Supporting Information

Raising the Bar: Increased Hydraulic Pressure Enables Unprecedented High Power Densities in Pressure Retarded Osmosis

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SUPPLEMENTARY MATERIALS AND METHODS

SEM Imaging. Micrographs were acquired using a Hitachi ultra-high resolution analytical field emission scanning electron microscope (FE-SEM) SU-70. Membrane cross sections were obtained by flash-freezing wet membrane samples in liquid nitrogen and subsequently cracking them. After fracturing, fibers of the embedded polyester mesh were manually cut using a scalpel. All samples were dried overnight and coated with chromium for 30 s using an Emitech SC7620 sputtering machine.

Bench-scale Experimental Setup. A schematic diagram of the bench-scale pressure retarded osmosis (PRO) setup is shown in Figure S2. A variable speed gear pump (Cole-Parmer, Vernon Hills, IL) and a high-pressure positive displacement pump (Hydra-cell, Wanner Engineering, Inc., Minneapolis, MN) were used in a closed loop to circulate the feed solution and draw solution, respectively. The applied hydraulic pressure difference, ΔP, was always from the high-pressure draw solution to the low-pressure feed solution. The feed channel flow rate was kept constant at 12 mL/min and draw solution flow rate was maintained at 0.8 L/min in cocurrent crossflow. Flow rate and pressure of the draw solution were controlled by adjusting a bypass needle valve and backpressure valve installed downflow of the test cell. Water flux through the membrane was measured using the weight of the feed solution. Feed and draw solution NaCl concentration were monitored using calibrated conductivity probes (Oakton Instruments, Vernon Hills, IL) and NaCl reverse flux was calculated using the water flux and feed NaCl concentration measurements as described previously.[1] Temperature was measured near the flow cell using a thermocouple and maintained at 25 ± 0.5 °C.

Determination of Mass Transfer Coefficient and Membrane Selectivity. In the PRO cell, the water permeability coefficient, A, was calculated by dividing the DI water flux, J_w^{DI}, by the corresponding applied pressure, $A = J_w^{DI} / \Delta P$. The draw solution mass transfer coefficient, k, was determined after increasing the draw solution NaCl concentration to 50 mM. The stable water flux, J_w, and salt flux, J_s, were measured and used to calculate the permeate concentration, $c_p = J_s / J_w$. The mass transfer coefficient, k, was then determined from:[2]

$$k = \frac{J_w}{\ln\left[\frac{\Delta P - J_w / A}{\pi_b - \pi_p}\right]} \tag{S1}$$

where the bulk feed solution and permeate solution osmotic pressures (π_b and π_p, respectively) are calculated using the van't Hoff equation.

The salt permeability coefficient, B, was also determined from these measurements using:[3]

$$B = J_w \left(\frac{1-R}{R}\right) \exp\left(\frac{J_w}{k}\right) \tag{S2}$$

where the salt rejection, R, is calculated using the bulk feed (c_b) and permeate (c_p) concentrations, $R = 1 - c_p / c_b$. Membranes demonstrating an A / B value less than 2 bar^{-1} during the 50 mM salt rejection test were assumed flawed and experiments were discontinued.

Determination of Intrinsic Membrane Properties. The water permeability, A, salt permeability, B, and structural parameter, S, of the membranes were determined in a reverse osmosis (RO) and forward osmosis (FO) characterization as described in previous publications.[3,4] For RO testing, membranes were compacted overnight at 31.1 bar (450 psi). Water flux and salt rejection were measured at 27.6 bar (400 psi) with a 50 mM draw solution and a crossflow velocity of 21.4 cm/s. FO water flux measurements were taken after RO with a 1 M NaCl draw solution. Temperature was maintained at 25 ± 0.5 °C for all experiments.

REFERENCES

(1) Tiraferri, A.; Yin Yip, N.; Straub, A. P.; Romero-Vargas Castrillon, S.; Elimelech, M. A Method for the Simultaneous Determination of Transport and Structural Parameters of Forward Osmosis Membranes. *J. Memb. Sci.* **2013**.

(2) Baker, R. W. *Membrane Technology and Applications, 2nd Edition*; J. Wiley: New York, 2004; p. 538.

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(4) Tiraferri, A.; Yip, N. Y.; Phillip, W. a.; Schiffman, J. D.; Elimelech, M. Relating performance of thin-film composite forward osmosis membranes to support layer formation and structure. *J. Memb. Sci.* **2011**, *367*, 340–352.

TABLE S1. Complete set of experimental water fluxes and power densities.

c_D (mol/L)	Sample	ΔP (bar)	J_w (L m^{-2}h^{-1})	W (W/m^2)
0.6	1	4.8	33.7	4.5
		9.0	27.3	6.8
		13.8	19.6	7.5
		19.0	11.5	6.1
		22.8	5.4	3.4
	2	4.8	30.7	4.1
		9.0	26.5	6.6
		13.8	19.5	7.5
		19.0	11.6	6.1
		22.8	6.0	3.8
1	1	6.9	37.3	7.1
		13.8	30.1	11.5
		20.7	23.8	13.7
		27.6	17.9	13.7
		34.5	11.1	10.6
		41.4	3.8	4.4
	2	6.9	34.2	6.5
		13.8	29.2	11.2
		20.7	24.5	14.1
		27.6	16.4	12.6
		34.5	9.5	9.1
		41.4	1.9	2.2
2	1	6.9	54.4	10.4
		13.8	52.2	20.0
		20.7	49.7	28.5
		27.6	42.8	32.8
		34.5	38.6	37.0
		41.4	34.3	39.4
		48.3	25.4	34.0
	2	6.9	48.2	9.2
		13.8	45.7	17.5
		20.7	43.9	25.2
		27.6	36.8	28.2
		34.5	34.2	32.7
		41.4	29.4	33.8
		48.3	26.0	34.9
3	1	6.9	52.8	10.1
		13.8	53.2	20.4
		20.7	53.8	30.9
		27.6	51.4	39.4
		34.5	49.3	47.3
		41.4	47.1	54.1
		48.3	44.5	59.7
	2	6.9	61.1	11.7
		13.8	60.4	23.1
		20.7	59.0	33.9
		27.6	52.5	40.3
		34.5	50.0	47.9
		41.4	47.3	54.4
		48.3	43.4	58.2

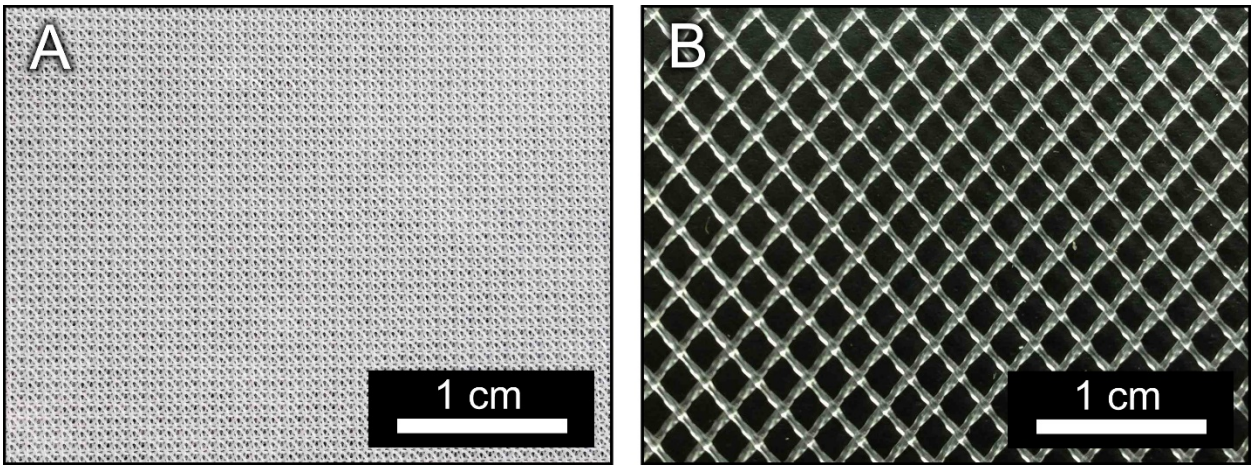

FIGURE S1. Images of the (A) tricot woven fabric and (B) biplanar extruded netting spacer. The images were acquired with a digital camera.

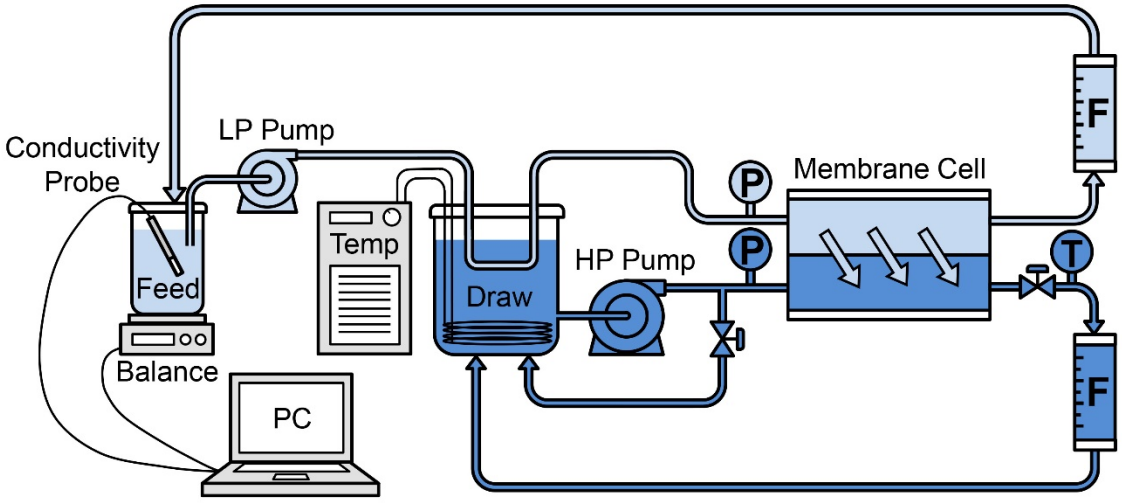

FIGURE S2. Schematic diagram of the bench-scale PRO experimental setup. The weight and conductivity of the feed solution were continually monitored to determine the water and salt flux. Low pressure (LP) and high pressure (HP) pumps were used to circulate the feed and draw solution, respectively. Pressure (P), temperature (T), and flow rate (F) were monitored.

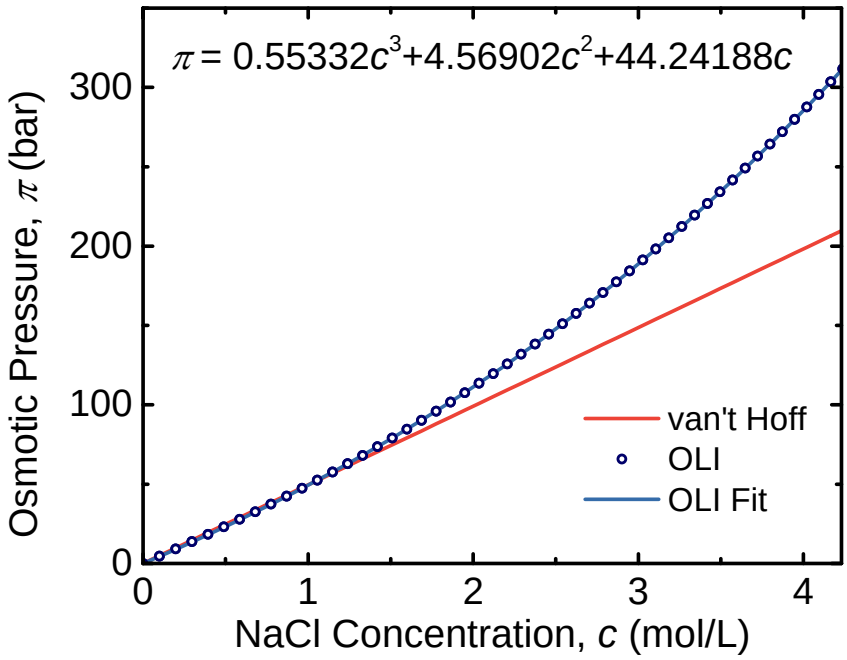

FIGURE S3. Osmotic pressures calculated using the van't Hoff equation (red line), OLI Stream Analyzer (hollow blue circles), and a third-order polynomial equation fit to the OLI data (blue line). The polynomial fit equation is inset.