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Design and Evaluation of a Scalable Shock Wave Electrodialysis with Multi-Cell Stack for Efficient Desalination

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Abstract Shock Wave Electrodialysis (SWED) is an innovative separation technology that integrates microfluidic principles into electrodialysis stacks, pioneered by MIT's Bazant Research Group. By operating under over-limiting current conditions, SWED enhances ion separation through the formation of shock waves in charged porous media. While previous studies have focused on small, single-cell devices, scaling SWED for industrial use requires the development of multi-cell stacks. In this study, we present the first scalable SWED device with multiple cell pairs, designed for desalination. The system features an active membrane area of 4000 mm² and a flow rate of 2.5 mL/min—offering over ten times the capacity of earlier models. Experimental results show continuous salt rejection exceeding 90%. Energy consumption is about 46 kWh/m³ depending on operating conditions and stack design. We also explore strategies to optimize the trade-off between separation efficiency and energy use, based on data from performance, water recovery, and energy metrics. This work represents a significant step toward realizing SWED as a practical, energy-efficient solution for large-scale water treatment and resource recovery.

Keywords: Electrokinetics, Desalination, Ion separation, Limiting current, Ion concentration polarization

1. Introduction

Electrochemical membrane separation operates in three regimes: Ohmic, limiting current, and overlimiting current (OLC). In the Ohmic regime, ion transport increases linearly. As voltage rises, ion depletion near membranes leads to a plateau in current, defining the limiting regime where diffusion dominates. Ion concentration polarization (ICP) occurs here, creating near-zero ion zones due to counterion transport and electroneutrality. At even higher voltages, the OLC regime is reached, where additional transport mechanisms enable ion movement through depleted zones. Traditionally limited to the diffusion-controlled regime, recent advances in microporous conductive materials now support efficient OLC operation, enhancing performance while reducing membrane costs(Wenten et al. 2020). These innovations have enabled new separation methods, including micro/nanoscale ICP, SWED, and electrodeionization, greatly expanding the capabilities of electrochemical membrane technologies(Mani and Bazant 2011; Dydek et al. 2011; Li and Anand 2016). SWED is one such advancement, introduced by Bazant's group at MIT. It modifies conventional electrodialysis by embedding charged porous materials in the dilute chambers, generating a "shock-wave" ion depletion front under OLC conditions. This shock front separates deionized and ion-concentrated fluid zones, which are then split via flow control at the outlet—yielding high-efficiency ion separation. Although SWED shows promise, its development remains at lab scale, with small flow rates (0.02–0.60 mL/min) (Schlumpberger et al. 2015; Alkhadra et al. 2020; Alkhadra et al. 2022). Research has focused on water recovery, including seawater desalination(Alkhadra et al. 2020) and heavy metal removal (Alkhadra et al. 2022; Tian, Alkhadra, and Bazant 2021). Studies have shown >99% salt removal and improved water recovery through electroosmotic flow. However, no work has yet explored modular, scalable SWED reactor designs—a gap this current project aims to address, moving toward practical industrial applications.

2. Method and Materials

The schematic diagram of the first multiple cell pairs SWED we developed is shown in Figure 1. A cell of SWED was composed of a weakly charged microporous material (G3 Borosilicate Glass) sandwiched between two cation exchange membranes (CEM). With electric field, anions will tend to move towards the anode. But CEM is there, so anion would be restricted in the reservoir. In contrast, cations will tend to move towards the cathode. Because the phenomenon of concentration polarization happened near the membrane, the concentration of ions in the solution near the membrane is still almost zero. Therefore, with a slitter put in the middle of the channel, clean water can be produced.

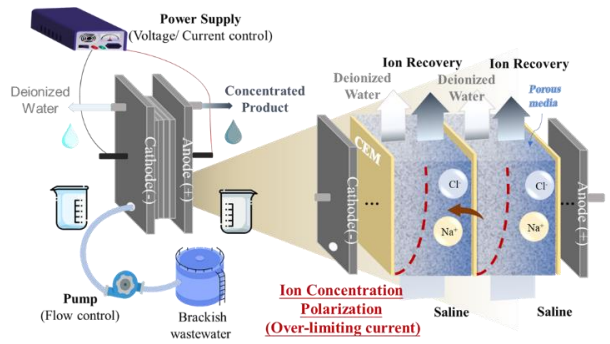

Figure 1. (a) Experiment equipment and the flow scheme (b) diagram of stack configurations.

3. Results and Discussion

2.1. Desalination Performance

Figure 1 presents the preliminary results, where the red dashed vertical line marks the transition to the OLC regime, and the blue dotted horizontal line at 50% indicates the onset of nonlinear ICP. Both single-cell and multi-cell configurations (10 mm media in one cell, and 4 mm media in two cells) exhibit increasing salt removal efficiency as the system enters the OLC regime.The SWED device with a 10 mm porous medium achieves salt removal rates of 65%, 75%, and over 94% at dimensionless currents of 0.9, 1.3, and 2, corresponding to applied voltages of 40 V, 60 V, and 100 V, respectively. The two-cell configuration using 4 mm porous media (blue triangles) achieves over 90% salt removal at a dimensionless current of 1.5, demonstrating that even compact, multi-cell setups can reach high separation performance in the OLC regime.

2.2 Energy consumption and current efficiency

The energy consumption required and current efficiency to achieve a certain percentage of desalination as calculated from the performed experiments, considering only the electrical component and not the pumping. For the configuration with 2 cells of 4 mm thickness porous media, energy consumption was approximately 45 kWh per tonne of diluted solution (final concentration <100 µS/cm) from a 0.01 M NaCl brackish feed, achieving over 90% removal. The corresponding current efficiency was around 75%. In contrast, the single-cell 10 mm configuration required 131.1 kWh per tonne to reach a similar removal target, with a significantly lower current efficiency of 45%. Notably, a substantial pH increase was observed under high-voltage operation in the single-cell setup, indicating water dissociation and increased energy loss due to parasitic reactions.

In summary, this study demonstrates the effectiveness of operating SWED in the overlimiting current regime, where nonlinear electrokinetic phenomena enhance salt removal. It also shows that even multi-cell, smaller-channel setups can benefit from these effects, which is promising for scalable SWED designs.

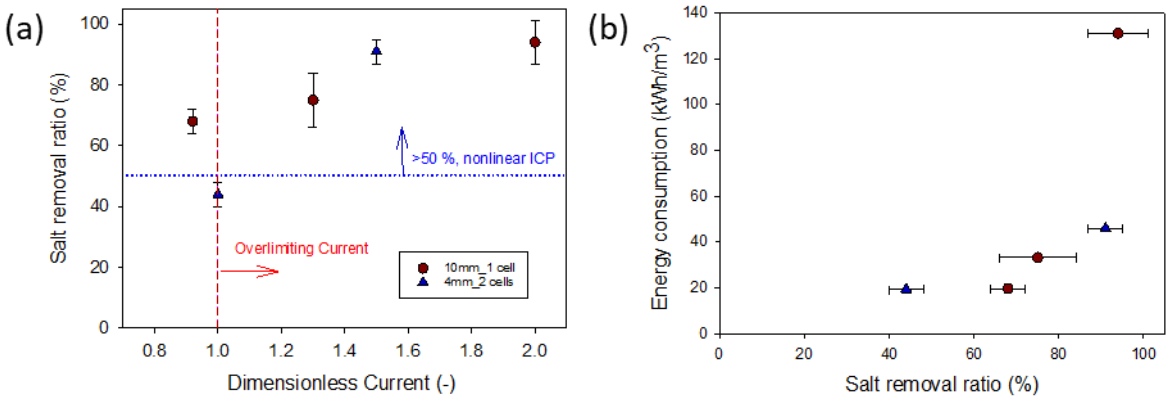

Figure 1. Desalination performance of the SWED for desalination with different configurations and operating conditions.

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