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System scaling approach and thermoeconomic analysis of a pressure retarded osmosis system for power production with hypersaline draw solution: A Great Salt Lake case study

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ABSTRACT

Osmotic power with pressure retarded osmosis (PRO) is an emerging renewable energy option for locations where fresh water and salt water mix. Energy can be recovered from the salinity gradient between the solutions. This study provides a comprehensive feasibility analysis for a PRO power plant in a hypersaline environment. A sensitivity analysis investigates the effects of key technical and financial parameters on energy and economic performances. A case study is developed for the Great Salt Lake in Utah, USA (which has an average 24% salt concentration). A 25 MW PRO power plant is investigated to analyze the necessary components and their performances. With currently available technologies, the power plant would require 1.54 m^3/s (24,410 GPM) fresh water flow rate and 3.08 m^3/s (48,820 GPM) salt water flow rate. The net annual energy production is projected to be 154,249 MWh, with capital cost of \$238.0 million, and operations and maintenance cost of \$35.5 million per year. The levelized cost of electricity (LCOE) would be \$0.2025/kWh, but further design improvements would reduce the LCOE to \$0.1034/kWh. The high salinity of the Great Salt Lake is a critical factor toward making the osmotic power plant economically feasible.

1. Introduction

Renewable energy is a growing portion of the power generation sector. Compared to traditional power generation methods, the benefits of generating power from renewable energy sources include the reduction in greenhouse gas emissions. Pressure retarded osmosis (PRO) makes use of energy recovery from a salinity gradient between two bodies of water. Fig. 1 illustrates the schematic of the PRO process. The higher saline solution is called the draw solution while the lower saline solution is referred to as the feed solution. Semipermeable membranes, which only allow fresh water to pass through while preventing salt water from permeating, are placed between the two solutions. Electric power then can be recovered as the permeate solution is run through a hydroturbine. Practical PRO systems are most suitable for locations with fresh water and saline water sources nearby. For example, river-to-sea or river-to-hypersaline-lake sites can become potential locations for future PRO power plants.

Recent PRO studies have mostly focused on investigating PRO performance with bench-scale systems. Membrane behaviors and influence of operating conditions toward PRO performance have been studied with bench-scale systems and commercially available membranes [1–3]. In bench-scale studies, the use of forward osmosis (FO) membranes in PRO applications introduces the possibility of membrane rupture. This is due to the fact that FO membranes are not designed to withstand high hydraulic pressure in PRO experiments. Mesh spacers within PRO membrane housings have been introduced as an effective solution for this problem. Hickenbottom et al. investigated different mesh spacers configuration to achieve higher PRO performance [4]. The presence of mesh spacers provides membranes with better mechanical support and longer operation, although they affect the water flux across the membrane [3,4].

Improving membranes for PRO applications has naturally become a next step in the development of PRO power generation technology. Several membrane modification methods have been utilized to alter membrane structure. Among all, interfacial polymerization is the most widely used method, especially with thin film composite (TFC) FO membranes [5]. The advantage of using

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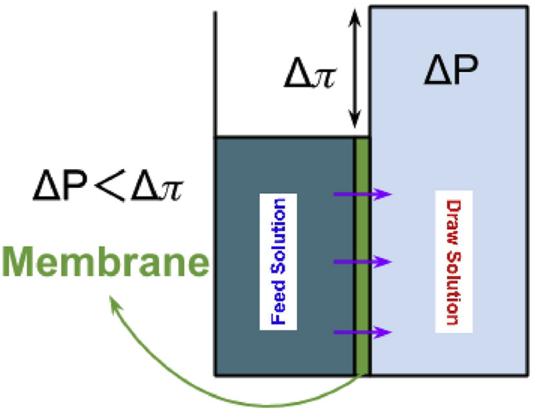

Fig. 1. Illustration of PRO process.

interfacial polymerization can be shown by the flexibility to individually tailor and optimize the structure and properties. As a result, desired permeability coefficients can be achieved and concentration polarization is reduced [5]. Modified TFC membranes for PRO experiments have been tested to perform better than typical TFC membranes under the same conditions [6,7].

Osmotic pressure is also an important factor in PRO performance. Due to the difference in salt concentration, water tends to flow from the feed solution to the draw solution. The osmotic pressure is defined as the pressure that should be applied to the draw solution to stop the osmotic water flow [8]. Experimental studies of bench-scale PRO systems with higher osmotic pressure yielded higher power density compared to similar experiments with lower osmotic pressure [1,4,9]. As a result, local sites providing higher osmotic pressure difference between the feed solution and the draw solution can potentially generate more electric power. The Great Salt Lake in Utah, USA has been identified for its high salinity, ranging from 6% to 27% [10]. To put this in perspective, the average salinity of seawater is 3.5%. The saltiest natural water source in the world is the Dead Sea with an average salt concentration of 33.7% [8]. In addition to the high saline water, the Great Salt Lake is also located near fresh water sources such as the Bear, Weber, and Jordan Rivers. The Great Salt Lake has been identified as a possible location for future implementation of PRO in power generation, given the availability of high saline draw solution and fresh water supplies.

In this study, a practical 25 MW PRO system is investigated by considering the Great Salt Lake as a potential location. The interactions between system components are investigated and integrated into a system-level model. The results from this study test the feasibility of a PRO power generation implementation with currently available technology, and an economic analysis is presented incorporating a number of technical costs. A sensitivity analysis is used to identify the relative impacts of specific parameters in the model. Furthermore, recommendations are provided for reducing cost in an effective way toward enhancing PRO's competitiveness with other renewable technology. The results from this study can increase understanding of large-scale PRO systems and inform decision making for those interested in future PRO implementations.

2. Osmotic power with PRO

2.1. PRO power density

In PRO, the power density is used to define the power that can be obtained per unit area of membrane. The ideal power density of PRO is described by:

$$W = J_w \Delta P = A(\Delta\pi - \Delta P)\Delta P \tag{1}$$

where W (W/m^2) is the power density, J_w (m^3/m^2·s) is the water flux, A (m/s·kPa) is the water permeability coefficient, $\Delta\pi$ (kPa) is the osmotic pressure difference, and ΔP (kPa) is the hydraulic pressure difference.

However, Eq. (1) does not consider the concentration polarization across the membrane. Concentration polarization is a type of membrane fouling which produces a concentration gradient, accumulates particles near the membrane, and reduces available surface area. McCutcheon et al. showed that concentration polarization has adverse impacts on the performance of PRO [11]. There are two types of concentration polarization: internal concentration polarization (ICP) and external concentration polarization (ECP). ECP happens when salt is collected on the external side of the membrane while ICP is due to the accumulation of salt inside the support layer of the membrane [11]. By considering the concentration polarization, the power density equation in PRO can be modified as [1,8,12]:

$$W = A\left[\pi_{D,b} exp\left(-\frac{J_w}{k}\right)\frac{1-\frac{\pi_{F,b}}{\pi D,b} exp(J_w K) exp\left(\frac{J_w}{k}\right)}{1+\frac{B}{J_w}\left[exp(J_w K)-1\right]} - \Delta P\right]\Delta P \tag{2}$$

where $\pi_{D,b}$ (kPa) is bulk osmotic pressure in the draw solution, $\pi_{F,b}$ (kPa) is bulk osmotic pressure in the feed solution, B (m/s) is the salt permeability coefficient, k (m/s) is external concentration polarization mass transfer, and K (m/s) is internal concentration polarization mass transfer coefficient.

2.2. Annual energy production

Annual energy production from a PRO power plant can be calculated from the expected level of power generation and the number of hours that the power plant is operated. As a result, the annual produced energy equation is:

$$E_{production} = \dot{W}_{net} \times CF \times t \tag{3}$$

where $E_{production}$ (MWh) is the annual energy production, $\dot{W}_{net}$ (MW) is the power capacity of the power plant, CF is the capacity factor, and t (hour) is the number of hours in a year.

2.3. Gibbs free energy of mixing

The osmotic energy in PRO can be derived from the Gibbs free energy of mixing, which occurs when two solutions with different compositions are mixed. In a reversible PRO process, the maximum extractable work is equal to the Gibbs free energy of mixing [13]:

$$\frac{\Delta G}{iRT} = \frac{c_{final}}{\phi}\ln c_{final} - c_{fs}\ln c_{fs} - \frac{1-\phi}{\phi}c_{ds}\ln c_{ds} \tag{4}$$

where ΔG (or $E_{osmotic}$) (kWh/m^3 of fresh water) is the mixing energy per unit volume of fresh water. Initial feed solution concentration, initial draw solution concentration, and final solution concentration are represented by c_{fs} (mol/L or M), c_{ds} (mol/L or M), and c_{final} (mol/L or M), respectively. Furthermore, ϕ is the ratio of the initial volume of the feed solution to the initial total volume of both the feed and draw solutions, R (L·kPa/mol·kPa) is the universal gas constant, T (K) is the absolute temperature, and i is the number of osmotically active particles in the solution. The Gibbs free energy of mixing is maximum when the ratio of the initial volume of the feed solution to the total initial volume approaches zero. Calculation of a