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# Enhancement of the Dual Pressure Retarded Osmosis (PRO) Process for Power Generation Utilising Seawater and Brackish Water as Draw and Feed Solutions

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**Abstract:**

In this paper, new enhancements of the dual PRO process for power generation have been suggested and tested theoretically. Seawater and brackish water were exploited as draw and feed solutions in the processes. The dual PRO process, which has been previously suggested as efficient cycle for power generation, was used as stranded or reference power cycle. The assessment of the newly suggested PRO cycles was done based on the total water volume produced as permeate across a selective membrane and hence on the net power generated for an individual process. The results indicated that under the same operational conditions, the newly suggested PRO cycles were produced higher power than that produces by the standard one. In addition, the cycle given by case (3) represented the most powerful PRO cycle.

Keywords: PRO, water flux, power generation

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## Introduction

Energy consumption increases steadily around the world because of the population growth and development of technology. Fossil fuel is the leading energy resources implementing with about 80%. Only 11% of the gross energy required is provided by renewable energy resources [1]. Accordingly, many environmental problems such as global warming, ozone depletion and air pollution are coming up which become serious issues facing the human existing. Therefore, high attention is currently directed on the renewable energy resources. Pressure Retarded Osmosis (PRO), as a type of renewable energy resource, has been suggested and investigated for power generation from salinity gradient resource. Conversely to other renewable energy resources [Ali and Adel], such as solar and wind energy, PRO can be worked along 24- hours, where, it is not affected by solar radiation or wind. It can be established on a small area. It has a less scale-up problem and it can be used as a pre-treatment of the RO rejection. Nevertheless, PRO process is not commercialised yet.

The power generation via the PRO process can be achieved by a mixing of two solutions with different salinity or other osmotic pressure sources through a semi permeable membrane. The osmotic pressure, however, prefunds as a results to the presence of solute in the solution. The higher the solute concentration, the higher the osmotic pressure and vice versa. The main function of the membrane is to permit the solvent to move from the low osmotic pressure side (low solute concentration) towards the high osmotic side (low solute concentration). Accordingly, the term "draw solution" is used to define the high solute concentration side, while "feed" is used for another. The movement of the solvent results in an increased the concentration of the solute in the feed side and dwindle it in the draw solution side. This is increased the solvent volume can be exploited to generate electricity via a hydraulic turbine.

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Practically, an open and a closed cycles can be used through the PRO process. The main difference is that in the former both feed and draw solutions are drawn out after they left the membrane unit. While, a regenerating step is necessary to regenerate the draw solution (solute recovered) and send it back again to the FO unit to maintain the PRO process. The regeneration step represents the bottleneck of the power generation process by PRO. Different techniques, such as evaporation, crystallization and membrane separation can be used. Unfortunately, these processes almost energy tentative, which affects the fusibility of using the PRO for power generation. Therefore, the efficiency of closed system PRO strongly depends on availability of renewable energy resources for osmotic agent regeneration [2].

Forward osmosis, which is the basis of PRO process, could be used as a pre-treatment process for the concentrate stream produces by RO before it is drained out. The high salinity of draining RO rejection could be resulted in significant environmental problems. Different techniques are currently used to treat the rejected stream in RO, which is already contained high energy content as a hydraulic pressure. Therefore, using the pressure exchanger (PE) to exploit the concentrate hydraulic pressure to drive the RO process has been used. This technique could be reduced the entire energy consumption of RO process by 35% with no solution of the environmental impact. This encourages investigating the possibility of using the concept of PRO to havens the energy content of RO concentrate.

**Theoretical part**

Mathematically, the gross power generation by PRO is limited by the volume water permeate and the applied hydraulic pressure as:

$$P_G = \Delta P . Q_p \qquad (1)$$

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where $P_G$, $\Delta P$ and $Q_p$ represent the net power generation (W), the hydraulic pressure of the pressurised draw solution (bar) and the permeate volumetric flow rate $(m^3/h)$, respectively.

Many investigators have suggested the RO concentrate as a draw solution in PRO system because it has a high osmotic pressure (high salt concentration) and free of charge [3]. Achilli et al. [4] investigated experimentally and theoretically the power generation with PRO using sodium chloride as feed and draw solution. The experiments were carried out using a flat sheet cellulose triacetate (CTA) FO membrane. The maximum power density was found to be equal to 2.7 and 5.1 W/m2 for draw solution concentrations 35 and 60 g/L, respectively and at a hydraulic pressure of 970 kPa. Kim and Elimelech [5] observed the deformation of a membrane due to the action of the high hydraulic pressure on the feed channel spacer and its effect on the performance PRO unit. They introduced new experimental protocol to determine the membrane properties (A, B and S), which are used for accurately predicting the water flux as a function to hydraulic pressure difference. Their experimental results were fitted successfully with the model developed. Altaee et al. [6] demonstrated that the dual stages PRO process can be generated power more than the single stage one. Accordingly, the effect of different operational parameters, such as feed, draw solution and osmotic pressure on the net power generation were tested. Lee, and Kim [7] used sodium chloride solutions as feed and draw solution in a single PRO unit and predicted theoretically water and reveres solute flux (Jw and Js) as function of the hydraulic pressure.

In the present investigation, new enhancements on Ataee et al. [6] dual PRO process were suggested and assessed theoretically. Three new PRO processes were presented and compared with the standard [6] process.

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**Methodology**

Following equation is used to determine the water flux $(J_w)$ through the membrane in PRO processes:

$$J_w = A_w(\Delta\pi - \Delta P) \qquad (2)$$

where $A_w$, $\Delta\pi$ and $\Delta P$ represent the coefficient of membrane permeability, the differential osmotic pressure across the membrane and net hydraulic pressure, respectively.

To obtain the density of the power $(W)$ of the PRO process, the following expression can be used:

$$W = J_w \Delta P \qquad (3)$$

From Eq. (2&3) we get to:

$$W = A_w(\Delta\pi - \Delta P)\,\Delta P \qquad (4)$$

Gerstandt et al. [17] determined the useful power density of the PRO process between 4 to 6 $W/m^2$. And the maximum power density has been determined theoretically (Achilli,) [18], by considering the applied hydraulic pressure $\Delta P$ equals to a half of the osmotic pressure across the membrane:

$$\Delta P = \Delta\pi/2 \qquad (5)$$

Using Eq. (3), the maximum power density can be found as:

$$W_{max} = A_w \frac{\Delta\pi^2}{4} \qquad (6)$$

The applied hydraulic pressure difference $(\Delta P)$ and osmotic pressure difference $(\Delta\pi)$ are normally calculated by assuming linear hydraulic and osmotic pressure drops across the membrane as [18] :

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$$\Delta P = \frac{P_{DS-in}+P_{DS-out}}{2} - \frac{P_{F-in}+P_{F-out}}{2} \quad (7)$$

and

$$\Delta\pi = \frac{\pi_{DS-in}+\pi_{DS-out}}{2} - \frac{\pi_{F-in}+\pi_{F-out}}{2} \quad (8)$$

where, the subscripts DS and FW refer to the Draw Solution (the high concentration side) and the Feed Water (the low concentration side), respectively.

In general the net power generated is obtained by using Eq. (1) above. Only permeate has to be arranged to involve the additional amount which produces as a result of using more than one PRO process. However, Eq. (1) can be written in more general form as:

$$P_{net} = \Delta P\, Q_{pi} \quad (9)$$

where $Q_{pi}$ represents the total volumetric permeate of $i$ number of PRO processes.

It is clear from Eq. (9), for a constant hydraulic pressure, the net power produce by a single PRO process is less than other process exploited more than one (two or three as presented in the present research). This is because of the total permeate of the single process is less than produces by other once.

## Results and discussion

Four different scenarios (cases) have been suggested and tested through the present investigation. Theses PRO scenarios can be shown as following:

1- Case (1): this case is the same to that suggested by Altaee et al [4] and represented the reference or the standard to estimate the enhancement of the newly suggested PRO processes. Fig. 1, shows the schematic diagram of the

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process. Seawater is used as a draw solution while brackish or effluent water as a feed. Pressure exchanger is used to reduce the power consumed by the high pressure pump. The total net power produce is calculated by the applied hydraulic pressure times the total permeate (flux).

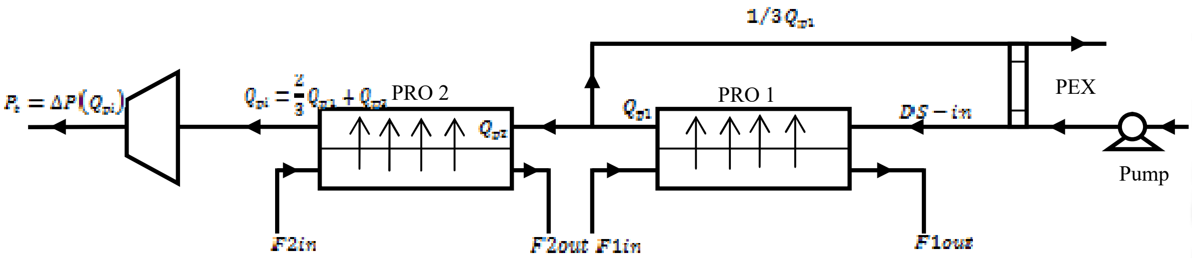


Fig. 1: dual PRO process

2- Case (2): in this process, $Q_E$ which is used to derive the pressure exchanger is return to the draw solution feed after the second PRO process (see Fig. 2). In this case, the total water volume enters to the turbine will be higher than the first case (fig. 1). This of course reflects positively on the amount of the net power generating.

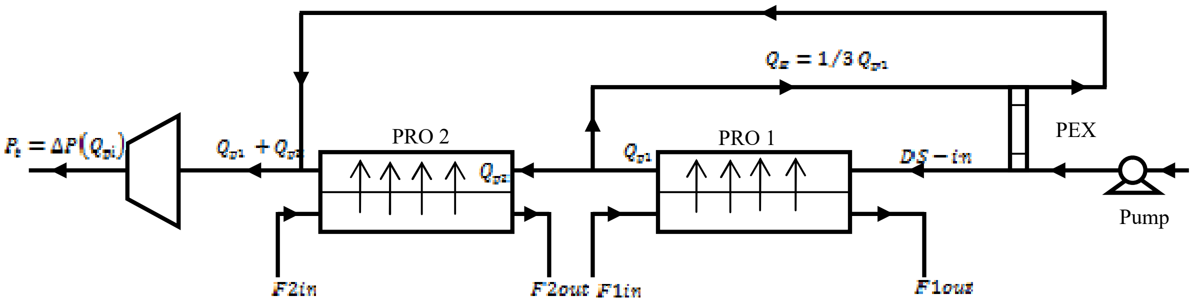


Fig. 2: first enhancement PRO process cycle

3- Case (3): in this case, the part of the draw solution feed is exploited in third PRO process and return to the main feed before the entrance of the second stage (see Fig. 3). A new permeate $Q_{p3}$ is obtained throughout this stage. Therefore the draw solution flow rate enters the

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second stage will be higher than that of the previous two stages above and hence the power produce will be higher.

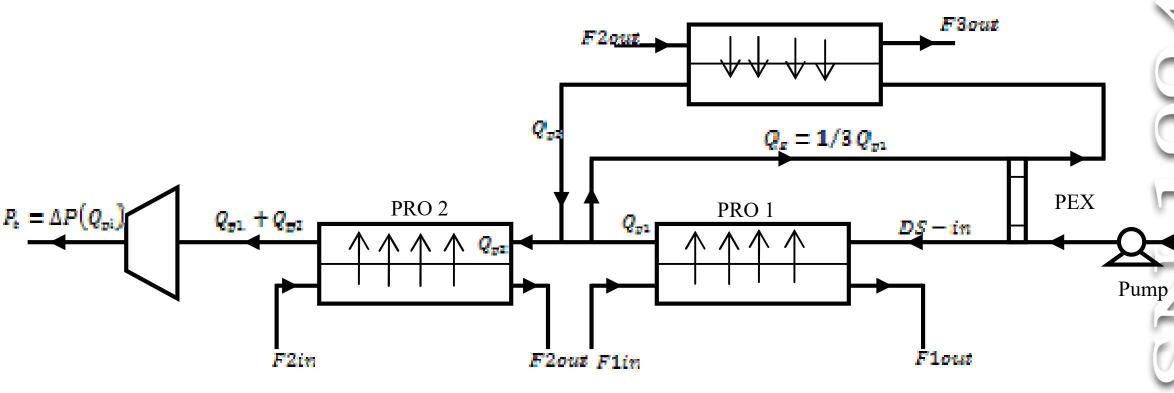


Fig.3 : Second enhancement PRO process

4- Case (4): as in Fig. 3 above, only the new $Q_{p3}$ which produces by PRO3 is sent directly to the turbine show in Fig. 4.

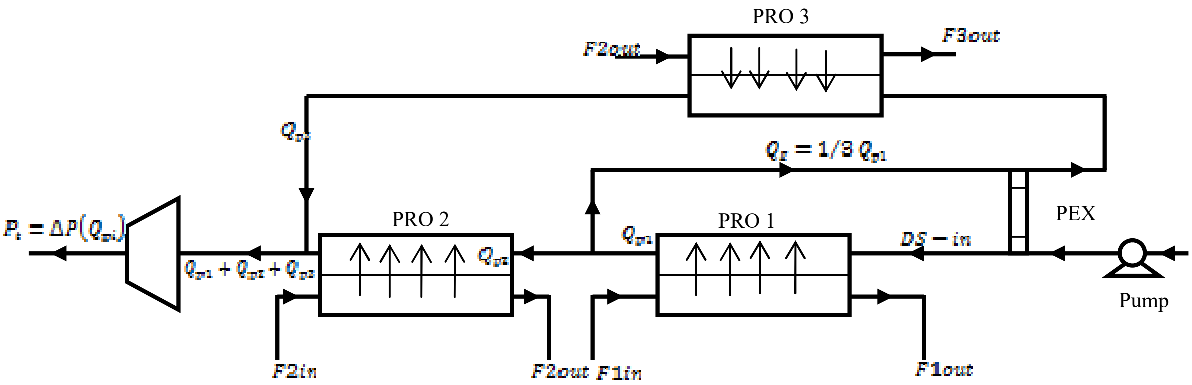


Fig.4 : Third enhancement PRO process

Fig(5) shows the variation of the total water volume that enters to the turbine with applied hydraulic pressure for four different cases described above .In general the total volume decreases with increasing of the applied hydraulic pressure which is consistence with literatures and the concepts of FO . The increase of the hydraulic pressure tends to make the FO process working inversely (RO). Apparently case 3 produces the highest volume of water

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whilst the case 1 gives the minimum. This could be attributed by that in case 3 there's in addition water flux produces by exploiting a new FO unit (unit 3) (see fig.3). The new membrane unit helps to increase the total flux and extends the new draw solution FO side that enters to the unit 2. It is clear that in spite of this process is led to dilute the draw solution concentration; the gain in the flux harvested in unit 3 is still useful and bifacial. Unsurprisingly, both case 2 and 4 gave the same water volume. The same total water volume for case 2 and 4 is resulted by that in both cases the addition flux produces by unit 3 is directly exploited at the turbine. Therefore there is no benefit from this flux at unit 2. This indicates that there is no benefit of using unit 3 in this case.

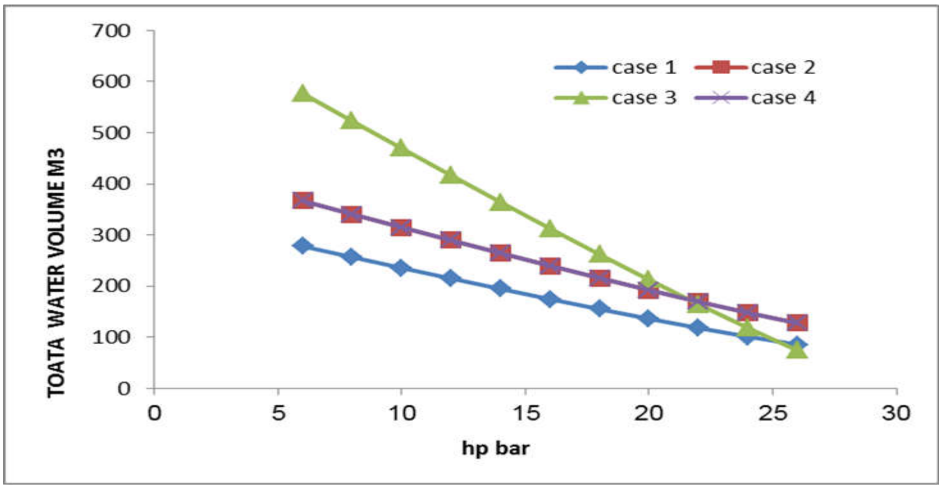


Fig. (5): Total volume of water produced versus the hydraulic pressure supplied

Figure 6 shows the relationship between the power density and the applied hydraulic pressure for the four different cases. Again case 3 exhibits the most useful case, where it obvious gives the highest possible power density among other results shown by the Fig. 6. At the same time, both cases 2 and 4 give the same results. This is completely agreed with the results give in Fig. 5 above. Conversely to other cases that appear in Fig. 6, the enhancement achieved by case 3 has an optimal value of the power density at a specific applied hydraulic

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pressure. The optimum power density value is 5.08 w/m$^2$ corresponding to Hp nearly 6 bar. This could be result from that the osmotic pressure (OP) of the draw solution side which enters to unit 2 is less than the OP of other cases. This is because of the further dilution happened at unit 3.

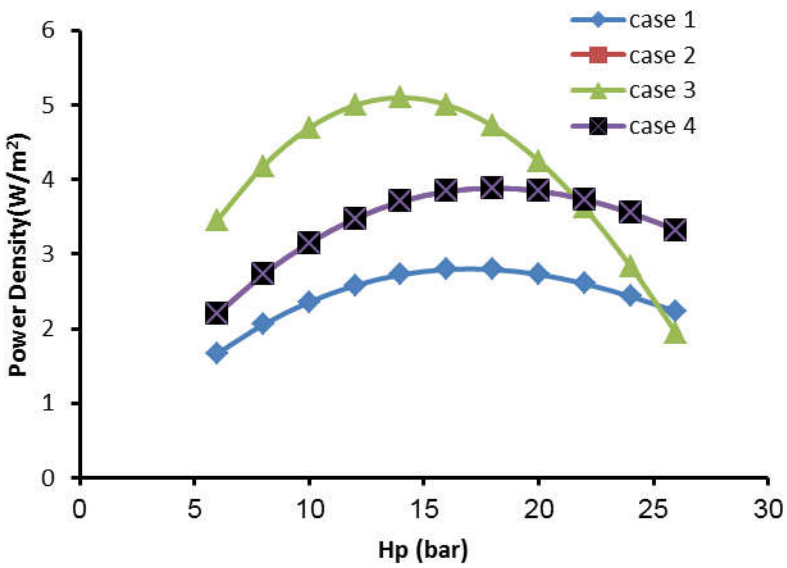


Fig. (6): Power density versus the hydraulic pressure

Figure 7 gives the relationship between the net power production and the applied hydraulic pressure for the four different cases. Obviously the case 3 gives the maximum net power production among other cases, this is agreed with our finding above where the net power production proportional directly with the volume of fluid. Although the case 3 represents the most beneficial case, it has an optimum value 115.698 kW corresponding to applied hydraulic pressure supplied 16 bar.

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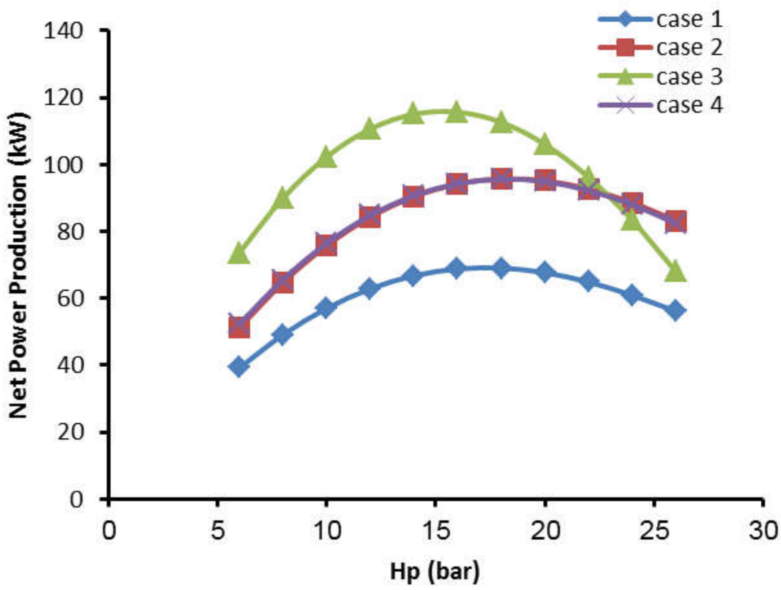


Fig. (7): Net power production versus the hydraulic pressure supplied

**Conclusions**

New PRO processes for power generation have been suggested and theoretically tested and compared with the standard dual stages PRO process. The assessment of the new PRO processes are based on the net water volume produced as permeate or flux across the membrane. However, only the net water volume, the power density and the net power generation were estimated. The results were compared with the standard dual stage PRO process. According to the results, it possible to conclude that the new PRO processes are generated power more than the dual stages PRO process. The process, namely case (3) represents the most promised PRO process.

**الخلاصة**

في هذا العمل تم تحسين المنظومة المزدوجة المستخدمة في توليد الطاقة باستخدام الخاصية التنافذيه(PRO)،تم في هذا البحث أقتراح موديلات نظريه في التصميم في الاشكال 1و 2و 3و4 حيث أستخدم ماء النهر وماء البحر كمصدر أساسي في المنظومة .

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المنظومة السابقة او التصميم المزدوج كان قد تم من خلاله انتاج طاقة كهربائية لكن بمستوى غير كافي ،في هذا العمل تم استخدام حجم الماء المملح الخارج من المنظومة التنافذيه الثانية ومعالجته من خلال تدويره وإرجاعه كمصدر جديد للمياه بعدة خيارات موضحه بالأشكال داخل البحث ،التعديل الجديد على عمل المنظومة كان قد انتج طاقه كهربائية بمستويات اعلى من المنظومة المزدوجة السابقة وكان افضل تحسين حصلنا علية يتمثل بالحالة الثالثة للتصميم.

**References**

[1] H.B. Mahood, A.N. Campbell, R.B. Thorpe, A.O. Sharif, Heat transfer efficiency and capital cost evaluation of a three-phase direct contact heat exchanger for the utilisation of low-grade energy sources, Energy Conv. Mang. 106(2015) 101-109.

[2] Adel O. Sharif, Ali A. Merdaw, Maryam Aryafar and Peter Nicoll, Theoretical and Experimental Investigations of the Potential of Osmotic Energy for Power Production, Membrane, 4(2014) 447-468.

[3] Ali Altaee, Guillermo Zaragoza, Adel Sharif, Pressure retarded osmosis for power generation and seawater desalination: Performance analysis, Desalination 344 (2014) 108–115.

[4] Andrea Achilli a, Tzahi Y. Cathb, Amy E. Childress, Power generation with pressure retarded osmosis: An experimental and theoretical investigation, J. Memb. Sci., 343(2009) 42-52.

[5] Yu Chang Kim, Menachem Elimelech, Potential of osmotic power generation by pressure retarded osmosis using seawater as feed solution: analysis and experiments, J. Membr. Sci. 429 (2013) 330–337.

[6] Ali Altaee, Guillermo Zaragoza, Adel Sharif, Pressure retarded osmosis for power generation and seawater desalination: Performance analysis, Desalination 344 (2014) 108–115.

ISSN-1994-697X

[7] Junseo Lee, Suhan Kim, Predicting power density of pressure retarded osmosis (PRO) membranes using a new characterization method based on a single PRO test, Desalination, 389 (2016)224-234.