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Modeling of full-scale reverse osmosis desalination system: Influence of operational parameters

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ABSTRACT

Reverse osmosis (RO) has proven to be an efficient technique for desalination of seawater, brackish water, and reclaimed wastewater. However, the performance of RO desalination is sensitive to its design parameters and operating conditions. In this study, a design method based on a simulation technique has been developed for optimizing two pass RO desalination systems. A dynamic model based on RO membrane transport incorporating concentration polarization and mass balance equations was developed and used to estimate the performance of RO system. Various objective functions were considered, including maximization of permeate throughput (overall recovery), minimization of energy consumption, and minimization of boron concentration in permeate. The simulation was carried out under a wide range of operation conditions. Results concerning the performance and economics of the process were also presented.

1. Introduction

Reverse osmosis (RO) processes have been gaining popularity as a major desalination technology over the last few years [1,2]. RO is a water purification technology that uses a semipermeable membrane [3]. It allows the removal of ions, proteins, and organic chemicals which are generally very difficult to remove using other conventional treatments. RO has many advantages including small footprint, modular design, possibility of automatic process control, and relatively low cost for water production [4]. As seawater desalination and wastewater reclamation have become important in the regions suffering water scarcity, RO has been has been widely applied in various water and wastewater treatment processes [5–8].

However, there are several issues for RO desalination, including energy requirement, membrane fouling, and product water quality [1,3]. RO require hydraulic pressure to overcome the osmotic pressure of the feed solution, leading to high energy requirement to pressurize the feed flow. In fact, energy requirements for RO desalination have declined dramatically over the past 40 years due to a variety of technological advances [8]. Nevertheless, the energy requirement is still substantial for RO desalination, which may raise several concerns, including sensitivity to energy price variability and increased greenhouse gas emissions [7]. Typically in a RO plant, 3–10 kWh of electric energy is required to produce one cubic meter of freshwater from seawater [4]. Disposal of RO brine, along with the energy consumption, is also a debating issue due to its potential of adverse impact on marine environment [9].

Another major issue for RO system is membrane fouling, which is caused by an accumulation of foulants in the feed solution on the surface of the membranes [10,11]. This is particularly problematic in the use of RO for the wastewater reuse, where the feed water contains a large amount of foulants. Membrane fouling is a complex phenomenon involving the deposition of several types of foulants on the membrane surface. If it occurs, the permeability of the RO membrane decreases, thereby affecting the energy requirement [12]. Membrane fouling can be alleviated by the use of an appropriate pretreatment, which also requires energy.

Seawater desalination using RO membrane is challenged by new types of contaminants, such as boron (B). Boron is naturally occurring and is present in seawater at an average concentration of 4.6 milligrams per liter (mg/L). Current World Health Organization (WHO) Guidelines for Drinking Water Quality propose a maximum recommended boron concentration of 0.5 mg/L [4]. Unfortunately,

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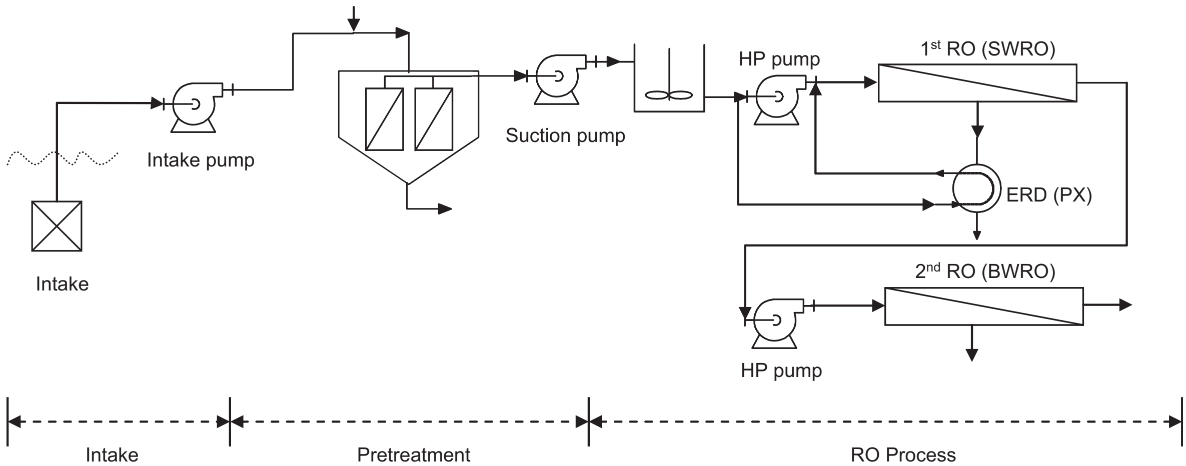

Fig. 1. Schematics of RO desalination system.

it is generally difficult for RO processes to achieve an average boron rejection over 90 percent (%) [13], which is typically required to produce permeate that meets the provisional WHO boron guidelines. Improved rejection can be achieved by adding treatment stages or polishing steps, which could increase costs substantially.

Accordingly, there have been a lot of works to overcome the limitations of RO desalination. Novel RO membranes, which have high permeability to water and low permeability to salt, have been developed [14,15]. The hydrodynamics of feed flow inside the RO membrane module have been investigated to reduce energy consumption and fouling [16]. Various techniques for pretreatment and posttreatment have been considered [1,17,18] together with the analysis of feed water characteristics [19].

Since the success of an RO system largely depends on the system design and operation condition, the availability of reliable RO models is essential for efficient design and operation [20]. Although the membrane makers have developed computer models to help possible customers to design an RO plant, they mainly focus on the performance analysis of some RO modules rather than the optimization of RO process in terms of energy consumption and product water quality. A few works have been focused on the development of new RO models for the optimization of membrane module and desalination plant [4,21–25]. Nevertheless, the effect of various design and operating conditions on RO desalination performance has not been extensively studied using these models.

The main objective of this paper is to develop a mathematical model that simulates RO efficiency in full-scale seawater RO desalination plant to take into account for the effect of operating conditions. The effect of operating conditions such as recovery ratio, salinity, and temperature was quantitatively analyzed using the mechanistic predictive model. Moreover, the RO desalination system was optimized in terms of energy requirement and boron rejection.

2. Model development

We have applied the solution–diffusion equations modified with the thin-film model to predict RO performance and optimize energy requirement as well as permeate quality. Since details on this model are shown in our previous paper [26], only a brief

Table 1
Summary of model equations.

Meaning	Equation	Ref.
Solvent transport	$J = L_v(P_f - P_{loss})$	[28–30]
Solvent transport parameter	$L_v = L_{v,0}e^{1965((1/298)-(1/t))}$	[22,31]
Pressure loss	$P_{loss} = \sum_i^n \Delta\prod_i + P_d$	[28]
Osmotic pressure	$\Delta\prod_i = (c_{m,i} - c_{p,i})RT$	[22,28]
Pressure drop in an element	$P_d = \gamma_1\left(\frac{ud_h}{\nu}\right)^{\gamma_2}$	[22]
Solute transport	$J_{s,i} = Jc_{p,i} = L_{s,i}(\bar{c}_{m,i} - c_{p,i})$	[28,29,32]
Solute transport parameter	$L_{s,i} = L_{s,i,0}e^{\beta_1(T-298)}$	[22]
Concentration polarization	$\frac{c_{m,i}-c_{p,i}}{c_{b,i}-c_{p,i}} = e^{(J/k_i)}$	[29,32,33]
Mass transfer coefficient	$k_i = 0.5510\left(\frac{ud_h}{\nu}\right)^{0.4}\left(\frac{\nu}{D_i}\right)^{0.17}\left(\frac{c_{b,i}}{\rho}\right)^{-0.77}$	[22]
Viscosity	$\eta = 2.414 \times 10^{-5} \times 10^{(247.8/(T-140))}$	[34]
Recovery ratio	$Rec = \frac{Q_p}{Q_f}$	-
Specific energy	$E = \frac{P_f Q_f(\varepsilon_{pump})^{-1} - P_b Q_b \varepsilon_{ERD}}{Q_p}$	-
Boron transport	$L_{s,B,0} = a_0 L_{s,H_3BO_3,0} + a_1 L_{s,H_3BO_3^-}$	[4,35]
Dissociation constant for boric acid	$K_a = \frac{2291.9}{T} + 0.01756 - 3.385 - 3.904S^{1/3}$	[4,35]
Dissociation ratio	$a_0 = \frac{[H^+]}{[H^+] + K_a}$ $a_1 = 1 - a_0$	[4,35]