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Simulation of enhanced power generation by reverse electrodialysis stack module in serial configuration

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HIGHLIGHTS

- Simulations of reverse electrodialysis (RED) stack module in serial configuration
- Orthogonal collocation on finite element solution to convection–diffusion problem
- Unique implication of Legendre polynomial and Gaussian quadrature integration
- Performance evaluations and validity of the module from power and energy densities
- Adverse ion flux can occur with condition of extremely low Peclet number.

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ABSTRACT

By extending the theoretical model previously formulated for the single unit problem, we fully analyze the performance of the reverse electrodialysis stack module aiming for electric power generation. In our prototype, each single unit is assembled in serial, where the mixing is allowed in connecting channels to exclude the ionic polarization. The numerical algorithm accompanying the orthogonal collocation on finite element method is applied with Legendre polynomial and Gaussian quadrature integrations to predict the ion concentration profile in each compartment, power, energy, and corresponding current densities. As the number of units increases from 1 to 8, the maximum power and the maximum current densities decrease from 9 to 1 mW/m^2 and from 3.6 to 1.3 A/m^2, respectively, but the maximum energy density increases from 1.5 to 4 mW h/m^3. Pursuing the justification of the validity of our RED stack module, we determine the unique compartment thickness that makes each density maximum for the specified number of units. Power and current densities increase with increasing characteristic fluid velocity, while the energy density maintains constant (ca. 0.36 mWh/m^3) prior to monotonic decreasing at $Pe > 70$.

1. Introduction

Reverse electrodialysis (RED), or sometimes called electrodialysis reversal, is one of the reverse desalination processes, and recently noticed that electrical energy can be produced through the salinity gradients [1–10]. This principle can be also applied in reactivation of filtration membranes by removing fouling deposits [11]. The initial attempt to materialize the thermodynamic concept can go back to 1950s [12], and the success has been given consistent spotlights due to its potential to be a good alternative and sustainable energy source. Nowadays, the advancement of the RED process results in the hybrid system with the seawater desalination units [13], the pressure retarded osmosis [14], and the microbial power cell [15].

There are many efforts to maximize the performance and efficiency of the energy harvesting in the RED by avoiding power loss [5] or by expanding module dimension [6,7]. It should be pointed out that power density is a key performance to evaluate the RED as an established process. Therefore, further studies are required to enhance the power density, *inter alia*, by designing more innovative stack system [9,10]. For enhancing the power generation, the effect of time-periodic pulsatile counter-current flow has been investigated by simulating the single RED unit [16]. Due to the polarization of the ions near the ion-exchange membrane surface, the voltage drop was observed before the flow gets into the steady state, which is consistent with the experimental results [2].

In this study, we develop the numerical framework capable of evaluating of performance for the RED stack module in serial configuration and with mixing between two consecutive compartments, which were not elaborated in previous studies. The module dimension is mainly

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decided by the number of units and the compartment thickness. The ion transport within compartment is analyzed by using the convection–diffusion model with the slit laminar counter-current flow. The orthogonal collocation on finite element (OCFE) method applied here to generate the mesh grid is known to be superior to the finite difference method in the aspects of the convergence, the numerical stability, and the computational load [17]. Special benefit lies on the settlement of the stability problem that is stemmed from the discontinuity of the solution. As the process parameters, we change the values of the number of units, the compartment thicknesses, and the characteristic fluid velocities to examine the behaviors of the power density, the energy density, and the current density. Although the adoption of the serial connection and the mixing should be a challenging issue, its full practical consideration is a beyond the scope of this study.

2. Theoretical considerations

2.1. The RED stack module in serial configuration

The stack sequence of the conventional RED module can be easily found in the literatures [5–8]. The prototype of the module studied here consists of multiple sheets of cation-exchange membranes (CEMs) and anion-exchange membranes (AEMs) with the length L and the width W, denoted in Fig. 1. They are placed in the alternating order, and both ends of the module are equipped with the anode and the cathode plates. In Fig. 2, the compartment thickness δ_C is much less than the length and the width, indicating a configuration of the slit channel.

As shown in Fig. 1, one unit is designed to comprise a pair of compartments: one is the saline compartment and the other is the fresh compartment. The color arrows denote connecting channels between the compartments, where mixing is accomplished for the reduction of the ionic polarization. The saline water is supplied to the bottom of the saline compartment in the unit 1, and leaves it through the top, losing sodium cations and chlorine anions to the adjacent fresh compartments. Fresh water can be supplied to the module in two ways: being introduced to the unit 1 (as illustrated in Fig. 1) and to the last unit (not shown here). In the former case, the inlet is placed at the top of the compartment to form a counter-current flow. In the latter case, however, the position of the fresh inlet depends on the number of the units N, i.e., if N is even, the inlet is at the bottom; otherwise, it is at the top. This study has mainly focused on the computations for the case where the fresh water is supplied to the unit 1. The other case is addressed briefly for comparison.

2.2. Transport analysis in RED unit

The saline and fresh streams switch their directions (upward $\longleftrightarrow$ downward) in the next compartments. To avoid any confusion, we set the Cartesian coordinates such that the origin is placed at the bottom in the middle of the unit, the x-axis is toward the fresh compartment and the z-axis toward the top (see Fig. 2), regardless of the flow directions. Consequently, the y-axis goes down the paper. According to a reasonable assumption of neglecting membrane thickness δ_M [16], the computational domain is defined as $-\delta_C < x < \delta_C$ and $0 < z < L$.

Since the diffusion of anion (e.g., Cl^-) takes place around 1.5 times faster than that of cation (e.g., Na^+) [18], the transport of cation is the rate-controlling mechanism and can consistently represent the entire species balance. Thus, the "ion" hereafter in this paper refers to the

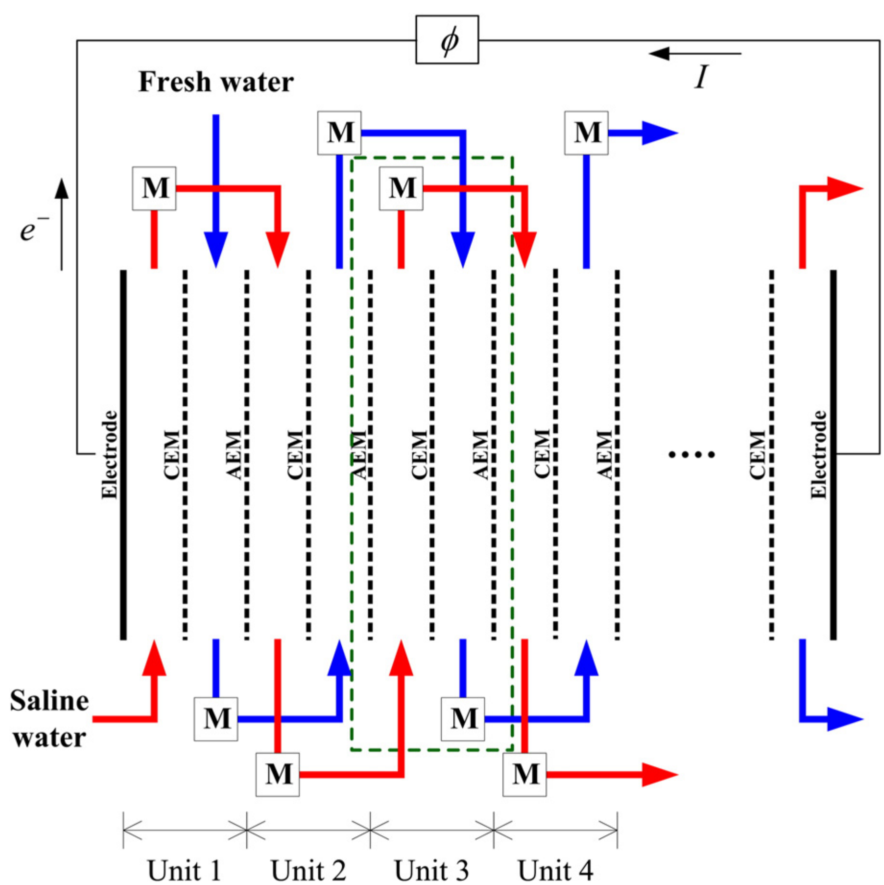

Fig. 1. Schematic diagram of the serial RED stack module consisting of saline and fresh compartments, ion exchange membranes (AEMs and CEMs), connection channels, and voltage output. The M in the square indicates mixing.