A DYNAMIC SIMULATION MODEL OF REVERSE OSMOSIS DESALINATION SYSTEMS

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ABSTRACT

It is known that the water desalination industry was started early in the 20th century and true expansion and spread of this industry occurred during the 1960s. The multi-stage flash (MSF) unit and reverse osmosis (RO) process are the most popular desalination systems for the industry standard. In recent years, the market share of RO desalination has widely expanded because of significant improvements and advantages in membrane technology. To obtain the feasible operating conditions of the RO desalination system, an efficient and accurate process model used in the plant is necessary. This work tries to study the dynamic characteristics and process operation aspects of a large-scaled RO desalination plant. The steady-state and dynamic mathematical models for the membrane modules and RO plants presented in the literature are first studied. The feasible dynamic RO models are then utilized to develop the overall process flow sheets for the industrial scale RO desalination process by using powerful commercial process design simulators. Satisfactory results of the steady-state and dynamic operating conditions of the proposed RO process flow sheet are compared to those shown in the literature.

Keywords: Dynamic Simulation; Model; Design; Reverse Osmosis; Desalination System.

1. INTRODUCTION

The water desalination industry was started early in the 20th century. True expansion and spread of the water desalination industry occurred during the 1960s. There are several commercial methods such as multistage flash (MSF), multi effect distillation (MED), vapor compression (VC) distillation, reverse osmosis (RO), and electrodialysis (ED) proposed for water desalination. Table 1 illustrates the worldwide capacity for several commercial desalination process (Lee, 2009). It is apparent that multistage flash and reverse osmosis technologies remain the main standards in today’s seawater desalination industry. Alatiqi et al. [1999] presented a review for the control loops and instrumentation used in MSF and RO plants. Van der Bruggen and Vandecasteele [2002] provided an overview of important process improvements in seawater desalination using RO, MSF, MED and ED.

Recently, the market share of RO desalination has significantly increased because of low operating temperature, modular design, low energy requirements and low water production costs. The spiral wound module is most popular among RO membrane modules. Many mathematical models have been proposed to characterize the separative properties of membranes during the past two decades. But far fewer models have been developed to

As mentioned by Marriott and Sorensen [2003], due to the complex mechanism of flow through membrane module and lots of idealized assumptions, existing RO unit models are usually process specific and are only valid within a limited operating range. They developed a detailed mathematical model of a general membrane separation process from rigorous mass, momentum and energy balances and disregards some common assumptions. This work tries to study the dynamic characteristics and process operation aspects of an industrial large-scaled RO desalination plant. The feasible steady-state and dynamic models of the membrane modules and RO plants presented in the literature are effectively combined to develop the overall process flow sheets for the industrial scale RO desalination process by using powerful commercial process design simulators. Simulation results of the steady-state and dynamic operating conditions of the proposed RO process flow sheet are compared to those shown in the literature.

Table 1: Worldwide capacity for several commercial desalination process (Lee, 2009)

<table>
<thead>
<tr>
<th>Desalination process</th>
<th>% total world capacity (1996)</th>
<th>% total world capacity (2003)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSF</td>
<td>56</td>
<td>36.1</td>
</tr>
<tr>
<td>RO</td>
<td>31</td>
<td>51.6</td>
</tr>
<tr>
<td>MED</td>
<td>5</td>
<td>3.0</td>
</tr>
<tr>
<td>ED</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>VC</td>
<td>3</td>
<td>4.8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

2. RO DESALINATION SYSTEM DESCRIPTION

Reverse osmosis is a pressure-driven membrane process used to separate solute and solvent of the same order of molecular size. It is well known the most common application of RO unit is the separation of salt from water to obtain portable water. There are four types of membrane modules available in the marketplace: plate and frame, hollow-fiber, spiral-wound and tubular. Among these membrane modules, the spiral wound module occupies the largest market share due to its relative ease of cleaning, fabrication technology and very large surface area per unit volume. In general, the RO desalination system includes feed and
product treatment units, membrane modules, feed pumps and energy recovery device (ERD). Figure 1 shows a simplified sketch of the RO plant.

The Jeddah 1 RO desalination plant Phase II in the Kingdom of Saudi Arabia was commercially operated on 1994. Jeddah 1 RO plant has a production capacity of 30 MGPD (113,600 m$^3$/day). At that time, combining phase I and phase II plants gave the largest seawater RO plant in the world. By using actual operating data from this large scale commercial RO desalination plant, Al-Shayji [1998] first developed a neural-network approach for the prediction and optimization of process performance variables of this RO plant. Table 2 gives design specification for this industrial desalination process (Al-Shayji, 1998). This work tries to study the dynamic characteristics and process operation aspects of the mentioned large scale RO desalination plant. The feasible dynamic RO models are studied to develop the overall process flow sheets for the industrial scale RO desalination process by using powerful commercial process design simulators.

![Figure 1: Schematic diagram of the reverse osmosis process](image)

### Table 2: Design specification for an industrial RO Plant (Al-Shayji, 1998)

<table>
<thead>
<tr>
<th>Plant:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of trains</td>
<td>10 (trains k to T)</td>
</tr>
<tr>
<td>Capacity</td>
<td>1.5 MGPD x 10 trains (5,680 m$^3$/day each)</td>
</tr>
<tr>
<td>Permeate quality (Cl)</td>
<td>&lt; 625 mg/l</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operation condition:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater TDS</td>
<td>43,300 mg/l</td>
</tr>
<tr>
<td>Temperature</td>
<td>24-35 °C</td>
</tr>
<tr>
<td>Recovery ratio</td>
<td>35%</td>
</tr>
<tr>
<td>Max feed pressure</td>
<td>70.42kg/cm$^2$</td>
</tr>
<tr>
<td>Silt density index (SDI)*</td>
<td>&lt; 3.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>TOYOBO HOLLOSEP HM10255F</td>
</tr>
<tr>
<td>Number of modules</td>
<td>148 pieces x 10 trains</td>
</tr>
<tr>
<td>Membrane guarantee</td>
<td>5 years with 10% annual replacement</td>
</tr>
</tbody>
</table>

* Silt density index (SDI) is the rate of plugging of 0.45-micron filter when the water is passed through the filter at 30 psig.
3. MODELING OF A SPIRAL WOUND MODULE

In general, the following factors may directly affect the performance of RO desalination processes: (1) Effectiveness of the pre-treatment units. (2) Membrane: type, size and the number of modules used and their arrangement. (3) Rate and degree of fouling and cleaning ability. (4) Operating conditions such as feed pressure, temperature and permeate recovery. (5) Efficiency of pumps and energy recovery device. In this study, the effectiveness of the pre-treatment units is neglected and a binary system is considered. The spiral wound module with general property is used in the RO membrane module. To investigate the dynamic characteristics and process operation aspects of an industrial RO desalination plant, the steady-state and dynamic mathematical models for the membrane modules are developed below.

3.1 Model Assumptions

The main assumptions used for the RO model derivation include: (1) The solution-diffusion model is valid for the transport mechanism of the solute and solvent through the membrane. (2) The RO membrane module is non-porous and is treated as a flat sheet with spacers. (3) The RO process is isothermal. (4) Osmosis pressure is proportional to the salt concentration and pressure drop in permeate side is negligible. (5) The film model theory and Fick’s law for diffusion are applicable for calculating concentration polarization effect. (6) Diffusion coefficient is independent of solute concentration. (7) Mass transfer coefficient is constant for a given fluid condition.

3.2 Membrane Transport Modeling

Senthilmurugan et al. [2005] and Oh et al. [2009] have applied the solution-diffusion model modified with the concentration polarization theory for analyzing the operation, optimization and performance of RO systems. According to the schematic diagram of the RO process shown in Figure 1, the following steady-state membrane transport equations can be derived.

The solvent flux, $J_v$, through the membrane is given by

$$J_v = L_v (P_f - P_{loss}) = L_v [P_f - (\Delta \pi + P_d)]$$

where $L_v$ is the solvent transport parameter, $P_f$ is the feed pressure and $P_{loss}$ is the pressure loss by osmosis pressure $\Delta \pi$ and the pressure drop along a RO system $P_d$. Here, $L_v$, $\Delta \pi$ and $P_d$ are expressed by (Oh et al., 2009)

$$L_v = \frac{1}{\frac{1}{a_1(T-293)} - \frac{a_2}{293} P_f} + \eta R_c$$

$$\Delta \pi = (c_m - c_p)RT$$

$$P_d = \gamma_1 \left( \frac{v_s d_h}{v} \right)^{\gamma_2}$$
where $L_{v0}$ is the intrinsic solvent transport parameter, $T$ is the temperature, $\eta$ is the viscosity, $R_e$ is the resistance due to cake formation, $A_s$ is the membrane area occupied by precipitation, $A_m$ is the total membrane area, and $\alpha_1$ and $\alpha_2$ are two constants for solvent transport. $c_m$ and $c_p$ are solute concentration at the membrane surface on the feed side and solute concentration on the permeate side, respectively. $R$ is the ideal gas constant. $\gamma_1$ and $\gamma_2$ are two constants for pressure drop along a RO system. $v_z$, $d_h$ and $\nu$ denote the feed solution velocity on the bulk solution side, hydraulic diameter and kinematic viscosity, respectively.

The solute flux, $J_s$, through the membrane is given by

$$J_s = J_s c_p = L_s (c_m - c_p)$$

where $L_s$ is the solute transport parameter

$$L_s = L_{s0} e^{\frac{\beta_1 (T-273)}{273}}$$

where $L_{s0}$ is the intrinsic solute transport parameter and $\beta_1$ is constants for solute transport.

Accumulation of the impermeable solutes on the membrane surface leads to the development of a concentration polarization layer which may be determined by the concentration polarization. That is

$$\phi = \frac{c_m - c_p}{c_b - c_p} = e^{\frac{J_s}{k}}$$

where $c_b$ is the solute concentration in the bulk solution and $k$ is the mass transfer coefficient for the back diffusion of the solute

$$k = 0.5510 \left( \frac{v_z d_h}{v} \right)^{0.4} \left( \frac{v}{D} \right)^{0.17} \left( \frac{c_b}{\rho} \right)^{-0.77} \left( \frac{D}{d_h} \right)$$

where $\rho$ is the density and $D$ is the solute diffusion coefficient.

### 3.3 Feed and Permeate Channel Flow Modeling

Marriott and Sorensen [2003] have developed a two-dimention flow model to describe flow in the axial and spiral directions on both the feed and permeate sides. According to the schematic diagram of a flat membrane envelope shown in Figure 2, the following dynamic mass balance can be derived.

$$\frac{\partial c_b}{\partial t} = -\frac{\partial F_c}{\partial z} - \frac{1}{h} J_s = -\frac{\partial}{\partial z} \left( c_b v_z - D \frac{\partial c_b}{\partial z} \right) - \frac{1}{h} J_s$$

where $c_b$ is the solute molar flux in the axial direction and $h$ is the channel height on the feed side. In this work, the effect of the solute molar flux in the spiral direction is neglected for simplifying Eq. 9. On the other hand, the effect of the change in concentration due to the flux of solvent through the membrane is not considered in Eq. 9. As mentioned by Lee et al. [2001], Eq. 9 can be modified as
Furthermore, the overall material balances for the feed and the permeate sides proposed by Senthilmurugan et al. [2005] are given by

\[
\frac{\partial c_b}{\partial t} = -\frac{\partial F_y}{\partial z} - \frac{1}{h} J_y + \frac{1}{h} J_z c_b = -\frac{\partial}{\partial z} \left( c_b v_z - D \frac{\partial c_b}{\partial z} \right) - \frac{1}{h} J_y + \frac{1}{h} J_z c_b \tag{10}
\]

where \( v_z \) is the feed solution velocity on the permeate side and \( h_p \) is the channel height on the permeate side.

3.4 Simulation Results for a Spiral Wound Module

In this work, the relative mathematical models for the membrane modules depicted above are applied for RO process simulation. Most of the values of parameters and specifications are taken from the literature of Senthilmurugan et al. [2005] and Oh et al. [2009]. Some unknown parameters are found from the literature of Lee et al. [1999] and Abbas [2007].

Here, the RO system simulation model is built on Aspen Custom Modeler platform. The model is then used for analyzing the effect of the variation of the feed parameters on the permeate flowrate. As shown in Figure 3, the permeate flowrate is seen to decrease with increasing feed concentration. In Figure 4, the permeate flowrate is seen to increase with increasing feed pressure. The above simulation results are consistent with those reported by Senthilmurugan et al. [2005].
4. DYNAMIC SIMULATION MODEL OF AN INDUSTRIAL RO PLANT

This work tries to study the dynamic characteristics and process operation aspects of a large-scaled RO desalination plant. Jeddah 1 RO plant commercially operated in Saudi Arabia is taken as a demonstration example. The feasible dynamic RO models are studied to build the overall process flow sheets for the industrial scale RO on Aspen Custom Modeler platform. Satisfactory results of the steady-state and dynamic operating conditions of the industrial RO desalination system are compared to those shown in the literature.

4.1 Process Flowsheet of an Industrial RO Plant

In general, the RO desalination system includes feed and product treatment units, membrane modules, feed pumps and energy recovery device (ERD). The Jeddah 1 RO desalination plant Phase II in the Kingdom of Saudi Arabia was commercially operated on 1994. This Jeddah 1 Phase II plant has a production capacity of 15 MGD (56,800 m³/day) with 10 trains. That is, the production capacity is about 5,680 m³/day for each train. By using design specification of this industrial desalination process given in Table 2 (Al-Shayji, 1998), the overall RO process flow sheet of this industrial RO plant is built on Aspen Custom Modeler platform. Figure 5 illustrates the proposed RO process flow sheet.
Figure 5: Proposed process flowsheet for RO desalination system

4.2 Simulation Results for an Industrial RO Plant

According to the overall RO process flow sheet built on Aspen Custom Modeler platform, Table 3 shows part of the simulation results. In this case, the obtained production capacity is about 2,670 m$^3$/day for each train. The corresponding recovery ratio is about 16.5%. These results are about half of those given in Table 2. In this direction, the 148 RO pieces for each train ought to be rearranged for the proposed RO flow sheet. The effect of the variation of the feed flowrate and feed pressure on the recovery ratio is shown in Figure 6.

Table 3: Simulation results for the industrial RO Plant

<table>
<thead>
<tr>
<th></th>
<th>Input</th>
<th>Brine output</th>
<th>Permeate output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate (m$^3$/hr)</td>
<td>676.2</td>
<td>565.41</td>
<td>111.15</td>
</tr>
<tr>
<td>Concentration (mole/m$^3$)</td>
<td>746.5</td>
<td>1068.72</td>
<td>1.62</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>80</td>
<td>80</td>
<td>1.01</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

Figure 6: Recovery ratio vs. feed flowrate for the proposed RO flow sheet
5. CONCLUSIONS

In recent years, the market share of RO desalination has widely expanded because of significant improvements and advantages in membrane technology. To obtain the feasible operating conditions of the RO desalination system, an efficient and accurate process model used in the plant is necessary. This work tries to study the dynamic characteristics and process operation aspects of a large-scaled RO desalination plant. The feasible steady-state and dynamic models for the membrane modules and RO plants presented in the literature are utilized to develop the overall process flow sheets for the industrial scale RO desalination process. The overall RO process flow sheet of the industrial RO plant is successfully built on Aspen Custom Modeler platform. Simulation results of the steady-state and dynamic operating conditions demonstrate the satisfactory effectiveness of the proposed RO process flow sheet.

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REFERENCES

Brief Biography of the Presenter

Chen-Jen Lee received B.S. degree in Chemical Engineering from Chang Gung University, Tao-Yuan, Taiwan, in 2009. He is currently pursuing the Ph.D. degree at the Department of Chemical and Materials Engineering, Chang Gung University. His main research interests include seawater desalination process simulation, process modeling and control.