Desalination 443 (2018) 27–43

Contents lists available at ScienceDirect

Desalination

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

A robust model of brackish water electrodialysis desalination with experimental comparison at different size scales

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ARTICLE INFO

Keywords:
Electrodialysis
Brackish groundwater
Energetic model
Desalination model

ABSTRACT

This paper presents a robust analytical model for brackish water desalination using electrodialysis (ED), with prediction of the desalination rate, limiting current density, and total energy use including pumping energy. Several assumptions reduce computation time and accurately model ED system behavior. The predicted desalination rate, limiting current density, and total energy usage agree with measurements across two diverse ED stack designs, differing in total membrane area (0.18 m^2, 37.1 m^2), membrane manufacturers (GE Water, PCA GmbH), and flow channel spacers. The commercial-scale stack was additionally tested with real groundwater, demonstrating that brackish groundwater may be modeled as an equivalent concentration NaCl solution. Sensitivity to the membrane diffusion coefficient, area available for ion transport, level of discretization along the flow channel length, boundary layer and membrane resistances, and water transport are analyzed to guide empirical characterization when higher accuracy is required. No single existing model for pressure drop in the membrane spacers could accurately predict pumping power in both stacks. One model for each stack was found to reasonably approximate pressure drop, however experimental validation of specific spacer designs is recommended. The fully quantitative, parametric description of electrodialysis behavior presented forms a useful tool to design, evaluate, and optimize ED systems.

1. Introduction

This study presents and evaluates a model for electrodialysis (ED) desalination capable of predicting desalination rate, limiting current density, and total energy use including pumping energy. ED is a membrane-based desalination technology used to treat approximately 425,000 m^3 of brackish water (salinity < 3000 mg/L) daily [1]. While this accounts for only 6% of the total brackish water desalination capacity (86% is completed using reverse osmosis) [1], the growing demand for low cost, low energy-consuming, high-recovery brackish water desalination solutions has created a renewed interest in ED [2-7]. In addition, other applications of ED, such as desalination of dyes and removal of copper and nitrates, continue to be investigated [8-10].

There are several approaches to modeling ED systems that span from simple polynomial correlations [11] and analytic derivations [12,13] to computational fluid dynamics (CFD) simulations [14,15]. Simple correlations do not maintain fidelity over a broad range of system configurations while CFD solutions have a high computational cost. There is a need to predict desalination performance and pressure losses across the wide variety of ED systems used in water treatment using models that are less computationally intensive, in order to facilitate parametric design studies.

Several authors separately model the mass transfer [12,16], limiting current density [17-19], and pressure losses throughout the ED membrane stack [20-24]. However, few authors have united all of these aspects into a single model. A combined model is critical to develop a complete understanding of the behavior of an ED system. For example, while increased linear flow velocity (obtained by increased flow rate, thinner channels, or lower spacer void fractions) increases mass transfer rates and raises the limiting current density, it also increases the pressure drop over the stack, thereby increasing total energy consumption. Including these types of coupled interactions improves the accuracy of the model as well as its usefulness as a tool to design and optimize ED systems for performance, cost, and energy consumption.

Of the few models that do consider combined effects [3,4,13,16], all rely on empirically derived parameters that require experimental characterization of a specific ED system prior to use of the model. Here, we provide further experimental validation of their work, and present simplifying approximations that predict, with good accuracy, the performance of stack configurations that deviate from those tested by other

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https://doi.org/10.1016/j.desal.2018.04.018
Received 20 November 2017; Received in revised form 2 April 2018; Accepted 17 April 2018

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In this paper, we present a model of ED to predict desalination rate, limiting current density, and energy consumption. We offer simplifying approximations to make the model easier to implement for simulation and design optimization purposes, and present the sensitivity of the model to those simplifications. We then compare model predictions and the measured performance for two diverse size scales and designs of ED stacks: a PCA GmbH 64 0 02 bench-scale stack (0.18 m^2 total membrane area), and a GE Water & Process Technologies commercial-scale stack (37.1 m^2 total membrane area). In both cases, we find good agreement with model predictions without explicitly deriving empirical parameters or conducting prior system characterization. The two stacks incorporate different membranes, flow channel geometries, and spacer thicknesses and porosity, thus demonstrating the model's flexibility. The commercial-scale stack configuration was tested in a laboratory setting with a pure NaCl feed water solution as the model assumes, as well as in a pilot water treatment plant in Chelluru, India using real groundwater. The model presented will be useful to engineers and designers tasked with evaluating the performance of an existing ED process, or sizing and optimizing new systems.

2. Model description

In the ED process, saline water is circulated through an electrodialysis stack (Fig. 1) which contains a series of alternating anion exchange membranes (AEM) and cation exchange membranes (CEM). When an electric potential difference is applied across the stack, anions are drawn towards the anode, and cations towards the cathode. AEMs only pass anions, while the CEMs only pass cations, therefore generating alternating channels of diluate and concentrate.

This section describes three interdependent models to predict the desalination rate and total energy consumption for the ED process described above. First, we use a circuit analogy to model the rate of ion transfer (in the form of current) as a function of the applied voltage and given diluate and concentrate concentrations, in Section 2.2. Next, Section 2.3 provides a mass transfer model to predict the concentration along the ED stack as a function of current and time. The current and concentration in the channels are interdependent, and therefore solved simultaneously. Lastly, Section 2.7 models the pressure drop over the ED stack as a function of geometric properties and the flow rate in the channels. While this third model can be solved independently, the desalination rate and maximum applied current depend on the flow rate through the system. In order to estimate the flow rate for a given stack-pump combination, or the pressure drop at a desired flow rate, and subsequently understand the resulting energetic and desalination rate repercussions, it is prudent to consider all three models simultaneously.

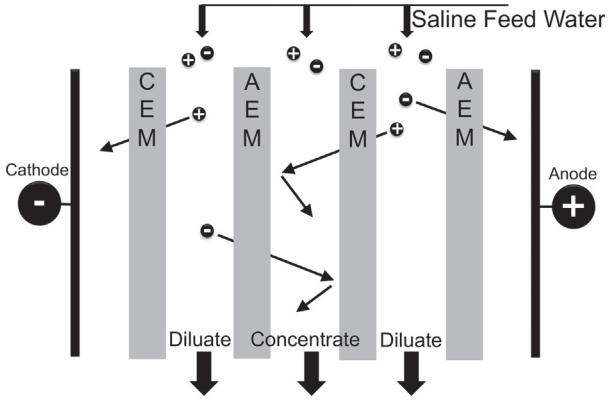

Fig. 1. Electrodialysis (ED) is the process of drawing ions out of a feed solution by applying an electric potential across a series of alternating anion (AEM) and cation (CEM) exchange membranes.

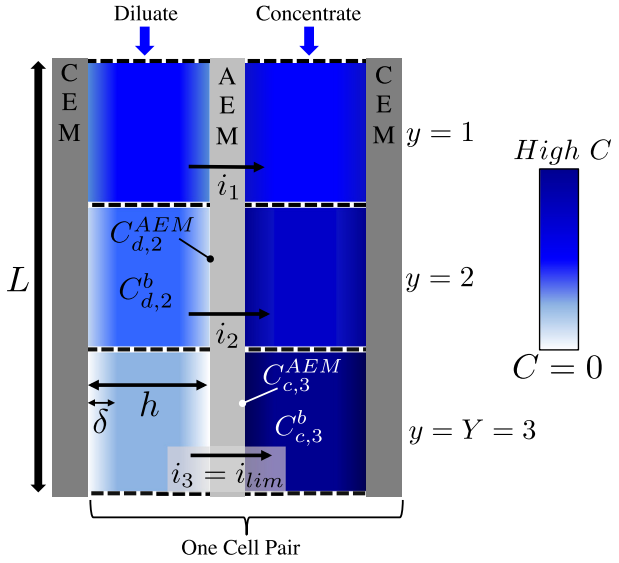

Fig. 2. Description of key dimensions and notation.

2.1. Variables and setup

We begin by considering the geometric and concentration variables for a single cell pair (Fig. 2). Molar concentration is denoted by C, where the superscript denotes the bulk, C^b, the AEM surface, C^{AEM}, or the CEM surface, C^{CEM}. The first subscript defines the concentration as being either in the diluate or concentrate channel (C_d, C_c respectively), and the second subscript denotes the lengthwise segment of the channel, y. The segment of the channel provides discretization for modeling purposes only; ED stacks are not physically segmented in this manner.

C_d decreases in the direction of flow until the final segment, $y = Y$. The opposite is true for C_c. Within any given segment (for example, $y = 2$), the volume is considered small enough such that both the bulk and membrane surface concentrations are assumed to be length-wise constant. When a voltage is applied, a concentration boundary layer of thickness δ extends from the membrane surfaces, where the concentration is $C^{AEM/CEM}_{d/c}$, to the bulk, where the concentration is $C^{b}_{d/c}$ (Fig. 2).

This model assumes that the same flow conditions exist in the diluate and concentrate channels. This is standard practice in commercial ED stacks to ensure that the pressure difference across the membranes is negligible and does not contribute to water transport. Both channels are the same dimensions and utilize the same turbulence-promoting spacer. This model assumes that the feed water contains a single 1:1 electrolyte. The extent to which it can be applied to solutions containing divalent ions is discussed in Section 5.7.

2.2. Circuit analogy and current calculation

The ED stack is modeled as an analogous DC circuit whereby the voltage applied at the electrodes (E_{total}), and the resulting current are related by

$$E_{\text{total}} = E_{\text{el}} + NE_{\text{mem},y} + Ni_y(R^b_{d,y} + R^b_{c,y} + R^{BL}_y + R^{AEM} + R^{CEM}), \quad (1)$$

where N is the number of cell pairs in the stack, and i_y is the per-segment current density (A/m^2). The area resistances $R^b_{d,y}$, $R^b_{c,y}$, R^{BL}_y, R^{AEM}, and R^{CEM} are associated with the bulk diluate and concentrate streams, the concentration boundary layers lumped together, and the exchange membranes (AEM, CEM), respectively (Ω m^2). Finally, E_{el} is the electrode potential difference and $E_{\text{mem},y}$ is the potential across each membrane-pair (V). The subscript y refers to the segment of the stack in all cases (Section 5.3 discusses discretization).