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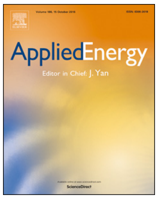

An Adsorption Reverse Electrodialysis system for the generation of electricity from low-grade heat

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HIGHLIGHTS

- Closed-loop energy generation from Adsorption Desalination/Reverse Electrodialysis.
- Among monovalent salts, LiCl achieves 44.6% exergy efficiency.
- Adsorption regeneration performance is insensitive to salt concentration.

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ABSTRACT

A novel process is presented to generate electricity from low-grade heat by combining a Reverse Electrodialysis membrane with an Adsorption desalinator in a closed-loop system. A Reverse Electrodialysis membrane generates electricity by controlled mixing of two salt solutions of different concentrations. An Adsorption desalinator restores the initial salt gradient by utilising low-grade heat for the separation. In this study the process is designed from optimising the salt and material selection to the development of the real system application. Energy and exergy efficiencies of the proposed system show the potential of this novel renewable energy technology. The efficiencies of 227 salts with a range of different valences and 10 adsorption materials have been investigated over a large number of system parameters. The results show that the optimised system can achieve an exergy efficiency of up to 30%. Moreover, high salt concentrations do not significantly increase the specific energy consumption of the Adsorption desalinator, which allows operating the Reverse Electrodialysis membrane at the optimal salt concentrations.

1. Introduction

Climate change, water scarcity and energy security are some of the world's major issues. It is widely recognized that a key role in solving these issues is a sustainable and efficient use of the planet's limited resources. However, energy is not used efficiently, with estimates showing that 72 % of the global primary energy produced is converted to waste heat [1,2]. Low-grade heat available from numerous sources such as industrial sites, power plants, geothermal areas or solar collectors [3,4].

Papapetrou et al. analysed the availability of industrial waste heat in the EU and estimated the availability at 300 TW h per year excluding power plants and transportation [5]. They categorised waste heat at different temperature levels between ambient temperature up to 1000 °C, where the highest waste heat potential lies below 200 °C representing one third of the emitted waste heat. Rattner and Garimella evaluated the waste heat potential in the USA in a comprehensive study including power plants, transportation and manufacturing [6]. They found that 4000 TW h of waste heat are annually available from condensers of power plants in the temperature range from 40–49 °C. Another 4500 TW h per year are emitted at temperature levels between 50–99 °C. Both temperature ranges amount to a total of 78% of the entire waste heat available below 100 °C.

Recently, the utilisation of low-grade heat has attracted much attention, but only few of the proposed systems are able to operate at temperatures below 100 °C. The Organic Rankine Cycle (ORC) usually utilises waste heat between 100–300 °C [7]. Although, ORC systems operating between 80–100 °C have been proposed in simulations, which achieved exergy efficiencies of 54% using highly toxic refrigerant R123 [8].

Thermoelectric systems are solid state power generators built of semiconductors that can generate electricity from a temperature

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Nomenclature

α	constant
β	coefficient of thermal expansion (1/K)
$\beta_{MX}^{(0)}$	viral coefficient
$\beta_{MX}^{(1)}$	viral coefficient
ΔG_{mix}	gibbs free energy of mixing (kJ/kg)
Δh	isosteric heat of adsorption (kJ/kg)
η	thermal efficiency
η_c	carnot efficiency factor
η_{ex}	exergy efficiency
γ	activity coefficient
Λ	fraction of system's total moles
Φ	osmotic coefficient
Ψ	volumetric ratio
a_s	activity of water
A_Φ	Debye Hückel coefficient
b	constant
BPE	boiling point elevation (K)
C_i	salt concentrations (mol/kg)
c_p	specific heat (kJ kg^{-1} K^{-1})
C_{MX}^{Φ}	viral coefficient
D	dielectric constant
E	Dubinin-Astakhov parameter (kJ/kg)
e	electron charge (C)
F_i	salinity solution flow rates (kg/s)
I	ionic strength (mol/kg)
k	Boltzmann constant (m^2 kg s^{-2} K)
L	latent heat (kJ/kg)
M	molar mass (g/mol)
m_{AD}	mass of silica gel (kg)
M_{water}	mass of water produced in each cycle (kg)
N	Avogadro constant (mol^{-1})
n	Dubinin-Astakhov parameter
P	pressure (bar)
R	gas constant (J/mol K)
SEC	specific energy consumption (kJ/kg)
SEC_{ex}	specific exergy consumption (kJ/kg)
T	temperature (K)
U_i	dielectric constant parameters
v	number of dissociated ions
W_i	adsorption uptake (kg/kg)
X	conversion factor
x	mole fraction
z	charge of ion

difference, where any source of heat above ambient temperature can be used [9]. However, their efficiencies have been too low to be used in commercial applications [10] achieving exergy efficiencies of 10% [9].

Another system utilising waste heat between 50–100 °C are Osmotic Heat Engines (OHE), which combine pressure retarded osmosis PRO with membrane distillation MD [11]. PRO membranes are semi-permeable, they convert the energy potential between salinity gradients into pressure first and then into electricity [12]. The salinity gradient is then restored by the MD unit in a closed-loop system. Lin et al. estimated the maximum thermodynamic limit of an OHE at an exergy efficiency of 81%, which is a theoretical value neglecting all limitations of a real system [13].

However, none of these technologies have demonstrated the conversion of low-grade heat below 100 °C to electricity at efficiencies and costs sufficient to generate commercial interest [7].

Reverse Electrodialysis (RED) membranes are semi-permeable like PRO membranes, but RED is an electrochemical process directly converting the energy potential of the salinity gradients into electricity [12]. In 1977, Wick estimated the global potential of natural salinity gradients for the utilisation by either RED or PRO at 2.6 TW (≈22,800 TW h/year) [14]. Recently, Veerman et al. have experimentally explored the generation of electricity by RED from naturally occurring salt gradients between river water and seawater [15]. Experimental work has demonstrated that the electric power output of the RED membrane can be further improved by using concentrated brines from seawater brine basins [16]. However, naturally occurring salt gradients are relatively small, their availability is geographically limited and they cause membrane fouling, which reduces the membrane performance by 40% without pre-treatment of the feed water [17].

The closed-loop system of salinity solutions overcomes these issues and the salinity gradient is restored by a thermal regeneration system as illustrated by Logan and Elimelech [18]. The general schematic of RED in a closed-loop system is shown in Fig. 1. The RED membrane generates electricity through the salt gradient of two feed solutions where one has a low and the other a high salinity. After flowing through the membrane, the thermal desalination unit utilises low-grade heat to regenerate the two solutions to their initial salt concentrations. The optimal performance of the system is a trade-off between the electricity generation and energy requirements for the separation process.

The most common thermal desalination technology is multi effect distillation (MED), which has the highest efficiency among all thermal desalination technologies [19]. However, MED systems are very large as their efficiency improves with the number of stages and higher waste heat temperature [20], where their specific thermal energy consumption can be as low as 40 kW h/m^3 using 90 °C heat source temperature [7]. In addition, a MED plant requires an electrical input of 2.0–2.5 kW h/m^3 [21]. The number of stages and therefore the efficiency is limited at high salt concentrations.

Smaller desalination systems include membrane distillation MD, which can utilise low-grade heat 45–85 °C, but the thermal energy consumption varies widely for seawater from 200 to 6000 kW h/m^3 [22]. In addition, Zaragoza et al. reported a specific electric consumption of 20 kW h/m^3 [22].

MED and MD are a well established commercial thermal desalination techniques, while other emerging techniques include temperature swing adsorption systems [23]. Wu et al. introduced the thermodynamic specific energy consumption in adsorption desalination [24], which ranges between 700 and 1000 kW h/m^3. However, the electric energy consumption is only 1.4 kW h/m^3 [25]. Heat source temperatures used for adsorption desalination are usually 50–85 °C [25].

Any thermal desalination method can be coupled with RED in a closed-loop system to generate electricity from low-grade heat. A closed-loop system of an MED-RED plant was modelled by Tamburini et al. presenting exergy efficiencies of up to 30%, which could be increased to 85% by future optimising the membranes [7]. The proposed RED-MED system would utilise a low-grade heat source at 90 °C.

Adsorption desalinators can utilise low-grade heat sources between

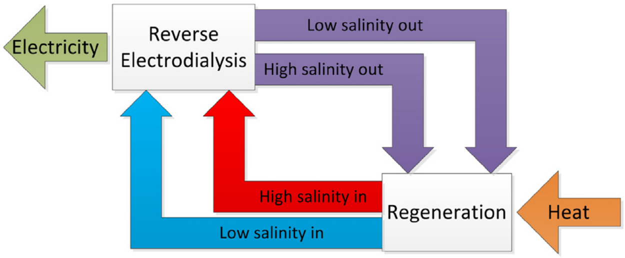

Fig. 1. A simplified representation of the closed-loop system converting low-grade heat into electricity.