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Optimization of resin wafer electrodeionization for brackish water desalination

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ABSTRACT

Resin wafer electrodeionization is an energy-efficient technology for brackish water desalination without the use of harmful chemicals. In this study, the performance of resin wafer electrodeionization under different applied voltages and feed flow rates was measured for a feed salt concentration of 3.0 g L^{-1}. The results indicated that a salt removal efficiency of 94% could be achieved. In addition, the removal kinetics of NaCl from the brackish water was studied via a first-order kinetic model. The maximum kinetic rate constant was found to be 0.091 min^{-1} at a cell voltage of 2.53 V. The kinetic rate constants varied with the applied voltage and feed flow rate to the 1.52 and 0.33 power respectively. Furthermore, the productivity and energy consumption were balanced by using the response surface methodology. The optimized operating conditions should be set at an applied voltage of 2.28 V per cell pair with a feed flow rate of 810 mL min^{-1}, corresponding to a productivity of 55.5 L h^{-1} m^{-2} at an energy consumption of 0.66 kWh m^{-3}. Compared with other water desalination processes, resin wafer electrodeionization can offer relatively a higher energy-efficient performance for the brackish water desalination.

1. Introduction

With the rapid development of industrialization and urbanization, the demands of water resource and energy become more and more urgent for keeping up with the pace of industrialization and urbanization. In northern and northwestern China, the traditional water sources such as rivers or lakes are very few due to unfavorable topographical, climatic, or pollution factors [1]. The proposed resolution to the water shortage in these areas is water reusing as well as energy constraints. Approximately 97.4% of the available water on the earth is salty. Salt water includes sea water (with a salinity of 10–60 g L^{-1}) and brackish water (with a salinity of 1–10 g L^{-1}) [2,3]. The desalination of seawater or brackish water, such as plant (process) water, could be a resource-efficient alternative to solve water shortage problem.

The existing technologies, such as reverse osmosis (RO) and electrodialysis (ED), have been well developed and deployed for seawater desalination, with the advantages of low operation cost and modular design [4]. However, the energy efficiency of the above processes for brackish water desalination cannot approach their optimization since the low salt concentration (i.e., low conductivity) of brackish water. A high cell voltage is typically required to increase the salt removal efficiency; however, it would also lead to an increase of energy consumption and operating cost [5]. As shown in previous study, a 10-stage ED system was used for the desalination process, each of the ten stages was designed such that the dilute conductivity was halved in each successive stage. It is found that the cost per unit of salt removal increases significantly at low salt concentration (e.g. in high number stage), indicating ED is unfeasible for the desalination of low salt concentration water [6]. Another research also showed that current efficiency decreased as the salt concentration of the influent decreased. When the salt concentrations varied from 50 g L^{-1} to 10 g L^{-1}, the current efficiencies decreased from 75% to 27% [7]. In addition, ED has another problem known as concentration polarization that builds up a high cumulative resistance and leads to a decrease in efficiency.

To facilitate the ion transport rate in ED, ion exchange resins have been incorporated into the dilute compartment of ED. Thus, another technology called electrodeionization (EDI), which combines ED with ion exchange column (IEC) has been developed [8]. The ion exchange resins increase the conductivity to enable ions to be transferred through the ion exchange membranes in water with a low conductivity. EDI is also successful in counteracting concentration polarization. In EDI, the ion exchange resin beads are continuously regenerated by protons (H^+)

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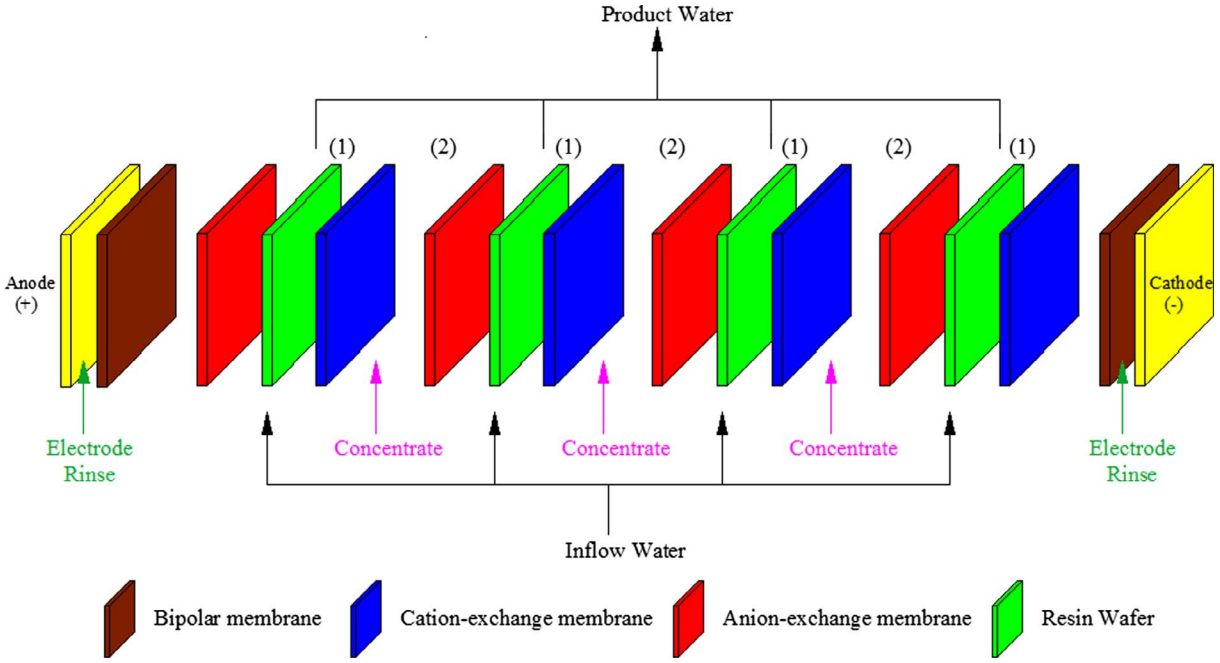

Fig. 1. Schematic diagram of resin wafer electrodeionization (RW-EDI) device: (1) dilute compartment with resin wafer and (2) concentrate compartment without resin wafer.

and hydroxyl ions (OH^-) via a water splitting reaction. Hence, EDI requires no regenerative agents or other chemicals, it is considered as a green process [9]. EDI combines the benefits of IEC (for capturing impurity ions) and ED (for ion removal without chemical regeneration) while avoiding the disadvantages of each technology [10]. The EDI process includes three simultaneous stages: (1) ion exchange between resin beads and impurity ions; (2) transportation of ions via an applied electric field; (3) regeneration of resin beads by electricity.

The traditional EDI technology has two limitations due to the use of loose resin in EDI stack: (i) the non-uniform flow distribution in the stack, causing an unstable and decreased removal efficiency; and (ii) the leakage of ions between the compartments, significantly affecting the removal efficiency and cost of the desalination process. As a result, an integrated approach to overcoming these challenges has been proposed by immobilizing the loose resin beads into a wafer form, known as resin wafer electrodeionization (RW-EDI) [11]. Compared with conventional EDI, RW-EDI can be easily assembled and operated more efficiently. By using different ion exchange membranes and resins, RW-EDI technology can be customized for various types of applications, such as in the removal of acidic impurities from corn stover hydrolysate liquor [12] and lignocellulosic biomass hydrolysate liquor [13], CO_2 capture [10], and purification of organic acid [14].

In this study, the RW-EDI technology was used as an energy-efficient method to desalinate brackish water. The objectives of this study were to (1) evaluate the removal efficiency of RW-EDI under various operating conditions such as feed flow rates and applied voltages; (2) determine the salt removal kinetics by using the first-order model; (3) optimize the operating conditions to achieve a high productivity and a low energy consumption by using the response surface methodology (RSM); and (4) compare the performance of various water desalination processes, in terms of specific energy consumption and production.

2. Materials and methods

2.1. Materials

The RW-EDI experiments were conducted in a modified commercial electrodialysis stack (EUR2B-10) purchased from Ameridia Corp. (Somerset, NJ, USA). Membranes, such as cation-exchange membranes (Neosepta CMX, strong acid cation), anion-exchange membranes (Neosepta AMX, strong basic cation) and bipolar membranes (Neosepta BP, thickness 0.22 mm), were also purchased from Ameridia. Porous resin wafers were fabricated with a mixture of anion-exchange resin beads (Purolite PFA444) and cation-exchange resin beads (Purolite PFC100E). The mixture was heated to ~120 °C and cast in a mold to form a resin wafer with an area of 195 cm^2. Other reagents, such as NaCl (> 99%, J. T. Baker, USA) and Na_2SO_4 (> 99%, Sigma-Aldrich, USA), used in this study were analytical grade.

2.2. Resin wafer electrodeionization (RW-EDI)

A four cell pair configuration RW-EDI device for desalination experiments was used. As shown in Fig. 1, each cell pair contained two different compartments, a dilute compartment with a porous resin wafer and a concentrate compartment, that were separated by cation, anion and bipolar membranes. Bipolar membranes were only used at the end of the stack and a 2.5% Na_2SO_4 solution was used as the electrode rinse solution.

As inflow water flowed throughthe dilute compartment, the Na^+ and Cl^- ions in water were adsorbed by cation-exchange resin beads and anion-exchange resin beads respectively. When a voltage was applied to the dilute compartment, the captured Na^+ and Cl^- ions began to migrate across the resin bed in the direction of cathode and anode, respectively. The ions passed through the ion-exchange membrane were kept in the concentrate compartment by the reverse ion-exchange membrane on the adjacent dilute compartment. Ions kept in the concentrate compartment were swept away by a circular flow (the concentrate loop) to prevent an excessive buildup. At the end of the desalination, the concentrations of Na^+ and Cl^- were low, and H^+ and OH^- generated by water splitting began to regenerate the resin beads. The overall reactions in the RW-EDI process are described as follows:

a. Electrode reactions:

$$2H_2O + 2e^- \leftrightarrow H_2 + 2OH^- \quad \text{Cathodic reaction} \tag{1}$$

$$2H_2O \leftrightarrow O_2 + 4H^+ + 4e^- \quad \text{Anodic reaction} \tag{2}$$

b. Ion-exchange adsorption: