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Integrating reverse electrodialysis with constant current operating capacitive deionization

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ABSTRACT

The presence of a salinity gradient between saline water streams may result in the production of electricity via either reverse electrodialysis (RED) or forward osmosis. While the former system generates electricity because of the ionic current, the latter process produces electricity due to the osmotic pressure. In this study, RED is coupled with capacitive deionization (CDI) so that highly pure water, fresh water and electricity could be generated simultaneously. A CDI cell is operated at constant current, and it generated ultrapure water and two streams (a lower salinity stream of approximately 17.4 mol NaCl per m^3 and a high salinity stream of approximately 512.8 mol NaCl per m^3) to be fed to the RED stack from a 15,000 ppm CDI feed concentration. The performed simulation reveals that, the total power generated from the RED using infinitely divided electrodes is 0.57 W/m^2 electrode area. The use of RED in a CDI plant introduces a new approach to minimize CDI brine concentration, which would otherwise have a negative impact on the environment if it were disposed directly without prior treatment.

1. Introduction

Pure water and energy are some of the key issues in the world today that are being tackled. Only around 0.01% of the available water sources can directly produce clean water (Fujioka et al., 2013). Alternative methods such as membrane technologies, thermal processes and electrochemical-based desalination technologies are consequently employed to produce fresh water from seawater, industrial wastewater and underground water by desalting it to a desired quality level (Al-Karaghouli and Kazmerski, 2013; Welgemoed and Schutte, 2005; Mtombeni et al., 2013; Khayet and Matsuura, 2011).

Capacitive deionization (CDI) is an electrochemical-based desalination process in which the system is composed of a pair of porous electrodes and a DC power supply (Fig. 1). The removal of ions from the saline water stream happens when the ionic solution passes between the charged pair of porous electrodes (Farmer et al., 1996; Jande et al., 2013). The complete operation of the CDI cell is achieved after undergoing a full cycle composed of charging and discharging time. The definition of anode and cathode in CDI technology is defined during charging; which is different from conventional electrochemical cells (batteries) (Porada et al., 2013). The brine from a CDI cell has to be treated to minimize the negative effects on the environment upon direct disposal, such as in a reverse osmosis (RO) system in which different approaches such as reverse electroadialysis (RED) are used to treat RO concentrate (Li et al., 2013a; Subramani and Jacangelo, 2014). The use of CDI desalination technology may rise in the future due to its advantage of utilizing low energy compared to conventional technologies such as RO and distillation methods (Anderson et al., 2010).

Similarly, alternative sustainable energy sources are being sought to reduce the use of environmentally unfriendly energy sources such as fossil fuels and nuclear power plants. Research is underway to utilize the CO_2 gas generated in post-combustion to produce energy by alternatively pumping it into a membrane-enhanced capacitive cell (Hamelers et al., 2013; Paz-Garcia et al., 2014). Also, power can be generated due to mixing between high salinity water and lower salinity water in ways like pressure retarded osmosis (Yip and Elimelech, 2012; Achilli and Childress, 2010; Loeb and Norman, 1975) and RED (Post et al., 2008; Vermaas et al., 2013; Veerman et al., 2010).

In the RED process, two different salinity water streams are used in producing energy: a high salinity stream and a low salinity stream (Fig. 2). The cation exchange membrane (CEM) and anion exchange membrane (AEM) are selective to cations and anions, respectively (Brauns, 2009; Pattle, 1954; Veerman et al., 2011;

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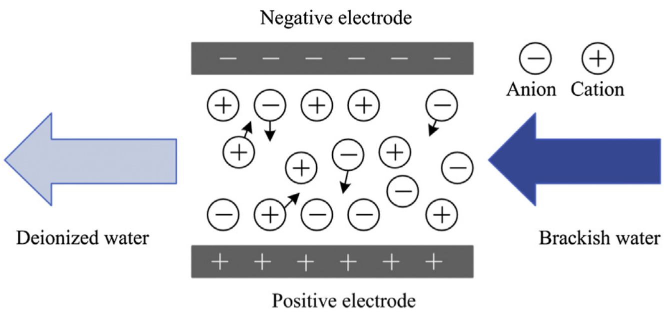

Fig. 1. Half cycle of the CDI cell.

Lacey, 1980). The presence of salinity gradient, i.e., low sanity water stream on one side of the selective membrane and high salinity water stream on the other side, results in the electrical potential development. This voltage is called Donnan potential; and it can be used to power any external electrical device (Vermaas et al., 2013). The salinity streams can flow concurrently or in a counter-flow and/or in cross-flow (Vermaas et al., 2013; Veerman et al., 2011). Fig. 2 shows a concurrent flow; for the details of other types of flows please refer to (Vermaas et al., 2013).

In this study, the use of a hybrid CDI-RED system is investigated to produce desalinated water and energy simultaneously. A CDI cell can generate a high salinity stream during discharging (regeneration period) and purified water during charging (ions adsorption period). The brine concentration from the CDI cell can be minimized by inserting a RED cell next to it. Thus, desalinated water and power can possibly be generated at the same time using the integrated CDI-RED system. In the present study, the constant current operated CDI (CCOCD) cell is used due to its advantage of having a longer steady state during charging and discharging compared to a constant voltage operated CDI (CVOCD) cell (Farmer et al., 1996; Zhao et al., 2012; Hou et al., 2013).

2. Materials and methods

2.1. Capacitive deionization

Jande and Kim (2013a) proposed a model for a CCOCD cell. The steady state concentration during charging is given by Eq. (1), which represents the lowest effluent concentration during CDI ions adsorption.

$$C_{\mathrm{lowest}} = C_f - \frac{\lambda I}{zF\phi} \tag{1}$$

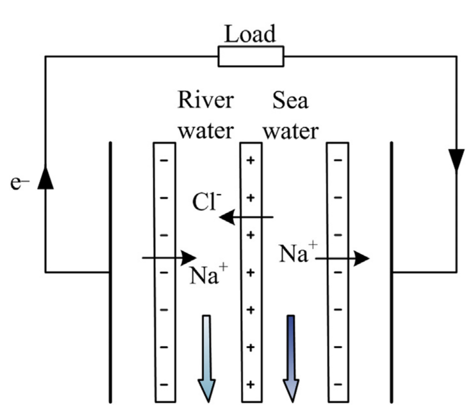

Fig. 2. Schematic diagram of a co-flow RED system.

where C_f is the feed concentration in moles per unit volume (256.4 mol/m^3 (15,000 ppm) in this study), λ is the charge efficiency, it can be taken to be unity when either good charge barrier membranes are used (Andelman and Walker, 2004; Andelman, 2011; Lee et al., 2006) or when the electrodes are electrostatically redesigned (Andelman, 2012), I is the applied constant current in ampere, z is the average ionic valence, F is Faraday's constant (96,540 C/mol) and ϕ is the flow rate of the fed saline water in unit volume per unit time. In order to have the lowest concentration of the steady state, the applied current is chosen in such a way that the effluent concentration is close to zero.

For the CDI cell to be charged to a target voltage, V_t, the required time is

$$t_a = \frac{CV_t}{I} \tag{2}$$

where C is the capacitance of the CDI cell in farad, and is taken to be 8000 F in the present study. The emergence of nanotechnology has led to the discovery of higher capacitive electrode materials (Li et al., 2013b; Yang et al., 2011; Barakat et al., 2014). During this charging time, the amount of energy in joules is stored in the CDI cell, which is the amount of power used to desalt saline water during ions adsorption, which is given by

$$E = \frac{1}{2} nCV_t^2 \tag{3}$$

where n is the number of porous CDI electrode pairs used to form a cell.

2.2. Reverse electrodialysis

In this study, the model for the infinite segmented electrode by Veerman et al. (2011) is used to compute the possible power generated by the RED cell, considering the RED system given in Fig. 3, where L and b is its length and width, respectively. The flow rate of the low salinity stream (LSS) and of the high salinity stream (HSS) are ϕ_H and ϕ_L, respectively. The RED compartments for the

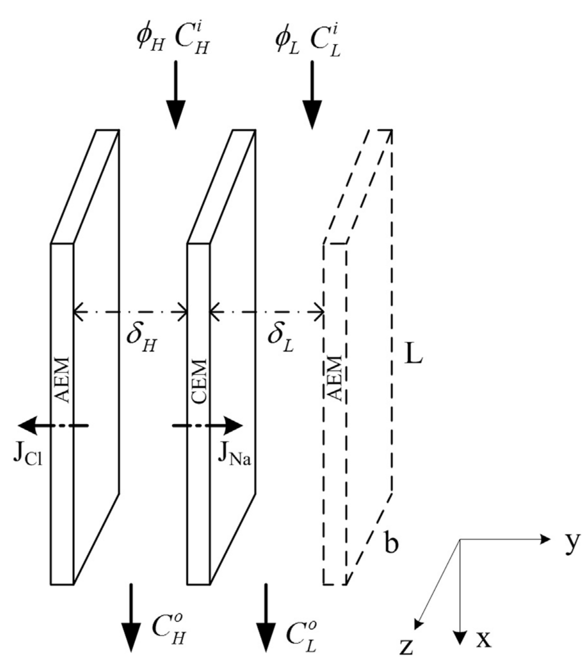

Fig. 3. A cell in a RED stack (Veerman et al., 2011).