Modelling and Optimization of Modular System for Power Generation from a Salinity Gradient

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Abstract

Pressure Retarded Osmosis (PRO) has been proposed for power generation from a salinity gradient resource. The process has been promoted as a promising technology for power generation from renewable resources, but most of the experimental work was about the laboratory size. To date, PRO optimization and operation is based on parametric studies performed on a laboratory scale units, which left a gap in our understanding of its behavior in a full scale modular system. A computer model has been developed to predict the performance of PRO process and optimization of key operating parameters. Process modeling process has been performed on a multi-modules system and impact of key operating parameters on the process performance has been evaluated.

The results showed that the optimized operating parameters in a laboratory scale PRO unit are not valid in the full scale module. Many studies have suggested that power generation in the PRO process reaches an optimum amount when the hydraulic pressure is equal to $\Delta P = \Delta\pi / 2$. Furthermore, for a PRO process operating under constant pressure, the optimum power generation is achieved at the feed/draw solution fraction in a mixed solution equal to 50%. While these optimum values are valid in a laboratory scale unit or in the ideal PRO process, they are not applicable for an ideal PRO process. Simulation results revealed that the optimum hydraulic pressure in the PRO process depends on the salinity gradient and the osmotic pressure gradient across the PRO membrane. Also, feed/draw solution fraction in mixture in entirely dependent on the salinity gradient and the number of the PRO modules in the pressure vessel. In fact, the optimized PRO process would operate at a hydraulic pressure less than, hence the characteristics of the PRO membrane and pump specifications are different to that suggested in previous studies. The results here demonstrate that the energy output from the optimized PRO process is up to 54% higher than that in the normal (unoptimized) PRO system. The results are promising and will encourage further research in the salinity power plant technology.

Keywords: Renewable energy, Pressure retarded osmosis, Membrane technology, Salinity gradient, Process optimization

1. Introduction:

Renewable energy resources have been profoundly investigated over time to provide an alternative source to fossil fuel energy and secure long term increasing demands on energy. Amongst the emerging renewable energy technologies, salinity gradient power plant stands out as one of the most promising process [1-5]. Salinity gradient energy conversion can be achieved by pressure retarded osmosis (PRO) or reverse electrodialysis (RED) processes [6]. In the RED technology, ions diffuse from the high to the low salinity solution cell separated by an ion exchange membrane [7, 8]. Stacks of cation and anion exchange membranes are alternately packed between two electrodes connected to an electrical load. Pressure retarded osmosis operates in a slightly different way to ERD. The high and low concentration solutions are separated by a semipermeable membrane that rejects ionic species but allows water molecules to pass through [8]. The high concentration solution (draw solution) is pressurized and fed into a PRO membrane for fresh water extraction from the low salinity (feed solution). Chemical potential converts into hydraulic energy as fresh water transports from the feed to the draw solution side. Draw solution is depressurized in a hydroturbine after leaving the PRO membrane for power generation [figure 1].

Despite the high potential of salinity power plant, PRO technology has not been commercialized yet. Several pilot plants have been tested worldwide in addition to the large number of laboratory size experiments. First pilot plant was tested by Statkraft using seawater and river water as a salinity gradient was less successful to satisfy the required energy demands [3]. This is, probably, because of the low osmotic pressure driving force across the PRO membrane [3]. Subsequent pilot plant test in Mega-ton project, Japan, demonstrated better results with 7.7 W/m^2 power density [9], that is greater than recommended threshold of 5.5 W/m^2 [3]. Toyobo hollow fiber membrane was used in conjunction with reverse osmosis (RO)-wastewater salinity gradient for power generation. With Toyobo membrane, a maximum 30 bar feed pressure can be applied on the draw solution side if the PRO membrane [10]. However, researchers have developed laboratory scale membranes with high water flux and can tolerate a wide range of hydraulic pressure that exceeds 30 bar. Henrik et al, carried out PRO experiment at 70 bar using 5M NaCl draw solution to reach power density in excess of 5.5 W/m^2 [11]. Rong et al, reported 4.3 W/m^2 power density at 12 to 13 bar hydraulic pressure using wastewater RO retentate and 1M NaCl feed and draw solution, respectively [12]. The research group used in house developed hollow fiber PRO membrane and experiment was performed at Forward Osmosis (FO) mode [AL-FS] to eliminate the pretreatment of feed solution. Shung and co-workers achieved 38 W/m^2 at 30 bar hydraulic pressure using thin film composite hollow fiber membrane [13]. The salinity gradient resource was DI water feed solution and 1.2M NaCl draw solution. In an experiment to evaluate the structural stability of PRO membrane researchers conducted PRO experiment over 10 hours on a laboratory fabricated membrane polyamide membrane [14]. A power density of 12.8 W/m^2 was achieved at 17.2 bar hydraulic pressure. Rong et al, performed a laboratory test to evaluate the stability of polyamide PRO membrane [15]. The research group reported 19.2 W/m^2 power density at 15.0 bar hydraulic pressure using 1.0 M NaCl and DI water as the draw and feed solution, respectively. Cath et al, evaluated commercially available membrane for POR process [16]. The study found that thin film composite (TFC) polyamide membrane from Hydration Technology Innovations (HTI) is the most stable membrane with 22.6 W/m^2 power density at 41 bar hydraulic pressure using 2M NaCl draw solution. Unfortunately, membrane deformation was detected at 35 bar hydraulic pressure.

Most of researchers and scientists still recommend optimum values of hydraulic pressure and feed to draw mixing ratio that obtained from a laboratory scale PRO process ignoring the difference in the hydrodynamic conditions between laboratory and full scale membrane [5, 17]. Dilution and concentration of draw and feed solution in a full scale PRO module affect the osmotic driving force and extractable energy along the PRO membrane. In the current study, Gray Wolf Optimization (GWO) algorithms was applied to identify the optimum hydraulic pressure and feed to draw ration that is required to maximize the energy output from salinity gradient in the PRO process. The performance of PRO was optimized in a full scale PRO module using a computer model and GWO algorithms. Different types of salinity gradients were tested to mimic a number of natural feed and draw solutions that would have been suggested in the PRO process.

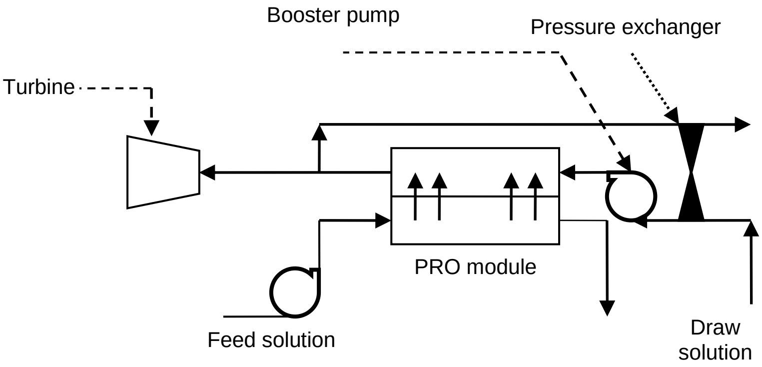


Figure 1: A schematic diagram of PRO process

2. Methodology

2.1 PRO model

The computer model was used to calculate water flux in the PRO process taking into account the impact of concentration polarization and external resistance along the PRO module. Water flux along the PRO module was calculated from the following equation [18]:

$$J_{w,nx} = A_w\left(\frac{(nRTM_{Di,nx}(1+\frac{Q_{Di,nx}}{Q_{Do,nx}})/2)\exp(\frac{-J_w}{k_d}) - (nRTM_{Fi,nx}(1-\frac{Q_{Fi,nx}}{Q_{Fo,nx}})/2)\exp(J_wK+\frac{J_w}{k_f})}{1+\frac{B}{J_{w-x}}(\exp(J_wK+\frac{J_w}{k_f})-\exp(\frac{-J_w}{k_d}))} - \Delta P\right)$$

(1)

where, n is number of ions in the solution, R is the gas constant, and T is the temperature in Kelvin (^{o}C+273). A_w and B were assumed to be 1.23 L/hm^2·bar and 2.6 kg/hm^2 respectively, k_d=k_f=0.18 m/h, and K=31 h/m, $C_{Di,nx}$ is the inlet concentration of the draw solution at the distance x along the membrane, $C_{Fi,nx}$ is the inlet concentration of the feed solution at the distance x along the membrane, $Q_{Di,nx}$ and $Q_{Do,nx}$ are the inlet and outlet flow rate of the draw solution, respectively, and $Q_{Fi,xn}$ and $Q_{Fo,xn}$ are in the inlet and outlet flow rate of feed solution at distance x along the membrane, respectively [18]. Equation 1 accounts for concentration polarization and external resistance in the PRO membrane [9, 21]. Equation 1 is valid for PRO membrane operating on the PRO mode; i.e. draw solution faces the active layer. More details on the model derivation can be found on literature [18]. The fractions of draw and feed volumes, λ_D and λ_F respectively, in the mixture solution were calculated from the following equations:

$$\lambda_D = \frac{\gamma_D}{\gamma_D + \gamma_F} \quad [2]$$

$$\lambda_F = \frac{\gamma_F}{\gamma_F + \gamma_D} \quad [3]$$

where, γ_D and γ_F are the volumetric flow rates of draw and feed solution. Specific energy generation, Es (kWh/m^3), was calculated at different operating conditions using the following expression:

$$Es = \frac{\Delta P * Q_p}{Q_D + Q_F} \quad [4]$$

where, ΔP is the hydraulic pressure of the draw solution entering the hydroturbine (bar) and Q_p, Q_D and Q_F are the permeate, draw and feed solution flow rates, respectively. In this study, GWO was applied to find the optimum hydraulic pressure and mixing ratios in the PRO system. Es in the optimized PRO process was compared with that in the unoptimized PRO process using salinity gradient resource.

2.2. Grey Wolf Optimization (GWO)

The Grey Wolf Optimization (GWO) is a meta-heuristic method proposed by Mirjalili and Lewis [19]. It mimics the leadership hierarchy and the hunting process of the grey wolves in nature. The social dominant hierarchy including three different types of grey wolves in GWO: the leader, namely α, the second level grey wolf, namely β and the third level grey wolf, namely δ. The grey wolf α is the leader of the navigation whereas β and δ are responsible for provide promising solutions. The hunting and navigating behaviour for every grey wolf is the same. When the hunting mechanism is introduced in designing the GWO technique, there are three main characteristics of grey wolves: tracking prey, encircling prey and attacking towards prey.

In the mathematical GWO model, the prey is considered as the optimum. The above hunting strategy is simulated as the optimization process. The three-dominant hierarchy α, β and δ are considered as the best solution, the second fittest solution and the third fittest solution, respectively. The next move of the current search agent is decided based on the current best solution and the global best three candidate solutions α, β and δ.

3. Results

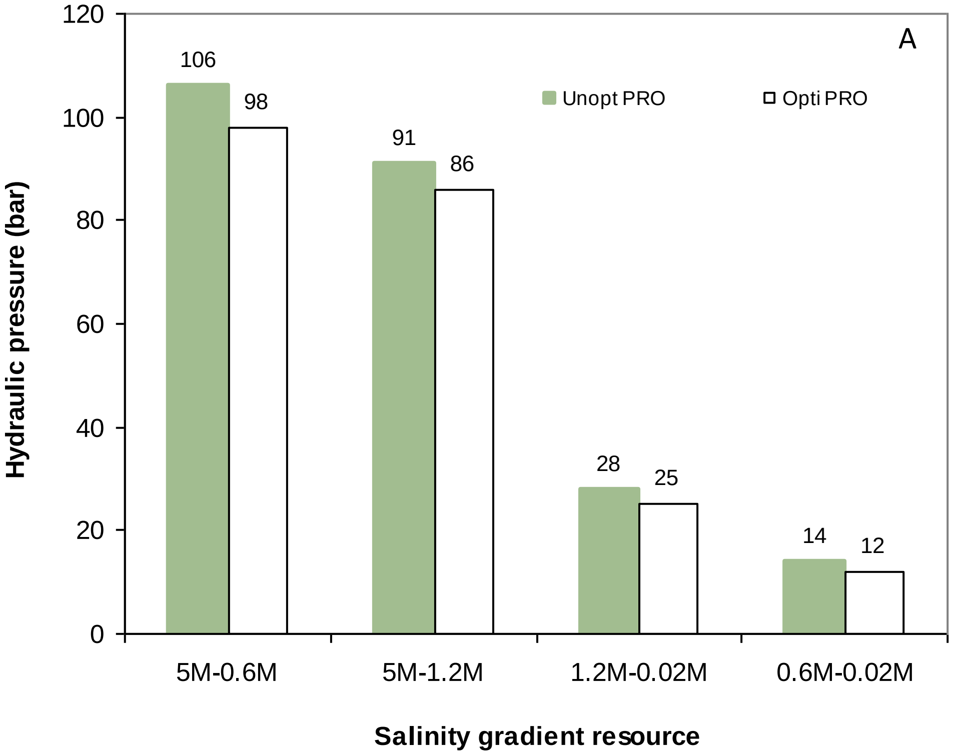
3.1 Hydraulic pressure optimization

Previous studies recommended that the optimum hydraulic pressure for the power density to reach a maximum amount is $\Delta P = \Delta \pi / 2$ [4, 5]. The value has been experimentally validated on a flat sheet PRO unit as well as in a full scale ideal PRO process; i.e. ignoring the effect of concentration polarization [5]. We performed PRO optimization for a full scale module taking into account the impact of concentration polarization and results were compared with that from unoptimized PRO process. Four salinity gradient resources were evaluated using sodium chloride salt, these are 5M-0.6M, 5M-1.2M, 1.2M-0.02M and 0.6M-0.02M to resemble field situation of Dead Sea-seawater, Dead Sea-RO brine, RO brine-wastewater, and seawater-wastewater, respectively.

Results in Figure 2A show hydraulic pressure in optimized and unoptimized PRO process consists of one full scale module. In general, hydraulic pressure was 5% to 14% lower in the optimized PRO compared to the unoptimized PRO process. The largest difference was 14% for 0.6M-0.02M salinity gradient followed by 7.5%, 5.5% and 11% for 5M-0.6M, 5M-1.2M and 1.2M-0.02M salinity gradients, respectively. Water flux in the POR module is shown in Figure 2B. Optimized PRO processes exhibited higher water flux than unoptimized PRO processes because of the higher net driving force across the optimized PRO process. Water flux decreased across the PRO membrane due to osmotic pressure decrease as a result of the dilution of draw solution and the concentration of feed solution. Figure 2C shows the net energy output in the optimized and unoptimized PRO processes. Hydraulic pressure optimization resulted in none to subtle increase in the energy output in the PRO process. 5M-0.6M and 5M-1.2M salinity gradients witnessed 0.7% and 0.6% increase in energy output due to pressure optimization while 1.2M-0.02M and 0.6M-0.02M salinity gradients showed no improvement in energy output due to optimization. However, the advantage of optimization was that optimized PRO process requires less pressure for operation. This would be reflected on the type and characteristics of PRO membrane and high pressure pump and eventually the capital cost of the PRO process.

3.2. Optimization of draw solution in mixture

In irreversible PRO process, researchers proposed that the optimum draw solution to mixtures ratio is 50% at a hydraulic pressure equal to $\Delta P = \Delta \pi / 2$ so that the energy output reaches a maximum value [4]. We performed draw solution optimization in the mixture at $\Delta P = \Delta \pi / 2$ for a number of salinity gradients [Figure 3]. Apparently, optimized PRO process required γ_D less than 0.5 that is recommended in previous studies [Figure 3A]. The optimum γ_D was between 0.35, 0.33, 0.31, and 0.26 for 5M-0.6M, 5M-1.2M and 1.2M-0.02M salinity gradients, respectively. This suggests that γ_D decreased with decreasing the osmotic pressure gradient across the membrane due to the lower permeation flow and hence draw solution effect. Optimization results in 30% to 48% decrease in γ_D.



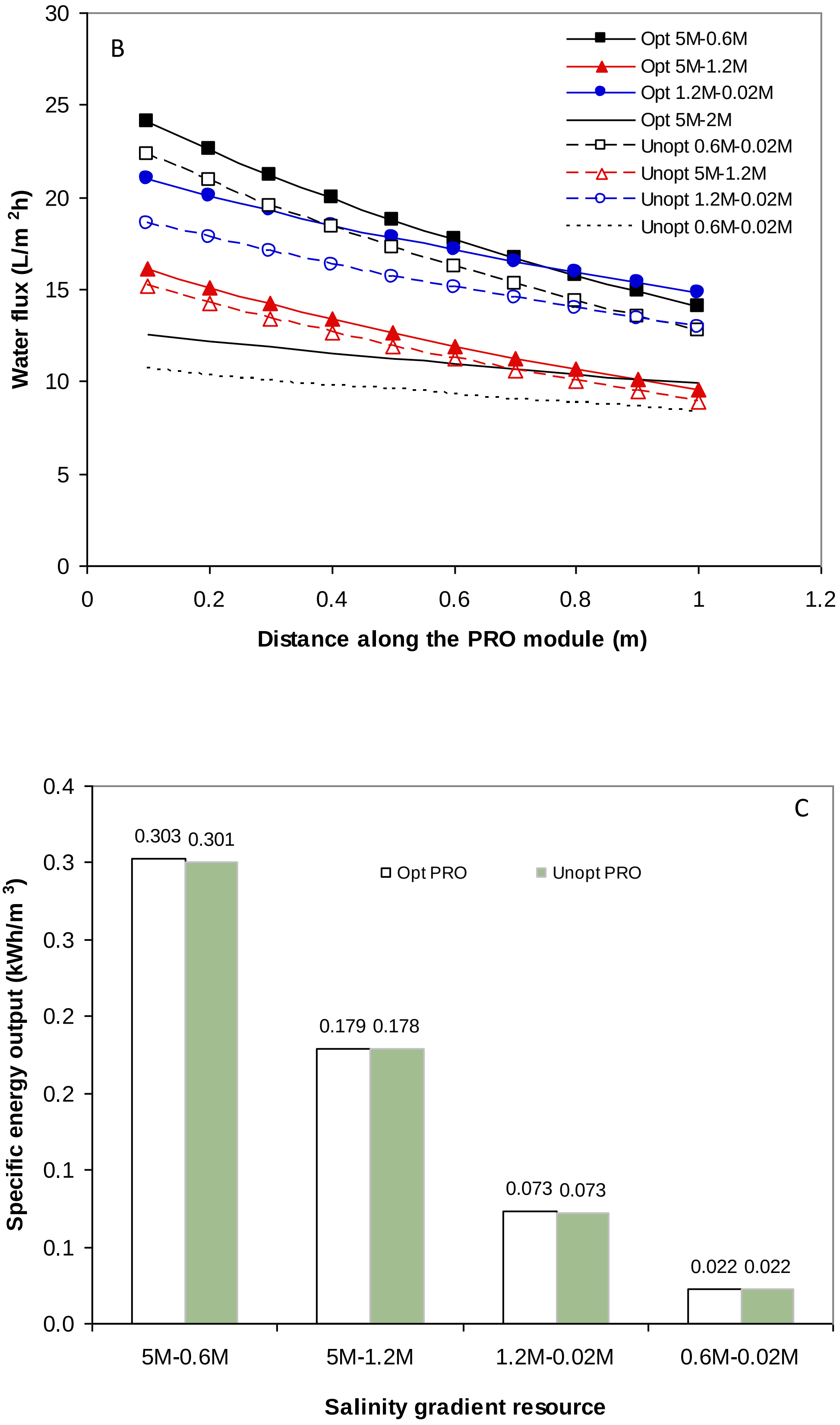
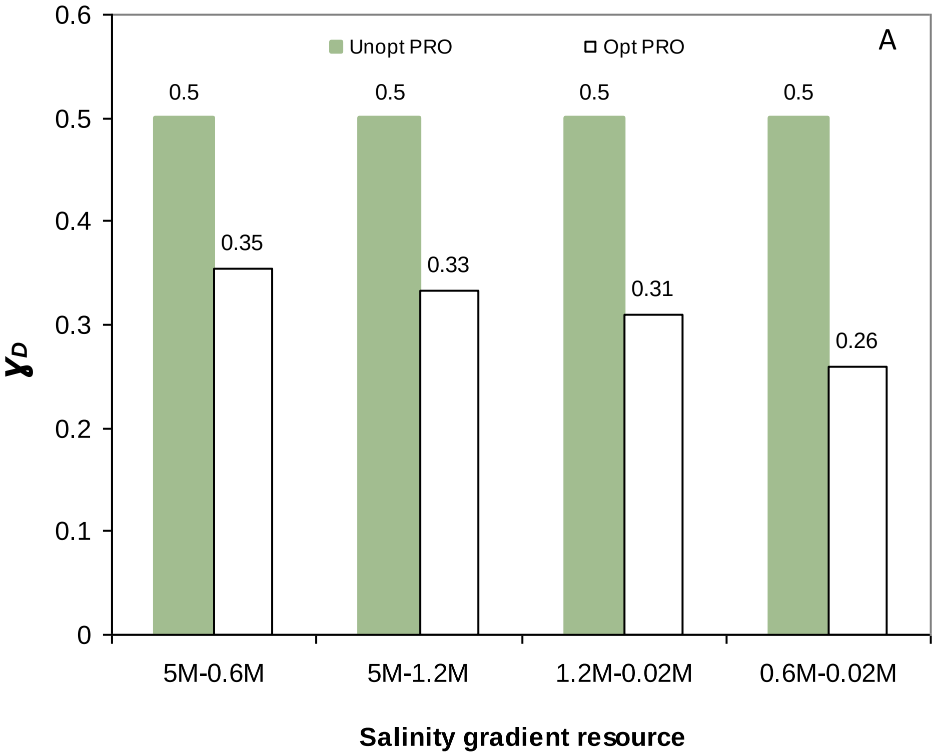
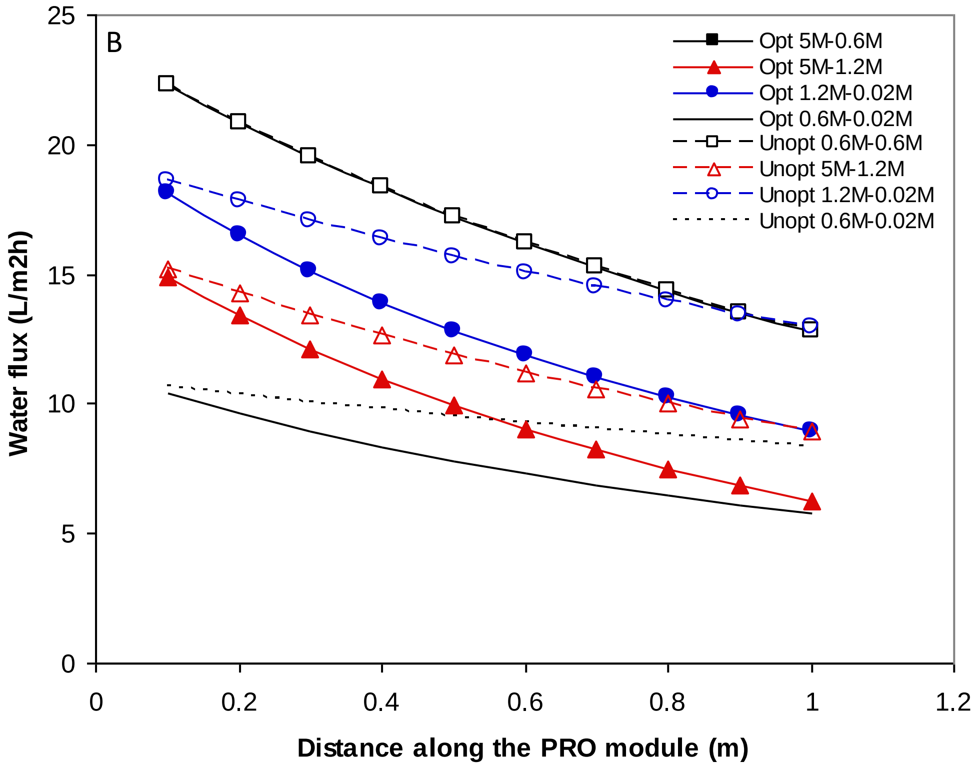


Figure 2: Optimization of hydraulic pressure A) optimized and unoptimized PRO processes hydraulic pressure B) membrane flux C) energy output

Water flux in optimized and optimized PRO process is shown in Figure 3B. Results show a decrease in water flux along the PRO module due to the decrease in osmotic pressure driving force across the membrane [Figure 3B]. Water flux in the optimized and unoptimized PRO process was equal for 5M-0.6M salinity gradient. For the rest salinity gradients, optimized PRO process demonstrated lower water flux than unoptimized water flux. This was due to the intensive concentration polarization at the draw solution side because of the lower flow rate compared to unoptimized PRO process. On the other hand, specific energy output was higher in the optimized PRO process than in the unoptimized process, this observation holds true for all salinity gradients. Despite the lower water flux in unoptimized PRO process, specific energy output was higher because of the lower draw solution flow rate as per Equation 4. The highest increase in specific energy output was 23% for 0.6M-0.02M salinity gradient followed by14%, 13% and 10% for 1.2M-0.02M, 5M-1.2M and 5M-0.6M salinity gradient, respectively. Overall, results show that the optimization of draw solution flow rate has more impact on improving the specific energy output in the PRO process. Optimization of feed pressure resulted in a subtle increase of the specific energy output, <1%, while optimization of draw solution flow rate increased the specific energy output by 23%.





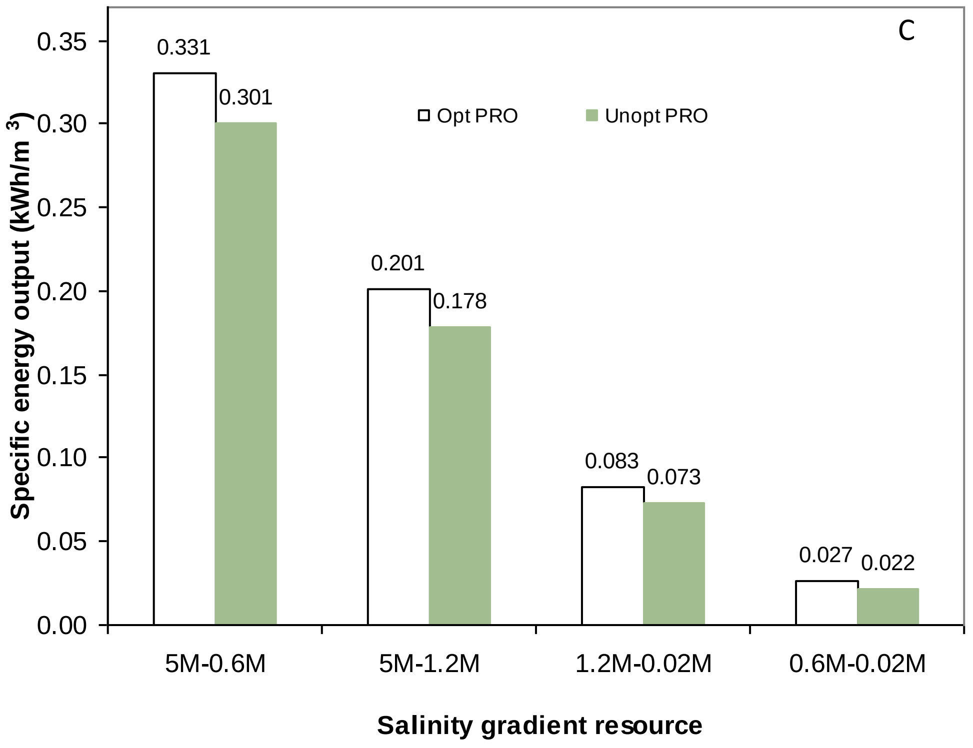
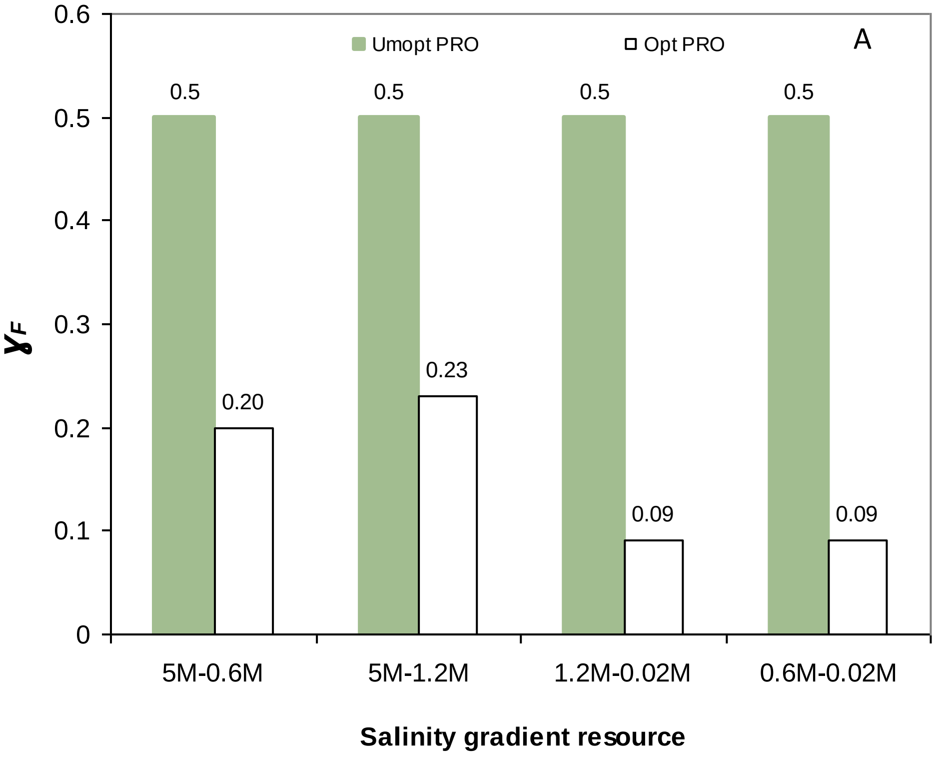
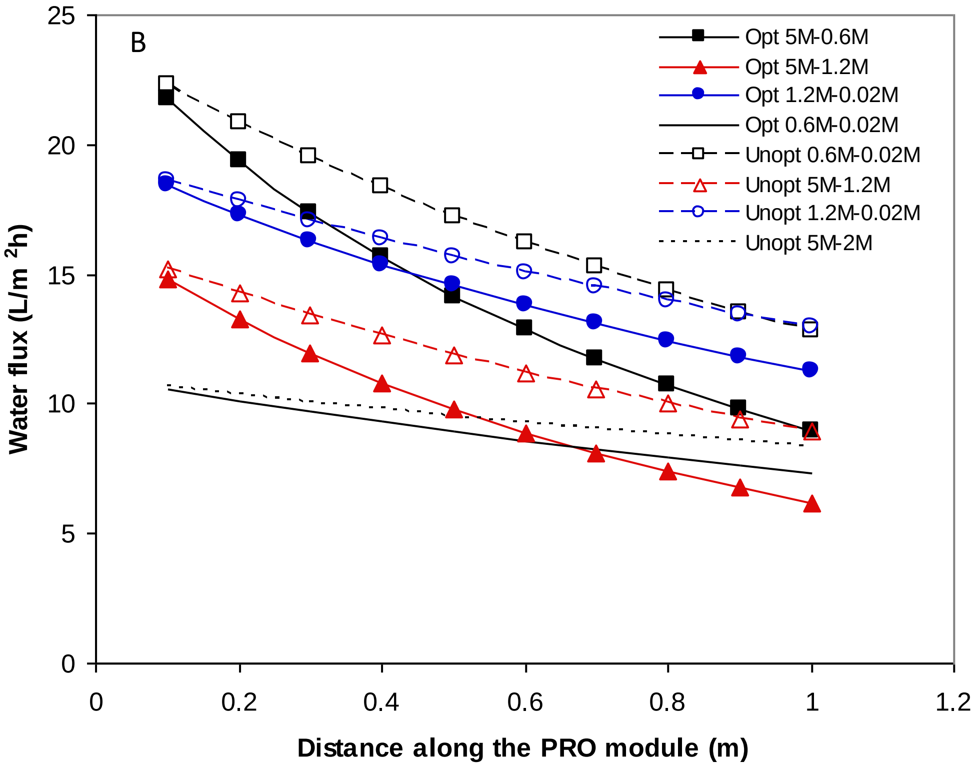


Figure 3: Optimization of draw solution flow rate A) optimized and unoptimized draw solution mixing ratio B) membrane flux C) energy output

3.3. Optimization of feed solution in mixture

Optimization of the feed solution in the mixing solution was carried out for a number of salinity gradient resources and results were compared with unoptimized PRO process. All results were obtained at a hydraulic pressure gradient equal to $\Delta P = \Delta\pi / 2$. The ratio of feed flow rate in the mixing solution, γ_F, was lower than the optimum value recommended in previous studies and equal to 50% [5]. The optimum γ_F was 0.2, 0.23, 0.09, and 0.09 for 5M-0.6M, 5M-1.2M, 1.2M-0.02M and 0.6M-0.02M salinity gradient, respectively [Figure 4A]. These ratios were even lower than the optimum γ_F in the PRO process. Water flux, on the other hand, decreased along the PRO module and was lower in the optimized PRO process than in the unoptimized processes [Figure 4B]. Difference between optimized and unoptimized water flux increased with the increase of the osmotic pressure driving force across the PRO membrane because lower feed flow rate brought about more intense internal concentration polarization. There was 30% decrease in water flux for both 5M-0.6M and 5M-1.2M salinity gradients, 13% for 1.2M-0.02M salinity gradient and 10% for 0.6M-0.02M salinity gradient. Despite the lower water flux in the optimized PRO process, specific power generation was higher in the optimized PRO than in unoptimized PRO process [Figure 4C]. This was because of the higher energy generation per cubic meter in the optimized PRO process. The highest specific energy generation was 0.402 kWh/m^3 for 5M-0.6M salinity gradient followed by 0.229, 0.123, and 0.037 for 5M-1.2M, 1.2M-0.02M and 0.6M-0.02M salinity gradient resource, respectively.





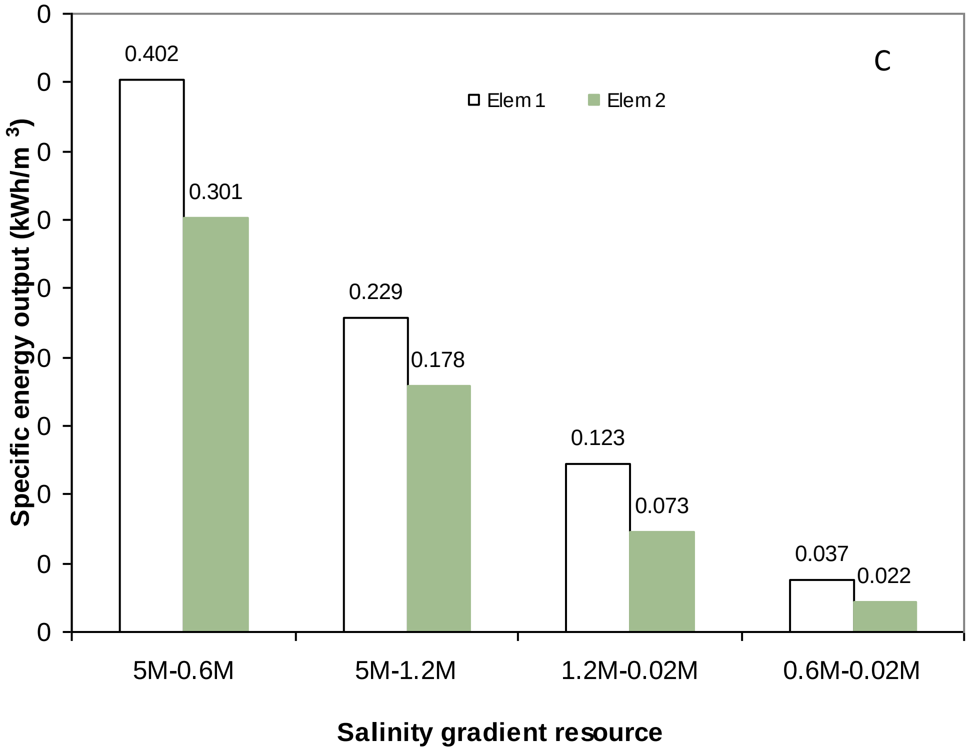


Figure 4: Optimization of feed solution flow rate A) optimized and unoptimized draw solution mixing ratio B) membrane flux C) energy output

As a matter of fact, feed flow optimization resulted in up to 68% increase in the specific energy generation for 0.6M-0.02M salinity gradient and about 65% increase in the specific energy generation for 1.2M-0.02M salinity gradient. Results also indicate that optimization of feed flow rate had the highest impact on the specific energy generation in the PRO process, followed by draw solution flow rate and finally the hydraulic pressure. It should be mentioned that although hydraulic pressure optimization resulted in subtle increase in the specific energy generation, it also allowed PRO process to operating at lower pressure which may reduce the capital cost because of the lower high pressure pump and PRO membrane specifications are required.

4. Conclusion

PRO process was evaluated for power generation from salinity gradient resources under different operating conditions. Key operating parameters such as the hydraulic pressure and feed and draw fractions in the mixing solution were optimized using Grey Wolf Optimization algorithms. The results showed that the specific energy output in the PRO process could be increased by process optimization. The impact of the operating parameters on the energy output in the PRO process varied from a subtle to a tangible. Hydraulic pressure was found to have a subtle impact on the energy output in the PRO process while the optimization of draw solution flow rate brought out up to 23% increase in the energy yield. However, optimization of the feed flow rate demonstrated the highest impact on the energy yield in the PRO process with up to 68% increase. The study showed the importance of using computer based algorithms in engineering and renewable energy field.

Reference:

[1] Ali Altaee, John Zhou, Adnan Alhathal Alanezi, Guillermo Zaragoza, Pressure retarded osmosis process for power generation: Feasibility, energy balance and controlling parameters, Applied Energy, V 206 (2017), 303-311

[2] Wei He, Yang Wang, Mohammad Hasan Shaheed, Maximum power point tracking (MPPT) of a scale-up pressure retarded osmosis (PRO) osmotic power plant, Applied Energy, V 158 (2015), Pages 584-596

[3] Stein Erik Skilhagen, Dr. Rolf Jarle Aaberg, Osmotic power - Power production based on the osmotic pressure difference between fresh water and sea water, Owemes 2006, 20-22 April. Citavecchia, Italy.

[4] A. Achilli, T. Y. Cath and A. E. Childress, Power generation with pressure retarded osmosis: An experimental and theoretical investigation, Journal of Membrane Science, V 343 (2009), 42–52

[5] S. Lin, A. P. Straub, M. Elimelech, Thermodynamic limits of extractable energy by pressure retarded osmosis, Energy Environmental Science, V 7 (2014), 2706–2714

[6] S. Loeb, F. Van Hessen, D. Shahaf, Production of energy from concentrated brines by pressure-retarded osmosis: II. Experimental results and projected energy costs, J. Membr. Sci., V 1(1976), 249–269

[7] J. Veerman, M. Saakes, S. J. Metz, G. J. Harmsen, Reverse electrodialysis: evaluation of suitable electrode systems, Journal Applied Electrochemistry, V 40 (2010), 1461–1474

[8] Fei Liu, Orlando Coronell, Douglas F. Call, Journal of Power Sources, Electricity generation using continuously recirculated flow electrodes in reverse electrodialysis, Volume 355 (2017), 206-210

[9] Masaru Kurihara, Masayuki Hanakawa, Mega-ton Water System: Japanese national research and development project on seawater desalination and wastewater reclamation, Desalination, Volume 308 (2013), 131-137

[10] Keiichiro Saito, Morihiro Irie, Shintaro Zaitsu, Hideyuki Sakai, Hidechito Hayashi & Akihiko Tanioka, Power generation with salinity gradient by pressure retarded osmosis using concentrated brine from SWRO system and treated sewage as pure water, Desalination and Water Treatment, V 41 (2012), 114-121.

[11] Henrik T.Madsen, Steen Søndergaard Nissen, JensMuffc, Erik G.Søgaard, Pressure retarded osmosis from hypersaline solutions: Investigating commercial FO membranes at high pressures, Desalination, Volume 420 (2017), 183-190

[12] Ye Li, Shanshan Zhao, Laurentia Setiawan, Lizhi Zhang, Rong Wang, Integral hollow fiber membrane with chemical cross-linking for pressure retarded osmosis operated in the orientation of active layer facing feed solution, Journal of Membrane Science, Volume 550 (2018), 163-172

[13] Chun Feng Wan, Tianshi Yang, Wenxiao Gai, Yu De Lee, Tai-Shung Chung, Thin-film composite hollow fiber membrane with inorganic salt additives for high mechanical strength and high power density for pressure-retarded osmosis Journal of Membrane Science, Available online 26 March 2018.

[14] Ye Li, Rong Wang, Saren Qi, Chuyang Tang, Structural stability and mass transfer properties of pressure retarded osmosis (PRO) membrane under high operating pressures, Journal of Membrane Science, Volume 488 (2015),143-153.

[15] Yunfeng Chen, Laurentia Setiawan, Shuren Chou, Xiao Hu, Rong Wang, Identification of safe and stable operation conditions for pressure retarded osmosis with high performance hollow fiber membrane, Journal of Membrane Science, Volume 503 (2016), 90-100.

[16] Kerri L. Hickenbottom, Johan Vanneste, Menachem Elimelech, Tzahi Y. Cath, Assessing the current state of commercially available membranes and spacers for energy production with pressure retarded osmosis, Desalination, Volume 389 (2016), 108-118

[17] Ali Altaee, John Zhou, Adnan Alhathal Alanezi, Guillermo Zaragoza, Pressure retarded osmosis process for power generation: Feasibility, energy balance and controlling parameters, Applied Energy, V 206 (2017), 303-311

[18] Ali Altaee, Guillermo Zaragoza, Enrico Drioli, John Zouh, Evaluation the Potential and Energy Efficiency of Dual Stage Pressure Retarded Osmosis Process, Applied Energy, V 199 (2017), 359–369

[19] Mirjalili, Seyedali, Seyed Mohammad Mirjalili, and Andrew Lewis. "Grey wolf optimizer." *Advances in Engineering Software* 69 (2014): 46-61.

[20]