ENERGY UTILIZATION OF BRINE FROM AN MSF DESALINATION PLANT BY PRESSURE RETARDED OSMOSIS

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Abstract

Seawater desalination plants discharge brine which is at higher salt concentration than the supplied seawater feed. Diluting this brine by mixing it with the lower concentration feed (seawater) will reduce the environmental hazards associated with the high salt concentration of the disposed brine. Energy can be generated from the dilution process in which two streams of different salt concentrations are mixed. Different methods have been proposed to generate energy by mixing two streams of different salt concentrations. This includes pressure retarded osmosis (PRO), reverse electrodialysis (RED) and hydrocratic generation (HG). However, these methods have not been used on a large commercial scale and are still undergoing development. In this paper, the potential of energy generation from applying PRO to the disposed brine blown down from a Multi-Stage Flash (MSF) plant is estimated. In the PRO process, the feed solution, a low salinity stream, and the draw solution, a high salinity stream, are pumped to the opposing sides of semi-permeable membranes. Water permeates through the semi-permeable membrane, from low hydrostatic pressure stream (feed solution) to the higher hydrostatic pressure stream (draw solution), due to the osmotic pressure difference. This increases the mass flow rate of pressurized draw stream, and energy is then obtained by depressurizing the draw stream through a hydro turbine. A differential model is developed for the PRO system that takes into consideration the concentration variation of both the feed stream and the draw stream along the PRO membrane. Available reverse osmosis (RO) membranes characteristics currently on the market are used to make the calculation. Membrane characteristics, especially water permeability coefficient, and flow conditions such as mass transfer coefficient significantly affect the PRO plant performance. An improvement in the membranes could significantly increase the energy produced by PRO plant.

I. INTRODUCTION

Seawater desalination is a prominent industrial process which plays an important role in the production of fresh water in Arabian Gulf region. Thermal desalination has been extensively used for large scale production of fresh water, about 54% of the total water production in Arabian Gulf region is produced by thermal desalination processes. Multistage flash desalination (MSF) is the dominant technology among thermal desalination plants. The MSF process accounts more than 85% of thermal desalination plants in Arabian Gulf region, while in the entire desalination industry its contribution in producing fresh water is more than 23% [1]. The water production capacity of MSF plants has been increased in the last decades due to the continuous improvement and vast field experience in operation, construction and design. Mathematical modeling has also played an important role in improving system design, individual processes, control, and operation.

All desalination plants reject brine which is at a higher salinity than the supplied feed seawater. This brine is usually discharged back to the feed seawater source. The discharge of the concentrated brine can damage aquatic ecosystems in particular if it contains pretreatment chemicals. Diluting this brine will reduce the environmental hazards associated with the discharged high salt concentration brine. Energy can be generated when the high salinity brine stream is mixed with the low salinity feed stream before discharging it. Different method have been proposed to generate energy by mixing two streams of different salt concentrations [2,3]. Loeb [4–6] discussed the basic concept of using liquids of different osmotic pressures to generate power. He suggested different combinations such as seawater and fresh water, or highly saline bodies such as the Dead Sea and seawater. The process of using two different salinity streams is now become known as Pressure Retarded Osmosis (PRO).

The recently intensified investigation in renewable energy sources for power generation and the latest developments in membrane science have led to the installation of first prototype PRO system in Norway [7], which is referred to as an osmotic power plant. Ahmad and Williams [8] investigated different salinity gradient power processes, including reverse electrodialysis (RED) and hydrocratic generation (HG), and they concluded that PRO has superior potential for energy harvesting because of the substantial amount of energy that can be generated and the lack of CO_2 emissions that will harm the natural climate. Gerstandt *et al*. [9] optimized a PRO plant by using two different types of membranes. The results showed that improvement of the membrane characteristics of this process will make it more feasible. Skilhagen *et al*. [7] and Gerstandt *et al*. [9] discussed the work done by the Statkraft company which built the first osmotic power plant in Norway. They indicated that PRO is getting closer to become a practical alternative for renewable energy production. Panyor [10] emphasized on the importance of osmotic power plant using PRO process.

It is important to mention here that PRO technology has not been introduced as an energy recovery device (ERD) in desalination plants. In this paper, the PRO system is used to estimate the potential of energy generation from the disposed brine of a Multistage Flash (MSF) desalination plant. Fig. 1 illustrates the proposed MSF-PRO system where the rejected brine from the MSF plant is used as the draw solution in the PRO unit.

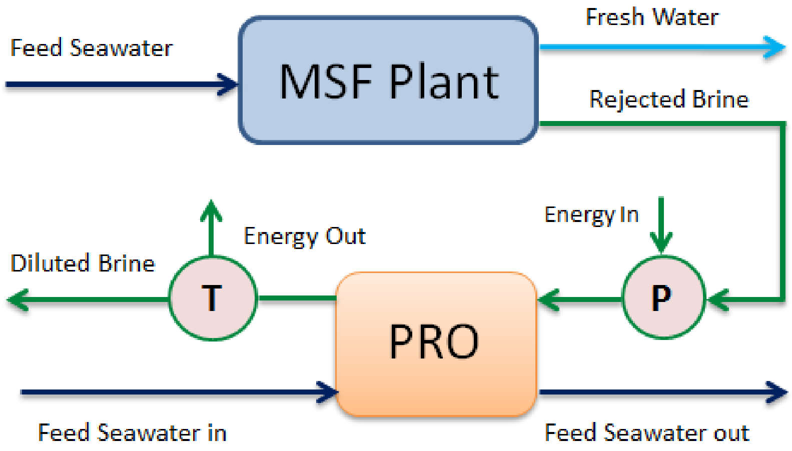

Figure 1 : MSF-PRO Plant

1.1 MSF Brine Circulation

The brine circulation MSF desalination plant consists of four sections, a heat rejection section, a heat recovery section, a brine heater, and a mixer. A schematic diagram of an MSF plant with brine circulation in Jubail, Saudi Arabia is shown in Fig. 2. The heat input section consists of a brine heater which heats the seawater using steam from a back pressure turbine to heat the brine up to the top brine temperature. The heat recovery and heat rejection sections are of the same construction and divided into a number of stages. Each stage consists of a flashing chamber, a condenser, a demister, and a distillate tray. The intake seawater (state 0) is pumped into the condenser tubes of the heat rejection section at ambient temperature of sea where its temperature increases by absorbing the latent heat of condensing the vapor formed in each flashing chamber. The warm intake feed is divided into two streams: one is the cooling water which is discharged back to the sea (state 17), while the other is feed which is introduced into the mixer to mix with the brine leaving the last stage of the heat recovery section (state 4). The purpose of the cooling water is to control the temperature of the circulated brine by removal of extra heat energy added in brine heater to the MSF system. The circulated brine flow is taken from the mixer and introduced in the tubes of the heat recovery section (state 8). As this recycled brine flows across the stages inside the condenser tubes, it absorbs the latent heat of vaporization of the distillate vapor formed in each stage. The recycled brine then enters the tubes of the brine heater where it is heated by the condensation of low pressure steam on the tube surface to the maximum temperature, or top brine temperature (state 10).

The hot brine stream is directed into the first flashing chamber of the heat recovery section and evenly distributed along the stage width. A small amount of recycled brine flashes off and forms distillate vapor which results in a decrease of temperature in the circulated brine flow. The distillate vapor flows across the demister which absorbs entrained brine droplets and then the distillate vapor condenses outside the condenser tubes, releasing its latent heat to the feed stream flowing inside tubes. The vapor condensed outside the condenser tubes is collected as fresh water in the distillate tray.

The intake seawater has a salinity of 46.5 g/kg and is pumped into the plant at 35^{o}C at atmospheric pressure at a rate of 3597 kg/s [11]. The majority of this intake seawater serves as a coolant (1589 kg/s) and is discharged back to the sea, while the remaining feed seawater (808 kg/s) is supplied to the last stage flashing chamber. The circulated brine from the mixer, at 44.3°C with salt concentration of 64.8 g/kg at a rate of 3621 kg/s, is pumped into the condenser tubes of heat recovery section, and its temperature increases to 85°C by absorbing latent heat from the water vapor in the flashing stages. This circulated brine is further heated up to top brine temperature of 90.8 °C in the brine heater with supplied steam at 98.9 °C and at a rate of 34.93 kg/s. The circulated brine is then flashed consecutively in the flashing chambers from 635 kPa to 8 kPa. The condensed vapor is accumulated in the tray and discharged as a distillate at a rate of 272 kg/s, while the part of circulated brine is discharged from the last stage at a rate of 536 kg/s and a salt concentration of 70 g/kg. This blow down brine will be used as the draw solution in the pressure retarded osmosis (PRO) process.

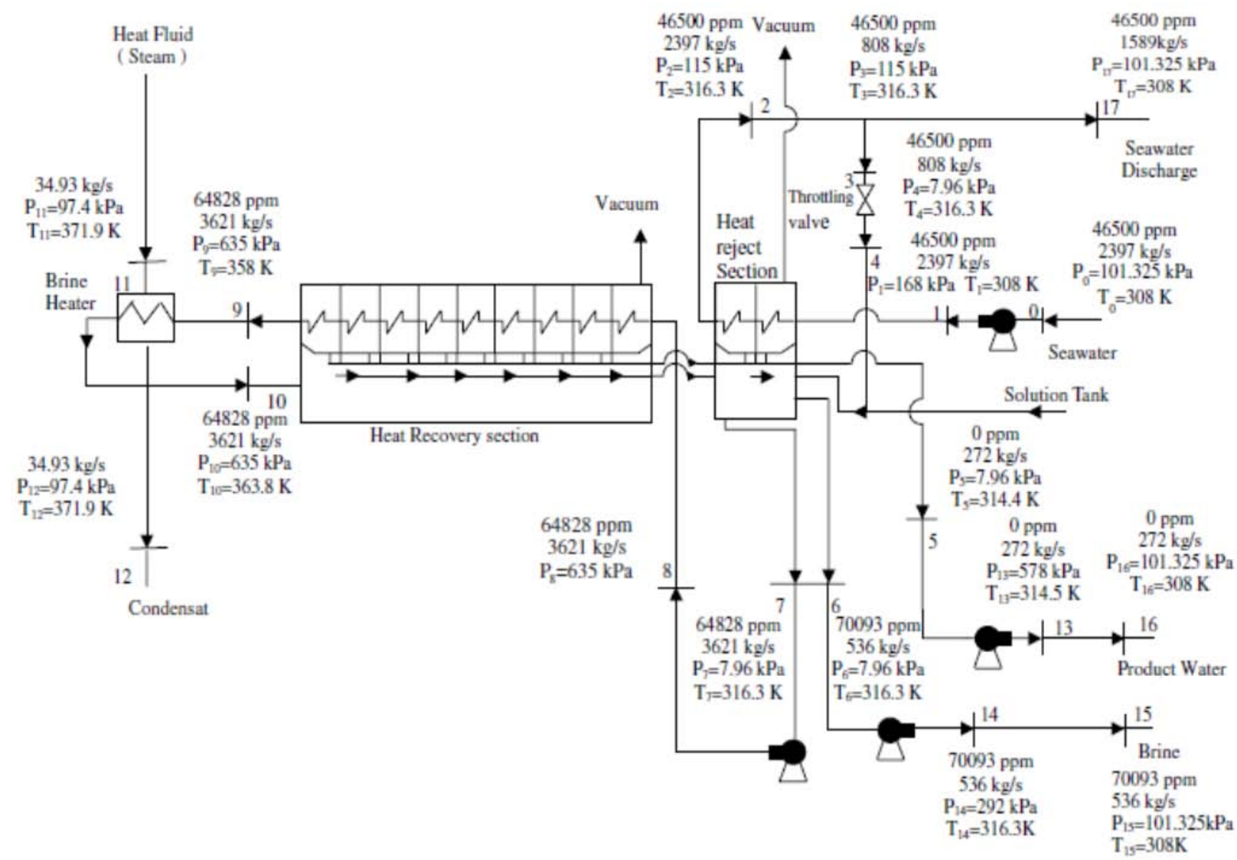

Figure 2 : Schematic diagram of MSF brine circulation plant [12]

1.2 Pressure Retarded Osmosis (PRO)

A schematic diagram of the PRO system is shown in Fig. 3. In PRO process, the feed solution with the low salinity and low hydrostatic pressure and the draw solution with the high salinity and high hydrostatic pressure flow to the opposite sides of semi-permeable membranes. Water permeates through the semi-permeable membrane, from the low hydrostatic pressure stream (feed solution) to the higher hydrostatic pressure stream (draw solution) due to the osmotic pressure difference. This increases the mass flow rate of the pressurized draw stream and energy is obtained by depressurizing the draw stream through a hydro turbine. For this system, the osmotic pressure difference must be higher than the hydraulic pressure difference to permeate water through the semi-permeable membrane and to have a net power output.

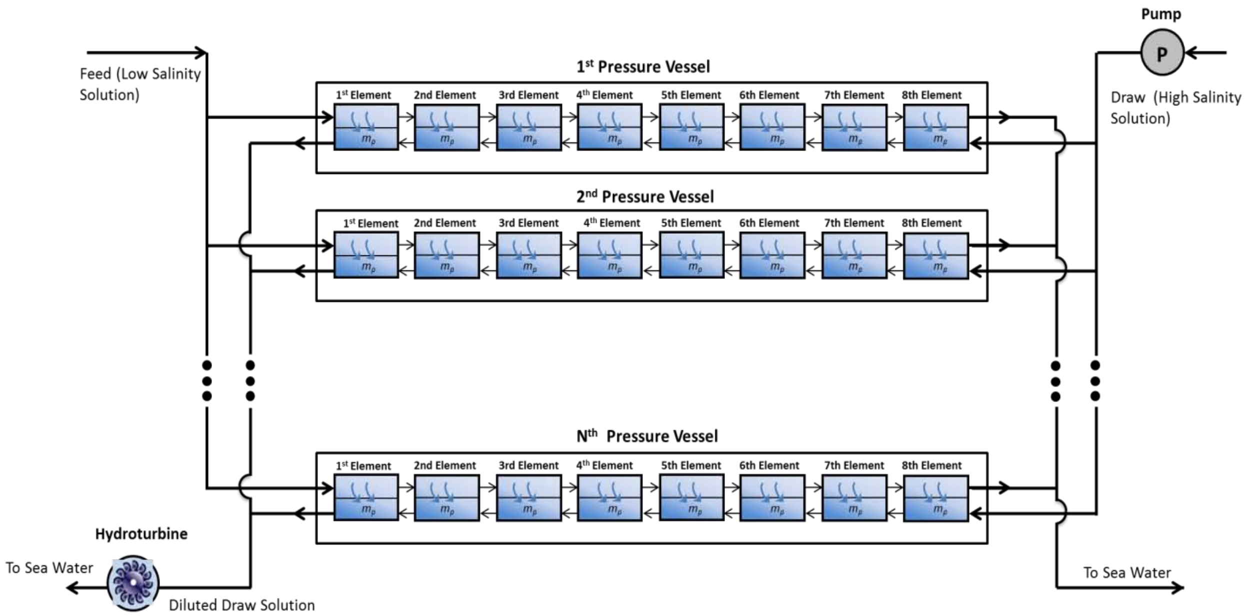

Figure 3 : Pressure Retarded Osmosis (PRO) system

II. MATHEMATICAL MODEL

2.1 MSF Brine Circulation

Several studies related to the modeling of multi-stage flash (MSF) desalination are in the literature [12–18]. The mathematical model of the Multi-stage flash (MSF) desalination is developed under the following assumptions: (1) steady state operation; (2) the distillate product is salt free; (3) the steam condensate is not subcooled in the brine heater; (4) heat loss to the surroundings is negligible; and (5) all the saline liquid droplets are retained in the demister. The governing equations for the MSF system are a set of continuity equations on water mass and salt mass flow rates, and energy balances. All thermophysical properties of seawater are taken from the correlations provided by Sharqawy et al. [19] as a function of temperature, pressure, and salinity.

2.2 Pressure Retarded Osmosis (PRO)

A one-dimensional differential model is developed for the PRO system that takes into consideration the salinity variation of both the feed and brine streams along the membrane area [2,3,20,21]. Available reverse osmosis (RO) membrane characteristics are used to make the calculation. The PRO model consists of four mass balance equations and two transport equations. The mass balance equations are written for water molecules and salt molecules on the draw side and feed side (Eq.1 to Eq.4). The membrane area is divided into finite number of control volumes, each of an infinitesimal area of dA_m. The continuity equations in the differential forms are given as follows.

Water mass balance:

$$d\left[\left(1-w_f\right)Q_f\right]=-J_w dA_m \tag{1}$$

$$d\left[\left(1-w_d\right)Q_d\right]=J_w dA_m \tag{2}$$

Salt mass balance:

$$d(w_f Q_f)=J_s dA_m \tag{3}$$

$$d(w_d Q_d)=-J_s dA_m \tag{4}$$

where Q_f and Q_d are the volume flow rates of the feed stream and the draw stream, respectively, while J_w is the water flux permeated from the feed stream to draw stream and J_s is the salt flux, w_f and w_d are the salinity of feed stream and draw stream respectively. The transport equations for water and salt across an ideal membrane; that ignores the concentration polarization effect, are given by Eq. (5) and (6).

$$J_w = A(\Delta\pi - \Delta P) \tag{5}$$

$$J_s = B\left(w_d - w_f\right) \tag{6}$$

where A (m/s-kPa) and B (m/s) are the water permeability coefficient and salt permeability coefficient respectively, $\Delta\pi$ (kPa) is the osmotic pressure difference across the membrane (difference between osmotic pressure at the draw solution and feed solution), and ΔP (kPa) is the hydraulic pressure difference. It is assumed that there is a negligible hydraulic pressure drop along the feed stream and draw stream paths. Therefore, ΔP is assumed to be constant along the membrane area.

Concentration polarization (CP) is the main hurdle in membrane permeation as it diminishes the effective osmotic pressure difference across the membrane. Lee et al. [22] developed an expression to incorporate the effect of internal concentration polarization which was further modified by Achilli et al. [3] and Xu et al. [20], by including both internal and external concentration polarization. The resulting equation for water flux is

$$J_w = A\left(\left(\pi_d\right) exp\left(-\frac{J_w}{k_m}\right)\frac{\left(1-\left(\frac{\pi_f}{\pi_d}\right) exp(J_w k_s)\, exp\left(\frac{J_w}{k_m}\right)\right)}{1+\left(\frac{B}{J_w}\right)\left(exp(J_w k_s)-1\right)} - \Delta P\right) \tag{7}$$

where k_m is the mass transfer coefficient and k_s is the solute resistivity. Mass transfer coefficient (k_m) depends on the diffusion coefficient, flow channel geometry and flow conditions. Osmotic pressures are calculated using correlations provided by Sharqawy et al. [19] as a function of temperature, pressure and salinity. Due to large concentration difference across a semi permeable membrane, a small amount of salt permeates from the draw stream to the feed stream which results in the reduction of effective osmotic pressure difference across the membrane. Therefore, salt flux (J_s) should be taken into consideration in the PRO model. The expression for salt flux as a function of water flux (J_w), salt permeability (B), solute resistivity (k_s) is given by [23],

$$J_S = \left(\frac{B}{k_S B + 1}\right)\left(w_d - w_f - k_S w_f J_w\right) \tag{8}$$

The total permeate flow rate Q_p (m^3/s) transferred through the membrane is the integration of the water flux over the membrane area.

$$Q_p = \int_0^{A_m} J_w dA_m \tag{9}$$

The power produced from the PRO system is equal to the product of the total permeate flow rate and the hydraulic pressure difference across the membrane as given by Eq. (10).

$$Power = Q_p \Delta P \tag{10}$$

The governing equations for PRO are solved numerically to calculate permeate flow rate, and produced power as a function of ΔP. Under idealized conditions, the water flux decreases as hydraulic pressure increases, and finally reaching to zero $\Delta\pi = \Delta P$ (flux reversal point). Concurrently, power increases with increasing hydraulic pressure and reaches a maximum at $\Delta P = \Delta\pi / 2$ then decreasing with further increase of hydraulic pressure until it reaches zero at the flux reversal point. Under actual conditions, reverse salt diffusion and concentration polarization reduce the effective osmotic pressure difference which lowers the permeate flow rate and power as compared to the idealized case.

III. RESULTS

For model validation, the results of the PRO mathematical model are compared with the experimental data provided by Achilli et al. [3] by assuming the same input values and membrane characteristics. It is shown in Table 1 that the results of the current model are in good agreement with the experimental data.

Table 1 : Comparison between Achilli et al. [3] experimental results and the current study

	Draw solution salinity (g/kg)	Feed solution salinity (g/kg)	ΔP (kPa)	Water flux (10^{-6} m/s)	Power (W)
Achilli [3]	35	0	972	2.81	0.00512
Present work	35	0	972	2.51	0.00458
Achilli [3]	60	0	972	5.21	0.00949
Present work	60	0	972	5.08	0.00924

For the PRO system shown in Fig. 3, the counter flow configuration is used. The membrane characteristics are taken from a commercially available RO membrane SWC5 1640 (Hydranautics corporation) [24]. The membrane parameters and the input data for the PRO system are listed in Table 2.

Table 2 : Input data to PRO plant

Surface area of one pressure vessel	1264 (m^2)
Water permeability coefficient (A)	1.87×10^{-9} (m/s-kPa)
Salt permeability coefficient (B)	1.11×10^{-7} (m/s)
Mass transfer coefficient (K_m)	8.48×10^{-5} (m/s)
Solute resistivity (K_s)	$4.5\times10^{+5}$ (s/m)
Feed solution salinity (w_f)	46.5 (g/kg)
Draw solution salinity (w_d)	70 (g/kg)
Intake draw stream to one pressure vessel	6.5 (kg/s)
Mixing ratio (feed stream / draw stream)	1
Total blow down from MSF plant (draw solution)	536 (kg/s)

The variation of draw and feed salinity along the normalized membrane area is shown in Fig. 4. The draw streams enter at a salinity of 70 g/kg which decreases along the membrane due to addition of permeate flow and exits at a salinity of 59.4 g/kg. On the contrary, the feed streams enter the system at a salinity of 46.5 g/kg and leaves at 56.5 g/kg. The normalized area is the accumulated area at a given location divided by the total membrane area and ranges from zero to one. The water flux transferred from the feed stream to the draw stream varies with the of the pressure difference across the membrane. However, the salts transfer, in the opposite direction of water flux, from the draw stream (high salinity) to the feed stream (low salinity) due to the salt concentration gradient. The variation of water flux, salt flux with and without considering concentration polarization (CP) is illustrated in Fig. 5. As the pressure difference increases, the water flux transfer rate also increases. Similarly salt flux also increases, as the difference between salinities is higher at the later stages of the system.

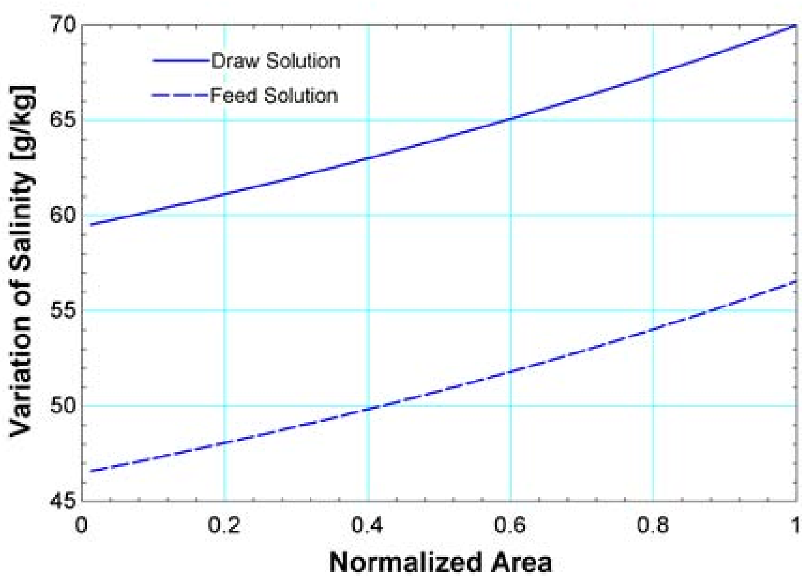

Figure 4 : Variation of draw and feed solution salinity along the membrane

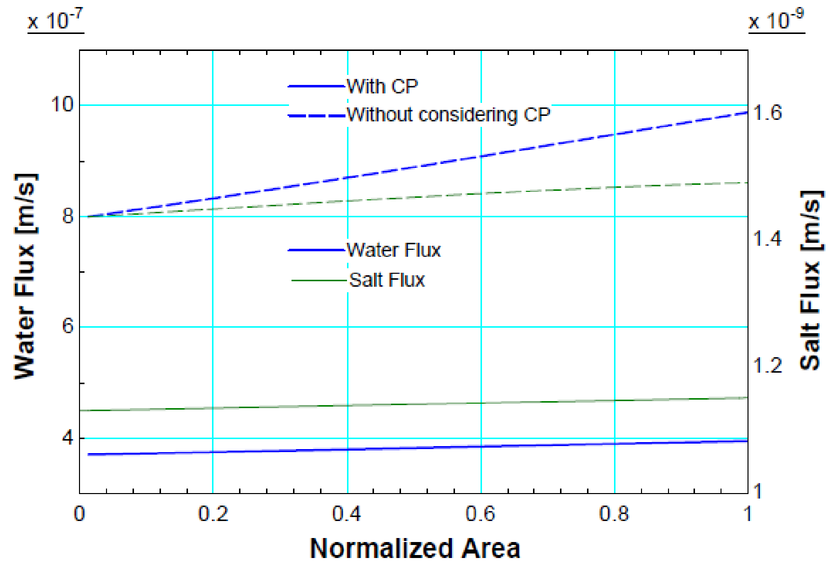

Figure 5 : Variation of water flux, salt flux with and without considering CP

The total power produced by the PRO system with and without considering concentration polarization (CP), as a function of hydraulic pressure difference, is shown in Fig. 6. It is noted that the maximum power obtained from the PRO plant without considering CP is 72.1 kW while with considering the effect of CP the power produced is 30.8 kW at a hydraulic pressure of 1010 kPa. This power is very small as compared to the pumping power required for the Jubail MSF Desalination plant (i.e., 3649 kW) [12]. This process can be improved by optimizing operating conditions and system configuration. The maximum reversible mixing work that can be achieved from this PRO system with streams of 70 and 46.5 g/kg is 0.4 kJ/kg (or 214.4 kW for the draw solution of 536 kg/s) [25]. Therefore, the proposed system shown in Fig. 3 has a second law efficiency of about 33% (14% with considering CP). The results are much dependent upon membrane characteristics like the water permeability coefficient and flow/module conditions such as the mass transfer coefficient. An improvement in the membrane properties could significantly increase the power produced by PRO plant. About 46% (16% with considering CP) increase in power could be achieved if membrane with water permeability coefficient of 2×10^{-8} instead of 1.87×10^{-9} (m/s-kPa) is used (Fig. 7).

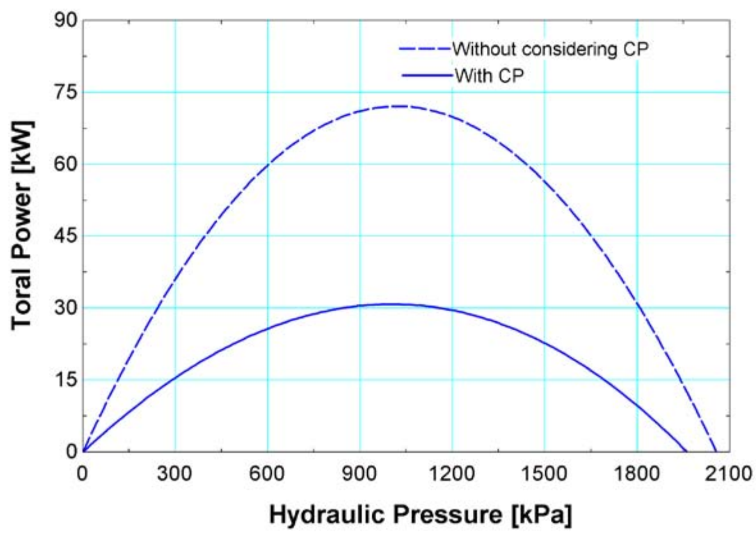

Figure 6 : Total power produced by PRO plant as a function of hydraulic pressure

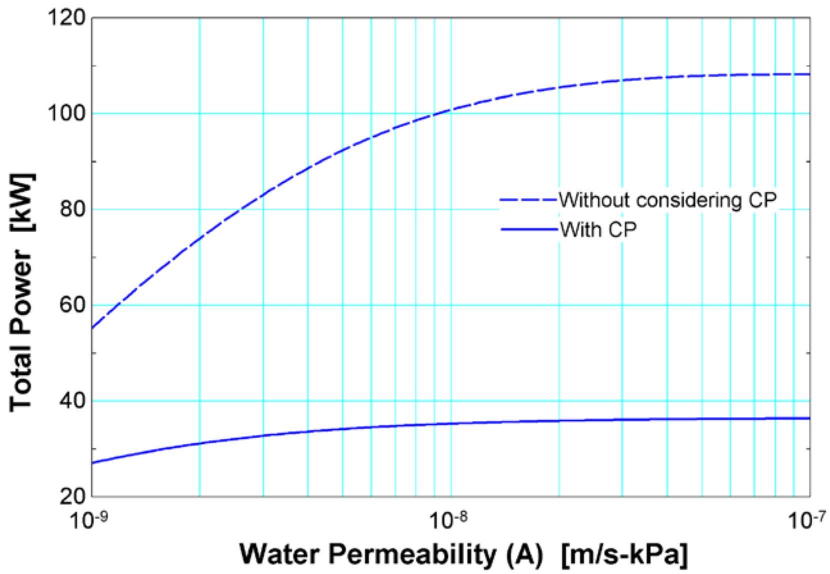

Figure 7 : Effect of water permeability on Power

IV. SUMMARY

In this study, a mathematical model of a pressure retarded osmosis system is developed to investigate the potential of PRO as an energy recovery process for desalination plants. For this purpose, the rejected brine from a desalination plant is used as the draw solution and seawater is used as the feed solution. The present model uses the characteristics of available RO membranes for the proposed PRO system. At 1010 kPa hydraulic pressure, the power produced by the PRO system is 30.8kW which is much less than the power required by the pumps of the MSF desalination plant (3649 kW) studied. The power produced by PRO can be increased by optimizing the flow rates of the draw solution and feed solution and improving the system configuration. The major barrier to better power production is the lack of membranes designed for the PRO process. The PRO plant performance is dependent on membrane properties, especially water permeability coefficient, and to flow conditions such as mass transfer coefficient. About 16% increases in power is achieved if the membrane water permeability coefficient is of order 10^{-8} m/s-kPa. The improvements in the membrane characteristics will significantly increase the power produced by PRO plant and make it feasible to use PRO as an energy recovery process for desalination plants.

V. ACKNOWLEDGEMENTS

The authors would like to thank King Fahd University of Petroleum and Minerals in Dhahran, Saudi Arabia, for funding the research reported in this paper through the Center for Clean Water and Clean Energy at MIT and KFUPM under project number R13-CW-10.

VI. REFERENCES

[1] 25th GWI DesalData/IDA, Worldwide Desalting Plant Inventory, IDA Desalination Yearbook 2012-2013, Media Anlytics Ltd. Oxford, Uk, 2012.

[2] A. Achilli, A. Childress, Pressure retarded osmosis: From the vision of Sidney Loeb to the first prototype installation—Review, Desalination. 261 (2010) 205–211.

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

[4] S. Loeb, Energy production at the Dead Sea by pressure-retarded osmosis: challenge or chimera?, Desalination. 120 (1998) 247–262.

[5] S. Loeb, Large-scale power production by pressure-retarded osmosis, using river water and sea water passing through spiral modules, Desalination. 143 (2002) 115–122.

[6] S. Loeb, One hundred and thirty benign and renewable megawatts from Great Salt Lake? The possibilities of hydroelectric power by pressure-retarded osmosis, Desalination. 141 (2001) 85–91.

[7] S. Skilhagen, J. Dugstad, R. Aaberg, Osmotic power—power production based on the osmotic pressure difference between waters with varying salt gradients, Desalination. 220 (2008) 476–482.

[8] M. Ahmad, P. Williams, Application of salinity gradient power for brines disposal and energy utilisation, Desalination and Water Treatment. 10 (2009) 220–228.

[9] K. Gerstandt, K. Peinemann, S. Skilhagen, T. Thorsen, T. Holt, Membrane processes in energy supply for an osmotic power plant, Desalination. 224 (2008) 64–70.

[10] L. Panyor, Renewable energy from dilution of salt water with fresh water: pressure retarded osmosis, Desalination. 199 (2006) 408–410.

[11] M.H. Sharqawy, J.H. Lienhard V, S.M. Zubair, On exergy calculations of seawater with applications in desalination systems, International Journal of Thermal Sciences. 50 (2011) 187–196.

[12] N. Kahraman, Y.A. Cengel, Exergy analysis of a MSF distillation plant, Energy Conversion and Management. 46 (2005) 2625–2636.

[13] H. El-Dessouky, H. Shaban, H. Al-Ramadan, Steady-state analysis of multi-stage flash desalination process, Desalination. 103 (1995) 271–287.

[14] H. Baig, M. Antar, S. Zubair, Performance evaluation of a once-through multi-stage flash distillation system: Impact of brine heater fouling, Energy Conversion and Management. 52 (2011) 1414–1425.

[15] M. Rosso, A. Beltramini, M. Mazzotti, M. Morbidelli, Modeling multistage flash desalination plants, Desalination. 108 (1996) 365–374.

[16] O. Hamed, M.A. Al-Sofi, M. Imam, Simulation of multistage flash desalination process, Desalination. 134 (2001) 195–203.

[17] N.M. Abdel-Jabbar, H.M. Qiblawey, F.S. Mjalli, H. Ettouney, Simulation of large capacity MSF brine circulation plants, Desalination. 204 (2007) 501–514.

[18] A. Husain, A. Woldai, A. AI-Radif, A. Kesou, R. Borsani, H. Sultan, et al., Modelling and simulation of a multistage flash (MSF) desalination plant, Desalination. 97 (1994) 555–566.

[19] M. Sharqawy, J.H. Lienhard V, S.M. Zubair, Thermophysical properties of seawater: A review of existing correlations and data, Desalination and Water Treatment. 16 (2010) 354–380.

[20] Y. Xu, X. Peng, C. Tang, Q. Fu, S. Nie, Effect of draw solution concentration and operating conditions on forward osmosis and pressure retarded osmosis performance in a spiral wound module, Journal of Membrane Science. 348 (2010) 298–309.

[21] T. Thorsen, T. Holt, The potential for power production from salinity gradients by pressure retarded osmosis, Journal of Membrane Science. 335 (2009) 103–110.

[22] K.L. Lee, R.W. Baker, H.K. Lonsdale, Membrane for Power generation by pressure retarded osmosis, Journal of Membrane Science. 8 (1981) 141–171.

[23] S. Van Der Zwan, I. Pothof, Feasibility of osmotic power from a hydrodynamic analysis at module and plant scale, Journal of Membrane Science. 389 (2011) 324–333.

[24] SWC5 1640 Hydranautics Membrane, http://www.pure-aqua.com/swc-5-1640-hydranautics-membrane.html, Accessed on 2nd October 2012.

[25] M.H. Sharqawy, S.M. Zubair, J.H. Lienhard, Second law analysis of reverse osmosis desalination plants: An alternative design using pressure retarded osmosis, Energy. 36 (2011) 6617–6626.