Applied Energy 191 (2017) 328–345

Contents lists available at ScienceDirect

Applied Energy

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

Single and dual stage closed-loop pressure retarded osmosis for power generation: Feasibility and performance

Ali Altaee [a,*], Patricia Palenzuela [b], Guillermo Zaragoza [b], Adnan Alhathal AlAnezi [c]

[a] School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia
[b] CIEMAT, Plataforma Solar de Almería, Ctra. de Senés s/n, 04200 Tabernas, Almería, Spain
[c] Department of Chemical Engineering Technology, College of Technological Studies, The Public Authority for Applied Education and Training (PAAET), P.O. Box 117, Sabah Alsalem 44010, Kuwait

HIGHLIGHTS

- Closed-Loop PRO (CLPRO) coupled with MED for power generation.
- Single and dual stage CLPRO processes were simulated.
- Free source of waste heat was assumed available for thermal regeneration process.
- Dual stage CLPRO efficiency was 20% higher than the single stage CLPRO.

ARTICLE INFO

Article history:
Received 17 October 2016
Received in revised form 20 January 2017
Accepted 27 January 2017
Available online 7 February 2017

Keywords:
Pressure retarded osmosis
Dual stage pressure retarded osmosis
Osmotic power plant
Thermal regeneration
Dual stage PRO optimization

ABSTRACT

This work proposes an analysis of conventional (single stage) and dual stage Closed-Loop Pressure Retarded Osmosis (CLPRO) for power generation from a salinity gradient resource. Model calculations were performed taking into account the influence of operating parameters such as the draw solution concentration, membrane area, and draw solution pressure on the performance of the CLPRO process. Modeling results showed that the dual stage CLPRO process outperformed the conventional CLPRO process and power generation increased 18% by adding a second stage of PRO membrane. Multi-Effect Distillation (MED) was selected for the regeneration of the draw solution taking advantage of an available source of waste heat energy. The performance of MED process has been assessed by investigating two key parameters: the specific thermal consumption and the specific heat transfer area. The model calculations showed that the power generation by the single and dual stage CLPRO was higher than the electrical power consumption by the MED plant. In the case of the power generation obtained by the dual stage CLPRO, it was 95% higher than the electrical power consumption by the MED plant, proving the possibility of using low-grade heat for producing electricity from a salinity gradient resource.

1. Introduction

The application of salinity gradient resource for power generation has been widely recognized as an efficient and low cost approach of renewable energy [1–8]. The most common techniques for power generation from a salinity gradient are the Pressure Retarded Osmosis (PRO) and Reverse Electrodialysis (RED) [1–13]. PRO process has attracted a lot of attention for harvesting the energy of salinity gradient because of its high efficiency and flexibility to be combined with desalination technologies such as Reverse Osmosis (RO) [6,7,10,11]. Experimental works have demonstrated the feasibility of PRO process application in a small commercial power plant [14]. Closed-Loop PRO (CLPRO) has also been proposed for power generation as a heat engine but only few studies have been published in this field [8,15,16]. Previous studies focused on the performance of the PRO part and no data have been provided about the performance of the entire

---

Abbreviations: CLPRO, Closed-Loop Pressure Retarded Osmosis; MED, Multi-Effect Distillation; RO, Reverse Osmosis; PRO, Pressure Retarded Osmosis; RED, Reverse Electrodialysis; DS, Draw Solution; FS, Feed Solution; CP, Concentration Polarization; DSPRO, Dual Stage Pressure Retarded Osmosis; SSPRO, Standard Single Stage Pressure Retarded Osmosis; ERD, Energy Recovery Device; TBT, Top Brine Temperature; BPE, boiling point elevation; RR, Recovery Ratio; S_{TC}, Specific Thermal Consumption.

[*] Corresponding author.

E-mail address: alialtaee@hotmail.com (A. Altaee).

http://dx.doi.org/10.1016/j.apenergy.2017.01.073
0306-2619/

Nomenclature

Q_p	PRO permeate flow rate (m^3/h)
π_{Db}	osmotic pressure of the bulk draw solution (bar)
π_{Fb}	osmotic pressure of the feed draw solution (bar)
k	mass transfer coefficient (m/s)
A_m	PRO membrane area (m^2)
A_w	water permeability coefficient (L/m^2 h bar)
ΔP	hydraulic pressure difference (bar)
$\Delta\pi$	osmotic pressure gradient (bar)
B	solute permeability coefficient (m/h)
K	solute resistivity for diffusion within porous support layer (s/m)
J_w	membrane flux (L/m^2 h)
T	feed temperature (K)
m_n	molar concentration of nth ion species
C_{Nab}	bulk concentration of Na ion (mg/L)
C_{Clb}	bulk concentration of Cl ion (mg/L)
Mw_{Na}	molecular weight of Na (mg/M)
Mw_{Cl}	molecular weight of Cl (mg/M)
C_{Di}	inlet concentration of draw solution (mg/L)
C_{Do}	outlet concentration of draw solution (mg/L)
Q_{Di}	inlet flow rate of draw solution (L/h)
Q_{Do}	outlet flow rate of draw solution (L/h)
C_p	permeate concentration (mg/L)
W	power density (W/m^2)
C_p	permeate concentration (mg/L)
P_w	power generation (kW)
Re	PRO recovery rate
Q_F	feed flow rate (L/h)
Q_P	permeate flow rate (L/h)
$\Delta\pi$	osmotic pressure gradient (bar)
$Es\text{-}_{RO}$	specific power consumption of RO (kWh/m^3)
P_f	RO feed pressure (bar)
P_p	RO permeate pressure (bar)
$P_{W\text{-}RO}$	RO power consumption (kWh)
η	pump efficiency
Q_{hpp}	feed flow rate of high pressure pump (m^3/h)
Q_{bp}	feed flow rate of booster pump (m^3/h)
Q_{sp}	feed flow rate of supply pump (m^3/h)
P_{bpin}	inlet pressure of booster pump (bar)
P_{hpp}	outlet pressure of high pressure pump (bar)
$P_{f\text{-}hpp}$	pressure of feed flow to the high pressure pump (bar)
$P_{f\text{-}sp}$	pressure of feed flow to supply pump (bar)
η_{hpp}	efficiency of high pressure pump
η_{bp}	efficiency of booster pump
η_{sp}	efficiency of supply pump
N	number of effects
N_{ph}	number of preheaters
$T_{v,i}$	vapour temperature generated in the i effect (°C)
$T_{v,N}$	vapour temperature generated in the last effect (°C)
$T_{b,1}$	brine temperature of un-evaporated solution through MED (°C)
$\Delta T_{eff,i}$	temperature difference in MED effects (°C)
T_f	temperature of feed water (°C)
$T_{cw,in}$	cooling water inlet temperature (°C)
$T_{cw,out}$	cooling water outlet temperature (°C)
T_s	temperature of low pressure steam (°C)
$T_{ph,i}$	feed water temperature in the bundle tube of a preheater ***i***
$\Delta T_{preh,i}$	temperature difference between preheaters (°C)
$T_{db,i}$	un-evaporated brine temperature after flashing (°C)
$A_{eff,i}$	area of each effect (m^2)
$U_{eff,i}$	total heat transfer coefficient (W
$Q_{eff,i}$	heat transfer provided to the i-effect of MED
M_s	flow rate of low pressure steam mass
M_{prod}	total distillate flow rate
M_f	mass flow rate of feed solution sprayed in 1st effect
λ_s	enthalpy change related to the vapour condensation
$\lambda_{gb,i}$	latent heat of vaporization
$M_{v,i}$	vapour mass flow rate going to the bundle tube of each effect
$M_{gb,i-1}$	vapour mass flow rate generated by boiling of the brine
$M_{gf,i-1}$	vapour mass flow rate generated by flashing of the brine
$M_{df,i-1}$	vapour mass flow rate generated by flashing of the distillate water
$M_{vh,i-1}$	vapour mass flow rate consumed in preheater
$M_{db,i}$	mass flow rate of the brine solution after flashing

CLPRO-thermal system. Furthermore, no studies have been published yet on the potential of using closed-loop dual stage PRO process for power generation.

PRO process uses osmotic energy as the driving force for power generation. A high osmotic pressure draw solution (DS) is fed at one side of a semipermeable membrane whereas a low osmotic pressure feed solution (FS) is pumped into the opposite side of the membrane to create an osmotic pressure gradient, which induces fresh water transportation towards the DS (Fig. 1). Fresh water transport across the membrane will convert the chemical potential into a hydraulic energy. Finally, the diluted DS is depressurized by a hydroturbine for power generation. Although PRO was suggested in the seventies [17], it did not receive considerable attention due to the technical limitations associated with the membrane permeability and rejection rate [13–18]. Recent developments in the membrane manufacturing industries have brought back the strong interest in the PRO concept for power generation [18,19]. New PRO membranes have high water permeability and rejection rate, which revolutionized the PRO and enhanced its performance [17]. Pilot plant tests using Toyobo membrane demonstrated high power density of 7.7 W/m^2 [14], which was more than the theoretical recommended value (5 W/m^2) for an economic PRO process [19]. Furthermore, previous studies have achieved power density larger than 10 W/m^2 using a laboratory fabricated PRO membrane and 6–0.06% salinity gradient resource [18].

One of the operating challenges for the PRO process is the selection of a suitable salinity gradient resource to create a sufficient driving force across the PRO membrane. A number of salinity gradients have been suggested by coupling seawater or brine from a Reverse Osmosis (RO) process with wastewater effluent or fresh water [13,14,19–21]. It is preferable applying high concentration DS to obtain high membrane flux across the PRO membrane. Previous works showed that Concentration Polarization (CP) across the membrane increases with increasing permeation flow and reducing the efficiency of PRO process [22–24]. CP is divided into dilutive and concentrative; dilutive CP occurs usually on the DS side whereas the concentrative CP occurs on the FS. However, using deionized water negates the effect of concentrative CP and improves the performance of PRO [22].

Closed-Loop PRO (CLPRO) has been proposed as a means for salinity gradient energy capture when no natural streams are available [24]. The salinity gradient resource in the CLPRO process consists of a high osmotic pressure DS and deionized/low concentration FS (Fig. 1A). In this case, the diluted DS goes to a