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Review of Flow-Electrode Capacitive Deionization: From Fundamentals to Future Perspectives

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Abstract: Flow Capacitive Deionization (FCDI) has emerged as an innovative electrically driven separation technology with distinct advantages over conventional desalination methods. Utilising flowable carbon electrodes and ion exchange membranes, FCDI enables continuous operation, high water recovery, and selective ion removal at relatively low energy consumption. This review critically examines the historical development, operational mechanisms, cell architectures, and configurations of FCDI systems, with particular focus on recent advances in materials, flow-electrode formulation, and regeneration strategies. This review also highlights emerging opportunities for FCDI in selective ion recovery and resource extraction. Despite its promise, FCDI remains at a pre-commercial stage due to high capital costs and system complexity. Ultimately, progress in advanced materials, system modelling, and scalable cell design will be essential to realise its transition from laboratory innovation to a commercially viable solution for sustainable water treatment.

Keywords: Flow-Electrode Capacitive Deionization, Flow-Electrode, Electrosorption, Desalination.

1 Introduction

Over the past ten years, Capacitive Deionization (CDI) technologies have received significant attention [1]. In these processes, ions are transported to the oppositely charged electrodes by applying potential difference. Then, ions are adsorbed within the electrode material. Porous carbon electrodes are typically used to achieve high surface areas and, hence, high capacity of ion adsorption [2].

The addition of Ion-Exchange Membranes (IEMs) to CDI innovated a new configuration known as Membrane Capacitive Deionization (MCDI), makes CDI processes more energy-efficient with improved desalination performance [3], benefiting from the IEMs' ability to selectively permit counter-ion transport while effectively suppressing the back-diffusion of co-ions into the feedwater compartment [4]. This effect is particularly advantageous at low salinity levels, where co-ion leakage would otherwise diminish the ion removal capacity of conventional CDI [2].

All solid electrodes used in CDI and MCDI systems are immobile and become progressively saturated with ions during operation [5]. As a result, these electrodes require periodic regeneration through desorption, necessitating discontinuous operation in the form of charge-discharge cycles [6]. This cyclic nature, along with the depletable ion storage capacity of fixed electrodes, restricts the practical applicability of CDI and MCDI technologies to feedwaters with relatively low salinity levels [1].

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A new technology based on capacitive deionization and flow capacitor systems [8] is Flow-Electrode Capacitive Deionization (FCDI). Unlike CDI and MCDI, which utilise solid and static stationary carbon electrodes, FCDI employs fluidised, pumpable carbon suspensions, referred to as flow or slurry electrodes [9], as illustrated in Figure 1.

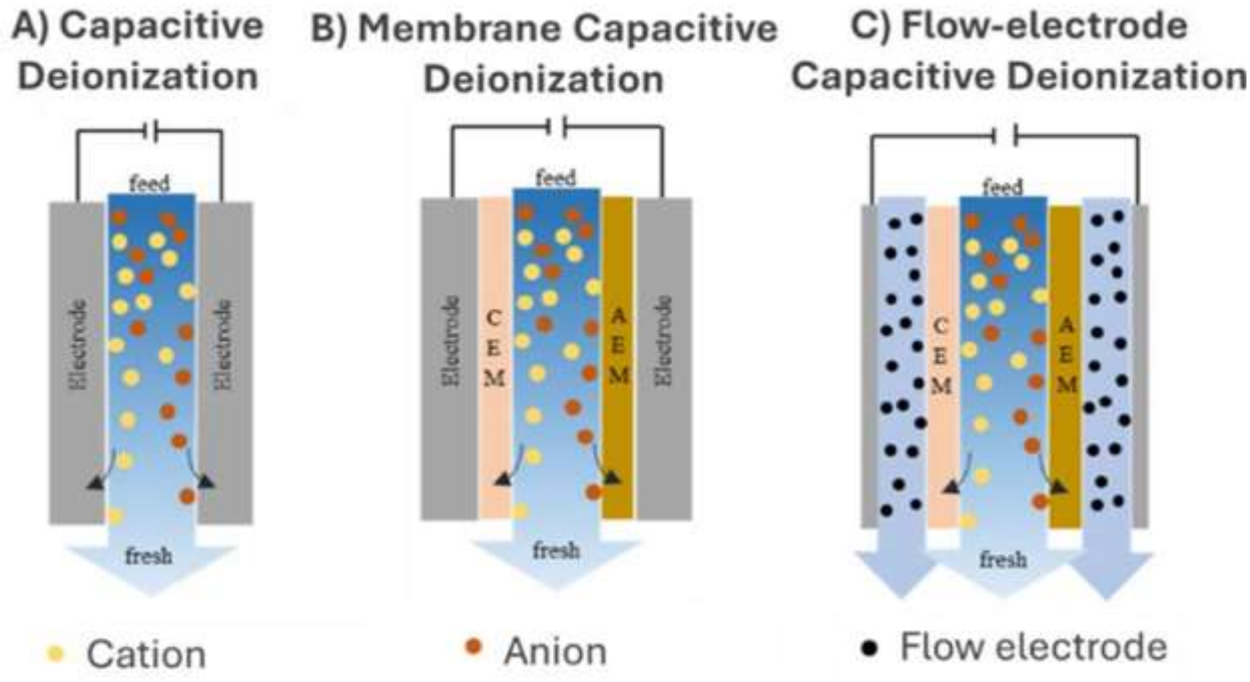

Fig. 1: Schematic diagrams of (a) Capacitive Deionization (CDI); (b) Membrane Capacitive Deionization (MCDI); and (c) Flow-Electrode Capacitive Deionization (FCDI) [7].

Upon applying an electrical potential, ions in the feed migrate across IEMs and are adsorbed onto the surface of the carbon particles [10]. These charged flow electrodes can then be continuously transported out of the desalination cell to a separate regeneration unit, allowing for uninterrupted continuous operation and sustained ion removal performance [11]. Overall, FCDI is positioned as a promising technology due to the high salt adsorption capacities [11,12], good desalination performance [12], and the continuous operation [11,14,15].

This review article provides an overview of FCDI technology. It begins with FCDI's history, principle of operation and mechanism, followed by the system's design, including cell architecture, electrode materials, separator materials, and operational modes. Some emerging applications of FCDI beyond desalination are also presented. Finally, current commercialisation status, challenges, and the future outlook of FCDI are discussed.

2 Historical Developments and Evolution

FCDI is a relatively recent innovation that evolved from foundational concepts first explored in the 1960s. The concept of "electrochemical demineralization" or "electrosorption" of water was first reported by Blair and Murphy in 1960 [16]. Early studies by Johnson and Newman in 1971 laid the groundwork for ion electrosorption using carbon electrodes [17]. However, it wasn't until the 1990s that CDI gained renewed attention with the development of advanced porous carbon materials such as carbon aerogels [18]. The membrane-enhanced CDI (MCDI) was introduced in 2004 [3], integrating ion-exchange membranes to enhance ion selectivity and charge efficiency, laying groundwork for future advancements.

FCDI was pioneered in 2013 by Jeon et al. [13], as a response to inherent limitations of CDI and MCDI, particularly their batch-mode operation and limited salt removal capacity. The key innovation was the use of flowable carbon slurry electrodes that could be regenerated outside the desalination cell, enabling continuous operation without the interruption of periodic electrode regeneration. This breakthrough sparked a wave of innovation, with subsequent advancements in both design and application [19].

Since then, research focused on optimising desalination performance by innovating the flow electrodes through exploring various carbon materials and improving their conductivity, stability, and flowability [19,20]. Concurrently, system-level enhancements were introduced, including improved cell geometries and innovative regeneration schemes which allow for energy recovery and stable continuous performance [10,21,22].

By the late 2010s, FCDI systems were successfully demonstrated for selective ion removal [23]. Studies also confirmed FCDI’s ability to operate at high water recovery and handle higher salinity feeds, making it a strong candidate for brine concentration applications [24]. Modelling and simulation work matured in parallel, offering insights into the combined electrodialytic and capacitive mechanisms and enabling performance prediction under various operational modes [25].

In the early 2020s, the scope of FCDI research broadened significantly. The technology was applied to emerging areas such as resource recovery (nutrients and valuable ions) and contaminant removal (organic and heavy metals) [19]. Today, FCDI remains a pre-commercial but rapidly advancing technology [26]. Its continuous operation, high recovery, tunable selectivity, and relatively low energy consumption, all position it as a compelling candidate for future desalination and resource recovery systems [19,27].

3 Principle of Operation and Advantages

FCDI was proposed to overcome several limitations of traditional CDI and MCDI systems by replacing the fixed porous electrodes with dynamic, pumpable carbon suspensions that circulate through designated channels on the current collectors [13]. This configuration allows ions to be continuously removed from the feed solution and adsorbed onto the surface of flowing carbon particles via the formation of electric double layer [28].

A standard FCDI module, illustrated in Figure 2, typically consists of three compartments: two outer electrode chambers (one for the cathode and one for the anode), and a central water chamber. The electrode compartments house the carbon-based slurry, while the central channel contains a spacer to allow feed flow. The electrode and water compartments are separated by IEMs, or any porous separating material [19].

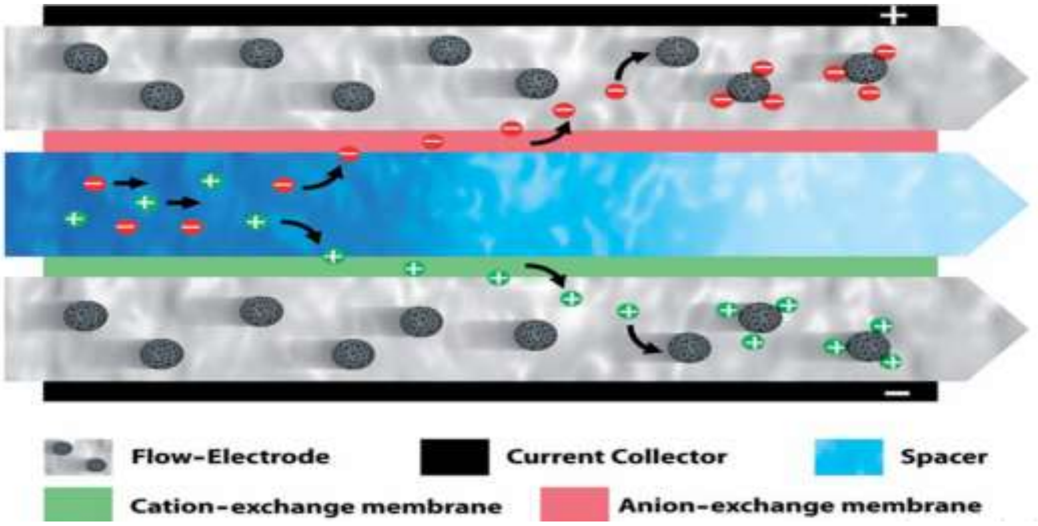

Fig. 2: Schematic representation of a typical FCDI cell [29].

When a low electric potential (~1.2 V) is applied, cations and anions migrate across the separating material towards oppositely charged flow electrodes, where they are electrostatically adsorbed [30]. This process resembles that of static CDI, but with a key distinction: the charge/discharge cycles occur outside the main desalination cell. The used flow-electrodes from the cathodic and anodic chambers are pumped into an external regeneration unit, where the oppositely charged suspensions are mixed, allowing spontaneous neutralization and salt release [13]. The regenerated carbon suspensions are then recirculated into the electrode compartments, enabling continuos operation. This arrangement supports a steady-state operation in which the compositions of effluent streams remain constant over time [31].

The unique configuration of FCDI leads to several operational advantages. Unlike static CDI or MCDI, where electrode saturation limits the cycle duration, FCDI offers continuous operation, reducing downtime and enhancing overall desalination efficiency. The ability to regenerate electrodes externally makes the process inherently more scalable, as performance can be improved simply by increasing the flow-electrode volume [13]. Additionally, the external regeneration system opens opportunities for energy recovery, as the mixing of oppositely charged suspensions can theoretically produce usable energy [31].

Studies have also shown that FCDI can achieve higher salt removal rates and maintain more consistent ion removal performance than traditional CDI systems, especially over long durations. FCDI's ability to desalinate high salinity feeds has been well reported in literature [32,33].

Compared to electrodialysis (ED), FCDI performs competitively in treating complex water chemistries and brackish water, with the added benefit of potentially lower energy consumption in certain scenarios. Furthermore, flow electrodes are less prone too fouling compared to stationary electrodes, as the continuous movement of the slurry helps minimise foulant accumulation on the surface of suspended carbon particles [34]. Although FCDI may not yet compete with the energy efficiency of RO, particularly of large-scale systems, it is more modular and requires less infrastructure, making it suitable for decentralized and flexible water treatment applications [19].

The comparison in Table 1 reveals that FCDI outperforms conventional capacitive technologies and electrodialysis in several critical aspects, with its main advantages include: i) continuous desalination enabled by external electrode regeneration

ii) Enhanced ion adsorption capacity and salt removal performance

iii) Potential for energy recovery during flow-electrode regeneration

iv) Ability to desalinate water with higher salinity levels

v) High scalability through increasing flow-electrode volume

vi) Ability to handle complex water chemistries while resisting fouling

vii) Modular and decentralised design

These features underline FCDI's potential for industrial-scale applications and position it as a promising candidate for next-generation desalination systems.

Table 1: Comparison of the key features and limitations of electrically driven desalination technologies [35,36,37,38].

Parameter	**CDI**	**MCDI**	**FCDI**	**ED**
Mode	Intermittent	Intermittent	Continuous	Continuous
Cell Complexity	Simple	Moderate	Complex	Complex
Charge efficiency	Low	Low to Moderate	High	Moderate to High

Salt Removal Capacity	Low	Low	High	High
Fouling Tolerance	Poor	Moderate	High	Poor
Ion selectivity	Limited	Improved with IEMs	Tunable (electrode design)	Fixed (by membrane type)
Key limitation	Low capacity and low salinity limit	Non-continuous operation	Risk of electrode clogging	Water splitting leading to pH shifts
Maturity level	Commercial	Commercial	Emerging	Industrial
Brine treatment feasibility	Not feasible	Not preferred	Promising	Possible

4 Mechanism and Advanced Operating Principles

The performance of FCDI is governed by electrochemical and mass transport phenomena that underpin both ion removal and charge transfer processes. This section provides a detailed explanation of the core mechanisms that define FCDI operation, focusing on ion storage within the flow-electrode and the associated mechanisms of charge transport. A clear understanding of these principles is essential for optimising system design, improving salt removal capacity, and tailoring electrode and cell configurations for advanced performance.

4.1 Ion Storage Mechanisms

4.1.1 Capacitive Ion Storage

In CDI technologies, ion removal is fundamentally driven by the formation of Electrical Double Layers (EDLs) on the surfaces of porous carbon materials [39]. Upon the application of an external voltage, ions in the feedwater migrate toward the oppositely charged electrode and are electrostatically adsorbed, forming EDLs on the accessible electrode surfaces [40]. Figure 3 illustrates commonly used EDL models, with a focus on the structure around a positively charged electrode [19].

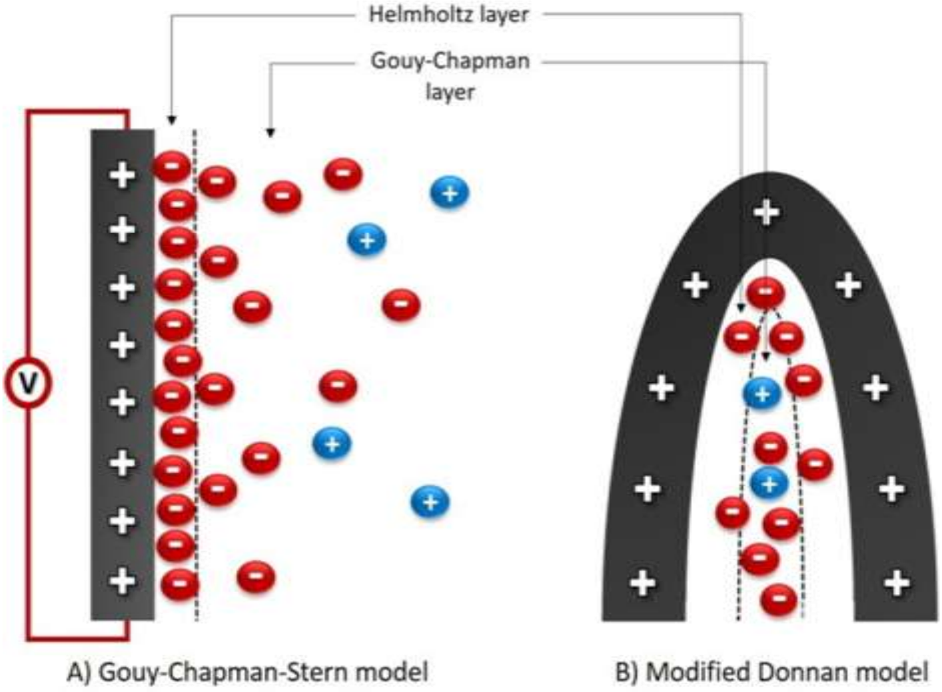

Fig. 3: Models explaining EDL formation and ion distribution [23].

The classical Gouy-Chapman-Stern model describes the EDL [41] as a combination of two distinct regions: 1) a compact layer where ions of the opposite charge are electrostatically accumulated close to the charged electrode's surface, followed by 2) a diffuse ion cloud, where ions disperse farther away [19].

Since CDI technologies primarily employ microporous electrodes [42,43], the applicability of the Gouy-Chapman-Stern model becomes limited. Instead, the modified Donnan model offers a more suitable theoretical framework, as it accounts for the overlapping of EDL within finite pores [44]. This mechanism emphasizes the importance of using materials with high surface area and porosity to enhance ion adsorption efficiency [45].

4.1.2 Faradic Ion Storage

FCDI technology can facilitate both capacitive and Faradaic ion storage mechanisms, depending on variables such as the electrode material and the magnitude of the applied electrical protentional. Nonetheless, Faradaic side reactions are typically unintended and remain relatively minor under standard operating conditions [46].

Upon applying a voltage difference, minor Faradaic side reactions may occur on the surface electrodes, such as carbon oxidation or water electrolysis, leading to pH changes in the electrolyte [47]. Although FCDI operates under relatively low voltages, faradaic reactions still occur during the process [48]. However, capacitive ion storage is the dominating mechanism in CDI processes under typical operating voltages (~1.2 V) and when standard carbon electrodes are employed [19].

In contrast, Faradaic ion storage mechanisms, such as redox reactions or ion intercalation, only become significant when using redox-active electrodes (such as transition metal oxides or conductive polymers) [49] or operating at higher voltages. These are typically associated with pseudocapacitive or hybrid CDI configurations, where at least one electrode is designed to engage in Faradaic processes. Such hybrid systems are being actively explored for their enhanced ion removal capacity, but they differ fundamentally from conventional FCDI systems [19].

4.1.3 Ion Storage Under Flow Conditions

A unique characteristic of FCDI is that even while carbon particles are in motion within the slurry, the suspension remains electrically conductive, and the EDLs on the particles persist during flow [31]. In fact, from a theoretical standpoint, the equilibrium electrosorption capacity of the carbon particles should remain the same regardless of whether the system is in a flow or static configuration [50]. Figure 4 illustrates the charge storage mechanism within a flow electrode system. In this configuration, a carbon-electrolyte suspension is circulated between two polarised current collectors, where ions from the electrolyte migrate to counterbalance the surface charges on the suspended carbon particles, allowing energy to be stored in the EDL during operation.

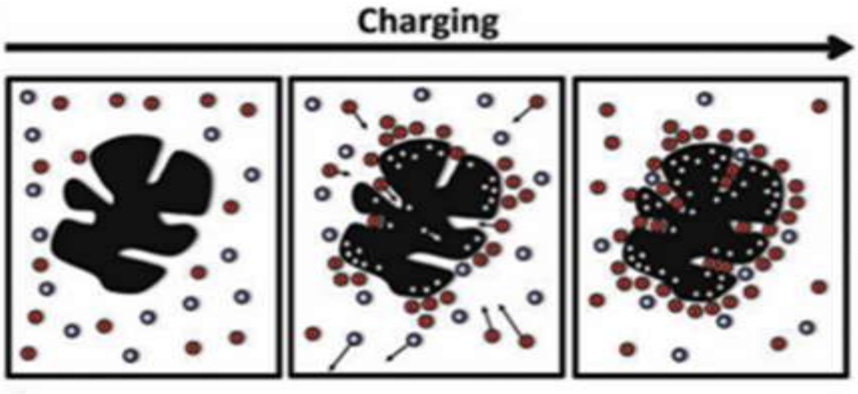

Fig. 4: Ion storage mechanism of flow electrode in FCDI [50].

4.2 Charge transport in flow-electrode

Charge transport in the flow-electrode includes the transport of both electrons and ions, as shown below in Figure 5. Electron transport occurs via three primary pathways: 1) direct contact between the carbon particles and the current collector, 2) conduction via a continuous network of physically connected carbon particles, and 3) transfer facilitated by redox reactions between particles, requiring the addition of a redox-active species in the flow-electrode. Meanwhile, ion transport occurs through two pathways: 4) through the bulk electrolyte along the surface of the particles, or via 5) migration within the EDLs surrounding the particles [51].

A deeper understanding of charge transport mechanisms within flow-electrodes are essential for enhancing FCDI desalination. It is widely accepted that electron percolation is highly dependent on the extent and quality of physical contact between conductive particles. Studies found that increasing the carbon content improved the connectivity between particles, hence it made electron movement more directional, but it also made ion movement more complex and indirect [51].

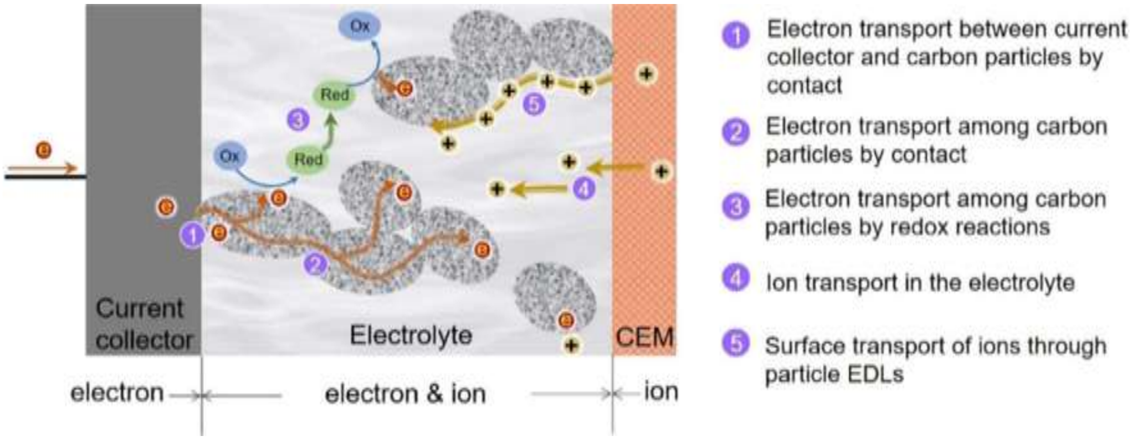

Fig. 5: Main charge transport mechanisms in flow-electrodes in FCDI [51].

4.3 Effect of Applied potential

The influence of applied voltage variation has been a central focus since the early development of CDI technology [52], and research continues to explore its effect for the optimisation of FCDI cell operation [53].

Recent investigations into the voltage-current characteristics revealed that increasing the applied voltage substantially enhances ion removal efficiency. This outcome can be readily explained through the lens of the EDL theory: higher applied voltage results in greater accumulation of surface charge on the electrode, thereby increasing adsorption capacity. However, the applied voltage must be limited to avoid water electrolysis. Given that the standard potential of water electrolysis is 1.23 V, studies restrict the operating voltage to around 1.2 V [54].

Electrochemical reactions associated with different applied potentials have also been examined by tracking pH variations during adsorption and desorption. These studies showed that the solution pH changed with applied voltage. For instance, at 1.0 V, the pH increases due to dissolved oxygen reduction, whereas at voltages >1.2 V, pH drops rapidly due to chloride oxidation at the anode. Specifically, applying 1.2 V can cause the pH to rise to 10 and decline to below 8 [55].

5 Cell Design

While the critical roles of electrode and membrane design are well acknowledged, it is equally important to emphasise the significance of overall system design. A commonly adopted configuration is depicted in Figure 6, which illustrates the primary components of a typical FCDI cell.

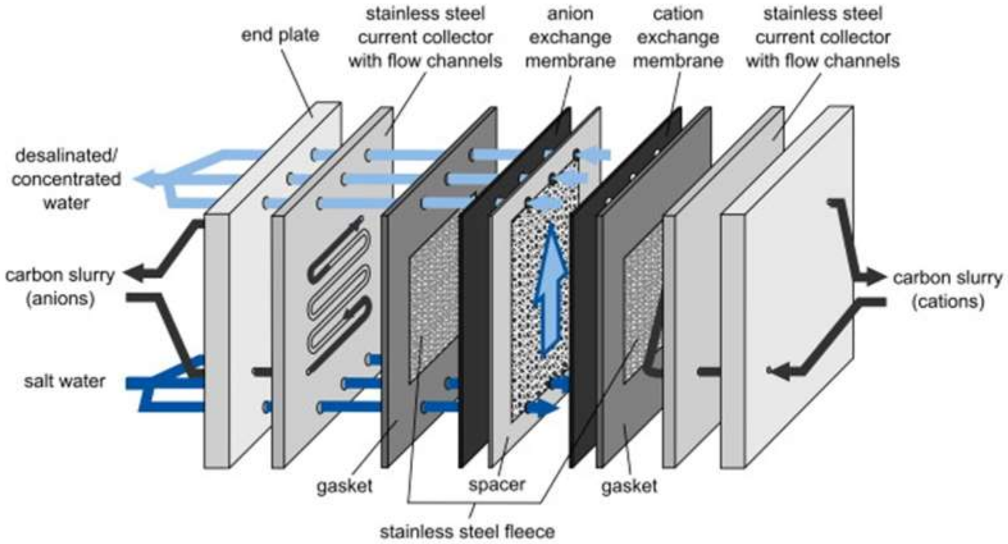

Fig. 6: Structure and components of conventional FCDI module [14].

Since Jeon et al. revolutionised the CDI cell architecture by introducing the flow-electrode concept, researchers have concentrated on optimising the design and functionality of each module component to improve the system's performance, longevity, and cost-efficiency [19]. The following section highlights several significant advancements that have emerged in this context.

5.1 Cell Architecture

The different FCDI cell architectures and designs can be divided into single- or dual-channel cells according to the number of outlet channels (excluding the flow-electrodes), as illustrated in Figure 7.

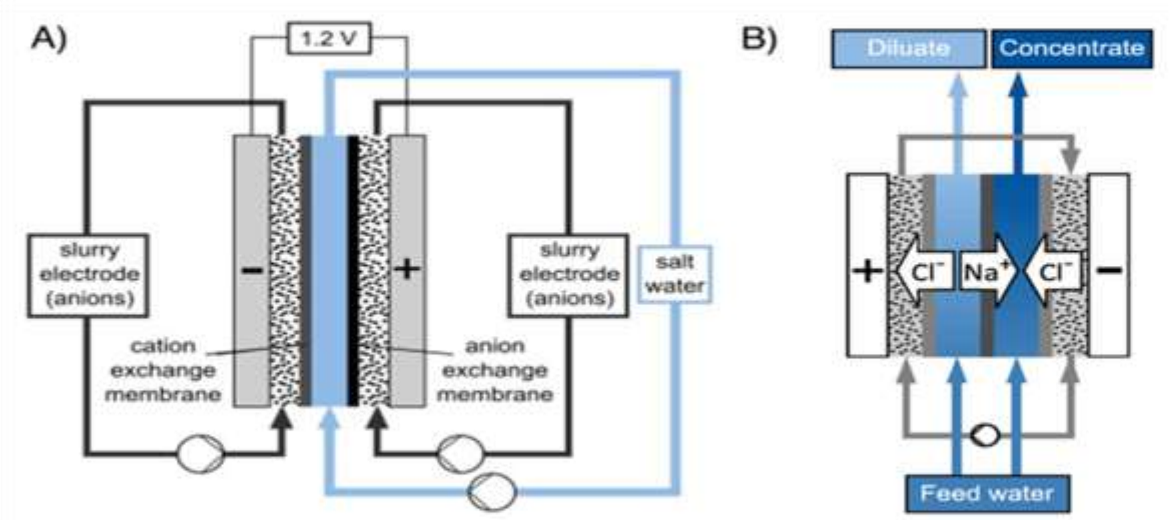

Fig. 7: Structure of (a) single-channel FCDI cell [11] and (b) dual-channel FCDI cell [24].

In a single-channel FCDI cell, the slurry electrode circulates through a serpentine flow path embedded in the current collector and enters the cell for ion adsorption [13]. The adsorbed ions can subsequently be desorbed by either neutralising the charge or applying a reverse potential, followed by electrode regeneration using standard techniques such as settling or filtration [11]. Although this configuration features a relatively simple design, it does not allow for simultaneous desalination and concentration processes. This limitation is effectively addressed by the dual-channel FCDI cell design.

In a dual-channel FCDI cell, the incoming saltwater is split into two streams, each flowing through separate channels divided by an IEM, facilitating simultaneous desalination and concentration. The electrode that adsorbs a specific type of ion is circulated to the opposite chamber for ion release [24]. This configuration bears resemblance to ED systems [19]. A key advantage of this cell design is its ability to produce two distinct outlet streams simultaneously (one of desalinated water and the other of concentrated brine) enabling continuous and efficient operation.

Other innovative cell arrangements have been reported in literature. For instance, although the majority of FCDI cells have a planar configuration, Porada et al. [31] introduced a design that incorporates tubular IEMs, illustrated in Figure 8. This new configuration not only enabled continuous desalination, but also continuous energy recovery.

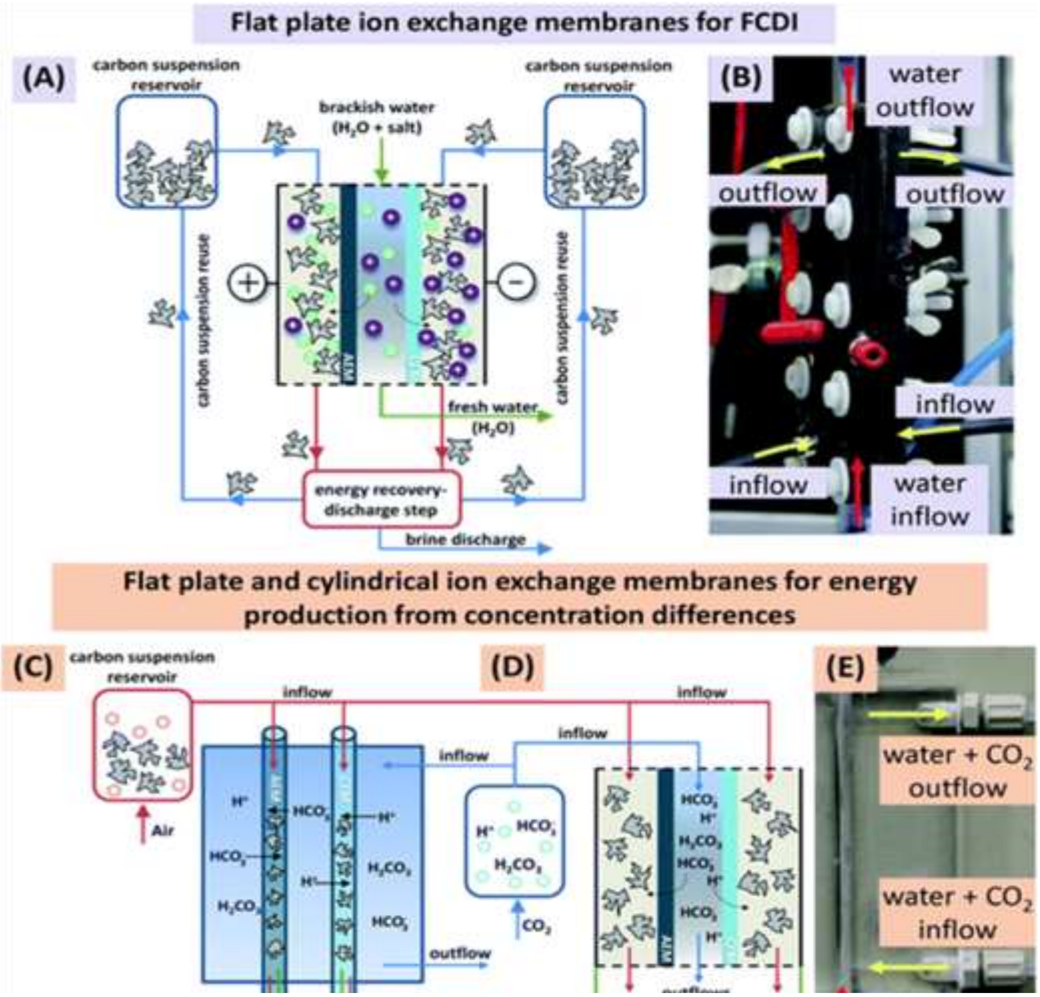

Fig. 8: A) Schematic diagram of continuous FCDI operation and (B) a photograph of the cell. Schematic diagrams of (C) tubular and (D) flat plate IEMs used for energy recovery. (E) A photograph of the tubular cell design [31]

Other ground-breaking design is by Cho et al. [56] utilised a "honeycomb-shaped" structure for a compact and scalable 3D FCDI, which could be used in a repetitive manner for upscaling. As illustrated in Figure 9, the insides of the channels were coated with IEM and a graphene layer (functioning as current collector). The porous structure provides structural support as well as a path for ion transfer.

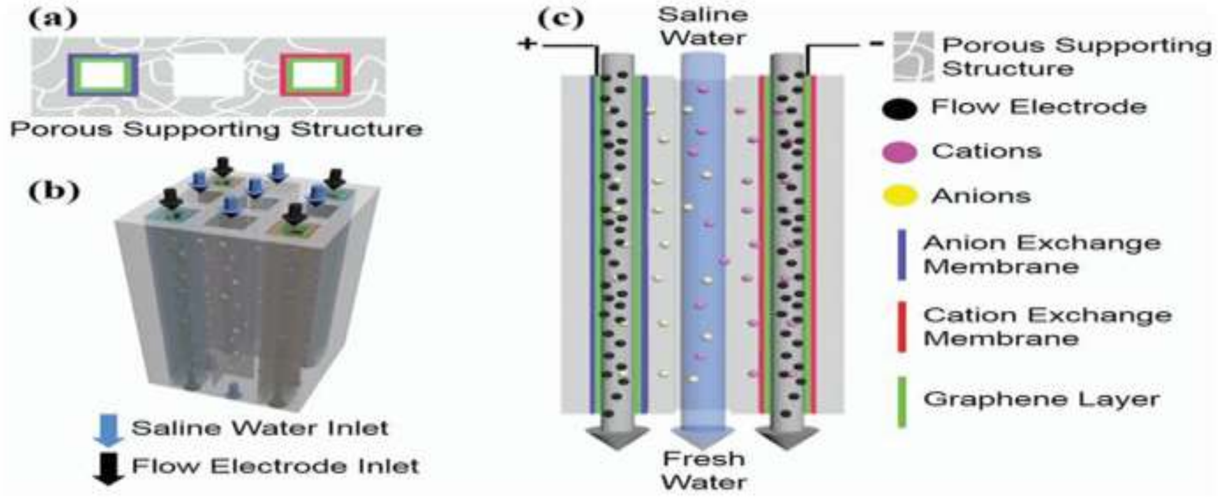

Fig. 9: Three-dimensional honeycomb-shaped FCDI cell: (a) top-view (1×3 channel cell), (b) 3×3-channel cell, and (c) desalination process [56]

The 3D FCDI system eliminates the need for a spacer, free-standing IEMs, and bulky current collectors, resulting in a significantly more compact and space-efficient cell design compared to conventional FCDI configurations. While the system is impressively scalable, the observed current density was lower than in conventional FCDI cells, but the desalination efficiency has increased threefold [56]. Moreover, the unit cell lends itself well to 3D scaling, with both desalination efficiency and capacity improving markedly as cell size or the number of units increases [57]. This innovative design has stimulated further exploration into advanced FCDI cell architectures.

5.2 Current Collectors

Current collectors are a core component of the FCDI module, responsible for creating the potential difference across the flow electrodes. Their material properties and dimensions play a critical role in facilitating charge transport by influencing the system's electrical resistance [19].

Ideal current collectors should exhibit high electrical conductivity, mechanical robustness, low weight, and cost-effectiveness. Additionally, they should be readily machinable, available, and offer excellent corrosion resistance within the operating voltage range of the FCDI cell [27].

In early FCDI studies [11,13], including the pioneering work by Jeon et al., stainless steel was commonly used for current collectors, often designed with carved, serpentine flow channels. However, stainless steel suffers from corrosion, particularly at the anode during the treatment of chloride-containing solutions. Consequently, graphite plates have become the preferred current collector material in subsequent research due to their superior corrosion resistance and overall stability such environments [29,58].

Porada et al. [31] used titanium wires and platinum plates as current collectors, but another innovative design was reported last year by Zhang et. al. [59] where 3D titanium mesh, illustrated in Figure 10, was used as current collector in FCDI for salt separation and enrichment. This new approach substantially enhanced the charge transfer process and exhibited exceptional cyclic stability over 100 desalination cycles. Other reported current collector materials include gold-plated copper [60] and epoxy-impregnated graphite plates [61].

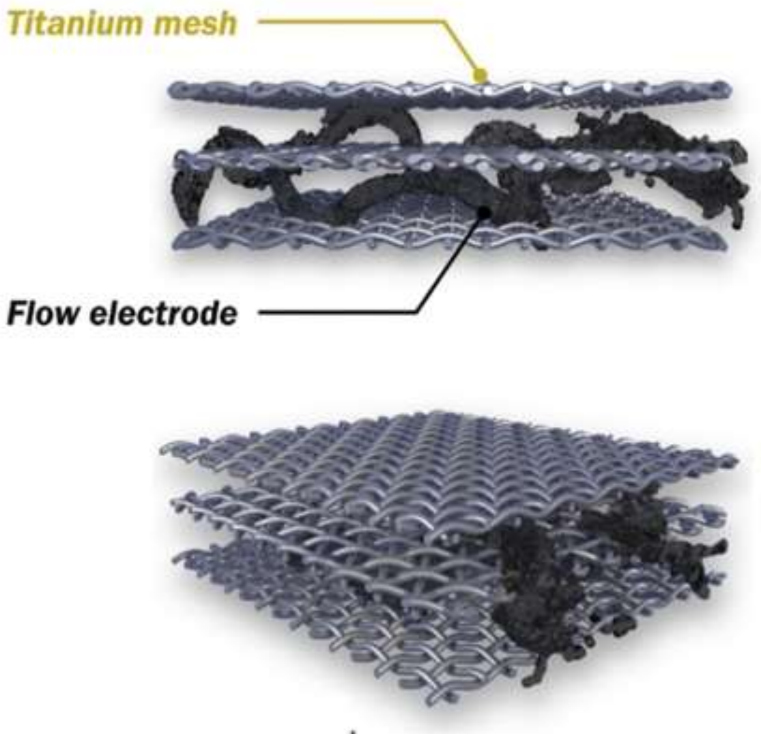

Fig. 10: Three-dimensional titanium mesh current collectors [59].

5.3 Flow Channels

The design of flow channel geometry, including the configuration of inlets, outlets, and the distribution of streams within the cell compartments, differs across studies. The geometry of the channels engraved on the surface influences the contact area, which significantly impacts ion transport. Moreover, it affects the system's energy consumption, largely governed by the rheological behaviour of the carbon slurry [19].

Typically, these channels are carved on a single side of the current collector. However, graphite collectors with channels etched on both sides have also demonstrated effectiveness in stacked FCDI cell configurations [19]. A recent innovative approach is Yang et al.'s [62] use of titanium meshes instead of the bulky current collectors. This modification reduces the charge transport distance and enhances ion adsorption onto the carbon particles.

5.4 Separating Material

The separator plays a pivotal role by preventing the mixing of the flowing carbon particles with the feed water, while permitting selective ion transport to and from the electrode channels. It also serves as a barrier against the intrusion of foulants into the flow electrode solution. Nevertheless, separator fouling remains a potential challenge in the operation of FCDI systems.

In most FCDI cell architectures, IEMs are employed as separators [63]. IEMs originally developed for ED applications, such as Neosepta membranes from Astom Corporation and fumasep membranes from Fumatech BWT GmbH, have been widely used in FCDI studies [11,13,29,31].

Yang et al. showed that IEMs with low electrical resistance and high exchange capacity are essential for facilitating effective charge transfer, thus improving the overall desalination efficiency in FCDI systems [64]. Notably, a recent study reported that performance deterioration due to IEM fouling was minimal, attributing this to the inherently low fouling tendency of the membrane [65].

To simplify the FCDI system and reduce material costs, Lee et al. developed a hybrid structure in which IEMs were coated directly onto a porous ceramic spacer, effectively combining the membrane and the spacer. This innovation eliminated the need for costly free-standing IEMs [66].

Beyond the conventional use of IEMs, alternative separators have also been explored. Nativ et al. [67] proposed the use of NF membranes in FCDI cells to achieve selective separation between monovalent and divalent ions. Hatzell et al. [58] proposed a configuration utilizing a porous separator, representing a promising direction for developing low-cost FCDI systems [63].

5.5 Spacer and Endplates

The spacer, which channels the flow of water between the separating materials, influences FCDI's performance by determining the hydraulic retention time. Materials commonly used for spacers include nylon [68] and polyester [32], owing to their mechanical stability and chemical resistance. In addition, various alternative materials have been explored, such as mesh spacers, polymeric flannel spacers, and shaped silicone gaskets, each tailored to fit specific FCDI cell architectures [11,13,29,31]. Cho et al. [56] utilised a cordierite spacer to prolong the residence time of saline water, thereby improving ion removal efficiency. Additionally, coating a porous spacer with CEM and AEM has been proposed as a cheaper alternative to standalone IEMs [66].

Although endplates do not directly influence the performance of FCDI systems, they play a role in ensuring the structural integrity and longevity of the module [19]. The complex design and stringent sealing requirements of FCDI units contribute to elevated operational costs [69]. To balance durability and affordability, materials such as polyvinyl chloride, polycarbonate, and acrylic are commonly employed [70].

Researchers explored innovative ways to improve the performance and broaden the range of applications of FCDI [19]. The following section presents the diverse modes of FCDI configuration.

6 Operating Configuration

The operational mode has a considerable influence on the FCDI system's desalination performance. Studies on FCDI operation are mainly classified into two categories: single- and multi-module configurations. In single-module setups, the flow electrodes circulate within a single unit, whereas in multi-module configurations, electrodes flow across multiple modules to enable continuous desalination [54].

6.1 Single Module Configuration

In open-cycle operation with continuously refreshed flow electrodes, the system can theoretically achieve infinite ion adsorption capacity. However, the high operating costs of maintaining a constant supply of fresh flow electrodes render this approach economically infeasible in most practical applications [57]. Therefore, closed-cycle operation modes are used in practical FCDI operation. Two types of closed-cycle operation are the Isolated Closed-Cycle (ICC) mode and Short-Circuited Closed-Cycle (SCC) mode, illustrated in Figure 11, different depending on whether the flow electrodes are mixed or not.

In ICC mode, the cathode and anode flow electrodes are directed into two different reservoirs following the adsorption process. Electrosorption and desorption occur sequentially, resembling the batch mode of traditional CDI systems [51]. Initially, conductivity decreases rapidly as ions are adsorbed, but it soon increases again due to electrode saturation and the limited availability of active adsorption sites, characteristic of fixed electrode systems [7].

In contrast, in SCC mode, the cathode and anode flow-electrodes are mixed in a single reservoir. This shared recirculation facilitates faster ion release and regeneration, improving ion removal and reducing energy demand compared to ICC [51].

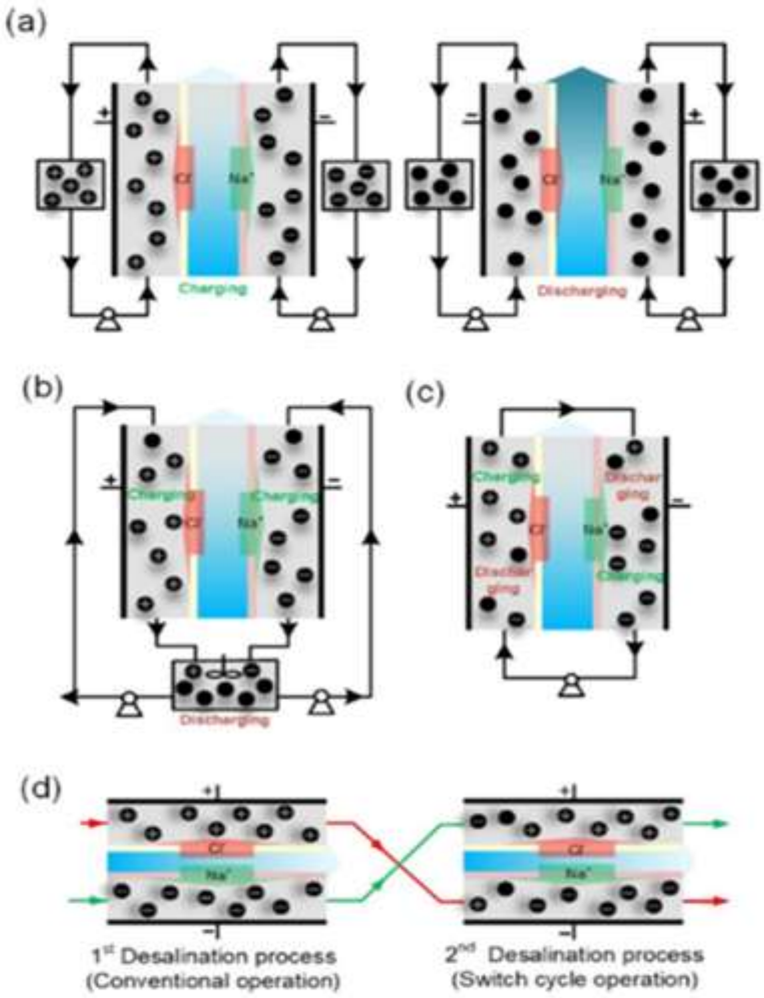

Fig. 11: FCDI operation modes: (a) Isolated Closed-Cycle (ICC), (b) Short-Circuited Closed Cycle (SCC), (c) Single Cycle (SC), and (d) switch cycle [51].

The simple design of Single Cycle (SC) mode innovated by Ma et al. [71], incorporates a single flow loop in which flow-electrode adsorbing and desorbing occur simultaneously. SC mode offers a more compact system configuration and enhances ion removal rates.

In both SCC and SC modes, ions ultimately accumulate in the circulating electrolyte [51]. Carbon particles can be separated from the concentrated brine or electrolyte via filtration. Nevertheless, efficient brine separation from the solid electrode material remains a major challenge. Some studies have proposed solutions such as incorporating microfiltration modules into the electrode reservoir to enable continuous ion removal and brine discharge [72].

In 2015, Rom et al. [14] proposed the first continuous single-module FCDI system using a single flow electrode stream that combines desalination and regeneration. The module integrates three IEMs and two spacers, resembling an ED cell pair. This configuration allows for the simultaneous production of a dilute and a concentrate stream, as the flow-electrode is always recycled and regenerated [14].

Doornbusch et al. (2016) [15] proposed an innovative FCDI configuration employing fluidized bed electrodes. In this design, relatively large carbon beads are suspended within a vertically oriented flow cell, leveraging gravity to extend their residence time. Because the particles settle faster than the continuous water phase flows, their concentration within the module increases, enhancing performance. Meanwhile, the overall carbon concentration in the system, including tubing, remains lower, which eases pumping requirements.

In 2016, Yang et al. [70] introduced the first FCDI stack design, which was developed by simply stacking individual FCDI cells, each incorporating a single pair of IEMs. This configuration enabled compact cell integration and enhanced scalability.

6.2 Multi-module Configuration

Jeon et al. [73] introduced an innovative FCDI operation mode called the switch cycle mode, where the charged cathode and anode flow electrodes of the first module are rerouted to the opposite channels of a second module. This setup achieved improved desalination performance over the SCC mode.

Moreover, by altering the position of the IEMs in the second module, the system can be transformed into a new configuration known as continuous cycle mode, wherein the effluent from the first module corresponds to desalinated water and that from the second module represents the concentrated brine stream [57].

7 Flow Electrode

Flow electrodes are fundamental to achieving continuous operation in FCDI systems. They consist of charged carbon particles suspended in an electrolyte [31] To optimise process stability, energy efficiency, and the quality of the treated water, it is crucial to understand how electrode properties influence FCDI operational parameters [74]. Given their central role, considerable research has focused on enhancing both the carbon materials and the electrolyte composition that constitute the flow electrodes.

7.1 Carbon-based Materials

Activated Carbon (AC) was predominantly employed in early FCDI studies [8,11,13] as the active material for preparing flow-electrode suspensions. AC is considered highly suitable due to its favourable electrochemical characteristics, including high surface area, low cost, and ease of processing [74]. In FCDI systems, the effectiveness of ion separation is largely determined by critical characteristics of the AC electrodes, including particle size, pore volume, surface area, and surface functional groups [32].

Rommerskirchen et al. [75] demonstrated that the presence of mesopores in AC improves desalination performance by facilitating ion transport compared to predominantly microporous structures. Most commonly used AC materials in FCDI have specific surface areas in the range of 1000-1500 m^2/g. Although high surface area generally correlates with improved ion adsorption capacity, material selection is also driven by cost, particle morphology, and size distribution [15].

The electrical conductivity of the flow-electrode is highly dependent on the carbon mass loading (wt%) in the flow-electrode suspension [15]. Initially, flow electrodes were formulated with low carbon content so as to be less viscous and more pumpable. However, Porada et al. [31] later showed that increasing AC content significantly enhances desalination performance due to improved electrical conductivity and charge transport. Despite these benefits, higher AC concentrations result in elevated suspension viscosity, thereby increasing the required pumping energy. This trade-off relationship of improved salt removal versus energy efficiency constrains the practical carbon loading to below 20 wt%, beyond which the risk of clogging and flow issues becomes significant due to the physical nature of the carbon particles [32].

Consequently, two main targets have emerged to develop optimum AC electrodes for FCDI operation: 1) maximising loading capacity to enhance salt adsorption, while 2) minimising viscosity to reduce pumping energy and operational complications. Simultaneously achieving both objectives remains a significant challenge. Therefore, recent research has focused on optimising charge percolation and exploring alternative carbon materials, non-carbon additives, and surface treatments. Hatzell et al. [9] presented a comprehensive review on materials used in flow-electrodes.

Hatzell et al. [76] modified AC using nitric acid to introduce oxygen-containing surface functional groups. This chemical oxidation process was found to reduce the viscosity of carbon suspensions, thereby enabling higher carbon mass loadings while maintaining pumpability.

Similarly, Park et al. [32] developed and evaluated surface-modified AC suspensions incorporating ion-selective functional groups. Their aim was to achieve greater carbon loadings without compromising the flowability of the suspension.

To further enhance FCDI performance, Xu et al. [77] proposed an asymmetric FCDI configuration using an AC/manganese-dioxide suspension as the anodic flow electrode, and a conventional AC suspension as the cathodic one. This system successfully expanded the operational voltage window to 1.8 V, significantly improving salt removal efficiency compared to traditional symmetric FCDI cells.

Chang et al. [74] also explored asymmetric FCDI systems, using activated carbon at the anode and copper hexacyanoferrate at the cathode. This combination also enabled operation at higher voltages and improved ion removal performance. However, the system exhibited a greater pH shift in the concentrate stream compared to conventional symmetric systems, posing potential challenges for downstream applications.

All these studies share a common conclusion: the properties and composition of flow-electrode materials are critical determinants of FCDI performance. The research to date has laid a strong foundation and provided an essential set of strategies for tailoring flow-electrode materials. Importantly, the selection of the optimal flow electrode may vary depending on the target application.

7.2 Electrolyte Concentration and Composition

In a deionized water solution with a typical electrolyte such as NaCl, the solution itself exhibits relatively low electrical resistance. However, the introduction of AC to the electrolyte creates a non-homogeneous mixture, resulting in a moderate yet non-negligible electrical conductivity ranging from approximately 0.1 to 1 mS/cm [78]. Within the FCDI system, when the flow electrodes come into contact with the current collector, electrons are transferred to the carbon particles. Despite this mechanism, the overall flow-electrode’s electrical conductivity is generally lower than that of static electrodes in conventional CDI systems [15]. This reduced conductivity in FCDI poses a limitation: charge transport is primarily hindered by the relatively high internal electrical resistance of the flow-electrodes, which constrains the desalination and energy efficiency of the process.

To address this limitation without resorting to increasing the carbon loading, two alternative strategies have been explored [33]: 1) increasing the electrolyte salinity, which can reduce the internal resistance within the flow electrode suspension by enhancing ionic conductivity; in addition to 2) adding supplementary charged species, such as conductive additives or redox-active agents, to facilitate charge transfer and percolation efficiency.

Yang et al. [33] employed high salt concentration electrolyte and confirmed its effectiveness in reducing the internal resistance of the electrode and improving desalination efficiency. However, it can lead to undesired ion diffusion into the feed water, compromising product quality. Therefore, optimisation is essential to balance desalination efficiency with minimal reverse ion diffusion [10].

Another strategy to improve the conductivity of the flow-electrode is the introduction of conductive additives, which could be of two: (i) highly conductive solids, or (ii) aqueous electron-mediators.

Liang et al. [79] incorporated carbon black into AC-based flow electrodes. Despite its relatively low specific surface area (<120 m^2/g), carbon black significantly enhanced desalination and charge transport by lowering the internal resistance of the FCDI system. Surprisingly, this additive also reduced the system’s energy consumption and enabled a broader voltage operation window.

Yang et al. [64] evaluated graphite powder and demonstrated that its particle size, shape, conductivity, and pore structure influence FCDI performance. The authors concluded that plate-shaped graphite particles showed improved conductivity without clogging issues and attributed this observation to the particles' alignment with the direction of flow and its larger size.

Both Cho et al. [80] and Tang et al [81] demonstrated excellent electrochemical properties when adding carbon nanotubes to the flow-electrode, due to their hollow tubular structure and interconnected nanoscale network. Just 0.25 wt% carbon nanotubes addition enhanced the electrical connectivity leading to double the salt removal rate. However, carbon nanotubes tend to agglomerate due to strong van der Waals forces and poor hydrophilic properties [57].

Graphene and reduced graphene oxide have also proven effective. Li et al. [82] reported that these additives improve electron transport and dispersion of carbon particles, contributing to enhanced salt removal efficiency.

Nonetheless, while solid additives can significantly improve conductivity, they pose a risk of aggregation and clogging, especially at high loadings [19]. Beyond solid additives, electrolyte pH control has also been proven beneficial, particularly that pH fluctuations caused by minor Faradaic reactions can impair desalination efficiency [33]. Nativ et al. [48] mitigated this by introducing acid and base to neutralise the pH in the anodic and cathodic flow-electrodes, thereby enhancing the salt adsorption capacity.

Electron mediators represent another approach to improve charge transport. These additives function via fast, reversible redox reactions.

Hatzell et al. [8] found that p-phenylenediamine significantly increased the capacitance and reduced ohmic resistance compared to unmodified carbon slurries. Similarly, Ma et al. [83] incorporated hydroquinone, enabling rapid redox cycling with benzoquinone. This approach significantly boosted both ion adsorption and desorption rates.

However, the addition of chemical mediators must be approached cautiously. Since ion migration across the membrane is governed by chemical potential gradients, there is a risk of chemical transfer into the product stream. Preventing the introduction of toxins into the effluent water necessitates careful selection and monitoring of conductive additives [10].

7.3 Regeneration

The flowability of the flow-electrode enables regenerating the carbon material elsewhere outside the main cell, allowing for a wide range of configurations. The earliest FCDI experiments employed simple single-pass operation modes for both the saline feed and the flow electrodes [13]. In these initial studies, regeneration was implemented in batch-like charge-discharge cycles [29], through a separate regeneration module [11], a dedicated tank [19], or via an external treatment step [58]. As the technology evolved, researchers proposed novel regeneration strategies to support more efficient or continuous operation, such as 1) regeneration by mixing, 2) electrical regeneration, and 3) chemical reactivation.

The research group who reported the first FCDI publication also pioneered the concept of regeneration by mixing [29]. In this method, oppositely charged flow electrodes are combined, enabling electrical neutralisation and ion desorption. The adsorbed salt ions are released into the continuous phase, while the carbon particles are simultaneously regenerated. This approach can be sustained for extended periods as the salinity of the liquid increases gradually. This method has been widely adopted in subsequent FCDI studies because of its technical simplicity and semi-continuous operation potential [84,85].

Electrical regeneration was introduced in 2014 [11], where two FCDI cells share the flow-electrode in a circuit. One cell continuously performs desalination, while the other operates as a regeneration module, concentrating saline water and electrically discharging the flow electrodes. This approach also opened the door to energy recovery from the flow electrodes during regeneration, a concept first investigated by the same research group that introduced FCDI [29]. They demonstrated that energy could be harvested during the discharge phase in a manner analogous to the charge-discharge cycles of conventional CDI systems. A key advantage of electrical regeneration is its operational stability, which can be challenging to achieve in systems relying on mixing-based regeneration. The latter necessitates additional operations (i.e. settling or crossflow filtration) to retain the carbon particles in the flow-electrode.

Complete charge-discharge reversibility in any of the above-mentioned regeneration methods is unachievable due to the concentration gradient between the feed and the electrolyte [86]. Maintaining performance over long-term operation requires effective regeneration and activation to restore the adsorption capacity of the carbon-based material. While thermal regeneration of spent carbon-materials is generally the most popular choice due to its simplicity, the energy demand is not called for in the case of FCDI applications. Hence, chemical reactivation, which only involves acid washing followed by neutralisation, is recommended. It is worth mentioning that this process also often enhances the surface area [87].

8 Applications beyond Desalination

While the most extensively studied application of FCDI is water desalination [27], more studies have explored FCDI for resource recovery, contaminant removal, and other emerging applications [19,27].

Linnartz et al. [88] used FCDI for salt metathesis through a double displacement reaction. Their study employed four identical FCDI cells to concentrate magnesium sulphate from dilute feed solutions. This method shows significant potential for salt recovery processes by allowing concurrent salt recombination and concentration, yielding high-value product streams.

Zhang et al. [89] developed an FCDI process targeting ammonia recovery, wherein a membrane module was submerged in the flow cathode, enabling the direct stripping of ammonia from the electrode stream. This approach facilitates the selective removal and preconcentration of ammonia, which can subsequently be recovered as ammonium salts, with potential market value as fertilizers. The same research group later presented a simplified FCDI system based on charge-discharge cycles for ammonia recovery from wastewater [90]. Similarly, Fang et al. [85] employed an SCC FCDI system for ammonia recovery, achieving favourable concentration factors using synthetic wastewater as a feed.

Beyond nutrient recovery, He et al. [91] applied FCDI in brackish water softening, again using the SCC mode. The system was shown to be cost-effective, and the continuous mixing of charged carbon particles played a critical role in inhibiting scaling on the electrode surface.

FCDI was employed for the simultaneous removal of multiple heavy metals. Researchers explored cadmium removal [92] and copper removal [93] using FCDI under continuous operation mode. Notably, the setup enabled efficient regeneration and reuse of the electrode material, highlighting FCDI's potential for sustainable and scalable treatment of metal-contaminated water.

The growing interest in FCDI in recent years reflects the technology's flexibility and promising potential. Beyond the previously discussed applications, FCDI has been explored for nutrient recovery, including nitrogen and phosphorus [94], as well as for the removal of contaminants like nitrate [68] and uranium [84].

In addition to standalone FCDI systems, hybrid configurations integrating FCDI with conventional processes, such as NF [95], have also been investigated. Similar to ED, FCDI could further concentrate RO brine [24], as a step towards achieving ZLD.

9 Commercialisation Status, Challenges, and Future Perspectives

FCDI has emerged as a promising electrically driven desalination technology, offering continuous operation, high water recovery, and unique advantages in treating high salinity streams. However, its development remains in the early stages [19]. The transition from laboratory prototypes to commercially viable systems is still hindered by a range of technical and economic challenges.

9.1 Current Status

Despite growing interest in FCDI, most reported systems remain limited to small-scale setups (less than 100 L/day) [27], with no pilot- or full-scale commercial units currently in operation [19]. This limited scale hinders accurate assessment of capital costs and long-term stability under industrial conditions, thereby delaying its market readiness [96]. While the flat systems are currently predominant [97], ongoing research is exploring alternative geometries to improve scalability and operational efficiency [56]. Nonetheless, system durability remains a concern, especially due to carbon particle clogging within the flow channels. CFD simulations have proven valuable in designing flow paths and reducing dead zones [98,99], thereby enhancing mass transfer and operational longevity.

9.2 Economic and Energy Perspectives

Regarding FCDI’s total capital costs, more than 50% is attributed to the high cost of IEMs [100], which is a primary barrier to FCDI deployment. This encouraged researchers to use other more cost-efficient types of separators as discussed above [63]. Similarly, current collectors and flow-electrodes remain costly but could be improved by better design and material selection [101]. Pumping costs contribute to most operating costs [102], while the pretreatment requirements to mitigate fouling and scaling further increase the economic burden [27]. Despite these challenges, the modularity of FCDI systems and potential for diverse applications could enhance economic feasibility [19].

Regarding FCDI’s energy efficiency, it is substantially better than conventional CDI [72]. This is largely attributed to the pseudo steady-state operation of FCDI, enabled by continuous electrode regeneration [27]. Furthermore, 36% of energy stored in the charged electrodes was successfully recovered before regeneration, further improving system efficiency [103].

Nevertheless, a key disadvantage lies in the high pumping energy required for electrode slurry recirculation, contributing to as high as 60% of the total electrical energy [27]. Optimising system-level operation to balance electrical and hydraulic energy demands is crucial for achieving overall efficiency.

Importantly, FCDI operates at low voltages (~1.2 V), making it suitable for integration with off-grid renewable energy sources. Pilot-scale CDI systems powered by photovoltaics have already demonstrated continuous desalination, suggesting a viable pathway for future FCDI deployments in remote or decentralised contexts [104].

9.3 Operational Challenges

While FCDI can achieve high water recovery (up to 97%) [103], this performance can be compromised by water transport through IEMs diluting the brine, which is the challenge faced by electrodialysis [27]. Another common challenge is the fouling and scaling of membranes, which reduce system performance, elevate energy demands, and shorten lifespan, particularly when treating complex feedwaters [27]. Although pretreatment and cleaning protocols are effective, they add cost and maintenance burdens.

9.4 Future Outlook and Research Needs

To accelerate the commercialisation of FCDI, several key research directions must be prioritised. One critical area is ell design and system optimisation. Novel architectural designs and assemblies can improve modularity and scalability while reducing component bulk.

Equally important is the development of advanced materials. Innovations such as profiled or composite IEMs and charge-transfer flow-electrodes offer the potential to enhance ion selectivity, reduce energy consumption, and ultimately lower capital costs.

Another promising pathway lies in system modelling. Comprehensive and experimentally validated models capturing both capacitive and electrodialytic mechanisms are needed to predict and optimise performance under varying operational conditions.

Despite FCDI's clear potential as a brine concentrator, its integration with RO is overlooked. FCDI–RO hybrid systems for ZLD remains a major research gap, with only one study to date [105]. Their potential for energy-efficient, high-recovery desalination warrants focused attention.

In parallel, application targeting can significantly strengthen the case for FCDI commercialisation. Niche markets that require selective ion removal or resource recovery, such as phosphate, lithium, or ammonia extraction, offer opportunities where FCDI may outperform conventional technologies, both technically and economically.

Finally, industry–academia collaboration is essential. Robust partnerships can support prototype validation, reduce production costs through economies of scale, and facilitate the customisation of systems to meet specific industrial or municipal requirements.

10 Conclusion

Flow Capacitive Deionization (FCDI) is emerging as a promising electrically driven technology. Its unique ability to operate continuously, tolerate high salinities, and achieve high water recovery at relatively low specific energy consumption positions it as a compelling candidate for advanced brine management and Zero Liquid Discharge (ZLD) strategies.

Yet, despite these advantages, the pathway to commercial deployment remains hindered by technical, economic, and scalability challenges. In particular, the integration of FCDI with reverse osmosis for complete ZLD has not been adequately explored, representing a critical opportunity for future research. Continued progress in materials development, system modelling, targeted applications, and collaborative scale-up efforts will be essential to unlock FCDI's full potential and position it as a viable solution for next-generation desalination and resource recovery.

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