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Cost-optimal design of a batch electrodialysis system for domestic desalination of brackish groundwater

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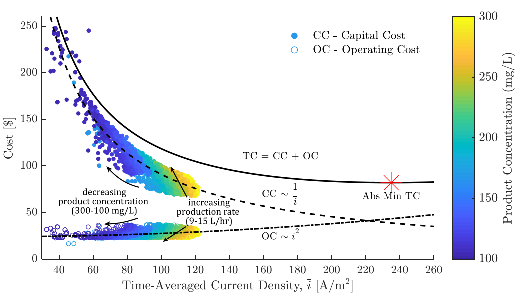
GRAPHICAL ABSTRACT



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ABSTRACT

This study presents the pareto-optimal design of a domestic point-of-use batch electrodialysis (ED) system. Specifically, the optimal geometry, flow-rates, and applied voltage for total cost minimization were explored for varying production rate (9–15 L/h) and product concentration (100–300 mg/L) requirements, while feed concentration and recovery ratio were maintained at 2000 mg/L and 90%, respectively. Capital cost dominated over energetic cost; hence, optimal designs maximized current density. Capital cost was significantly higher for 100 mg/L systems, than 200 and 300 mg/L: \$141 vs. \$93 and \$79, at 12 ± 0.5 L/h of production. Pumps were an important consideration, contributing up to 46% of the total cost. Large membrane length-to-width aspect ratios (3.5:1 to 6:1) and thin channels (0.30–0.33 mm) promoted high current densities, and 11–21 cm/s velocities optimized mass transfer against pressure drop. Optimal voltages were 0.9–1.3 V/cell-pair at 9 L/h, and decreased at higher rates. Lastly, higher production was obtained primarily by increasing cell-pair area rather than number of cell-pairs (36–46). It was additionally observed that active area increased linearly with feed concentration (1500–2500 mg/L), while recovery (60–90%) minimally affected design. This work also suggests that voltage control during the batch process, and less expensive pumps, can further reduce cost.

1. Introduction

Domestic reverse osmosis (RO) systems are widely used in Indian homes to desalinate groundwater to a total dissolved salt (TDS) content that is suitable for drinking (less than 500 mg/L [1]), but they recover only 25–40% [2] of the feed. The domestic scale addressed here refers to point-of-use (POU) systems that typically produce 8–15 L/h of drinking water, store 7–10 L, weigh 8–11 kg, and are usually wall-mounted or placed on kitchen counters in individual homes [3,4]. Since the market for POU RO devices at this scale is forecast to grow at a compound annual growth rate of 18.2% between 2016 and 2024 [5], there is also a commercial incentive for developing more efficient

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desalination solutions that operate at the same scale.

Given that the concentration of the groundwater underlying a majority of India is under 2000 mg/L, electrodialysis (ED) can provide a higher recovery and more energy-efficient desalination compared to RO for this domestic application [6,7]. Similarly, growing concern over water scarcity and the need for more energy-efficient desalination has also recently revived an interest in the possibility of using ED for brackish water desalination and tap-water softening in European cities [8].

Despite the interest surrounding the use of ED for domestic purposes, little work has been performed to characterize the design of an appropriate ED system for the application. Pilat developed and piloted more than 200 domestic ED units before 2001, but little information regarding cost or the design of the system was provided [9]. More recently, Thampy et al. investigated a hybrid approach whereby ED was used to initially desalinate 2000–4000 mg/L water to 500 mg/L and further desalination to 120 mg/L or lower thereafter was achieved using RO [10]. Given that their small-scale system operated in a continuous process, without the recirculation of product water, only 50–60% of the feed supply was recovered. Instead, Nayar et al. showed that it was feasible to implement ED solely in a batch architecture (Fig. 1), where product water is recirculated, to desalinate from 3000 mg/L to 350 mg/L, at a competitive production rate of 12 L/h while providing 80% recovery [11]. However, their system was not designed to minimize capital cost which was an estimated $206 for the entire system, $138 of which was attributed to the ED stack and pumps.

While Nayar et al. have demonstrated that batch ED is a viable technology for satisfying household desalination needs, further cost reduction is required to be competitive with existing RO devices which are priced between $200–$300. Therefore, in this work we investigated the pareto-optimal design of the proposed domestic batch ED system considering production rate, product water concentration, and cost using simulation. In particular, we aimed to address the following:

1. How should a domestic ED system be designed to minimize cost?
2. How do water quality and production requirements affect the design?
3. What are the primary contributors to cost?
4. What developments are necessary for further cost reduction?

Prior design and optimization work has been performed for large-scale systems which are typically operated in a continuous architecture [12] for industrial applications. For these systems, the pump cost and energy consumption are often neglected because they are low relative to cost of the ED stack and the energy consumed by desalination [13,14]. Optimization at the domestic scale presents a different scenario where the pumps were found to strongly affect the cost, energy consumption, and performance of the ED system.

In addition, minimization of operating costs is often the most important consideration in industrial applications whereby the energy consumption can not be neglected [15]. In the present study, it was found that capital cost was the dominant factor affecting the affordability of the domestic system.

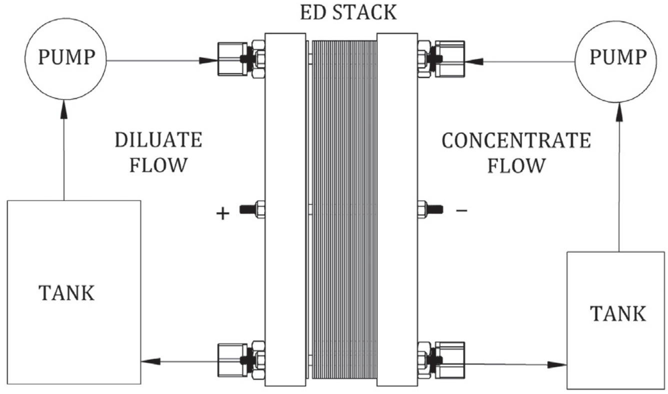

Fig. 1. Schematic of proposed domestic ED system operating in batch mode.

2. System description

The batch ED system (Fig. 1) proposed by Nayar et al. [11] and analyzed here consists of two primary flow circuits: one for the diluate, and the other for the concentrate. At the start of each batch process, both tanks hold feedwater at the same concentration. The relative volume of water in the diluate versus the concentrate circuits governs the recovery ratio of the process. During desalination, a voltage is applied and fluid is recirculated through the stack until the desired concentration is achieved in the diluate tank. The voltage and recirculation flowrates are held constant during this batch process, which is consistent with the work of others, both in simulation and practice [16-19], and would facilitate the simplest commercial product.

An additional circuit may be required for the electrode rinse stream; however, its design is not considered here because it is not expected to strongly affect desalination performance. Furthermore, for the hybrid ED-RO system investigated by Thampy et al., the RO reject was used to rinse the ED electrodes [10]. It may therefore be possible to integrate the rinse with the concentrate circuit to eliminate a third pump.

3. Models

The models used in this analysis have been thoroughly described and validated by Wright et al. [20]. However, a brief overview of the theory relevant to this optimization problem is presented herein to facilitate the reader's understanding of the work. For a more detailed description of the mass transfer processes in electrodialysis, Ortiz et al. [19], Strathmann [21], and Tanaka [22] also are recommended.

Following common practice, this work models desalination assuming a sodium-chloride solution. While production rates may vary for other ions, design insights obtained through this analysis are expected to remain relevant [20].

3.1. Mass transfer

Mass transfer was modeled using a similar approach as Ortiz et al. [19]. The full details are spared here. Instead, an analogous circuit (Fig. 2) is used to facilitate a discussion surrounding the principal terms affecting ion movement from the diluate to the concentrate channels.

An applied voltage V drives the movement of ions, represented by an equivalent current density i [A/m^2], through a series of diluate and concentrate channels separated by alternating cation (CEM) and anion (AEM) exchange membranes with static resistances R_{CEM} and R_{AEM} [Ω-m^2], respectively. Other ohmic resistance terms are associated with the

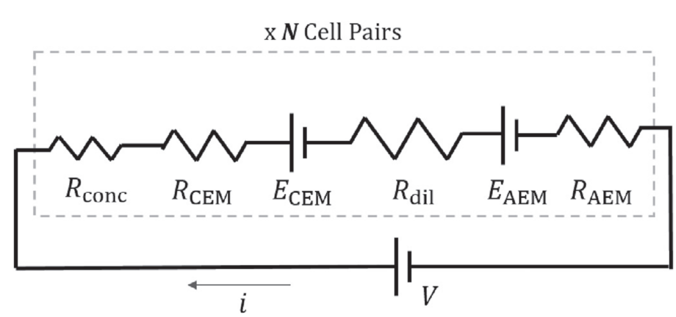

Fig. 2. ED is represented by an analogous circuit whereby ion transport is modeled by a current i due to the application of a voltage V over N cell-pairs. Exchange membranes (AEM and CEM) and channels (diluate and concentrate) are modeled using effective resistances R and back-potentials E.

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