

Laboratory-scale evaluation of capacitive deionisation for efficient desalination and industrial water reuse

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Capacitive deionisation (CDI) is an electrochemical desalination technology that removes dissolved ions from water through electrostatic adsorption onto charged porous electrodes under low applied voltage. In CDI, when an electric potential is applied between a pair of electrodes, cations and anions in the feed solution migrate toward electrodes of opposite polarity and accumulate in the electrical double layers (EDLs) formed on the electrode surfaces. Once the electrodes reach saturation, the applied potential is reduced or reversed, causing the adsorbed ions to desorb and allowing electrode regeneration (Figure 1). This reversible adsorption–desorption cycle enables repeated desalination with limited material degradation and the opportunity for partial energy recovery during regeneration, distinguishing CDI from traditional pressure-driven or thermal desalination methods such as reverse osmosis or multi-stage flash distillation. The absence of high hydraulic pressure and membrane separation steps reduces mechanical stress and can lower operational costs, making CDI a promising approach for brackish and industrial water treatment (Taufik et al., 2024).

The fundamental operating principles of CDI allow it to address several limitations associated with conventional desalination technologies. Since CDI targets dissolved ions electrostatically rather than forcing water through a membrane, common issues related to membrane fouling, compaction and replacement are inherently avoided. In addition, the low-voltage operation provides flexible control of desalination rates and opens up the potential for energy recovery during electrode discharge. Recent research has explored advances in CDI system design, including improvements in electrode materials, cell architectures and hybrid configurations that extend the effective salinity range and improve charge efficiency and ion selectivity (Pang et al., 2024; Suwaileh et al., 2020; Wu et al., 2022).

In recent years, CDI has attracted growing attention for industrial water treatment and resource recovery, complementing established technologies. While forward osmosis has been deployed commercially for seawater desalination under specific high water cost conditions, CDI remains under active development, with laboratory and pilot-scale studies demonstrating its potential for efficient ion removal, energy recovery and operational flexibility (Khali et al., 2025).

This work presents a comprehensive laboratory-scale experimental study of capacitive deionisation at TRL 5 aimed at evaluating its desalination performance, operational stability and suitability for industrial water treatment applications. The main objective was to assess the ability of CDI to remove dissolved salts from representative industrial water streams while maintaining stable electrochemical performance over repeated adsorption–desorption cycles. The experimental system was designed with a modular configuration, allowing controlled operation, systematic variation of operating conditions and detailed monitoring of key electrochemical and water quality parameters. Generating robust experimental data at this development stage is crucial to support process optimisation, system design and future scale-up activities.

From a methodological perspective, particular emphasis is placed on analysing how changes in electrical operating conditions and hydraulic regimes affect the dynamic response of the CDI system. Variations in applied voltage and current density influence ion adsorption kinetics and charge efficiency, while residence time governs the balance between desalination performance and energy consumption. At laboratory scale, these parameters can be systematically explored to identify operating windows that favour stable and reproducible behaviour, providing valuable insights into the mechanisms governing ion transport and storage within the electrodes. Such understanding is essential for translating laboratory findings into robust design criteria for larger-scale systems (Wang et al., 2025).

In addition, the laboratory-scale assessment allows the evaluation of CDI as a flexible and modular technology capable of adapting to fluctuating water quality and operational demands. This flexibility is particularly relevant for industrial applications, where feed water composition and flow rates can vary significantly over time. By investigating the response of the CDI system to different operating scenarios, this study contributes to defining operational strategies that enhance resilience and reliability, which are key aspects for industrial adoption and long-term deployment of the technology.

From an applied and strategic viewpoint, the results obtained at TRL 5 provide a solid foundation for advancing CDI toward higher technology readiness levels and integration into more complex water treatment schemes. In particular, CDI is regarded as a key enabling technology for future hybrid systems, such as forward osmosis–CDI configurations, where CDI can be employed to regenerate draw solutions and harness energy during desalination, potentially contributing to significant reductions in both capital and operational expenditures in integrated water treatment systems (Zou et al., 2022). Continued research and demonstration at higher TRLs are expected to further validate CDI’s role in sustainable industrial water reuse frameworks.

In conclusion, this laboratory-scale study demonstrates the technical feasibility, operational stability and energy efficiency potential of capacitive deionisation for industrial water desalination at TRL 5. The knowledge generated provides valuable insights for process optimisation and future scale-up, while also identifying key challenges related to electrode performance, energy management and system integration. Overall, the results contribute to the growing body of evidence supporting CDI as a viable and sustainable technology for advanced industrial water treatment and circular water management.

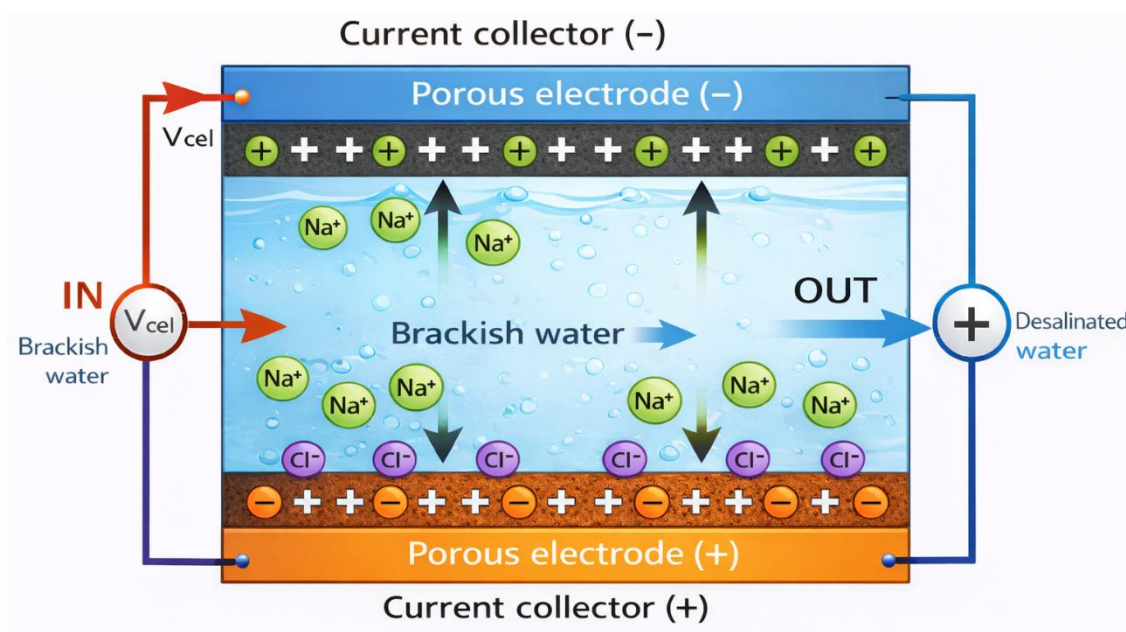


Figure 1. Capacitive deionisation process

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