

## Rotating Reverse Osmosis System Based on Taylor-Couette Flow

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### Abstract

Reverse Osmosis (RO) is a compact 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. Among various anti-fouling techniques, rotating filtration, which takes advantage of Taylor-Couette flow instabilities, has potential to the control of flux decline related to concentration polarization and membrane fouling. In this work, a rotating RO system was investigated as a novel method to reduce polarization and fouling in water purification. A dynamic model based on RO membrane transport incorporating concentration polarization is used to predict the performance of a rotating RO system. Operating parameters such as rotational speed and transmembrane pressure play an important role in determining the flux and rejection in rotating RO. For a given geometry, a rotational speed sufficient to generate Taylor vortices in the annulus is essential to maintain high flux as well as high rejection.

### Introduction

Recently, reverse osmosis (RO) filtration has been considered a promising technology for wastewater recycling. RO filtration removes ions and organic chemicals, and its treatment efficiency and performance are stable and predictable. RO filtration has been shown to be adequate for producing clear water from recycled wastewater in various applications [1]. However, a problem that needs to be resolved in the application of RO membranes for wastewater recycling is the sensitivity to fouling, which results in a decrease in filtrate flux. Concentration polarization and subsequent membrane fouling are the most serious obstacles that limit the acceptance of RO membrane treatment. In many cases, the potential for membrane fouling is high, since the wastewater contains large amounts of inorganic and organic solutes, pathogenic microorganisms, and debris. Therefore, techniques to reduce membrane fouling are of great significance

Rotating filtration takes advantage of centrifugal flow instabilities to reduce concentration polarization and membrane fouling. The system consists of a cylindrical filter rotating within a stationary cylindrical shell. Toroidal Taylor vortices are induced by the rotation of the inner cylinder as a result of a centrifugal flow instability. The unique advantage of a rotating membrane filtration is that the build-up of particles and other species near the filter surface is very slow compared to dead-end or crossflow filtration [2]. However, relatively little work has been done to further the application of rotating membrane filtration. Moreover, the use of a rotating system for reverse osmosis has not been investigated yet.

In this work, the implementation of rotating RO filtration for wastewater recovery is theoretically studied using combined transport models to help the design and development of the membrane module. Taking into consideration the complex time-dependent behaviors of filtration, the performance of rotating RO filtration is predicted as a function of recovery, rotational speed, and transmembrane pressure.

### Modeling approach

The solution-diffusion model modified with the concentration polarization theory was applied to predict rotating membrane performance over a wide range of conditions. Figure 1 illustrates the flow and geometry in a rotating RO membrane system. Feed solution enters the bottom of the annulus between the coaxial cylinders and travels axially in the annulus. The filtrate passes through the porous inner cylinder and exits at the bottom of the device. Finally, the concentrate exits at the top of the annulus.

The effect of the concentration boundary layer is determined by the radial mass transfer coefficient, which in turn depends on the axial and rotational motion of the fluid. For axial flow, the mass transfer coefficient depends on the axial Reynolds number  $Re_a = 2ud/\mathbf{n}$ , where  $u$  is the axial flow velocity,  $d = r_o - r_i$  is the gap width,  $r_o$  is the outer cylinder radius,  $r_i$  is the inner cylinder radius, and  $\mathbf{n}$  is the kinematic viscosity. For rotational shear flow, the mass transfer coefficient depends on the Taylor number (also known as the rotational Reynolds number),

$Ta = r_i w d / \nu$ , where  $w$  is the rotational speed. The mass transfer coefficients for the stable Couette-Poiseuille flow and vortical Taylor-Couette flow used here are based on Ref. 3 and 4. From a mass balance of solute, the time rate of change in concentration in an annular fluid element can be calculated for a given geometry,  $w$ ,  $DP$ , and recovery. Thus, the flux and solute concentrations can be calculated as functions of time and axial position. Details of the analysis are included in Ref. 5.

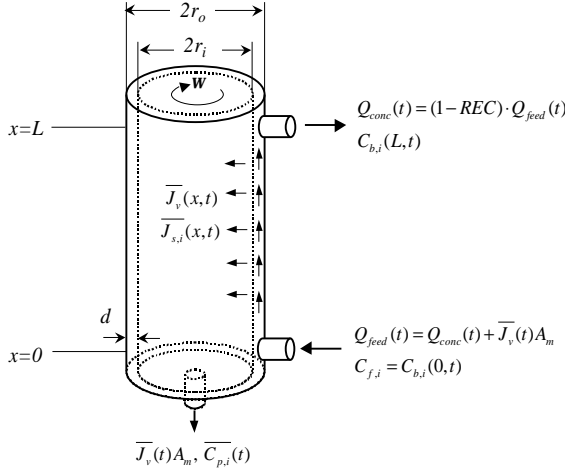


Figure 1: Sketch of the flow and geometry in a rotating RO membrane system.

## Results and Discussion

The wastewater that we consider here is space mission wastewater. This wastewater contains wash water, condensate, and urine. During storage, urea and other organic nitrogen compounds are converted to ammonium ions in the presence of enzymes from microorganisms in the wastewater. The simplified composition of a synthetic model for space mission wastewater is given in Table 1. In addition to ammonium ions from urine, the wastewater contains NASA body soap and ions. Preliminary studies using a stirred cell showed that Low Pressure Reverse Osmosis (LPRO) membranes appear to be most desirable because of their high permeate flux and rejection [1]. Thus, the membrane parameters for LPRO membranes are used for the calculations. The geometric parameters in Table 2 that were used in the calculations are similar to those for a rotating reverse osmosis module that we are currently fabricating.

Table 1: Composition of Space Mission Wastewater

Component	Concentration (mg/L)	Total Nitrogen (mg/L)
$(NH_4)_2CO_3$	3449.1	1006
NASA body Soap	190.6	7.8
NaCl	1000	0

Table 2: Parameters for the Rotating RO Membrane System. (Water Permeability Based on Experiments Using ESPA Membranes [1])

Parameter	Value
Outer Radius ( $r_o$ )	2.86 cm
Inner Radius ( $r_i$ )	2.50 cm
Filter Area Length ( $L$ )	12.70 cm
Annular Gap ( $d$ )	0.36 cm
Membrane Area ( $A_m$ )	0.0199 m <sup>2</sup>
Water Permeability ( $L_v$ )	$2.00 \times 10^{-11}$ m/sec-Pa
Kinematic Viscosity ( $\nu$ )	$0.98 \times 10^{-6}$ m <sup>2</sup> /sec

The local permeate flux profiles for different times are shown in Figure 2. All calculations are for room temperature operation. For these calculations the transmembrane pressure was 1800 kPa and the rotational speed was 200 rad/min. This corresponds to a Taylor number of 179, above the critical Taylor number for the appearance of vortical flow at this radius ratio. The recovery, or fraction of the feed that passes through the membrane ( $REC$ ), was set to 0.9.

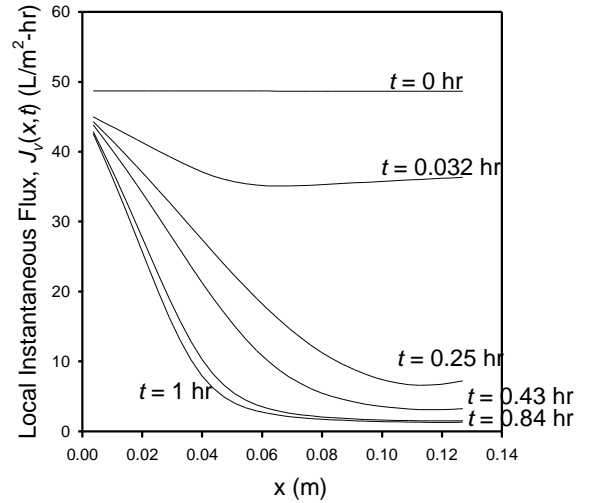


Figure 2: Local flux of permeate as a function of time and position. Modeling condition:  $\Delta P = 1800$  kPa;  $w = 200$  rad/min ( $Ta/Ta_c = 2.54$ );  $REC = 0.9$

Initially the flux is uniform, but the flux quickly decreases at the downstream end of the device because of the higher solute concentration there. The difference in flux between the upstream and downstream ends increases with time. Clearly, membrane fouling occurs first at the downstream end of the module because of the high solute concentration.

Figure 3 shows the dependence of flux on recovery at different rotational speeds. A recovery of 1.0 corresponds to dead-end filtration; a recovery of 0.2 corresponds to 20% of the feed passing through the membrane.

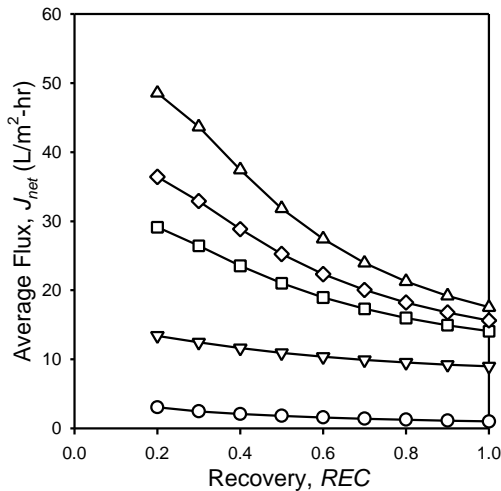


Figure 3: Effect of recovery on permeate flux and nitrogen rejection in a rotating RO system. Modeling condition:  $\Delta P=1800$  kPa; operating time, 1 hour.

( $\circ$ ):  $Ta/Ta_c = 0$  (0 rad/min); ( $\nabla$ ):  $Ta/Ta_c = 0.9$  (70.8 rad/min); ( $\square$ ):  $Ta/Ta_c = 1.1$  (86.5 rad/min); ( $\diamond$ ):  $Ta/Ta_c = 2.0$  (157.3 rad/min); ( $\triangle$ ):  $Ta/Ta_c = 4.0$  (314.6 rad/min))

It is evident that the flux increases with rotational speed and decreases for high net recoveries. The dependence on rotational speed can be attributed to the mass transfer coefficient. At 0 rad/min, the mass transfer is quite low due to a lack of shear resulting in only a small flux through the membrane. At 70.8 rad/min, corresponding to  $Ta/Ta_c = 0.9$ , rotational shear enhances the mass transfer. At 86.5 rad/min, corresponding to  $Ta/Ta_c = 1.1$ , vortical motion also results in the transport of solute away from the membrane. This significantly increases the mass transfer and, consequently, the flux through the membrane. The increase in flux is substantially greater at low recovery than at high recovery, although vortical flow always results in significantly higher flux than non-vortical flow. A low recovery

corresponds to a high axial flow rate,  $Q_{conc}$ , that washes solute out of the device. The resulting lower solute concentration at the membrane permits a higher flux.

Figure 4 shows the the time dependent variations in flux for several rotational speeds of the inner cylinder. Rotating RO has much higher flux than no rotation. The flux is higher for Taylor vortex flow ( $Ta/Ta_c > 1$ ) than for circular Couette flow ( $Ta/Ta_c = 0.9$ ) because of enhanced mass transfer caused by the greater rotating shear flow and the Taylor vortices. The advantage of higher rotational speed decreases as time progresses, although it remains far superior to crossflow alone (0 rad/min).

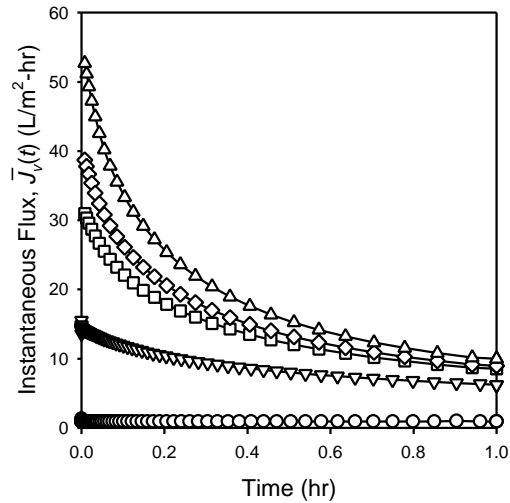


Figure 4: Effect of rotational speed on flux in a rotating RO system. Modeling condition:  $\Delta P=1800$  kPa; operating time, 1 hour;  $REC=0.9$

( $\circ$ ):  $Ta/Ta_c = 0$  (0 rad/min); ( $\nabla$ ):  $Ta/Ta_c = 0.9$  (70.8 rad/min); ( $\square$ ):  $Ta/Ta_c = 1.1$  (86.5 rad/min); ( $\diamond$ ):  $Ta/Ta_c = 2.0$  (157.3 rad/min); ( $\triangle$ ):  $Ta/Ta_c = 4.0$  (314.6 rad/min))

To further display the influence of operating conditions on rotating RO filtration, contours of constant flux is shown as a function of rotational speed and transmembrane pressure in Figure 5. The results are presented for 1 hour of operation at 90% recovery. As expected, the best flux occurs at high rotational speeds and high transmembrane pressures. However, dependence of the flux on rotational speed and transmembrane pressure is not linear. The flux is suddenly increased at  $w=78$  rad/min because of the transition from stable Couette flow to Taylor vortex flow. The flux increases somewhat with rotational speed as the enhanced mass transfer prevents the build-up of rejected species. Increasing the transmembrane pressure results in higher flux for both non-vortical circular Couette flow and Taylor

vortex flow conditions, but the degree of enhancement depends on the rotational speed. Increasing transmembrane pressure enhances flux more than increasing the rotational speed.

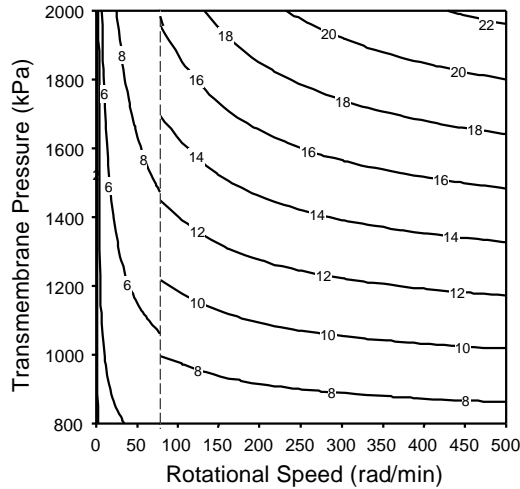


Figure 5: Contour diagrams of net flux at different pressures and rotational speeds. Modeling condition: operating time, 1 hour;  $REC=0.9$ .

## Conclusions

In this work, the flux for a rotating RO membrane system was theoretically predicted using a transient solution-diffusion model with concentration polarization. The following conclusions can be drawn:

1. The local flux is initially uniform, but the flux quickly drops off at the downstream end of the device because of the higher solute concentration there. The difference in flux between the upstream and downstream ends increases with increasing in time.
2. The recovery of the system changes the flux substantially. Flux is higher for the lowest recovery at all rotational speeds. Flux is improved much more by increasing rotational speed at low recoveries than at high recoveries, although vortical flow results in significantly higher flux than non-vortical flow in all cases.
3. Hydrodynamic operating conditions including transmembrane pressure and rotational speed greatly affect the flux and rejection. Operating in Taylor vortex regime is most important to enhance the filtration performance. These vortices apparently reduce concentration polarization near the membrane.

## Acknowledgements

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