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Membrane electrode assembly for energy harvesting from salinity gradient by reverse electrodialysis

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ABSTRACT

In this study, the potential of the application of membrane electrode assembly (MEA) to energy harvesting from salinity gradient by reverse electrodialysis is experimentally investigated. The MEA, which consists of a cation exchange membrane and two porous silver/silver chloride electrodes, is developed. Power generation from the MEA located between sodium chloride solutions having various differences in concentration is measured. The highest power generation density achieved is $4.1\ \mathrm{W\,m^{-2}}$, which is greater than those reported in previous studies on conventional reverse electrodialysis cells.

1. Introduction

The exploration of renewable energy sources has been conducted for several decades because of the environmental issues and limited availability of fossil fuels [1,2]. In particular, the oceans have been investigated as sources of various forms of renewable energy [3]. One of the ocean energy sources is salinity gradient energy, which is available from the change in Gibbs energy during mixing of seawater and fresh water [4]. The salinity gradient energy has a potential to generate a power of 2.4 TW, which is 80% of the projected global electricity generation in 2020 (about 3.0 TW), from the global runoff of river water into the sea [5,6].

The current techniques available for desalination could be operated in reverse mode to generate electrical power from salinity gradients [7]. These techniques include reverse electrodialysis [8], pressure-retarded osmosis [9], and vapor-pressure difference utilization [10]. Among these, the reverse electrodialysis technique produces electrical energy by using the ion flow induced when brine and dilute solutions are mixed through ion–selective membranes. The main components of a reverse electrodialysis system are highlighted in Fig. 1(a) [11,12]. In reverse electrodialysis, brine and dilute solutions are passed through a stack of alternating cation and anion exchange membranes. Then, both cations and anions in the brine solution diffuse spontaneously to the dilute solution across the membranes. Because of the cation-selective property of cation-exchange membranes, cations preferentially diffuse over anions through the cation-exchange membrane. In contrast, anions preferentially diffuse over cations through the anion-exchange membrane. Because of the resulting flows of cations and anions in opposite directions, a net diffusion current from one electrode to the other electrode is generated. As a result, salinity gradient energy is converted to electrical energy and can be harvested continuously.

A cell pair of the reverse electrodialysis system in Fig. 1(a) can be represented in terms of basic circuit elements as shown in Fig. 1(b). Power generation can be increased expeditiously by reducing the electrical resistance of the dilute compartment (R_{DC} in Fig. 1(b)) [4]. This is because power generation is inversely proportional to the total resistance and because the resistance of the diluted compartment has a large contribution to the total resistance [13,14]. Therefore, several research works have concentrated on reducing the resistance of the diluted compartment. For example, Długołęcki et. al improved the spacers, which are usually located in the compartments to keep the intermembrane distance constant [15]. They developed ion conductive spacers, which enable ionic transport from the solutions to the membranes through the spacers. They found that the ion conductive spacers can decrease compartment resistances effectively and the power density increases by a factor of three. On the other hand, Vermaas et al. developed a profiled membrane having 230 μm ion conductive ridges on one side of the membrane [16]. They showed that compartments could be created by stacking profiled membranes without the use of the spacers. They determined that the compartment resistance was lower and the power density was higher for the stack with profiled membranes compared to the stack with spacers. Vermaas et. al systematically investigated the effects of the compartment thickness on the power densities [4]. They measured the power densities for four different compartment thicknesses. They found that thinner compartments have lower resistances and, consequently, higher power densities. Recently, Kim et al. presented a reverse electrodialysis stack with thin pore-filling membranes and high-open-area spacers [17]. Because of the

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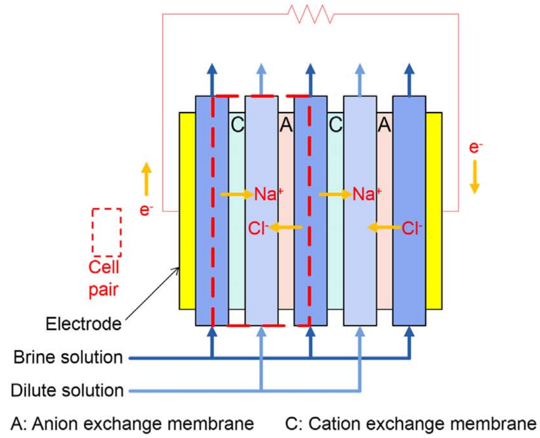
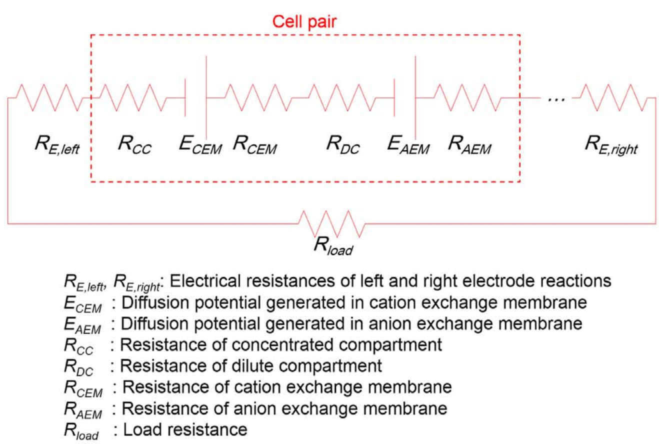
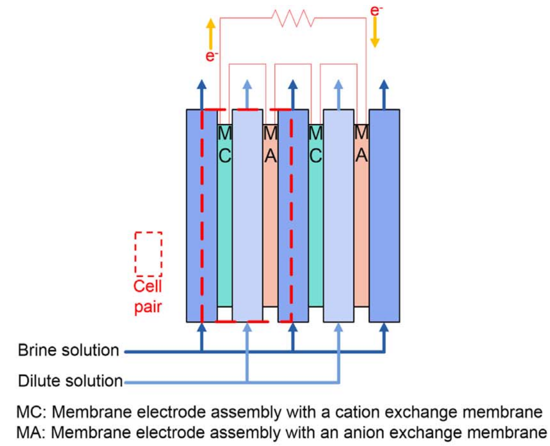


(a) Schematic diagram

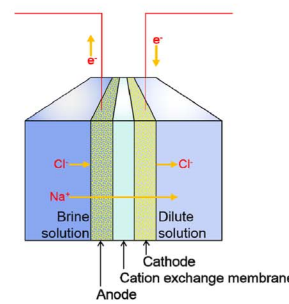


(b) Equivalent circuit

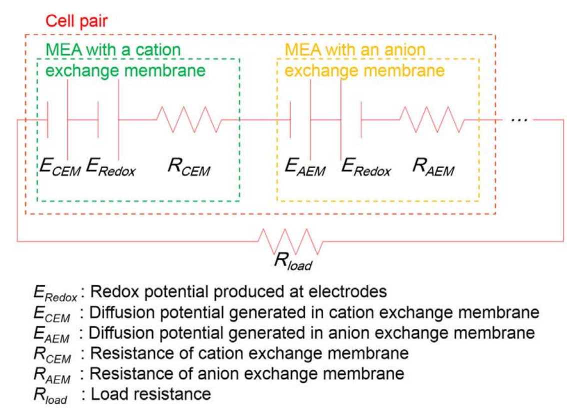
Fig. 1. Conventional reverse electrodialysis system.



(a) Schematic diagram



(b) Membrane electrode assembly with a cation exchange membrane



(c) Equivalent circuit

Fig. 2. Reverse electrodialysis system with membrane electrode assemblies.

low total resistance of their stack, they achieved a power density of 2.4 W m^{-2}, which is the best experimental value obtained with concentrations of sea water and river water so far.

A membrane electrode assembly (MEA) is a membrane sandwiched between two porous electrodes and is widely used in polymer electrolyte membrane fuel cells to minimize the internal electric resistance and to give the maximum possible contact between the electrode, the electrolyte, and the gas [18]. This MEA can be applied to energy harvesting from salinity gradient by reverse electrodialysis, as shown in Fig. 2(a) and (b). As shown in Fig. 2(b), in the MEA with a cation exchange membrane, cations in the brine solution selectively diffuse into the dilute solution through the cation exchange membrane, while anions are extracted by the anode and are released by the cathode electrochemically. As a result, salinity gradient energy is converted to electrical energy and can be harvested continuously. The equivalent circuit of the reverse electrodialysis system with the ideal MEAs is presented in Fig. 2(c). The electric resistance of the ideal MEA includes the resistance of the ion exchange membrane only and does not contain the resistances of the compartments because electrical current does not need to flow across the compartments. Therefore, the electrical resistance of the MEA is expected to be smaller compared to that of a conventional reverse electrodialysis cell. As a result, it is expected that power generation can be enhanced using the MEA. However, the degree of improvement in the performance of the MEA and the conditions under which this improvement is achieved are unclear. To the best of our knowledge, that is because there has been no previous study focused on power generation by reverse electrodialysis from membrane electrode assemblies located between brine and dilute solutions having various differences in concentration.

In this work, we investigated the potential of the application of a MEA to reverse electrodialysis. For this, the membrane electrode assembly, which consists of a cation exchange membrane and two porous silver/silver chloride electrodes, was developed. Power generation was measured from the MEA placed between two sodium chloride solutions with various combinations of concentrations. It will be shown that the highest power generation density achieved was 4.1 W m^{-2}, which is greater than those reported in previous studies so far.