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11 **Assessing the current state of commercially available membranes and spacers for**
12 **energy production with pressure retarded osmosis**
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ABSTRACT

Pressure Retarded Osmosis (PRO) is an osmotically driven membrane process that utilizes the energy of mixing between streams of high and low chemical potential to generate electrical energy. High power density of a PRO membrane is essential to maximize process efficiency and minimize the capital and operating costs. Thus, robust PRO membranes that can support high pressure, have high water flux, low reverse salt flux, low structural parameter, and a good membrane support structure are needed. In this study, four commercial forward osmosis (FO) membranes for use in PRO were compared. The effect of operating pressures, membrane spacers (type, orientation, and arrangement), and flow velocities on process performance were investigated. A thin film composite polyamide membrane from Hydration Technology Innovations was found to be the most robust and selective membrane. Compared to other spacer configurations, the use of unique feed channel spacer orientations was found to increase PRO power density by up to 46%, yielding power density of 22.6 W/m² (3 M NaCl draw solution and 4.1 MPa hydraulic pressure). However, membrane deformation was observed when operating pressures exceeded 3.5 MPa. The use of unique spacers coupled with decreased draw solution cross-flow velocities was found to increase PRO process efficiency.

Keywords: Osmotic power; pressure retarded osmosis; power density; energy-water nexus; membrane integrity

1 Introduction

Water and energy are interdependent and are increasingly in demand in both developed and developing countries, mainly due to population growth and economic expansion. Accordingly, it is essential to develop advanced technologies that maximize energy production, minimize emissions, reduce water consumption, and lessen reliance on fossil energy resources. In 2013, energy consumption surmounted energy production in the U.S. (where the remaining energy resources were imported), and only 11% of the energy produced in the U.S. was from renewables [1]. Renewable energy resources from water, or blue energy, are abundant and dependable [2, 3]; they include hydropower, geothermal, wave, tidal, algae biofuel, and salinity gradient energy.

Osmotic power, or salinity gradient power, harnesses the energy of mixing between high and low salinity streams. Pressure retarded osmosis (PRO) is an osmotically driven membrane process that can facilitate conversion of the energy of mixing to mechanical energy, which can further be converted to electrical energy [4-6]. In PRO, water permeates by osmosis through a semi-permeable membrane from a low concentration feed stream into a higher concentration brine (a.k.a. draw solution). The draw solution becomes diluted but is not allowed to spontaneously expand; thus, it is pressurized to a hydraulic pressure less than the osmotic pressure difference between the draw solution and feed. As a result, the net driving force for transport of water (permeate stream) remains in the direction of feed to the draw solution. The energy in the pressurized, diluted draw solution can then be converted into electrical energy via a turbine-generator set. Proposed configurations of PRO include stand alone PRO for energy recovery from mixing of low concentration (e.g., river water) and high concentration waters (e.g., Dead Sea, Great Salt Lake, or seawater) [4-11], PRO coupled with RO for low-energy desalination [12-14], and PRO hybridized with a thermal distillation process for energy generation from low-grade heat [15-18].

The cost, selectivity, and robustness of PRO membranes have been identified as the main limitations for commercialization of osmotic power [10, 19]. Currently, commercial PRO membranes are not available; therefore, forward osmosis (FO) membranes are used in all PRO investigations [20]. Ideally, PRO membranes would demonstrate high water permeability and high selectivity. Membranes with high selectivity limit the transport and accumulation of draw

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4 solution solutes in the feed solution, which would otherwise result in a lower driving force and
5 lower energy recovery [21-23].
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8 Power density is an important performance parameter in PRO and it is defined as the amount
9 of power generated (in watts) per unit membrane area used. In general, the maximum power
10 density is determined by multiplying the water flux through the PRO membrane by the hydraulic
11 pressure in the draw solution. Mathematically, the maximum power density for specific
12 operating conditions occurs at an applied pressure equal to half of the osmotic pressure of the
13 draw solution [19]. In order to achieve high PRO power density, internal and external
14 concentration polarization (CP) [8, 19, 21, 22, 24-27]—two phenomena governing process
15 performance in osmotically driven membrane processes—must be minimized. When water
16 permeates from the low concentration feed to the high concentration draw solution, the draw
17 solution at the draw solution-membrane interface becomes diluted and the osmotic pressure
18 driving force across the membrane declines. This phenomenon is defined as external CP (ECP).
19 Internal CP (ICP) in PRO is defined as the accumulation of salt in the membrane support
20 structure, which also reduces the osmotic pressure driving force in PRO. Increased mixing and
21 mass transfer at the feed and draw solution-membrane interfaces can reduce ECP. High cross-
22 flow velocities and turbulence-enhancing spacers can be used to increase mixing; however,
23 increasing flow velocities comes at the expense of increased pumping and pressure losses, which
24 result in decreased net energy production.
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28 High power density in PRO can also be generated by operating with high concentration draw
29 solutions (i.e., high osmotic pressure) and thus high hydraulic pressures in the draw solution
30 channels; therefore, PRO membranes must be mechanically stable at high operating pressures.
31 Results from recent studies have shown increased mechanical stability of PRO membranes when
32 feed-side tricot spacers (i.e., a densely woven mesh spacer typically used as a permeate carrier in
33 reverse osmosis (RO) spiral wound membrane elements) are used [28, 29]. In addition to
34 providing better support for the membrane against the high pressure in the draw solution
35 channels, membrane spacers must provide good mixing and adequate flow passage, thus
36 reducing energy loss induced by flow resistance in the PRO feed and draw solution flow
37 channels (Fig. 1) [29-35]. Poor selection of feed channel spacers can lead to increased feed
38 channel pressure drops in PRO membrane modules and cause a membrane shadow effect
39 (reduced effective membrane area and power density); both of which ultimately decrease net
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power output. Therefore, additional research is needed to optimize PRO membrane performance and spacer selection.

Fig. 1. Schematic of the PRO membrane flow cell with feed and draw solution spacers.

The main objectives of this study were to assess the performance of commercially available FO membranes for application in PRO and to evaluate key operating parameters for increased power density. Several commercial FO membranes were tested in PRO mode, and were evaluated in terms of water flux, reverse solute flux, power density, and mechanical integrity (i.e., burst pressure). Experiments were performed over prolonged periods of time to evaluate the effects of high operating pressures (up to 4.8 MPa (700 psi)) on membrane performance and mechanical stability. Finally, the use of unique spacer configurations and varying cross-flow velocities were evaluated in terms of their influence on PRO mass transfer, membrane cell pressure drop, and power densities.

2 Material and methods

Four commercial FO membranes were tested in a bench-scale system for use in PRO. Different feed and draw solution spacer configurations and orientations and different flow rates were used to evaluate their effect on mass transfer and process performance, including salt flux and process efficiency.

2.1 Membranes

Commercial, semipermeable, flat-sheet FO membranes were acquired from Hydration Technology Innovation (HTI) (Albany, OR), Oasys Water (Boston, MA), and from a third company, referred to as company X in this article. Membranes from HTI, Oasys, and X are polyamide-based, thin-film composites (TFC), and one additional membrane from HTI is made of cellulose triacetate (CTA).

2.2 Determination of membrane properties

Membrane properties (Table 1) were experimentally determined using methodologies previously proposed as standard methods [36]. The HTI TFC and CTA membranes were pre-compacted with a 50 mM NaCl draw solution at 3.1 MPa (450 psi) until the flux stabilized. The Oasys and X TFC membranes were not pre-compacted because of their low operating pressures (1.0 MPa (150 psi)). The membrane water permeability (A) and salt permeability (B) were determined by performing experiments in a modified RO mode [19, 35] using the PRO flow cell. The permeate stream (circulated in the PRO feed channel) was deionized water and the feed solution (circulated in the PRO draw solution channel) was 50 mM NaCl. The feed solution was pressurized at increasing pressure intervals of 690 kPa (100 psi) for high-pressure membranes (HTI TFC and CTA) and 340 kPa (50 psi) for low-pressure membranes (Oasys and X TFC). The mass transfer coefficient (k) was determined from the cell geometry, solution chemistries, spacer geometry, and operating flows [34]. Membrane burst pressure was found by closely monitoring the feed solution conductivity over each pressure interval, and the membrane was determined compromised when the feed solution conductivity sharply increased by more than 1,500 μ S over a 10-minute period.

Table 1. Membrane water permeability (a), salt permeability (B), water/solute selectivity, structural parameter (S), and burst pressure for X, Oasys, and HTI membranes. The HTI TFC and CTA membranes were pre-compacted at 3.1 MPa.

Membrane	A, 10^{-2} L/m ² -hr-kPa	B, L/m ² -hr	A/B, 10^{-2} /kPa	S, μ m	Burst pressure, MPa (psi)
X	1.50	3.76	0.40	159	1.0 (150)
Oasys	1.94	1.99	0.97	274	1.0 (150)
HTI CTA	0.51	2.19	0.23	600	3.5 (500)
HTI TFC	1.63	1.42	1.15	295	4.8 (700)

2.3 Membrane cells

A stainless steel modified SEPA-CF II cell (GE Water & Process Technologies) was used in this study. The active surface area of the membrane in the cell is 139 cm², with a feed and draw solution flow channel depth of 1 mm. Viton O-rings were placed on the outer edge of the draw solution channel and outer perimeter of the cell to prevent leakage and cross contamination of

the feed and draw solution streams. The feed and draw solution spacers were taped to the cell to prevent tearing of the membranes at the rims of the channels. Taping of the spacers decreased the effective membrane surface area to 124 cm².

2.4 Feed and draw solution spacers

Tricot warp knit (Hornwood Inc., Lilesville, NC) and non-woven extruded mesh spacers were used in this investigation (Fig. 2). The spacer properties are summarized in Table 2. The number of carrier channels per inch and thickness characterize tricot warp knit spacers. The extruded mesh spacers have square openings with a filament length of 3.24 mm. The spacer voidage was determined by a volumetric displacement method. A known amount of spacer area was submerged in deionized water. The voidage was determined by calculating the ratio of the volume of the free space in a spacer (through water displacement experiments) and the total spacer volume (known spacer area multiplied by total spacer thickness).

Fig. 2. Picture of the (a) 35-channel tricot, (b) 20-channel tricot, and (c) extruded mesh spacer.

Table 2. Spacer type, thickness, and voidage used in the experiments. The voidage was measured through a displacement method.

Spacer name	Mesh Type	Thickness mm	Voidage %
20-channel tricot	Warp knit	0.5	64
35-channel tricot	Warp knit	0.25	36
Diamond mesh	Extruded	0.68	86

Two layers of spacers were used in both the feed and draw solution channels, except if otherwise stated (Fig. 3). The draw solution spacer configurations investigated include two

extruded mesh spacers, and an extruded mesh spacer with a 20-channel tricot spacer (nearest to membrane surface and parallel to the flow).

Fig. 3. Schematic of the spacer configuration in the PRO membrane flow cell.

Two types of tricot spacers (20-channel and denser 35-channel) were used for feed channel spacers. Feed spacer orientations for the 20-channel tricot spacers are shown in Fig. 4. The 35-channel tricot spacers were oriented with the channels parallel to the feed flow (similar to Fig. 4a); four of these spacers were used to fill the feed channel. All tricot spacers were oriented with carrier channels facing away from the membrane.

Fig. 4. Illustration of different feed spacer orientations for the 20-channel tricot spacers: (a) both channels oriented parallel to the flow, (b) one channel parallel and one channel at 90° to the flow, and (c) both channels positioned at 45° to the flow. The arrows indicate the direction of feed flow. The top spacer is in contact with the membrane and the bottom spacer is in contact with the flow cell.

2.5 Bench scale system

Bench scale experiments were performed to investigate water flux, reverse solute flux, power density, flow channel pressure drop, and PRO process efficiency. A supervisory control and data acquisition (SCADA) system (LabVIEW, National Instruments, Austin, TX; and LabJack,

Lakewood, CO) was used to control and record pressures, flow rates, temperatures, and feed and draw solution concentrations.

A flow schematic of the test unit is illustrated in Fig. 5. The thermally insulated feed and draw solution reservoirs were connected to a gear pump (Micropump, Vancouver, WA) and a direct drive plunger pump (Cat Pumps, Minneapolis, MN), respectively, which circulated the two streams co-currently on the opposite sides of the membrane. In practice, the feed and draw solution would be circulated counter-currently; however, due to the small size of the test cell, operating in co-current mode has negligible effects on process performance. Echopod ultrasonic level sensors (FlowLine, Los Alamitos, CA) were installed on top of the draw solution, feed, and dosing solution reservoirs to monitor the levels of fluids, and thus calculate changes in volume in each reservoir. Pressure transducers (Omega Engineering, Stamford, CT) located at the inlets and outlets of the membrane cell monitored pressure drop in the feed and draw solution channels, and a proportional valve (Hass Manufacturing Co., Averill Park, NY) was used to control the hydraulic pressure in the draw solution flow channel in the membrane cell. Toroidal conductivity sensors (Sensorex, Garden Grove, CA), located at the membrane cell outlets, were used to monitor and facilitate the control of the feed and draw solution concentrations. A peristaltic pump (McMaster-Carr, Chicago, IL) was used to dose the draw solution with concentrated brine and maintain a constant draw solution concentration during the experiments. Stream temperatures were monitored with silicon crystal based sensors (LabJack, Lakewood, CO) and controlled with shell-and-tube heat exchangers, which were installed at the outlets of the membrane cell.

Fig. 5. Flow diagram of the bench scale PRO system used in the current study.

The feed and draw solution flow rates and temperatures were kept constant at 0.5 L/min and 20 °C, respectively, and the draw solution hydraulic pressure was varied between 340 kPa (50 psi) and 4.8 MPa (700 psi). Changes in feed tank volume, feed solution conductivity, and membrane cell inlet and outlet pressures were used to calculate water flux, reverse solute flux, and feed channel pressure drop, respectively. Power density was calculated by multiplying the water flux by draw solution inlet pressure. The potential power generated in the PRO experiments was calculated by multiplying the power density by the membrane area. Specific reverse solute flux was determined through calculating the ratio between the reverse solute flux and water flux. PRO process efficiency was determined by calculating the ratio between the PRO power generated (power density $\times$ membrane area) and the sum of feed and draw solution pumping power ($W_{\text{pump,feed}} + W_{\text{pump,draw}}$). The pumping power for the feed solution was calculated by multiplying the feed solution flow rate and feed inlet pressure, then dividing by the pump efficiency ($W_{\text{pump}} = Q \times P \div \eta_{\text{pump}}$). The pumping power for the draw solution was calculated by multiplying the draw solution flow rate, draw solution inlet pressure, and pressure exchanger (PX) efficiency, and dividing by the pump efficiency ($W_{\text{pump}} = Q \times P \times (1 - \eta_{\text{PX}}) \div \eta_{\text{pump}}$). A pump efficiency of 70% and a pressure exchanger efficiency of 95% were assumed.

2.6 Solution chemistry

Deionized water was used as the feed solution for all experiments. In PRO experiments, draw solutions of 1, 2, and 3 M NaCl (Certified ACS >99%, Fisher Scientific) were used. The feed solution conductivity was closely monitored throughout the experiments, and the feed solution was replaced once the conductivity reached 1,200 $\mu\text{S}/\text{cm}$ (equivalent to a concentration of 0.5 g/L NaCl). OLI Stream Analyzer software (OLI Systems Inc., Cedar Knolls, NJ) was used to calculate solution diffusivities and osmotic pressure.

3 Results and discussion

Currently available commercial FO membranes were tested under real PRO conditions and their performance in terms of water flux, power density, reverse solute flux, and mechanical stability was evaluated. Unique spacer configurations under different cross-flow velocities were evaluated and their effect on mass transfer, pressure drop, and energy efficiency were quantified.

3.1 Water flux, power density, reverse solute flux, and mechanical stability of commercially available FO membranes for PRO

Power density and specific reverse solute flux as a function of hydraulic pressure for the four membranes are shown in Fig. 6. The X, Oasys, and HTI TFC membranes all have similar power densities when tested at pressures lower than 1.0 MPa (150 psi) (Fig. 6a). However, the X and Oasys TFC membranes are limited to operation at pressures of up to 1.0 MPa (~150 psi); reverse solute flux sharply increases and the membrane's mechanical integrity becomes compromised at higher pressures. The HTI CTA and TFC membranes can withstand operation at pressures up to 3.5 MPa (~500 psi) and 4.8 MPa (~700 psi), respectively (Table 1). Operating the HTI TFC membrane at an applied hydraulic pressure of 2 MPa results in a membrane power density of 9 W/m^2 . The HTI CTA membrane was one of the least permeable membranes. Compared to the TFC membranes, the CTA membrane is thicker and has a denser skin layer [20] and a higher structural parameter (Table 1), which results in lower water fluxes and power densities.

The HTI TFC membrane had the lowest specific reverse solute flux (highest selectivity), followed by the HTI CTA, X, and Oasys membrane (Fig. 6b). Although the HTI CTA membrane has a higher solute permeability compared to the Oasys membrane (Table 1), the membrane's mechanical integrity remains intact at higher operating pressures (up to 3.5 MPa). For all

membranes, the specific reverse solute flux increased and the selectivity decreased with increasing applied pressures. Decreased membrane selectivity results in increased feed solution concentrations and thus a decreased net driving force. Over time, the solute concentration in the feed stream will continue to increase and power density will decrease—specific reverse solute fluxes higher than 5 g/L reduce the effective driving force in PRO [19]. Additionally, solute accumulation in the feed stream is especially problematic in closed-loop PRO systems, such as in osmotic heat engines [15-18].

Although X and Oasys TFC membranes are limited to operating at low-pressure PRO applications (i.e., mixing of river water and seawater), it is important to note that these membranes are well suited for FO applications [37, 38]. Of the membranes investigated, the HTI TFC membrane demonstrated the highest mechanical strength, power density, and selectivity, and was used for the rest of the experiments.

Fig. 6. (a) Power density and (b) specific reverse solute flux as a function of draw solution hydraulic pressure for the X, Oasys, and HTI TFC membranes and HTI CTA membrane. Experiments were conducted with stream temperatures of 20 °C, flow rates of 0.5 L min⁻¹, deionized water as the feed, and a 1 M NaCl draw solution. Two parallel 20-channel spacers were used in the feed channel and one 20-channel spacer with an extruded mesh spacer was used in the draw solution channel.

The performance of the HTI TFC membrane was evaluated with 1, 2, and 3 M NaCl draw solution concentrations (deionized water as the feed solution) with two parallel 20-channel tricot

spacers in the feed channel and one 20-channel spacer and an extruded mesh spacer in the draw solution channel. Power density and specific reverse solute flux as a function of hydraulic pressure are shown in Fig. 7. Experiments were performed with multiple membrane coupons to eliminate bias due to manufacturing defects. The error bars represent the standard error amongst membrane coupons. Power density increased with increasing driving force (draw solution concentration) and draw solution hydraulic pressure. The specific reverse solute flux also increased with increasing draw solution hydraulic pressure. However, the increased driving force (concentration difference) does not affect specific reverse solute flux in PRO. Similar to FO, the reverse solute selectivity is independent of the draw solution concentration and is solely determined by the active layer selectivity and inherent number of dissolved species in the draw solute [22]. The standard error between membrane coupons for power density and specific reverse solute flux increased with increasing draw solution hydraulic pressure, indicating that the membrane was losing its mechanical integrity and more prone to deformation at applied hydraulic pressures higher than 3.5 MPa (TMP of 3.3 MPa).

Fig. 7 (a) power density and (b) specific reverse solute flux as a function of draw solution hydraulic pressure for the HTI TFC membrane at 1, 2, and 3 M NaCl draw solution concentrations. The error bars represent the standard error amongst membrane coupons. Two parallel 20-channel spacers were used in the feed channel and one 20-channel spacer with an extruded mesh spacer was used in the draw solution channel.

Although the HTI TFC membrane can be operated at 4.8 MPa (700 psi) with a 3 M NaCl draw solution, when operated over a prolonged period of time (Fig. 8) the water flux decreased and the specific reverse solute flux increased. The decrease in permeability and selectivity indicates that the membrane was deforming and losing its integrity at high operating pressures. Membrane deformation increases ICP, which subsequently lowers power density in PRO [29, 35]. Deformation of the HTI TFC membrane at high operating pressures (>3.5 MPa) is further confirmed by evaluating membrane characteristics (Fig. 9), modeling results (Table 3), and SEM micrographs (Fig. 10).

Fig. 8. Water flux and normalized reverse solute flux as a function of elapsed time for the HTI TFC membrane operated at applied hydraulic pressure of 4.8 MPa (700 psi) (TMP of 4.5 MPa) and 3 M NaCl draw solution.

Theoretical maximum power densities for 1, 2, and 3 M NaCl draw solutions were modeled and compared to maximum experimental power densities (results from Fig. 7) and are summarized in Table 3. The theoretical maximum power density was modeled using HTI TFC membrane characteristics (determined experimentally (Table 1)) and a previously established PRO model by Yip et al. [39]. For a 1 M NaCl draw solution, modeled and experimental power densities (9 and 8.3 W/m², respectively) were in relatively good agreement. However, there is a large deviation between modeled and experimental power densities for the 2 and 3 M NaCl draw solutions. For the experiments performed with 2 and 3 M NaCl draw solution concentrations, the

maximum experimental power density occurs when the applied pressure is at or greater than 3.5 MPa, which is when the HTI TFC membrane begins to lose its mechanical stability and selectivity. Once the membrane deforms, the membrane characteristics are no longer constant and the modeled values are not valid.

Table 3. Experimental and modeled power densities for the HTI TFC membrane operated with 1, 2, and 3 M NaCl draw solution concentrations and deionized water as the feed. The power density was modeled with A, B, and S values of 1.63×10^{-2} L/m²-hr-kPa, 1.42 L/m²-hr, and 295 μ m, respectively.

Draw solution concentration g/L NaCl	Draw solution osmotic pressure MPa (psi)	Modeled		Experimental	
		Applied pressure	Power density	Applied pressure	Power density
		MPa (psi)	W/m ²	MPa (psi)	W/m ²
58 (1 M)	4.8 (690)	2.4 (350)	9	2.1 (300)	8.3
117 (2 M)	10.5 (1,520)	5.25 (760)	26	3.5 (500)	11.5
175 (3 M)	17.4 (2,520)	8.7 (1,260)	44	4.1 (600)	15.5

The selectivity of the membranes compacted at 3.1 and 4.1 MPa is shown in Fig. 9. Once operated at pressures greater than 3.5 MPa, the membrane properties change and the membrane becomes less selective. Examination of the membrane surface and cross-section with SEM imaging indicates that with increasing pressure, the finger like structure of the support layer becomes more compressed and deformed (Fig. 10). Therefore, although the HTI TFC membrane can operate up to 4.8 MPa, the membrane becomes compromised above 3 MPa applied hydraulic pressure. At increased pressures, the membrane support layer becomes thinner, which increases the apparent tortuosity and decreases the porosity. The overall increase in tortuosity and decrease in porosity results in an increased membrane structural parameter and decreased PRO power densities.

Fig. 9. Membrane water/solute selectivity (A/B) for the HTI TFC FO membrane after pre-compaction at 3.1 MPa (~450 psi) and 4.1 MPa (~600 psi). The error bars represent the standard error amongst membrane coupons.

Fig. 10. SEM micrographs of the HTI TFC virgin membrane (a) surface and (b) cross section; after compaction at 3.1 MPa (450 psi) (c) membrane surface and (d) cross section; and after compaction at 4.1 MPa (600 psi) (e) membrane surface and (f) cross section.

3.2 Spacer selection

Several spacer orientations were used to investigate their effect on mass transfer in PRO (Table 4). Feed channel spacer configurations and orientations include two 20-channel tricot spacers with both channels oriented parallel to the flow (configuration A), one channel parallel and one channel at 90° to the flow (configuration B), both channels positioned at 45° to the flow (configuration C), and four 35-channel tricot spacers with channels oriented parallel to the feed flow (configuration D). The draw solution spacer configurations include two extruded mesh spacers (configuration E) and one tricot spacer with one extruded mesh spacer (configuration F). It is important to note that because of the small size of the flow cell, recoveries were low (i.e., low efficiencies and energy recovery); therefore, the PRO process efficiency, defined as the ratio

of PRO power output to pumping power input (i.e., $W_{\text{pro}}/W_{\text{pump}}$), is simply a qualitative measurement used to compare the performance of different spacer orientations.

Table 4. Feed and draw solution spacer configurations and orientations used in the experiments.

Spacers configuration	Channel	Spacers used	Orientation
A	Feed	Two 20-channel tricot	Parallel to feed flow
B	Feed	Two 20-channel tricot	90° to feed flow
C	Feed	Two 20-channel tricot	45° to feed flow
D	Feed	Four 35-channel tricot	Parallel to feed flow
E	Draw	Two extruded mesh spacers	90° to feed flow
F	Draw	One 20-channel tricot spacer and One extruded mesh spacer	Parallel to feed flow (tricot) 90° to feed flow (mesh)

3.2.1 Effect of feed spacer on power density and process efficiency

Power density, feed channel pressure drop, and process efficiency as a function of draw solution hydraulic pressure for different feed spacer configurations (spacerless draw solution channel) are shown in Fig. 11. Feed spacer configuration C resulted in the highest PRO power density and process efficiency. Compared to configuration A, the feed channel pressure-drop for configuration C was reduced by 73%, thus increasing overall process efficiency. Spacer configuration A had a high feed channel pressure drop because the spacers most likely compressed—the ridges of the spacer near the membrane collapsed into the channels of the spacer beneath it.

Fig 11. (a) Power density, (b) feed channel pressure drop, and (c) W_{pro}/W_{pump} as a function of draw solution pressure for the HTI TFC FO membrane with different feed spacers and spacer orientations (Table 4) and a spacerless draw solution channel. Experiments were performed with 1 M NaCl draw solution, and feed and draw solution flow rates and temperatures were kept constant at 0.5 L/min and 20 °C, respectively.

Although power density increased with increasing applied pressure, PRO process efficiencies decreased due to increased feed channel pressure drop and increased energy demand for pumping. The flow path in spacer configuration C most resembles what can be described as a “corkscrew” flow pattern (Fig. 12). Changing the orientation of the feed spacers increased mass

transfer at the feed membrane interface, thus decreasing concentration polarization at the membrane boundary layer in the draw solution channel. Da Costa et al. observed similar results for ultrafiltration; increasing the hydrodynamic angle of the spacer (i.e., direction that the fluid flows within the channel) greatly influences the hydrodynamics in spacer filled channels [40].

Although spacer configuration B has the largest hydrodynamic angle, power densities with this feed spacer configuration were not as high as the power densities for feed spacer configuration C. In spacer configuration B, the spacer adjacent to the membrane was oriented perpendicular to the feed flow and the spacer adjacent to the flow cell had its channels parallel to the feed flow. The feed stream most likely flowed preferentially in the path of least resistance (spacer parallel to flow), limiting mass transfer at the feed-membrane interface.

Fig. 12. Schematic of corkscrew flow for 45° feed spacer orientation.

The motivation for using dense feed channel spacers (35-channel tricot) was to provide additional membrane support and reach higher membrane burst pressures. However, the dense tricot spacers did not result in higher burst pressures; it actually reduced the effective membrane area (increased shadow effect), limited mass transfer, and lowered power density. Furthermore, use of the dense spacers resulted in higher feed channel pressure drops and lower PRO process efficiencies.

3.2.2 Effect of draw solution spacer on process performance

Power density and process efficiency as a function of draw solution hydraulic pressure for different draw solution spacer configurations is shown in Fig. 13. The best-case feed spacer configuration (C) was used for these experiments. Compared to draw solution spacer

configuration E, configuration F resulted in increased power densities (76% increase) and process efficiencies (2.5 times higher). Compared to the tricot spacer, the extruded mesh spacer has a higher voidage and thicker filaments, which result in increased turbulence [34]. Therefore, it is likely that the draw solution flows preferentially through the channels of the tricot spacer (path of least resistance), thus increasing mass transfer at the draw solution-membrane interface.

Fig. 13. (a) Power density and (b) W_{pro}/W_{pump} as a function of applied pressure for the HTI TFC membrane with different draw solution spacer configurations (E and F) and configuration F in the feed channel. Experiments were performed with 1 M NaCl draw solution, and feed and draw solution flow rates and temperatures were kept constant at 0.5 L/min and 20 °C, respectively.

3.2.3 Best-case spacer configurations

Experiments were performed with the best-case feed and draw solution spacer configurations: configuration C in the feed channel and configuration F in the draw solution channel. Water flux and specific reverse solute flux as a function of draw solution hydraulic pressure is shown in Fig. 14. The orange asterisks represent the maximum power densities from experimental results shown in Fig. 7. Implementing this unique feed spacer orientation increased power densities from previous experiments by 28, 31, and 46 % for 1, 2, and 3 M NaCl draw solutions, respectively. Selection of spacers that increase process performance is impactful in future module design and system performance.

Although this unique feed spacer orientation was impactful in increasing power densities, power densities are still not as high as other reported values for HTI TFC membranes (60 W/m² operated with 3 M NaCl draw solution, cross flow velocity of 21.4 cm/s, and operating temperature of 25 °C) [28]. In addition to increased flow velocities and elevated temperatures, the effective membrane area in the other study was six times smaller than the membrane area in this study (0.002 m² vs. 0.012 m²) and experiments were performed over a shorter duration (35 minutes vs. two hours). Although larger membrane areas result in increased recoveries, effective membrane power densities are lowered. As water permeates from the low concentration feed stream into the higher concentration draw solution stream, the driving force and hence power densities decrease over the length of the module. Furthermore, operating membranes at high pressures over prolonged periods of time result in lower water fluxes (and hence power densities) and higher specific reverse solute fluxes, as illustrated in Fig. 8.

Fig. 14. (a) Power density and (b) specific reverse solute flux for the best-case spacer configuration (configuration C in the feed channel and configuration F in the draw solution channel) at 1, 2, and 3 M NaCl draw solution. The orange asterisks represent the maximum power densities from results shown in Fig. 7 (configuration A in the feed channel and configuration F in the draw solution channel).

3.3 Flow conditions

Power density, feed pressure drop, and PRO process efficiency as a function of feed cross-flow velocity are shown in Fig. 15, where each data series represents a different draw solution cross-flow velocity. Similar to other findings [12], power density increases with increasing feed cross-flow velocity. Compared to draw solution cross-flow velocities, increasing feed cross-flow velocity has a higher impact on membrane power densities, indicating that mass transfer in the feed stream is more critical to process performance. Increasing the feed flow velocity from 0.026 to 0.13 m/s resulted in a 48% increase in power density; however, when the draw solution velocity was increased from 0.026 to 0.13 m/s, power density increased by only 36%. Although increasing feed and draw solution cross-flow velocities result in increased power densities, PRO process efficiency is reduced due to increased energy demand for pumping.

Fig. 15. (a) Power density and (b) $W_{\text{pro}}/W_{\text{pump}}$ as a function of feed cross-flow velocity for the HTI TFC membrane operated with 1 M NaCl draw solution at 2.76 MPa (400 psi) hydraulic pressure, spacer configuration C in the feed channel, and spacer configuration F in the draw solution channel.

4 Conclusions

Several commercial FO membranes were investigated for use in PRO. The HTI TFC membrane was found to be the best membrane for PRO among the four membranes investigated in this study. This membrane has the highest selectivity and mechanical stability, which result in

high PRO power densities. This study established that the HTI TFC membrane can withstand operating pressures of up to 3.5 MPa (500 psi) before significant membrane deformation occurs, which leads to higher ICP and decreased process performance. The specific reverse solute flux for the HTI TFC membrane was found to sharply increase at hydraulic pressures exceeding 2.0 MPa, which has significant impact in closed-loop PRO systems. Furthermore, membrane characteristics and performance change once the membrane is deformed and modeled results are no longer valid. The use of unique feed and draw solution spacers and orientations tested in this study enhanced mass transfer through the membrane, achieving a theoretical PRO power density of more than 22 W/m^2 , which is a 46% improvement from other spacer orientations. Reducing both feed and draw solution flow rates resulted in four fold increase in overall PRO process efficiencies (4 to 16%). Furthermore, decreasing feed and draw solution flow rates resulted in lower parasitic pumping losses and decreased capital pumping costs. Although increased PRO power densities continue to be realized, PRO membrane development, module design, and pilot scale testing are essential for enabling PRO commercialization.

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Feed spacer orientations