Energy 158 (2018) 427–436

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance analysis of reverse electrodialysis stacks: Channel geometry and flow rate optimization

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ARTICLE INFO

Article history:
Received 19 September 2017
Received in revised form
1 June 2018
Accepted 10 June 2018
Available online 11 June 2018

Keywords:
Reverse electrodialysis
Optimization
Net power
Energy efficiency

ABSTRACT

In this paper, the optimal channel geometry and flow rate of the concentrated and diluted solutions under the maximum net power output for the reverse electrodialysis (RED) stacks at a confined size are systematically investigated. A model considering the change in volume flow rate along the flow direction is employed to illustrate the process of the RED stack. For systematisms, under the maximum net power output, we first consider the optimal channel thicknesses at a given identical inlet flow rate and then the optimal channel thicknesses and flow rates. The profiles of flow rate, concentration, power density, and hydrodynamic loss along the flow direction are discussed. The net power output and energy efficiency for different membranes under the above two optimization situations are analyzed and compared. The results reveal that the optimal channel thickness of the high-concentration (HC) compartment is slightly larger than that of the low-concentration (LC) compartment for a given identical inlet flow rate. When both channel thickness and flow rate are optimized, the optimal channel thicknesses and volume flow rates of the HC compartment are, respectively, less than those of the LC compartment and the net power output and energy efficiency are significantly improved.

1. Introduction

Recently, to alleviate the consumption of traditional fossil fuels, new and renewable resources have been explored and new utilization technologies have been developed [1,2]. Among them, salinity gradient power generation technologies such as pressure retarded osmosis (PRO) [3–5] and reverse electrodialysis (RED) [6–9] are the most appealing ones, and have been extensively investigated as they extract energy from solutions with different concentrations, which can be obtained from the sea water and river water that exit widely with vast amount throughout the world. Compared to the PRO system with a hydro-turbine, the RED system, which directly converts the Gibbs free energy of mixing into electricity through an ion-selective exchange membrane (IEM), contains no moving components, making it less demanding from operation and maintenance viewpoints.

Even though the RED system was first proposed in 1954 [10], it did not attract enough attention until the 21st century owing to the limited performance of IEMs. Now, IEMs with high performance and low cost are reliable, rendering it possible to install commercial electrical production plants. The first RED pilot plant was installed in southern Italy to extract energy from saline waters and concentrated brines with a power of up to around 40 W [11].

Besides experimental investigation of the performance of RED systems, numerical modeling and analyses also play important roles. The key points lie in describing the ion transfer process through IEMs. Many models have been developed based on the Nernst–Planck equation and mass and species conservation. Tedesco et al. [12] presented a multiscale mathematical model based on a mass balance and constitutive equation. Veerman et al. [13] proposed a 1D model to describe the RED process without considering changes in the volume flow rate along the flow direction. However, as the 1D model could not reflect the concentration polarization on the membrane–solution interface, which degraded the performance of the RED system, models with higher dimensions were further developed by solving the strongly coupled Nernst–Planck equation and the Navier–Stokes equations [14]. Long et al. [15] investigated the RED process in a bilayer nanochannel based on the Poisson–Nernst–Planck and Navier–Stokes equations. In another study, Long et al. [16] investigated the impacts of temperature gradient on ion transportation and power generation performance, and deduced a theoretical description to

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https://doi.org/10.1016/j.energy.2018.06.067
0360-5442/

illustrate the energy conversion efficiency. Tedesco et al. [17] developed a simple 2D model by using the Nernst–Planck equation not only in the flow channels but also in the membranes.

Parameters impacting the performance of the RED system mainly include channel geometry and flow rate [18], membrane properties, fouling [19], multivalent ions [20], and electrodes [21]. Zhu et al. [18] reduced the pumping energy by using different flow rates of high-concentration (HC) and low-concentration (LC) solutions in RED cells. Moya et al. [22] studied an RED stack with a bilayer membrane based on the Nernst–Planck–Donnan equations with different ion diffusive coefficients. In addition, the thickness of the diffusion boundary layer was systematically investigated, which was further researched by Zhang et al. [23] through electrochemical impedance spectroscopy. Cassady et al. [24] investigated the effects of specific ions on the permselectivity of sulfonated poly-cation exchange membranes, and found that co-ion polarizability was the primary factor for co-ion effects on permselectivity. Fontananova et al. [25] demonstrated that the ionic resistance and permselectivity of ion exchange membranes were not constant, and strongly depended on the concentration and electrolyte solution types. Furthermore, the study on the RED process in nanopores has also attracted attention. Tseng et al. [26] conducted a theoretical analysis on the influences of temperature and nanopore size on nanofluidic reverse electrodialysis, and found that a larger temperature increases the power output but does not obviously impact the energy conversion efficiency.

Present literature on improving the performance of the RED system mainly focuses on effects of membrane properties such as pore size, permselectivity, resistance, and diffusion coefficients on the performance of the RED system. The operation condition (volume flow rate) and channel geometry also play important roles in determining the performance of RED stacks, which have been studied separately to reduce the hydrodynamic loss with fixed cell numbers. However, the coordination of flow rate and channel size has rarely been researched. In addition, in previous studies on the performance optimization of the RED system, the cell number was fixed, which led to different sizes (width, length, and height) of the RED stack. No study has yet reported the optimization under the given size of the RED stack. Here, we employ the model proposed in our previous paper [27], which considered the changes in volume flow rates along the flow direction, to investigate the optimal channel thicknesses and volume flow rates of the concentrated and diluted solutions under the maximum net power output. As for the nonlinearity of the system, a genetic algorithm (GA) is adopted to obtain the optimal parameters under different conditions. For systematisms, under the maximum net power output, we first investigate the optimal channel thicknesses for the given identical inlet flow rate and then the optimal channel thicknesses and flow rates. The profiles of flow rate, concentration, power density, and hydrodynamic loss along the flow direction are systematically discussed. The net power output and energy efficiency for different membranes under the above two optimization cases are analyzed and compared. Finally, some conclusions are drawn.

2. Model development

In the RED process, concentration polarization occurs, which reduces the effective concentration difference across the membrane. For simplicity, the following assumptions are made to model the RED process: (1) The concentration polarization on both the HC side and LC side is ignored. (2) The ions carried by the trans-membrane water flux are not included. (3) The diffusion coefficients for the water and ions are constant. (4) The membrane resistance and membrane permselectivity are treated as constants under different operating conditions. The modeling for the mass transfer characteristics in the RED process is presented in the Appendix.

2.1. Performance specifications for the RED stack

Fig. 1 shows a schematic of the RED stack, which comprises repeating HC and LC compartments separated by IEMs. For actual application, conditioned on the feasible and modularized installation and maintenance, the stacks are assumed to be equipped in a constrained space with a fixed cross-sectional area $(W \times L)$ and height (H), where W and L are the width and length of the RED stacks, respectively. The cell number (N_{cell}) of the stack is calculated by

$$N_{cell} = \left\lfloor \frac{H - \delta_m}{\delta_H + \delta_L + 2\delta_m} \right\rfloor \tag{1}$$

where $\lfloor . \rfloor$ is the rounding down operation, and δ_m, δ_H, and δ_L are the membrane thickness, HC compartment thickness, and LC compartment thickness, respectively.

The RED voltage is calculated as [28]

$$E_{cell}(x) = \alpha_{CEM}\frac{RT}{F}\ln\frac{\gamma_H^{Na}(x)C_H(x)}{\gamma_L^{Na}(x)C_L(x)} + \alpha_{AEM}\frac{RT}{F}\ln\frac{\gamma_H^{Cl}(x)C_H(x)}{\gamma_L^{Cl}(x)C_L(x)} \tag{2}$$

where α is the permselectivity of the membrane and γ is the activity coefficient [29]. The activity coefficient is a factor used in thermodynamics to account for deviations from the ideal behavior in a mixture of chemical substances, which depends on the mole fraction of the substance in the mixture. The permselectivity is mainly determined by intermolecular forces, which mediate the interaction between molecules. The resistances on the RED system include the resistance due to conductivity in the HC and LC solutions, the resistance in the ion exchange membranes, and the resistance of the electrode. For the repeated RED pairs, the space-dependent area-specific resistance $R_{a,cell}(x)$ is expressed as [28,29]

$$R_{a,cell}(x) = N_{cell}\left(\frac{f}{\Lambda_m}\left(\frac{\delta_H}{C_H(x)} + \frac{\delta_L}{C_L(x)}\right) + R_{AEM} + R_{CEM}\right) + R_{el} \tag{3}$$

where Λ_m is the molar conductivity of the electrolyte (NaCl) solution, δ_H and δ_L are the thicknesses of the HC and LC solution compartments, f is a measure for the increase in electrical resistance due to the negative effects of the spacer, R_{AEM} and R_{CEM} are

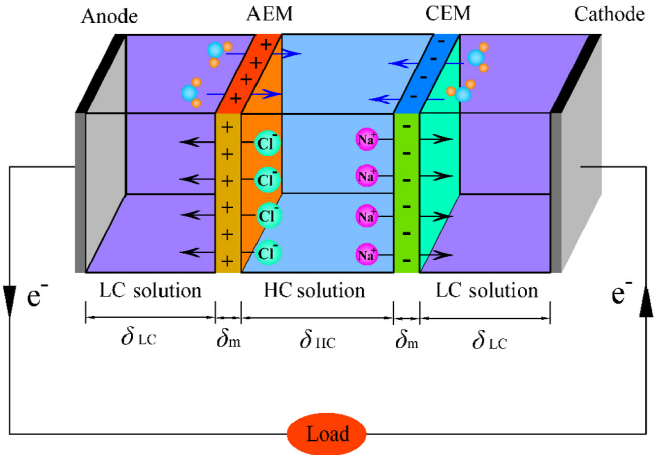

Fig. 1. Schematic diagram of the RED stack.