A Novel RO/FO Hybrid Seawater Desalination System and Its Software Implementation

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Abstract. Seawater reverse osmosis (SWRO) desalination technology is being widely used in coastal countries to meet the supply demand of fresh water for living and industry using. Despite major advancements in SWRO technology, the desalination industry is still facing significant practical issues. Generation of higher volumes of pretreatment sludge and low overall water recovery are the two of the major issues. A novel hybrid reverse osmosis-forward osmosis (RO/FO) system is proposed to overcome the above two drawbacks. Mass balance calculations based on laboratory experiments have been used to predict increased water recovery and reduced pretreatment sludge volume arising from large scale (340,000 m³/day of intake) and small scale (15,000 m³/day of intake) hybrid SWRO desalination plants. After that, we developed a software for the RO/FO hybrid system in MATLAB, and different water flux values were studied to verify the system. It was packaged into executable files and it can run smoothly on computers without MATLAB installed. By setting different operating parameters in the RO/FO system software interface, the percentage reduction of pretreatment sludge volume, increase in overall RO water recovery, FO membrane area required and dilution in RO reject can be estimated quickly in a variety of different options.

1. Introduction
Seawater desalination has become an important method to solve the problem of water shortage in the world [1]. Desalination using reverse osmosis (RO) membranes has rapidly developed since the 1960's and has been the most frequently employed technology for desalination over the last 10 years [2]. Seawater desalination technology, as the main means of fresh water production, has been gradually recognized and widely used all over the world since it came into being in the 20th century [3]. So far, more than 13,000 desalination plants have been put into operation worldwide, and the desalinated water output can reach 35 Mt/d, with an annual growth rate of 10% to 20%. The total global desalination
capacity was about 40 million cubic meter per day (Mm3/day) in 2013, and has reached 88.6 Mm3/day in 2016 [4]. Reverse osmosis seawater desalination has become the mainstream seawater desalination technology, accounting for 62% of the global seawater desalination technology distribution. Other technologies include multi-stage flash desalination and multi-effect distillation desalination. Reverse osmosis process has the advantages of high desalination rate, high removal rate of organic pollution and blockage, optimized design of components, high degree of automation and high quality reclaimed water production. However, the lack of fouling and blockage limits the application of RO membrane, resulting in a series of problems such as increased membrane resistance, enhanced concentration polarization, increased energy consumption, and decreased water yield.

A novel hybrid RO/FO system is proposed that will improve both water recovery and reduce the volume of pre-treatment sludge. In a typical pre-treatment sludge treatment process, clarified backwash sludge gets mechanically treated until the solids content meets the required landfill conditions. However, this process yields high operations and maintenance (O&M) costs [5].

| Item             | Cost (AUS$/day) |
|------------------|-----------------|
| Chemicals        | 47              |
| Power            | 35              |
| Transportation   | 465             |
| Disposal         | 1978            |
| Total            | 2525            |

Table 1 shows the O&M cost for a sludge treatment process where daily sludge generation is 275 m³/day. Transportation and disposal of sludge costs $465 and $1,978 AUS$/day, respectively, which is a significantly high cost.

Figure 1 shows an existing treatment process (System E) for pre-treatment of sludge in a seawater desalination plant in Perth, Australia, where a centrifuge increases the sludge solids content from 2-4% to 25% [6]. The ultimate solids content of sludge is an important factor to consider when proposing a sludge dewatering FO system, as the solids content is similar to the requirements currently reached or higher. However, existing FO membranes are incapable of producing solids contents of up to 25%, so the FO system considered was to be installed between the clarifier and centrifuge [7-9]. The FO system
increases the solids content to a designated extent following which the sludge is centrifuged until solids content reaches 25%. This may reduce energy consumption because FO systems require less energy to run and maintain than centrifuges [10, 11]. FO system consumes merely 17.3 kWh/day of power to increase sludge content from 3% to 10% (refer supporting documents). Further, the volume of filtrate from the centrifuge, which is known as centrate, will be reduced which generally needs treatment before discharge [8, 12]. Recent developments in membrane materials, modules and process design have contributed to the reduction of energy consumption for production of desalinated water by SWRO to 3 to 6 kWh/m³, which is lower than the typical energy required by conventional thermal desalination processes (10 to 15 kWh/m³) [13, 14]. According to Amy et al., development of emerging, potentially disruptive technologies through advances in material science, process engineering, and system integration will further reduce the energy consumption of a SWRO plant [15].

2. Materials and methods

2.1. Proposed RO/FO hybrid systems

DefineIn order to evaluate the feasibility of RO/FO hybrid system, we will carry out the quality balance calculation from the following three options.

1) Option 1

![Flow chart of process Option 1](image)

**Figure 2.** Flow chart of process Option 1 (System A - FO process; System B - Pre-treatment process; System C - HPP and desalting process; System D - Post treatment process).

In addition to an existing 2-stage RO desalination process, a FO system is proposed to reduce the volume of pre-treatment sludge. For RO processes, it is recommended to use the 2nd pass RO concentrate backwash media filter, as 2nd pass RO processes the 1st pass osmosis solution with a significantly lower salt concentration. Figure 2 shows the process flow chart. Because of the high concentration of FO (therefore high conductivity and osmotic pressure), an optimized ratio of 1st pass reverse osmosis concentrate is used to pump water through FO. The diluted primary reverse osmosis concentrate is mixed with pretreated seawater and circulated to the primary reverse osmosis system for desalination to improve the overall water recovery rate.

2) Option 2

This Option, shows in Figure 3, is suggested for existing desalination processes, where filtered / polished seawater is used to backwash media filters. Because FO system has a higher concentration, so it has high conductivity and osmotic pressure, so the proposed FO system through 1st pass RO
concentrate on the draw water. Diluted 1st pass RO concentrate gets blended with pre-treated seawater send back to the 1st pass RO for further desalting in order to increase the overall water recovery.

Figure 3. Flow chart of process Option 2 (System A - FO process; System B - Pre-treatment process; System C - HPP and desalting process; System D - Post treatment process).

3) Option 3

Figure 4. Flow chart of process Option 3 (System A - FO process; System B - Pre-treatment process; System C - HPP and desalting process; System D - Post treatment process).

Figure 4 is a flowchart of option 3. This process is used for dilution of RO concentrate, which is very important, especially before discharge into the water body. Dilution will significantly increase the discharge rate, hence higher production rate could be obtained. As with option 1 and option 2, both filtered/polished water after pre-treatment and 2nd pass RO concentrates can be used to backwash media filter. Because FO has a higher TDS (hence high conductivity and osmotic pressure), 1st pass RO concentrate can draw water from FO. The diluted seawater is mixed with the concentrate from 1st pass and 2nd pass before being returned to the water body.
2.2. Mass balance

There are several factors to be considered when mass balancing a hybrid RO / FO system. Since the feed is a mixture of pre-treated seawater and a draw solution from FO, the water recovery of RO must be established at various osmotic pressures of the feed. Information about the amount of backwash required for the pre-treatment process (usually a sand filter) will help determine how much volume of backwash water can be reduced by the FO process. The above information, as well as the performance of the FO in terms of water flux, can estimate the flow rate of the extraction solution (RO concentrate) entering the FO and the area of the FO membrane.

Table 2 shows the initial assumptions for subsequent mass balance calculations. The mass balance calculation is based on the conditions of large-scale and small-scale desalination plants [16].

| Table 2. Initial assumptions for subsequent mass balance calculations |
|----------------------------------------------------------|
| **Intake flow rate, \( Q_{in} \)**                        |
| Large scale plant | 340,000 | 15,000 | m³/day |
| Small scale plant | 100     | 100    | %      |
| **RO rejection**                                         |
| Large scale plant | 100     | 100    | %      |
| Small scale plant | 100     | 100    | %      |
| **Total amount of pre-treatment sludge, \( Q_{B} \)**     |
| Large scale plant | 275     | 100    | m³/day |
| Small scale plant | 100     | 100    | %      |
| **RO 1 recovery, \( R_1 \)**                            |
| Large scale plant | 50      | 50     | %      |
| Small scale plant | 90      | 90     | %      |
| **RO 2 recovery, \( R_2 \)**                            |
| Large scale plant | 90      | 90     | %      |
| Small scale plant | 90      | 90     | %      |
| **Overall recovery (Without FO)**                        |
| Large scale plant | 45      | 45     | %      |
| Small scale plant | 45      | 45     | %      |
| **Nominal FO membrane surface area of 8 inch spiral wound modules** |
| Large scale plant | 18.13   | 18.13  | m²     |
| Small scale plant | 18.13   | 18.13  | m²     |
| **Initial solids content of Pre-treatment sludge**       |
| Large scale plant | 4       | 3      | %      |
| Small scale plant | 3       | 3      | %      |

1) Mass balance for option 1

The FO system uses 1st pass RO brine as the extraction fluid. Mass balance and salt balance were applied to FO system (System A in Figure 2).

\[
Q_c = Q_f \cdot 0.024 J_w A
\]  
\[
C_p = 2 \frac{Q_d}{Q_f + 0.024 J_w A} C_o
\]

Where, \( Q_f \leq Q_d \leq (Q_{in} + Q_o)(1-R1\%)

\( Q_c \) = concentrate flow rate (m³/day), \( Q_f \) = Feed flow rate to the FO system (m³/day), \( J_w \) = water flux through FO unit (LMH), \( A \) = FO membrane area (m²), \( C_p \) = salt concentration of diluted brine (mg/L), \( Q_d \) = draw flow rate to the FO unit (m³/day), \( C_o \) = salt concentration of intake seawater (mg/L), \( Q_{in} \) = intake flow rate (m³/day), \( Q_o \) = diluted brine flow rate (m³/day), \( R1 \) = recovery of the 1st pass RO unit (%).

In the filtration process, due to the dilution of draw solution, a lower \( Q_d \) may reduce the water flux through FO, so the minimum value of \( Q_d \) is set equal to the volume of \( Q_f \). Further increase the concentration of the extract to twice the concentration of sea water to simplify the equation [17]. According to equation (1) and (2), higher water flux will lower not only the concentration of diluted brine but also the concentrated sludge volume. The performance of FO membrane and the performance of draw and feed solutions affect \( J_w \) need to be obtained through experiments.

The diluted brine is mixed with pre-treated seawater before entering the 1st pass RO. Therefore, it is necessary to check the concentration of the inlet to 1st pass RO, \( C_R \), because the higher the concentration is, the lower the recovery rate of RO is under the condition of constant operating pressure.

\[
C_R = \frac{Q_f + Q_r}{Q_{in} + Q_o} C_o
\]
Where \( C_r \) can be obtained through equation (2) and \( C_a = \) salt concentration of RO 1st pass inlet (mg/L).

Increased overall recovery of the system is given by;

\[
R_1 = R_2 \times R_2 \times (Q_a + Q_p)
\]

(4)

Where, \( R = \) overall recovery of the RO/FO hybrid system (%), \( R_2 = \) recovery of the 2nd pass RO unit (%).

Furthermore, to check the dilution of the concentrated brine waste before discharging, it is important to check the concentration of concentrated brine waste. Assuming concentration of reject from 2nd pass RO, \( C_{RR2} \) is negligible, \( C_w \) can be obtained using following relationship;

\[
C_w = \frac{(Q_{RR} - Q_a)}{(Q_{RR} + Q_a)} C_d
\]

(5)

Where, \( C_w = \) salt concentration of the blended RO concentrate (reject) (mg/L), \( C_d = \) salt concentration of draw solution/brine from 1st pass unit (mg/L), \( Q_{RR} = \) brine flow rate of 1st pass RO unit (m\(^3\)/day), \( Q_a = \) reject flow rate of 2nd pass RO unit (m\(^3\)/day), \( Q_b = \) backwash sludge flow rate (m\(^3\)/day).

This relationship can be simplified as;

\[
C_w = 2 \frac{1}{1 + \frac{R_1(1-R_2)(Q_a + Q_p) - Q_a}{Q_{RR}} C_o}
\]

(6)

Where \( C_w = \) salt concentration of the blended RO concentrate (reject) (mg/L), \( R_1 = \) recovery of the 1st pass RO unit (%), \( R_2 = \) recovery of the 2nd pass RO unit (%), \( Q_a = \) intake flow rate (m\(^3\)/day), \( Q_b = \) backwash sludge flow rate (m\(^3\)/day), \( Q_d = \) draw flow rate to the FO unit (m\(^3\)/day), \( C_o = \) salt concentration of intake seawater (mg/L).

2) Mass balance for option 2

Similar equations obtained in Section 2.2.1 can be applied for the FO system in Option 2 (Figure 3) i.e. equation (1) and (2). However, conditions of feed solution vary as follow;

\[
(C_f)_{Option1} < (C_f)_{Option2}
\]

Where \( C_f = \) salt concentration of backwash sludge (mg/L). Also the range of \( Q_a \) is given by;

\[
Q_t < Q_d < (Q_{ta} - Q_B + Q_p)(1 - R1\%)
\]

Where \( Q_t = \) Feed flow rate to the FO system (m\(^3\)/day), \( Q_d = \) draw flow rate to the FO unit (m\(^3\)/day), \( Q_{ta} = \) intake flow rate (m\(^3\)/day), \( Q_b = \) backwash sludge flow rate (m\(^3\)/day), \( Q_p = \) diluted brine flow rate (m\(^3\)/day), \( R_1 = \) recovery of the 1st pass RO unit (%).

Part of the filtered seawater is used to backwash the pre-treatment system, generally media filter. Therefore the amount of water enters the 1st pass RO system, \( Q_R \) is given by;

\[
Q_R = Q_{ta} - Q_B + Q_p
\]

(7)

Thus the concentration of the fluid stream entering the 1st pass RO system, \( C_R \) is given by;
7

\[ c_b = \frac{(Q_m - Q_b) + C_P/C_Q Q_p}{(Q_m - Q_b) + Q_p} \]  

(8)

Where \( C_P/C_Q \) is given by Equation (2).

Due to the increased volume to the desalting process, increased overall water recovery is given by;

\[ R\% = R1 \times R2 \times (Q_m - Q_b + Q_p) \]  

(9)

Concentration of the concentrated brine waste is given by;

\[ C_w = 2 \frac{1}{1 + \frac{R(1 - R2)(Q_m - Q_b + Q_p)}{(1 - R1)(Q_m - Q_b + Q_p) + Q_d}} C_o \]  

(10)

Where \( C_w = \) salt concentration of the blended RO concentrate (reject) (mg/L), \( R1 = \) recovery of the 1st pass RO unit, \( R2 = \) recovery of the 2nd pass RO unit (\%), \( Q_m = \) intake flow rate (m³/day), \( Q_b = \) backwash sludge flow rate (m³/day), \( Q_p = \) diluted brine flow rate (m³/day), \( Q_d = \) draw flow rate to the FO unit (m³/day), \( C_o = \) salt concentration of intake seawater (mg/L).

3) Mass balance for option 3

The difference in this Option is, without increasing the overall recovery, diluted brine is used to dilute the blended reject from 1st and 2nd pass RO units. Therefore, the important parameter that is needed to be checked is \( C_w \). However, \( C_w \) depends on the backwash method. \( C_w \) at each backwash method can be obtained using following mass balance relationships;

If 2nd pass RO reject is used as backwash water;

\[ C_w = \frac{Q_o C_P/C_Q + 2(Q_m \cdot (1 - R1) \cdot Q_b)}{[Q_m \cdot (1 - R1) \cdot Q_b] + [Q_m \cdot (1 - R2) \cdot Q_p + Q_d]} C_o \]  

(11)

If filtered seawater is used as backwash water;

\[ C_w = \frac{Q_p C_P/C_Q + 2(Q_m \cdot Q_b \cdot (1 - R1) \cdot Q_b)}{[Q_m \cdot Q_b] \cdot (1 - R2)} + [Q_m \cdot Q_b \cdot (1 - R2) + Q_p]} C_o \]  

(12)

Where, \( C_w = \) salt concentration of the blended RO concentrate (reject) (mg/L), \( Q_o = \) diluted brine flow rate (m³/day), \( C_P = \) salt concentration of diluted brine (mg/L), \( C_o = \) salt concentration of intake seawater (mg/L), \( Q_o = \) intake flow rate (m³/day), \( R1 = \) recovery of the 1st pass RO unit (\%), \( Q_d = \) draw flow rate to the FO unit (m³/day), \( R2 = \) recovery of the 2nd pass RO unit (\%), \( Q_b = \) backwash sludge flow rate (m³/day).

Water flux through FO would be significantly higher in first option than the second as the salt concentration of backwash sludge is lower in the former.

2.3. Software implementation of the proposed systems

The new proposed system is programmed by MATLAB to run independently. Based on the powerful mathematical operation ability of MATLAB, the software can quickly calculate the required results. The software is based on the graphical user interface (GUI) of MATLAB, so it is very convenient and friendly to use. After encapsulation into executable programs, the software can run on a computer without MATLAB installed. The only thing needs to do first is to install a MATLAB runtime environment (MCRInstaller) to load some functions needed for the program to run.
Figure 5 shows the start interface of the software on a computer. All the Options mentioned above are included as four buttons at the bottom of the page. Taking Option 1 as an example, Figure 6 shows the parameters setting page both of the large scale and small scale choices.

![Start interface of the software.](image1)

![Parameters setting page of Option 1](image2)

After setting down all the parameters we need, the system will be ready to get some required results shown in Figure 7.

![Results page after running the system](image3)

All the results can be output as separate files (refer Section 3).

3. Results and discussion

The flux value $J_W$ (normally we use 3 LMH) can try different values of it to see the changed. In reality, this will happen if we can manufacture better membranes. This kindly of analysis will be useful for new plant design.

3.1. MATLAB outputs for different FO flux values for a given option

Taking Option 1 as an example, the results will be shown in figure 8 to 10. One can download them and run to verify what will happen in other options.
Figure 8. Variation of $C_p$, $C_R$ and recovery with $Q_d$ at selected FO membrane area for Option 1 (when JW = 5 LMH). (a), (c) and (e) present the results of large scale desalination plants; (b), (d) and (f) present the results of small scale desalination plants.
Figure 9. Variation of $C_p$, $CR$ and recovery with $Q_d$ at selected FO membrane area for Option 1 (when $J_W = 7$ LMH). (a), (c) and (e) present the results of large scale desalination plants; (b), (d) and (f) present the results of small scale desalination plants.
Figure 10. Variation of $C_p$, $C_R$ and recovery with $Q_d$ at selected FO membrane area for Option 1 (when JW = 10 LMH). (a), (c) and (e) present the results of large scale desalination plants; (b), (d) and (f) present the results of small scale desalination plants.

Figure 8 to 10 show the changes of $C_p$, $C_R$ and recovery with $Q_d$ at selected FO membrane area for Option 1 in different water flux values. The variation of $C_p$ at selected draw flow rates with different membrane area. In the case of large scale desalination plants, when membrane area increases from 100 m^2 to 500 m^2, increase in
concentration of diluted brine is marginal at the lowest \( Q/Q_d \). However, there is a significant increase in small scale plants in the lowest \( Q/Q_d \).

As mentioned in Option 1, it is important to check \( R_c \) in order to understand the dilution factor to the 1st pass RO. Similarly, in large scale plants dilution is lower (maximum ratio is 1.013) compared to small scale plants (maximum ratio is 1.095). However, for small scale plants lower membrane area can be suggested since the \( c_r/c_o \) ratio is less than 1.01.

As far as increase in overall recovery concerned, small scale plants show better performances. Calculated overall recovery values are plotted and shown in Figure 8 to 10. Maximum change in recovery is by 0.5% in the case of large scale desalination plants. Interestingly, small scale plants show overall recoveries up to ~50%.

### 3.2. MATLAB outputs for a given FO flux under different options

Table 3 shows the calculation results of final solids content after passing through the FO system both of large scale and small scale plants undertaken Option 1 and Option 2, when JW is 6 LMH. In Option 1, When the membrane area is 100 m² it reduces sludge volume by 5.24%, but the final solids content has increased only up to 4.22%. When membrane area increases, both solids content and sludge volume reduction increase in large and small scale plants. When membrane area of a large scale plant is increased to 910 m², sludge volume has reduced by almost 50% with a final solids content of 7.64%. In Option 2, when the membrane area is 100 m² it reduces sludge volume by 7%, but the final solids content has increased only up to 3.2% in small scale plants. When membrane area increases, both solids content and sludge volume reduction increase in both the scales. When membrane area of a small scale plant is increased to 500 m², sludge volume has reduced by 36% with a final solids content of 4.69%.

In summary, the novel proposed FO/RO hybrid system’s sludge treatment process shows lower operation and maintenance costs compared to existing system. After installing an FO system prior to centrifuge, number of centrifuges in operation can be reduced, which leads to lower energy costs. Further, the volume of centrate generates through centrifuges can be minimized. In addition existing sludge clarifiers are not necessary as sludge flow pass through FO process before entering the mechanical dewatering system. Increase in water recovery and final solids content of both large and small desalination plants considered. By increasing FO membrane area up to 900 m² (where it needs 50 8” spiral wound membrane modules), pre-treatment sludge volume can be reduced up to 47% in large scale desalination plants. Further final solids content and overall water recovery of RO system can be increase up to 7.6% and 45.6%, respectively. Interestingly in small scale plants, having membrane area up to 500 m², the volume of sludge can be reduced by 72%.

| Membrane area (m²) | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 910 |
|--------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Sludge reduction through FO (%) |     |     |     |     |     |     |     |     |     |     |
| Small scale Option 1 | 14.4 | 28.8 | 43.2 | 57.6 | 72 | 86.4 | * | * | * | * |
| Large scale Option 1 | 5.24 | 10.47 | 15.71 | 28.8 | 26.18 | 31.42 | 36.65 | 41.89 | 47.13 | 47.65 |
| Small scale Option 2 | 7.2 | 14.4 | 21.6 | 36 | 43.2 | 50.4 | 57.6 | 64.8 | 65.52 |     |
| Large scale Option 2 | 2.62 | 5.24 | 7.85 | 10.47 | 13.09 | 15.71 | 18.33 | 20.95 | 23.56 | 23.83 |
| Final solids content (%) |     |     |     |     |     |     |     |     |     |     |
| Small scale Option 1 | 3.50 | 4.21 | 5.28 | 7.08 | 10.71 | 22.06 | * | * | * | * |
| Large scale Option 1 | 4.22 | 4.47 | 4.75 | 5.06 | 5.42 | 5.83 | 6.31 | 6.88 | 7.57 | 7.64 |
| Small scale Option 2 | 3.23 | 3.50 | 3.83 | 4.21 | 4.69 | 5.28 | 6.05 | 7.08 | 8.52 | 8.70 |
| Large scale Option 2 | 4.11 | 4.22 | 4.34 | 4.47 | 4.60 | 4.75 | 4.90 | 5.06 | 5.23 | 5.25 |

During dewatering, the final solids content and overall water recovery increased to 10.7% and ~ 50%, respectively. 28 8” spiral wound membrane modules are estimated to be required to operate in this mode.
Therefore, small scale desalination plants tend to show better performance than large scale plants with the hybrid system.

4. Conclusion

(1) A novel hybrid reverse osmosis - forward osmosis (RO/FO) system is proposed in this paper focusing at two key issues: (i) generation of higher volumes of pre-treatment sludge and (ii) low overall water recovery in desalination plants. Experiments and mathematical modelling suggest that proposed FO/RO hybrid systems are capable of reducing the volume of pre-treatment sludge.

(2) Software implementation of the proposed system can help the designer to analyze different scenarios of RO/FO hybrid system. Draw to feed flow rates of FO membrane, flux through FO membrane and the area of FO membrane can be changed to obtain the reduction in pre-treatment sludge volume, increase in water recovery as well the dilution obtained for the final discharge of the concentrate. Thus, the software can become an important tool to design RO/FO hybrid seawater desalination plants.

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