

Mathematical Analysis of the Performance of A New Commercial Thin-Film Composite Forward Osmosis Membrane for Osmotic Hydro-Power Production

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Abstract— Driven by global demand for continuous and clean energy resources, hydro-osmotic power emerged as one of the most promising emission-free energy resources. A recently developed thin-film composite membrane by HTI Company for FO desalination that possesses high water permeation rate and good mechanical properties is considered in this analysis to examine its applicability for power generation under pressure-retarded osmosis operating conditions. The mathematical analysis revealed that that prewetted TFC membrane in 50 wt% isopropyl solution under hydraulic pressure difference of 12.5 bar for brine solution of 35.5 g/l NaCl against a 0.15 g/l NaCl solution brine solution velocity of 1.3 m/s gives a power density value of 5.2 W/m², a value higher than the economical reported value.

Keywords— Renewable Energy, Osmotic Hydro-Power, Pressure Retarded Osmosis, Thin-Film Composite Membrane, Mathematical Analysis.

I. INTRODUCTION

During the past four decades, power generated from pressure-retarded osmosis had attracted a great deal of scientists' attention due to the immense potential of the osmotic pressure (about 27 bar) available from sea water when mixed with low salinity water [1], which represents a valuable source of inexpensive and clean energy that can be estimated to be near 1TW on global scale [2].

Despite the great potential of the osmotic hydro-power, it remains difficult to harness its full potential. These difficulties can be represented in two major problems: The low permeation water rate under PRO condition for the available membranes and scale up problem that will decrease the pilot-scale efficiency even further [3].

Many studies were dedicated to develop and investigate semipermeable membrane to make the process viable, starting from using commercial RO membranes Du Pont Permasep [4], [5]. The Du Pont Permasep B-10 fibres gave poor power density of about 0.781 W/m² under hydraulic pressure difference 37 atm & osmotic pressure 52 atm [4], Lee et al (1981) [6] investigated several asymmetric and composite membranes but still the permeation rate was found to be too low such that the max. Power density is 1.55 W/m² for 3.5 wt % NaCl vs. fresh water under 12.5 atm operating pressure. In [7] the economic power density 5 W/m² has been achieved but

only with the use of 60 g/l NaCl brine solution and CTA membrane.

On the other hand, the mathematical approach to study the process of PRO also has reached high degree of describing the process variables and its imitations, which lead to make quick and inexpensive estimation of the feasibility of every newly developed membrane in the past years. Most notably was the analysis performed by Lee et al (1981) [6] that provided deep insight to the behaviour and description of the concentration polarization, the major limiting factor for making PRO commercially unviable.

This work aims to use a mathematical model for water permeation to simulate the performance of a recently developed TFC from HTI for power production under PRO operation. This is to be accomplished by testing the model validity and prediction accuracy using the experimental work of [8]. Then wider ranges flow rates, salt concentrations, and hydraulic pressure drop values are examined to find the conditions and the membrane that demonstrates higher power density.

II. METHODOLOGY

A. Mathematical Model

A model derived for an asymmetric membrane with the active layer facing the brine water side as used in PRO operation (Fig. 1) to predict the water permeation rate [9] which is suitable for flat sheet membrane. The difference between this model and the listed models in literature, i.e. [7], is the effect of concentration gradient at the fresh water side, which will prove to be useful when considering dilute brine concentrations on the fresh water side,

$$J_w = A \left(\pi_{B_b} \exp \left(-\frac{J_w}{k_B} \right) \left(\frac{1 - \frac{\pi_{F_b}}{\pi_{B_b}} \exp \left(J_w \left(\frac{1}{k_B} + \frac{1}{k_F} \right) \right) \exp(J_w K)}{\frac{B}{J_w} (\exp(J_w K) - 1) + 1} \right) - \Delta P \right) \quad (1)$$

and the power generation is found from

$$W = \Delta P J_w \quad (2)$$

where J_w is the water flux through the membrane in m/s, A is the water permeation coefficient in m³/m².s.Pa, π_{B_b} is the osmotic pressure in the bulk brine solution in Pa, π_{F_b} is the osmotic pressure in the bulk fresh water in Pa, k_B and k_F are the mass transfer coefficients on the brine solution and fresh

water sides respectively in m/s, B is the salt permeation coefficient in $m^3/m^2.s$, K is the resistance to salt transport, W is the power density in W/m^2 , ΔP is hydraulic pressure drop between the brine solution and the fresh water sides in Pa.

The mass transfer coefficients used in this study is calculated from the exact analysis of the laminar concentration boundary layer [10]: An approach that is valid for flat sheet membrane. The obtained local Sherwood number is then integrated over the membrane length to get the average Sherwood number from which mass-transfer coefficient is calculated

$$\overline{Sh} = 0.664 Re_L^{0.5} Sc^{1/3} \quad (3)$$

where \overline{Sh} is the average Sherwood number and it is defined :

$$\overline{Sh} = \frac{kL}{D} \quad (4)$$

where L is the channel length, D is the diffusion coefficient which can be taken constant $1.6 \times 10^{-9} m^2/s$, k is the mass transfer coefficient, Re_L is the average Reynolds number, and Sc is Schmidt number.

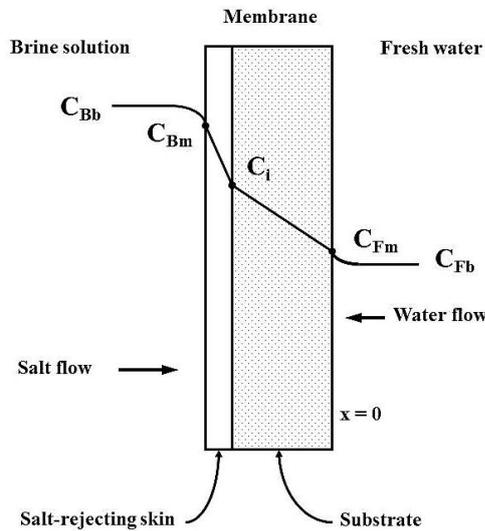


Fig. 1 Schematic diagram of an asymmetric membrane operated in PRO mode

The dimensions are taken from the experimental set up conducted by [11] such that: channel length 77mm, width 26mm, and depth 3mm. The physical properties for 1M NaCl were calculated elsewhere [9].

B. Membrane Parameters

The membrane parameters (A and B) for the three types investigated in [8] are calculated from RO operation (as shown in Table I) and K (resistance to salt transport) is calculated according to the following expression:

$$K = \frac{1}{J_W} \ln \left(\frac{B + A \pi_{B_m} - J_W}{B + A \pi_{F_b}} \right) \quad (5)$$

where π_{B_m} is the osmotic pressure at the brine solution/membrane interface and is obtained from

$$\pi_{B_m} = \pi_{B_b} \exp \left(\frac{-J_W}{k_B} \right) \quad (6)$$

TABLE I

WATER PERMEATION COEFFICIENT, SALT PERMEATION COEFFICIENT, AND THE RESISTANCE TO SALT TRANSPORT FOR THE THREE MEMBRANES UNDER FEED PRESSURE 8.62 BAR, THE FEED FLOW REYNOLDS NUMBERS IN CA AND TFC MEMBRANES ARE 1125 AND 1350, RESPECTIVELY. THE FEED TEMPERATURE IS 20 °C [8]

Membrane	A ($l/m^2.h.bar$)	B ($l/m^2.h$)	K
CA	0.86	0.59	643983
TFC	1.78	1.22	333729
Prewetted TFC	2.47	1.73	334021

III. RESULTS & DISCUSSION

A. Calculation of Resistance to Salt Transport

For PRO operation mode, K is obtained from equations (5) and (6). The membranes parameters A and B are taken from [8], the mass transfer coefficient from equations (2) and (3) using the unit dimension of [11] as shown earlier in section II. The osmotic pressure was calculated using HSYS [9].

B. Model Verification

A comparison was made between the mathematical model results for PRO mode and the experimental results of [8] to give credibility to the model's results and the calculated membrane parameters (Table II). Both experimental and predicted water flux show a great agreement

TABLE II
REPORTED WATER FLUX AND PREDICTED VALUES UNDER PRO CONDITION FOR THE CONDITIONS REPORTED IN [8]

Membrane	Water flux in $l/m^2.h.bar$	
	Experimental	Predicted
CA	17.42	17.36
TFC	30.54	29.85
Prewetted TFC	32.69	32.43

C. Calculation of Power Density Curve for 1M Brine Solution Against Deionized Water

For the same conditions given in [8] (concentrations and velocities), the complete power sensity curve for the HTI TFC membrane is estimated (Fig. 3) with maximum power density of $8.77 W/m^2$ at 18 bar hydraulic pressure difference for the prewetted TFC, the TFC had about $8.70 W/m^2$ at 18 bar while the CA gave $5.5 W/m^2$ at 22 bar. These results indicate that the effect of soaking the TFC in the isopropyl alcohol solution had slight effect on increasing the water permeation rate. Using deionized water on the fresh water side will have a significant effect on increasing the osmotic pressure difference that lead high permeation rate.

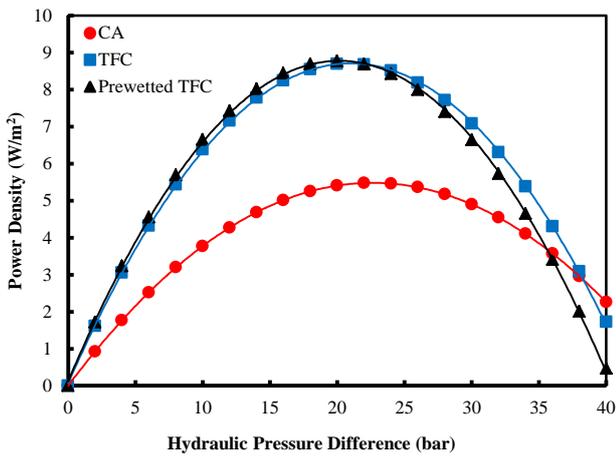


Fig. 2 Potential power density curve for CA, TFC, and Prewetted TFC HTI membranes for 1 M NaCl solution against deionized water at 20°C. The velocities are 0.25 m/s for both brine solution and deionized water

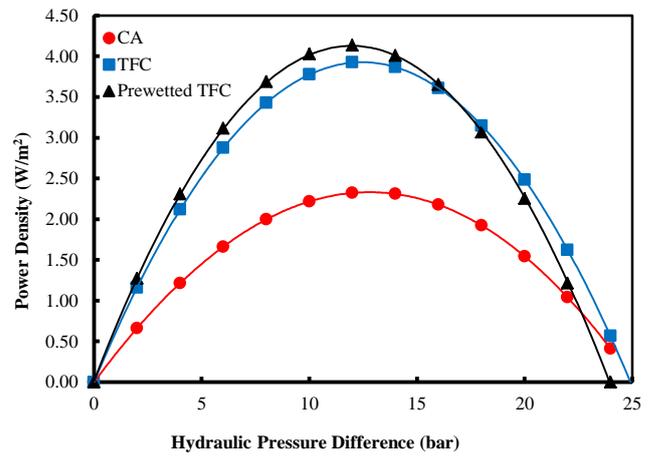


Fig. 3 Potential power density curve for CA, TFC, and Prewetted TFC HTI membranes for 35.5 g/l NaCl solution against 0.15 g/l NaCl solution at 20°C. The velocities are 0.25 m/s for both brine solution and deionized water

Figure 2, however, is so idealized since a commercial application should include a continuous low-cost source of brine solution as well as fresh water; both can be found at rivers downstream. The sea water salt concentration is equivalent to about 35.5 g/l which is less than the 1 M (58.5 g/l) and rivers have an approximate concentration of 0.15 g/l. These values are not standards but rather location dependants.

D. Calculation of Power Density Curve for 35.5 g/l NaCl Solution Against Simulated River Water

Thus, the more realistic scenario of simulated sea water (35.5 g/l NaCl) against simulated river water is studied (Fig. 3). The potential performance under these conditions showed a decline in the power density due to the low value of the osmotic pressure difference in comparison with Fig. 2 conditions. The maximum power density is 4.13 W/m² for the prewetted TFC, 3.9 W/m², and the CA has a very poor power density of about 2.3 W/m². Further investigation of the ideal power density can be attained both ICP and ECP are omitted as shown in Fig. 4. The TFC and the prewetted TFC appear to be very promising having 9.9 and 13.7 W/m²; both surpassing the economical power density value. The CA membrane on the other hand has an ideal maximum power density of 4.8 W/m². Therefore CA membrane has been excluded from the subsequent analysis.

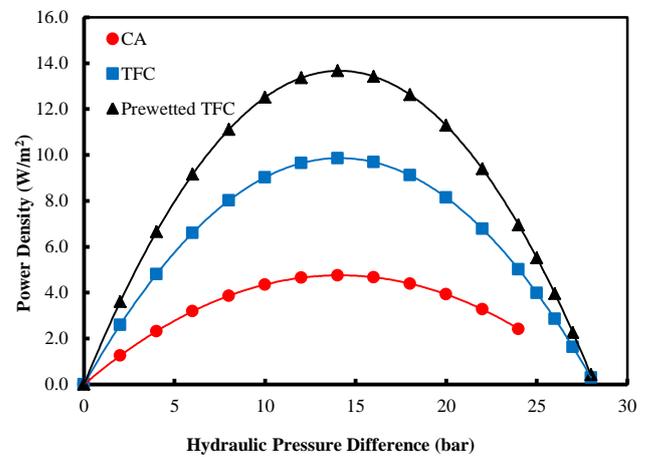


Fig. 4 Ideal power density curve for CA, TFC, and Prewetted TFC HTI membranes for 35.5 g/l NaCl solution against 0.15 g/l NaCl solution at 20°C. The velocities are 0.25 m/s for both brine solution and deionized water

E. Effect of Brine Solution Velocity on Power Density

The ECP can be significantly reduced by increasing the velocity of brine solution since the within this compartment even a slight concentration gradient between the bulk of solution and the membrane surface would lower the water permeation rate. Figures 5 & 6 reveal that only prewetted TFC membrane has the potential to reach and surpass the economical power density at 12.5 bar pressure difference giving 5 and 5.2 W/m² for brine solution velocities of 0.9 and 1.3 respectively. Although these results appear to be promising but achieving 0.9 m/s velocity and higher is quite challenging since it depends on the used membrane configuration that can be: flat sheet module with its low compact area or the spiral wound of the high area and limited velocity to about 0.6 m/s [12]. These velocities correspond to Reynolds number of 9518 and 13750 for the 0.9 and 1.3 m/s respectively.

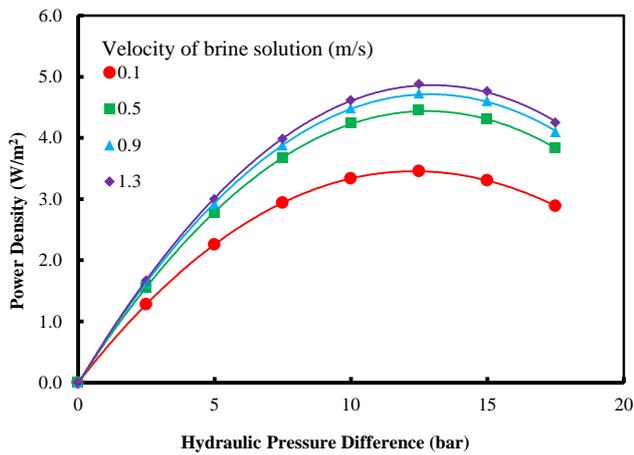


Fig. 5 Ideal power density curve for TFC HTI membranes for 35.5 g/l NaCl solution against 0.15 g/l NaCl solution at 20°C and different brine solution velocities

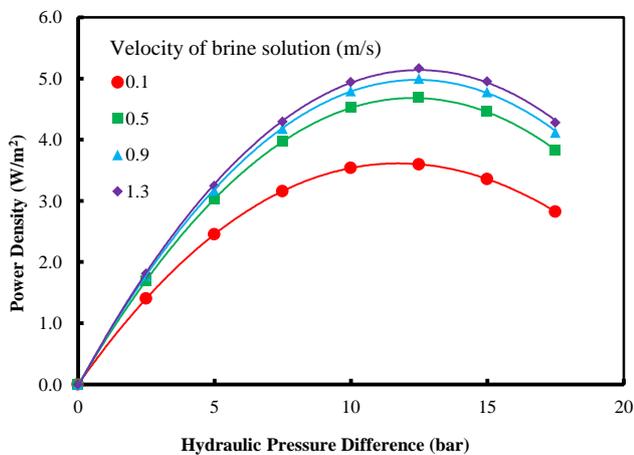


Fig. 6 Ideal power density curve for Prewetted TFC HTI membranes for 35.5 g/l NaCl solution against 0.15 g/l NaCl solution at 20°C and different brine solution velocities

For the TFC membrane, increasing the velocity had barely made the power to reach 5 W/m² which would also exclude the dry TFC and insure the necessity of its treatment with isopropyl alcohol solution as described in [8]. The only side effect that arises from the prewetting treatment is increased salt permeation rate which may considered unfavourable if the membrane is used for desalination purposes.

IV. CONCLUSIONS

In this study we focused on studying the potential of power generation of a recently developed TFC membranes by HTI: cellulose acetate (CA) and a pretreated thin-film composite with isopropyl alcohol and untreated TFC. Our aim was to find the optimum membrane that can surpass or reach the economical power density value. The study revealed that only prewetted TFC can be exploited for power generation under PRO conditions at 12.5 bar hydraulic pressure difference and brine solution velocity of 0.9 m/s (Reynolds number of 9518).

The suggested operating ΔP of 12.5 bar is below the maximum pressure difference 250 psi (17.2 bar), a limit that restricts investigating higher brine solution concentrations because optimum ΔP might exceed the 17.2 bar as shown in the 1 M brine solution.

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