Mass Transfer in Rotating Reverse Osmosis Based on Couette-Taylor Flow

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ABSTRACT

Reverse Osmosis (RO) is an efficient process for the removal of ionic and organic pollutants from wastewater. However, flux decline and rejection deterioration due to concentration polarization and membrane fouling hinders the application of RO technology. Rotating RO takes advantage of high shear and the Taylor vortex instability to reduce the flux decline related to concentration polarization and membrane fouling. This process was investigated as a novel method for wastewater recovery. The mass transfer coefficient in rotating RO was experimentally determined based on film theory. A model developed for rotating RO allowed the prediction of flux and pollutant rejection over a wide range of design and operational parameters. The model matches the experimental results from a lab-scale rotating RO system very well. According to the model, rotating RO shows better flux and rejection than a non-rotating system by effectively reducing concentration polarization.

INTRODUCTION

Reverse Osmosis (RO) is a promising technology for water treatment and wastewater recovery. RO removes ions and organic chemicals in a stable and predictable manner, and it has been shown to have the potential for producing clear water from recycled wastewater in various applications. However, concentration polarization and membrane fouling are significant obstacles that limit the acceptance of RO membrane treatment.

Recently, we have examined rotating filtration as a new method to minimize concentration polarization and membrane fouling in reverse osmosis by taking advantage of the Taylor instability [1]. The system consists of a cylindrical reverse osmosis filter rotating within a concentric cylindrical shell. The Taylor instability results in counter-rotating vortices stacked in the annulus upon exceeding the critical Reynolds number, $Re_c = r_i \omega d / v$, where r_i is the inner cylinder radius, ω is the rotational speed, d is the gap between the inner and outer cylinders, and v is the kinematic viscosity. These vortices cause a redistribution of the azimuthal momentum in the annulus resulting in a steep velocity gradient at the RO membrane mounted on the inner cylinder [2].

Several studies have been performed to obtain mass transfer correlations in vortical flow devices for a suspension in a rotating cylindrical filter device and for a solute in a cylindrical chemical reactor with a non-porous inner cylinder. However, no measurements have been made for rotating RO membrane filtration systems where solute concentration polarization at a porous inner cylinder is of primary importance. In this study, we measured the mass transfer coefficient in a rotating RO system to determine its dependence on the Reynolds number. The measured mass transfer coefficient was then used in analytical models of rotating RO to predict filtration performance.

THEORY

To evaluate the mass transfer coefficient of a rotating RO membrane system, we used film theory and Fick's law for diffusion. The mass transfer coefficient in rotating RO can be shown to be [3]:

$$k_i = \frac{J_v}{\ln\left(\frac{1}{RT}\left(\Delta P - \frac{J_v}{L_v}\right) \Big/ \left(C_{b,i} - C_{p,i}\right)\right)} \qquad (1)$$

where k_i is the mass transfer coefficient for the back diffusion of solute i from the membrane to the bulk solution on high pressure side of membrane, J_v is the solvent flux through the inner cylinder membrane, R is the gas constant, T is temperature, ΔP is the pressure difference from the device inlet to the permeate side of the membrane, L_v is the solvent transport parameter, $C_{b,i}$ is the solute concentration in the bulk solution, and $C_{p,i}$ is the solute concentration on the permeate side of the membrane. Using this equation, the mass transfer coefficient was found based on a relatively simple experiment where the permeate flux, applied pressure difference, bulk solute concentration, and permeate concentration were measured.

The experimentally measured mass transfer coefficient was used to predict flux and rejection in rotating RO using the solution-diffusion model modified with the concentration polarization theory. The model permits the prediction of rotating RO performance over a wide range of conditions. Details are provided separately [1, 4].

MATERIAL AND METHODS

The rotating RO module consisted of a RO membrane rotating within an outer cylindrical housing. A commercially available thin film polymeric RO membrane (Hydranautics, USA) having a water permeability of 1.6×10^{-11} m^2-sec/kg (measured using pure water) was bonded to a porous plastic cylinder mounted on an aluminum support cylinder on a hollow steel shaft. The filter outer radius was $r_i = 2.41$ cm, the gap width was $d = 0.47$ cm, the length of the filter surface was 12.70 cm, and the overall length of the filter chamber was 23.2 cm. A DC motor permitted rotation of the inner cylindrical RO membrane at rotational speeds from 1 to 180 rpm. Details for experimental procedures are provided separately [3].

To determine the mass transfer coefficient in rotating RO, two different feed solutions were used: 4000 mg/L of NaCl and 4000 mg/L of Na$_2$SO$_4$. All other experiments were performed using a synthetic wastewater that models space mission wastewater, which typically contains wash water, condensate, and urine. In addition to 3429 mg/L of ammonium ions from urine, the wastewater contains 190.6 mg/L of NASA body soap and 1000 mg/L of NaCl [5]. The concentrations of detergent and ions were determined using standard measurement techniques [6]. These concentrations were used to calculate the rejection for each solute, $R_i(t) = 1 - C_{p,i}(t)/C_{b,i}(t)$, where $C_{p,i}(t)$ is the concentration in the permeate, and $C_{b,i}(t)$ is the average concentration in the bulk solution. The solute permeability parameters of the membrane used in this study for NaCl, (NH$_4$)$_2$CO$_3$, and the detergent were 1.3×10^{-6} m/sec, 7×10^{-7} m/sec, and 1.4×10^{-7} m/sec, respectively.

RESULTS AND DISCUSSION

Mass Transfer in Rotating RO

The experimental and theoretical results in the literature for measurements of the mass transfer coefficient for cylindrical rotating filtration of suspensions in a cylindrical porous rotating cell or the transport of a chemical species in a cylindrical chemical reactor with a nonporous inner cylinder satisfy the relation:

$$\text{Sh} = A \, [\text{Re} \, (d/r_i)^{1/2}]^a \, \text{Sc}^{1/3} \qquad (2)$$

where $\text{Sh} = 2kd/D$ is the dimensionless mass transfer rate (Sherwood number), $\text{Sc} = \nu/D$ is the Schmidt number, and D is the diffusion coefficient of the solute [7, 8]. In this study, 40 experimental trials, each done in triplicate, were conducted for various transmembrane pressures and rotational speeds. The mass transfer coefficients were calculated using Eqn (1). Figure 1 shows the dependence of the experimentally measured mass transfer coefficient, represented as Sh/Sc$^{1/3}$, on the Reynolds number. The Sherwood number increases with Reynolds number as the rotational shear increases. In addition, the Sherwood number jumps to a higher value at the transition from non-vortical to vortical flow as the vortices redistribute azimuthal momentum leading to a higher shear and convective mass transfer. The thick solid lines through the data indicate the least squares fit for each flow regime corresponding to A = 2.15 and a = 0.18 for non-vortical flow and A = 1.05 and a = 0.51 for vortical flow.
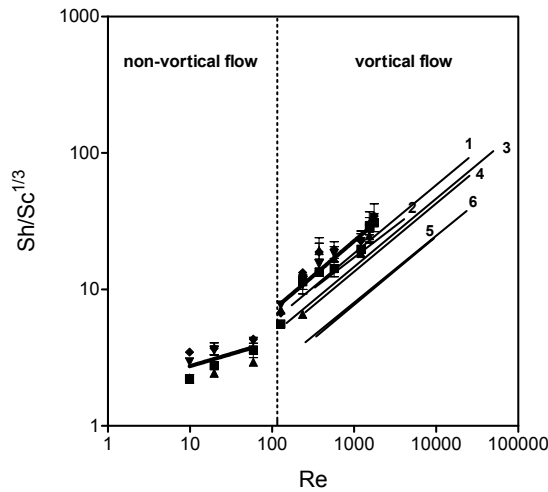
Figure 1.Mass transfer correlations in rotating RO. Filled symbols indicate the experimental data. Error bars are smaller than the symbol size except in cases where error bars are shown. Bold lines indicate a least squares fit. (■: NaCl, 6 atm; ▲: NaCl, 8 atm; ▼: NaCl, 10 atm; ◆: Na_2SO_4, 10 atm). 1. [7] 2. [8] 3. [9] 4. [10] 5. [11] 6. [12]

Figure 1 also compares our results with previous studies for rotating filtration and rotating chemical reactors (but not for rotating RO) using various methods to determine the mass transfer coefficient including electrochemical methods for non-porous inner cylinders [9, 11, 12], an ultrafiltration system [7], a helical-tube analogy [10], and a theoretical model based on the boundary layer theory [8]. The Sherwood numbers measured for rotating RO are slightly higher than those previously reported for other rotating systems, although the trend is consistent with previous measurements.

Comparison of Rotating RO with Non-Rotating RO

Using the synthetic wastewater, we compared rotating RO with non-rotating RO in terms of permeate flux and solute concentration. The transmembrane pressure was $\Delta P = 1000$ kPa, the concentrate flow rate was $Q_{conc} = 0.2$ mL/min, and the rotational speed was $\omega = 90$ rpm. The resulting flux is shown in Figure 2. This rotational speed corresponds to a Reynolds number of Re = 1032, well above the critical Reynolds number for the appearance of vortical flow (Re/Re$_c$=9.75). In this case, the model matches the experiments quite well. The initial permeate flux is nearly twice that for non-rotating RO, which is shown as a dashed curve. The flux decreases with time. But even after 180 minutes, the flux is still 74 % higher than that for no rotation. The permeate flow rate after 180 minutes is $\overline{J_v} A_m = 2.6$ mL/min while the concentrate flow rate is only $Q_{conc} = 0.2$ mL/min. Thus, at this point, 93% of the initially contaminated fluid is recovered as purified permeate.

Using our theoretical model, we can compare the solute concentrations in the bulk fluid ($C_{b,i}$) with that at the membrane surface ($C_{m,i}$) to determine the extent of concentration polarization for non-rotating RO and rotating RO. Figure 3 shows $C_{b,i}/C_{f,i}$ and $C_{m,i}/C_{f,i}$ for NaCl, $(NH_4)_2CO_3$, and detergent halfway along the length of the device as a function of time, where $C_{f,i}$ is the feed concentration. Although the data is not shown here, $C_{m,i}/C_{f,i}$ increases very rapidly as solutes build up at the membrane just after t=0 for non-rotating RO. The solute concentrations at the membrane surface remain 1.5-2.1 times higher than those in the bulk solution. However, with rotation the difference between $C_{b,i}/C_{f,i}$ and $C_{m,i}/C_{f,i}$ is negligible, as shown in Figure 3, indicating a uniformly high concentration across the entire annular gap rather than a strong concentration polarization layer at the membrane. This can be attributed to the enhanced mass transfer in the rotating RO system. The consequence is high flux and rejection.

CONCLUSIONS

Mass transfer and concentration polarization in rotating RO were experimentally investigated based on film theory. The mass transfer increases with increasing rotational speed, exhibiting a large

positive jump at the transition from non-vortical to vortical flow, suggesting that a rotational speed sufficient to generate vortical flow in the annulus is essential to minimize concentration polarization. When treating space mission wastewater, rotating RO shows higher flux and rejection than non-rotating RO due to the decreased concentration polarization with rotating RO. The theoretical model based on mass conservation and the solution-diffusion model with concentration polarization predicts the flux and rejection very well.
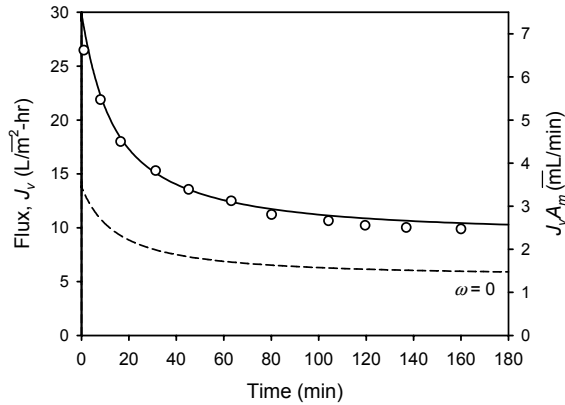
Figure 2. Time dependence of permeate flux. Condition: ΔP= 1000 kPa; Q_{conc}= 0.2 mL/min; ω = 90 rpm (Re/Re$_c$=9.75). ($\bigcirc$: Experimental permeate flux and flow rate; ——: Model). The dashed line indicates the model flux for no rotation.

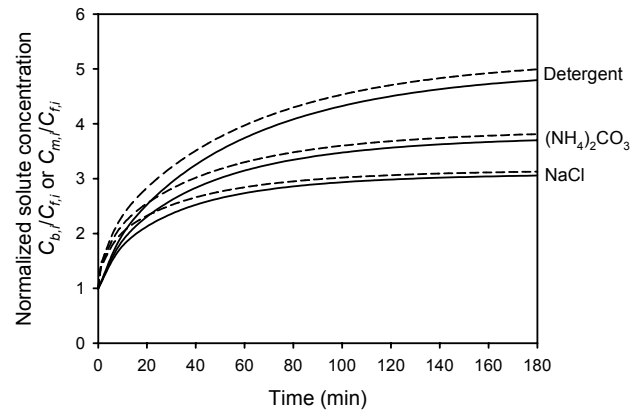
Figure 3. Dependence of C_b and C_m on time at halfway along the length of the device for ΔP= 1000 kPa, Q_{conc}= 0.2 mL/min, and ω= 90 rpm (Re/Re$_c$=9.75). ——: $C_{b,i}/C_{f,i}$ ----: $C_{m,i}/C_{f,i}$

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