Impact of Membrane Orientation on the Energy Efficiency of Dual Stage Pressure Retarded Osmosis

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Abstract:

The performance of Dual Stage Pressure Retarded Osmosis (DSPRO) was analyzed using a developed computer model. DSPRO process was evaluated on Pressure Retarded Osmosis (PRO) and Forward Osmosis (FO) operating modes for different sodium chloride (NaCl) draw and feed concentrations. Simulation results revealed that the total power generation in the DSPRO process operating on the PRO mode was 2.5 to 5 times more than that operating on the FO mode. For DSPRO operating on the PRO mode, the higher power generation was in the case of 2M NaCl-fresh and 32% the contribution of the second stage to the total power generation in the DSPRO. To the contrast, he total power generated in the DSPRO operating on the FO mode was in the following order 5M-0.6M>5M-0.7M>2M-0.01>2M-0.6M. Interestingly, single stage process operating on the FO mode performed better than DSPRO process due to the severe concentration polarization effects. The results also showed that power density of the DSPRO reached a maximum amount at a hydraulic pressure less than the average osmotic pressure gradient, $\Delta\pi/2$, due to the variation of optimum operating pressure of each stage.

Moreover, results showed that the effective specific energy in the PRO process was lower than the maximum specific energy. However, the effective specific energy of the DSPRO was larger than that of the single stage PRO due to the rejuvenation of the salinity gradient, emphasizing the high potential of the DSPRO process for power generation.

Keyword: Salinity Gradient, Osmotic Energy, Dual Stage PRO, Renewable Energy, PRO Process

1. Introduction:

Dual stage pressure retarded osmosis (DSPRO) has been recently proposed for power generation using a two-stage membrane process [1-4]. Draw and feed solutions enter the first DSPRO stage and diluted draw solution from the first stage goes to a second membrane process to maximize energy recovery from the salinity gradient resource before discharge [Figure 1]. The contribution of the second stage to the total power generation in the DSPRO process depends on the salinity gradient resource and operating parameters [2]. Furthermore, type and concentration of feed and draw solution have a considerable impact on the performance of DSPRO process. For example, experimental work has demonstrated that PRO process performs better on the FO mode when feed solution contains high concentrations of fouling matters [5]. To date, however, there is no study identifying the impact of membrane orientation, active layer facing draw solution (PRO mode) or active layer facing feed solution (FO mode), on the performance of DSPRO process and whether a second stage will be justified when the membrane orientation is switched.

Salinity gradient resource is a key parameter in the design and operation of a successful DSPRO process. Seawater, RO brine, inorganic metal salts, Dead Sea brine, Rift valley water, Jordan water, and Salt Lake water are some examples of the draw solutions proposed [6-9]. These draw solution can be paired with a feed solution of lower osmotic pressure such fresh water, wastewater effluent and seawater to create a sufficient osmotic pressure gradient for water permeation across the PRO membrane. Type of feed and draw solution has significant impact on the performance and operating conditions of the DSPRO process. Wastewater feed solution has been found to promote membrane fouling especially when the process is operated on the PRO mode; i.e. draw solution faces the membrane active layer (DS-AL) [5]. Operating the PRO on the FO mode, i.e. feed solution facing the active layer (FS-AL), has been reported to reduce the membrane fouling propensity but also reduces the water flux [10-14]. Insufficient membrane flux has been reported in the FO mode due to the inability of the membrane to effectively overcome the effects of concentration polarization [8-9]. This phenomenon is not fully understood in the DSPRO process, particularly in the second stage in which the concentration of draw solution is different to that in the first stage. In the DSPRO process, diluted draw solution from the first PRO stage is coupled with a fresh feed solution in the second stage of the DSPRO process. Using fresh feed solution in the second stage rejuvenates the salinity gradient resource and expands the operating conditions beyond the conventional boundaries [2]. The present study evaluated the performance of the DSPRO process on the FO and the PRO operating modes to identify the performance of each stage. Several salinity gradients were considered in this study to investigate the impact of feed and draw solution concentrations on the performance of the first and second stage of the DSPRO process. 5M-0.6M NaCl, 5M-0.7M NaCl, 2M-0.01M NaCl and 2M-0.6M NaCl salinity gradients were investigated in the DSPRO process. 5M NaCl mimics the concentration of Dead Sea solution whereas 0.6M and 0.7M NaCl mimic the concentration of standard seawater (35 g/L) and moderate salinity seawater such as the Mediterranean Sea. On the other hand, 0.01M NaCl resembles the concentration of fresh water and 2M is the concentration of natural salinity gradient resource such as the Salt Lake solution; concentration between 50 g/L and 270 g/L [15].

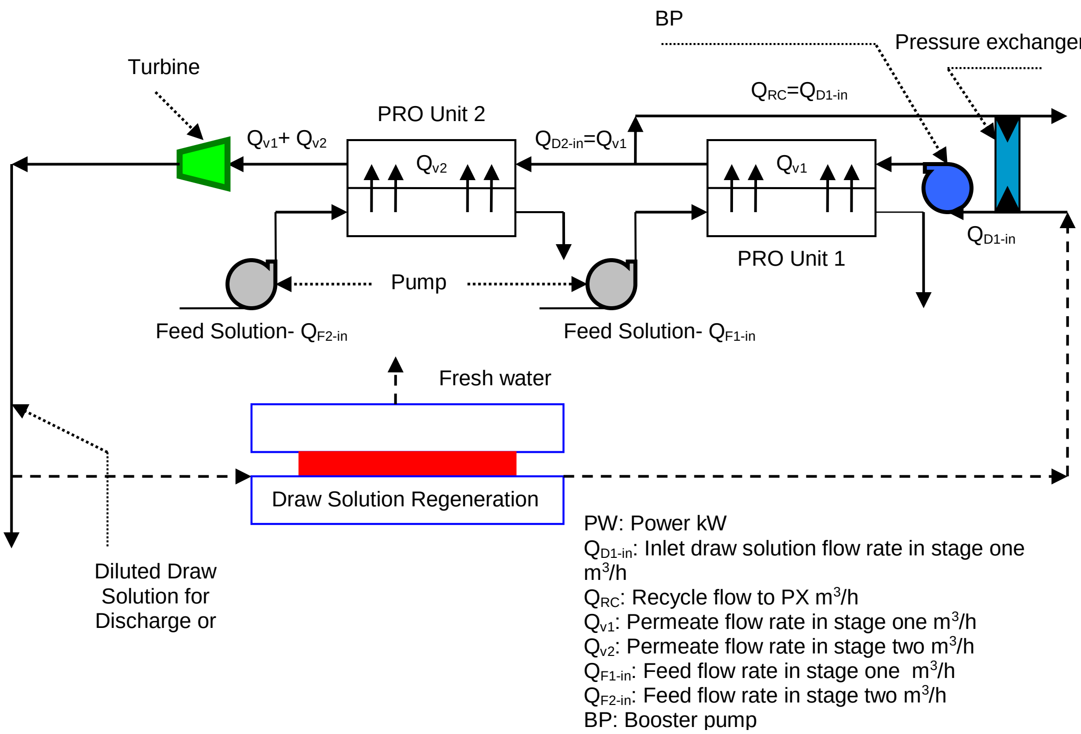


Figure 1: Dual Stage PRO process for power generation from salinity gradient resource

2. Process Modelling

Previous studies demonstrated that theoretical membrane flux is lower than the experimental membrane flux due to the effect of concentration polarization and reverse salt diffusion which is an inherent phenomenon in the membrane filtration processes [16, 17]. As such, the effects of internal and external concentration polarization should be accounted for in the calculations of the PRO water flux. Although many models have been developed for the calculation of water flux in osmotically driven processes [18-20], the following expression has been considered relatively accurate in estimating water flux in the PRO process [18, 21]:

Equation 1 $$J_{w-PRO} = A_w\left(\frac{\pi_{DB}\exp(\frac{-J_w}{k_d}) - \pi_{FB}\exp(\frac{J_w}{k_f} + J_w\frac{S}{D_f})}{1 + \frac{B}{J_w}(\exp(\frac{J_w}{k_f} + J_w\frac{S}{D_f}) - \exp(\frac{-J_w}{k_d})} - \Delta P\right)$$

where, $J_{w\text{-}PRO}$ is the membrane flux in PRO mode (L/m^{2}h), π_{DB} and π_{FB} is the osmotic pressures of the bulk draw and feed solution, respectively (bar), k_d *and* k_f are the mass transfer coefficient of the draw and feed solution respectively (m/h), S is the structural parameter of the support layer (µm), D_f is the solute diffusion coefficient inside the support layer (m^2/h), B is the solute permeability coefficient (kg/m^{2}h), and K is the solute resistivity for diffusion within the porous support layer (h/m). Equation 6 accounts for the effect of external mass transfer on the porous structure PRO membrane process when the draw solution faces the membrane active layer (DS-AL), also called as the PRO mode. It should be mentioned that the ratio of S/ D_f is equal to the solute resistivity for diffusion within the support layer when facing against the feed; K_f (s/m). FO mode, feed solution faces the membrane active layer (FS-AL), has been recommended when feed water contains high fouling matters [12, 13]. The mathematical expression to estimate membrane flux in the FO mode is [14, 18]:

Equation 2 $$J_{w-FO} = A_w\left(\frac{\pi_{DB}\exp\left(\frac{-J_w}{k_d} - J_w\frac{S}{D_d}\right) - \pi_{FB}\exp\left(\frac{J_w}{k_f}\right)}{1 + \frac{B}{J_w}\left(\exp\left(\frac{J_w}{k_f}\right) - \exp\left(\frac{-J_w}{k_d} - J_w\frac{S}{D_d}\right)\right)} - \Delta P\right)$$

where, $J_{w\text{-}FO}$ is the membrane flux when operated in the FO mode (L/m^{2}h). S/ D_d is the solute resistivity for diffusion within the support layer when facing against the draw solution; K_d (s/m). We assumed that k_d=k_f throughout this study. Equations 1 and 2 taking in the consideration the effect of external mass transfer at the porous layer in the calculation of water flux in the PRO membrane [18]. We assumed A_w=1.8*10^{-3}, B=4*10^{-4} m/h, k=0.18 m/h, S=7.2*10^{-4} m, and K=125h/m [18]. Additionally, Van't Hoff equation ($\pi = nCRT$, π is the osmotic pressure, n number of ions, C molar concentration, R gas constant, and T temperature in Kelvin) was used to estimate the osmotic pressure of seawater although it may result in inaccuracies in the predicted water flux at high feed and draw concentrations.

Adding a second stage PRO enhances the energy yield of the salinity gradient resource [1, 2]; power generation in the first and second stage of the DSPRO process is given as [2]:

Equation 3 $$PWn_1 = \Delta P_1 * Q_{v1}$$

Equation 4 $$PWn_2 = \Delta P_2 * Q_{v2}$$

PWn_1 and PWn_2 are the gross power generation in the first and second stage of the DSPRO process, respectively (kW), ΔP_1 and ΔP_2 is the hydraulic pressure difference across the membrane in the first and second stage, respectively (bar), and Q_{v1} and Q_{v2} are the permeate flow rates in stage one and two of the DSPRO process, respectively (m^3/h). Assuming that hydraulic pressure losses in the first stage of the DSPRO process are negligible; i.e. $\Delta P_1 = \Delta P_2$, the total power generation, $PWn\text{-}_{tot}$, in the dual stage PRO process is given as [2]:

Equation 5 $$PWn -_{tot} = \Delta P * (Q_{v1} + Q_{v2})$$

3. Harvesting the osmotic energy of concentrated brine

Defined as the power generated per square meter of membrane (W/m^2), power density (*W*) has been used as an indicator to the PRO process performance [20]. Power density can be calculated from the expression shown in Equation 6 [2]:

Equation 6 $$W = \Delta P * J_w$$

where, ΔP is the hydraulic pressure difference across the membrane (bar) and J_w is the PRO membrane flux (L/m^2h). The maximum specific power generated from a salinity gradient resource can be represented by free Gibbs energy [23]. For a PRO process operating on a counter-current mode, the maximum extractable specific energy from a salinity gradient resource is represented by the following equation [2]:

Equation 7 $$E_m = \frac{nRT(C_D - C_F)^2}{4(C_D - C_F)}$$

Where, E_m is the maximum specific power generation (kWh/m3), n is number of ionic species in solution, R is the gas constant (0.082 L atm/K mol), C_D and C_F are the molar concentrations of draw and feed solutions respectively (M), and T is the temperature in Kelvin. Following Equation 2, E_m increases with the increase of the draw solution concentration and the decrease of the feed concentration. For simplicity, NaCl solution was used for expressing the concentrations of feed and draw solutions in this study. The maximum power generation from salinity gradient resources is explained in Figure 2. Ignoring the effects of internal and external concentration polarization and reverse salt diffusion, coupling Dead Sea (5M) with different seawater (SW) solutions resulted in 1.2 kWh/m^3 to 0.99 kWh/m^3 E_m, the lowest energy yield was for coupling Dead Sea draw solution with 50 g/L salinity SW. On the other hand, E_m of coupling SW with FW increased from 0.17 kWh/m^3 to 0.27 kWh/m^3 with the increase of seawater salinity from 32 g/L to 50 g/L. The maximum energy harvested from Dead Sea-seawater salinity gradients was 4 to 7 times higher than that from seawater- fresh water salinity gradients. This was due to the large osmotic driving force across the PRO membrane in the case of DS-SW salinity gradient resources.

Theoretically, the mixing energy of two solutions of different concentrations would result in a maximum specific energy of E_m but this would not necessarily result in equilibrium between the draw and feed solution concentrations at end of the PRO process. If not recovered, this energy will be wasted with the diluted draw solution discharged to sea. Incomplete osmotic energy recovery in the PRO process is partly due to the phenomenon of concentration polarization in the PRO process. DSPRO process with a separate feed stream to each stage has been proposed to alleviate the effect of concentrated feed solution in the second stage [2, 4]. Fresh feed solution, with concentration lower than that of the first stage feed brine, enhances the energy yield of the second stage because of the increased net osmotic driving force. Greater osmotic pressure triggers high water flux but also high internal concentration polarization as shown in Figure 3. The modulus of internal concentration polarization was calculated from, $e^{J_w K}$, and results show it was larger in the second stage of the DSPRO process with fresh feed than that with feed recycle. Recycling feed solution from the first to the second stage decreased the osmotic driving force and water flux across the membrane. On the other hand, using a fresh feed solution in the second stage promoted higher water flux which is clearly manifested in the higher internal concentration polarization [Figure 3]. Therefore, fresh feed solution will be used in the second stage as illustrated in the Figure 1.

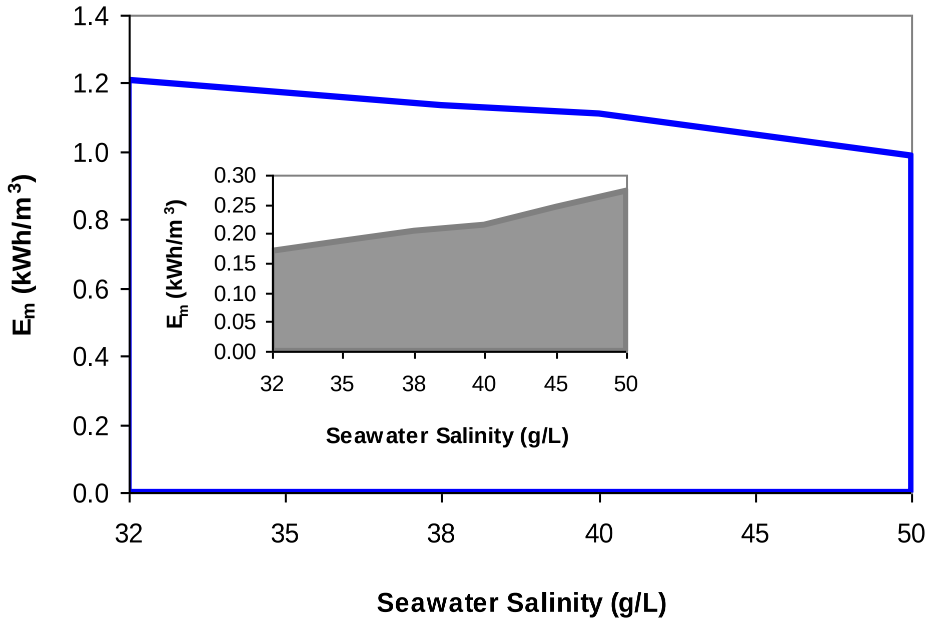


Figure 2: Maximum specific power generation from a number of salinity gradients made of coupling Dead Sea (DS) with seawater (SW) of salinities between 32 g/L and 50 g/L or coupling seawater (SW) with fresh water (FW).

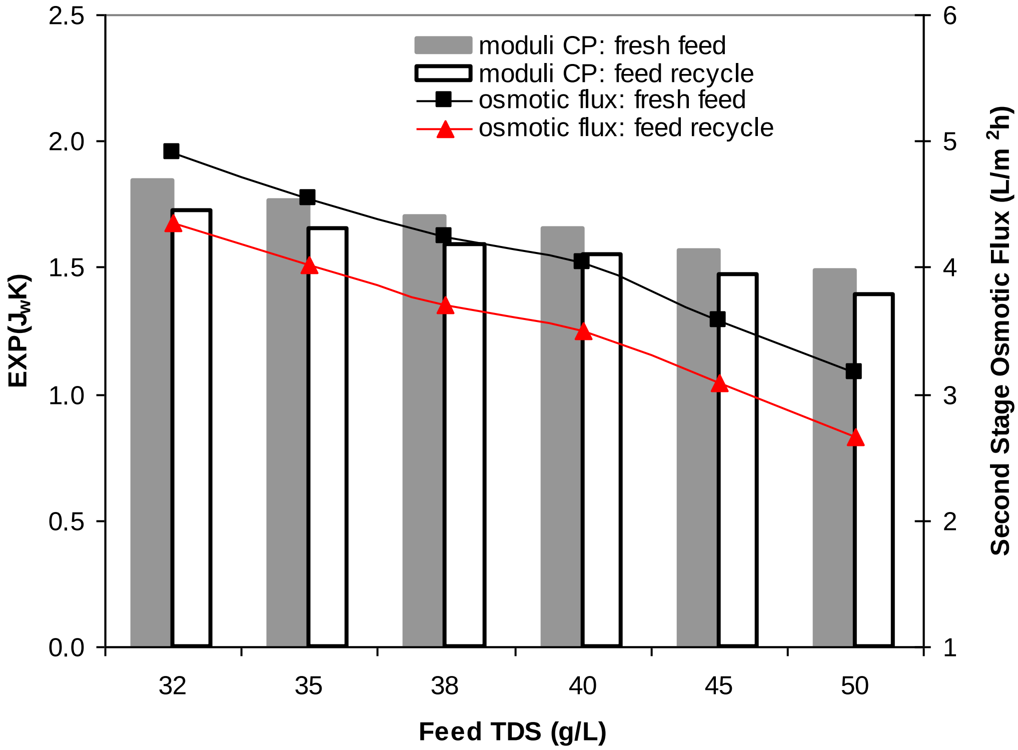
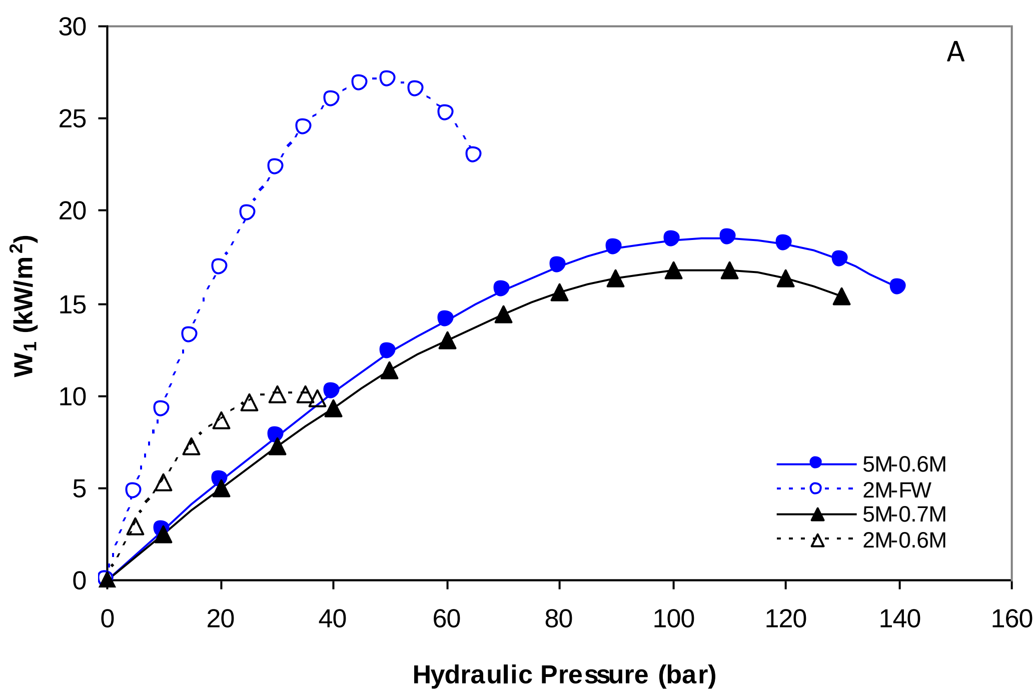


Figure 3: Modulus of internal concentration polarization and net osmotic pressure across the PRO membrane for different salinity gradient resources, draw solution is 5M NaCl, the feed and draw solution flow rates are equal, membrane flux was calculated using Equation 1. Operating parameters are A_w=1.8*10^{-3}, B=4*10^{-4} m/h, k=0.18 m/h, S=7.2*10^{-4} m, and K=125h/m.

4. Performance of Dual stage PRO performance in PRO mode

Performance of the DSPRO process was evaluated in the PRO mode for 5M-0.6M, 5M-0.7M, 2M-0.01M, and 2M-0.6M salinity gradient resources. Results show that power density of the first stage of the DSPRO process, W_1, increased with the increase of hydraulic pressure and reached a maximum amount, W_{max1}, at a hydraulic pressure equals to $\Delta\pi/2$; this observation holds for all type of the salinity gradient resources [Figure 4A]. Increasing the hydraulic pressure over $\Delta\pi/2$ resulted in a gradual decrease of the W_1. For salinity gradient resources 5M-0.6M, 5M-0.7M, 2M-FW, and 2M-0.6M, W_{max1} was 18.5 W/m^2, 16.8/m^2, 27.1 W/m^2 and 10.1 W/m^2 respectively, which is higher than the power density threshold of 5 W/m^2 recommended for an economical PRO process [9]. The higher power density of 2M-FW salinity gradient compared to other salinity gradients emphasized the negative impact of internal concentration polarization on the process performance. Although 5M-0.6M has greater osmotic driving force than 2M-FW salinity gradient resource, severe internal concentration polarization associated with SW feed solution in 5M-0.6M salinity gradient caused a significant drop in the membrane flux and power density. Increasing the concentration of feed solution from 0.6M to 0.7M did not significantly affect the power density of the process when coupled with 5M draw solution. W_{max1}, however, decreased more than 60% when the concentration of feed solution increased from 0.01M (for freshwater) to 0.6M using 2M draw solution concentration. For 0.6M feed solution, increasing the draw solution concentration from 2M to 5M, 2.5 times, did not cause a proportionate increase in W_{max1}. W_{max1} increased from 10.1 W/m^2 for 2M-FW to 18.5 W/m^2 for 5M-0.6M salinity gradient. The disproportionate increase of W_{max1} was due to the severe internal concentration polarization and reverse salt diffusion from the draw to the feed solution. The results suggest that increasing the concentration of draw solution has a limited impact on the performance of PRO process in the case of high concentration feed solution. Furthermore, increasing the osmotic pressure gradient should be encountered with an increase of the hydraulic pressure which could be an issue since the current commercial PRO membranes do not tolerate hydraulic pressures more than 30 bar [2, 13].

For the second stage of the DSPRO process, W_2 increased with increasing the hydraulic pressure and reached a maximum amount of W_{max2} at $\Delta P < \Delta\pi / 2$ then dropped down gradually with the increase of hydraulic pressure over $\Delta\pi / 2$ due to the negligible water flux [Figures 4B]. W_{max2} was 6.8 W/m^2, 5.5 W/m^2, 18.3 W/m^2 and 3.7 W/m^2 for 5M-0.6M, 5M-0.7M, 2M-FW, and 2M-0.6M salinity gradient resources respectively. Results show that W_{max2} was about 37%, 33%, 68%, and 36% of W_{max1}, respectively for 5M-0.6M, 5M-0.7M, 2M-FW, and 2M-0.6M salinity gradient resources. W_{max2} was more than the recommended threshold of 5 W/m^2 for most salinity gradient resources except 2M-0.6M salinity gradient resource in which W_{max2} was 3.7 W/m^2. The results also show that efficiency of the second stage of the DSPRO process was higher when fresh water was the feed solution; i.e. 2M-FW, because of the negligible internal CP effects. Furthermore, the hydraulic pressures for W_{max2} were 35 bar and 60 bar for 2M-FW and 5M-0.6 salinity gradient respectively; the corresponding values for W_{max1} values were 50 bar and 110 bar for 2M-FW and 5M-0.6 salinity gradient respectively. Results show a gap in the optimum hydraulic pressures between the first and second stage of the DSPRO process and this gap increases with the concentration of draw solution. Apparently, increasing the concentration of draw solution induces higher water flux but promotes higher concentration polarization effects at the same. DSPRO process can partially alleviate the impact of concentration polarization in the second stage in which a fresh feed solution is applied. However, the maximum performance of DSPRO occurs at a hydraulic pressure less than the average osmotic pressure gradient of the salinity gradient resource which should be considered in the design criteria of the osmotic power plant.



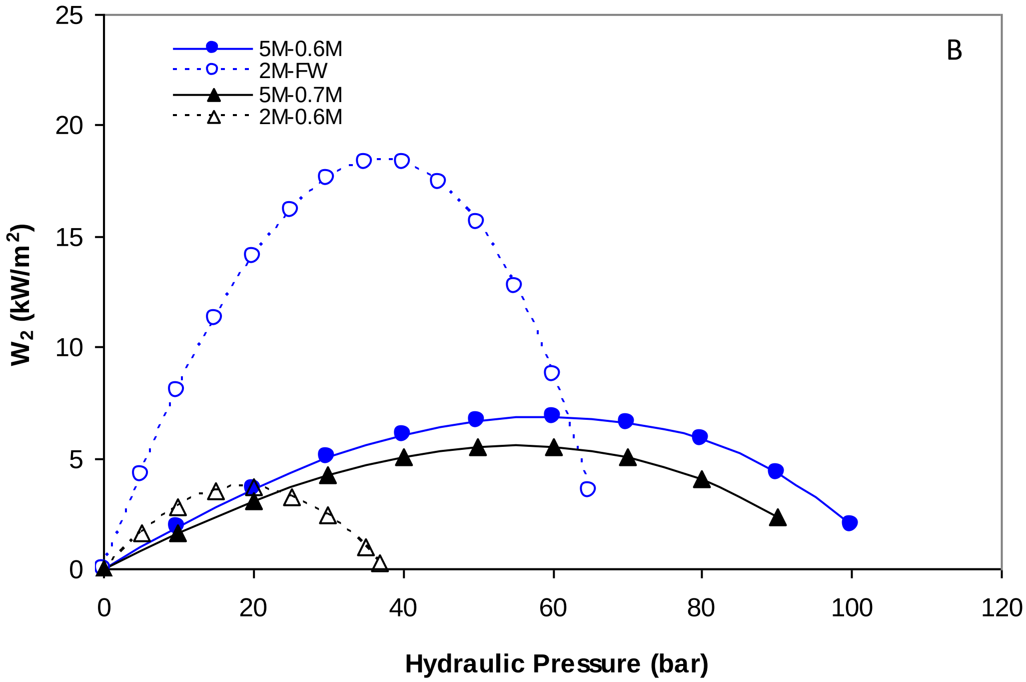
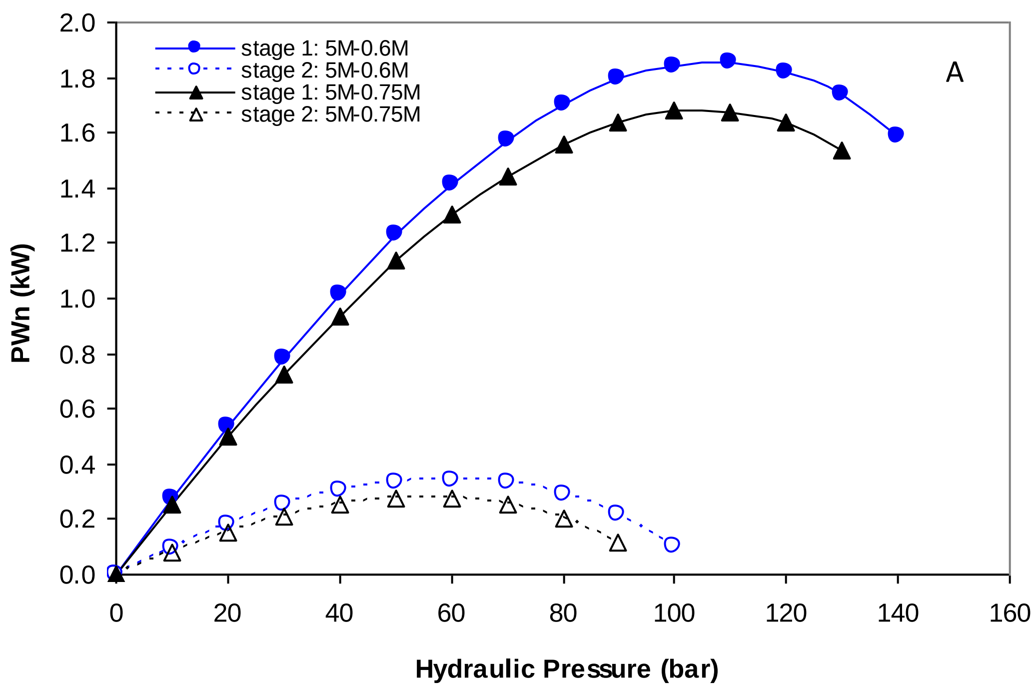


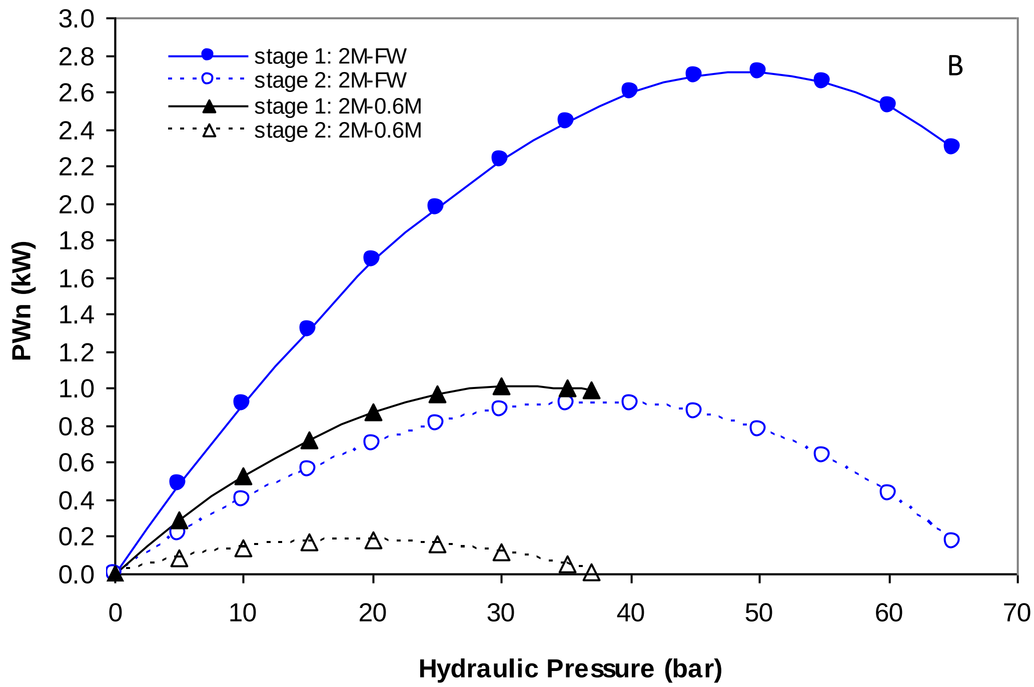
Figure 4: Performance of dual stage PRO process A) power density in stage one B) power density in stage two

Power generation, PWn, of each stage of the DSPRO were calculated to find out the maximum total power generation, PWn_{-tot}, in the DSPRO process. Figure 5A and 5B show the PWn of the first and second stage of the DSPRO process. For 5M-0.6M and 5M-0.7M salinity gradient resources, the range of operating hydraulic pressure in the second stage was narrower than that in the first stage of the DSPRO process [Figure 5A]. The maximum PWn of the first stage occurred at $P = \Delta\pi / 2$; i.e. 110 bar and 100 bar for the 5M-0.6M and 5M-0.7M salinity gradients respectively. On the other hand, the operating pressure of the second stage ranged between 0 bar and 100 bar for 5M-0.6M salinity gradient and 0 bar and 90 bar for the 5M-0.7M salinity gradient. For the second stage of the DSPRO, the maximum PWn occurred at 60 bar for both 5M-0.6M and 5M-0.7M salinity gradients. The maximum PWn-$_{tot}$, which is the sum of first and second stage PWn, occurred at 90 bar and 80 bar for the 5M-0.6M and 5M-0.7M salinity gradients respectively [Figure 5C]. Interestingly, the maximum PWn-$_{tot}$ of the DSPRO occurred at a hydraulic pressure $<\Delta\pi/2$ for both salinity gradient resources. These hydraulic pressures, however, were within the hydraulic pressures range of the first and second stage of the DSPRO process.

For 2M-FW and 2M-0.6M salinity gradient resources, PWn of the first and second stage of the DSPRO process is illustrated in Figure 5B. The maximum PWn of the first and second stage was 2.7 kW and 0.92 kW respectively for 2M-FW salinity gradient resource; PWn in the second stage was about 34% of that in the first stage of the DSPRO process. The maximum PWn of the first and second stage for 2M-0.6M salinity gradient resource was 1 kW and 0.18 kW respectively. Figure 5B shows that the maximum PWn for the first stage occurred at 45 bar and 30 bar for 2M-FW and 2M-0.6M salinity gradient respectively. The corresponding values for the second stage were at 35 bar and 20 bar for 2M-FW and 2M-0.6M salinity gradient respectively. Additionally, the maximum PWn-$_{tot}$ for 2M-FW and 2M-0.6M was at 45 bar and 25 bar respectively. In effect, these hydraulic pressures were within the range of hydraulic pressure in the second stage of 2M-FW and 2M-0.6M. Furthermore, the maximum PWn-$_{tot}$ of 2M-FW was three times higher than that for 2M-0.6M salinity gradient because of the higher net driving force.

Results show that the maximum PWn_{-tot} was 3.7 kW and achieved by 2M-FW salinity gradient then followed by 2 kW for 5M-0.6M, 1.8 kW for 5M-0.7M, and finally 1.1 kW for 2M-0.6M. Low internal concentration polarization on the feed side of the 2M-FW salinity gradient was the trigger for high PWn_{-tot} compared to other salinity gradients which indicates to the significance of feed concentration on the performance of DSPRO. Increasing the concentration of draw solution positively affected the performance of DSPRO but intensifies the effect of concentration polarization and reverse salt diffusion. Introducing a second stage PRO process maximized the energy yield of the process; however, the lower the salinity of feed solution the higher the performance of DSPRO. Fresh water is preferred over a saline feed solution if available to be coupled with a suitable draw solution for the DSPRO process.




stage 1: 2M-FW
stage 2: 2M-FW
stage 1: 2M-0.6M
stage 2: 2M-0.6M
B
PWn (kW)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
70
Hydraulic Pressure (bar)

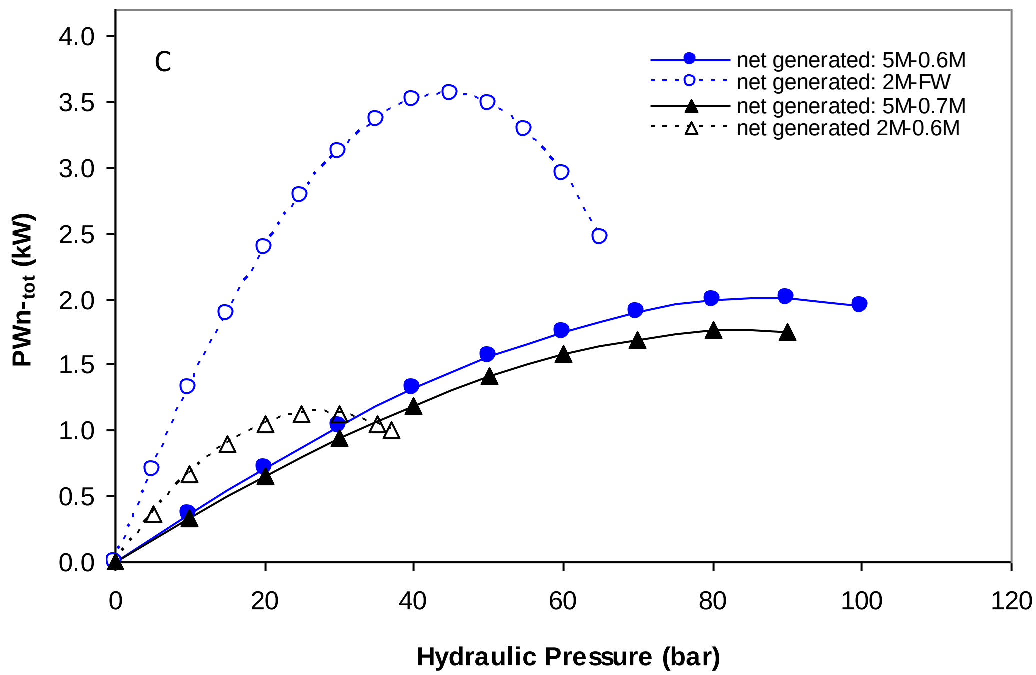


Figure 5: Power consumption in the dual stage PRO process A) net power generation for 5M-0.6M and 5M-0.7M salinity gradient resource B) net power generation for 2M-FW and 2M-0.6M salinity gradient resource C) total net power generation in the PRO process, PWn_{-tot}

5. Dual stage PRO performance in FO mode:

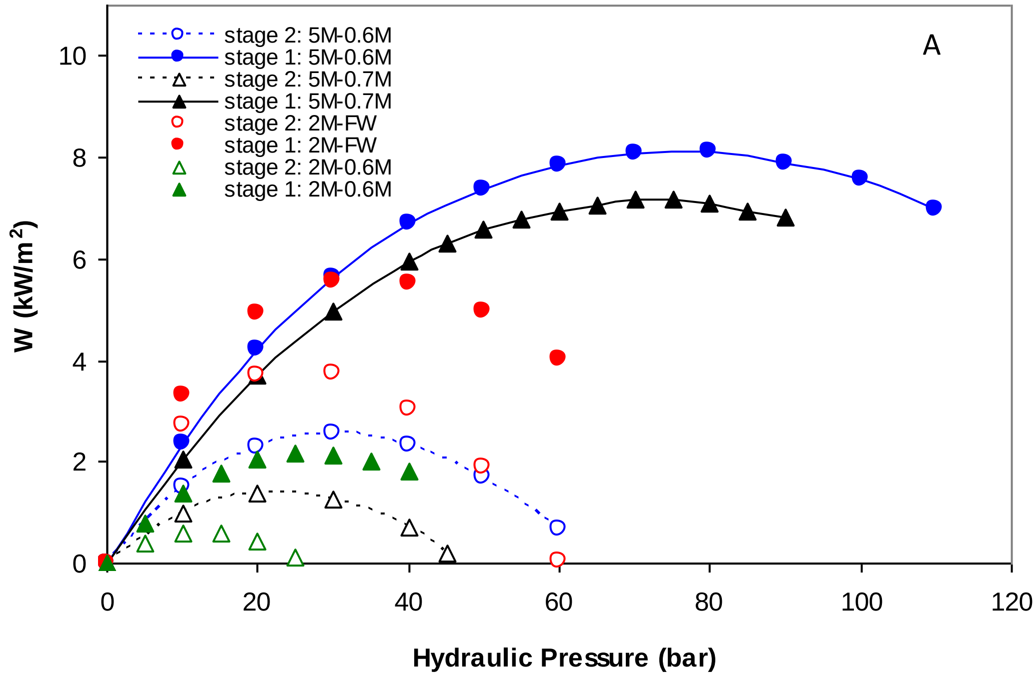
The performance of DSPRO process operating on the FO mode was evaluated and compared with that on the PRO mode [Figure 6]. For 5M-0.6M and 5M-0.7M salinity gradient resources, power density of the first stage increased with increasing the hydraulic pressure and reached a maximum amount, W_{max1}, of 8.1 W/m^2 and 7.2 W/m^2 at 80 bar and 70 bar hydraulic pressures respectively [Figure 6A]. These hydraulic pressures were less than $\Delta\pi/2$ and was due to large difference between the theoretical and effective osmotic driving force as will be illustrated in the following section. W_{max1} for 2M-FW and 2M-0.6M salinity gradient was 5.6 W/m^2 and 2.5 W/m^2 at 30 bar and 25 bar respectively which are slightly deviated from $\Delta\pi/2$. The highest power density in the FO mode belongs to 5M-0.6M salinity gradient followed by 5M-0.7M, 2M-FW and 2M-0.6M salinity gradients respectively. Changing the operating mode from PRO to FO mode caused about 80% reduction in the power density of 2M-FW salinity gradient. This refers to the fact that internal concentration polarization has more serious impact on the process performance than the external concentration polarization hence; higher osmotic driving force would be required in the former operating mode. Table 1 shows the maximum power density of the first and second stage of the DSPRO and hydraulic pressures. W_{max1}, in general, was lower in the FO mode than in the PRO mode for all salinity gradient resources.

For the second stage of the DSPRO process, the maximum power density, W_{max2}, for all salinity gradients occurred at a hydraulic pressure less than that of the first stage [Figure 6A]. W_{max2} for 5M-0.6M and 5M-0.7M salinity gradients was, respectively, 63% and 75% lower than that at the PRO mode. For 2M-FW and 2M-0.6M salinity gradients, more than 80% of power density was lost by changing the operating mode from the PRO to FO mode. Additionally, W_{max2} for all salinity gradient resources was lower than the threshold of 5 W/m^2 which is has been suggested for an economic PRO process [Table 1]. Apparently, PRO process suffers when it is operated on the FO mode although it was recommended in the case of impaired quality feed solutions to reduce membrane fouling [5]. But this would be achieved on the expense of power density and should be accounted for in the early stage of the process design.

Power generation, PWn, of the first and second stage of the DSPRO process was calculated to evaluate the process efficiency (Figure 6B). There was a mismatch of the optimum hydraulic pressure of the first and second stage of the DSPRO process. For 5M-0.6M salinity gradient, the maximum power generation was 0.81 kW and 0.13 kW for the first and second stage of the DSPRO process at 80 bar and 30 bar respectively, and the maximum PWn_{-tot} was 0.82 kW at 50 bar. The hydraulic pressure gap between the first and second stage of the DSPRO process was 50 bar for the 5M-0.7M salinity gradient. The maximum PWn was 0.72 kW and 0.07 kW for the first and second stage at 70 bar and 20 bar respectively, but the maximum PWn_{-tot} was 0.64 kW at 45 bar. As a matter of fact, the maximum PWn of the first stage was 0.72 kW at 70 bar; this hydraulic pressure was out of the hydraulic pressure range of the second stage which was between 0 bar and 45 bar. In such cases it is, probably, better to apply a single stage PRO process. For the 2m-FW salinity gradient, the maximum PWn was 0.56 kW and 0.2 kW at 30 bar for the first and second stage of the DSPRO respectively [Figure 6B]. The maximum PWn_{-tot} was 0.74 kW at 30 bar; this was 20% of the maximum PWn_{-tot} on the PRO mode and attributed to the severe concentration polarization effects. For 2M-0.6M salinity gradient, the maximum PWn of the first stage was 0.22 kW at 25 bar and was 0.03 kW at 10 bar for the second stage of the DSPRO process. However, the maximum

PWn_{-tot} was 0.23 kW at 20 bar; this hydraulic pressure lies at the upper hydraulic pressure range of the second stage which rendered its contribution to the maximum PWn_{-tot} insignificant [Figure 6C]. Therefore, adding a second stage PRO process can not be justified in such case.

In general, the performance of DSPRO was better on the PRO mode. The contribution of the second stage of the DPSRO was insignificant for most salinity gradients when the process was operating on the FO mode. This was due to the severe impact of concentration polarization on the water flux. Despite the advantages of FO operating mode, it has been recommended to reduce the membrane fouling when wastewater effluent is the feed solution [5]. In such cases, the feed solution would be facing the membrane active layer to avoid serious fouling problems caused by the organic constituents in the feed solution [25]. For example, Megaton pilot plant which uses RO brine and wastewater effluent as the salinity gradient resource is operating on the FO mode [13]. The pilot plant satisfactory performance could be attributed to the advanced specifications of the PRO membrane used in the process.


A
stage 2: 5M-0.6M
stage 1: 5M-0.6M
stage 2: 5M-0.7M
stage 1: 5M-0.7M
stage 2: 2M-FW
stage 1: 2M-FW
stage 2: 2M-0.6M
stage 1: 2M-0.6M
W (kW/m2)
Hydraulic Pressure (bar)
0
2
4
6
8
10
0
20
40
60
80
100
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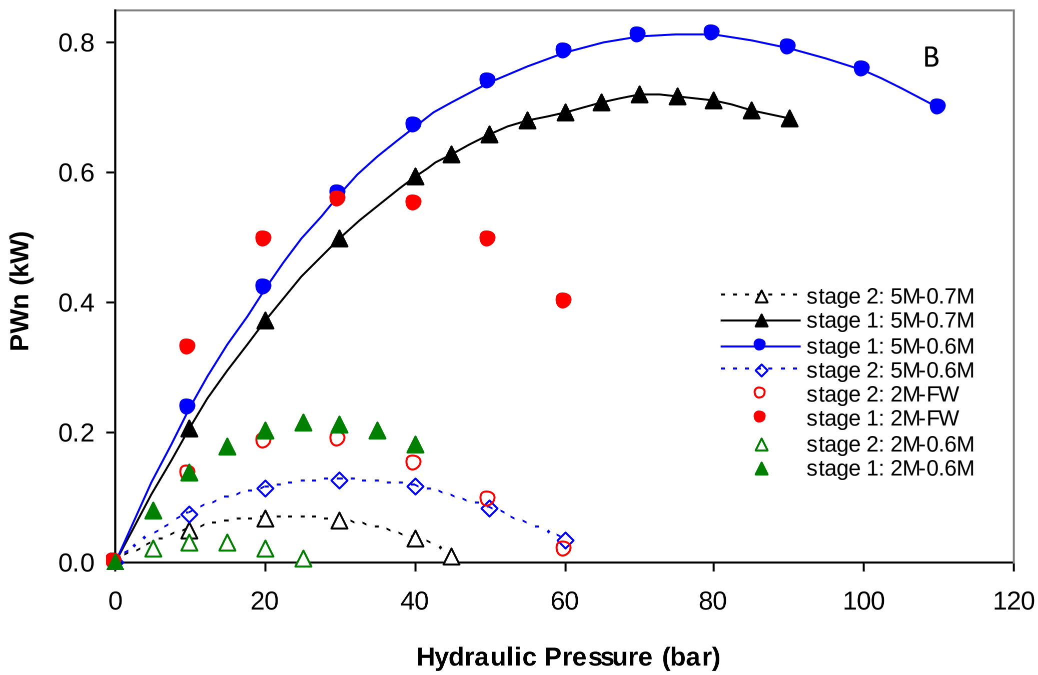


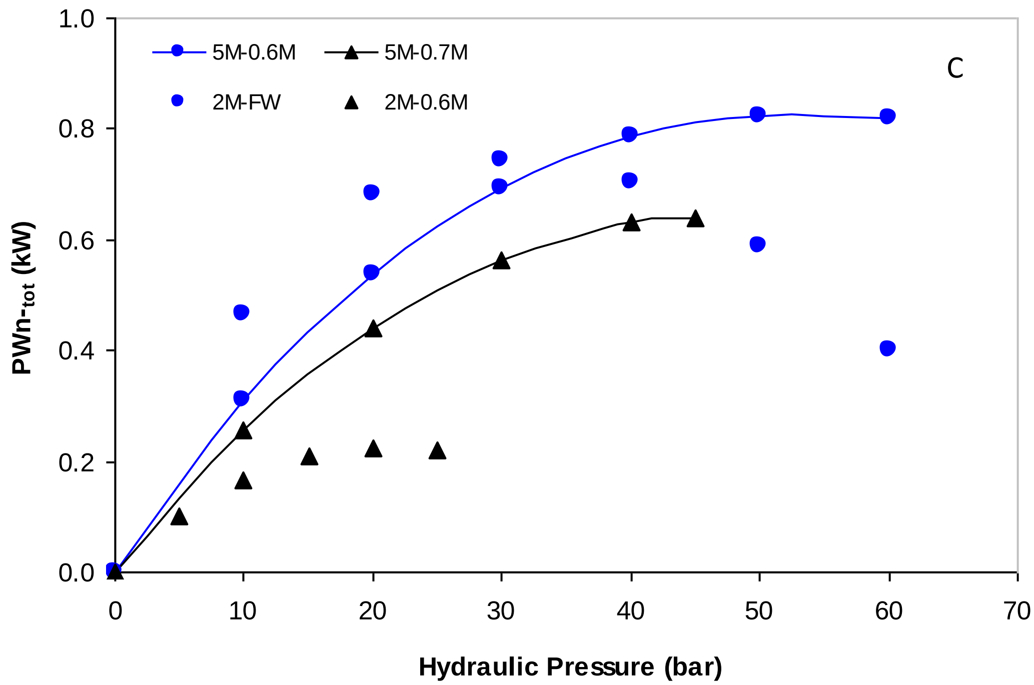


Figure 6: Performance of dual stage PRO process (FO Mode) A) power density B) PWn C) PWn-tot

Table 1: maximum power density of the first and second stage of the DSPRO process, total power generation and the hydraulic pressure for 5M-0.6, 5M-0.7M, 2M-FW, 2M-0.6M salinity gradients. P_1 and P_2 are the hydraulic pressure of the first and second stage of the DSPRO process, P is the hydraulic pressure at which power density reaches a maximum amount for the DSPRO system

			FO Mode			
SGR	W_{max1}	P_1	W_{max2}	P_2	$Pwn\text{-}_{tot}$	P
5M-0.6M	8.1	80	2.5	30	2	50
5M-0.7M	7.2	70	1.4	20	1.8	45
2M-FW	5.6	30	3.7	30	3.6	30
2M-0.6M	2.2	25	0.6	10	1.1	20
			PRO Mode			
5M-0.6M	18.5	110	6.9	60	0.82	90
5M-0.7M	16.8	100	5.5	60	0.64	80
2M-FW	27.1	50	18.3	35	0.74	45
2M-0.6M	10.1	30	3.7	20	0.23	25

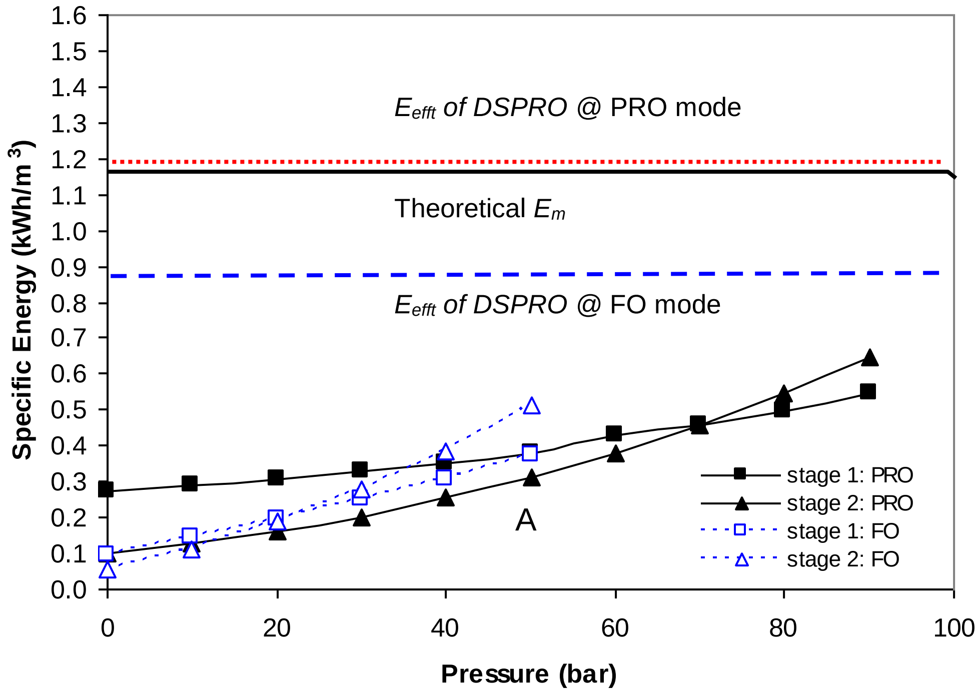
6. Effective salinity gradient resource:

Maximum specific energy, E_m, is the maximum energy can be extracted from a salinity gradient resource in the PRO process at designated hydraulic pressure. In non-ideal PRO system, E_m is affected by the intrinsic properties of the PRO membrane during the filtration process. Therefore, there is a gap between the theoretical E_m and effective specific energy E_{eff} due to the difference between the theoretical and the effective concentrations of feed and draw solutions at the membrane surface. In the ideal system, the theoretical maximum specific energy, E_m, does not include the effects of concentration polarization (CP) and reverse salt diffusion (RSD) while the E_{eff} should account for these effects in the calculation of osmotic energy. During the filtration process, the effective concentration of draw and feed solutions at the membrane surface, C_{DM} and C_{FM} respectively, are affected by the internal, external concentration polarization and reverse salt diffusion phenomena which result in the dilution and concentration of the draw and feed solution respectively. The intrinsic properties of PRO membrane and type of salinity gradient resource determine the amount of these effects on the E_{eff}.

The total effective specific energy, E_{efft}, was calculated as the sum of E_{eff} in the first and second stage of the DSPRO process, $E_{efft} = E_{eff1}+E_{eff2}$, and results were compared with the E_m to highlight the adverse impact of CP and RSD. C_{DM} and C_{FM} were calculated on the FO and PRO modes for each stage of the DSPRO process for 5M-0.6M and 5M-0.68M salinity gradient resources knowing that the outlet concentration of draw solution from the first stage were the inlet concentrations of the second stage. E_m was calculated at $P = \Delta\pi / 2$ and compared with the E_{eff} obtained at 50 bar and 45 bar for 5M-0.6M and 5M-0.7M salinity gradient operating on the FO mode, respectively. The corresponding values for 5M-0.6M and 5M-0.7M salinity gradients operating on the PRO mode were 90 bar and 80 bar respectively. As mentioned before, these hydraulic pressures are the optimum operating pressures for the DSPRO process; i.e. E_{eff} reaches a maximum amount. Furthermore, it is worth reminding here that E_m for 5M-0.6M and 5M-0.7M salinity gradients at $P = \Delta\pi / 2$ was 1.17 kWh/m^3 and 1.11 kWh/m^3 respectively. In the case of DSPRO and 5M-0.6M salinity gradient, the calculated E_{eff1} was 0.54 kWh/m^3 and 0.37 kWh/m^3 in the PRO and FO modes respectively; the corresponding values of E_{eff2} were 0.65 kWh/m^3 and 0.51 kWh/m^3 in the PRO and FO modes respectively [Figure 7A]. According to these results, E_{eff1} was only 46% and 32% of the E_m for DSPRO process operating on the PRO and FO mode respectively; the corresponding values for E_{eff2} were 55% and 44% of the E_m for DSPRO process operating on the PRO and FO modes respectively. CP and RSD are responsible for the underperformance of the DSPRO process, i.e. $E_{eff} < E_m$, and these effects were more severe in the first stage than in the second stage of the DSPRO process because of the larger permeation flow which resulted in a higher dilution and concentration of the draw and feed solution respectively. On the other hand, E_{efft} was 1.19 kWh/m^3 and 0.88 kWh/m^3 on the PRO and FO mode, respectively. Apparently, E_{efft} of the PRO mode approached the E_m of 5M-0.6M salinity gradient resource. Mainly, this was due to i) replacement of feed solution brine of the second stage with a fresh one which expanded the operating boundaries of salinity gradient resource, and ii) dilution and concentration of feed and draw solution, respectively, along the PRO module in a full POR module has not been accounted for the limited area PRO system.

For 5M-0.7M salinity gradient operating on the PRO mode, the values of E_{eff1} and E_{eff2} were 0.47 kWh/m^3 and 0.56 kWh/m^3, respectively; the corresponding values for the FO mode were 0.27 kWh/m^3 and 0.61 kWh/m^3, respectively [Figure 7B]. E_{eff1} was 43% and 24% of the E_m for the PRO and FO modes respectively, whereas E_{eff2} was 50% and 55% of the E_m for the PRO and FO mode respectively. E_{efft} was 1.03 kWh/m^3 and 0.88 kWh/m^3 for the PRO and FO mode respectively; these values are lower than the E_m of 5M-0.68M salinity gradient, 1.11 kWh/m^3 [Figure 7B]. E_{efft} of the PRO mode was 26% higher than that of the FO mode for 5M-0.6M salinity gradient whereas the difference was 15% between the PRO and FO mode for 5M-0.7M salinity gradient.

Simulation results show that E_m was higher than the E_{eff} of the first stage of the DSPRO process. Adding a second PRO stage reduced the gap between E_m and E_{eff} but DSPRO process performed better in the PRO mode than in the FO mode because of the higher CP and RSD in the FO mode. PRO mode is more suitable for seawater and freshwater feed solutions which can be treated by conventional processes whereas FO mode is suitable for a low quality feed solutions. It should be noted that the total E_{eff} is strongly dependent on the intrinsic properties of the PRO membrane and higher performance can be achieved by reducing the effects of CP and RSD.


E_{efft} of DSPRO @ PRO mode
Theoretical E_m
E_{efft} of DSPRO @ FO mode
A
stage 1: PRO
stage 2: PRO
stage 1: FO
stage 2: FO
Specific Energy (kWh/m^3)
Pressure (bar)

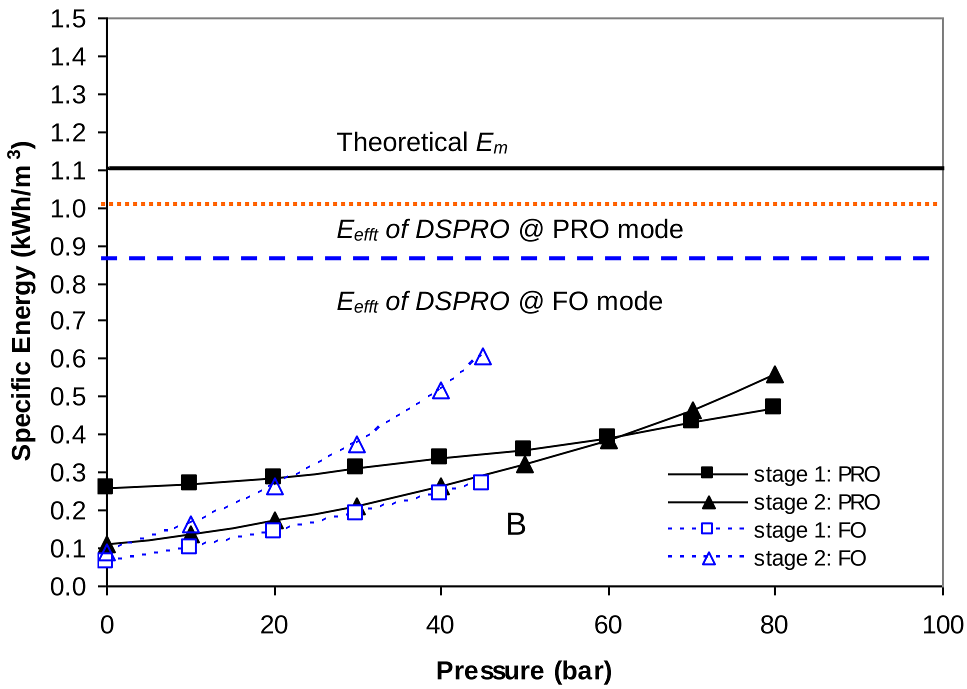

Theoretical E_m
E_{efft} of DSPRO @ PRO mode
E_{efft} of DSPRO @ FO mode
B
stage 1: PRO
stage 2: PRO
stage 1: FO
stage 2: FO
Specific Energy (kWh/m^3)
Pressure (bar)

Figure 7: Impact of feed pressure on the maximum specific energy of DSPRO at different salinity gradient resources A) 5M-0.6M B) 5M-0.68M g/L. Theoretical maximum energy, E_m (solid line), theoretical effective E_m of PRO mode (intermittent line), and theoretical effective E_m of FO mode (dashed line)

Conclusion:

The impact of membrane orientation on the performance of the DSPRO was evaluated using different salinity gradients. Results showed that performance of the DSPRO was higher at lower feed solution concentrations. High feed concentrations affected the process performance significantly and particularly the second stage, which becomes superfluous at high feed concentrations. Furthermore, the DSPRO process performed better when was operating on the PRO mode with a maximum $PWn\text{-}_{tot}$ 5 times higher than that on the FO mode. Severe concentration polarization and reverse salt diffusion were responsible for the underperformance of the DSPRO operating on the FO mode. the contribution of the second stage to the total power generation in the DSPRO process was inconsiderable when it was operated on the FO mode, particularly at low draw solution concentrations; i.e. 2M-0.6M and 2M-0.01M salinity gradients. For the PRO mode, 32% increase in the power generation was achieved in the second stage for 2M-0.01M salinity gradient resource. The results indicate that the performance of the DSPRO varies according to the type of the salinity gradient resource and membrane orientation, which should be considered in the design criteria of the DSPRO plant.

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