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Parametric study of reverse electrodialysis using ammonium bicarbonate solution for low-grade waste heat recovery

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ABSTRACT

Waste heat recovery has attracted a significant attention because of the world growth in energy demand. In this paper, we report the study on an energy recovery system utilizing low-grade waste heat below 100 °C. This system called a thermal-driven electrochemical generator is composed of reverse electrodialysis (RED) power generation and thermal separation using waste heat. We especially focus on the experimental characterization of the RED process with ammonium bicarbonate (NH_4HCO_3) solution, which is known to be easily decomposed at the temperature around 60 °C. We characterized this NH_4HCO_3-RED system with various parameters including the concentration difference, the membrane type, the inlet flow rate, and the compartment thickness. We found the best power density at the concentrated solution of 1.5 mol L^{-1} and the diluted solution of 0.01 mol L^{-1}. The maximum power density increases as the inlet flow rate increases or the compartment thickness decreases owing to the decrease in the internal resistance. We obtained the excellent power density of 0.77 W m^{-2}, compared with the previous studies.

1. Introduction

It is critical to improve the efficiency of energy conversion systems owing to the growing concern over the fossil fuel depletion and the environmental pollution resulting from combustion byproducts [1,2]. The rate of converting useful output from primary energy resources is significantly low [3]. The unused energy is lost in operation and mostly released as thermal energy. Technologies to recover these waste heat, otherwise discarded toward the environments, therefore, have received significant interests over the past decades. Several techniques like combined heat and power plants (CHP) are successfully applied in industrial fields [4–6].

It is still difficult to harvest low-grade thermal energy (*e.g.* waste heat) below the temperature of 100 °C because it contains very little capacity to conduct work from the exergetic viewpoint [7]. Two methods, including an organic Rankine cycle (ORC) and thermoelectric generators, have been actively studied for the purpose of recovering this low-grade energy [7–15]. The ORC employs an organic solution such as refrigerants and hydrocarbons as the working fluid in place of water, compared with the conventional Rankine cycle [7–9]. It requires a relatively lower evaporation pressure and temperature, a less heat, and a smaller temperature difference. The ORC however suffers an environmental concern over refrigerants and it has a clear limitation in reducing its size. The thermoelectric device generates electrical power by the Seebeck effect where a temperature difference between two locations of a conductor or a semiconductor results in a voltage difference [11–13]. It has some advantages including a simple structure without moving parts, compared to the ORC. Yet, several problems like low efficiency and so poor form factor should be resolved for its commercialization.

Recently, a new method (called a thermal-driven electrochemical generator) was proposed for waste heat recovery, as shown in Fig. 1 [16]. It is essentially a combination of thermal separation process and reverse electrodialysis (RED) process, which generates electrical power from mixing two solutions of different concentrations. It uses thermolytic solutions (solutions easily decomposed by thermal energy) in place of sodium chloride solutions used in the conventional RED. The energy conversion consists of three steps: thermal energy → chemical energy → electrical energy. The thermolytic solution first separates into the solute and the remaining solution by the waste heat in the thermal separation process. Here, the solute-separated solution is used as the diluted solution and the solute mixed with the original solution is used as the concentrated solution for the RED system. The RED generates the electrical power by ion migration from the concentrated solution to the diluted solution through ion exchange membranes (IEMs). The diluted stream whose concentration increases through the

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Nomenclature

F	Faraday constant (96,485 C mol^{-1})	α	permselectivity (–)
L	length (m)	γ	activity coefficient (–)
Q	flow rate (L s^{-1})	δ	intermembrane distance (m)
R_g	universal gas constant (8.315 J mol^{-1} K^{-1})	ε	porosity (–)
T	temperature (K)	η_{pump}	pump efficiency (–)
V	voltage (V)	μ	viscosity (Pa s)
c	concentration (mol L^{-1})		
i	current density (A m^{-2})	*Subscripts*	
p	power density (W m^{-2})	*AEM*	anion exchange membrane
t_{res}	residence time (s)	*CEM*	cation exchange membrane
z	ion valence number (–)	*H*	concentrated solution
		L	diluted solution
Greek symbols			
Δp	pressure drop (Pa)		

RED system flows into the thermal separation system and becomes diluted again. The concentrated stream is circulated and mixed with the solute supplied from the thermal separation system. This system can ideally operate in a closed loop configuration.

The ammonium bicarbonate (NH_4HCO_3) solution is considered as one of promising thermolytic solutions for the thermal-driven electrochemical generator owing to the low decomposition temperature around 60 °C [16–21]. Luo et al. demonstrated the NH_4HCO_3-RED device experimentally [16]. They obtained the maximum power density of 0.33 W m^{-2} when the concentrations of the concentrated and diluted solutions are 1.5 mol L^{-1} and 0.02 mol L^{-1}, respectively. Hatzell et al. reported the effect of both the channel geometry and the CO_2 bubbles inside the channel in the NH_4HCO_3-RED system [19]. They found that the narrower channel can be beneficial in removing the bubbles. Geise et al. conducted the study on efficient anion exchange membranes for the NH_4HCO_3-RED system [20]. They showed that the membrane resistance can decrease with increasing the water uptake. An extensive analysis is yet to be performed for the major parameters of the NH_4HCO_3-RED system, compared with various conventional NaCl-RED system study [22–27]. The power reported in the previous studies is somewhat insufficient for practical applications [19,20].

This study presents the extensive characterization of the NH_4HCO_3-RED system producing electrical power from waste heat recovery. We investigated various parameters including the concentration difference, the IEM, the inlet flow rate, and the intermembrane distance. We also computed the net power with consideration of the pressure drop, which results in the external loss. We obtained the net power density of 0.62 W m^{-2}, which is the highest so far. The performance with NH_4HCO_3 is compared with NaCl as a control because NaCl is the most common salt types in diverse RED studies. We aimed that our experimental characterization in this study would be beneficial in the development of the NH_4HCO_3-RED system.

2. Experimental

Fig. 2 shows the schematic representation of the RED stack. Endplates are made of polymethyl methacrylate (PMMA) with the thickness of 30 mm and contains iridium and ruthenium-coated titanium electrodes (7 cm in width and length). Silicone rubber sheets are employed as a gasket to prevent the internal and external leakage of the working solution. A spacer, which plays vital roles as a membrane supporter as well as the suppressor of concentration polarization, is fabricated with polymer woven

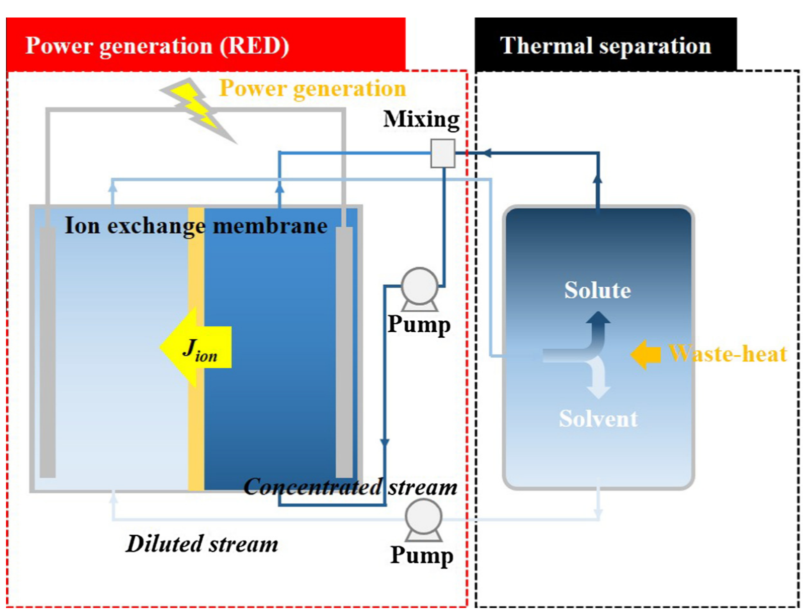

Fig. 1. Schematic illustration of a waste heat recovery system using reverse electrodialysis.