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Analysis and Optimization of Dual-stage Pressure Retarded Osmosis for Renewable Power Generation

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This work addresses theoretical analysis and optimization of osmotic energy extracting from the concentrated brine using a pressure retarded osmosis process. The major contribution is that the existing multi-parametric optimization model is extended from the single-stage PRO process to the dual-stage PRO process. In this process, the diluted seawater from the first stage of PRO process is used as the draw solution in the second stage, while the second stage feed solution is the industrial wastewater effluent with a lower salinity. A model-based optimization method is developed to maximize the performance of PRO in terms of the normalized specific energy production. Through this work, the results show that the multi-stage PRO process is more efficient and has greater potentials in power generation in comparison with the single-stage PRO process.

1. Introduction

Global climate change challenges and the world's steadily growing demand for energy have brought the significant need for more renewable energy. A tremendous amount of energy is stored in the waters of the earth, because of the unequal different salinity of fresh water and seawater (Altaee et al., 2016). The volume of global river discharge is approximately 37,300 km^3/y, which can release around 27,200 TWh renewable energy when it is infinitely diluted by the seawater (Yip and Elimelech, 2012). Much of this energy could be recovered by utilizing an osmotic membrane module which can convert the salinity energy into a hydrostatic pressure to drive a turbine and generate electricity. The concept of harvesting energy generated during mixing of fresh and salt water was proposed in the mid-1950s (Pattle, 1954), and then was realized for utilization of this osmosis pressure in power generation using membrane-based pressure retarded osmosis (PRO) technology in the 1970s (Loeb and Norman, 1975). Although several processes were invented for extracting salinity gradient energy including reverse electrodialysis, capacitive mixing and hydrogel swelling, the PRO process is most widely investigated (Straub et al., 2016). In a PRO process, fresh water transports from a low osmotic feed solution (FS) across a semi-permeable membrane to a pressurized high osmotic draw solution (DS), which produces a power equal to the product of hydraulic pressure and water permeation rate. The conventional PRO process related drawbacks, such as low specific energy generation, leads to a number of application barriers. In some previous studies on reverse osmosis (RO), the researchers had demonstrated that the specific energy consumption (Li, 2010) and the overall cost per unit permeate (Kotb et al., 2016) of a multi-stage RO reduce as the increase in number of RO stages. It has been concluded that the dual stage closed-loop PRO process outperforms the single stage one in terms of specific energy production (Altaee and Hilal, 2017). Increase the module stage of PRO process is potentially an effective approach to enhance the performance of PRO process. However, to the best of our knowledge, there is a lack of comprehensive optimization model to improve the performance of a multi-stage PRO process.

Recently, Li (2015) developed a multi-parametric optimization model to explore the effect of some significant factors on a single-stage PRO performance such as the membrane properties (e.g. hydraulic permeability and mass-transfer characteristics), design conditions (e.g. inlet flow rate, inlet osmotic pressure, and membrane area) and operating condition (e.g. applied pressure). This article extends the work of Li (2015) from the single-stage PRO process to the dual-stage PRO process. This work focuses on the system-level analysis and

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optimization of power generation from a constant-pressure, counter-current dual-stage PRO process. Several simple and physically meaningful dimensionless parameters are applied in this model to clearly illustrate the coupled behaviours among the membrane properties, feed conditions, and operating conditions. A dimensionless mathematical model is developed to obtain the optimal performance of the PRO process in terms of normalized specific energy production (NSEP).

2. Dual-stage PRO Model Development

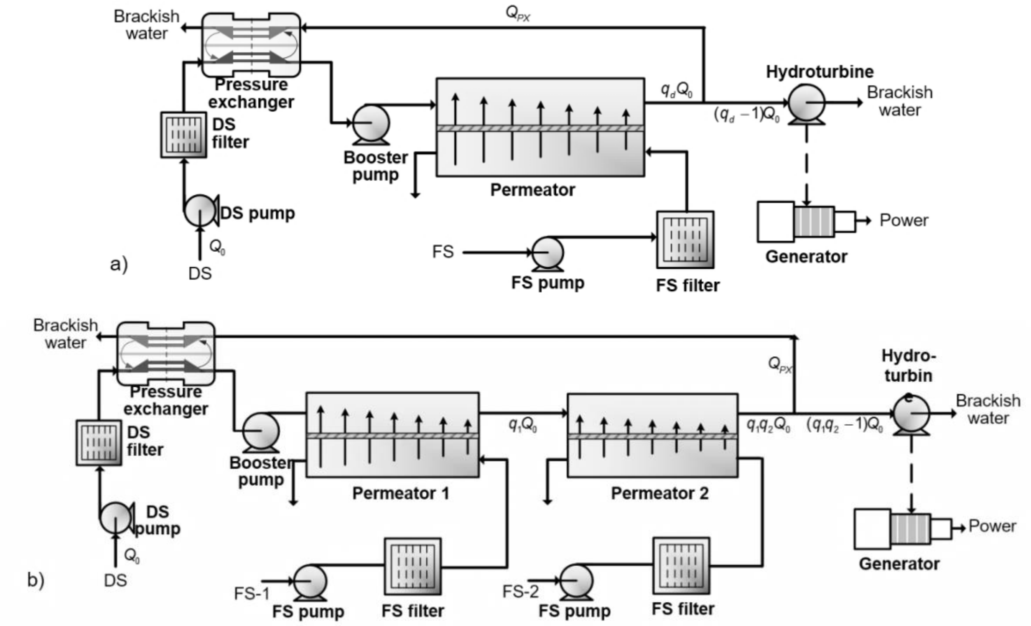

Figure 1: Schematic diagrams of (a) a single-stage PRO process, and (b) a dual-stage PRO process.

In the derivations that follow, the pressure drop in both FS and DS channels are ignored and the change in the FS osmotic pressure along the membrane channel is also negligible as the concentration of the DS is much larger than that of FS or the flow rate of permeate water is extremely small. Additionally, it is assumed that the PRO membrane has a perfect salt resistance property so the quantity of salt in DS can remain constant.
In a typical PRO process, the flow rate of permeate water for a differential area of membrane, based on the solution–diffusion model, is calculated by

$$dQ = L_p(\Delta\pi - \Delta p)dA \tag{1}$$

where L_p, $\Delta\pi$ and Δp are the membrane hydraulic permeability, the osmotic pressure differential, and the hydraulic pressure differential across the membrane, respectively. For the DS, the osmotic pressure, π, is related to the salt concentration, c, using the Van't Hoff equation: $\pi = vRTc$. Because the quantity of salt in the DS is a constant, the osmotic pressure varies linearly with the flow rate of DS.

$$dQ = L_p(\frac{Q_0}{Q}\pi_0^D - \pi^F - \Delta p)dA \tag{2}$$

where Q is the DS flow rate. Subscript 0 is the properties at entrance. Superscripts D and F are the properties at DS and FS. Eq(2) can be integrated as in Eq(3) from inlet to outlet of the PRO membrane channel:

$$\int_{Q_0}^{Q_0+Q_p} (\frac{Q_0}{Q}\pi_0^D - \pi^F - \Delta p)^{-1} dQ = \int_0^A L_p dA \tag{3}$$

where Q_p is the permeate water flow rate.
Eq(3) can be simplified to

$$\int_1^{q_d} \frac{q}{1-q\theta} dq = \int_0^1 \gamma dx \tag{4}$$

where $q = Q/Q_0$, $\gamma = AL_p\pi_0^D$, $\theta = (\pi^F + \Delta p)/\pi_0^D$. The dilution ratio, q_d is the flow rate of DS at the channel outlet divided by the one at the inlet. Note that the γ used as an important design parameter that can reflect the influence of the dilution in DS along the membrane channel. An expression for γ as a function of q and θ can be obtained by Eq(5).

$$\gamma = \frac{1}{\theta}[1 - q_d + \frac{1}{\theta}\ln(\frac{1-\theta}{1-q_d\theta})] \tag{5}$$

Eq(5) is a characteristic equation for the PRO process that clearly reveals the coupled behaviour among the design parameter γ, operating parameter θ, and performance parameter q_d. Eq(5) can be considered as a significant constraint equation for the optimization problem which will be present later.
To evaluate the efficiency of power generation, the specific energy production of the PRO process is defined as the extractable energy per unit volume of the initial DS used. Ignoring the energy loss of hydraulic turbine efficiency, it can be calculated by dividing the power output, $Q_p\Delta_p$, by the sum of the initial DS rate, Q_0,

$$SEP = \frac{Q_p \Delta p}{Q_0} = \frac{Q_0(q_d - 1)\Delta p}{Q_0} = (q_d - 1)\Delta p \tag{6}$$

Dividing the SEP by the DS inlet osmotic pressure, a dimensionless metric can be obtained, namely NSEP,

$$NSEP = \frac{SEP}{\pi_0^D} = (q_d - 1)(\theta - r) \tag{7}$$

where the inlet osmotic pressure ratio, $r = \pi_F/\pi_0^D$.
The relationship between θ and $\Delta p/\Delta\pi_0$ can be described by the following equation.

$$\frac{\Delta p}{\Delta \pi_0} = \frac{\theta - r}{1 - r} \tag{8}$$

To obtain the exact solutions of θ and the maximum NSEP, an optimization problem is formulated for the single-stage PRO (see Figure 1a). Herein, Eq(7) is the objective function and Eq(5) is a nonlinear equality constraint. A variable $z = \ln[(\alpha - 1)/(\alpha - q_d)]$ is introduced to decrease the iterations in optimization, where $\alpha = 1/\theta$ (Li, 2015). The optimization problem is thus given by

$$\begin{aligned} &\max_{\alpha,z} NSEP = (q_d - 1)(\frac{1}{\alpha} - r) \\ &\qquad s.t. \\ &q = \alpha - (\alpha - 1)e^{-z} \\ &\gamma = \alpha(1 - q_d + \alpha z) \\ &1 - \alpha \le 0 \\ &1 - q \le 0 \end{aligned} \tag{9}$$

which can be solved using optimization tools like Fmincon in Matlab R2017a (Arora, 2017).

The schematic diagram of the investigated multi-stage PRO process for power generation is shown in Figure 1b. In this process, the diluted DS from the first stage is sent to the second PRO module directly. The osmotic mass modules, like heat exchangers, can operate at a high efficiency when the driving force is consistent (Sharqawy et al., 2013). Following this principle, the concentrations of the FSs for the first two stages are different to guarantee the driving force. The corresponding osmotic pressure of the first stage (π_1^F) is always greater than that of the second stage (π_2^F). According to the result obtained from a single-stage PRO, the optimization of the multi-stage PRO process can be further formulated using a similar derivation procedure. The corresponding NSEP can be calculated by

$$\begin{aligned} NSEP &= \frac{(q_1 - 1)Q_0\Delta p + (q_2 - 1)q_1 Q_0 \Delta p}{Q_0 \pi_0^D} \\ &= (q_1 - 1)(1/\alpha_1 - r_1) + (q_1 q_2 - q_1)(1/\alpha_2 - r_2) \end{aligned} \tag{10}$$

where all its important model parameters and derivations are listed in Table 1.
The overall optimization problem of the dual-stage PRO process can be formulated as

$$\max_{\alpha_1,\alpha_2,z_1,z_2} NSEP = (q_1 - 1)(\frac{1}{\alpha_1} - r_1) + (q_1 q_2 - q_1)(\frac{1}{\alpha_2} - r_2)$$
$$\begin{aligned}
&s.t.\\
&q_1 = \alpha_1 - (\alpha_1 - 1)e^{-z_1}\\
&q_2 = \alpha_2 - (\alpha_2 - 1)e^{-z_2}\\
&\gamma_1 = \alpha_1(1 - q_1 + \alpha_1 z_1)\\
&\gamma_2 = \alpha_2(1 - q_2 + \alpha_2 z_2)\\
&\frac{1}{\alpha_1} - r_1 = \frac{1}{\alpha_2} - r_2\\
&\gamma_{total} = \gamma_1 + q_1^2 \gamma_2\\
&1 - \alpha_1 \le 0\\
&1 - \alpha_2 \le 0\\
&1 - q_1 \le 0\\
&1 - q_2 \le 0
\end{aligned} \tag{11}$$

where $\gamma_{total} = A_{total} L_p \pi_0^D$ is related to the total membrane area. In order to guarantee that the applied pressures in both two stages are equal, an equality constraint, $1 - \alpha_1 - r_1 = 1 - \alpha_2 - r_2$, is employed. In addition, the inequality constraints, $1 - \alpha_1 \le 0$ and $1 - \alpha_2 \le 0$, are used to guarantee that the driving forces across the membrane in each stage are nonnegative. The remaining inequality constraints, $1 - q_1 \le 0$ and $1 - q_2 \le 0$, can guarantee that the permeate flow rates in both stages are nonnegative. Once the values of r_1, r_2 and γ_{total} are determined, the optimal value of NSEP can be solved by Eq(11).

Table 1: Expression of parameters in the multi-stage PRO process

stage	1	2
A	A_1	A_2
$\pi^D_{entrance}$	π^D_0	π^D_0/q_1
π^F	π^F_1	π^F_2
q	q_1	q_2
Δp	Δp	Δp
$Q_{entrance}$	Q_0	$q_1 Q_0$
γ	$(A_1 L_p \pi^D_0)/Q_0$	$(A_2 L_p \pi^D_0)/q_1{}^2 Q_0$
α	$\pi^D_0/(\Delta p+\pi^F_1)$	$\pi^D_0/q_1(\Delta p+\pi^F_2)$

3. Result and discussion

As shown in Figure 2, the optimal NSEPs for a single-stage PRO and a dual-stage PRO processes using several reprehensive values of r and a wide range of γ (from 0.1 to 100) are present. It is can be seen that, when $r = 1$ and $r_1 = r_2 = 1$, in horizontal axis the curves of two processes both start from the zero. Herein, the osmotic pressure differential across the membrane and the permeate flow rate are nearly both equal to zero, resulting in a negligible NSEP. The optimal NSEPs remarkably increase as the r approaches to 0. This is because a smaller r relatively represents that a lower concentration of the inlet FS, further indicating a larger driving force between the DS and FS. In Figure 2, when r is lower than 1, the optimal NSEPs linearly increase as the increasing of γ, but the increasing rate becomes slower as γ becomes adequately large ($\gamma = 100$). It can be attributed to that, herein, both the driving force at outlet and the average driving force approach zero. That is, the thermodynamic equilibrium has nearly achieved.

Compared with the single stage PRO scheme, the dual-stage one allows the second stage that processes a lower concentration of FS, implying that the dual-stage scheme can operate in a way which is closer to the thermodynamic equilibrium. The optimal NSEP of thermodynamic limit of multi-stage is larger than the one of single-stage. As shown in Figure 2, it can be found that the advantage of using two stages configuration becomes apparent as the increasing of γ. For example, when $\gamma = 0$ (e.g. fresh water is used as the FS) and $\gamma = 100$, the optimal NSEP of dual-stage PRO is more than twice the one of single-stage PRO. It can be concluded that the multi-stage PRO process is more effective for power generation. The optimal q_d for the single-stage and multi-stage PROs are shown in Figure 3. When γ is low (< 10), the increase rate of optimal q_d is very slow with the growth of γ. The difference in optimal q_d between the single-stage and multi-stage PROs is not obvious. In comparison with Figure 3a, the optimal q_d of the multi-stage PRO process shown in Figure 3b is relatively less affected by the variation of r. However, in the high γ mode, multi-stage PRO shows a greater strength in improving the q_d. This phenomenon can be clearly reflected by the optimal q_d at each stage and the overall q_d for the multi-stage PRO process, as shown in Figure 2. In this figure, it can be found when γ is smaller than 5.5, the optimal q_d of the second stage is equal to 1, indicating that the two-stage PRO is actually equivalent to a single-stage PRO. This result answers the reason why the differences in optimal NSEP and q_d between the single stage and multi-stage PROs are existed when γ is relatively small.

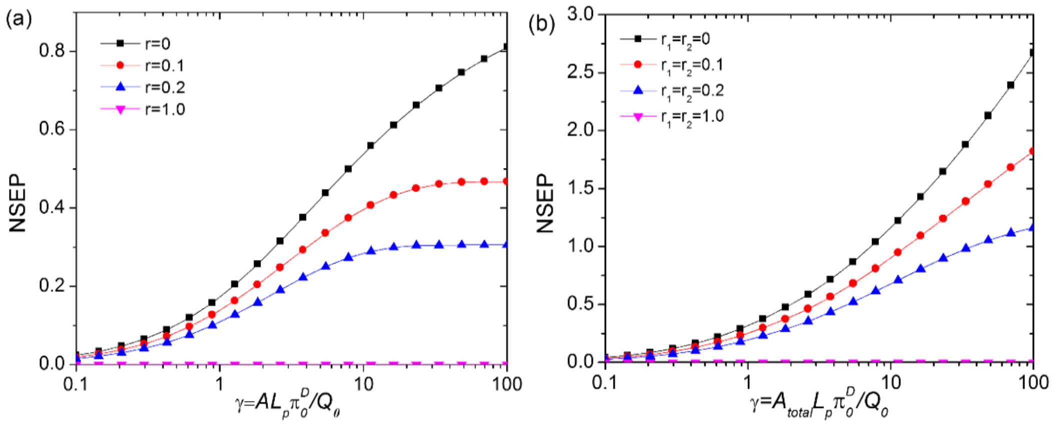

Figure 3: Optimal NSEPs in (a) a single-stage PRO and (b) a multi-stage PRO as a function of γ and r. The log scale is used in x-axis in the plots

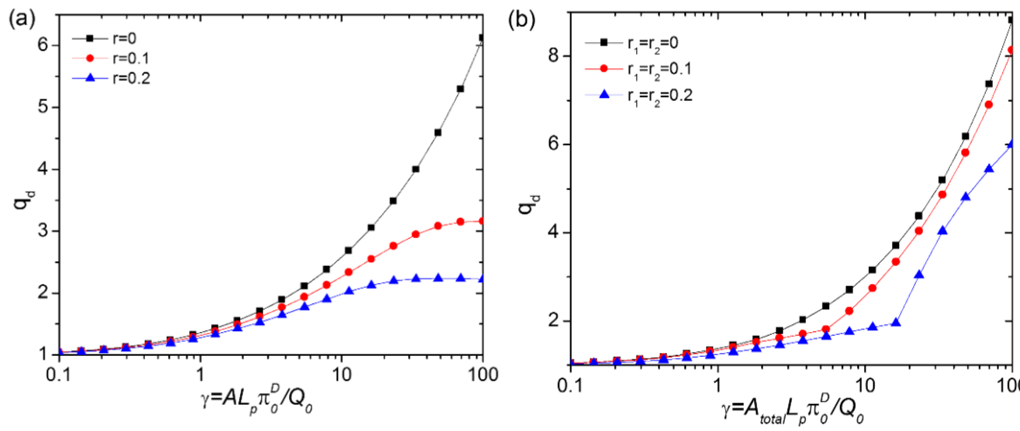

Figure 4: Optimal q_d in (a) a single-stage PRO and (b) a dual-stage PRO. The log scale is used in x-axis in the plots

According to the results obtained, it is can be found that the proposed model-based optimization model is useful to determine the optimal design and operation of the multi-stage PRO process since that the interrelationship of operating parameters, design parameters, and performance parameters can be clearly figured out. Note that the slope of the curves shown in Figure 3b continues to increase because of ignoring the effects of concentration polarization, which is arguably the most significant problem that dramatically reduces the power output of the PRO process. That is, the optimal results obtained in an ideal case would reduce the practicability of the proposed optimization model. With the increase in γ, the corresponding membrane area, membrane permeability, and the hydraulic pressure difference across the membrane will increase, which inevitably leads to more economic costs.

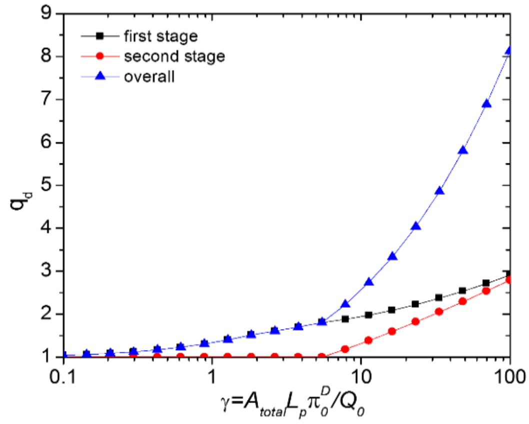

Figure 5: Optimal q_d at each stage and overall q_d for the multi-stage PRO process at $r_1 = r_2 = 0.1$. The log scale is used in x-axis in the plots

4. Conclusions

This work investigated the power generation from a multi-stage PRO process where the seawater and brackish water were used as the DS and FS, respectively. The diluted seawater from the first stage of PRO process was further used as the DS in the second stage, the second stage FD was the wastewater effluent with a lower concentration of salt. Through parametric analysis, this work established an optimization model for the multi-stage PRO process using the NSEP as objective function. The results showed that, compared to the single-stage PRO process, the multi-stage PRO process was more effective for power generation especially in the high γ mode (> 10). This optimization model can be used to predict the optimal performance of the PRO configuration in terms of NSEP. In the future study, the trade-off between the economic cost and power production of the multi-stage PRO process with consideration of the effects of concentration polarization will be explored.

Acknowledgments

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References

Altaee A., Hilal N., 2016, Dual stage PRO power generation from brackish water brine and wastewater effluent feeds, Desalination, 389, 68-77.

Altaee A., Palenzuela P., Zaragoza G., AlAnezi A.A., 2017, Single and dual stage closed-loop pressure retarded osmosis for power generation: Feasibility and performance, Applied Energy, 191, 328-345.

Arora J.S.(Ed.), 2017, Optimum design with MATLAB®. In: Introduction to optimum design (fourth edition), Academic Press, Boston, USA, ISBN: 978-0-12-800806-5, pp. 279-305

Kotb H., Amer E.H., Ibrahim K.A., 2016, On the optimization of RO (Reverse Osmosis) system arrangements and their operating conditions, Energy, 103, 127-150.

Li M., 2015, Analysis and optimization of pressure retarded osmosis for power generation, AIChE Journal, 61(4), 1233-1241.

Li M., 2010, Minimization of energy in reverse osmosis water desalination using constrained nonlinear optimization, Industrial & Engineering Chemistry Research, 49(4), 202-205.

Loeb S., Norman R.S., 1975, Osmotic Power Plants, Science, 189(4203), 654-655.

Pattle R.E., 1954. Production of electric power by mixing fresh and salt water in the hydroelectric pile, Nature, 174(4431), 660-660.

Straub Anthony P., Deshmukh A., Elimelech M., 2016, Pressure-retarded osmosis for power generation from salinity gradients: is it viable?, Energy Environmental Science, 9(1), 31-48.

Sharqawy M.H., Banchik L.D., Lienhard V J.H., 2013, Effectiveness–mass transfer units (ε–MTU) model of an ideal pressure retarded osmosis membrane mass exchanger, Journal of Membrane Science, 445, 211-219.

Yip N.Y., Elimelech M., 2012, Thermodynamic and energy efficiency analysis of power generation from natural salinity gradients by pressure retarded osmosis, Environmental Science & Technology, 46(9), 5230-5239.