Applied Energy 199 (2017) 359–369

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Evaluation the potential and energy efficiency of dual stage pressure retarded osmosis process

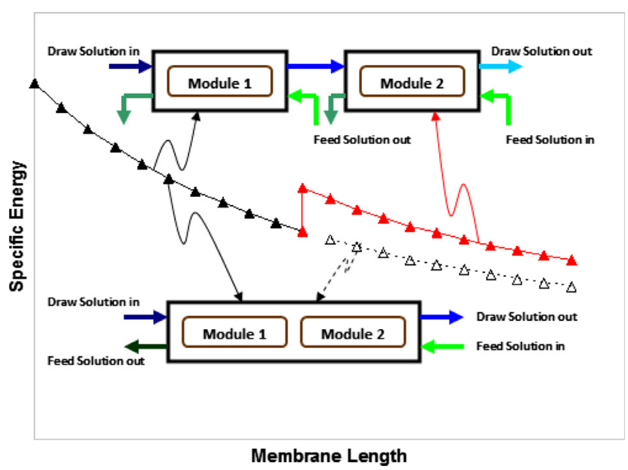
Ali Altaee [a,*], Guillermo Zaragoza [b], Enrico Drioli [c], John Zhou [a]

[a] School of Civil and Environmental Engineering, University of Technology Sydney, 13 Broadway, Ultimo, NSW 2007, Australia
[b] CIEMAT, Plataforma Solar de Almería, Ctra. de Senés s/n, 04200 Tabernas, Almería, Spain
[c] Institute on Membrane Technology (ITM-CNR), National Research Council, c/o University of Calabria, Cubo 17C, Via Pietro Bucci, 87036 Rende, CS, Italy

HIGHLIGHTS

- Single and dual stage PRO was evaluated at different membrane configurations.
- Impact of increasing module area or numbers on the power efficiency was studied.
- DSPRO reduced the impact of CP & restored the osmotic potential of salinity gradient.
- DSPRO outperforms single stage PRO process but depends on salinity gradient type.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 November 2016
Received in revised form 10 April 2017
Accepted 4 May 2017

Keywords:
Dual stage pressure retarded osmosis
Osmotic energy
Osmotic power plant
Pressure retarded osmosis
Salinity gradient resource

ABSTRACT

Power generation by means of Pressure Retarded Osmosis (PRO) has been proposed for harvesting the energy of a salinity gradient. Energy recovery by the PRO process decreases along the membrane module due to depleting of the chemical potential across the membrane and concentration polarization effects. A dual stage PRO (DSPRO) design can be used to rejuvenate the chemical potential difference and reduce the concentration polarization on feed solution. Several design configurations were suggested for the membrane module arrangements in the first and second stage of the PRO process. PRO performance was evaluated for a number of salinity gradients proposed by coupling Dead Sea water or Reverse Osmosis (RO) brine with seawater or wastewater effluent. Maximum specific energy of inlet and outlet feeds was calculated using a developed computer model to identify the amount of recovered and remaining energy. Initially, specific power generation by the PRO process increased by increasing the number of modules of the first stage. Maximum specific energy is calculated along the PRO module to understand the degradation of the maximum specific energy in each module before introducing a second stage PRO process. Adding a second stage PRO process resulted in a sharp increase of the chemical potential difference and the specific energy yield of the process. Between 10% and 13% increase of the specific power generation was achieved by the DSPRO process for the Dead Sea-seawater salinity gradient depending on the dual stage design configuration. For Dead Sea-RO brine, 12–16% increase of the specific power generation was achieved by the dual stage PRO process. For Dead Sea-wastewater and RO

* Corresponding author.
E-mail address: ali.altaee@uts.edu.au (A. Altaee).

http://dx.doi.org/10.1016/j.apenergy.2017.05.031

brine-wastewater, a neutral and sometimes negative impact occurred when a second stage PRO process was introduced. We concluded that, for a given draw solution concentration, dual stage performs better than the conventional PRO process at high feed salinities, yet requires lower hydraulic pressure.

1. Introduction

Salinity gradient is an interesting resource for power generation which is increasingly acknowledged as a cheap and efficient way for renewable energy [1,2]. Currently, there are two main techniques to extract energy from a salinity gradient; Reverse Electrodialysis (RED) and Pressure Retarded Osmosis (PRO). The former uses a stack of anion and cation exchange membranes placed in alternate positions to generate a voltage difference from the chemical potential difference of two solutions [3]. The latter has been under investigation over the last four decades [4–7]. PRO process converts the chemical potential of a salinity gradient resource into a hydrostatic potential and eventually to an energy source after passing through a hydro turbine system [6]. At onset, technical issues represented by finding a suitable membrane have adversely affected the efficiency of PRO process and lessened its attractiveness for further development [8,9]. Low membrane flux has been attributed to the severe concentration polarization (CP) phenomenon at the solution-membrane interface [9]. Intensive research, however, has led into the development of better performance PRO membranes and revolutionized the process [10–13]. Unsurprisingly, the number of research studies to explore the potential of PRO process on osmotic power plants has been increased over the last decade [14–19].

Developing a PRO membrane was a step forward towards high performance PRO process but has not entirely resolved the issue of unsatisfactory performance due to the concentration polarization effects and low chemical potential difference of a salinity gradient resource. Statkraft PRO pilot plant, the world first osmotic power plant, was a setback for the PRO process; the plant shut down shortly after starting due to an unsatisfactory performance [20]. Nevertheless, recent pilot plant studies reported 13.3 W/m^2 power density using a modified four ports Toyobo hollow fiber (HF) membrane and RO brine-wastewater effluent as a salinity gradient resource [10]. The modified Toyobo membrane has been able to reduce the effect of concentration polarization and maintaining the satisfactory power density at 30 bar hydraulic pressure. Pairing RO brine with wastewater effluent has overcome the problem of insufficient membrane flux associated with the low chemical potential of a salinity gradient resource which has been encountered in the Statkraft pilot plant. Mega-ton project has demonstrated a recurring interest in the process and potential application for power generation [21]. The other interesting finding which has been demonstrated by the project was the membrane capability to withstand an operating pressure of 30 bar [10]. This reflects the high mechanical strength of the new developed Toyobo membranes which has been an obstacle in the past. The application of high concentration brine (such as Dead Sea water) has been suggested in a number of studies to boost the performance of PRO process [8,17,22]. However, the effects of concentration polarization and reverse salt diffusion on the membrane flux and performance intensify at elevated draw solution concentrations; this has been experimentally demonstrated in several studies [23,24]. Ignoring the effects of concentration polarization, a maximum power density of 230 W/m^2 can be achieved when Dead Sea water is coupled with 35 g/L seawater [25]. The maximum power density drops down to 70 W/m^2 when the effect of concentration polarization is taken into account [25]. The implication of concentration polarization phenomenon on the performance of PRO process is usually realized by the reduction of membrane flux and power density. This affects the maximum osmotic energy that can be harvested by the PRO process especially when the concentration polarization phenomenon acts on both sides of the membrane. Unfortunately, concentration polarization is an inevitable phenomenon in the osmotically driven membrane technologies and can not be eliminated even in the most developed PRO membranes.

In non-ideal systems, PRO process can only recover part of the salinity gradient energy while the non-recoverable energy remains in the salinity gradient resource for discharge. Practically, this reduces the efficiency of PRO process and makes its application less productive. Recent research has suggested adding a second stage PRO process to capture the rest of osmotic energy from the diluted draw solution before discharge [25–27], hence maximizing the energy efficiency of PRO process. The diluted draw solution from the first stage and a raw feed solution are coupled to form the salinity gradient of the second stage (Fig.1); this will rebuild the chemical potential difference across the PRO membrane. Therefore, the thermodynamic limits of conventional (single stage) and dual stage PRO process are different. Practically, the rejuvenated salinity gradient resource of the second stage of the dual stage PRO (DSPRO) induces a tangible increase of water flux across the PRO membrane. Previous studies referred to the advantage of DSPRO in reducing PRO membrane fouling when two different sources of feed solution were coupled with a draw solution [26]. The effect of feed and draw solution flow rates, feed pressure, and feed concentration on the performance of conventional PRO was evaluated in the previous studies [15]. However, the performance of DSPRO process needs to be characterized in terms of thermodynamic limits of the process and specific energy yield along the PRO module. This will provide more knowledge about the preferable configuration of membranes arrangement for the DSPRO process and justification for use instead of the conventional PRO process.

In this paper, we performed an energy comparison simulation study between the conventional PRO and the DSPRO process to evaluate the energy efficiency of each system. Typically, the chemical potential of salinity gradient resources decreases along the membrane [17,18]. To address the impact of increasing number of membrane modules or area on the performance of PRO process, we suggested a number of scenarios for membrane modules arrangement and configuration in the first and second stage of the PRO process. Each design configuration addressed the impact of salinity gradient concentration and feed hydraulic pressure on the performance of single and DSPRO processes. The simulation results were analyzed to explain the advantages of the DSPRO compared with the conventional PRO process.

2. Effect of membrane area

The driving force across the membrane in the PRO process is the osmotic pressure of the salinity gradient resource. Accordingly, the higher the difference between the concentration of draw and feed solutions is, the larger the driving force across the PRO membrane. As fresh water permeates across the membrane, draw solution becomes more diluted whereas the feed solution gets concentrated. This suggests that the driving force across the membrane decreases along the membrane module and adversely affects the