Applied Energy 104 (2013) 592–602

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

A novel hybrid process of reverse electrodialysis and reverse osmosis for low energy seawater desalination and brine management

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HIGHLIGHTS

- ▶ A hybrid process combining RO and RED is proposed.
- ▶ The complementary effects between RO and RED are mathematically interpreted.
- ▶ Designs of the hybrid process with different configurations are demonstrated.
- ▶ The operating conditions of the RED unit is optimized for the hybrid process.
- ▶ The energy consumption and discharge salinity are compared for different modes.

ARTICLE INFO

Article history:
Received 23 August 2012
Received in revised form 26 November 2012
Accepted 27 November 2012

Keywords:
Reverse osmosis
Reverse electrodialysis
Hybrid process
Energy consumption
Brine management

ABSTRACT

This paper introduces a novel concept for a hybrid desalination system that combines reverse electrodialysis (RED) and reverse osmosis (RO) processes. In this hybrid process the RED unit harvests the energy in the form of electricity from the salinity gradient between a highly concentrated solution (e.g., seawater or concentrated brine) and a low salinity solution (e.g., biologically treated secondary effluent or impaired water). The RED-treated high salinity solution has a lower salt concentration and serves as the feed solution for the RO unit to reduce the pump work. The concentrated RO brine provides the RED unit a better high salinity source for the energy recovery compared to seawater. In addition, the concentration of the discharged brine can be controlled by the RED unit for improving the water recovery and minimizing the impact on the environment. Different configurations of the hybrid RED–RO processes are presented for a comparative study on the basis of mathematical modeling. Specifically, various operating conditions for the RED unit are investigated for better adaptation to the hybrid system. The variations of the total specific energy consumption and the discharge brine concentration for various hybrid modes are simulated to verify the conceptual designs. The modeling results indicate that the RED–RO hybrid processes could substantially reduce the specific energy consumption and provide a better control of the discharge brine concentration in comparison to conventional seawater desalination RO processes.

1. Introduction

Reverse osmosis (RO), one of the most important techniques for seawater desalination, has been rapidly growing since the 1960s, due to the increasing worldwide water scarcity as along with a significant improvement in membrane materials and dramatic reduction in desalination cost [1]. However, its further development is challenged in several aspects.

During RO processes, fresh water is obtained by filtering seawater or brackish water through a semipermeable membrane under a high transmembrane pressure (TMP, e.g., 10–20 bar for brackish water and ~60 bar for seawater) [2–4]. In spite of the major advancements in RO technology towards a higher productive efficiency, RO processes are still characteristic of an energy-intensive approach to acquiring fresh water from various brackish water

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http://dx.doi.org/10.1016/j.apenergy.2012.11.064

Nomenclature

A_m	area of the ion-exchange membranes in the RED stack (m^2)
a_H	activity of the high salinity solution
a_L	activity of the low salinity solution
c_B	concentration of the discharge brine in the hybrid process (mol/m^3 or mol/L)
c_B^*	concentration of the discharge brine in the RO process (mol/m^3 or mol/L)
c_e	concentration of the solution at the equilibrium state (mol/m^3 or mol/L)
c_F	concentration of the feed solution for the RO unit (mol/m^3 or mol/L)
c_H	concentration of the high salinity solution (mol/m^3 or mol/L)
c_L	concentration of the low salinity solution (mol/m^3 or mol/L)
c_R	concentration of the retentate in the RO unit (mol/m^3 or mol/L)
E	specific energy based on the high salinity solution or product water ($kW h/m^3$)
F	Faraday constant (96,485 C/mol)
f_{RED}	mixing extent of the RED process
I	current handling of the RED stack (A)
N_m	number of the ion-exchange membrane pairs in the RED stack
N_p	number of the branches in the RED network
N_s	number of the RED stacks in a branch of the network
p	hydraulic pressure in the RO unit (Pa)
q	total transported charges through the external circuit for the RED stack (C)
R	apparent rejection of RO membranes
R_g	gas constant (8.314 J/mol K)
R_l	electrical resistance of the external load (Ω)
R_s	electrical resistance of the RED stack (Ω)
$\bar{R}_a$	area resistance of the anion-exchange membranes the RED stack ($\Omega\, m^2$)
$\bar{R}_c$	area resistance of the cation-exchange membranes the RED stack ($\Omega\, m^2$)
T	absolute temperature (K)
t	filtration time (s or h)
V_E	electromotive force of the RED stack (volt)
V_F	volume of the feed solution for the RO unit (m^3 or L)
V_H	volume of the high salinity solution (m^3 or L)
V_L	volume of the low salinity solution (m^3 or L)
V_{re}	volume of the reflux in the complex hybrid process (m^3 or L)

Greek letters

α_m	selectivity of the ion-exchange membranes in the RED stack
γ	recovery of the desalination processes based on the fresh seawater
β	volumetric ratio of V_L to V_H
λ_H	thickness of the fluid channels for the high salinity solution in the RED stack (m)
λ_L	thickness of the fluid channels for the high salinity solution in the RED stack (m)
π	osmotic pressure of the salinity solutions (Pa)
σ_g	molar conductivity of the salinity solutions ($m^2/\Omega\, mol$)
φ	volumetric ratio of V_{re} to V_H

resources. The typical specific energy consumption of seawater reverse osmosis (SWRO) is ~3.0 kW h/m^3 based on the product water [5]. This significant energy consumption is primarily caused by the pump work required to overcome the high osmotic pressure of the feed solutions. The quest for higher potable water recovery has necessarily resulted in the retentate from SWRO becoming more concentrated.

Not only does the concentrated brine limit the improvement of the SWRO recovery, its disposal also creates a lot of problems concerning environmental and ecological issues [6,7]. For example, a typical method for disposing of the RO brine is to discharge to coastal water. Despite its economical viability, this method usually results in density plumes in the receiving water, which could have an adverse impact on the related ecological systems [8]. Other approaches, such as disposal to a sewer or via an evaporation pond and irrigation, are restricted to RO plants of small size (capacity less than 0.4 or 1 MGD) [9,10]. Another means of brine disposal, the method of deep well injection remains controversial since it has not been implemented long enough to assess the potential environmental risks [1]. From another perspective, the huge amount of free energy stored in the RO brines, which could have been scavenged via appropriate approaches, is wasted in the current disposal methods.

Reverse electrodialysis (RED) is an emerging membrane-based technique that draws electrical power from the salinity gradient between two solutions [5,11,12]. During the RED process, the constituent ions in the solutions are driven through ion-exchange membranes by the salinity gradient. The ion flows are converted into the electron flows at the electrodes. This process can be viewed as a controlled mixing, where the salt concentration of the high salinity solution is reduced while that of the low salinity solution is increased until equilibrium is reached. Prior studies [13–19] have investigated the RED process as an independent unit operation, and primarily focused on improving the power density and the conversion efficiency in RED.

In this work, the RO and RED processes are integrated so as to design a novel hybrid process that exploits the synergy of RO and RED processes. From the viewpoint of the RED process, the RO process can supply the concentrated brine as the high salinity feed solution for a higher power density. At the same time the environmental impact of the RO brine could be minimized by decreasing the salinity of the discharged brine via the RED process. On the other hand, the energy consumption of the RO process can be reduced by pre-treating the feed solution through the RED process; i.e., the osmotic pressure of the feed solution is decreased and converted into electrical energy. These complementary effects make RO and RED an ideal combination for low energy seawater desalination and brine management.

This work is focused on validating the conceptual design of the RED–RO hybrid process via a theoretical approach. In this paper a variety of RED–RO configurations are proposed, for which the corresponding mathematical models are developed. The modeling is first performed to analyze the key factors affecting the adaptation of the RED process. Particularly, the current design of the RED unit is based on a batch-wise mode, though the presented methodology is readily modified to account for the continuous mode, which might be adopted for the design of large full-scale desalination plants. The theoretical analysis then focuses on the energy consumption and the variation of the discharge brine concentration while varying the system configuration and the operating conditions. Based on the modeling results, the implications for developing the RED–RO hybrid processes will be discussed.