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Pressure retarded osmosis process for power generation: Feasibility, energy balance and controlling parameters

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ABSTRACT

The feasibility of pressure-retarded osmosis (PRO) for power generation was evaluated with consideration of the energy inputs and losses in the process. The effects of the concentration polarization, reverse salt diffusion, and external resistance at the membrane porous layer were quantified, for the first time, along the membrane module to determine their contributions to the energy loss in the PRO process. Concentration polarization was responsible for up to 40% of the energy loss during the PRO process. However, increasing the PRO membrane modules from 1 to 4 resulted in a variable increase of the energy output depending on the salinity gradient. The energy requirements for draw and feed solution pretreatment were estimated to be over 38% of the total energy inputs. Results showed that coupling seawater (SW) with river water (RW) was unable to generate sufficient energy to compensate for the energy inputs and losses during the PRO process. With 0.39 kwh/m^3 maximum specific energy in the PRO process, the energy yield of reverse osmosis brine (ROB)-wastewater (WW) salinity gradient was slightly greater than the total energy inputs, although using Dead Sea-SW/ROB salinity gradient was more promising. Overall, the primary current limitation is the lack of suitable PRO membranes that can withstand a high hydraulic pressure.

1. Introduction

In the past decade, pressure-retarded osmosis (PRO) has been extensively investigated for power generation from salinity-gradient resources [1–7]. Numerous experimental studies have been performed to understand the process behavior, performance, and membrane efficiency for power generation from a salinity-gradient process. The process has been tested in a pilot plant to demonstrate its performance and feasibility in practical applications [8–10]. The results of the bench and pilot plant tests indicate that the process can be source of renewable energy, especially after the commercial development of a PRO membrane [10–12]. Recently, thermodynamic analysis of PRO process has revealed that the energy input may exceed the energy output because of an insufficient osmotic energy of the salinity gradient and energy losses due to membrane imperfection [7,13]. Therefore, the minimum energy requirements, including energy losses and pretreatment energy, should be identified. To date, lack of studies evaluating the exergy of the PRO system and limitations with regard to the type of salinity gradients and membrane inefficiencies are there and this has led to a gap in the research focus. Furthermore, most of the PRO experiments were performed on laboratory scale units which exaggerated the process performance. As such, the impact of PRO module length on the performance of PRO has been underestimated in the previous works.

The PRO process has been proposed for power generation using seawater (SW) and river water (RW) as a salinity-gradient resource. Power densities between 2.2 and 5.8 W/m^2 have been reported, depending on the membrane type and hydraulic pressure [14]. A power density of 5 W/m^2 was recommended for an economical PRO process based on a pilot plant test performed by Statkraft Company, Norway [10,14]. This value has not been commented on by recent pilot plant studies, therefore, still widely accepted in literature. SW-RW was investigated in a pilot plant by Statkraft; the pilot plant test was performed for few years and shut down in 2011 because of unsatisfactory performance [3]. There is little information available about the reasons for shutting down the Statkraft pilot plant, but it is considered that the energy efficiency was one of the main reasons. Reverse osmosis brine (ROB)-wastewater (WW) salinity resources have been evaluated for power generation by the PRO process. Wan and Chung reported power densities of 6.6 and 8.9 W/m^2 for the Ultrafiltration (UF) and nanofiltration pretreatment of WW, respectively [15]. In a recent pilot plant

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study, Saito et al. used a Toyobo membrane and a ROB-WW salinity gradient and achieved a power density of 7.7 W/m^2; UF membrane was used for WW filtration [8]. Although ROB does not require pretreatment, no data have been reported regarding the energy requirements for the pretreatment of the feed solution. High-salinity draw solutions, such as Dead Sea (DS) and Salt Lake solutions, have been proposed for the PRO process. DS coupling with WW, SW, or RO brine would improve the PRO performance owing to the high energy potential of the salinity gradient. Theoretically, coupling DS water with 35 g/L SW water has the potential to increase the power density to 44 W/m^2, which is 8 times higher than the suggested threshold for an economical PRO process [16–17]. A recent study for evaluating the process viability for power generation from the SW-RW salinity gradient showed that the power generated by the PRO process was lower than the energy required for the pumping and pretreatment of feed and draw solutions [13]. The maximum energy generated by SW-RW is 0.25 kWh/m^3, whereas the maximum extractable energy by the PRO process is lower than that because of energy loss and membrane inefficiency. Furthermore, the energy required for the pretreatment and pumping was between 0.17 and 0.5 kWh/m^3, which could be more than the maximum energy yield of the SW-RW salinity gradient [18–19].

In the present study, we examined the energy efficiency of the PRO process for different salinity-gradient resources, considering the energy requirements for pretreatment and energy losses. Thermodynamically, PRO is feasible when the power output is higher than the power input; therefore, the power input was calculated including energy losses due the membrane imperfection, pretreatment of feeds, losses in pressure exchanger and due to pumping. The energy requirements for the pretreatment of the draw and feed solution were evaluated for several commonly used feed and draw solutions. The energy yield for an ideal membrane (no concentration polarization and reverse salt diffusion) was calculated and compared with that for a non-ideal PRO membrane (including concentration polarization and reverse salt diffusion). The underperformance of PRO process represented by concentration polarization, reverse salt diffusion, and external resistance of the support layer was quantified separately to identify their effects on the energy output of the PRO process. The energy input for the pretreatment and the energy losses were quantified for each salinity gradient investigated. We also estimated the extracted specific energy along the PRO membrane module for the multi-modules PRO system to identify the number of PRO membranes required in the PRO process for different type of salinity gradients. The computer model used in this study has already been validated using experimental data with more than 90% agreement [2,6]. The model accounts for the effects of internal and external concentration polarization and was further developed to include impacts of external resistance at membrane support layer. The findings of this study is to identify (i) salinity gradients which have higher power output than power input due to membrane imperfection, losses and process pre-requirements and (ii) key limitations of current PRO membrane to be considered in future studies on membrane fabrication.

2. Energy yield and membrane module

The energy yield of the salinity-gradient resource is affected by the membrane area and the feed characteristics along the PRO module, due to the dilution and concentration of the draw and feed solutions, respectively [6,20]. For an ideal membrane, the membrane concentration polarization and reverse salt diffusion are ignored. Accordingly, the water flux, J_w, is estimated using the following equation [13,21]:

$$J_w = A_w(\Delta\pi - \Delta P), \tag{1}$$

where A_w is the membrane permeability (L/m^2 h bar), $\Delta\pi$ is the osmotic pressure gradient across the membrane (bar), and ΔP is the hydraulic pressure difference across the membrane (bar). For a non-ideal PRO process, the water flux is affected by the phenomena of concentration polarization and salt reverse diffusion, as follows [4]:

$$J_w = A_w\left\{\frac{\pi_{Db}\exp\left(\frac{-J_w}{k_d}\right) - \pi_{Fb}\exp\left(J_wK + \frac{J_w}{k_f}\right)}{1 + \frac{B}{J_w}\left[\exp\left(\frac{J_w}{K} + \frac{J_w}{k_f}\right) - \exp\left(\frac{-J_w}{k_d}\right)\right]} - \Delta P\right\} \tag{2}$$

where $\Delta\pi_{Db}$ and $\Delta\pi_{Fb}$ are the bulk osmotic pressure of the draw and feed solutions, respectively (bar); k_d and k_f are the mass-transfer coefficients of the draw and feed solutions, respectively (m/h); K is the solute resistivity in the case where the feed is facing the feed solution (h/m); and B is the salt permeability coefficient (L/h m^2·bar). Eq. (2) predicts the membrane flux when the draw solution faces the membrane active layer (DS-AL), the PRO mode. It also accounts for the effect of external resistance (CPe) at the porous support layer which represented by J_w/K_f parameter. The water flux changes along the PRO membrane because of the water permeation across the module; hence, J_w and the concentrations of the feed and draw solutions along the PRO module should be calculated. This enables us to calculate the maximum specific energy generation by the PRO process from a salinity-gradient resource at any distance along the membrane module. At a distance x along the PRO module, the bulk concentration of the draw solution, $C_{Db,xn}$, can be estimated as follows:

$$C_{Db,nx} = \frac{C_{Di,nx} + C_{Do,nx}}{2} \tag{3}$$

where $C_{Di,nx}$ is the inlet concentration of the draw solution at the distance x (M), $C_{Do,nx}$ is the outlet concentration of the draw solution at the distance x (M), and n is the number of PRO module in the pressure vessel. $C_{Do,nx}$ was calculated using the flow rate and mass-balance equation assuming the complete rejection of ions by the membrane, i.e., a reflection coefficient of unity:

$$C_{Do,nx} = \frac{C_{Di,nx}Q_{Di,nx}}{Q_{Do,nx}} \tag{4}$$

where $Q_{Di,nx}$ is the inlet flow rate of the draw solution (m^3/h), $C_{Di,nx}$ is the outlet concentration of the draw solution (M), and $Q_{Do,nx}$ is the outlet concentration of the draw solution (mg/L). Eq. (3) can be rewritten using Eq. (4) to express $C_{Do,xn}$:

$$C_{Db,nx} = \frac{C_{Di,nx}\left(1 + \frac{Q_{Di,nx}}{Q_{Do,nx}}\right)}{2} \tag{5}$$

At a distance x along the PRO module, $Q_{Do,nx}$ is equal to the sum of the inlet flow rate of the draw solution and the water permeation flow rate ($Q_{p,nx}$); i.e. $Q_{Do,nx} = Q_{Di,nx} + Q_{p,nx}$. By applying the same method to the feed side, the bulk concentration of the feed solution at a distance x along the PRO module was calculated as follows:

$$C_{Fb,nx} = \frac{C_{Fi,nx}\left(1 - \frac{Q_{Fi,nx}}{Q_{Fo,nx}}\right)}{2} \tag{6}$$

Here, $Q_{Fo,xn}$ is the difference between the inlet feed flow rate and the permeation flow; i.e., $Q_{Fo,nx} = Q_{Fi,nx}Q_{p,nx}$. Assuming that the Van't Hoff equation is valid for the concentration of the feed and draw solutions in Eqs. (5) and (6), by substituting in Eq. (2), we obtain

$$J_{w,nx} = A_w\left(\frac{\left(\varphi RTC_{Di,nx}\left(1 + \frac{Q_{Di,nx}}{Q_{Do,nx}}\right)/2\right)\exp\left(\frac{-J_w}{k_d}\right) - \left(\varphi RTC_{Fi,nx}\left(1 - \frac{Q_{Fi,nx}}{Q_{Fo,nx}}\right)/2\right)\exp\left(J_wK + \frac{J_w}{k_f}\right)}{1 + \frac{B}{J_{w-x}}\left(\exp\left(J_wK + \frac{J_w}{k_f}\right) - \exp\left(\frac{-J_w}{k_d}\right)\right)} - \Delta P\right) \tag{7}$$

Here, Φ is number of ions in the solution, R is the gas constant, and T is the temperature in Kelvin. A_w and B were assumed to be 1.23 L/h