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Modeling of power generation from the mixing of simulated saline and freshwater with a reverse electrodialysis system: The effect of monovalent and multivalent ions

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HIGHLIGHTS

- A RED model was developed with considerations of mono- and multivalent salt ions.
- We quantified the level of power output by applying natural salinity conditions.
- Higher power density was predicted with higher flow rates in saline water compartment.
- Higher power density was predicted with shorter intermembrane distances in fresh water compartment.

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ABSTRACT

A reverse electrodialysis (RED) system utilizes the transport of cations and anions from controlled mixing of saline water (e.g., seawater) and freshwater (e.g., river water) through selective ion exchange membranes for power generation. Sodium chloride alone has been widely used to create power via salinity gradients in lab-scale RED systems. In an effort to simulate realistic salinity conditions in the natural water environment, in this study a new RED model was developed to quantify the power generation with coexisting monovalent and multivalent salt ions. The effects of different flow rate ratios (saline water flow, $\O_S$, over freshwater flow, $\O_F$) and intermembrane distance ratios on power density (amount of power per unit membrane area) were investigated. Our results indicated that magnesium sulfate, sodium sulfate, and magnesium chloride in the feed solutions of the RED system led to a 9–20% lower power density than when sodium chloride was the single ion source, largely because of the higher internal stack resistance of the multivalent ions. Higher power densities could be achieved with higher flow rates in the saline water compartment and shorter intermembrane distances in the freshwater compartment. For example, the power density increased by approximately 11% when the flow rate ratio was 5 compared with 1; similarly, an intermembrane distance ratio of 8 yielded an approximately 85% increase in power density compared with a ratio of 1. The goal of the present work is to advance our understanding of RED systems working in realistic salinity environments.

1. Introduction

Development of clean and sustainable energy to reduce dependency on limited fossil fuels has long been a national strategy in the United States. Several well-known energy conversion technologies have gained attention, including wind power [1,2], solar power [2,3], biofuels [4], hydropower [5], and geothermal power [6]. However, these technologies have not yet sufficiently lessened our reliance on unsustainable or non-renewable energy resources such as fossil fuels. Recently, salinity gradient power (SGP) has received much attention as a potential sustainable energy source. SGP is the energy that is harvested from reversible mixing of two water streams with different salt concentrations (e.g., saline water and freshwater). This mixing leads to a change in Gibbs free energy that can be converted to electricity via direct ion transport within selective membranes [7]. The worldwide availability of SGP makes this a huge energy resource with an estimated potential power of 2.4–2.6 TW [8,9] when total discharge of all rivers in the world is taken into account.

Of the existing techniques for harvesting SGP, pressure-retarded osmosis (PRO) and reverse electrodialysis (RED) are the most frequently studied membrane-based technologies [10–15]. PRO allows only water to contact the membranes, which creates a pressure difference that can be converted into electrical energy [12]. RED utilizes the transport of cations and anions present in

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Nomenclature

R	gas constant ($J\ mol^{-1}\ K^{-1}$)
T	temperature (K)
Fd	Faraday number ($C\ mol^{-1}$)
C_S	saline water concentration (M)
C_F	freshwater concentration (M)
z	valence of an ion
a	effective hydrated ion size (pm)
f	obstruction factor
R_{cem}	CEM area resistance ($ohm\ m^2$)
R_{aem}	AEM area resistance ($ohm\ m^2$)
D	diffusion coefficient of an ion ($m^2\ s^{-1}$)
D_{H_2O}	diffusion coefficient of water ($m^2\ s^{-1}$)
b	width of a cell (m)
L	length of a cell (m)
V_{H_2O}	molar volume of water ($m^3\ mol^{-1}$)

Greek symbols

α_{cem}	permselectivity of CEM
α_{aem}	permselectivity of AEM
μ	ionic strength of the solution ($mol\ L^{-1}$)
γ	activity coefficient
δ_S, δ_F	saline water and freshwater compartment thickness (μm)
$\Lambda_{m,S}$	molar conductivity of salt in saline water ($m^2\ ohm^{-1}$ - mol^{-1})
$\Lambda_{m,F}$	molar conductivity of salt in freshwater ($m^2\ ohm^{-1}$ - mol^{-1})
$\emptyset_S$, $\emptyset_F$	flow rates of saline water and freshwater ($m^3\ s^{-1}$)
δ_m	membrane thickness (μm)

Superscripts

AB	monovalent salt compound
CD	divalent salt compound

Subscripts

S	saline water
F	fresh water
ave	average
int	internal
ext	external

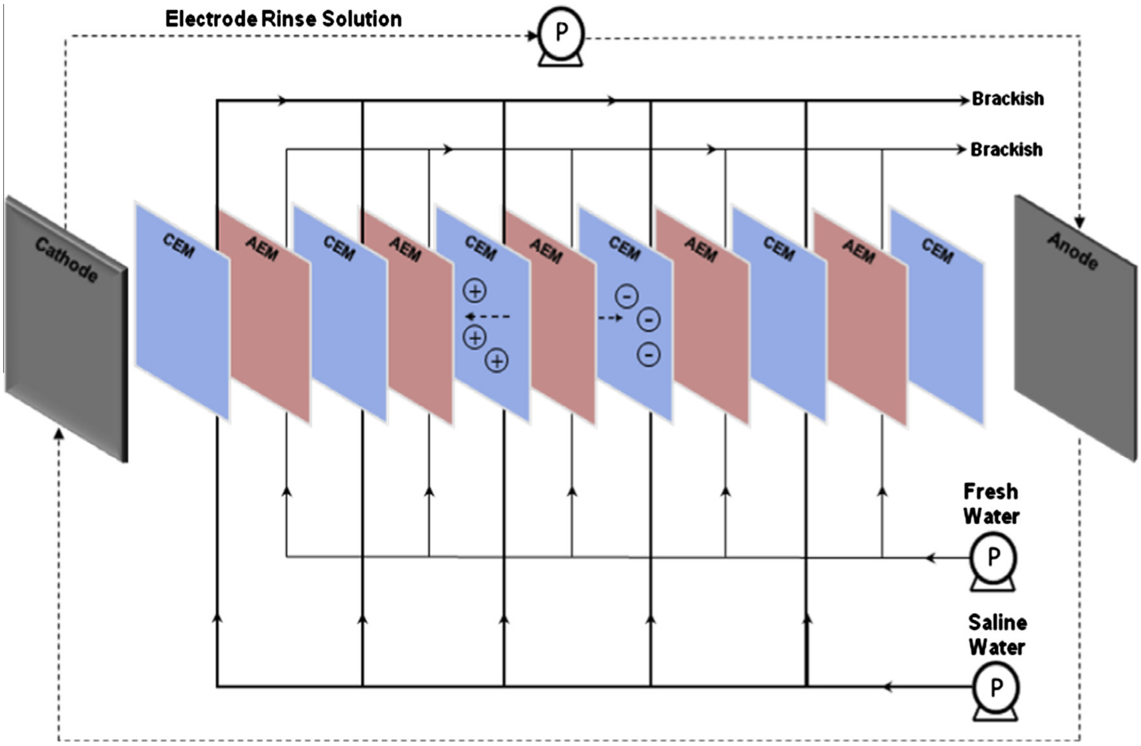

Fig. 1. Simplified schematic view of an RED stack representing the fluid transport through the ion exchange membranes (i.e., CEM and AEM). The solid line illustrates the flow of saline water and freshwater and the dashed line the flow of the electrode rinse solution.

the water through selective ion exchange membranes to generate electricity. Post et al. [10] and other studies [16,17] concluded that RED is more appropriate to seawater and river water salinity conditions, whereas PRO works better with more concentrated brines. Although its superiority is still controversial, RED is often considered to be more favorable for power generation owing to its greater energy efficiency and reduced sensitivity to membrane fouling compared with PRO [10,12].

A typical RED stack consists of alternating anion exchange membranes (AEMs) and cation exchange membranes (CEMs), as shown in Fig. 1. Spacers separate and position these membranes to form thin compartments. When the saline water and freshwater streams run through their respective compartments in contact with the membranes, the salinity difference between the two adjacent compartments drives cations toward the cathode by permeating the CEMs, whereas anions move in the opposite direction