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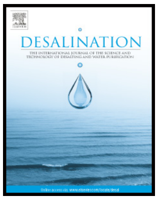

Potential of electrodialytic techniques in brackish desalination and recovery of industrial process water for reuse

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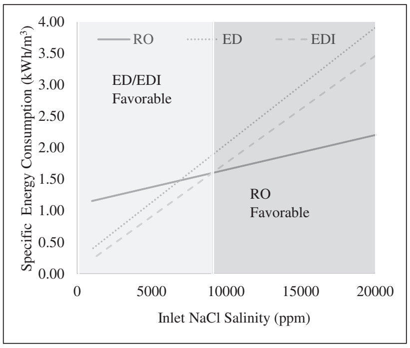
HIGHLIGHTS

- Electrodialysis and electrodeionization of brackish water was conducted.
- Systems demonstrated low specific energy consumption for low inlet salinity feeds.
- Competitive electrodeionization techniques are discussed for desalination.

GRAPHICAL ABSTRACT



Comparison of SEC for ED, ED, and RO separation processes. At low inlet salinities, ED and EDI are favorable while at high salinities RO becomes favorable. This suggests two regimes where the ideal separation process can be determined from feed conditions.

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ABSTRACT

Large demands for water in industry and consumer markets have led to the development of seawater desalination plants worldwide. Electrodialysis allows the removal of ions at a much lower specific energy consumption than pressure-driven systems and holds the potential to move the desalination industry to greater water yields, lowering the degree of water wasted and energy required for separations. This study investigates the use of traditional electrodialysis as well as electrodeionization for the removal of contaminant ions from brackish water as well as samples from industrial sources. Results indicated that conventional electrodeionization can successfully remove ion contaminants from brackish water at specific energy consumptions of approximately 0.9–1.5 kWh/m^3 water recovered with high water productivity at 40–90 L/m^2 h. Ion-exchange resin wafer electrodeionization showed greater promise with specific energy consumption levels between 0.6–1.1 kWh/m^3 water recovered and productivity levels between 10–40 L/m^2 h. From these results, electrodialysis and electrodeionization have demonstrated viability as alternatives to pressure-driven membrane systems for brackish water desalination.

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1. Introduction

With the ever increasing demand for water due to population growth and global industrialization, potable water production from seawater and brackish sources is an issue that must be addressed to limit global water scarcity. Water production is one of the largest topics and industries that have gained worldwide attention and significant research efforts in the scientific community [1–3]. Typically, the production of water occurs through seawater desalination and water reclamation. With global efforts for water recovery improving over the past few decades, focus has shifted to developing sustainable methods for seawater desalination [4,5]. Significant research on desalination has occurred in order to develop better methods which maximize water productivity while minimizing energy requirements, fouling, and cost [6–9]. Typical desalination and water reclamation occurs through membrane filtration or multi-stage flash distillation (MSF). MSF produces high quality water with high output volumes; however, the process is energy intensive [10,11]. Therefore, novel membrane processes for desalination and wastewater recovery have been implemented in several countries in order to modernize water production methods. The most common membrane techniques used in these plants are reverse osmosis (RO), forward osmosis (FO), and ultrafiltration (UF).

Reverse osmosis (RO) is the most common desalination process, due to its high salt rejection and ease of operation [12,13]. However, several problems persist with RO, including propensity of membranes to fouling and limitations on water recovery [14,15]. As such, UF membranes are often used to pre-treat water solutions before RO operations [16–18]. State-of-the-art RO operations can operate between 20–40 L/m^2 h with specific energy consumption (SEC) levels at approximately 1.5–4 kWh/m^3 water recovered [1,19,20]. The cost of energy and membranes in these plants account for approximately 2–5% and 10–15% of the total capital cost respectively with membrane replacement costs at \$0.10–0.30/m^3 water produced [21,22]. The thermodynamic limits of RO are currently 1.06 kWh/m^3 at 50% water recovery, demonstrating that further optimization of RO will have minimal impact on the industry [1]. For most countries, these levels are suitable for commercial and consumer demand. Unfortunately, as time progresses and water scarcity becomes a greater issue in developing and developed countries, greater water recoveries are needed at or below the current specific energy consumption (SEC) levels. In order to meet these future demands, new membrane techniques must be employed.

Forward osmosis (FO) has gained much attention recently due to advances in draw solutions and regeneration techniques [21,23,24]. Recent FO research in desalination investigated the incorporation of FO technology with RO for improved water productivity through retentate recovery [23,25,26]. Additionally, pressure recovery devices have been designed to reduce overall SEC by RO and FO pumps [27,28]. Current state-of-the-art suggests that FO process requires 1.3–8 kWh/m^3 water produced [26,29,30]. Limitations associated with FO technology include draw solution recovery, membrane fouling, and concentration polarization [27].

Electrodialysis (ED) and electrodeionization (EDI) offer great potential for increased water productivity in desalination. Electrodialysis is the use of electrical current to drive ions in solution from one solution to another [31]. This allows salt water solutions to be desalted using electrical power with little additional energy required. Electrodeionization (EDI) is a similar process in which current is used to drive ions from a solution; however, the major difference is the addition of ion exchange resins to reduce solution resistance limitations for the separation process [32]. EDI process is also advantageous in that the resins used during operation are self-regenerating. A small portion of the energy used during separation is also consumed to regenerate the resin charged groups, allowing continuous operation of EDI systems without need to recover resin performance. Many studies has been conducted in the use of ED and EDI in the food and beverage industry [33–35], the formation of acids and basis [36,37], and the development of specialty chemicals [38,39]. However, work conducted on the use of ED in the desalination industry, specifically when considering brackish water, has resulted in SEC levels ranging anywhere from 1–15 kWh/m^3 water treated with common values over 10 kWh/m^3. In addition, ion exchange membranes are more typically 2–3 times more expansive than RO membranes [40]. At these SEC levels and capital costs, ED and EDI are uncompetitive with RO and FO. Some research has been done on the applicability of ED in the desalination of high salinity feeds, however, production of potable water at lower salinities has yet to be fully considered [41]. With the development and maturity of RO, additional membrane techniques such as ED and EDI can be investigated for potential desalination applications. Table 1 summarizes the typical water productivity and SEC of each desalination technique.

This study investigated the applicability of ED and EDI techniques for water desalination and process water recovery. To our knowledge, this is the first study that compares the treatment of brackish water from industrial and drinking source waters by EDI and ED to current RO technologies. Sodium chloride was used as a model salt for brackish water desalination experiments. Brackish drinking water sources were also tested and the differences in productivity and water quality were discussed and compared to RO to determine commercial viability of ED and EDI. Additional contaminants were considered to determine the influence of contaminates on water productivity and SEC for the ED and EDI processes. Results suggest that while ED may be limited by high SEC levels and low salinity feeds, the benefits of EDI can overcome this obstacle through novel membranes and thinner materials which can lead to a cost-effective process for water desalination and recovery of contaminated process water.

2. Experimental

2.1. ED and EDI experimentation

Experiments were conducted with a Micro-Flow cell ED stack from Electro-Cell North America, a pilot TS-2 EDI stack from EURODIA, and a pilot EUR2B-10 ED stack from EURODIA. Table 2 shows the characteristics of each stack. In EDI, solution compartments are filled with ion exchange resin which enhances ion transport and solution conductivity at low ion concentrations. To minimize stack thickness and ensure resin retention, ion exchange resin wafers were used in experiments in lieu of ED flow spacers. For EDI experiments, resin wafers were produced through a combination of anion exchange resin, cation exchange resin, polymer, and sucrose according to previous synthesis methods with imaging available in prior publications [47–49]. Fig. 1 shows a process schematic for ED and EDI. For both ED and EDI, experiments were duplicated in order to confirm experimental results. Sodium chloride was used as a model contaminant because most desalination efforts are focused on the decreasing sodium and chloride to levels below 500 ppm as total dissolved solids (TDS) per EPA regulations on potable drinking water [43]. In the dilute chamber, sodium chloride began at 5000–50,000 ppm while the concentrate chamber had sodium chloride at a 0.1 N concentration (~5844 ppm). Current was introduced into the

Table 1
Current desalination output and SEC for brackish water treatment.

Separation method	Water productivity (L/m^2 h)	SEC (kWh/m^3)
Ultrafiltration [42][a]	>50	0.07
Reverse osmosis [43]	10.2–43.7	3–7
Forward osmosis [26,29,44]	3–8	1.5–8
Electrodialysis [45,46]	10–45	1–15
Electrodeionization [46]	7–40	0.2–1.5

[a] Desalination pretreatment only.