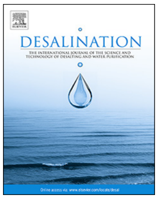
Desalination 443 (2018) 172–183

Contents lists available at ScienceDirect

Desalination

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



Theoretical simulation and evaluation for the performance of the hybrid multi-effect distillation—reverse electrodialysis power generation system

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ARTICLE INFO

Keywords:
Reverse electrodialysis
Multi-effect distillation
Power generation
Low grade heat
Heat engine

ABSTRACT

Reverse electrodialysis (RED) is a promising technology to extract electric energy from salinity gradient energy (SGE). Through being combined with multi-effect distillation (MED) where low grade heat is converted into SGE, a closed-loop system named hybrid MED-RED power generation system was presented. In this study, a detailed thermodynamic analysis for the system was performed to investigate how the relevant operation and structure parameters influence on the performance of the system. When hot and cooling water temperatures were respectively 80 °C and 20 °C and a six-effect distiller was applied, the energy conversion efficiency of the system reached 0.76% under the given operation conditions. The results showed that the increase of the hot water inlet temperature, initial salt molarity of brackish solution and effect number of MED all would positively influence on the performance of the system. The energy conversion efficiency of the system could be promoted to 0.85% when the hot water inlet temperature and initial salt molarity of brackish solution were 95 °C and 3.75 mol·kg^{-1} respectively. In addition, under the given operation conditions, when the effect number of MED reached 10, the energy conversion efficiency of the system could reach to 1.01%.

1. Introduction

At present, very huge amounts of low grade heat (LGH) from industrial thermal processes, solar and geothermal energies are not exploited fully. The recovery and utilization of LGH is an attractive and significant choice to efficiently decrease fossil fuel depletion and contaminant emissions. In order to harvest LGH, massive efforts have been devoted globally to develop effective strategies and technologies. One of the strategies is to convert LGH into electric energy, and the relevant technologies, like Organic Rankine Cycle (ORC) and Kalina Cycle (KC) etc., which are based on the principle of 'heat to mechanical work to power', have attracted extensive attention and been investigated deeply [1, 2]. However, the performances of those technologies are not satisfactory for the LGH with temperature below 100 °C [3].Currently, a series of technologies named 'salinity gradient heat engines' are burgeoning since they have the capacity to effectively harvest the LGH with very low temperature. Among of them, the reverse electrodialysis (RED) heat engine is quit promising [4–7].

As the core technology of the RED heat engine, RED can convert SGE into electricity directly through ion directional transportation among the alternately stacked anion exchange membranes (AMEs) and cation exchange membranes (CMEs) [8]. RED is initially used to produce electric power from natural SGE, like between fresh and sea water [9, 10]. Estimates indicate that there is about 2.6 TW global theoretical potential of SGE generated by rivers discharging into seas and oceans [11], which occupied almost 20% of global energy demand [12]. In order to harvest SGP efficiently, more and more effects start to focus on improving RED plants, especially the power density which is the key performance indicator (KPI) of the plants. Since the first experimental report about the power density of 0.05 W/m^2 in 1954 [10], the power density and scale of RED plants have been improved distinctly, which can be seen in Table 1. What is more, the huge amounts of LGH worldwide can be converted into SGP, which enhances the potential of this energy.

The RED heat engine is a closed-loop system which consists of two processes namely 'heat to SGE' and 'SGE to power' processes. Its working principle is that the brackish solution is separated firstly by LGH in a thermal separation unit to form high and low concentration (HC & LC) solutions, which is called 'heat to SGE' process. And then these two solutions flow through the RED stack where SGE is converted directly into electric energy, which is called the 'SGE to power' process. Finally, the brackish solution from the RED stack flows into the thermal separation unit again.

For RED heat engine, the choice about the form of thermal

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https://doi.org/10.1016/j.desal.2018.06.001
Received 23 February 2018; Received in revised form 15 May 2018; Accepted 1 June 2018
0011-9164/

Table 1
The performance of some existing RED plants in lab all over the world.

Active membrane area	Salt	Concentration of HC & LC solutions	Temperature (°C)	Maximum power density (W/m^2)	Location	Date	Ref.
8 cm × 8 cm	NaCl	29.2 g/L & 0 g/L	39	0.05	UK	1955	[10]
232 cm^2	NaCl	0.57 M/L & 0.0259 M/L	20	0.338	USA	1976	[9]
40 cm^2	NaCl	294 g/L & 1 g/L	25	0.407	France	1983	[13]
8 cm × 12.5 cm	NaCl	5.32 M/L & 0.05 M/L	25	1.25	Israel	1986	[14]
–	NaCl	35.4 g/L & 0.56 g/L	–	0.46	Poland	2007	[15]
–	NaCl	111 g/L & 0.56 g/L	–	1.04	Poland	2008	[16]
10 cm × 10 cm	NaCl	30 g/L & 1 g/L	25	1.18	Netherlands	2009	[17]
10 cm × 10 cm	NaCl	30 g/L & 1 g/L	25	0.93	Netherlands	2009	[18]
25 cm × 75 cm	NaCl	30 g/L & 1 g/L	25	0.85	Netherlands	2010	[19]
10 cm × 10 cm	NaCl	30 g/kg & 1 g/kg	25	2.2	Netherlands	2011	[20]
10 cm × 10 cm	NaCl	0.513 M & 0.017 M	25	1.3	Netherlands	2013	[21]
10 cm × 10 cm	NaCl	0.513 M & 0.017 M	60	6.7	Netherlands	2014	[22]
10 cm × 10 cm	NaCl	5 M & 0.1 M	40	6	Italy	2015	[23]
19.6 cm^2	NaCl	0.58 M & 0.017 M	–	2.4	South Korea	2015	[24]
44 cm × 44 cm	NaCl	4–5 M & 0.03 M	25	1.35	Italy	2016	[25]
44 cm × 44 cm	NaCl	215 mS/cm & 3–6 mS/cm	25	1.65	Italy	2017	[26]
10 cm × 10 cm	NH_4Cl-LiCl	5 M/0.05 M	25	8	Italy	2018	[27]

Table 2
The relevant information about the published RED heat engines.

RED heat engine	Literature 1 [29]	Literature 2 [7]
Authors	Rui Long et al.	M. Bevacqua et al.
Date	2017	2017
Location	China	Italy
Thermal separation unit type	Membrane distillation (MD)	Stripping column
Working fluid	NaCl aqueous solution	NH_4HCO_3 aqueous solution
Main operating parameters	**Thermal separation unit:** Heat source temperature: 60 °C, Cold source temperature: 20 °C, Inlet concentration: 5 M/kg, Outlet concentration: – **Power generation unit:** Concentrations of HC & LC solution: 5 M/kg & – Operating temperature: 20 °C	**Thermal separation unit:** Heat source temperature: 60 °C, Cold source temperature: 25 °C, Inlet concentration: 2 M/L, Outlet concentration: 0.02 M/L **Power generation unit:** Concentrations of HC & LC solution: 2 M/L & 0.02 M/L Operating temperature: 25 °C
Key performance indicators	**Thermal separation unit:** Specific heat duty: 950 kJ/kg **Power generation unit:** solution unit work potential: 11 kJ/kg **Energy conversion efficiency:** 1.2% (maximum)	**Thermal separation unit:** Specific heat duty: 76.64 kWh/m^3 (≈276 kJ/kg) **Power generation unit:** Power density: 3.5 W/m^2 **Energy conversion efficiency:** 1.2% (maximum)

separation is flexible. Luo et al. [28] presented a thermal-driven electrochemical generator equipped a distillation column as the thermal separation unit to generate HC and LC solutions by decomposing ammonium bicarbonate (NH_4HCO_3) thermally. And then M. Bevacqua et al. [7] presented the simulation analysis for this heat engine. Undoubtedly, this concept is feasible but one-off utilization of LGH limits the system electrical generation efficiency (output power divided by input heat) and, moreover, the HC solution concentration just can reach 2.6 mol/L, which dramatically restricts the performance of the RED plant. Long et al. [29] adopted membrane distillation (MD) as the thermal separation unit. When cold and heat source temperatures were 20 °C and 60 °C respectively and the concentration of NaCl aqueous solution was 5 $mol{\cdot}kg^{-1}$ fed into the MD, the electrical generation efficiency of the hybrid MD-RED system can reach 1.15% by recovering heat by a regenerator. The relevant information about these two kinds of RED heat engines can been seen in Table 2.

In this paper, we propose a novel RED heat engine with hybrid multi-effect distillation-reverse electrodialysis (MED-RED), in which a multi-effect distiller is used as the thermal separation unit. As one of the mature and competitive desalination technologies, MED has been proved to be the thermodynamically most effective thermal desalination technique [30]. The prominent advantages of MED lie in its high thermal efficiency and the possibility to utilize LGH. Generally, the operating temperature for MED is below 100 °C [31],and through repeatedly utilizing heat energy, the specific heat duty can drop to 40 kWh/m^3 (≈144 kJ/kg) [32]. Moreover, the demister which is used to reduce the salinity of product fresh water in traditional MED can be removed in the RED heat engine, which can increase the salt content in product to enhance conductivity of LC solution and distinctly decrease the pressure loss in MED. In this study, the performances of the RED heat engine and influence of the relevant operating and structure parameters on them were investigated theoretically by developing mathematical model and discussed.

2. System description

2.1. System

A schematic diagram of the hybrid MED-RED power generation system is shown in Fig. 1. The system consists of two units, thermal separation and power generation units. In the thermal separation stage, the brackish solution from the RED stack flows into MED where the solution will be separated into HC and LC solutions by LGH. In this stage, the thermal energy is converted to SGE. In the power generation stage, these two solutions flow simultaneously into the RED stacks where SGE can be converted into electricity directly. In order to harvest more SGE, it is viable to lead the two solutions through multiple RED stacks in series [13–15].

2.2. RED stack

A basic RED cell unit is composed by a CEM, an AEM, and a group of gasket and spacer. CEM only allows the transport of cations and AEM only allows the transport of anions. A practical size RED stack is composed by hundreds or thousands of basic cell units in series because the voltage and power output by one cell unit are too small to be used [34]. The structure of the RED stack is shown in Fig. 2. In it, alternating arrangement CEMs and AEMs by integrating the gaskets and spacers form compartments for flowing of HC and LC solutions [15]. When the