

Advances in efficient desalination technology of capacitive deionization for water recycling

Yuhao Tong, Shuang Zhou, Jun Zhou, Guanteng Zhang, Xiaolin Li, Chunxia Zhao and Pengyan Liu

ABSTRACT

Available freshwater resources are becoming harder to obtain due to climate change, population growth, industrial development, and water pollution. The main technologies in the field of wastewater desalination include reverse osmosis, electrodialysis, thermal distillation, and adsorption etc. Capacitive deionization technology (CDI) belongs to a novel electrochemical desalination technology with low energy consumption and low environmental impact, simple equipment structure and convenient operation. With the importance of wastewater desalination highlighted, some great technological progress of CDI has been made in electrode materials, reactor structure and the hybrid process. In this paper, the development of CDI technology was expounded from three aspects to achieve the goal of strong adaptability, low cost and strong adsorption capacity by analysis of the latest research papers. Corresponding improved methods of CDI are summarized to solve the main technology bottlenecks such as the inefficient and vulnerable electrode materials, low selectivity and unreasonable unit structure, and limitations of single CDI unit for promoting the continuous development of CDI technology.

Key words | capacitive deionization, desalination, electrode materials, reactor structure, water recycling

Yuhao Tong
Shuang Zhou
Jun Zhou
Guanteng Zhang
Xiaolin Li
Chunxia Zhao (corresponding author)
Pengyan Liu
College of Chemistry and Environmental Science,
Hebei University, Institute of Life Science and
Green Development, Hebei University, Key
Laboratory of Analytical Science and Technology
of Hebei Province,
Baoding 071002,
China
E-mail: zhaocxhbu@edu.cn

HIGHLIGHTS

- The main technology bottlenecks of CDI were analyzed from three aspects.
- Review the development of CDI based on electrode material, novel process and hybrid process.
- New electrode materials are introduced and analyzed for the future development of CDI.
- The energy consumption of novel FCDI-NF hybrid process is significantly reduced.

INTRODUCTION

Freshwater resources are essential for the sustainable development of human society. Rapid population growth, urbanization, and climate change are putting tremendous stress on freshwater resources (Fan *et al.* 2020); approximately one-fifth and one-third of the world's population live in areas of water scarcity and in countries with

moderate to high water stress, respectively, according to the report of UN Water (Chen *et al.* 2020). In the past decades, the usage and treatment of water in China has grown tremendously due to the large population and rapid economic development (Xu *et al.* 2020). Water recycling can be an effective option for saving water resources, reducing the environmental impacts from the discharge of treated wastewater, and reducing the cost and energy involved in water resource management (Lyu *et al.* 2016; Takeuchi & Tanaka 2020). The development of novel

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water regeneration technology is of great significance to alleviate the crisis of freshwater resources.

Traditional nonthermal distillation methodologies, such as reverse osmosis (RO), adsorption/ion exchange, and membrane desalination (MD) (Burakov *et al.* 2018; Folaranmi *et al.* 2020; Shi *et al.* 2020), have wide applications in desalination and water purification, while membrane fouling, adsorbent regeneration and high energy consumption are always problems to be solved (Naushad *et al.* 2015). Capacitive deionization (CDI) is a promising new technology for water desalination and ions removal compared to other traditional desalination methodologies, due to its low energy consumption (i.e. room temperatures, low pressures and low voltages), low capital and processing costs, easy operation and maintenance processes, and environmentally friendly characteristics (i.e. without chemicals or hazardous substances) (Khalil *et al.* 2020). CDI has emerged as a promising alternative desalination technology of reverse osmosis, electrodialysis and thermal distillation (Zhang *et al.* 2018; Tang *et al.* 2019). The electrosorption/desorption processes of CDI for deionization is based on electric double layer theory. Ions in the feed water will be attracted on the electrode with opposite charge by an external electrical potential (very low voltage, 1.2 V), and desorbed into the concentrate from the electrode by a reversing potential for a continuous desalination process (Faisal *et al.* 2020).

The technical principle of CDI is shown in Figure 1. Ions are removed by transferring from aqueous solution to

the electrode surface, the charge balance is achieved on the electric double layer, and the effluent is purified (Figure 1(a)). The ions or charged particles adsorbed on the surface of the electrode material are released into solution to realize the electrode regeneration through reverse connection or short-circuit voltage (Figure 1(b)). During the charging and discharging process of the CDI electrodes, the absorption and desorption of ions are completed, respectively. Therefore, the electrode materials with huge surface, ultra-high capacitance and high desalination efficiency are essential to CDI technology for water resources recycling.

Porous carbon electrodes materials are widely used in electrostatic adsorption of ions in the CDI process. Significant efforts have been made in recent decades in the development of customized porous carbon materials for CDI including carbon nanotubes, graphene, MXene, aerogels, xerogels, mesoporous carbon, and activated carbons. Although posing unique benefits, so far these materials have generally failed to provide a significant competitive advantage to traditional adsorption and RO in either capital or operating cost due to low salt adsorption capacity and carbon electrode oxidation (Landon *et al.* 2019). Nowadays, how to promote the desalination efficiency of CDI device is still a difficult problem for many researchers to develop materials with ultra-high capacitance or new processes with more efficient desalination performance (Zhao *et al.* 2020).

The desalting performance of CDI also depends on the operating parameters including external voltage, inflow velocity, thickness of interlayer between two electrodes and design of flow channel, and quality, species and concentration of solution ions etc. (Chen *et al.* 2018). Commonly used CDI desalination performance evaluation indicators mainly include electroadsorption capacity, charge efficiency, average desalination rate, and long-term stable desalting belonging to reactor structure optimization (Yasin *et al.* 2018; Maheshwari *et al.* 2020; Wang *et al.* 2020).

In this paper, the three main technology bottlenecks have been analyzed for the desalination performance of CDI device such as the inefficient and vulnerable electrode materials with low selectivity, unreasonable unit structure and limitations of single CDI unit (Figure 2). Furthermore, the corresponding improved methods of CDI were

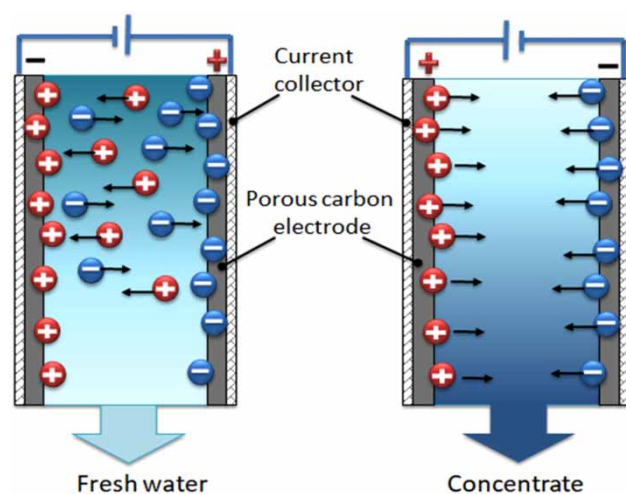


Figure 1 | Schematic diagram of the working and regeneration principle of CDI.

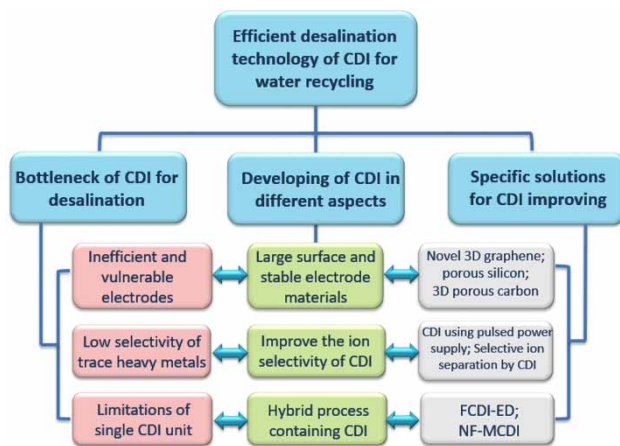


Figure 2 | Overview of the bottlenecks, developments and solutions of CDI for water recycling.

summarized for promoting the continuous development of CDI technology based on the electrode material, novel process and hybrid process.

NEW CDI ELECTRODE MATERIAL

Among the various factors that affect the desalination performance of CDI, the most important one is the selection of electrode materials. The pore size distribution, specific surface area, hydrophilicity, stability, specific capacitance and resistance of the electrode material all have the most direct impact on the capacitance adsorption effect (Shi *et al.* 2020; Zhao *et al.* 2020). This section focuses on solving the problems of instability and low performance of traditional CDI electrodes. Based on the research of the past five years, researchers have developed new electrode materials with a large specific surface area and stable electrochemical performance. Next, three representative new electrode materials are introduced and analyzed, the advantages and disadvantages of each new electrode material are explored, and the future development of CDI electrode materials is expected.

Electrospun network electrode

Conventional CDI electrode materials include activated carbon, graphite and carbon nanofibers (CNFs), but these materials have the problems of high manufacturing cost

and low adsorption capacity, which limits the large-scale application of CDI. Researchers find that the high surface area and porosity of the electrode material are very important to enhance the specific capacitance and cycling stability of the capacitor to achieve high performance (Jiang & School of Petrochemical Engineering 2020). Electrospinning, as a simple yet effective technique to fabricate continuous CNFs, has attracted much attention in the CDI field (Feng *et al.* 2019). The combination of free-standing e-CNFs and PCP with hierarchical pore structure should be a promising electrode material for CDI application (Liu *et al.* 2015). A new CNFs reinforced 3D PCP network (e-CNF-PCP) was fabricated through electrospinning followed by thermal treatment and used as electrode materials for CDI with an EC of 16.98 mg/g in 500 mg/L NaCl solution (Figure 3), which shows great improvement compared to those of PCP and e-CNFs (Liu *et al.* 2016). The CDI performances and manufacturing difficulties of e-CNF-PCP were compared with those of other carbon electrode materials reported in the literature, as shown in Table 1.

However, due to the complex processing technology and high cost of CNF materials, it is difficult to realize large-scale industrial application. Therefore, in the future development of this technology, researchers should focus on the realization of low-cost electrospinning and thermal treatment process to reduce the manufacturing cost of e-CNF-PCP, so that e-CNF-PCP can be widely used as a CDI electrode (Wang *et al.* 2020).

Novel 3D graphene electrode

In order to achieve optimal desalination during CDI, CDI electrodes should possess high electrical conductivity, large surface area, good wettability to water, narrow pore size distribution and efficient pathways for ion and electron transportation (Shi *et al.* 2016). Graphene is one of the thinnest materials in the world, and the theoretical thickness value, band length, and bond angle are 0.335 nm, 0.142 nm, and 120°, respectively. Compared with 2D graphene, 3D graphene is an ideal electrode material for CDI because of its large surface area, good mechanical strength and flexibility (Yu *et al.* 2016). The researchers fabricated a novel CDI electrode based on a three-dimensional graphene (3DG) architecture by

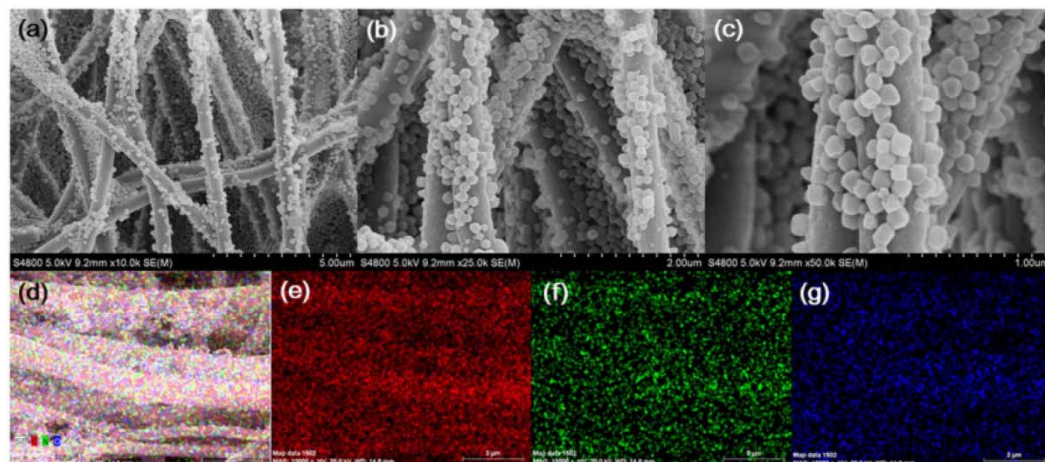


Figure 3 | (a–c) FESEM images of e-CNF-PCP at different magnifications and elemental mapping images of (d) e-CNF-PCP, (e) C element, (f) N element and (g) O element (Liu *et al.* 2016).

Table 1 | Comparison of CDI performances and manufacturing difficulties among various carbon electrode materials from the literature (Liu *et al.* 2016)

Electrode material	CDI performances		Manufacturing difficulties
	NaCl concentration (mg/L)	Electrosorption capacity (mg/g)	
CAs	~500	2.9	Supercritical drying, binder
AC	500	9.72	Coating process, binder
	1,000	10.80	
	1,500	11.00	
	2,000	11.76	
CNTs	500	2.57	Chemical vapor deposition, binder
	1,000	3.71	
	1,500	4.76	
	2,000	5.24	
e-CNF-PCP	100	10.03	–
	300	12.56	
	500	16.98	

constructing interconnected graphene sheets with in-plane nanopores (NP-3DG). As compared to 3DG, NP-3DG features a larger specific surface area and therefore higher specific capacitance (Figure 4). The NP-3DG electrode can be used as a promising electrode material for high-performance CDI applications. The results of NP-3DG exhibit ultrahigh CDI performance with a superior electrosorption capacity of 22.09 mg/g, high adsorption rate, good deionization cyclic stability and high salt removal percentage. Furthermore, due to its excellent electrosorption performance, it is expected that NP-3DG will also

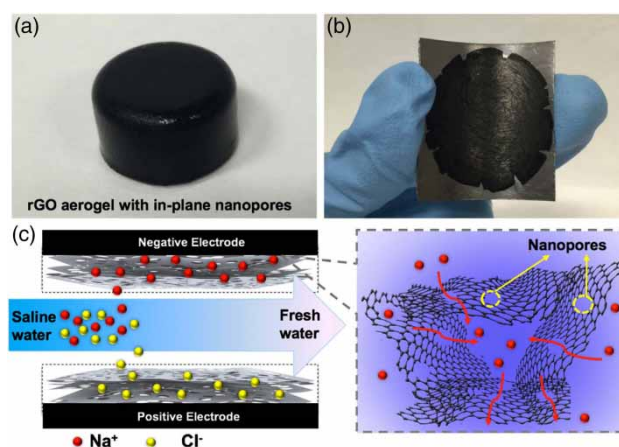


Figure 4 | Photographs of (a) as-prepared rGO hydrogel with in-plane nanopores (NP-3DG) and (b) CDI electrode, (c) Schematic diagram of the CDI process (Shi *et al.* 2016).

play an important role in the removal of charged hazardous species and other heavy metal ions (Khan *et al.* 2018).

As a new type of 3D carbon nanomaterial, NP-3DG has incomparable advantages for use in CDI electrodes. Because it is still in the initial stage of development, there are some problems such as high cost, imperfect theoretical system and unsatisfactory treatment effect (Zhang *et al.* 2018). In recent years, although some progress has been made in the design and preparation of graphene CDI electrode materials, further research on the construction of graphene pore structure and the comprehensive performance of CDI graphene electrode materials is needed to

promote the large-scale practical development and application of graphene electrode materials in CDI.

High efficiency particle free porous silicon network electrode

An energy saving water desalination process using low-cost materials is a key step for the sustainable demand of clean water resources in the future. Here, porous silicon has been proven to be a kind of material with rich content, low cost and strong biocompatibility (Gu *et al.* 2016). With appropriate surface passivation of the porous silicon material to prevent surface corrosion in aqueous environments, the results showed that porous silicon templates can enable salt removal of 0.36 and 0.52% in brackish water (10 mM, or 0.06% salinity) and ocean water (500 mM, or ~2.9% salinity) by CDI, respectively. The use of porous silicon for CDI enables new routes to directly couple water desalination technology with microfluidic systems or photovoltaics cells (Figure 5), while mitigating adverse effects of water contamination occurring from nanoparticulate-based CDI electrodes (Metke *et al.* 2016).

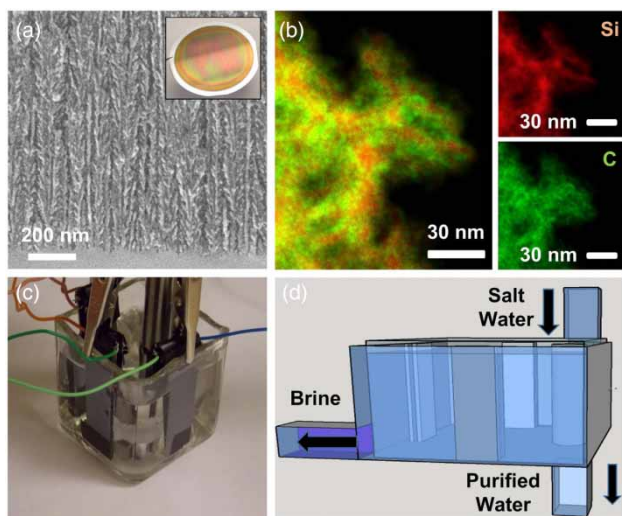


Figure 5 | Porous silicon-based CDI electrodes: (a) Cross-sectional SEM image of a carbon passivated porous silicon electrode for water desalination; (b) Analytical elemental TEM analysis a carbon passivated porous silicon material showing uniform carbon passivation on the material; (c) Photograph of the CDI testing cell combining four pairs of silicon-based electrodes, and (d) illustration of a CDI module in the context of the testing apparatus for continuous flow-through CDI water desalination using porous silicon (Metke *et al.* 2016).

According to Figure 6, the porous silicon network electrode described in this section has a specific salt removal rate of 3.8–5.2 mg/g, ranging from fresh water to seawater salt concentration, and only 1.45 Wh/L of energy input is needed to convert seawater into drinking water (Yu *et al.* 2017; Zhao *et al.* 2019a, 2019b).

In summary, compared with the traditional carbon-based electrode, the main advantage of a porous silicon network is that the silicon content is huge, resulting in lower cost, and it has a tunable pore morphology and structure that can optimize CDI performance in different flow architectures and mitigate the effect of fouling. Therefore, a porous silicon network can be used in developing countries on a large scale, thus becoming a low-cost and easy to operate basic seawater purification equipment.

NEW CDI PROCESS

Although CDI has made great breakthroughs in electrode materials, architecture and system integration, it has no advantages over traditional desalination technologies in terms of energy efficiency, water recovery rate, desalination concentration range and capital cost. However, CDI has illustrated great potential for selective removal of target ions because of its tailorable electrode materials and ability to couple with selective ion exchange membranes (Zhang *et al.* 2020; Park *et al.* 2021). In this section, two novel CDI processes were introduced for their higher ability of selective ions removal, and the application feasibility was explored.

Novel CDI using a pulsed power supply

In recent years, capacitive deionization technology (CDI) has been widely used in many fields due to its environmental protection, low energy consumption, simple operation, and safety (Cho *et al.* 2019). For the desalination of low-concentration brine (50 mg/L), electrodialysis, reverse osmosis and ion exchange are usually used. However, the above technologies have high energy consumption and high additional costs. Therefore, the CDI desalination was proposed to provide new ideas for the preparation of ultrapure water and the advanced treatment of wastewater (Yang *et al.* 2017).

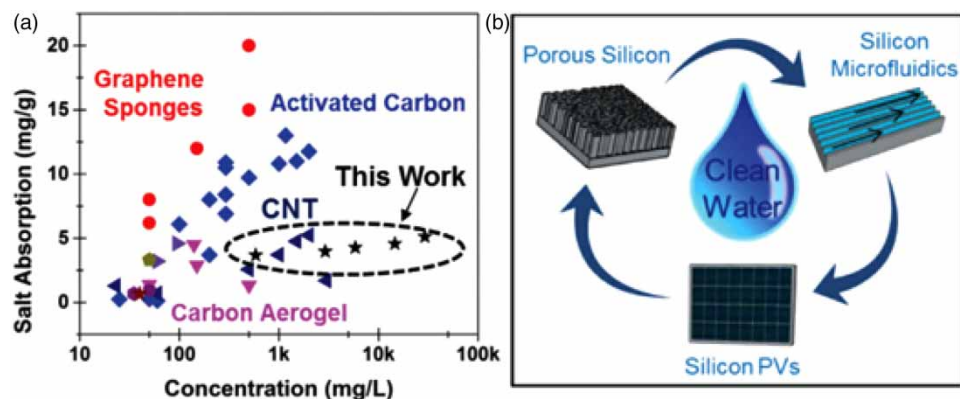


Figure 6 | High performance of porous silicon CDI electrodes and integration vision: (a) Comparison of average specific salt removal capacity for porous silicon electrodes compared to other notable forms of carbon; (b) Scheme emphasizing the vision of porous silicon integration with microfluidics and/or solar cells for technological water desalination platforms (Metke *et al.* 2016).

Pulsed electric field is a new technology to treat liquid and semi-solid objects with high electric field intensity (10–50 kV/cm), short pulse width (0–100 μ s) and high pulse frequency (0–2000 Hz) (Sistat *et al.* 2015). Under the pulsed electric field, ions transfer from solution to the electrode or the electro-dialysis membranes (Kim *et al.* 2019). The CDI cell, including the reactor and the activated carbon coated electrode, was designed. The pulsed power supply was applied in CDI for the electric field. In Figure 7, the removal rate of direct current-CDI (DC-CDI) and pulsed-capacitive deionization (pulsed-CDI) are compared (Jin *et al.* 2019).

In all, compared with the traditional direct current-CDI, novel pulsed-CDI has better ion removal rate and lower energy consumption, which proves that pulsed CDI can be

an excellent alternative to traditional DC-CDI. However, due to the high cost and complex operation of a pulsed electric field, and the diversity of capacitive deionization electrode materials, repeated testing is needed to find the best voltage condition. Therefore, in the future, researchers should focus on enhancing the compatibility of the pulsed electric field so that it can better adapt to various CDI electrode materials, so as to realize large-scale industrial application.

Selective ion separation by CDI based technologies

Selective ion extraction from aqueous solution is of great significance for water purification as well as resource recovery (Kavitha *et al.* 2019). However, despite the great

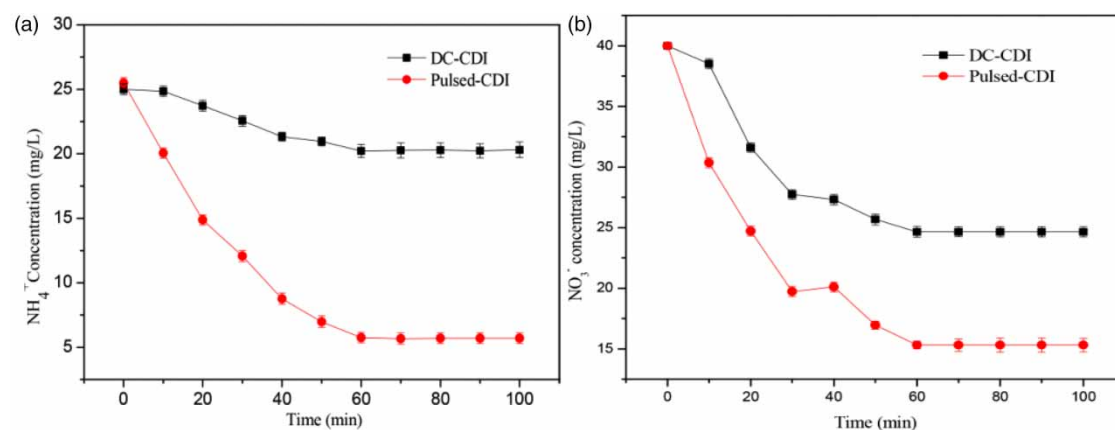


Figure 7 | Performance comparison of DC-CDI and pulsed-CDI (a frequency of 100 Hz and a duty ratio of 50%) in desalination. (a) NH_4^+ , (b) NO_3^- (Jin *et al.* 2019).

development in the material, architecture, and system integration in the past 15 years, CDI was reported to have no advantages on energy efficiency, water recovery, salinity range, salt rejection, and capital cost compared with reverse osmosis (RO) (Jain *et al.* 2018). Nevertheless, due to its tailorable electrode materials and ability to couple selective ion exchange membranes/coatings on the electrode interface, the great potential of CDI has been shown for selective ions removal, which cannot be effectively solved by other desalination technologies including RO, electro-dialysis or thermal evaporation (Zhang *et al.* 2020). Therefore, how to improve the ion selectivity of CDI has become an important development goal of CDI.

Hence, asymmetric activated carbon (AC) electrodes have been designed and grafted by sulfonic groups and amine groups on the surface of AC through covalent bonds as a cation-selective electrode and an anion-selective electrode respectively for enhanced capacitive deionization (Choi *et al.* 2019; Cen *et al.* 2020). Ten pairs of asymmetric electrodes are assembled with sulfonic AC as positive electrodes and aminated AC as negative electrodes. The scheme of co-ion minimization is illustrated in Figure 8. The electrosorption capacity and charge efficiency of asymmetric AC electrodes have been significantly improved because of not only preventing co-ion expulsion effect but also promoting the wettability and accelerating salt solution infiltration. These results will be beneficial to solve the technical bottlenecks and accelerate the practical engineering

application of CDI. These electrodes have higher charge efficiency (0.84) and higher electrosorption capacity ($23.2 \text{ mg}\cdot\text{g}^{-1}$) compared to pristine AC electrodes (0.54 of charge efficiency and $11.0 \text{ mg}\cdot\text{g}^{-1}$ of electrosorption capacity) due to the wettability and hydrophilicity effectively enhanced by grafting ion-selective functional groups (Yan *et al.* 2018).

Asymmetric AC electrodes show better cycling stability (Zuo *et al.* 2018). The modification of the ion-selective functional groups on the surfaces of AC could reduce the co-ion effects effectively and improve the salt removal efficiency from the solution. This will provide a new opportunity for the practical development of capacitive deionization technology.

In all, compared with the traditional symmetrical electrode CDI, CDI using the asymmetric activated carbon electrode has higher charge efficiency and higher electrosorption capacity. However, many factors, including the oxidation of carbon-based materials, decomposition of intercalation structures, blockage of electrode pores caused by fouling and scaling, and membrane fouling resulting from heavy metals, would lead to the decline of desalination performance and also affect the stability of selective separation. Therefore, long-term operation stability should be evaluated, and protection measurements (such as water pretreatment, developing new materials, etc.) can also be adopted to enhance the system stability in the future (Zhang *et al.* 2020).

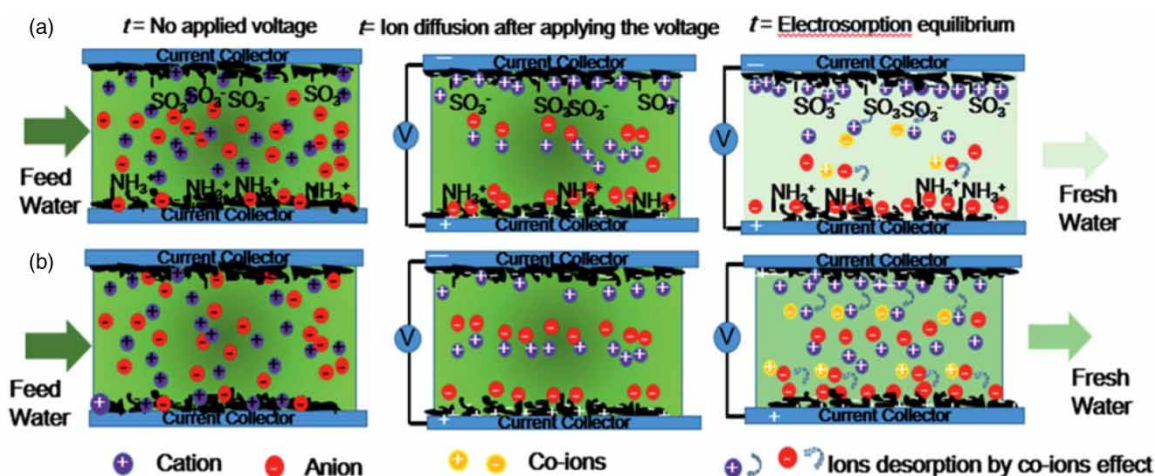


Figure 8 | Scheme illustration of the time-dependent CDI model of (a) asymmetric AC electrodes and (b) symmetric activated carbon electrodes (Yan *et al.* 2018).

HYBRID CDI PROCESS

Although CDI has been developed for many years, there are still some problems that are difficult to solve, such as difficult regeneration and low treatment efficiency. These problems are usually attributed to the limitations of the device itself, which cannot be fundamentally solved by conventional device adjustment (Campione *et al.* 2020; Wu *et al.* 2020). The purpose of this section is to introduce the coupling application of CDI with other water treatment technologies. Through the advantages of other devices, the shortcomings of traditional CDI unit are supplemented. This method effectively frees CDI from its own limitations, solves the problems in traditional CDI and makes the industrial development of CDI have practical significance.

Electrodialysis and FCDI coupling technology in continuous desalination

Membrane capacitive deionization (MCDI) and capacitive deionization (CDI) both adopt the fixed electrode mode, so the adsorption capacity is low and needs frequent regeneration, which does not fundamentally solve the problems of continuous desalination and low water efficiency caused by

the small adsorption capacity of the fixed electrode. Researchers put forward the concept of flow capacitive deionization. Activated carbon (AC) was used as the mobile electrode. The scale of the project was realized by increasing the amount of the flow electrode (Jeon *et al.* 2019). By using electrodialysis (ED) as the regeneration unit of mobile electrode, and using flow capacitance deionization (FCDI) for desalination, the continuous and stable desalination process of brine can be realized (Cho *et al.* 2019). FCDI plays a role in the salt concentration of medium and low concentration brine (to obtain concentrated solution and desalination water), while ED carries out intermittent high-efficiency and rapid desalination of concentrated solution with high salt concentration. The FCDI-ED coupling process can realize industrial application of low energy consumption, high water efficiency and continuous treatment of brine (Hassanvand *et al.* 2017; Chen & Hou 2019; Gao *et al.* 2020). The processing route of FCDI-ED is shown in Figure 9.

However, the disadvantages of FCDI-ED technology are complex process, high cost and easy failure, so it is difficult to carry out large-scale industrial application at this stage. Therefore, researchers should focus on improving the stability of the process and using renewable materials, so as to make the FCDI-ED coupling process better developed.

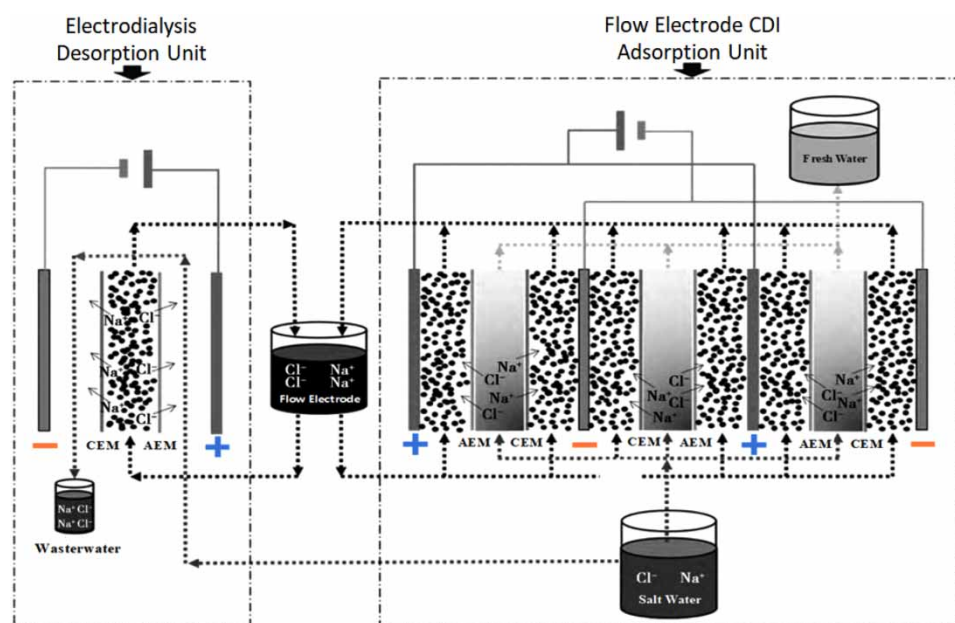


Figure 9 | Schematic diagram of deionization principle of FCDI-ED process (Mo *et al.* 2017).

Novel nanofiltration and membrane capacitive deionization (NF-MCDI) hybrid system

Among various desalination processes, CDI has advantages in terms of cost and energy efficiencies and ease of operation and maintenance, as it can remove salts by adsorbing the ions on the surface of an electrode with a relatively low cell voltage of 1–1.4 V and without high pressure pumps or heat sources (Suss *et al.* 2015). However, single CDI has demonstrated low removal efficiency with a high-concentration (TDS > 3,000 mg/L) because of the ion saturation on the electrode (Choi *et al.* 2019). Using the combined RO-MCDI system, TDS of seawater was decreased from 35,000 to 200 mg/L (Abdelkader *et al.* 2018). However, the operation cost of this process is high, so it is difficult to use in a large-scale seawater desalination plant.

In recent years, a novel hybrid process that combines CDI with nanofiltration (NF) has received growing attention for implementation in energy-efficient desalination systems. Researchers proposed an MCDI unit with flow-electrodes followed by NF, abbreviated as FCDI-NF (Choi *et al.* 2017; Oatley-Radcliffe *et al.* 2017; Sami *et al.* 2018). The energy consumption of FCDI-NF (70% water recovery with 0.460 kWh m^{-3}) was lower by 16% when treating water in comparison with the practical minimum energy consumption of the RO (0.550 kWh m^{-3}) unit for 10,000 ppm NaCl solution desalination to drinking water range. Moreover, the FCDI-NF system attained the drinking water TDS standard ($\leq 500 \text{ mg/L}$) in the final effluent. The schematic of nanofiltration and membrane capacitive deionization (NF-MCDI) hybrid system configuration is

shown in Figure 10. The location and sequence of NF unit and CDI unit should be comprehensively considered by the influent quality, requirements of effluent and energy consumption.

After study, researchers found that the standalone NF system was insufficient for salty water desalination due to its comparatively low removal rate of <60% (NaCl). However, it was improved through combination with the MCDI unit to adsorb the remaining salts in the NF-treated water, thereby achieving a total salt removal rate of up to 95% (Jeon *et al.* 2019). Therefore, compared with the single NF or FCDI process, the desalination rate of FCDI-NF is significantly improved, and the energy consumption of the process is also significantly reduced.

However, this hybrid system may require a higher capital cost than the typical RO membrane system because of the price of the electrodes and ion-exchange membranes (Marchetti *et al.* 2017). Also, the NF-MCDI system performance is influenced by the feed concentration, MCDI flow rate and the NF recovery rate. Therefore, the complexity of the system will result in a significant increase in the capital cost and maintenance complexity of the specific equipment used to couple the MCDI system with the NF system. In future work, how to overcome the limitations of industrial applications brought about by the high cost and high complexity of FCDI-NF devices is very important.

CONCLUSION AND PROSPECTS

In less than 20 years CDI technology has developed into the most attractive research field and it is expected that in the

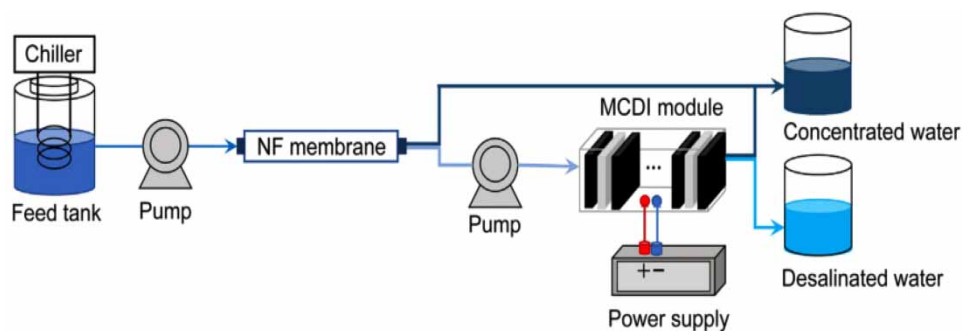


Figure 10 | Schematic of nanofiltration and membrane capacitive deionization (NF-MCDI) hybrid system configuration (Jeon *et al.* 2019).

next few years CDI will further explosive growth in a more mature and advanced direction. Nowadays, CDI has begun to adopt a variety of new technologies and electrode materials, which have unique functions and characteristics, and have made significant progress.

Through the systematic review of the current research it is found that improvement of the structure and composition of electrode materials can improve the desalination effect of CDI technology. However, further research is needed to realize the large-scale industrialization of CDI technology in the following aspects. (1) It is necessary to expand the research on the mechanism of influencing factors of adsorption performance and the kinetics of electro adsorption reaction, so as to provide theoretical basis for the study of electrode materials. (2) Improving the ability of CDI to remove ions selectively can develop CDI into a desalination device that can specifically remove specific ions, thus making up for the deficiency that traditional desalination technology can not specifically remove ions. (3) The development of electrode materials with strong adaptability, low cost and strong adsorption capacity can provide convenience for future research and development, and further promote the application of CDI technology.

The exciting development in the field of CDI is the emergence of FCDI batteries. The selection and synthesis of carbon electrode materials in FCDI have revolutionary changes because there is no need for polymer binders which have side effects on ion adsorption. The FCDI system not only has strong salt adsorption capacity to treat high salinity water, but also can continuously produce fresh water and regenerate electrodes by using non-charged carbon-based materials to continuously supplement the electroactive region. However, FCDI is still in the initial development stage, and there are many possibilities for its future development. One of the main current challenges for FCDI is the low efficiency of charge transfer between collector and flow electrode, and much work needs to be done to solve this problem.

In conclusion, despite the challenges, CDI is still a promising water treatment technology and exciting research field. With the continuous solution to these challenges and the emergence of new CDI units, CDI may be regarded as the key to solve the global water shortage and water pollution in the future.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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