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Mass-transfer modeling of reverse-osmosis performance on 0.5–2% salty water

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ABSTRACT

This work investigates the desalination efficiency from 0.5 to 2% salty water using the RO process and establishes mass-transfer models for water and salt transports. The water flux, salt passage rate, salt rejection and water recovery were studied under various operating conditions to validate the model adequacy. Salt permeability in the three-layer composite was lower than that predicted on polyamide–polysulfone top-intermediate layer using permeation cells, possibly due to the membrane compaction at a high pressure and/or additional mass-transfer resistance from the non-woven support. The permeate flux was 1.83–3.67 × $10^{-5}\,m^3\,m^{-2}\,s^{-1}$ for 0.5–2% NaCl feed solution, significantly higher than literature data. The salt concentration was reduced to 350–700 ppm from 1 to 2% NaCl solutions, rendering salt rejections of 91.0 to 98.4% under the tested operating conditions. The membrane intrinsic retention was 96.1 to 99.8% considering the increased solute concentration adjacent to the membrane surface resulting from concentration polarization phenomena. The salt flux did not show a particular trend with respect to the permeate flux resulting from various applied pressures, indicating a negligible flux coupling effect between the water and salt molecules. The salt transported mainly through solution-diffusion mechanism and water flow followed a pressure-driven process.

1. Introduction

In the last few decades, water has become in short supply in many regions all over the world. This may be attributed to population growth and increased industrial activities. Seawater desalination and reclaimed wastewater have been considered the most promising techniques for supplying fresh water in regions suffering from water scarcity [1,2]. In recent years, desalination technology has received significant attention, including the use of multi-stage flash, multi-effect distillation, electrodialysis, and reverse osmosis (RO) processes [3]. Desalination based on RO membrane technology has become a viable and dominant option for the development of new regional water supplies.

RO membrane technology has been used for brackish and wastewater treatments. RO membranes for brackish water applications typically have higher product water (permeate) flux, lower salt rejection and require lower operating pressures (due to the lower osmotic pressures of less saline waters). Conversely, RO membranes for seawater desalination require maximum salt rejection. The RO membrane performance index—including permeate flux and salt rejection—is determined mainly by the transport properties of the dense top layer of the composite membranes. Performance is also highly dependent on the membrane fouling/plugging, solution chemistry and operating conditions. Many researchers reported RO efficiency in sea water desalination processes [4,5]. Zhou and Song indicated that salt transport was highly dependent on both operating pressure and feed salt concentration [6]. Rao et al. reported that with increasing operating pressure, values of both flux and salt rejection also increase simultaneously [7]. RO systems for desalination were theoretically investigated using a simple model based on the solution-diffusion theory [8]. Recently, a few works have focused on the development of new RO models for membrane module and desalination plant process optimization [9–11]. This work investigates the desalination efficiency from 0.5 to 2% salty water using the RO process and establishes mass-transfer models for water and salt transports. Various quality parameters were measured in the RO permeates, such as water recovery, permeate flux, and salt rejection coefficient, as functions of salt concentration in feed, operating pressure and temperature. The water and salt permeability coefficients were determined and compared with results from the literature.

2. Theory

The RO process uses membranes and high pressure to separate ionic species from aqueous solutions. The objective is to achieve high water flux through the membrane and low salt concentration in the permeate. The water flux through the membrane depends on the membrane characteristics and operating conditions. The water flux can be represented using the following equation:

$$J_w = \frac{Q_P}{a} = A(\Delta p - \Delta \pi) \tag{1}$$

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where J_w is the water flux, Q_p is the product water (permeate) flow rate, a is the membrane area, A is the water permeability coefficient, Δp is the operation pressure, $\Delta\pi$ is the osmotic pressure difference between feed and permeate solutions. In this study, J_w was expressed in $m^3\,m^{-2}\,s^{-1}$ in most cases but was converted to $L\,m^{-2}\,h^{-1}$ for direct comparison with literature data.

The water permeability coefficient (A) is constant for a given membrane and salt concentration, and contains the following parameters [3]:

$$A = \frac{D_w^M N_w^M V_w}{RTL} \tag{2}$$

where D_w^M is the diffusion coefficient of water inside the membrane, N_w^M is the water solubility inside the membrane, V_w is the molar volume of water, R is the gas constant, T is the temperature and L is the thickness of the separation layer.

The osmotic pressure ($\Delta\pi$) is calculated using the following equation:

$$\Delta\pi = \beta RT\Delta C_s = \beta RT(C_f - C_p) \tag{3}$$

where β is the number of dissociated ions from the dissolved solute (salt), ΔC_s is the salt concentration difference between upstream and downstream of the membrane, C_f and C_p are the salt concentrations in the feed stream and in the permeate, respectively. The salt passage rate through the membrane can be described using the solution-diffusion model:

$$J_s = J_w C_p = \frac{D_s^M K_s \Delta C_s}{L} = \frac{D_s^M K_s (C_f - C_p)}{L} = B\Delta C_s = Br_j C_f \tag{4}$$

where, J_s is the salt flux through the membrane, D_s^M is the salt diffusion coefficient inside the membrane, K_s is the partition coefficient of salt between the membrane and the solution, B is the salt permeability coefficient and equivalent to $D_s^M K_s / L$, r_j is salt rejection coefficient shown in Eq. (5).

The separation efficiency of an RO membrane for a given solute is expressed by the rejection coefficient (r_j):

$$r_j = 1 - \frac{C_p}{C_f} = \frac{C_f - C_p}{C_f} = \frac{\Delta C_s}{C_f}. \tag{5}$$

Combining Eqs. (1), (4) and (5), the rejection coefficient can be written as:

$$r_j = \frac{A(\Delta p - \Delta\pi)}{A(\Delta p - \Delta\pi) + B}. \tag{6}$$

The recovery (Y) is defined as the fraction of the feed flow which passes through the membrane:

$$Y = \frac{Q_p}{Q_f} = \frac{Aa(\Delta p - \Delta\pi)}{Q_f} \tag{7}$$

where Q_f is the feed flow rate and Q_p is the permeate flow rate.

3. Experimental

3.1. RO process

The RO system used in this study consisted of a pump (2SF35SEEL, Cat Pumps, Minneapolis, MN, USA), controlled by a frequency converter. The feed water temperature was controlled using a heat exchanger upstream of the membrane module. The studied RO membrane (AG1812C, GE Osmosis, Trevose, PA, USA) had a $0.20\,m^2$ effective area in a spiral-wound configuration. This composite membrane had a three-layer structure: polyamide (PA) top layer, intermediate layer of polysulfone (PSf), and non-woven support. NaCl solutions (2 L each) were fed into the RO module in a recycle mode. The feed contained 0.5–2% NaCl was prepared by mixing NaCl (Sigma-Aldrich, St. Louis, MO, USA) in purified water (produced with a Milli-Q Gradient system, Millipore Corp., Bedford, MA, USA). The feed flow rate was set at $2.08 \pm 0.083 \times 10^{-4}\,m^3\,s^{-1}$ into the RO system. The experimental set-up is shown in Fig. 1. The conductivity for 0.5–2% NaCl solution was about 8–32 $mS\,cm^{-1}$. The salt concentrations in the RO permeate were too low to be precisely measured with the conductivity meter and were determined using an ion analyzer (IA-300, DKK-TOA Corp., Tokyo, Japan). The operating variables and their ranges in this study are shown in Table 1. The permeate flux, salt flux, salt rejection coefficient, and permeate recovery were calculated using the first terms in Eqs. (1), (4), (5), and (7), respectively. Based on six replicate runs, the standard deviation of permeate flux, salt rejection coefficient, and permeate recovery were $1.03 \times 10^{-6}\,m^3\,m^{-2}\,s^{-1}$, 0.71%, and 0.18%, respectively.

3.2. NaCl permeability in PA-PSf layer

The PA-PSf layer was peeled off from the non-woven support and tested for NaCl permeability using two stirred double-jacked glass reservoirs (capacity of $1.15 \times 10^{-4}\,m^3$ each), separated by this material [12]. The effective membrane area was $1.13 \times 10^{-3}\,m^2$. One reservoir was filled with 1.5% NaCl (referred as the donor reservoir) and the other with de-ionized water (referred as the receiving reservoir). The permeation temperature was maintained at 25–26 °C throughout the experiments.

According to Fick's law, Eq. (8) holds true for this diffusion process:

$$J_s' = D_s' K_s' (C_A - C_B) / L' = P_s' (C_A - C_B) / L' \tag{8}$$

where J_s' is the NaCl flux across the PA-PSf layer, D_s' is the salt diffusion coefficient in the PA-PSf layer, K_s' is the NaCl solubility coefficient, P_s' is the salt permeability coefficient, C_A and C_B represent the NaCl concentrations in the donor and receiving reservoirs, respectively, and L' is the PA-PSf layer thickness. When the diffusion process is in the initial stage, C_B is negligible compared with C_A and (C_A–C_B) approaches C_A. Therefore the salt permeability (P_s') in the PA-PSf layer becomes:

$$P_s' = J_s' L' / C_A = C_B V L' / (a' t C_A) \tag{9}$$

where V is the solution volume in the reservoir, a' is the effective membrane area in the permeation cell, and t is the time elapsed. The permeability coefficient can be obtained as a slope by plotting $C_B V L' / (a' C_A)$ versus t.

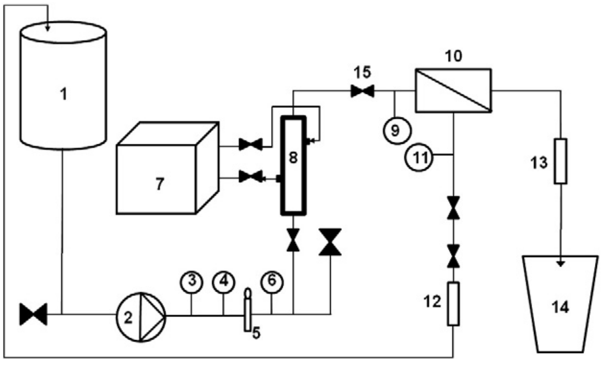

Fig. 1. Schematic diagram of RO experimental set-up (1: feed tank; 2: pump; 3, 9, and 11: pressure gauges; 4: pressure transducer; 5: safety valve; 6: thermometer; 7: water bath: 8: heat exchanger; 10: spiral-wound RO membrane module; 12 and 13: flow meters; 14: permeate tank; 15: ball valve).