

# Advances in Desalination Technology Based on Pure Water Production

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## Abstract

The shortage of freshwater resources has become a global challenge, and the current methods of freshwater production include thermal separation, membrane separation, and electrochemical methods. Thermal separation requires high energy consumption and is prone to secondary pollution; membrane separation is affected by membrane contamination, resulting in poor stability of the device; capacitive deionization technology in the electrochemical method has the advantages of high efficiency, environmental protection, simple devices, and stable water production, which has the potential for industrial application.

## Keywords

Thermal Separation Technology, Pure Water Preparation, Capacitor Deionization

## 1. Introduction

Fresh water is an indispensable and precious resource on Earth, and although there are many water resources on Earth, 97.5% of them are seawater and less than 2.5% are freshwater resources [1] [2]. Scarcity of freshwater resources not only poses a direct threat to human survival and development but also has a serious impact on a number of key sectors, including agriculture, energy, and industry, globally [3]. In the area of agriculture, the scarcity of freshwater resources directly leads to a reduction in the availability of water for irrigation, which in turn affects the yield and quality of food crops and poses a serious challenge to global food security [4]. In terms of energy production, hydropower, as an important compo-

ment of clean energy, is closely related to the abundance of freshwater resources, the shortage of which will undoubtedly limit the development potential of hydropower, thus affecting the optimization of the global energy structure and sustainable development [5]. And in the industrial sector, whether it is chemical, textile, or food processing industries, it cannot be separated from freshwater resources to support [6].

On the other hand, the increasing pollution of water bodies leads to water shortages, which mainly include industrial wastewater pollution, agricultural wastewater pollution, domestic sewage discharge, and so on. Pollutants in industrial wastewater mainly contain heavy metals, organic pollutants, pathogenic microorganisms, and so on. Agricultural wastewater mainly contains nitrogen, phosphorus, and other nutrients, but also contains certain heavy metal pollutants and difficult-to-degrade organic matter. Domestic wastewater contains pollutants in a more complex composition, which generally comes from the life of production waste, which mainly contains nitrogen, phosphorus nutrients, heavy metal pollutants, antibiotics, and other toxic and harmful substances. These pollutants are discharged into the water body, easy on human health and the ecological environment, causing multiple hazards.

In the face of the challenges of both quantitative and qualitative water scarcity of freshwater resources, the development of efficient and sustainable technologies for freshwater acquisition and purification has become a focus of global attention. These technologies not only need to have high water production efficiency and treatment efficiency to reduce treatment costs but also need to have better environmental adaptability and stability to ensure stable operation under a variety of complex water quality conditions.

Commonly used desalination methods are categorized into thermal separation techniques [7], membrane separation techniques [8], and electrochemical desalination techniques [9]. Thermal separation techniques include Multi-Stage Flash Distillation (MSF) [10] and Multi-Effect Distillation (MED) [11]; membrane separation techniques are categorized into Microfiltration (MF) [12], Ultrafiltration (UF) [13], and Reverse Osmosis (RO) [14]. The main electrochemical desalination techniques are Electrodialysis (ED) [15], Electrodeionization (EDI) [16] and Capacitive desalination (CDI) [17].

## 2. Desalination by Thermal Separation

Thermal separation technology is one of the core methods in seawater desalination and industrial water treatment, of which multi-stage flash evaporation and multi-effect distillation are two widely used thermally driven desalination technologies. Multi-stage flash (MSF) technology is relatively mature; the technology is seawater or brackish water heated to the target temperature, placed in the flash chamber, part of the brine affected by high-temperature vaporization, then rapid condensation to get fresh water. The remaining brine cycle of the above operation will eventually desalinate all the brine. This method has the advantages of large

treatment capacity and stable operation, but the energy consumption required for the whole process is too high, and there are certain defects [18] [19]. Multi-effect distillation (MED) technology is a number of evaporators in series. The use of the steam generated by the former level as the heat source of the latter level can be a multi-stage utilization of thermal energy, compared with the MSF, which greatly improves the efficiency of heat utilization, but it is subject to the complexity of the equipment and investment cost constraints [20] [21].

Thermal separation desalination equipment consumes high energy during operation and also produces large amounts of flue gas containing CO<sub>2</sub>, NO<sub>x</sub>, and particulate matter, which negatively affects the environment. Thermal separation desalination technology is essentially a high-energy process, and its energy consumption usually ranges from 10 to 15 kWh/m<sup>3</sup> [22].

### 3. Desalination by Membrane Separation

Membrane separation technology is an efficient and energy-saving water treatment method, which is widely used in the fields of seawater desalination, wastewater treatment, and drinking water purification. It mainly includes microfiltration, ultrafiltration, and reverse osmosis. The core principle of membrane separation technology is to drive the solution flow through the pressure difference between inside and outside and utilize the selective permeability of the functional membrane to realize the separation of ions in the solution [23].

Depending on the pore size of the membrane, the driving pressure to be applied varies, thus realizing selective retention and separation of particles of different sizes. Microfiltration (MF) uses membranes with a pore size of 0.1 - 10 μm and is generally used as a pre-treatment operation in modern processes to filter out micron-sized particles from solutions, with the advantages of high stability, long membrane service life, and large-scale application in water treatment. Ultrafiltration (UF) uses a membrane pore size of 1 - 100 nm and can effectively remove suspended particles, colloids, macromolecules, organic matter, pathogens, microorganisms, etc. [24]. Reverse osmosis (RO) technology is relatively mature, mainly through the pressure difference so that water molecules pass through the semi-permeable membrane while retaining salts and impurities. RO has a highly efficient desalination rate and low energy consumption; desalination efficiency is usually more than 99%, and the energy consumption is about 3 - 5 kWh/m<sup>3</sup>, but its pre-treatment requirements are high, and the RO device produced by the membrane contamination and clogging problems limits the stability of its long-term operation [25].

In essence, thermal separation technology is a heat-driven process that consumes large amounts of energy and emits harmful flue gases, resulting in higher operating costs and carbon emissions, and may cause localized environmental heat pollution due to waste heat emissions, but has the advantages of stable operation and large treatment capacity. Membrane treatment technology is pressure-driven and has the advantages of environmental protection, energy saving, and

high efficiency compared to thermal separation technology, but the high cost of membrane materials, susceptibility to contamination or clogging, and the need for frequent replacement or cleaning increase maintenance and waste disposal costs, and discarded membrane materials may pose a risk of chemical contamination. Overall, thermal separation technology is suitable for large-scale, high-tolerance separation scenarios, while membrane separation technology has more advantages in terms of energy saving and precise separation, but needs to be weighed against membrane life and environmental protection treatment.

## 4. Electrochemical Desalination

The three main electrochemical desalination techniques include electrodialysis (ED) [26], electrodeionization (EDI) [16], and capacitive deionization (CDI) [27].

### 4.1. Electrodialysis Desalination

The principle of ED technology is to use an electric field to drive the migration of ions; cations move to the cathode through the cation exchange membrane, anions move to the anode through the anion exchange membrane, and finally get fresh water in the fresh water chamber [28]. ED technology has the advantages of low energy consumption and large treatment capacity, but at the same time there are shortcomings in the treatment of low concentrations of water with low efficiency [29].

### 4.2. Electrodeionization Desalination

EDI technology is a combination of electrodialysis and ion exchange, in which the pale chamber of the electrodialysis unit is filled with a mixture of anion and cation exchange resins, and deionization is achieved under the action of a direct current electric field.

In the process, the fresh chamber is filled with conductive ion exchange resin, which plays a role in improving the ion transport and, at the same time, achieves the effect of deep deionization. EDI technology overcomes the shortcomings of electrodialysis technology, which is prone to concentration polarization and unsuitable for the treatment of dilute solutions, and at the same time retains the advantages of the depth treatment of ion exchange technology and the continuous operation of electrodialysis technology, but there are high requirements for the quality of feed water, and the membrane stack is prone to scaling.

### 4.3. Capacitive Deionization and Desalination

Capacitive deionization technology relies on the double-layer capacitance effect of electrode materials and a reversible electrochemical adsorption process, applicable to low salinity water desalination and specific ion resource recovery, with low energy consumption, no chemical by-products, and other advantages [30].

In the 1990s, Farmer *et al.* [31] discovered the potential of CDI technology for practical applications by using high specific surface area carbon aerogel electrodes

in a CDI device, which led to an increase in the adsorption capacity of the CDI device. As the demand for fresh water increases, ordinary carbon-based material electrodes cannot meet the development needs. Most of these materials are microporous materials; this structure will limit the rate of ion diffusion and thus lead to a decline in the performance of the device desalination [32]. To overcome this shortcoming, researchers have developed electrodes that store ions through a Faraday reaction, an electrode known as a Faraday electrode. In 2012, Pasta *et al.* [33] applied a Faraday material electrode in a capacitive deionization device for the first time, which used  $\text{Na}_{2-x}\text{Mn}_5\text{O}_{10}$  as well as Ag as the electrode for the desalination test. The negative electrode is  $\text{Na}_{2-x}\text{Mn}_5\text{O}_{10}$  to store  $\text{Na}^+$ , and the positive electrode is the Ag electrode for storing  $\text{Cl}^-$ , but due to the high cost of Ag, it is not suitable for large-scale industrialized application.

In 2014, Lee *et al.* [34] investigated a hybrid capacitor deionization device, which realized the embedding and detachment of anions and cations through the Faraday reaction principle and the theory of double electric layer, which not only improved the desalination performance but also reduced the cost of the device. In general, CDI technology has the advantages of high efficiency, environmental protection, simple device, and high efficiency of water production, which is the hot spot of electrochemical desalination technology in recent years.

Compared with ED and EDI technology, CDI technology also has the advantages of low energy consumption, a wide range of concentrations of treatment solution, etc. At the same time, its equipment structure is simple and low cost, and with the development of electrode materials, this technology has broader and broader prospects for development.

#### 4.3.1. Capacitive Deionization Technology Classification

Improvements on the basis of traditional capacitive deionization technology can be divided into Flow-Through Capacitive Deionization (FT-CDI) [35], Membrane Capacitive Deionization (MCDI) [36], Flow Capacitive Deionization (FCDI) [36], Inverted Capacitive Deionization (I-CDI) [36], and Hybrid Capacitive Deionization (HCDI) [36].

##### 1) Flow-Through Capacitive Deionization

Flow-Through Capacitive Deionization was first proposed by Johnson *et al.* [37]. The core design employs a porous structure in which the electrolyte solution flows directly through the interior of the electrode, rather than the traditional CDI structure in which the solution flows on the surface of the electrode. As shown in **Figure 1(a)**, this design significantly improves ion transfer efficiency and deionization performance. FT-CDI has the advantages of high efficiency, low energy consumption and compact structure. However, in long-term operation, the internal pores of the electrode may be contaminated by organic matter or particles, which may easily lead to electrode clogging and contamination, and the cost of the equipment is high and is not applicable to the treatment of high-concentration salt water [38].

##### 2) Membrane Capacitive Deionization

As shown in **Figure 1(b)**, the membrane capacitor deionization technology is

based on the traditional capacitor deionization device by adding an ion-exchange membrane between the electrode and the compartment [39]. The ion exchange membrane can selectively carry out charge transfer in the adsorption stage, which improves the charge utilization efficiency and enhances the regeneration efficiency of the electrode. In the regeneration stage, the ion exchange membrane inhibits the re-adsorption of desorbed ions, which guarantees the regeneration of the electrode and provides certain protection for the electrode [40].

### 3) Flow-Electrode Capacitive Deionization

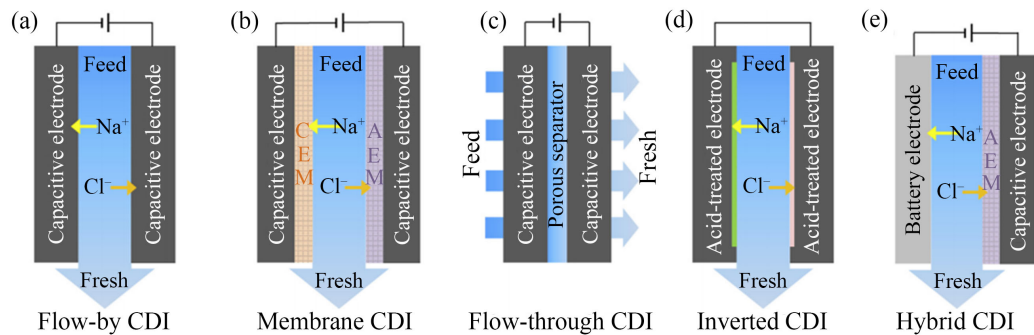
Flow Capacitor Deionization, the core feature of which is the use of Flow Electrode instead of the fixed electrode in conventional CDI [41]. As shown in **Figure 1(c)**, the flow electrode consists of a suspension of electrically conductive particles, such as activated carbon, and an electrolyte solution capable of circulating through the system. This design significantly improves ion adsorption capacity and system continuity for high salinity water treatment and large-scale applications [42].

### 4) Inverted Capacitive Deionization

Inverted capacitive deionization is an improved technique for capacitive deionization to avoid anodic carbon oxidation proposed by Gao *et al.* in 2015 [43]. As shown in **Figure 1(d)**, this technology reduces the risk of oxidation of the electrodes and improves the regeneration efficiency of the electrodes by periodically reversing the polarity of the electrodes, which enhances the stability of long-term operation of the device. The problem with I-CDI is that its desalination efficiency is limited by the electrode working voltage, and the desalination efficiency is generally [44].

### 5) Hybrid Capacitive Deionization

Heterogeneous capacitance deionization technology combines new material electrodes on the basis of traditional CDI device, which mainly provides large adsorption capacity through the double storage mechanism of new material electrodes, mainly including two storage modes of double layer capacitance and pseudo-capacitance. As shown in **Figure 1(e)**, A Hybrid Capacitive Deionization (HCDI) cell is fundamentally composed of a capacitive electrode, typically made of porous carbon like activated carbon for electrostatic ion adsorption, paired with a Faradaic (battery) electrode, made of materials such as sodium manganese oxide or silver chloride that store ions through reversible electrochemical reactions; these electrodes are often separated by ion-exchange membranes (cation-exchange and/or anion-exchange) to enhance selectivity and prevent crossover, with current collectors (e.g., titanium or graphite foil) attached to each electrode to facilitate electrical connection, all housed within a structure featuring flow channels for saline water passage and providing necessary electrical connections and structural support, thereby combining capacitive and Faradaic processes for improved desalination performance. HCDI has the advantages of large adsorption capacity, high adsorption efficiency, and the ability to operate continuously and stably. However, it has a certain limitation in the range of ions handled by the electrode material. However, this limitation is also an advantage in that the target ions can be selectively removed (**Table 1**).



**Figure 1.** Schematic diagrams of different capacitive deionization devices: (a) FT-CDI; (b) MCDI; (c) FCDI; (d) I-CDI; (e) HCDI.

**Table 1.** Comparison of advantages and disadvantages of different types of CDI systems.

CDI System	Advantaged	Disadvantaged
<b>Traditional CDI</b>	Stable operation; simple equipment; easy operation, energy recycling; environmentally friendly	Long processing time; low charge efficiency; poor selective separation
<b>FT-CDI</b>	Accelerated adsorption process; high adsorption capacity, high adsorption kinetic efficiency; high ion transfer efficiency; high continuous operation capability	Electrodes are easily contaminated; complex installations; higher costs, anodes are easily corroded
<b>MCDI</b>	High processing efficiency; wide range of applicable salt concentration; low energy consumption, easy operation; green environmental protection and no secondary pollution	Ion exchange membrane is easily contaminated; high maintenance and operation costs; not applicable to high concentration of salt water
<b>I-CDI</b>	Cyclic reversing electrodes are self-cleaning of contaminants and increase the cyclic stability of the device	Low desalination efficiency, susceptible to low operating voltage
<b>FCDI</b>	Strong continuous and stable operation capability; high electrode adsorption capacity, fast electrode regeneration speed	High cost of electrodes
<b>HCDI</b>	High adsorption capacity; high adsorption efficiency; selective removal of target ions	Highly influenced by electrode materials; higher cost

### 4.3.2. Faraday Electrode Materials

#### 1) Transition metal oxide

Transition metal oxides are pseudocapacitive transition metal compounds that remove sodium ions by forming a pseudocapacitance through a Faraday reaction. This material has the advantage of high desalination capacity and good cycling stability. Depending on the morphology of the prepared titanium dioxide, it can be classified into nanoparticles, nanorods/nanofibers and nanotubes, with nanoparticles being the most widely used [45]. Laxman *et al.* prepared granular  $\text{TiO}_2$  by depositing  $\text{TiO}_2$  onto a carbon surface, and showed that the structure of this material can improve the specific capacitance and desalination capacity of ordinary  $\text{TiO}_2$  [46]. Reduced graphene-coated nanorod-type  $\text{TiO}_2$  was prepared by El-Deen *et al.* The results showed that the incorporation of reduced graphene oxide increased the electrical conductivity of the material and the structure of the coated material increased the specific surface area. The specific capacity was up to  $443 \text{ F}\cdot\text{g}^{-1}$  and the desalination capacity was up to  $16.4 \text{ mg}\cdot\text{g}^{-1}$  at  $10 \text{ mV}\cdot\text{s}^{-1}$ ,  $1 \text{ mol}\cdot\text{L}^{-1}$

NaCl [47].

### 2) Transition metal sulfide

The most widely studied transition metal sulfide is molybdenum disulfide ( $\text{MoS}_2$ ), a layered material with a graphene-like structure in which the layers are bonded by van der Waals forces and the molybdenum (Mo) and sulfur (S) atoms within the layers are connected by strong covalent bonds [48]. Xing *et al.* prepared  $\text{MoS}_2$  with sizes and lattice spacings of 200 - 600 and 0.61 nm, respectively, by chemical stripping, and used it as a CDI electrode material with a desalination amount of 8.81 mg/g [49]. Wang *et al.* successfully prepared  $\text{MoS}_2$ /PDA complexes with flower-like structure by introducing hydrophilic polydopamine (PDA) into the  $\text{MoS}_2$  system, which significantly enhanced the surface wettability of the material, and the results showed that its desalting capacity could reach 16.94 mg/g [50].

### 3) Prussian Blue Analogs

Prussian blue (PB) is a material with a unique framework structure characterized by advantages including highly reversible redox reactions, excellent electrochemical stability, non-toxicity and low cost. These properties give it potential for a wide range of applications in electrochemical energy storage, catalysis, and sensing.

Guo *et al.* synthesized single-crystal  $\text{FeFe}(\text{CN})_6$  with a cubic structure and a size of about 200 - 300 nm, and further prepared CDI electrode materials by compositing  $\text{FeFe}(\text{CN})_6$  with GE, which had a desalination capacity of up to 120.0 mg/g and excellent cycling stability [51]. In addition, PBAs, as an important class of cation-embedded materials, have been widely used in the fields of batteries and supercapacitors due to their advantages such as low preparation cost and low toxicity [52].

The above is an introduction to common electrode materials for heterocapacitor deionization systems.

## 5. Conclusion

Among the desalination technologies for pure water production, thermal separation has the advantages of stable operation and large treatment capacity but faces bottlenecks such as high energy consumption and secondary pollution; membrane separation technology is highly efficient and energy-saving but is limited by membrane contamination and pretreatment costs. Capacitive deionization technology (CDI) in electrochemical methods stands out by virtue of low energy consumption, environmentally friendly and simple devices, and through the innovation of Faraday electrode material significantly improves the desalination performance and cost-effectiveness. However, there is still a need to break through the limitations of electrode materials and challenges of large-scale application. Future research should focus on electrode material optimization, hybrid technology development, and environmental compatibility enhancement in order to promote the development of desalination technology in the direction of high efficiency and

sustainability and to cope with the crisis of global freshwater shortage.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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