pressure drop bar

ΔP = membrane pressure gradient bar

Q_c = concentrate flow rate m^3/h

Q_f = feed flow rate m^3/h

Q_p = permeate flow rate m^3/h

q_{cave} = average concentrate side flow rate m^3/h

R = recovery rate

R_g = universal gas constant 0.082 kg.m^2/h^2.k

Rj = membrane rejection rate

T = feed temperature ^oC

TCF = temperature correction factor

$\Delta\pi$ = osmotic pressure gradient bar

π_{cave} = average concentrate side osmotic pressure bar

π_f = feed osmotic pressure bar

π_p = permeate osmotic pressure bar

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