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EFFECT OF TEMPERATURE ON ELECTRICITY PRODUCTION IN A CLOSED-LOOP PRESSURE RETARDED OSMOSIS PROCESS

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Abstract: The search for sustainable and environmentally friendly energy sources has been ramped-up by an ever-increasing global demand for energy as well as the need to reduce dependency on fossil fuels. Closed-loop pressure retarded osmosis is an integrated system of pressure retarded osmosis (PRO) with a thermally driven separation process feasible for recovering draw solutions. Harnessing pressure gradients (i.e. salinity gradient) via PRO is a promising technology for non-greenhouse emitting renewable energy production. Feed and draw solution temperature has an influence on water flux and, therefore, the temperature can play a significant role in overall electricity production via PRO. In order to investigate the effect of temperature on PRO process, this study primarily examines the impact of temperature on electricity production. Using 1 M NaCl as draw solution, an increase in power density of ~34% (from 6.7 Wm^{-2} to 9.0 Wm^{-2}) was observed when the feed solution temperature was raised from 20^0C to 40^0C in a PRO process using commercial thin-film composite (TFC) membrane.

1 INTRODUCTION

There has been a growing worldwide need for environmental friendly and sustainable sources of energy. Pressure retarded osmosis (PRO) is one emerging technology by which green energy (i.e. energy production without producing greenhouse gasses) is possible. Harnessing the osmotic pressure differences between two solutions of different salinity gradients can produce, energy in the form of electricity, without producing any CO_2 (Achilli and Childress 2010). It has been estimated that global osmotic power potential is equivalent to around 2.6 TW/year, which could be even higher if high salinity RO brine wastewater from reverse osmosis (RO) desalination plants is taken into consideration (Logan and Elimelech 2012; Chung et al. 2012; Kim, Lee, and Kim 2012). Intermittent energy production systems (solar, wind turbines etc.) cannot provide a continuous supply of energy. Therefore, to get energy without interruption, PRO is a potential viable alternative technology. In 1997, Stat Kraft first implemented PRO technology to produce power and achieved a maximum power density of 5.06 Wm^{-2} when concentrated brine (1.03 M NaCl) was used as the draw solution (Achilli, Cath, and Childress 2009). PRO can be considered economically viable if it produces more than 5 Wm^{-2} (Yip et al. 2011).

[1] $W = J_w \Delta P$

Where, W is the power density (Wm^{-2}), J_w is the water flux (LMH) and ΔP is the applied hydraulic pressure. The effect of operating temperature can play a significant role in overall power production in the PRO process since temperature affects solution physicochemical properties like viscosity, density and diffusion (Touati et al. 2015). Therefore, PRO could utilize existing, low-grade waste heat to affect production.

Because of this, PRO has gained more attention in recent times as a reliable, green energy source enhanced by the utilization of low-grade waste heat, In this research, the effect of temperature on the water flux, power density and reverse solute flux achieved by using a commercial TFC FO flat sheet membrane has been studied to understand the temperature-induced interaction between solute, water and membrane.

2 MATERIALS AND METHODS

2.1 Membranes

The commercial thin film composite FO membrane used in this study was provided by Porifera (Hayward, CA). The membrane is mechanically supported by an integrated woven mesh support layer. Table 1 provides the membrane's intrinsic properties at 20, 30 & 40^0C.

Table 1: Summary of membrane and draw solution properties at different operating temperatures

Temperature	Membrane	Water Permeability Coefficient, A (LMH/bar)	Salt Permeability Coefficient B (LMH)
20^0C	TFC	4.924 ± 0.074	2.11 ± 0.04
30^0C		5.940 ± 0.107	3.56 ± 0.07
40^0C		7.798 ± 0.125	5.44 ± 0.21

2.2 Solution chemistries

ACS grade sodium chloride, potassium acetate and sodium propionate (provided by Fisher Scientific) was used in this experiment. Ultrapure water with a resistivity of 18.2 MΩ cm was produced via a Milli-Q system (Millipore Integral 10 - Water Purification System). The performance of the membrane was determined via the conventional method (Han, Ge, and Chung 2014). The membrane was been supported by a fabric spacer on the support side. The membrane was soaked for at least 24 hours prior to use.

2.3 PRO experiment

The laboratory bench scale PRO setup is shown in Fig. 1. The membrane has an effective area of 19.94 cm^2. Mesh spacers placed in the feed channel supported the membrane and enhanced the turbulence in the feed stream. A 2 L reservoir was used for both the feed and draw solution. A hydra-cell, high-pressure pump was used to circulate the draw solution at specific velocities (flow velocity for both draw and feed solution was 0.5 L/min). Containers for each of feed and draw solutions were placed on analytical balances to provide weight of water flux. A thermostatic water bath was used to maintain the temperature. In our study, DI water was used as feed water and 1.0 M NaCl as draw solution.

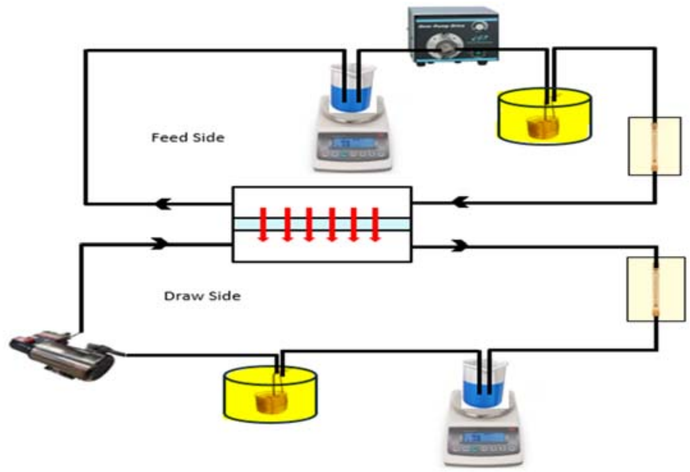


Figure 1: Schematic diagram of bench scale PRO set up

3 RESULTS AND DISCUSSIONS

3.1 Effect of operating temperatures on PRO performance

Fig. 2 summarizes the water flux data for the 1.0 M NaCl draw solution at three different operating temperatures tested under PRO conditions. Water flux increased with the increase in operating temperature of the feed solution. This can be attributed to the higher water permeability coefficient and higher mass transfer coefficient value associated with increased temperature. As seen in table 1, the increase in "A" has a positive impact on higher water flux. Also, with an increase temperature, diffusivity increases, which corresponds to a higher mass transfer coefficient. This higher mass transfer coefficient eventually reduces the internal concentration polarization (ICP) and, therefore, it increases water flux (She, Jin, and Tang 2012). As seen in Fig. 2, water flux increased to ~34% (34.8 LMH to 47.1 LMH) at 100 psi pressure when the feed solution temperature was increased from 20^{0}C to 40^{0}C. However, from Fig. 2, it is also evident that, as predicted, water flux decreased as the applied pressure increased.

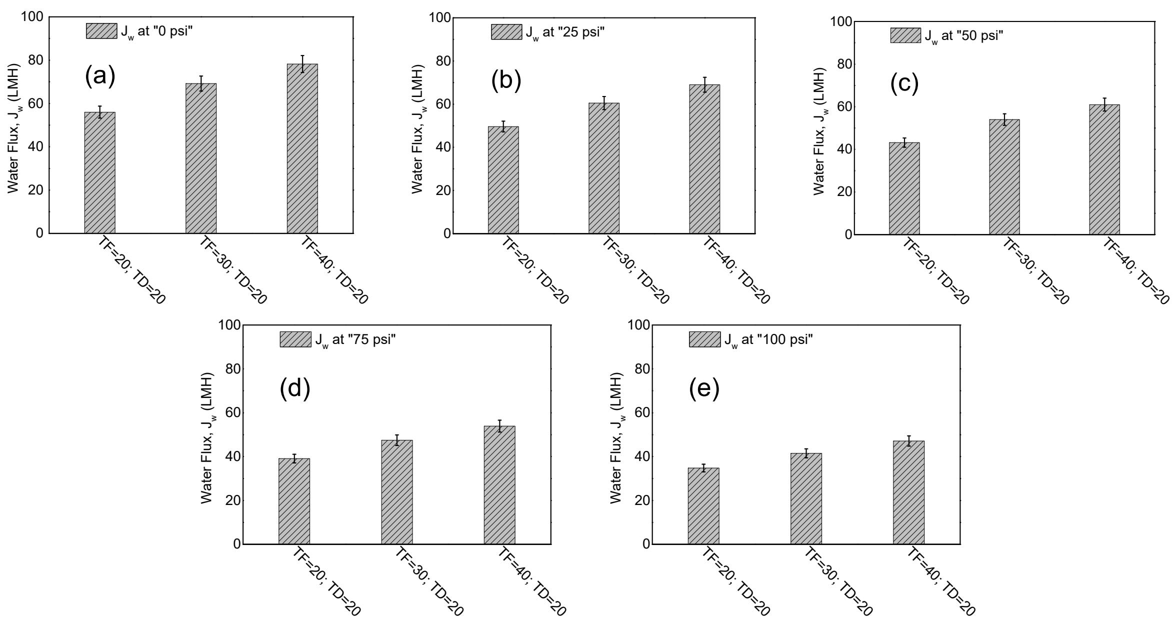


Fig 2. Water flux for 1.0 M NaCl draw solution as a function of working temperatures at the applied pressure of a) 0 psi; b) 25 psi; c) 50 psi; d) 75 psi; e) 100 psi. Membrane used was commercial TFC. Draw and feed flow rate were 0.50 L/min each. Error bars indicate standard deviation among three trials.

3.2 Effect of operating temperatures on power density

The power density illustrated in Fig. 3 has been calculated using equation 1. Fig. 3 shows power density as a function of draw solution pressure for a 1 M NaCl draw solution. This study was conducted for three different feed solution temperatures (20^{0}C, 30^{0}C and 40^{0}C) while draw solution temperature was kept constant (i.e. 20^{0}C). At a constant temperature and concentration, increasing hydraulic pressure caused power density to increase. Power density increased by about ~34% (6.7 Wm^{-2} to 9.0 Wm^{-2}). The highest pressure applied in this study was 100 psi, beyond that pressure membrane internal structure is known to deform. At a constant pressure, conditions that yield high net water flux—corresponding to higher temperature—also yield high power density.

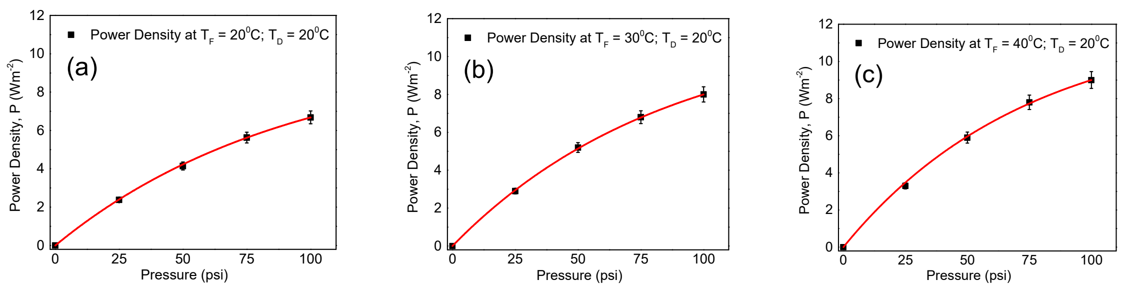
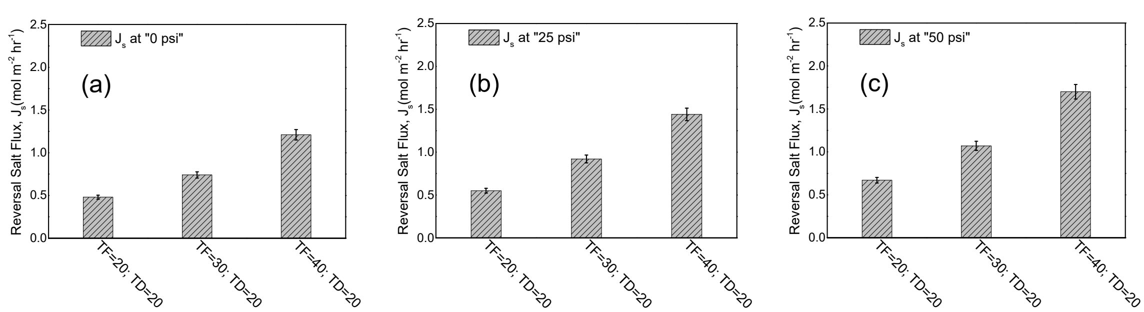


Fig 3. Power density for a 1.0 M NaCl draw solution as a function of draw solution pressure at working temperatures of a) T_F=20^{0}C, T_D=20^{0}C; b) T_F=30^{0}C, T_D=20^{0}C; c) T_F=40^{0}C, T_D=20^{0}C. Membrane used was commercial TFC. Draw and feed flow rate were 0.50 L/min each. Error bars indicate standard deviation over three trials.

3.3 Effect of operating temperatures on reverse solute diffusion on PRO performance

Reverse salt flux into the feed, as a function of temperature, at different applied pressures (0, 25, 50, 75 and 100 psi) is shown in Fig. 4. From this figure, it can be concluded that reverse salt flux shows an upward trend when pressure increases. This upward trend is due to the reduction of dilutive external concentration polarization (ECP) in the draw solution. As water flux decreases with increased pressure, this lowered water flux into the draw solution diminishes the dilutive ECP boundary layer, which causes the concentration at the draw-side membrane interface to increase (Touati et al. 2015). The resulting change in interface concentration causes greater reverse salt flux into the feed solution. Besides this, the increased temperature has a synergistic effect for the reverse salt flux. Since diffusivity increases with increased operating temperatures, the reverse salt flux will be greater for the membrane than at lower temperatures.



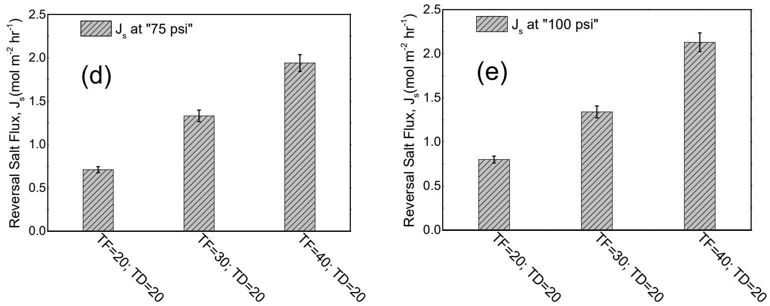


Fig 4. Reverse salt flux for a 1.0 M NaCl draw solution as a function of working temperatures at applied pressures of a) 0 psi; b) 25 psi; c) 50 psi; d) 75 psi; e) 100 psi. The membrane used was a commercial TFC. Draw and feed flow rate were 0.50 L/min each. Error bars indicate standard deviation over three trials.

3.4 Effect of operating temperatures on specific solute flux (Js/Jw) on PRO performance

Specific salt flux (J_s/J_w) is useful to study the effect of reverse salt flux diffusion on PRO performance due to the relationship with water flux and the salt flux. J_s/J_w describes the amount of draw solutes permeating through the membrane, normalized by volumetric water flux (Phillip, Yong, and Elimelech 2010; Tang et al. 2010; Zou et al. 2011). Larger specific solute flux is not desirable, since it may cause enhanced ICP (Lee, Baker, and Lonsdale 1981; Saren, Qiu, and Tang 2011; Yip et al. 2011), and more severe membrane fouling (Zou et al. 2011). The specific solute flux is found to increase along with higher applied pressures and higher operating temperature which can be attributed to the increase of salt flux at higher temperature and pressure.

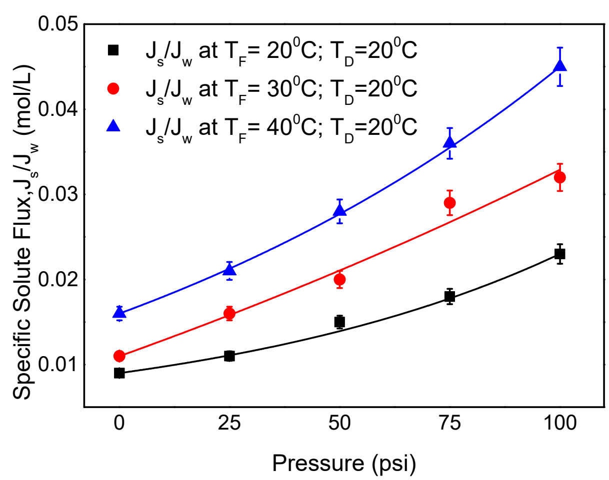


Fig 5. Specific solute flux (J_s/J_w) for a 1.0 M NaCl draw solution as a function of draw solution pressure at different working temperatures. The membrane used was commercial TFC. Draw and feed flow rate were 0.50 L/min each. Error bars indicate standard deviation over three trials.

4 CONCLUSIONS

In the current work, the effect of temperature on PRO performance was investigated. Operating temperature can play a significant role in power production, with an increase powered by waste heat resulting in an ~34% increase in power production. However, higher water flux is associated with higher salt diffusion which may cause severe ICP, which will eventually affects the performance of the membrane used in PRO.

From this study, it has also been seen that with an increase in temperature, specific solute flux (J_s/J_w) was found increased, leading to subsequent draw solute permeation through the membrane.

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