Simulation and Optimization of Full Scale Reverse Osmosis Desalination Plant

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Abstract
This paper focuses on steady state performance predictions and optimization of the Reverse Osmosis (RO) process utilizing a set of implicit mathematical equations which are generated by combining solution-diffusion model with film theory approach. The simulation results were compared with operational data which are in good agreement having relative errors of 0.71% and 1.02%, in terms of water recovery and salt rejection, respectively. The sensitivity of different operating parameters (feed concentration, feed flow rate and feed pressure) and design parameters (number of elements, spacer thickness, length of filament) on the plant performance were also investigated. Finally a non linear optimization framework to minimize specific energy consumption at fixed product flow rate and quality while optimizing operating variables (feed flow rate, feed pressure) and design parameters (height of feed spacer, length of mesh filament). Reduction in operating costs and energy consumption up to 50 % can be reached by using pressure exchanger as energy recovery device.

Keywords: reverse osmosis, spiral wound membrane, simulation, optimization, energy recovery

1. Introduction
The shortage of fresh water resources and growth of industrialization have increased the reliance on water production using desalination technology. Thermal and membrane processes are, by far, the major desalination systems used now-a-days. Pressure driven membrane processes are less energy intensive than thermal. Designing an efficient RO desalination system remained an elaborate work (Lu et al., 2006). It is connected to many variables, such as, feed flow rate, operating pressures, recovery rate, the type of membrane element and its geometry (i.e. spacer geometry) and RO system configuration. However, the prediction of RO process performance completely relies on the mathematical model accuracy. Kim et al. (2009) reviewed the analytical design methods of industrial RO plants, and the recent optimization techniques for predicting the optimal parameters values for RO plants using different mathematical programming.

In this work, the effect of different operating and design parameters such as feed pressure, salinity, spacer geometries, and number of membrane elements in the pressure vessel on the performance of RO performance is studied. An optimization problem incorporating a process model is formulated to optimize the design and operating parameters in order to minimize specific energy consumption constrained with fixed product demand and quality. Finally, energy recovery from brine is considered. Two different energy recovery devices are studied: hydrodynamic turbines and pressure exchanger.
Prediction of solute concentration polarization on the membrane surface in crossflow membrane processes has vital role in designing RO processes and estimating their performances. A film theory approach which was developed originally by Michaels (1968) is used in this work to describe the concentration polarization. It is simple, analytical, and (reasonably) accurate for most RO separations. Further, film theory can be extended to describe the effect of spacer-filled RO modules on concentration polarization which is inherently used in design and evaluation of the membrane processes. Solution-Diffusion model is used to illustrate solvent and solute transport through the membrane. This model is the most used and is able to provide an accurate prediction of the flow of water and salt through the membrane (Marcovecchio et al., 2005).

2. Reverse Osmosis Process Model
Fig. 1 summarizes the model equations for RO based on the following assumptions:
• Pressure drop along the permeate channel is neglected, this assumption is reasonable for 8 inches spiral wound module that has 37 membrane leafs with a length of 1 m (Geraldes et al., 2005).
• The feed channels of spiral wound element are flat. Feed stream flows along the channel parallel to the central line of the module and the curvature of membrane module was reported to have insignificant effect on system's performance (Meer et al., 1997). Therefore, an unwound flat sheet membrane with same channel height and spacers would adequately represent characteristics of the corresponding spiral-wound RO module.
• The feed concentration varies linearly along the feed side channel.

3. Optimization Problem Formulation
The performance of a membrane process is limited by the magnitude of the chemical potential driving force for mass transfer. This driving force can be maximised by manipulating temperature or pressure of the feed stream which require significant energy. This spending should be balanced against other costs in designing the membrane system. Consequently, proper optimization techniques are required to determine the best values for the various operating and design parameters. An optimization strategy which considers both operating and design parameters is shown in Fig. 2. This results in a non linear optimization problem solved using SQP method within gPROMS software. As shown in Fig. 2, there are four decision variables \( (P_f, Q_f, L_f, d_f) \). The bounds on each variable are specified in each case.

4. Case Study
In this work, a three-stage RO process described by Abbas (2005) is considered (Fig. 3). The plant nominal operating and design parameters are given in Table 1. Commercial Film Tec spiral wound RO membrane elements with three elements in each pressure vessel (connected in series) is considered. Each element is modeled by a set of nonlinear algebraic equations (Fig. 1). Operational data from Abbas (2005) are used to validate the model. The model yielded an overall 58.0 % water recovery and 98.6% salt rejection. The relative deviations of the simulated results compared to Abbas (2005) are 0.71% and 1.02%, respectively.

Then, the effect of different operating and design parameters on membrane performance was studied by varying one parameter and keeping the others constant (Table 1) as follow.
Water flux: \( J_w = A(\Delta P - \Delta \tau) \); Solute flux: \( J_s = B(C_\text{in} - C_\text{out}) \); Recovery %:

\[ R = (Q_s/Q_f) \times 100 \]

Concentration polarization: \( CF = \frac{C_m - C_p}{C_B - C_p} = \exp(J_w/K) \); Salt rejection %:

\[ SR = (1 - \frac{C_s}{C_f}) \times 100 \]

Pressure drop: \( \Delta P_i = \frac{du \cdot L C_{df}}{2d_i} \); Mass transfer coefficient:

\[ Sh = \frac{K_d}{D} = 0.0664K_s Re^{0.8} Sc^{0.8} \left( \frac{2d_i}{L} \right) \]

Mass balance: \( Q_s = Q_s + Q_s \); Flow balance: \( Q_s = \frac{Q + Q}{2} \); Average velocity in feed side: \( U = \frac{Q}{Wh_e} \); Water flow via membrane: \( Q_s = J_s, s \); Material balance around membrane: \( C_s = J_s/J_f \); Specific energy: \( E = \frac{\Delta P Q_s}{\eta Q_f} \); With turbine energy recover (ER):

\[ E = \frac{\Delta P Q_s}{\eta Q_f} - \frac{P Q \eta}{Q_f} \]

With pressure exchange (PX) ER: \( E = \frac{\Delta P Q_s}{\eta Q_f} \)

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**Given:** Feed water conditions; membrane properties and specifications

**Determine:** The optimal feed pressure; feed flow; the optimum design decisions (feed spacer filament length and diameter, feed spacer thickness)

**So as to minimize:** Specific energy consumption \( E \) (kwh/ m³)

**Subject to:** Equality and inequality constraints

Mathematically optimization problem can be represented as:

Minimize \( E \)

\( P_f, Q_f, L_f, d_f \)

Subject to:

Equality constraints: Process model; Product demand; Product specification

Inequality constraints:

\( P_f^{lower} \leq P_f \leq P_f^{upper} \)

\( Q_f^{lower} \leq Q_f \leq Q_f^{upper} \)

\( L_f^{lower} \leq L_f \leq L_f^{upper} \)

\( d_f^{lower} \leq d_f \leq d_f^{upper} \)

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Table 1 Membrane parameters and process operating conditions

<table>
<thead>
<tr>
<th>Feed conditions: ( Q_f (m^3/h) ) 20.4; ( C_f (kg/m^3) ) 2540 ppm; ( P_f (bar) ) 12.2; ( T_f (^\circC) ) 28.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane and spacer characteristics: ( A ) (m/bar s) 9.39×10^{-7}; ( B ) (m/s) 5.65×10^{-8}; ( L_f ) (m) 2.77×10^{-3}; ( L ) (m) 1; ( w ) (m) 37.2; ( S ) (m^2) 37.2; ( h_s ) (m) 5.93×10^{-4}; ( d_s ) (m) 8.126×10^{-4}</td>
</tr>
</tbody>
</table>
4.1 Sensitivity analysis of operating parameters

4.1.1 Pressure

Fig. 4a shows the effect of operating pressure on RO plant performance. Salt rejection increases linearly at low to moderate pressure. At high pressure, salt rejection decreases dramatically due to the increase in osmotic pressure along the feed channel. Average permeates flux curve is divided into two regions. In the lower pressure region, water flux increases linearly which illustrates a linear relationship between the permeate flux and the driving pressure. In the higher pressure region water flux starts to level-off at 16 bar (corresponding to flux $1.2 \times 10^{-3} \text{ m/s}$). This may be due to the accumulation of the salt along the membrane channel that exerts an increasing osmotic pressure. The limiting flux is $(1.4 \times 10^{-4} \text{ m/s})$ where the flux can not be increased even when the applied pressure increases. Variations of specific energy consumption (kwh/m$^3$) and concentration polarization factor (CF) are shown in Fig. 4b for operating pressure ranging from 6 to 25 bar. Higher pressure required less pumping energy. The minimum specific energy consumption is observed at 12 bar corresponding to water recovery rate 57%, followed by increase in specific energy due to the stabilization in the permeate production despite increasing applied pressure. As expected CF increase with increase in operating pressure due to the increase in water flux.

4.1.2 Number of elements in pressure vessel

It was observed that the water recovery ratio increases with the number of elements in the pressure vessel due to increased membrane area. There was a sharp increase at lower number of elements and a slow increase at higher number of elements. This was due to the salt build up on the brine channel as flux increases. Therefore adding more elements after certain limit not worthy.

4.1.3 Feed salinity

The effect of feed salinity on the total recovery ratio is shown in Fig. 5a. Two alternative feeds with 2500 ppm and 5000 ppm salt have been studied. Feed with low salt concentration produced 40% higher recovery ratios compared to that produced by high feed (5000 ppm) salinity. This is a consequence of the much higher driving force for the same exerted pressure to the feed. This is due to the fact that the osmotic pressure is proportional to the feed salt concentration.

4.2 Feed spacer

Feed spacer channel can affect RO performance significantly, compared to that with slit feed channel. Even though the pressure drop is increased from 0.122 bar for empty channel to 1.23 bar, the mass transfer is enhanced by 80%. CF on membrane surface is reduced by about 27%, and the specific energy consumption is reduced by 10%.
4.2.1 Length of filament mesh in feed spacer
Fig. 5a,b show the recovery of fresh water and pressure drop when mesh length is varied for the two transverse filament thicknesses. It can be seen the recovery rate increases with the increase of mesh length until a turning point at mesh length 3 mm, after which the recovery rate remained relatively stable regardless of further increase of mesh length. Small mesh length has the advantage of more turbulent flow and consequently the polarization phenomenon is decreased. On the other hand smaller mesh length has the drawback of higher pressure drops along feed channel and therefore less water flux as in Fig. 5a.

Fig. 5 Effect of mesh length on water recovery and axial pressure drop at different feed salinity

4.2.2 Filament diameter to feed spacer spacing ratio
Fig. 6 presents the water recovery, average concentration polarization factors and axial pressure drops for filaments of different diameter to feed spacer ratio. Pressure drop is significantly affected (increase by 342 %) at filament ratio 0.6 while the concentration polarization is reduced by 8 % at filament ratio 0.6. In general, larger filaments slightly enhance mass transfer by reducing concentration polarization, but significantly increase hydraulic pressure losses and consequently more expenditure. Therefore, spacers design should be optimized specifically for the particular operating conditions of the real application.

Fig. 6 RO performance for different spacer diameters and filament spacing

4.3 Optimization (Minimum specific energy consumption)
The optimized values for operating parameters (case 1) and both operating and design parameters (case 2) (at fixed product demand 10.8 m³/h and permeate salt concentration less than 100 ppm) are shown in Table 2. A substantial saving of about 20 % which is equivalent to 1.7 kWh can be acquired by only optimizing operating parameters. Reduced feed flow and slightly increased operating pressure yields higher driving force in the brine channel. This result is concordant with sensitivity analysis presented earlier. Further reduction in specific energy can be achieved in case 2 by enlarged feed spacer
thickness and shorter filament length. This gives less pressure drop and consequently, more water flux.

### Table 2 Optimization results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optimized Value</th>
<th>Design value</th>
<th>Objective function E (kWh/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>Design conditions (Table 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Feed pressure (bar)</td>
<td>13.6</td>
<td>12.20</td>
<td>0.7304</td>
</tr>
<tr>
<td>Feed flow (m³/h)</td>
<td>14.6</td>
<td>20.43</td>
<td></td>
</tr>
<tr>
<td>Case 2</td>
<td></td>
<td></td>
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<tr>
<td>Feed pressure (bar)</td>
<td>13.10</td>
<td>12.20</td>
<td>0.5781</td>
</tr>
<tr>
<td>Feed flow (m³/h)</td>
<td>14.91</td>
<td>20.42</td>
<td></td>
</tr>
<tr>
<td>Spacer thickness (mm)</td>
<td>2.20</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>Mesh length (mm)</td>
<td>2.37</td>
<td>2.77</td>
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</tr>
</tbody>
</table>

#### 4.4 Energy recovery

Three different options were considered in this work: (a) No energy recovery, (b) Energy recovery by turbine and (c) Energy recovery using pressure exchanger (PX). The efficiencies for the feed pump, turbine and pressure exchanger were assumed to be 0.8, 0.8 and 0.97, respectively. Pressure exchanger was found to be the most profitable option as the pumping cost (reflected in the calculation of E, see Fig. 1) will reduced up to 50% compared with 20% when turbine was used as energy recovery choice.

### 5. Conclusion

In this work RO process model based on solution-diffusion model and thin film theory have been developed to investigate the effect of different operating and design parameters on the performance of the system. The model is verified against the operational data and a good agreement was found.

Optimization problem formulation is presented to minimize an objective function while optimizing design and operating parameters of the process. It is found that considerable reduction in pumping cost around 20% is achievable. Furthermore, commercial module designs might be further refined in order to reach more economic improvements for RO processes subject to technical limitations.

Comparison of the two energy recovery alternatives including turbine and pressure exchanger showed that energy recovery by pressure exchanger yields the best results by 50% reduction in the pumping cost.

### References


