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Experimental and Modeling Study of Batch-Operated FCDI with Short-Circuited Closed-Cycle Regeneration for High-Salinity Brackish Water Desalination

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This research proposes an experimental setup for brackish water treatment employing flow capacitive deionization (FCDI). The FCDI cell runs activated carbon slurry with 10% carbon loading and applies a short-circuited close cycle for the regeneration of the flow electrode slurry. The flow electrode utilizes an electrolyte with the same TDS as the brackish water. A polyester separator is selected, and the FCDI is operated by applying a constant 1.2 V potential across the collectors. In operation, the brackish water leaving the FCDI is recirculated back to the cell for more residence time, and so is the flow electrode. A process model is also built to simulate an experimental FCDI cell based on salt balance and overall material balance. Experimental results show that the salinity of the bulk water (12 mL/min) is reduced from 8000 mg/L to 7310 mg/L after 7 minutes of recirculation at a slurry flow rate of 140 mL/min, achieving an average salt removal rate of 0.373 mmol/m^2·s. On the other hand, the model results reveal very good agreement with the experimental results and predicted an overall recirculation time of 78 minutes to obtain fresh water. The experimental setup, together with the process model, can be applied for further investigation and sensitivity analysis.

1. Introduction

Water scarcity has been a crucial global challenge to communities and industrial development for decades. Seawater and brackish water are sustainable resources for desalination technologies, which are reliable solutions to such challenges. Reverse osmosis (RO) is a promising desalination method despite two significant shortcomings: high energy consumption and low water recovery. On the other hand, FCDI (flow capacitive deionization) is a new desalination technique based on the electro-adsorption of salt ions onto a flowing slurry containing carbon particles. FCDI modules have one advantage over RO methods: low energy consumption (Porada et al., 2013). The concept of Flow-electrode Capacitive Deionization (FCDI) was pioneered in 2013 to overcome the drawbacks of Capacitive Deionization (CDI) and Membrane Capacitive Deionization (MCDI) (Fang et al., 2025). Instead of having the conventional static solid electrodes, a pumpable carbon suspension flows between the membranes and the current collector in the FCDI cell. A voltage is applied between both channels of flowing carbon slurries, and ions are adsorbed from the water into the carbon slurries. Unlike CDI or MCDI, a discharge step is not necessary; after leaving the cell, the carbon slurries are mixed, and ions desorb. Thereafter, the carbon slurry can be separated from the concentrated saltwater and reused. In this way, continuous desalination can be achieved as regenerated electrodes are constantly available in the desalination cell (Atia et al., 2021). FCDI offers enhanced water recovery compared to conventional CDI systems, primarily

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due to the decoupling of adsorption and desorption. In capacitive deionization (CDI), an electrical potential gradient drives the migration of dissolved ions toward oppositely charged electrodes, where they are retained through electrostatic adsorption at the electrode-electrolyte interface. The primary challenges in applying CDI to brine treatment include high salinity and a significant potential for fouling. The typical limit for conventional CDI treatment is around 10,000 mg/L, consuming between 0.4-8 kWh/m³. Higher salinity can increase energy consumption and reduce salt-removal efficiency. However, using membrane-based variants such as Membrane Capacitive Deionization (MCDI) and Flow Capacitive Deionization (FCDI) can enhance performance compared with traditional CDI methods (Ma et al., 2020). Batch recirculation combined with short-circuited closed-cycle (SCC) regeneration is a practically attractive operational mode for flow-electrode capacitive deionization (FCDI), particularly for desalination of high-salinity brackish water. In this configuration, anodic and cathodic flow electrodes are circulated in closed loops during desalination and are periodically mixed under short-circuit conditions to induce spontaneous charge neutralization and ion desorption, thereby regenerating the electrodes without polarity reversal or auxiliary regeneration units (Jeon et al., 2013). This simplified regeneration strategy reduces system complexity and enhances operational robustness compared with continuously regenerated FCDI architectures (He et al., 2018). Experimentally, batch recirculation with SCC is advantageous for high-salinity feeds because it decouples salt removal from the need for high instantaneous charge-storage capacity. In continuous operation, elevated active carbon (AC) loading is often necessary to avoid electrode saturation at fixed residence times, whereas in batch operation, comparable salt removal can be achieved by extending circulation time and periodically restoring electrode capacity via SCC regeneration, and the system often operates at a lower average current density (Ma et al., 2020). SCC operation has been shown to stabilize cell voltage, suppress pH excursions, and maintain consistent desalination performance over repeated cycles, even at elevated ionic strengths (He et al., 2018). From a hydraulic and energy perspective, batch/SCC operations allow operation at moderate AC loadings, which is significant because slurry viscosity increases nonlinearly with carbon concentration, leading to increased pressure drop and pumping energy in flow-electrode systems (Zhang et al., 2019). By relying on time-dependent utilization of electrode capacity rather than high instantaneous capacitance, batch recirculation reduces viscous losses and cumulative pumping energy while maintaining effective salt removal. This trade-off is particularly favourable at laboratory and pilot scales, where pumping energy can represent a substantial fraction of total process energy consumption. From a modelling standpoint, batch recirculation with SCC regeneration provides a well-defined framework for coupling electrochemical charge storage, ion transport, and hydraulic behaviour (Porada et al., 2013). The cyclic separation of adsorption and regeneration phases facilitates the identification of key parameters such as charge efficiency, salt adsorption capacity, and regeneration kinetics, enabling direct comparison of experimental results with dynamic FCDI models (Bisheuvel et al., 2010). This operational clarity makes batch/SCC systems especially valuable for mechanistic studies and model validation, while also generating insights relevant to the design of continuous FCDI processes. Overall, batch recirculation with SCC regeneration is a preferred operational mode when system simplicity, hydraulic efficiency, and experimental controllability are prioritized over continuous water production. Its ability to maintain stable desalination performance under high-salinity conditions with reduced carbon inventory and pumping penalties makes it particularly suitable for experimental investigations and early-stage process development (Luo et al., 2018). While FCDI promotes continuous operation and higher recovery of salt, the electrode regeneration is not addressed industrially in literature. In addition, most studies focus on lab scale FCDI. However, scaling up remains in short. Furthermore, models to predict the performance of FCDI cells are unaddressed. Driven by these shortcomings, the current work aims at setting up an experimental FCDI cell to investigate the treatment of brackish water, while developing models to predict the performance as function of time and provide basis for sensitivity analysis studies. The experimental setup is valuable for further industrial applications and scale up studies.

2. Methodology

2.1 Laboratory cell design and Experimental setup

The FCDI laboratory cell unit is centered around high-precision current collectors machined from SS 316 stainless steel, featuring CNC-milled serpentine channels to facilitate flow-electrode circulation over an active area of 1496 mm². A 3 mm thick Nylon-6 spacer defines the bulk water compartment, providing an internal volume of 18 mL, while the assembly is secured by 20 mm Nylon-6 end plates. The flow-electrode utilizes Extra Pure Activated Carbon (Titan Biotech Ltd., 881.22 m²/g) with an electrolyte of same TDS as the Bulk water. Non-woven polyester separators were utilized and were selected for their mechanical durability and chemical stability in high-salinity environments. Batch FCDI operation is achieved by applying a constant 1.2 V potential across the collectors, (DC power supply, 24 V-DC, 30 A) with flow-electrodes and saline feed delivered by G528

(12V DC, 140 mL/min) and Kamoer (NKP- NKP, 12V DC, 5-20 mL/min) peristaltic pumps, respectively. All components were integrated together with silicone tubing (¼ in ID).

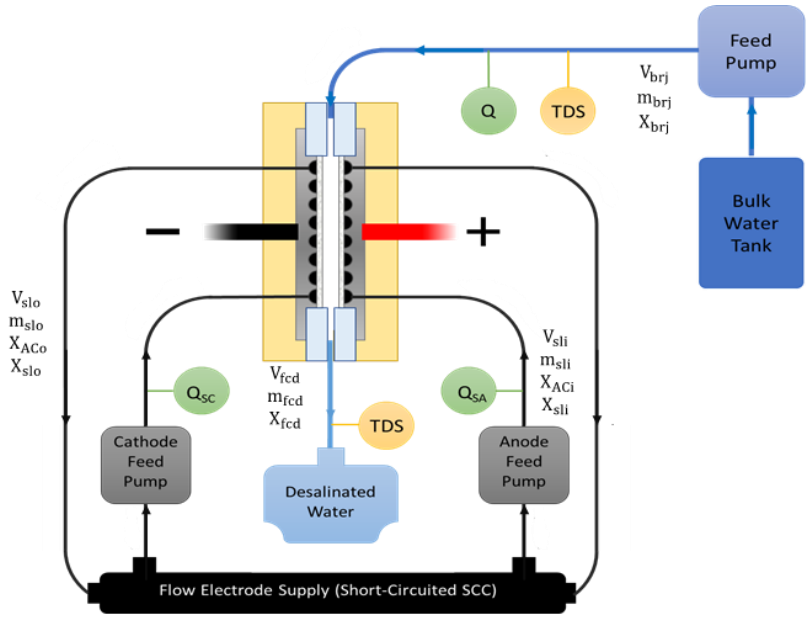

Figure 1: FCDI cell for batch circulation with short-circuited closed cycle

Figure 1 shows a schematic experimental setup for the FCDI cell proposed in this work for brackish water treatment.
For the SCC regeneration cycle, the charged anode and cathode slurries were continuously discharged by merging them into an external vessel. This vessel employs a magnetic stirrer to ensure vigorous mixing, facilitating rapid charge neutralization and ion release into a brine stream, thereby restoring the carbon's electro sorption capacity for batch recirculation. Performance is monitored in real-time through effluent TDS measurements (Adwa Instruments AD32), ensuring precise tracking of ion migration and regeneration efficiency. Table 1 presents the main performance parameters.

Table 1: Experimental performance parameters (FCDI)

Parameter	Measured Value
Applied Cell Potential	≤ 1.2 V
Current	0.03 – 0.06 A
Current Density	20 – 40 A·m^{-2}
Average Charge Efficiency	89 %
Pressure Drop (Slurry Pathway)	0.6 bar
SEC	1.342 kWh/m^3
Applied Cell Potential	≤ 1.2 V
Current	0.03 – 0.06 A
Current Density	20 – 40 A·m^{-2}

2.2 Process modeling

The brackish water treatment system described above is modelled based on the parameters shown in Figure 1. The brackish water feed with flow rate V_{brw} (mL/min) is passing through the FCDI cell in which an active carbon slurry electrode is pumped with flow rate V_{slin} (mL/min). through an engraved flow passage and ion exchange membranes. In this system, suspended carbon particles, i.e. flow electrodes in FCDI pass through a flow channel on the current collector. When a voltage is applied, charged ions are transported across the ion exchange membrane and adhere to the surface of suspended carbon electrodes. The discharged flow electrodes from the anodic and cathodic chambers are mixed and regenerated. The conceptual process model of this work employs mass balance, salt balance and activated carbon balance around the FCDI cell/ In addition to the balance equations, the model involves also the characteristic performance parameters of cell. Salt

concentration of brackish water and slurry electrode in this study is taken as 8000 ppm, while that for fresh water produced is of 400 ppm.
In FCDI, the activated carbon slurry electrode adsorbs the salt ions Na^+ and Cl^- and thus the salinity of the brine reject is reduced from X_{brw} to X_{fcd} (ppm). The volumetric flow rate (V_{fcd}) and salt concentration (X_{fcd}) of streams leaving the FCDI are determined through the following equation, assuming the density of brine streams is unchanged:

$$\mathrm{V_{fcd}} = \mathrm{V_{brw}} \times \left(\frac{\mathrm{r\%}}{100}\right) \quad (1)$$

where, $\mathrm{r\%}$ is the recovery of the treated brine volume with respect to the brine feed volume to the FCDI. Experimental measurements reveal that this value ranges from 88 to 94%. A salt balance around the FCDI cell results in determining the salinity of the treated brine, provided that the salt removal rate (S_{RR} in mmol/s·m^2) and exposure contact area (A_c in m^2) are experimentally defined, as shown below.

$$\mathrm{X_{brw}} \times \mathrm{V_{brw}} = \mathrm{X_{fcd}} \times \mathrm{V_{fcd}} + \mathrm{S_{RR}} \times \mathrm{A_c} \quad (2)$$

Thus, the salt concentration and mass flow of the treated brine leaving the FCDI cell is reduced as follows:

$$X_{fcd} = \frac{X_{brj} \times V_{brj}}{V_{fcd}} - \frac{S_{RR} \times A_c}{V_{fcd}} \quad (3)$$

$$m_{fcd} = m_{brw} - \frac{R\%}{100} \times m_{brw} \quad (4)$$

Where R% is the salt removal percent conducted by the slurry electrode, which can be given by the following equation:

$$\frac{R\%}{100} = \frac{S_{RR} \times A_c}{X_{fcd} \times V_{fcd}} \quad (5)$$

As the activated carbon slurry removes salt from the brine feed, its salt mass flow and concentration, and carbon concentration are due to change from m_{sli} to m_{slo} (mg/min), X_{sli} to X_{slo} (ppm), and from X_{ACi} to X_{ACo} (ppm), respectively as calculated below:

$$m_{slo} = m_{sli} + \frac{R\%}{100} \times m_{brw} \quad (6)$$

$$V_{slo} \times \rho_{AC} = V_{sli} \times \rho_{AC} + \frac{R\%}{100} \times V_{brj} \times \rho_{bw} \quad (7)$$

$$X_{slo} = \frac{X_{sli} \times V_{sli}}{V_{slo}} + \frac{S_{RR} \times A_c}{V_{slo}} \quad (8)$$

$$X_{ACo} = \frac{X_{ACi} \times V_{sli}}{V_{slo}} \quad (9)$$

where, ρ_{AC} is the density of activated carbon slurry (1200 kg/m^3), and ρ_{brw} is the density of fresh water (1015 kg/m^3). It is expected from the salt transfer from brine to activated carbon slurry that the salt concentration in slurry increases while carbon concentration decreases. Since the volumetric flow rate of the slurry electrode doesn't change much, the carbon concentration $X_{ACo} \approx X_{ACi}$.

2.3 Process model implementation

The model equations are solved using Excel® where input variables and FCDI performance characteristics are specified. The model results include flow rate of brackish water treated, its salt concentration, slurry electrode leaving the FCDI and its salt concentration, time required to reach fresh water specifications, accumulated salt in slurry electrode, etc. Base case data are given in Table 2.

Table 2: Base case data

Parameter	Value	Unit
Salt concentration of brackish water	8000	ppm or mg/L
Recovery of FCDI	88-94	%
Activated carbon concentration in slurry electrode	5	%
Salt (NaCl) concentration in slurry electrode	8000	ppm or mg/L
Salt removal rate of slurry electrode	0.373	mmol/s·m^2
Volumetric flow rate of brackish water feed	12	mL/min
Volumetric flow rate of slurry electrode	140	mL/min
FCDI active area	1496	mm^2
Salt concentration of fresh water	400	ppm or mg/L

3. Results and Discussion

3.1 Experimental results

During operation, the brackish water feed salinity decreased from 8000 to 7310 ppm over seven minutes, achieving an Average Salt Removal Rate (S_{RR}) of 0.373 mmol/m²·s. As illustrated in Figure 2, these experimental results demonstrate strong correlation with established literature values (Fang et al., 2025; Zhang et al., 2019) validating the system's performance under the specified operational parameters.

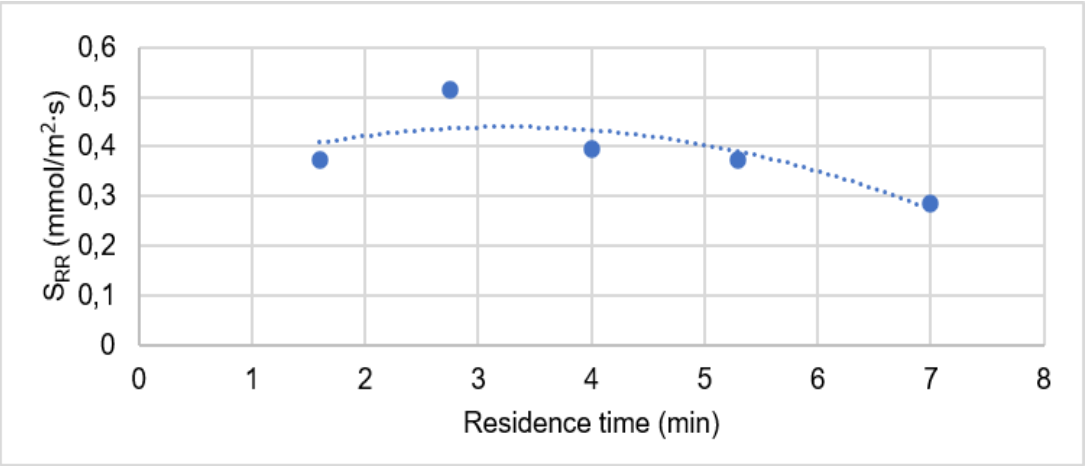

Figure 2: S_{RR} of the FCDI system at 8000 ppm bulk water salinity

Batch recirculation operation of the FCDI system with SCC exhibited stable electrochemical performance at applied potentials up to 1.2 V. Current densities in the range of 20–40 A·m^{-2} were achieved with a high average charge efficiency of 89%, indicating effective ion adsorption and limited parasitic reactions.
The measured pressure drop of 0.6 bar across the slurry pathway reflects favorable hydraulic behavior, suggesting that recirculation can be maintained without excessive pumping losses. Collectively, these results demonstrate efficient electrochemical operation coupled with manageable hydrodynamic resistance and Specific Energy Consumption.

3.2 Model results

Results of the model implementation are shown in Table 3, and are compared with experimental results. The comparison validated the process model with experimental data. The model predicted results in good agreement with experimental work after 7 min to reach salinity of 7290 mg/L compared with 7310 mg/L as achieved by experiments. Figure 3 displays the results of the model for treating brackish water for 7 minutes and compares results with experimental data. It is evident from the figure that results are comparable emphasizing the validity of the model. It further predicted 78 min time required to treat the brackish water to fresh water purposes.
The model can be further employed to perform sensitivity analysis to study the variation of brackish water and slurry electrode salinities. In addition, it can be integrated with more details to calculate the specific energy consumption as function of water salinity.

4. Conclusions

The work proposed an FCDI cell to treat brackish bulk water and reduce its salinity employing flow-electrode with activated carbon. An experimental setup has been built and tested to treat brackish water with salinity of 8000 mg/L and volume flow of 20 mL/min, utilizing 140 mL/min activated carbon slurry and 8000 mg/L salinity. Results of experiments showed a reduction of the salinity of bulk water from 8000 to 7310 mg/L after 7 minutes of operation. An average salt removal rate was obtained as 0.373 mmol/m^2·s. On the other hand, the FCDI process has been mathematically modeled using mass balance, salt and activated carbon balance.
The model was tested on the experimental data by fixing the average salt removal rate and operation time of 7 minutes. Model results showed that the salinity of bulk water was decreased from 8000 to 7290 mg/L, comparable with the experimental results. For the treatment to obtain fresh water, the model predicted 78 minutes circulation time and the flow electrode reached 9090 ppm salt concentration. Both the experimental setup and model are valuable for further applications to saline water treatment and sensitivity analysis studies.

Table 3: Model results

Parameter	Model	Experiment
Salinity of treated brackish water after 7 min (ppm)	7290	7310
Salinity of outlet slurry electrode after 7 min (ppm)	8058	8098
Time required for fresh water treatment (min)	78	77
Salinity of outlet slurry electrode after 78 min (ppm)	9090	
Salt removal percent (%)	8.56	8.63

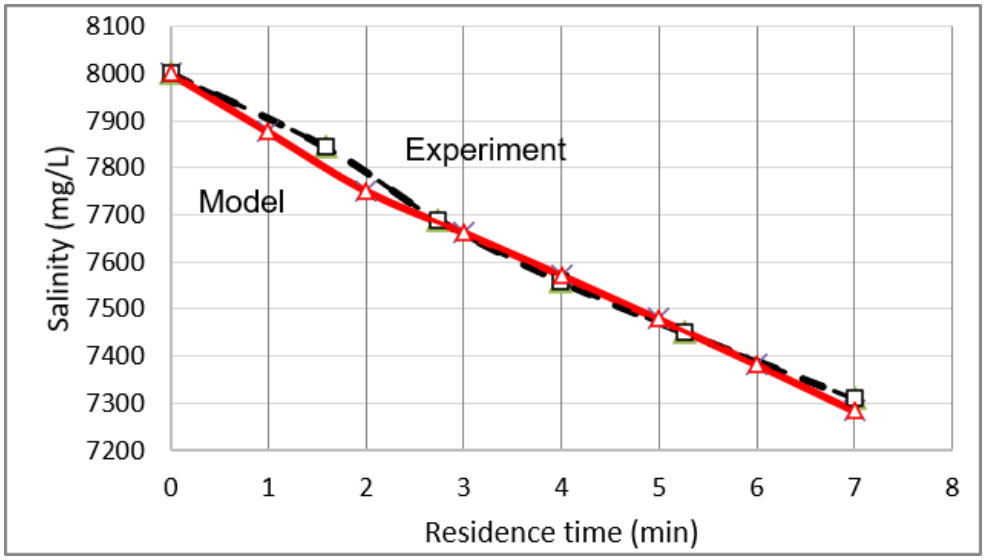

Figure 3: Salinity of treated brackish water during 7 minutes (experiment versus model results)

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