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Pressure retarded osmosis: advancement in the process applications for power generation and desalination

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HIGHLIGHTS

- PRO-RO system was evaluated for power generation and seawater desalination.
- The effect of feed and draw solutions flow rates and salinities were investigated.
- FO performance increased with SW TDS and decreased with increasing feed water TDS.
- Power generation by PRO increased with SW TDS and flow rate of feed and draw solutions.
- Up to 31% decrease in the desalination power consumption achieved by the PRO-RO process.

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ABSTRACT

The current study highlights the advancement in Pressure Retarded Osmosis (PRO) process and covers most recent development in the process applications. The first application of PRO process goes back to 1973 by Sidney Loeb who suggested using the concept of osmotic energy for power generation. In principle, two solutions of different concentrations are separated by semipermeable membrane of, relatively, high water permeability and solute rejection rate. The high-concentration solution is usually known as the draw solution while the low-concentration solution is called the feed solution. The draw solution is pressurized before entering the membrane. Due to the osmotic pressure gradient across the membrane, fresh water transports in the direction of the osmotic pressure gradients resulting in the dilution of the high-concentration solution. After leaving the membrane, the diluted draw solution is depressurized in a turbine system for power generation. Different types of membrane materials and solute gradient resources were proposed and their impact on the performance of PRO process was investigated. In addition to power generation, the hybridization of PRO process with membrane and thermal processes for power generation and seawater desalination is not unusual nowadays. The current study provides a critical review about the recent advancements in the PRO process and research outcomes.

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1. Introduction

Power generation from renewable resources has received a lot of attention due to the continuous increase in the cost of fossil fuels [1–7]. Many countries have reduced their fossil fuel consumption through investing on the technologies of power generation from renewable resources [8–15]. Nowadays, there are strict regulations and high penalties on companies which have low environmental performance represented by high waste discharge and greenhouse gas emissions [11,16–19]. Unfortunately, solar and wind energy have limited efficiencies and their performance is affected by the wind and solar radiation respectively. Continuous research, therefore, is necessary to find robust technologies which are competitive to the existing technologies and have low environmental impact. Electrodialysis reversal (EDR) has been proposed for seawater desalination and power generation [20, 21]. In the EDR, chemical potential difference between salt and fresh water generates a voltage over a stack of membranes. However, EDR requires high hands-on experience and operation skills. One of the promising technologies which have been, recently, investigated intensively is Pressure Retarded Osmosis (PRO) [22–28]. The PRO process consists of a number of developed and semi-developed components which can be assembled together easily. PRO technology has a number of advantages which makes it suitable for commercialization such as; i) it can be operated 24 h per day ii) is not affected by wind speed and solar radiation iii) has small foot print, and iv) easy to scale-up. Additionally, PRO could be a good method for the RO brine recycling and reuse when it is coupled with the RO system [26]. Instead of discharging to seawater, RO brine concentrate can be used as a feed or draw solution in the PRO process [27,28]. This is one of the unique advantages of the PRO process in which waste stream can be used as a feed source in the PRO module. Unfortunately, PRO process has limited field application and it is not fully commercialized yet. The first pilot plant operates by the PRO concept for power generation is built by Statkraft Company, Norway, and it uses fresh water and seawater as the feed and the draw solution respectively [29–32]. The plant was commissioned in 2009 and it is operated by SINTEF Energy Research to generate 10 kW by the PRO process. However, the capacity of Statkraft plant is small to be called commercial and investment in larger PRO plants is probably required.

2. Initial work on the PRO process

The concept of osmotic power or salinity gradient was introduced first in 1954 by R.E. Pattle [15]. However, the concept has been further developed by Sidney Loeb who proposed using salinity gradient for power generation [22,23]. In general, the PRO process has been tremendously evolved since 1973 because of the rapid development in membrane technologies. At the beginning, the major challenge towards the development of PRO technology was to find a suitable membrane which has moderate mechanical stability, high water permeability and high salt rejection rate [22,23,34,35]. The new generation of FO membranes have overcome this problem through reducing the thickness of the membrane support layer which became thinner than conventional RO membrane [36–42]. Therefore, Forward Osmosis (FO) membrane can not tolerate high feed pressures. Yet, osmotic power is still facing several challenges to be addressed before it can be fully commercialized such as membrane type, membrane fouling, optimization of operating parameters, and type of draw solution and regeneration of draw solution. These issues will be discussed in the following sections in light of the recent development in the PRO process technology.

3. PRO process description

Osmotic energy is the energy released when fresh water mixes with salt water [15,41]. The major components of the PRO power plant are i) PRO membrane module and ii) hydroturbine system to convert the hydraulic energy to electricity. The structure of PRO membrane is somehow similar to that of the RO membrane but the porous support layer in the PRO membrane is thinner than that in the conventional RO membrane. Additionally, the PRO membrane should enjoy good mechanical strength to withstand the applied hydraulic pressure on the draw solution side of the membrane. In the PRO process, draw solution is pressurized up to 30 bar, depending on the osmotic pressure of draw solution, and sent to a special semipermeable membrane while low osmotic pressure solution is circulated on the opposite side of the membrane (Fig. 1). Fresh water permeates across the membrane and dilutes the high-concentration draw solution. After leaving the membrane, the pressurized diluted draw solution goes to a turbine system to convert the hydraulic energy into electricity. Finally, the diluted draw solution is either discharged to the sea or treated by membrane or thermal processes for regeneration and reuse [22–24]. Seawater is a good draw solution candidate because of its relatively high osmotic pressure, free of cost (excluding pumping, pretreatment, etc. cost), and availability [25, 27,43,44]. It has been estimated that a maximum energy of 0.8 kWh can be generated when 1 m^3 of river water flows into seawater [45]. Of course this is depending on the salinity level of the seawater. However, in the PRO process net energy after pre-treatment and extra pumping is about 0.2 kWh/m^3. The general equation to estimate the PRO membrane water flux, J_w (L/m^2H), is:

$$J_w = A_w(\Delta\pi - \Delta P) \quad (1)$$

Where, A_w is the coefficient of membrane permeability (L/m^2h.bar), ΔP is the differential feed pressure across the membrane (bar) and $\Delta\pi$ is the differential osmotic pressure across the membrane (bar). In the PRO process, power density, W (W/m^2), is the power per unit membrane area and it is equal to the product of the membrane water flux multiplied by the differential hydraulic pressure across the membrane according to the following equation:

$$W = J_w \Delta P \quad (2)$$

Substituting 1 in 2 to give the following equation:

$$W = A_w(\Delta\pi - \Delta P)\Delta P \quad (3)$$

Lee et al. investigated the impact of ΔP on W and J_w as shown in Fig. 2 [45]. It has been found that the power density reaches a maximum theoretical value, W_{max}, when the hydraulic pressure is equal to the half value of the osmotic pressure gradient ($\Delta P = \Delta\prod/2$) across the PRO membrane. Eq. (3) can be rearranged to calculate W_{max}:

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

As illustrated in Fig. 2, three different membrane operating zones can be identified as ΔP increases from 0 to $\Delta P > \pi_{feed}$; i.e. FO, PRO and RO zones [46,47]. In the FO zone, the hydraulic pressure is equal to zero ($\Delta P = 0$). Water flux, in this zone, is driven by the osmotic pressure gradient across the semipermeable membrane or in the direction of the osmotic pressure gradient. Assuming feed pressure is

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