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Energy recovery by pressure retarded osmosis (PRO) in SWRO–PRO integrated processes

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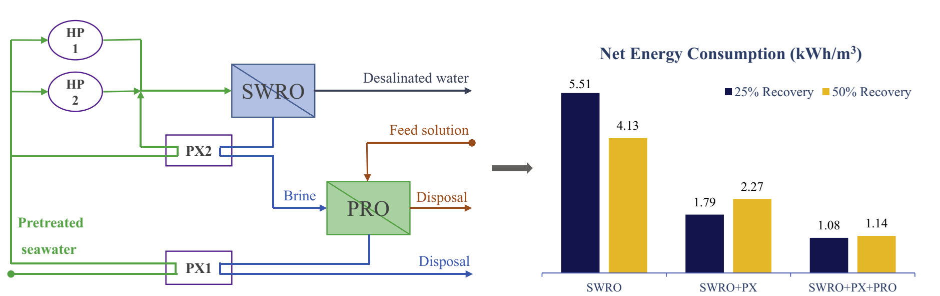
HIGHLIGHTS

- 2 detailed SWRO–PRO processes are developed with the option to form a closed-loop.
- Mathematical models on both module level and system level are developed.
- 25% recovery SWRO with PX and PRO has a SEC of 1.08 kW h/m^3.
- 50% recovery SWRO with PX and PRO has a SEC of 1.14 kW h/m^3.

GRAPHICAL ABSTRACT



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ABSTRACT

Pressure retarded osmosis (PRO) is a promising technology to reduce the specific energy consumption of a seawater reverse osmosis (SWRO) plant. In this study, it is projected that 25.6–40.7 million kW h/day of energy can be recovered globally, if the brines from SWRO are used as the draw solution and diluted to the seawater level in a PRO system. Detailed integrated SWRO–PRO processes are developed in this study with the option to form a closed-loop SWRO–PRO process that can substantially reduce the pretreatment cost of desalination. The governing mathematical models that describe both the transport phenomena on a module level and the energy flow on a system level are developed to evaluate the performances of the SWRO–PRO processes. The model aims to investigate the performance of the hollow fibers as dilution occurs and provides guidelines on hollow fiber module design and process operation. Determining the dilution factor and the corresponding operating pressure of PRO is the key to optimize the integrated process. The specific energy consumptions of three SWRO-involved processes; namely, (1) SWRO without a pressure exchanger, (2) SWRO with a pressure exchanger, and (3) SWRO with pressure exchangers and PRO are compared. The results show that the specific energy consumptions for the above three processes are 5.51, 1.79 and 1.08 kW h/(m^3 of desalinated water) for a 25% recovery SWRO plant; and 4.13, 2.27 and 1.14 kW h/(m^3 of desalinated water) for a 50% recovery SWRO plant, using either freshwater or wastewater as the feed solution in PRO.

1. Introduction

Water and energy are closely interlinked and interdependent. Water is essential for energy generation, while energy is crucial for water production, treatment and pumping. Energy consumption to produce potable water varies from 0.37–0.48 kW h/m^3 for surface and groundwater to 2.58–8.50 kW h/m^3 for seawater [1].

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Nomenclature

A	pure water permeability (PWP) [m^3/(m^2 s Pa)]
A_m	membrane area [m^2]
B	salt permeability [m^3/(m^2 s)]
C	concentration [g/m^3]
D	diffusivity [m^2/s]
d_i	inner diameter [m]
f	fraction
i	Van't Hoff factor
J_s	reverse salt flux [g/(m^2 s)]
J_w	water flux [m^3/(m^2 s)]
k	mass transfer coefficient [m^3/(m^2 s)]
P	pressure [Pa]
R	universal gas constant [J/(mole K)]
S	structure parameter [m]
t	residence time [s]
T	temperature [K]
V	flowrate [m^3/s]
W	work [J]

Greek symbols

ε	porosity
η	efficiency
τ	tortuosity
λ	wall thickness [m]
Π	osmotic pressure [Pa]

Abbreviations

DF	dilutive factor
PD	power density
PR	pressure ratio
Re	Reynold number
Rec	recovery
Sc	Schmidt number
Sh	Sherwood number
SEC	specific energy consumption [J/m^3]
SER	specific energy recovery [J/m^3]

Subscripts

a	process in Fig. 1(a)
b	process in Fig. 1(b)
E	energy recovery device
D	draw solution
F	feed solution
P	pump
PRO	pressure retarded osmosis
PX1	pressure exchanger 1
PX2	pressure exchanger 2
SW	seawater
SWRO	seawater reverse osmosis

Superscripts

0	initial state
f	final state
PRO	with pressure retarded osmosis
ERD	with energy recovery device

Though lower energies are required to produce freshwater from surface and groundwater, they only constitute 0.5% of the total water on Earth [2]. People have been long searching for technologies to produce drinkable water by desalination of saline water, which constitutes 97.5% of the total water on Earth [2]. According to International Desalination Association (IDA), there were more than 17,000 desalination plants operating worldwide with a total capacity over 80 million m^3/day in 2013 and is projected to increase to over 130 million m^3/day by 2016 [3]. The total capacity of seawater reverse osmosis (SWRO) alone will increase from 24.73 million m^3/day in 2013 to 36.33 million m^3/day by 2016 [3].

Though the current seawater reverse osmosis (SWRO) process is highly energy-efficient, it still consumes a large amount of energy to pressurize and pump water [4–6]. SWRO also receives social resistance because the disposal of its concentrated brine has negative impacts on the environments [4–6]. Development of high-efficiency pumps and high-efficiency energy recovery devices (ERD) have significantly reduced the specific energy consumption (SEC) of desalination towards its thermodynamic minimum [4–6]. Renewable energies, such as solar, wind, wave and geothermal energies, are exploited to further compensate the energy consumption of desalination [7,8]. Osmotic energy has emerged as a promising sustainable energy in the last decade [9]. Two technologies – namely reverse electro-dialysis (RED) and pressure retarded osmosis (PRO) [9] – have been extensively investigated to harvest the osmotic energy. Both technologies can be potentially integrated with SWRO to recover energy from the concentrated brine and cut down the energy consumption of desalination [10,11].

PRO extracts the Gibbs free energy of mixing by allowing water to spontaneously flow through a semi-permeable membrane from a low-salinity feed solution to a high-salinity draw solution against a hydraulic pressure [12–14]. The Gibbs free energy is converted to the hydraulic pressure of the diluted brine that can be further converted to mechanical energy by a pressure exchanger (PX) [11,15] or electrical energy by a hydro-turbine [16–19]. Comparing with the conventional seawater–freshwater PRO process, the SWRO–PRO integrated process offers a number of advantages [20]: (1) a higher power density is possible due to the increased difference in osmotic pressure; (2) the seawater brine has been pretreated in the SWRO system and will cause less fouling in the PRO system; (3) even though the pretreatment of the feed solution to the PRO system is still required, the overall pretreatment units can be significantly downsized if the brine is diluted to the seawater level in PRO and recycled to SWRO. Nonetheless, to take full advantages of the synergic SWRO–PRO process, strategic collocation of the SWRO plant and low salinity water sources is required during urban planning [21].

The SWRO–PRO integrated process has received increasing attention recently [11,15,19,22–25]. In the Japan Megaton Water Project, a PRO system where a maximum power density of 13.3 W/m^2 at a hydraulic pressure difference of approximately 27 bar was developed using the SWRO brine as the draw solution and freshwater as the feed [19,26]. In this prototyped plant, hydro-turbines were used to harvest the osmotic energy. In 2014, Sarper et al. [15] and Prante et al. [11] independently proposed two modeled SWRO–PRO processes, where the high-pressure diluted seawater brine from PRO was used to pressurize the seawater feed to SWRO through a PX.

However, most of the SWRO–PRO processes are conceptual and detailed process designs are missing in the literatures. Moreover, systematic SWRO–PRO models are needed for the integrated process design and optimization. In this study, detailed configurations of two novel SWRO–PRO integrated processes in terms of the positions and functions of each PX and HP were specified.