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Rotating reverse osmosis and spiral wound reverse osmosis filtration: A comparison

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Abstract

Wastewater produced by the crew members on a long-term space mission needs to be recovered as potable water. Reverse osmosis (RO) has long been in use as a physical membrane separation technology for wastewater treatment. However, membrane fouling and concentration polarization have limited the efficiency for high recovery reverse osmosis systems. An advanced high pressure rotating RO device was designed to minimize these problems by the rotation of the cylindrical RO filter producing shear and Taylor vortices in the annulus of the device. We compare the performance of the rotating RO device to a standard spiral wound RO module using a commercially-available RO membrane under conditions of very high recovery and similar permeate flux. The studies were conducted using 0.01N sodium chloride solution and biological water processor effluent (BWPE) as model wastewaters. The results for 100% recovery of water from 0.01N sodium chloride solution show that the spiral wound RO has poor rejection (<5%) compared to more than 75% rejection for the rotating RO over a period of 2 days. Similar differences in rejection were observed for BWPE for a 5-day test at high recoveries. The overall ion rejection, dissolved organic carbon (DOC) rejection, and ammonium ion rejection from BWPE was typically two times higher for the rotating RO system than for spiral wound RO at 70–80% recovery. Thus, while rotating RO is a more complicated system than spiral wound RO, it provides better rejection of contaminants at very high recoveries.

Keywords: Rotating reverse osmosis; Spiral wound membrane; Wastewater treatment; Rejection

1. Introduction

Providing adequate water, air, and food for the crew is a major challenge for long-term space missions. A major concern is the supply of drinking water and managing the wastewater produced by the crews. However, missions of long-term duration cannot depend on potable water storage or resupply. Therefore, recycling the wastewater stream to produce potable water and water for washing will be essential for long-term manned space missions. Reverse osmosis (RO) has been proposed to be used in a wastewater recovery system. However, several issues must be addressed before RO can be used to produce high-quality potable water from space mission wastewater.

Spiral wound RO systems are commonly used in industrial practices and desalination applications [1–5]. The fraction of water that is purified, or recovery, for a single-stage spiral wound RO is typically 20–40% [3,5,6]. This low recovery is necessary to avoid two problems that decrease the filtration efficiency, concentration polarization and membrane fouling. Rotating filtration is a dynamic method that may have advantages over spiral wound RO due to the Taylor vortices and high shear generated within the device [7,8]. The filter is a porous cylinder covered with a reverse osmosis membrane. The porous inner cylinder rotates concentrically within an outer non-porous cylinder. The wastewater feed solution flows along the annulus between the two cylinders at an elevated pressure that forces the water through the RO membrane. The purified water, or permeate, is collected in a hollow shaft in the center of the device. The rotation of the cylindrical RO filter produces shear and Taylor vortices in the annulus of the device that decrease the concentration polarization and fouling commonly occurring with conventional RO filtration techniques [7,8].

Solute rejection by RO membranes is significantly influenced by physico-chemical properties of the solute, membrane, and solvent, as well as by mass transfer, which is governed by the flow adjacent to the membrane. Previous RO studies have

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employed flat-sheet dead-end stirred-cells, cross-flow filtration systems, and spiral wound single element units for relatively short-term tests [9–11]. However, these short-term tests do not predict long-term performance for recovering potable water from typical wastewater nor do they consider high recovery conditions.

In this study, the rejection of inorganic and organic compounds by a RO membrane at high recovery conditions (>70%) is compared for realistic space mission wastewaters over several days using both rotating RO and spiral wound RO filtration systems. Spiral wound modules have a much higher surface area than flat-sheet membrane designs [4] or rotating RO. The larger membrane area allows for a greater amount of permeate to be collected within a similar module volume. On the other hand, the membrane area in rotating RO is limited, since a flat sheet of RO membrane is wrapped around the inner cylinder of the device. Therefore, the comparison in this paper is based on same flux, essentially offsetting the differences in the membrane areas between two systems. In addition, we consider a single RO "unit" with no recycle, although spiral wound systems are often operated in series and/or with recycle. Likewise, rotating RO units could be operated in series or set up to use a recycle path. Thus, a reasonable way to compare spiral wound RO with rotating RO is to use single units. Once the performance of a single unit is characterized, as we do here, it is not difficult to extrapolate to series processing or recycling.

The rotating RO system must have increased rejection of contaminants, longer membrane life, and high operational recovery to be an attractive alternative to spiral wound RO. The main objective of this research is to compare the long-term filtration characteristics of single-stage spiral wound RO and rotating RO at high recovery conditions for comparable flux through the membrane. Significant effort has been directed toward making the comparative assessment of the two systems fair based on similar water recoveries and process volumes, despite completely different geometries and membrane areas for the two systems. The results will be compared in terms of permeate flux decline, percentage recovery, and the rejection of ionic species and organic compounds from the feed solution.

2. Experimental

2.1. Materials and methods

It is quite difficult to directly compare spiral wound RO with rotating RO due to the very different geometries, membrane areas, and operation characteristics of the two systems. To maintain some degree of consistency between the two systems, the membrane used in the rotating RO system was chosen to match that of the commercial spiral wound cartridges used for comparison. The ESPA (ESPA1-2540, Hydranautics Inc.) membrane was used exclusively for all the comparative tests. The ESPA membrane was selected for use in this investigation because of its high rejection, high flux, and its availability in both spiral wound and sheet forms. The thin film composite polyamide membrane represents a typical low pressure RO membrane. It has a pore-radius of 0.33 nm [12] and an operating pH range of

Table 1
Composition of ersatz wastewater: biological water processor effluent

Parameters	BWPE
pH	6.6
Conductivity ($\mu S\,cm^{-1}$)	3750
DOC ($mg\,L^{-1}$)	51.8
Urea ($mg\,L^{-1}$) as C	2.45
Cl^- ($mg\,L^{-1}$)	638
NO_2^--N ($mg\,L^{-1}$)	1.89
NO_3^--N ($mg\,L^{-1}$)	13.5
$H_2PO_4^-$ ($mg\,L^{-1}$)	123
SO_4^{2-} ($mg\,L^{-1}$)	128
Na^+ ($mg\,L^{-1}$)	400
NH_4^+-N ($mg\,L^{-1}$)	173
K^+ ($mg\,L^{-1}$)	280
Creatine	8.46
Dextran	98

4–11. The pure water permeability measured at 800 kPa using a stirred-cell is $1.65\,L\,d^{-1}\,m^{-2}\,kPa^{-1}$.

For simplicity, the initial tests were conducted with 0.01N sodium chloride solution to compare the rejection performance of the spiral wound and rotating RO systems at different recoveries over a period of 2 days. In both cases, the same permeate flux was maintained for a specific recovery.

To model a realistic wastewater on board a space mission, an ersatz wastewater solution was used: biological water processor effluent (BWPE) [13,14], with the general properties given in Table 1. The BWPE ersatz is based upon the effluent that would occur from long-term planetary base wastewater after processing by a biological wastewater preprocessing system that might be used to remove organic and inorganic compounds as an adjunct to a physico-chemical system [15]. The BWPE ersatz wastewater solution was mixed according to standard procedures [14]. The BWPE ersatz includes nine inorganic compounds including sodium, potassium, ammonium, chloride, and sulfate. The 14 organic compounds in BWPE ersatz, all at various concentration levels, includes large quantities of dextran and creatinine (see Table 1). This wastewater has been previously tested with several RO and nanofiltration membranes in a stirred cell configuration [16].

In this study, experiments were performed using rotating RO and spiral wound RO filtration systems, similar to those that have been used for the study of various RO membranes [17–20]. Although a rotating RO filtration system has been described in some detail elsewhere [19–21], we briefly describe this system here. The permeate is forced through the reverse osmosis membrane covering a porous inner cylinder that rotates within a larger non-porous cylinder. The permeate is collected in a hollow shaft at the center of the device. The permeate is recycled back to a 20 L reservoir as shown in Fig. 1(a). The concentrated wastewater stream exits at the top of the filter device where the pressure is monitored by a transducer. The concentrate then flows through a small diameter pressure regulator tubing to reduce the pressure back to atmospheric pressure. The concentrate is returned to the reservoir where it is combined with the permeate stream and fed back into the loop. A constant flow Prep 100 Preparative HPLC Pump (Lab Alliance, PA) is used in the fluid circuit to provide

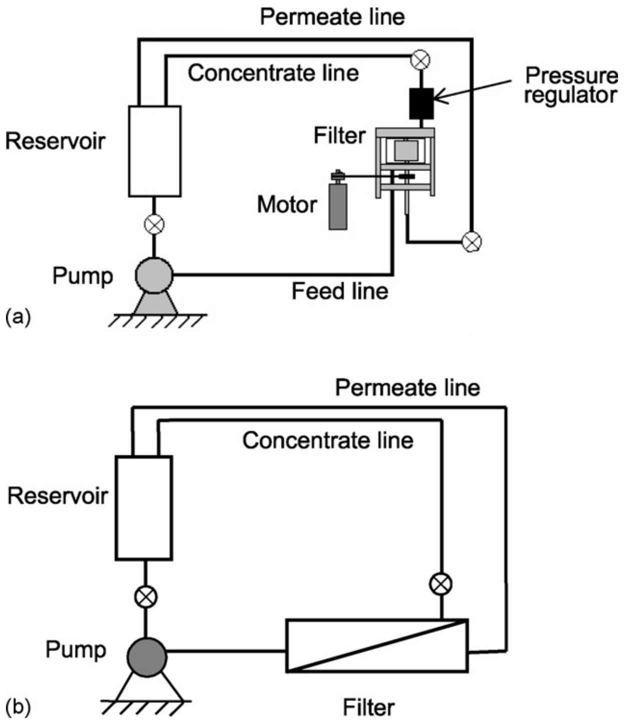

Fig. 1. Flow diagram of reverse osmosis filtration system: (a) rotating reverse osmosis and (b) spiral wound reverse osmosis. The rotating RO pressure regulator consists of a long length of small diameter tubing.

the high pressures necessary at the relatively low inlet flow rates. Each test was conducted using the computer controlled fluid circuit to provide constant feed flow rate and pressure control. The operating transmembrane pressure for the 0.01N sodium chloride solution and BWPE solution was in the range of 2–4 MPa (∼300–600 psi). The recovery was altered by choosing different lengths of small-diameter concentrate tubing, since, the flow rate through the concentrate line is inversely proportional to the length of the tubing. The rotating RO experiments were conducted at a rotational speed of 90 rpm. The membrane area for the rotating RO device, which has an internal fluid volume of 0.5 L, was 158 cm^2. The ESPA membrane was supported on a rigid porous ceramic cylinder with an average pore size of 30 μm (Kellundite, Filtros, NY). The detailed experimental setup and conditions are described in previous papers [20,21]. The single element bench-scale filtration system used for the spiral wound RO element, which has an internal fluid volume of 2.4 L, is shown in Fig. 1(b). The filtration system includes a feed tank of 20 L capacity and a membrane module containing a spiral wound membrane having an effective surface area of 2.6 m^2. A high-pressure pump was used to pump the feed solution to the membrane module. In this case, the operating transmembrane pressure was in the range of 830–1170 kPa (∼120–170 psi).

A fresh flat membrane sheet was used for each experiment in case of rotating RO. The membranes were soaked in ultra-pure deionized water at least for 1 day to clean any chemicals on the membrane. In case of spiral wound module, the membrane element was cleaned using deionized water after each experiment. This was accomplished by back flushing deionized water from the permeate side (about 24 h) until the conductivity of water from the feed side was measured to be less than 70 $\mu S\,cm^{-1}$. In addition, the membranes were further stabilized by pure water at pressure of 830 kPa (120 psi) and 2070 kPa (300 psi) in case of spiral wound RO and rotating RO, respectively. The pure water flux was measured at these pressures to confirm that the flux matched the original water flux of the new membrane. In order to avoid biofouling, 100 $mg\,L^{-1}$ of sodium azide (NaN_3) was added to the BWPE feed solution [20]. All of the experiments and analysis were conducted at room temperature with a change in temperature of 2–3 °C at most, mainly as a result of heating in the pump.

2.2. Analysis

Measurements of the flux were made using a graduated cylinder and stopwatch. The permeate recovery is defined as the percentage ratio of permeate flow rate to the feed flow rate. The rejection (R_i) of component i in the feed solution as a function of time was calculated as:

$$R_i(t) = 1 - \frac{C_{p,i}(t)}{C_{f,i}(t)} \quad (1)$$

where $C_{p,i}(t)$ is the permeate concentration at time t and $C_{f,i}(t)$ is the feed concentration of solute i at time t. Anion concentrations were measured using a commercial ion chromatography instrument (DX300, Dionex Corp., Sunnyvale, CA, USA), while cation concentrations were measured using inductively coupled plasma emission spectroscopy (Liberty-Series II, Varian, Australia). The ammonium ion concentration in the feed and permeate of BWPE wastewater was determined by Nessler's method [22] using UV–vis spectroscopy (Hitachi, U-2000 spectrophotometer). The rejection of 0.01N NaCl solution and all ionic species present in BWPE was analyzed using a conductivity meter (Oakton Con 5, Acon Series). The organic rejection was similarly measured based on the dissolved organic carbon (DOC) of the waste streams, using a Tekmar-Dohrmann DC-10 combustion organic analyzer [Teledyne-Tekmar, Los Angeles, CA] with an accuracy of ±0.2 $mg\,L^{-1}$ of organic content. After filtration tests, the BWPE permeate samples were acidified below a pH of 2.0 by adding 10% sulfuric acid to prevent the loss of compounds for DOC and cation analysis. The error bars for rejection were calculated based upon the standard deviation of triplicate samples.

3. Results and discussion

3.1. Comparison of NaCl rejection

In order to better understand the filtration performance characteristics of conventional spiral wound RO and rotating RO systems, it is useful to conduct tests at different recoveries for the same processing volume per unit membrane area. The preliminary examination was conducted with a sodium chloride solution. Fig. 2 shows the decline in the flux as a function of time for the filtration of 0.01N NaCl solution for the spiral wound and rotating reverse osmosis systems. The experiments were conducted with recoveries of 70–80% and 100%. Dead-end filtration

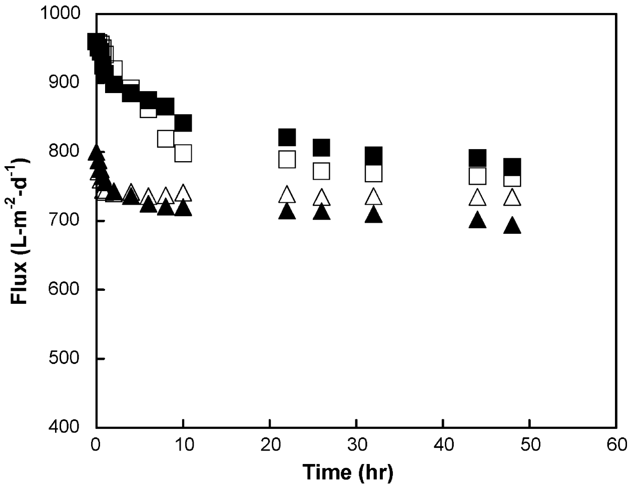

Fig. 2. Comparison of flux for the two RO systems for a 2-day 0.01N NaCl solution test: (■, rotating RO (Rec = 100%); (□) spiral wound (Rec = 100%); (▲) rotating RO (Rec = 70–80%); (△) spiral wound (Rec = 70–80%).

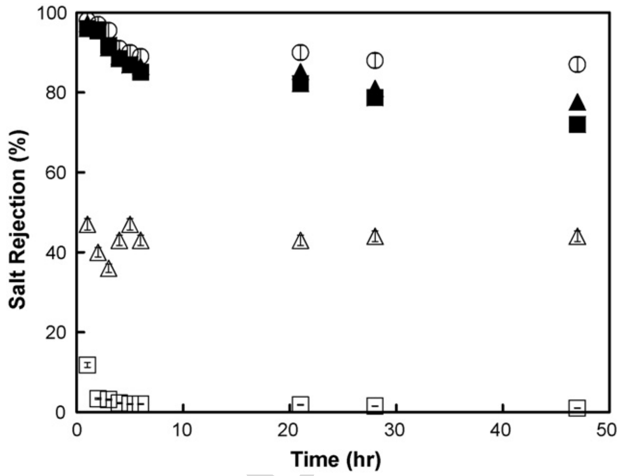

Fig. 3. Comparison of filtration efficiency of rotating RO and spiral wound RO for rejection of 0.01N NaCl: (■, rotating RO (Rec = 100%); (□) spiral wound (Rec = 100%); (▲) rotating RO (Rec = 70–80%); (△) spiral wound (Rec = 70–80%); (◯) spiral wound (Rec = 20%). Error bars based on triplicate samples are smaller than the symbols.

(100% recovery) was accomplished by closing the concentrate line so that all of the water was forced through the membrane. While this high recovery seems extreme for a RO system, long duration space missions require very high recovery, since, resupply is impossible and transporting large quantities of water is a very significant burden as far as launch mass and storage on board the spacecraft. The fluxes start at approximate initial values of 960 L m^{-2} d^{-1} (100% recovery) and 800 L m^{-2} d^{-1} (~80% recovery). The figure clearly shows an initial sharp decrease in the flux due to concentration polarization and the equilibration of the fluid circuit during the first 4 h in all cases. The flux continues to decrease gradually over the test period of 2 days for both the rotating RO and spiral wound RO experiments. By the end of 2 days, the permeate flux decreased by approximately 21% and 19% for spiral wound and rotating RO, respectively, for complete recovery. However, the percentage reduction in flux is less pronounced (10–13%) in both RO systems for 70–80% recovery. This is presumably because of reduced buildup of solute at 70–80% water recovery than at 100% water recovery. With the increase in the recovery of permeate, the osmotic pressure due to retained solutes increases thereby lowering the flux as a consequence of reduced effective transmembrane pressure. Moreover, it should be noted that there is a negligible difference (under 6%) in the overall flux performance at high recoveries between the two RO systems. Thus, approximately the same amount of the feed salt solution is processed per unit membrane area over a specific time period for these RO modules permitting direct comparison of the two systems.

The salt (0.01N NaCl) rejection performance over 2 days is shown in Fig. 3 for the rotating RO and spiral wound systems at different water recoveries. For comparison, we include rejection for 20% recovery using the spiral wound module. Nearly 90% salt rejection was observed in this case, confirming very effective salt rejection at low recoveries. However, the rejection of salt decreased as the recovery was increased. The spiral wound system removed only 44% and 1% of salt ions from the water at the end of 2 days for 70–80% and 100% recoveries, respectively. In contrast, the rotating RO system rejected 78% and 72% salt from the water at 70–80% and 100% recoveries, respectively. This is nearly a 2-fold increase in the rejection for 70–80% recovery. For complete recovery, using rotating RO provides fairly high rejection compared to virtually no rejection for spiral wound RO. The significant improvement in rejection for rotating RO mainly occurs because of the reduced concentration polarization and membrane fouling due to the rotation of the membrane and the resulting vortical flow structures in the annulus between the RO membrane and the housing.

3.2. *Comparison of the extent of concentration polarization and fluid flow analysis*

Although the main objective of this paper is to compare the rejection and flux behavior of rotating RO and spiral wound RO system experimentally, the mass transfer coefficient can be calculated and used to determine the extent of concentration polarization in order to compare the fluid dynamics in the two systems [19]. Assuming that the pressure within the membrane is constant, the fluid at the membrane surface is in equilibrium with the membrane on both sides of the membrane, and pressure losses due to hydrodynamic effects are negligible, the solvent flux, J_v, through the membrane is:

$$J_v = L_v(\Delta P - \Delta \Pi) \quad (2)$$

where L_v is the solvent transport parameter (1.17×10^{-9} m Pa^{-1} s^{-1} for the ESPA membrane based on water flux measurements), ΔP the pressure difference from the device inlet to the permeate side of the membrane, and $\Delta \Pi$ is the osmotic pressure, which can be calculated using Van't Hoff's equation [4]:

$$\Delta \Pi = (C_m - C_p)RT \quad (3)$$

where C_m and C_p are the solute concentrations at the membrane surface on the concentrate side and permeate side of the membrane, R the gas constant, and T is the temperature. Using Eqs. (2) and (3), the solute concentration difference across the membrane, $(C_m - C_p)$, can be estimated as:

$$C_m - C_p = \frac{1}{RT}\left(\Delta P - \frac{J_v}{L_v}\right) \quad (4)$$

The bulk concentration of solute (C_b) can be found using concentration polarization theory [4]:

$$\frac{C_m - C_p}{C_b - C_p} = e^{J_v/k} \quad (5)$$

where k is the mass transfer coefficient for the back diffusion of the solute from the membrane to the bulk solution on high pressure side of the membrane. Rearranging Eqs. (4) and (5) yields the time-dependent mass transfer coefficient:

$$k(t) = \frac{J_v(t)}{\ln((1/RT)(\Delta P(t) - J_v(t)/L_v)/(C_b(t) - C_p(t)))} \quad (6)$$

The permeate flux (J_v), applied pressure difference (ΔP), and permeate concentration (C_p) were measured during the experiments. The average bulk concentration at specific time is usually assumed to be the average of the inlet and exit concentrations of salt from the RO systems [19]. However, for 100% recovery, there is no exit concentration, so the bulk concentration at time t was calculated based on the mass balance to determine the amount of salt that is retained in the system. Using the mass transfer coefficient from Eq. (6), the solute concentration at the membrane surface $(C_m(t))$ can be determined using film theory (Eq. (5)) as:

$$C_m(t) = (C_b(t) - C_p(t))\, e^{J_v(t)/k(t)} + C_p(t) \quad (7)$$

Using the definition of the rejection of solutes from Eq. (1) and rearranging Eq. (7), the ratio of solute concentration at the membrane surface to the solute concentration in the bulk at time t is:

$$\frac{C_m(t)}{C_b(t)} = R_i(t)\, e^{J_v(t)/k(t)} + (1 - R_i(t)) \quad (8)$$

The rejection $(R_i(t))$ and permeate flux $(J_v(t))$ data are known from the experimental results of 0.01N NaCl salt rejection and the corresponding flux (Figs. 2 and 3). Thus, we can compare the extent of concentration polarization (C_m/C_b) for rotating RO and spiral wound RO systems at high permeate recoveries.

Fig. 4 shows the ratio C_m/C_b for 0.01N NaCl solution as a function of time at different operating recoveries in the two RO systems. Clearly, the concentration polarization, C_m/C_b, increases rapidly as the solute builds up at the membrane surface just after time $t = 0$ in all cases. This corresponds to the sharp decrease in the flux during the first few hours (Fig. 2) due to the build up of the concentration polarization layer. In case of the spiral wound system with 100% permeate recovery (dead-end filtration), the concentration polarization continues to increase throughout the course of the filtration as solute accumulates in the module. However, for 70–80% recovery using the spiral wound system and all recoveries for the rotating RO system, concentration polarization reaches equilibrium over the longer time intervals. The concentration polarization is quite

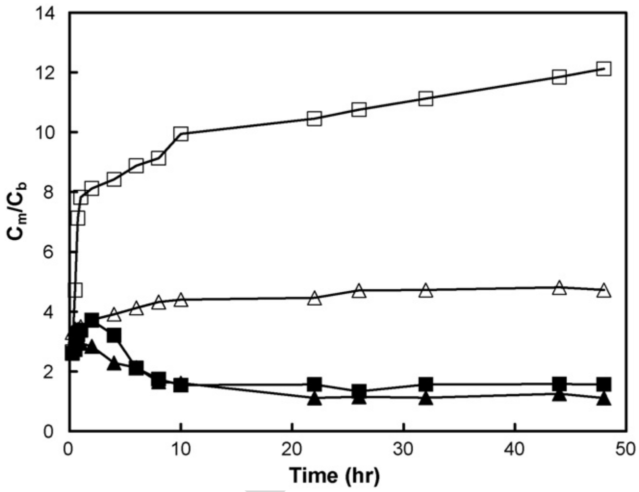

Fig. 4. Extent of concentration polarization as a function of time for rejection of 0.01N NaCl: (■, rotating RO (Rec = 100%); (□) spiral wound (Rec = 100%); (▲) rotating RO (Rec = 70–80%); (△) spiral wound (Rec = 70–80%).

high for spiral wound RO system at the end of 2 days, 4.72 and 12.1 at 70–80% and 100% recoveries, respectively. In the case of the rotating RO system, the concentration polarization decreases after initial solute build up. Eventually, the concentration polarization ratio is reduced to 1.11 and 1.56 at 70–80% and 100% recovery, respectively, at the end of 2 days. Thus, there is a uniformly high solute concentration across the entire annular gap due to the enhanced mass transfer in the rotating RO system related to vortical transport of fluid and high shear near the membrane. This is in contrast to the strong concentration polarization layer at the membrane that occurs in the spiral wound module. The consequence of this is higher rejection for the rotating RO system compared to the spiral wound RO system at high recoveries. Similar reductions in concentration polarization in case of rotating RO have been demonstrated in our previous studies [19].

3.3. Comparison of solute rejection using biological water process effluent (BWPE)

The effect of flux and solution rejection for a more complicated wastewater solution, the BWPE ersatz, was studied over a period of 5 days. Direct comparison tests were conducted for spiral wound RO and rotating RO systems at 70–80% and 100% recoveries. The flux decline for the 5-day long test is shown in Fig. 5. The fluxes start at 960 L m^{-2} d^{-1} and 800 L m^{-2} d^{-1} corresponding to 100% and 80% initial recoveries, respectively. The flux decline is similar to that observed with 0.01N sodium chloride solution, although the flux for BWPE is 5–15% less at the end of 2 days compared to the experiments conducted with salt solution (total concentration: 580 mg L^{-1}) starting at the same initial flux. This is due to the complexity of the BWPE ersatz solution containing both inorganic and organic compounds and its high total concentration (1196 mg L^{-1}), thereby increasing the osmotic pressure (nearly 840 kPa) and lowering the flux by reducing the effective transmembrane pressure. For complete water recovery, the flux declined by 32% for rotating RO

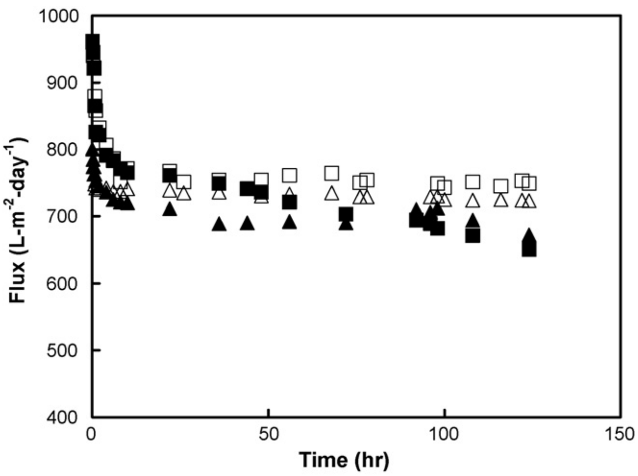

Fig. 5. Comparison of flux in the two RO systems for 5-day test of BWPE wastewater: (■, rotating RO (Rec = 100%); (□) spiral wound (Rec = 100%); (▲) rotating RO (Rec = 70–80%); (△) spiral wound (Rec = 70–80%).

and 21% for spiral wound RO. The minor variations in fluxes are presumably because of slightly different recoveries during the experiments and the different concentration polarization and membrane fouling behaviors over 5 days in the two RO systems.

The effectiveness of the filtration for the RO experiments is further characterized in terms of total ion, ammonium ion, and DOC rejections as a function of time, as shown in Fig. 6. Clearly, the rejections for total ions, ammonium ions, and DOC in the rotating RO system are higher than for the spiral wound system for similar permeate recoveries. In addition, it is evident that the rejection of these solutes for the spiral wound RO system is significantly influenced by the percentage recovery. The spiral wound RO membrane rejects over 34% of ions and over 38% of the ammonium ions and DOC at a recovery of 70–80%, while the rejection is less than 5% for all solutes at a recovery of 100%. On the contrary, the rotating RO system exhibits considerably better rejection of solutes. The ion rejection is 71% and 68% for 70–80% and 100% recovery, respectively, at the end of a 5-day test. The rejection of ammonium ions is in the range of 65–78%, while rejection of DOC varies from 69% to 75% at the end of 5 days. The rejection of DOC is slightly higher than that of total ions most likely because dextran, a very large molecule (M_W = 15K–20K g mol^{-1}), is the major carbon source for the BWPE. It is easily rejected by size exclusion.

As noted from Table 1, BWPE solution contains several monovalent and divalent ions. The removal of these ions can be characterized as a function of the solute radii. The percentage rejection of individual ions using RO systems at different recoveries is plotted in Fig. 7. Below this figure, the solute radius ($r_{i,s}$) and ratio of solute radius to effective membrane pore radius ($r_{i,s}/r_p$) are noted. The solute radii are calculated using Stokes–Einstein equation [23]. The membrane pore radius (r_p) is determined from experiments using uncharged organic compounds (urea and creatine) and an analysis based on extended Nernst–Planck equation [12]. It is clear from the figure that the rejection of all the monovalent and divalent ions from the wastewater by rotating RO system is higher than for the spiral wound RO system. The rejections of the solute ions decrease as

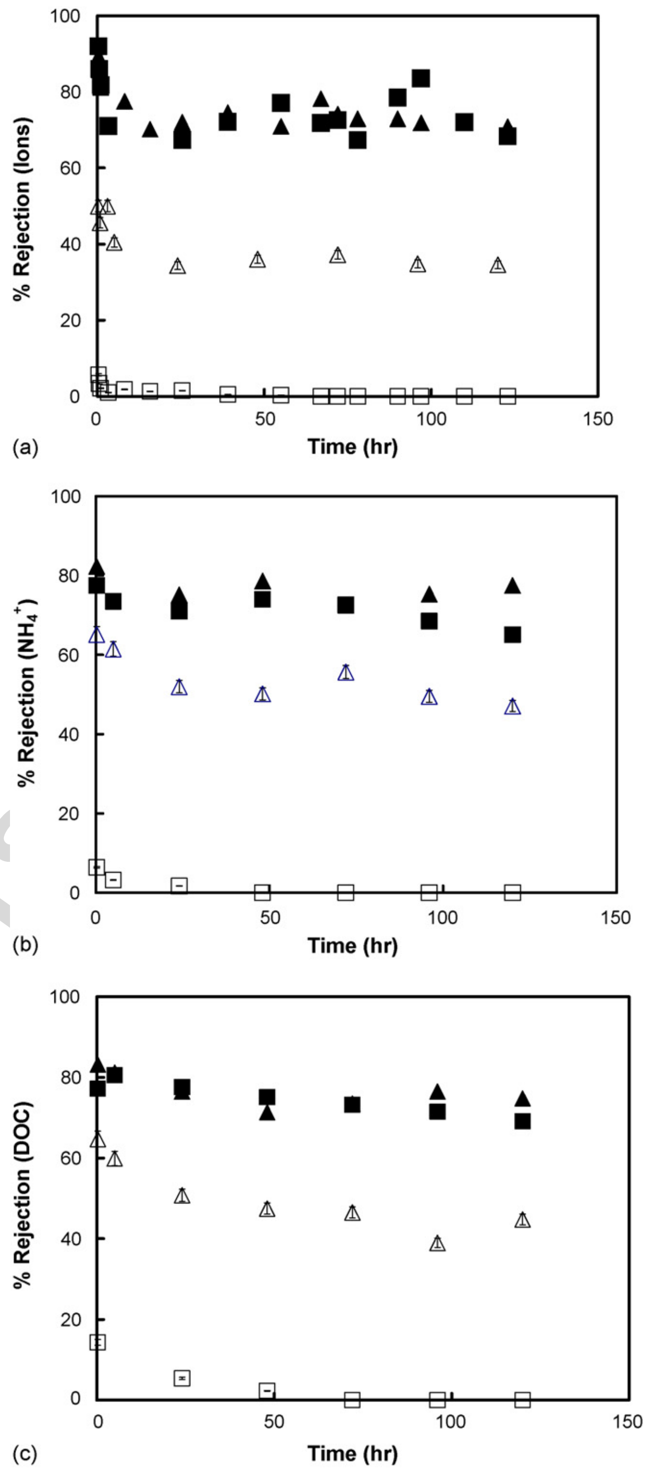

Fig. 6. Solute rejection from BWPE wastewater for 5-day test: (a) total ion rejection, (b) ammonium rejection, and (c) DOC rejection ((■, rotating RO (Rec = 100%); (□) spiral wound (Rec = 100%); (▲) rotating RO (Rec = 70–80%); (△) spiral wound (Rec = 70–80%)). Error bars based on triplicate samples are smaller than the symbols.

the recovery in both the RO modules increases from 70–80% to 100%. The difference is more pronounced in case of spiral wound system. For instance, the rejections of chlorine ions in a spiral wound RO system are 43% and 0% at 70–80% and 100% recoveries, respectively, while about 81% and 73% of chlorine

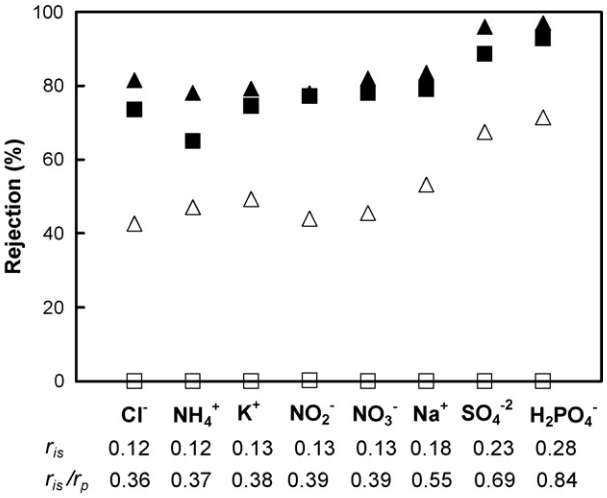

Fig. 7. Rejection of different ions from BWPE wastewater after 5-day test: (■, rotating RO (Rec = 100%); (□) spiral wound (Rec = 100%); (▲) rotating RO (Rec = 70–80%); (△) spiral wound (Rec = 70–80%).

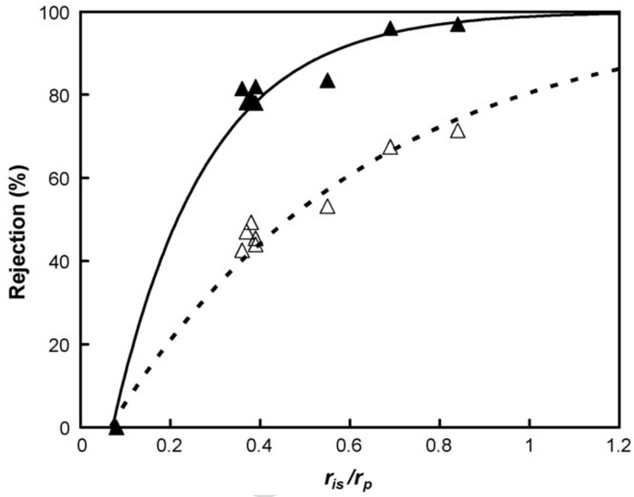

Fig. 8. Dependence of rejection of ionic compounds on the ratio of solute radius to effective membrane pore radius for BWPE wastewater at 70–80% recovery: (▲, rotating RO; (△) spiral wound). Solid curve: regression fit to rotating RO test data; dashed curve: regression fit to spiral wound test data.

ions are rejected by rotating RO device for similar recoveries. This again reflects the limitation of the single-element spiral wound module design when operating at very high water recoveries.

The rejection of ions is greatly influenced by the ratio of solute radius to effective membrane pore radius. The monovalent ions (Cl^-, NH_4^+, K^+, NO_2^- and NO_3^-), which have similar radius ratios (0.36–0.39), display rejections of 77–83% and 43–49% for the rotating RO device and the spiral wound system, respectively, at 70–80% recovery. Sodium ions are rejected somewhat more efficiently compared to other monovalent ions mainly because of increased $r_{i,\mathrm{s}}/r_\mathrm{p}$ ratio. Nonetheless, the order of magnitude of rejection of all the monovalent ions having similar ionic radii (except sodium) are similar for specific conditions at high recoveries. The rejection of a larger, divalent ion (sulfate, SO_4^{2-}) is higher than the monovalent ions. This is because sulfate has a larger size and greater charge than the monovalent ions. The rejection of monovalent dihydrogen phosphate ions ($H_2PO_4^-$) is comparable to the removal of sulfate ions from BWPE solution due to the relatively larger hydrated radius of $H_2PO_4^-$ (0.28 nm).

Since the rejection of solutes is extensively influenced by the physical properties of both the solute and the membrane, our previous work has employed the ratio of the solute radius ($r_{i,\mathrm{s}}$) to effective membrane pore radius (r_p) to predict the rejection for organic and inorganic compounds for the RO and nanofiltration (NF) membranes [9,16]. For inorganic compounds, the hydrated ionic radius is an important parameter to be considered. The rejections of ions from BWPE as a function of $r_{i,\mathrm{s}}/r_\mathrm{p}$ are compared for the two RO systems at 70–80% recovery in Fig. 8. In the figure, the data point having zero curves in the figure are rejection corresponds to water. The regression curves in the figure are based upon the measured rejection data with the curve forced through 0 for the water rejection value, such that:

$$R_i\,(\%) = (1 - e^{-b(r_{i,\mathrm{s}}/r_\mathrm{p})+a}) \times 100 \quad (9)$$

where a and b are the fitting constants for each RO system.

From the plot, it is clear that a higher rejection occurs when the $r_{i,\mathrm{s}}/r_\mathrm{p}$ ratio increases for both of the RO systems at 70–80% recovery. For most ionic compounds, the rejection is higher than 40% when $r_{i,\mathrm{s}}/r_\mathrm{p}$ exceeds 0.35 in both the systems. However, the rejection of solutes is considerably lower for spiral wound RO (dashed curve) compared to rotating RO experiments (solid curve) for this recovery.

4. Conclusions

The filtration characteristics of novel rotating reverse osmosis system were compared with a conventional single-stage spiral wound RO system using ESPA membranes for long-term behavior. The flux decline and rejection of contaminants were examined for similar permeate recoveries in both devices. The flux decline behavior for the salt solution (0.01N sodium chloride) and the BWPE ersatz solution was almost identical in both systems. The results for salt rejection at the end of 2 days clearly reflect the superior rejection performance of rotating RO at high recoveries. The rotating RO system removed more than 75% of the salt ions at higher recoveries compared to 0–50% rejection using spiral wound device. The spiral wound module displayed solute rejection of greater than 75% only at low recoveries (∼20%). A 5-day BWPE solution test further confirmed the enhanced contaminant removal efficiency of the rotating RO device. The rejections of overall solute ions, ammonium ions, and total organic carbon from BWPE solution were substantially higher for the rotating RO system compared to the spiral wound RO system operating at high recoveries. In addition, the analysis of the rejection of individual ions present in the permeate solution verified the improved rejection of solutes using the rotating RO system based on charge and solute radius. The rejection of ions increases with an increase in the ratio of solute size to membrane pore size.

The better rejection of the solutes in case of rotating RO occurs mainly because of the minimization of the concentration polarization and fouling at the membrane surface due to the shear produced by rotation. On the other hand, concentration polarization and fouling are quite problematic for a spiral wound system at high recoveries, because nearly all of the water is forced to pass through the membrane. As a result, the flow of solutes (contaminants) toward the membrane surface is much larger than the diffusion of the solutes back to the bulk wastewater resulting in an increase in the concentration of contaminants at the membrane surface. Furthermore, because of low cross-flow rate, the contaminants are not washed out of the system as quickly. Consequently, a significant decrease in the rejection of contaminants from the wastewater is observed for a single-stage spiral wound system at high recovery. Despite the fact that spiral wound RO has a significantly higher membrane area to module volume ratio, rotating RO could be of benefit because of the better filtration efficiency (high contaminant rejection at similar flux) for long-term, high recovery systems. This is especially important when considering the necessity for high recovery when recycling wastewater on board a spacecraft.

A few caveats are necessary with regard to comparing rotating RO to spiral wound RO. First, the rotating RO system is necessarily more complicated than a spiral wound RO system, since it requires a rotating seal and a motor to drive the system. Fortunately, rotating seal technology is quite advanced. The system uses a glass and molybdenum disulfide filled PTFE lip seal, which has worked very effectively in the tests described here and elsewhere [20,21]. Second, long-term reliability of the system is surely a critical concern, particularly for the application to extended space missions. The reliability depends crucially on the rotating seal as well as the secure, leak-proof mounting of the RO membrane on the rigid porous inner cylinder. While improvements in our design are possible, we have made refinements in both of these areas to bring the reliability to a point that NASA has asked us to transfer the technology to the NASA Johnson Space Center. Third, while the electric motor adds to the power requirements, its incremental increase is quite small in comparison to the power required to generate the high pressure necessary for RO [8]. Thus, its impact on the overall power requirements is small. Fourth, we do not consider systems of several units operating in series, recycle, or regeneration of the membranes, all of which are means to enhance the performance of both spiral wound and rotating RO systems. Instead, our intent was to fairly compare the two systems as individual unit operations. Finally, it is quite clear that the rotating RO system is unlikely to supplant large-scale spiral wound RO systems that have been developed and optimized over the last two decades for use in desalination and other large-scale applications. Nevertheless, rotating RO technology offers the opportunity for small-scale water purification with very high recovery. Thus, rotating RO technology should be considered as a viable candidate for a component of a long-term space mission wastewater treatment system.

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Nomenclature

C_b	concentration of the solute in the bulk solution (mol m^{-3})
C_f	concentration of the solute in the feed stream (mol m^{-3})
C_m	concentration of the solute at the membrane surface (mol m^{-3})
C_p	concentration of the solute in the permeate stream (mol m^{-3})
J_v	permeate flux of water (m s^{-1})
k	mass transfer coefficient for solute (m s^{-1})
L_v	solvent transport parameter (m Pa^{-1} s^{-1})
ΔP	transmembrane pressure (Pa)
$r_{i,s}$	solute radius of species i (nm)
r_p	effective membrane pore radius (nm)
R	gas constant (J/K)
R_i	rejection for solute
Rec	recovery
T	temperature (K)

Greek symbol

$\Delta\Pi$	osmotic pressure (Pa)

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