IJCPE

Iraqi Journal of Chemical
and Petroleum Engineering

University of Baghdad
College of Engineering

POWER GENERATION FROM "PRO" PROCESS USING FLAT SHEET TFC–ULP KOCH MEMBRANES

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ABSTRACT

The production of power using the process of pressure–retarded osmosis (PRO) has been studied both experimentally and theoretically for simulated sea water vs. river water and deionized water under two cases: the first is for simulated real conditions of sea water and river water and second under low brine solution concentration to examine the full profile of the power- pressure.   The influence of concentration polarization (CP) on water flux has been examined as well.
Keywords: Pressure–retarded osmosis; renewable energy; TFC-ULP membrane; concentration polarization

INTRODUCTION

Osmosis hydro power is one of the recently attractive types of renewable energy. Suggested only in the 1970s by Sidney Loeb (the co-inventor of Reverse Osmosis) through utilizing the osmotic pressure in power generation using membranes. It is a natural process occurred when salt solution and fresh water are portioned in two chambers separated by a semi-permeable membrane, made for example of a biological membrane, e.g. of hog bladder, fresh water will permeate through the membrane.

The driving force is capable of elevating the salt water level above the fresh water level, whereas the potential energy is obtained from the static water height. The process stops when the hydraulic pressure is equal to the potential osmotic pressure of the salt water. In theory, a stream flowing at 1 m3/s could produce 1 MW of electricity [1]. The global potential for Pressure-Retarded Osmosis is calculated to be about 1600 TWh/y and for Europe 200 TWh/y [2]. Significant research efforts took place between mid 1970s to the early 1990s, but due to ineffective membranes, the key part of process, the construction of a PRO power plant was not considered. In 1997, Statkraft, one of the leading energy providers in Norway, started their research on PRO, they have constructed a PRO prototype and claimed to construct commercial power plants in 2015[2]. Concentration

polarization a phenomenon of increasing the solute concentration at the low concentration side

(concentrative External Concentration Polarization) and d Concentration Polarization)

and the build up or dilution of solute at the interface between the membrane active and support layer (Internal Concentration Polarization).

The first two types can be reduced greatly by **PRO Membrane Cell and Experimental Procedure**

The PRO membrane cell is comprised of a two 3 in diameter QVF vessels capable of withstanding pressure up to 1.5 bar as shown in Fig. 1. The membrane area is 45.6 cm2.
providing agitation or circulation while the last type is strongly dependant on the resistance to solute transfer. This variable governs the rate of solute transfer within the support layer of the membrane and it is recommended to be as low as possible so that the solute will transport easily and hence prevent excessive concentration or dilution at the membrane inner interface [3].

The objective of the present study is describe the performance of PRO process under simulated real conditions using flat sheet TFC-ULP Koch membrane and to derive a simple relation to predict theoretically that

EXPERIMENTAL

Membrane

The membrane used for all experiments was provided by Koch Membrane systems. The membrane chemistry is uncertain but is believed to be composed of polyamide.

Brine and Fresh Water Solutions

Deionized water was used to prepare the sodium chloride solutions. These solutes were used to represent sea water (brine solution) and river water (fresh water). The brine solution concentration taken are as 26.5 and 35 g/l NaCl

to resemble the actual concentration of NaCl in sea water for the first and if the whole salts in sea water are represented by NaCl for the second. The osmotic pressures of the various

solutions were calculated using HYSYS® 3.1 software.
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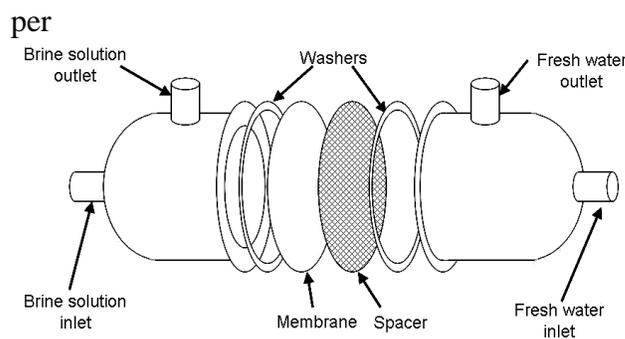
 Fig.1 Schematic diagram of the PRO membrane cell
formance.

This cell accepts flat sheet membranes. A plastic mesh spacer is provided on the fresh water side of to provide mechanical support to the membrane. The brine solution is flowing cocurrently to the fresh water and both solutions flow in closed circuits via plastic tubing. Two centrifugal pumps from STUART TURNER LTD. (England) were used for circulating the solutions through the system. Flowmeters measured the volumetric flow rates, which were fixed at 7 l/min for brine solution side and 5 for fresh water side with flow area around 11.4 cm2. Both solutions flow at the same constant temperature 25 ± 1.5oC. The detailed diagram of the PRO system is given in Fig. 2.
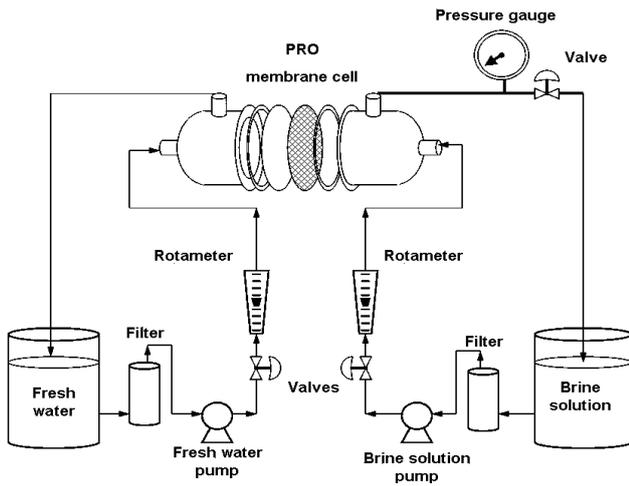
Fig. 2 Schematic diagram of the PRO system

A pressure gauge followed by control valve is installed at the brine solution outlet on the membrane cell in order to pressurize the solution to any desired pressure. Water and salt fluxes are determined by mass balance by measuring salt concentrations using calibrated conductivity meter provided by WTW (Germany) in both solutions every 1 hour of experiment for a total of five hours. The power generated is calculated from the product of the pressure difference across the cell and water flux according to Eq. 1

$$W = J_W \, \Delta P \qquad (1)$$

Where W is the specific power generated in Wm2, JW is the water flux in m3/ m2 (Lee et al, 1981)

RESULTS AND DISCUSSION

In PRO operation, the brine solution side is pressurized as mentioned earlier; the positive difference between the brine solution and fresh water sides causes the water flux to decrease and the FO process to deviate towards Reverse Osmosis mode if the pressure difference does not surpass the osmotic pressure difference. Figs. 3 and 4 show this behavior.
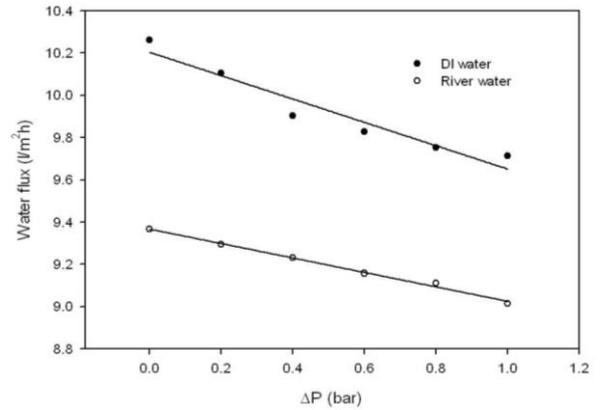
Fig. 3 Measured water flux vs. pressure for 35 g/l brine solution concentration using DI and river water at 7 and 5 l/min flow rates for brine solution side and fresh water respectively. All solutions are at 25 ± 1.5oC
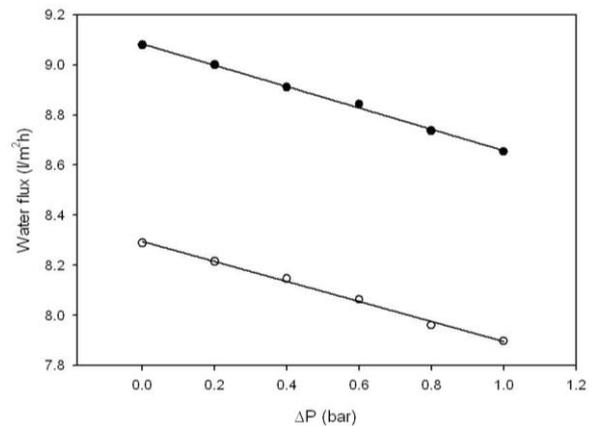
Fig. 4 Measured water flux vs. pressure for 26.5 g/l brine solution concentration using DI and river water at 7 and 5 l/min flow rates for brine solution side and fresh water respectively. All solutions are at 25 ± 1.5oC

The increase of the pressure difference is associated with drop in the water flux and is described by Eq. 2

$$J_W = A(\Delta \pi - \Delta P)$$

Where A is the water permeability coefficient, $\Delta \pi$ is the osmotic pressure difference, and ΔP is the pressure difference [4].

The decrease in the water flux with increasing the pressure difference seems to lower the power produced but the increasing pressure compensates that drop due to increased momentum of the solution.
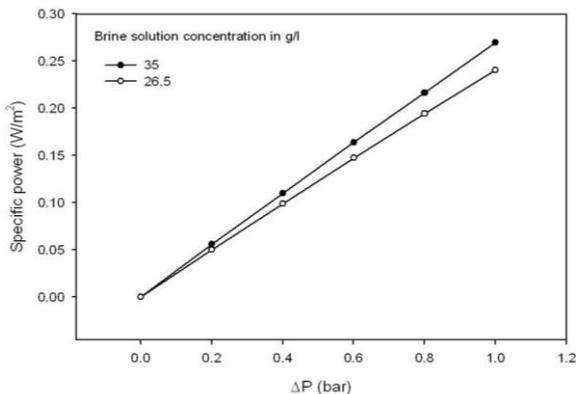
Fig. 5 Measured specific power in Watts/m2 vs. pressure for brine solutions of 35 and 26.5 and concentration and DI water at 25 ± 1.5oC
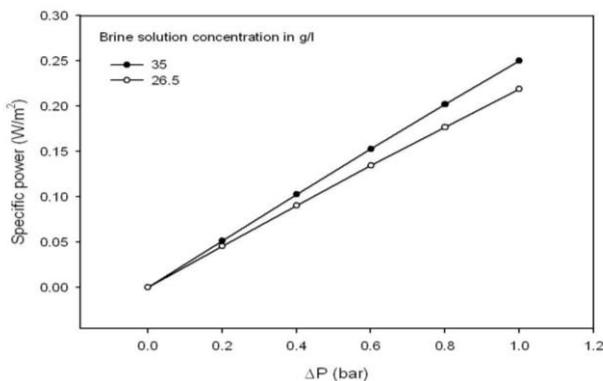
Fig. 6 Measured specific power in Watts/m2 vs. pressure for brine solutions of 35 and 26.5, concentration and river water at 25 ± 1.5oC

Figs. 5 and 6 justify the increasing power generation resulted from increasing pressure difference regardless of the decrease in the water flux, however above figures show that the power produced is susceptible to further increase at higher pressures. The experimental observation of Thorsen and Holt (2009) and simple mathematical analysis provided elsewhere[3] reveal that the optimum operating pressure is

about one-half the osmotic pressure difference show that the power pressure difference curve has a parabolic behavior were there is maximum point for the produced power and since such high pressure demanding operating condition is unattainable an alternative approach must be followed to predict experimentally the entire power – pressure curve. Such approach can be reached by using brine solution of low concentration that possesses an osmotic pressure within the operating pressure range of the current membrane cell (up to 1 bar). A relevant concentration of brine solution is 1.5 g NaCl/l which has an osmotic pressure of 1.17 bar and optimum pressure difference of 0.6 bar. This concentration is also studied for the cases of DI water and simulated river water, see Figs. 7 and 8.
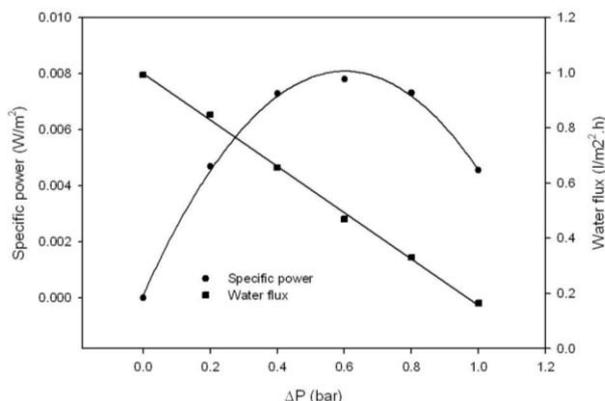
Fig. 7 Measured specific power and water flux against pressure difference for 1.5 g NaCl/l brine solution and DI water at 25C ± 1.5oC

Fig. 7 has matched the behavior of the earlier study5] in its parabolic form. The continuous increase of the pressure difference from FO conditions (where W has zero value) is accompanied by a decline in water flux and simultaneous increase in the specific power until a certain point in which Wmax (peak of the

curve) is reached. Wmax from Fig. 7 is about 0.00798 W/m2 at ΔP = 0.6 bar, this value is subjected to comparison with the theoretical value from [3]

$$W_{max} = A\,\Delta\pi^2\big/4 \qquad (A.4)$$

The water permeability coefficient for this system is found to be 2.335×10-12 m/s.Pa and with $\Delta\pi$ calculated from HYSYS 3.1 software Wmax is 0.0078 W/m2 which appreciably agrees with the experimental value.
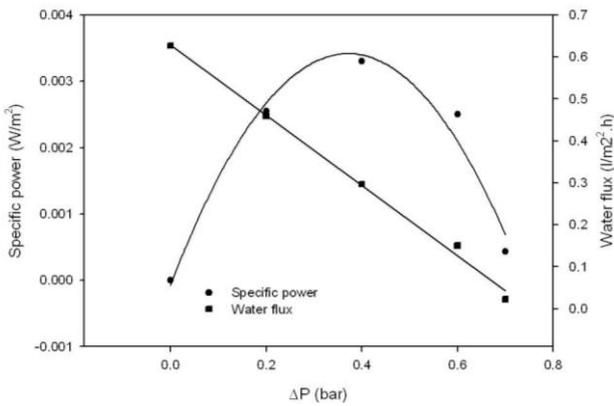
Fig. 8 Measured specific power and water flux against pressure difference for 1.5 g NaCl/l brine solution and river water at 25C ± 1.5^{o}C

From Fig. 8 W_{max} 0.0032 W/m^2 at ΔP = 0.4 bar with A_{app} = 2.096×10^{-12} m/s.Pa and $\Delta\pi$ = 78,567.142 Pa, theoretical value of W is found to be 0.003235 W/m2. The agreement between the experimental results and results of Eq. A.4 is ascribed to the trivial polarization effects.

The complete power – pressure difference curve using brine concentrations 35 and 26.5 g/l will be studied by the aid of Eq. 2 which neglects any polarization effects and modified form of Eq. 1 that allows for the concentration polarization to take place, see Appendix A for details.

Table 1 Values of permeability coefficient A, osmotic pressure difference and reflection coefficient for PRO system

System	A (m/s.Pa) ×1012	$\Delta\pi$ (bar)	σ
35 g/l vs. 0.01 g/l	1.351	27.8	0.7494
26.5 g/l vs. 0.01 g/l	1.558	21.0	0.7913
35 g/l vs. 0.5 g/l	1.363	27.4	0.7032
26.5 g/l vs. 0.5 g/l	1.533	20.6	0.7275

The values of A are determined from the slopes in Figs. 3 and 4, $\Delta\pi$ is calculated using HYSYS 3.1, and σ (reflection coefficient) is found from fitting data in Figs 5 and 6 to Eq. A.5

Figures 9 – 12 show a predicted profile of the specific power against pressure difference under pressure values up to 20 bars. The consideration of polarization effects in Eq. A.5 has greatly reduced the power generation to about 1 W/m2 as in Fig. 9 and 1.6 W/m2 as in Figs 10 – 12.
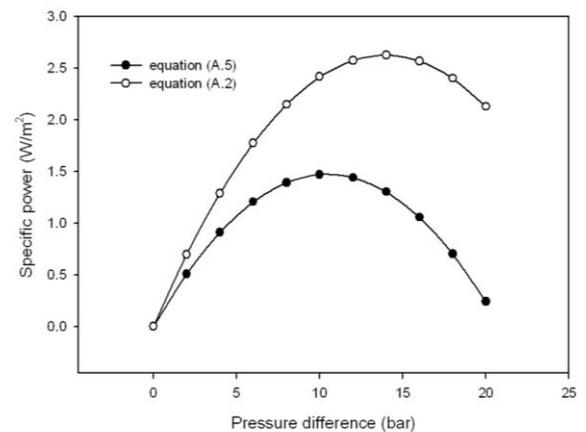
Fig. 9 Specific power against pressure difference for 35 g/l NaCl brine solution and DI water. Specific power is predicted from Eqs. A.2 and A.5 based evaluated parameters in Table 1
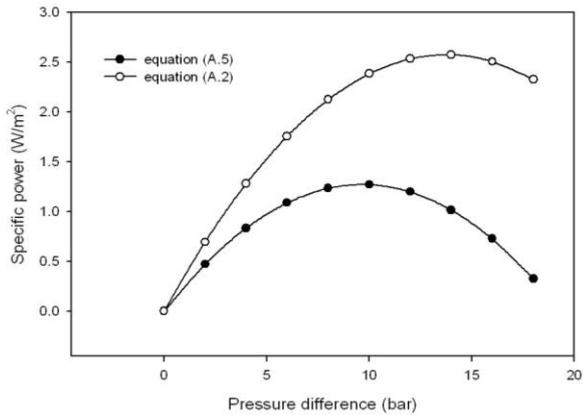
Fig. 10 Specific power against pressure difference for 35 g/l NaCl brine solution and simulated river water. Specific power is predicted from Eqs. A.2 and A.5 based evaluated parameters in Table 1
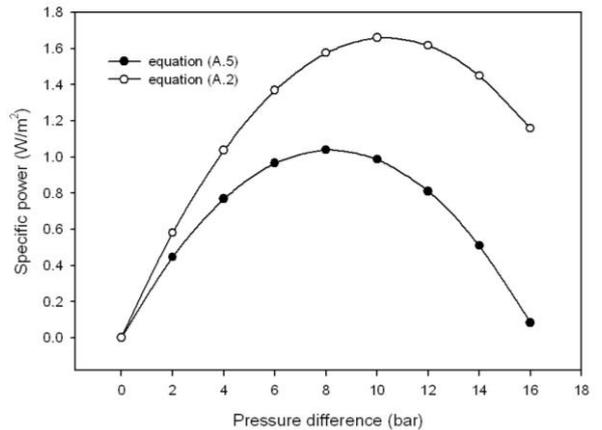
Fig. 11 Specific power against pressure difference for 26.5 g/l NaCl brine solution and DI water. Specific power is predicted from Eqs. A.2 and A.5 based on evaluated parameters in Table 1

Fig. 12 Specific power against pressure difference for 26.5 g/l NaCl brine solution and simulated river water. Specific power is predicted from Eqs. A.2 and A.5 based on evaluated parameters in Table 1
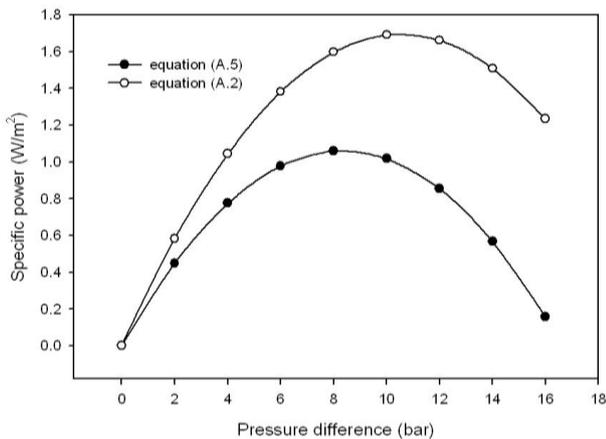
In Fig. 13 a comparison between the experimental results of Thorsen and Holt[5] and Eqs. A.2 and A.5 is made. The comparison shows the validity Eq. A.5) and also shows the error encountered when concentration polarization effects are omitted. Eq. A.5 has been in agreement with the experimental data to about 99.9 using Chi square test.
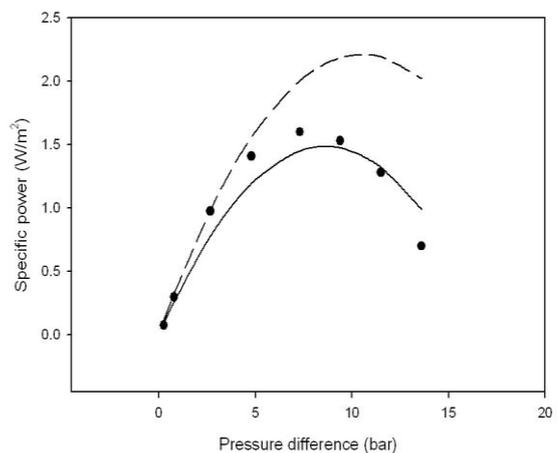
Fig. 13 Comparison between experimental results of Thorsen and Holt (2009) and the results of Eqs. A.2 and A.5. (●) symbols denote for experimental results, solid line for Eq. A.5 and dashed line for Eq. A.2

CONCLUSION

Osmosis hydro power seems to be very promising since it posses a capacity of 27 bar for sea water vs. river water but with the available membranes it is obvious that commercial production is beyond achieving yet. The reason is that the currently available membranes still have low water permeability coefficients.

The concentration polarization CP have reduced the water flux greatly and hence power generation by a value about 1.6 W/m2, with value of σ evaluated between 0.7 and 0.8 which represent the fraction that the total driving force Δπ has reduced to.

The comparison of the modified Eq. A.5 with the experimental work of Thorsen and Holt (2009) yielded an excellent agreement of 99%.

Nomenclature

A   water permeability coefficient (m.s-1.pa-1)
JW   water flux (l.m-2.h)
P   pressure of solutions (bar)
W   specific power (Wm2)

Greek letters

π   osmotic pressure (pa)
σ   reflection coefficient

Superscripts

*   denote for either P or W with considering concentration polarization

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Appendix A

Evaluation of Reflection Coefficient

Starting from Eq. 1

$$W = J_W \times \Delta P \qquad (1)$$

Suppose that water flux is calculated from

$$J_W = A(\Delta \pi - \Delta P) \qquad (A.1)$$

Substituting Eq. A.1 into 1 to get

$$W = A(\Delta \pi \Delta P - \Delta P^2) \qquad (A.2)$$

The maximum attainable theoretical power (for negligible concentration polarization effects) is evaluated at ΔPoptimum obtained from differentiating Eq. A.2 and equating to zero [3]. By donning so ΔPoptimum will be half the osmotic pressure difference

$$\Delta P_{optimum} = \Delta \pi / 2 \qquad (A.3)$$

Therefore substituting (A.3) into (A.2)

$$W_{max} = A \Delta \pi^2 / 4 \qquad (A.4)$$

Eq. A.4 presents an idealized approach for the calculation of the specific power since it is based on Eq. A.1 which does not allow for effects of ECP and ICP. Therefore the introduction of the reflection coefficient σ into Eq. A.1 is essential. By doing so result will be

$$W^* = A(\sigma \Delta \pi \Delta P - \Delta P^2) \qquad (A.5)$$

Recalculating the optimum pressure and the maximum specific power in similar manner

$$\Delta P^*_{optimum} = \sigma \Delta \pi / 2 \qquad (A.6)$$

$$W^*_{max} = A \sigma \Delta \pi^2 / 4 \qquad (A.7)$$