Activated Carbon Cloth for Desalination of Brackish Water Using Capacitive Deionization

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http://dx.doi.org/10.5772/intechopen.76838

Abstract

Capacitive deionization (CDI) is an emerging technology that is currently being widely explored for brackish water desalination. The theory behind the CDI technology depends on ion electrosorption at the surface of a pair of electrically charged porous carbon electrodes. Salt ions are removed upon applying an electrical low voltage of 1.2 V between two electrodes. Activated carbon cloth (ACC) electrodes have a significant potential for energy-efficient CDI water desalination due to the high surface area and salt storage capacity in which salt ions will be temporarily immobilized. The current state of the art of CDI technology is critically reviewed and evaluated to understand and summarize CDI background, phenomenon, advantages, operating conditions, performance metrics and equations, carbon electrode materials, cell architectures and CDI designs. We also provide a review study to evaluate the performance and feasibility of utilizing ACC-CDI systems for brackish water desalination.

Keywords: CDI, brackish water, treatment, activated carbon cloth, ACC, salt, desalination

1. Introduction

Water has always been prioritized as the most vital element for human existence since it makes up to 70% of human total body weight. Expected life quality and life span of any human are directly related to the presence of fresh water for drinking and other daily uses [1, 2]. Recent studies showed that both worldwide demand for drinking water and production of wastewater are increasing dramatically. By the year of 2025, it is expected that there will be 1.8 billion people suffering from fresh water shortage due to the high amounts of wastewater

produced from industrial wastes. Hence, improving water purification technologies is important to secure fresh water for the coming generations [3–6].

Today, there are numerous water and wastewater treatment technologies that are commercially selected and utilized based on both water feed characteristics and required water product quality. For example, high saline water (seawater) is usually treated in advanced reverse osmosis (RO) membrane desalination plants; a membrane consists of a porous layer of polymeric or metal material that allows the passage of fluid with restrictions to salt particles. Pressure-driven membrane technology has no side pollution effects and requires a small footprint for installation. However, membrane processes require applying low/high pressures to pump water for filtration and thereby increasing energy consumption and water production cost [4–6]. In contrast, low saline water (e.g., groundwater, surface water and brackish water) is better treated with industrial emerging technologies, which are different from membranes to reduce energy costs, such as electrodialysis (ED) and capacitive deionization (CDI) [7, 8].

2. Capacitive deionization

2.1. Historical background

In 1960s, the concept of capacitive deionization (CDI) was introduced at the University of Oklahoma by G.W. Murphy as an alternative water treatment method and was called "electrochemical demineralization of water." Activated carbon powder (charged electrode sheets) and flow-through electrode architecture were selected for the first designed CDI system to treat saline water. Carbon electrodes were capable of capturing salt ions as a result of the static electrical force and the physical adsorption [9–11]. Murphy and Caudle combined mass balance and transport equations to obtain a model which described the salt concentration as function of time [12]. It was believed that ion removal is attributed to specific chemical groups present on the surface which are reduced or oxidized (faradaic reactions) and create ionic bond with salts [13].

Evans studied the mechanism of "electrochemical demineralization," which is the CDI process, and carried out the mass balance analysis to explain the fundamental idea behind ion removal. Evans' explanation analysis was similar to Murphy's findings and it was added that the concentration of surface groups determines the salt removal efficiency [14].

However, Murphy's and Evans's classical views on water desalination by porous electrodes are no longer valid and have been replaced by the common electric double layer theory (EDL) which describes the capacitive storage of ions in electrode pores [9, 10].

In 1968, a commercialization study on CDI, a demineralization unit, was initiated by Reid et al. to sustain the CDI process for long-term operation and without losing electrode adsorption capacity over time. Furthermore, it was demonstrated that the CDI unit is effective for the removal of other ions besides sodium and chloride which include calcium, magnesium, sulfate, nitrate and phosphate ions [13].

In 1970s, Johnson et al. [15] proposed a reversible electrosorption model for electrode regeneration by removing the applied electric potential to release the captured ions back to a concentrate flow. Salt adsorption mechanism was investigated to be a result of the EDL theory which was known as "potential-modulated ion sorption." A porous electrode model and electrode charge voltage dependence were developed to conclude that electrode capacity depends on the EDL electrical capacity, the available surface area and the applied cell voltage. Johnson and Newman indicated that CDI is economically feasible only if stable electrodes can be produced [9, 10, 15, 16].

In 1990s, CDI technology captured the attention of scientific scholars and many released publications were about developing an effective carbon electrode with large internal surface area and good conductivity for better water deionization. The summarized timeline of CDI development is shown in **Figure 1** [13].
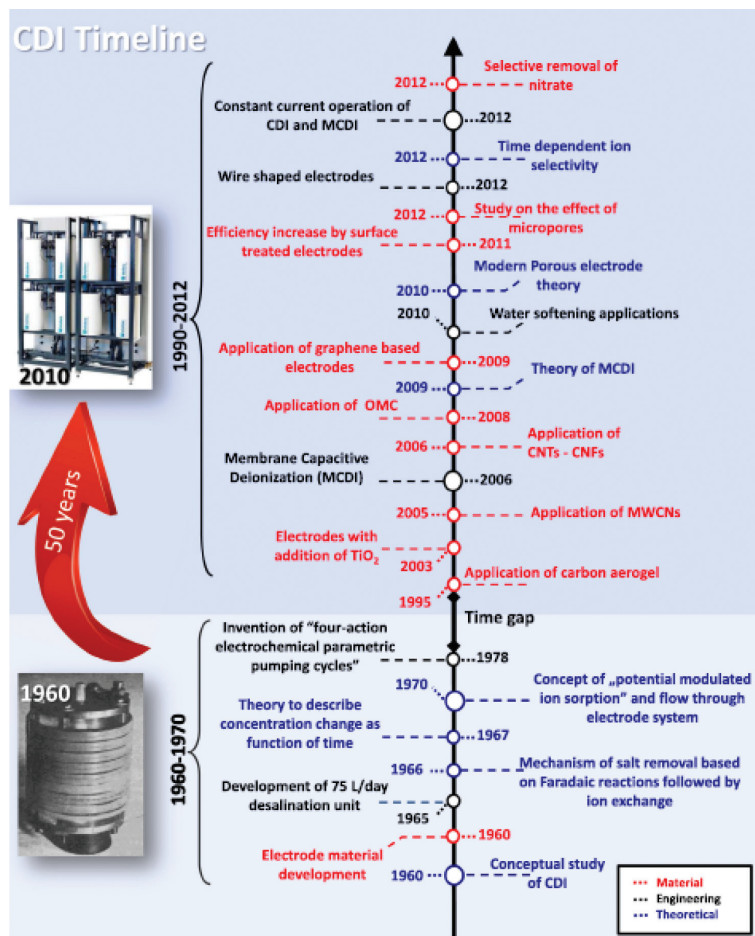

Figure 1. Timeline of scientific developments of CDI, indicating milestones since the inception of CDI in 1960 [13].

2.2. Fundamental concept

The fundamental concept of CDI technology is simply associated with electrosorption of ions at the surface of a pair of electrically charged electrodes (high porous carbon materials) [17]. The electrosorption phenomenon can be understood by the classical EDL theory which explains the charge-voltage and salt-voltage characteristics of the cell that strongly depends on electrodes properties. Basically, it is approximated that charge transfer along the cell is only attributed to electronic charge (in the carbon electrode) and ionic charge (in the aqueous phase), while surface charge from chemical adsorption/carbon redox chemistry is neglected [18]. In other words, there will be no voltage drop across the EDL if the material is not charged since the two components of charge sum up to zero, and only local voltage differences relative to a reference electrode play a role and not absolute potentials [13, 17, 18].

The concept of the EDL dates back to Helmholtz, in the nineteenth century, who assumed that there should be a condensed layer of counterions that directly compensates the surface charge, meaning that all surface charges are directly charge compensated by countercharges adsorbed to the surface [19]. If this holds, ion/charge transport in CDI would be ideally described by Helmholtz-model which states that one full salt molecule (one cation at the cathode and one anion at the anode) would be removed for every electron transferred from one electrode to the other giving us unity charge efficiency.

Unfortunately, porous CDI electrodes do not condense ions right next to their surface; instead, ions remain diffusively distributed in a layer close to the surface. Hence, Gouy-Chapman (GC) described that there must be a diffuse layer combined by an inner stern (or compact) layer in between the electrodes (the carbon matrix) and the diffuse layer. Structure of the EDL according to the Gouy-Chapman-Stern (GCS) theory for a single planar EDL is shown in **Figure 2** [20–22].

Diffuse layer observations show that ion concentrations progressively decay with increasing distance from the surface. The characteristic distance for the counterion concentration and potential to decay by a factor of e (~2.7) is known as the Debye length (λ_D). It was estimated that the diffuse layer starts to fade away after 2 or 3 times the Debye length. The Debye length of a sodium chloride (NaCl) solution of 10 mM ionic strength is approximately 3.1 nm at 20°C. GCS theory assumes that there is no overlapping of the diffuse layer extending from one surface with a nearby surface. However, micropores (<2 nm) in activated carbon particles are generally less than the Debye length, thus the EDL overlap situation occurs [13].

Based on the EDL concept, CDI desalination occurs when putting a charged carbon electrode in contact with ionic solution, and then counterions will occupy the electrode-electrolyte interface in the pores inside the carbon particles due to the presence of the Coulomb force which forms the EDL. It should be noted that ions are not only removed by the electrical adsorption, but there will be a contribution from the physical adsorption effect. However, the regeneration step takes place when there is reduction in the applied potential (charge) and/or reversed polarity which results in the removal of Coulomb force and/or reversing the force effect (i.e., there will be a repulsion force between held ions and charge) and therefore releasing the held ions back to the concentrate solution. Desalination/regeneration steps form one complete CDI treatment cycle [9].
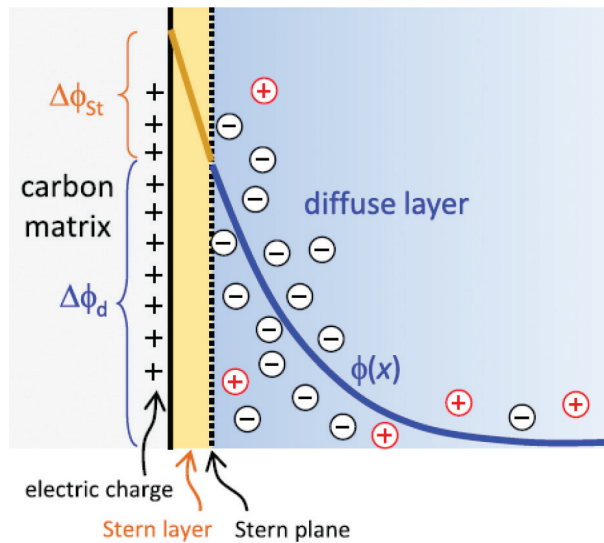
Figure 2. Structure of the electrical double layer (EDL) according to the Gouy-chapman-stern (GCS) theory for a single planar EDL [13].

2.3. Advantages

Effective water desalination at lower costs is considered as one of the grand technological challenges of the twenty-first century. Common commercial technologies such as reverse osmosis, electrodialysis, thermal distillation and multistage flash distillation have been developed to achieve efficient desalination. However, the latter technologies consume a lot of energy and may not be a cost-effective manner for water desalination. Recently, CDI has gained much attention as a desalination technology alternative for brackish water (which has low or moderate salt content) due to its simple design, low energy consumption, economical feasibility, high efficiency, safety and environmental friendliness [23–27].

CDI does not involve membranes and therefore it is a low-pressure process of deionization which does not require energy for pumping water or any other means (except for a fairly low applied voltage). Moreover, CDI stores applied potential as a capacitive energy and one may recover this energy again to further reduce power consumption and operating expenses [27, 28]. In other words, electrode discharge step (regeneration) can be recovered and utilized to charge a neighboring cell (electrosorption) for ion rejection [13]. Possibility of electrode fouling during the desalination-regeneration cycles is relatively low, hence, making this technology more attractive for desalting water. CDI does not have additional contaminants (e.g., chemicals) released from the process which makes CDI technology environmentally friendly [29].

From previous discussed advantages, CDI becomes very suitable in providing fresh water and agricultural water with low cost and without pollution [26, 30]. Despite that CDI may not

be capable of treating sea water (high saline water); it is still efficient to remove salt concentrations up to 10 g/L. Accordingly, water shortage problems in arid areas and contaminated brackish water-rich regions can be overcome with the advantageous CDI technology [13].

CDI technology does not require expensive designed parts/materials for the construction phase. Materials required to build a CDI cell are commercially available and cheap which include, but not limited to, a pair of porous electrodes (e.g., carbon), a porous separator between the two electrodes, a conductive rod material (e.g., graphite) to be attached to both electrodes and connected to a potentiostat (to transfer a typical applied potential of 1–1.4 V) and a designed acrylic support/reservoir with an inlet and outlet [17].

2.4. Operating conditions

Since this chapter is related to using activated carbon cloth (ACC) as an electrode in the CDI cell, the reported operating conditions in this section are for ACC-CDI systems. Laxman et al. and Myint et al. have investigated the use of ACC (Zorflex FM-100) for CDI brackish water desalination. Zorflex ACC thickness was about 1.0 mm, electrode area was 8.4 cm^2 and specific surface area was approximately 1100 m^2/g. The ACC was grafted/coated with zinc oxide (ZnO) micro/nanomaterials (nanoparticles, nanorods, microsheets and microspheres) by a simple and low-temperature hydrothermal method to enhance salt removal from the improved electrode conductivity [29, 31, 32].

Based on the literature data for ACC-CDI systems, studied feed water, NaCl solution concentration should be between 100 and 1000 ppm (typically a salt concentration between 5 and 50 mM and/or 0.5 and 5 mS/cm) and applied potential must be in the range 0.6–1.6 V DC (typically 1.2 V to avoid water hydrolysis at 1.23 V). The system should be operated under room temperature and normal atmospheric pressure with a flowrate of 2 mL/min (and may reach up to 1–4 L/min). Flowrate values could be changed/increased and might not have much effect on salt adsorption. Desalination/regeneration time should be approximately 25 min (typically 10 min for desalination and 10 min for regeneration, or charge–discharge cycle can have any duration/time, from very short ~4 min, with little adsorption, to very long >90 min, depending on when equilibrium concentration becomes steady with time). Salt rejections could reach up to 25 and 35% for plain ACC and ACC deposited with ZnO nanorods, respectively, and electrode electrosorptive capacity could reach up to 8.1 mg/g [17, 31, 32].

2.5. Performance metrics and equations

2.5.1. Desalination (salt removal) efficiency

It is defined as how much salt ions can be removed from brackish water in a CDI cell; see Eq. (1).

$$R\ (\%)\ =\ \frac{C_0 - C_f}{C_0} \times 100 \tag{1}$$

where C_0 and C_f are the initial and final (or equilibrium) concentration in ppm "mg/L" (or conductivity in µS/cm) of saline (NaCl) solution. Regeneration efficiency can also be calculated

from the abovementioned equation and multiplying the result by (−1) to have a positive number since C_f will be much higher than C_0 (due to flushing/cleaning the system with DI water) [29, 32].

2.5.2. Charge efficiency

It is defined as the ratio of adsorbed salt over charge and calculated from Eq. (2) by multiplying the total adsorbed salts on the electrodes (mol/g) by Faraday's constant (C/mol) and then divided by the total amount of charge density transferred for adsorption cycle (C/g). Charge efficiency is used to analyze static electrode CDI cycles as an integral property and it must be less than unity (or approaching one for the ideal case). Charge efficiency is a function of the applied potential during charging/discharging and initial salt concentration. Increasing charging and discharging voltages and decreasing feed concentrations will result in higher charge efficiency. Higher values of charge efficiency lead to lower energy consumption [17, 24, 25].

$$\Lambda \; = \; \frac{\Gamma \times F}{\Sigma} \; = \; \frac{(SAC/M) \times F}{\int I \, dt} \tag{2}$$

where Γ is the deionization capacity upon applying a cell voltage (mol/g), F is the Faraday's constant (96485.33 C/mol), Σ is the total charge transferred (C/g) and is calculated through integrating the current over time per electrode mass to give an estimate on the total amount of charge delivered in Coulombs per gram of electrode during the adsorption cycle, SAC is the salt adsorption capacity (see Section 2.5.3) and is calculated from Eq. (3) with the unit (mg/g), M is the molar mass of NaCl (58.4 g/mol), I is the measured current density (A/g, where A = Amperes = C/s), t is the charging time (s) and $\int I \, dt$ =C/g, where C = Coulomb. Current is generally higher in magnitude during charging when compared to discharging. The above equation is valid for any CDI system, symmetric or asymmetric cells with/without redox reactions as long as the current and salt rejection are measured from experiment [17, 24, 25].

2.5.3. Salt adsorption capacity

Salt adsorption capacity (SAC) is defined as the amount of ions in milligram electroadsorbed per gram of electrodes; see Eq. (3). This is also known as "specific salt adsorption capacity" and gives information on the electrosorption capacity of both electrodes of a cell's charge–discharge cycle. One may calculate the maximum salt adsorption capacity (mSAC), which is also known as equilibrium salt adsorption capacity (eqSAC), when the measured conductivity of the cell effluent no longer changes over time [17].

$$SAC \; (mg/g) \; = \; \frac{(C_0 - C_f)V}{m} \tag{3}$$

where C_0 and C_f are the initial and final (or equilibrium) concentrations of NaCl solution (mg/L), m refers to the total mass of the two carbon electrodes when dry (g) and V represents the volume of NaCl solution (L). However, if the effluent was discharged, the amount of ion adsorption per unit mass of carbon electrodes can be calculated from Eq. (4) [17, 23, 27];

$$SAC\ (mg/g)\ =\ \frac{C_f Qt}{m} \tag{4}$$

where C_f represents the final ion concentration of NaCl solution (mg/L), Q is the flow rate of the solution (L/min), t is the electrosorption time (min) and m is the mass of the two carbon electrodes (g) [17, 23, 27, 31, 33, 34].

2.5.4. Average salt adsorption rate

This metric gives information on the rate of salt sorption, and is usually in the units (mg/g/min) with the (min) referring to the charging time, (mg) referring to the mass of salt removed, (g) referring to the mass of the two electrodes together and average salt adsorption rate (ASAR) is calculated from Eq. (5).

$$ASAR\ =\ \frac{SAC}{t} \tag{5}$$

where t stands for the deionization time (min) and SAC refers to the salt adsorption capacity (mg/g). Zhao et al. reported the highest value of ASAR which is 2.3 mg/g/min for a membrane CDI cell architecture (see Section 4.3) with sub-equilibrium charging times and 300-mm-thick electrodes [17, 27, 35, 36].

Kim-Yoon proposed KY diagrams which combine two CDI metrics, salt adsorption capacity (SAC) and salt adsorption rate (ASAR), in a single plot. KY diagram can be used in optimization studies for CDI cells. For example, KY was plotted for a flow by CDI cell with static film electrodes (Kuraray YP50F-activated carbon powder) as a function of the charging voltage as shown in **Figure 3**, and the discharge voltage was set to zero for all experiments. Calculations were carried out at varied half-cycle time (HCT; the charging and discharging steps were of the same duration) and the charging voltage was set between 0.9 and 1.3 V. Dividing SAC by ASAR is equal to twice the half-cycle time (HCT) and optimum operational values are shown by black circles [17, 27, 35, 36].

2.5.5. Specific capacitance

It is defined as the cell or electrode charge storage capacity, expressed in Farads per gram (F/g), and is estimated from capacitive charge and the applied cell voltage as in Eq. (6) and/or Eq. (7). The specific capacitance is often referred to a single electrode capacitance. Capacitance and desalination (salt removal) are not equivalent but are linked by the charge efficiency (see Section 2.5.2). Cyclic voltammetry measurements should be performed on the working electrode using a potentiostat with a specific scan rate (mV/s) and a potential widow (e.g., −0.4 V to +0.4 V), to obtain voltammogram diagrams and then calculate the specific electrode capacitance from obtained data and given Equations [17, 27, 29, 31].

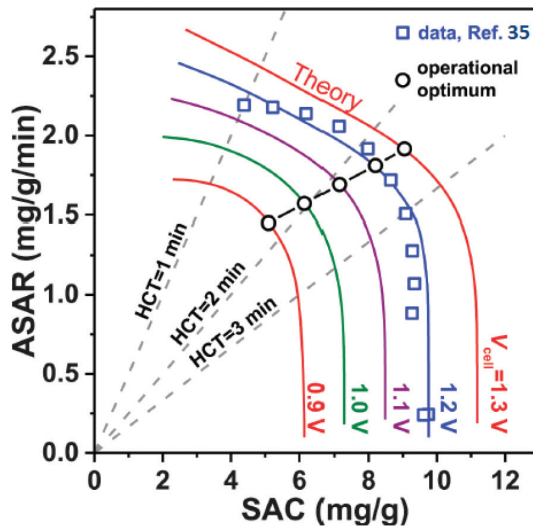$$C_s\ =\ \int_{E_1}^{E_2} \frac{i(E)dE}{[2(E_2 - E_1)mv]} \tag{6}$$

Figure 3. Kim-Yoon plot for (ASAR) in a flow by CDI cell vs. (SAC) as a function of charging voltage.

$$C_s = \frac{i(E)}{mv} \tag{7}$$

where E_1 & E_2 are the potential ranges (V), m is the electrode mass (g), v is the scan rate (mV/s), $i(E)$ is the instantaneous current and power delivered during the scan (A).

2.5.6. Langmuir isotherm

Adsorption data of the electrolyte with respect to carbon electrode in CDI systems can be simulated by the Langmuir isotherm (1918) as in Eq. (8), by plotting C_e/q_e vs. C_e.

$$\frac{C_e}{q_e} = \frac{1}{q_m K_L} + \frac{C_e}{q_m} \tag{8}$$

where C_e is the equilibrium concentration of salt ions (mg/L), q_e represents the amount of electroadsorbed ions at equilibrium per unit weight of carbon electrode (mg/g), q_m is the maximum adsorption capacity (mg/g) with respect to the complete surface monolayer coverage and K_L (L/mg) is the Langmuir constant related to the adsorption energy [33].

3. Carbon electrode materials for CDI

Carbon is a large chemical family and represents a wide range of materials that are mainly composed by the carbon element. Among them, graphite and diamond are the two with crystal

structures and are not property adsorption materials because of the lack of surface area. Others are normally referred to as amorphous carbon. Earlier studies in the last few decades showed that carbon electrodes are promising in CDI cells because of their very high specific surface area, and thereby resulting in better electrosorption and higher salt rejections. Common carbon electrodes, which are utilized for CDI, are activated carbon, activated carbon powder, activated carbon cloth, carbon aerogel, carbon nanotubes, carbon nanofibers, ordered mesoporous carbon and graphene [9, 13].

3.1. Selected parameters for an ideal electrode

1. High specific surface area; it allows for high electrical capacity and high ion capacity to hold considerable quantity of ions (high adsorption). However, not the entire surface area calculated from experimental methods may be available to ions [9, 13, 29].

2. High electrical conductivity; it offers higher ion capacity [9, 31]; one may increase electrical conductivity by coating the electrode surface with dielectric materials. Myint et al. studied the CDI electrode made of nano/micro-sized zinc oxide/ACC to achieve better performance. Metallic or metal-like (e.g., metal oxide; titania) electronic conductivity guarantees that the whole electrode surface of all particles is charged with low-voltage gradients within the carbon. Low energy dissipation and low heating are achieved by having a high electronic conductivity [29, 31, 32]. Jia et al. reported that titania-modified-ACC increased adsorption sites on the electrode surface and showed good reversibility [9].

3. High stability: high physical, chemical and electrochemical electrodes' stability over a wide range of pH values, and the ability to tolerate frequent voltage changes is important to ensure longevity and system stability [9, 37].

4. High and improved hydrophilicity: good wetting behavior, by introducing hydrophilicity, ensures that the whole pore volume participates in the CDI process [9, 13].

5. Lower spacing between the two electrodes and large spacer electrostatic permittivity (short distances between EDLs) [9]. Laxman et al. added an ion exchange membrane in CDI cells to achieve better surface energy and stability [31].

6. Fast ion mobility within the pore network: bottlenecks or very small pores cause diffusional limitations and limit the kinetics. This concerns the porosity within carbon particles as well as the pore structure of the entire CDI electrode, considering, for example, interparticle distances and electrode thickness [13].

7. Low costs and scalability: low costs are important for large-scale applications [9, 13].

8. High bio-inertness: for long-term operation biofouling needs to be avoided in surface or brackish water treatment [13].

9. Low contact resistance between the current collector and the porous electrode to avoid a large voltage drop; thus, a low interfacial resistance is required from the electrode to the current collector [9, 13].

10. Good processability, moldable into film electrodes based on compacted powders, fibers or monoliths [13].

Non-composites		Composites	
Electrode	Specific surface area (m²/g)	Electrode	Specific surface area (m²/g)
ACC*	1200–1980	ACC/titania*	~ 1890
AC powder*	730–3073	AC/titania*	~ 546
AC nanofiber*	670–712	AC/Graphene*	~ 779
Graphene	220–406.4	Graphene/mesoporous carbon	~ 685.2
Carbon aerogels	113–1100	Graphene/mesoporous	~ 400.4
Carbon nanofiber	~ 186	Graphene/CNT*	222.1–479.5
CNT*	129.2–359.6	CNT/carbon nanofiber*	~ 211
OMC*	~ 844	CNT/micro/mesoporous carbon*	526–990

*ACC: Activated Carbon Cloth; AC: Activated Carbon; CNT: Carbon Nanotubes; OMC: Ordered Mesoporous Carbon.

Table 1. Specific surface area of various carbon non-composite and composite electrodes, as measured and reported from several previous studies reported by Jia et al. [9].

3.2. Specific surface area of various electrodes

As discussed earlier, higher specific surface area is the most important parameter in selecting an ideal carbon electrode for the CDI cell to ensure the maximum adsorption. Hence, **Table 1** shows the specific area of various carbon non-composites and composite electrodes [9].

4. Cell architectures and CDI designs

4.1. Flow between electrodes

In this architecture, CDI contains a pair of porous carbon electrodes parted by a spacer where feed water flows (feed water flows perpendicular to the applied electric field direction (see **Figure 4A**)). Flow between electrodes, which is also known as flow by electrodes, is the oldest and most used CDI architecture and was widely employed in various experiment works, including, but not limited to, removing salt from numerous feed waters, inspecting novel electrode materials performance and performing fundamental studies of salt sorption on porous electrodes. Traditional CDI design has advantages over newer designs due to its simplicity (no membranes or flow electrodes), which can potentially lower the system cost and reduce fouling issues [17, 38–42].

4.2. Flow-through electrodes

This architecture is defined as a CDI cell, with a pair of porous carbon electrodes parted by a thinner spacer, in which the feed goes directly through the electrodes and parallel to the applied electric field direction (**Figure 4B**). Flow-through electrodes system is used in a three-electrode cell to study fundamental performance parameters such as charge efficiency. Flow-through electrodes allow faster cell charging relative to flow-between systems. The primary
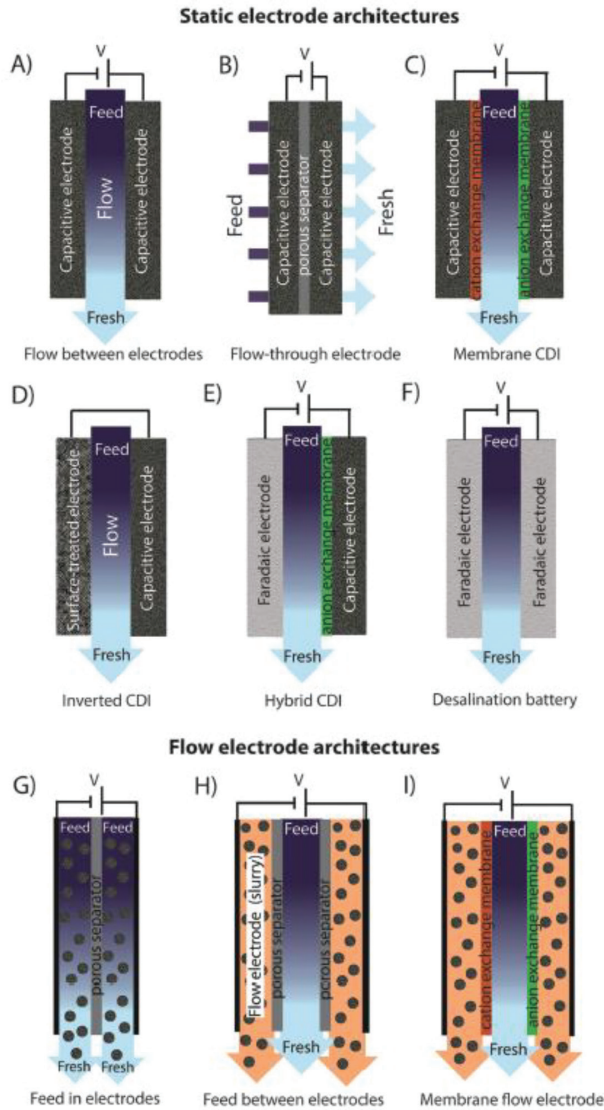
Figure 4. CDI architectures using static electrodes, including (A) flow between electrodes, (B) flow-through electrode, (C) membrane CDI and (D) inverted CDI. (E) and (F) show architectures which utilize static electrodes that depart from purely capacitive behavior, including (E) hybrid CDI and (F) a desalination battery. (G)–(I) show CDI architectures with flow electrodes, including systems with (G) feed-in electrodes, (H) feed-between electrodes and (I) membrane flow electrode CDI [17].

benefit of this architecture is to remove (or decrease) the separator layer which also serves as the feed flow channel, thus allowing a less separator thickness (from normally 200–500 μm to about 10 μm). The reduction of spacer thickness between electrodes allows for more compact

cells with lesser cell ionic resistance and faster desalination due to diffusion timescale reduction governing the removal of salt from the electrodes [17, 38, 42, 43].

4.3. Membrane CDI

This architecture uses ion exchange membranes on the separator side of each electrode (**Figure 4C**). As in electrodialysis cells, the feed water channels in membrane CDI (MCDI) cells are bounded by an anion exchange membrane (AEM) and a cation exchange membrane (CEM). The main benefit of the addition of membranes to the CDI cell is to improve the charge efficiency (which is linked to the efficiency of cell energy). Membranes may be tailored to have selectivity between different ions of the same charge sign which offers an additional level of tunability for complex multi-ion systems. The benefit of charging a CDI cell with constant current rather than constant voltage is that constant current allows for constant cell effluent concentration, which was first demonstrated on an MCDI cell which has the well-established advantage of improving the system's charge efficiency and sorption capacity because of the addition of ion exchange membranes, but this added a significant membrane cost as compared to other cell components [17, 13, 41–45].

4.4. Inverted-CDI

In this architecture, the flow between electrode CDI cell is modified by using a surface-treated carbon ^{A}node (negative surface charge via a chemical surface treatment), leading to the case of inverted-CDI (I-CDI, **Figure 4D**). Inverted cell demonstrates inverted behavior, whereby cell charging results in desorption of ions and cell discharging results in ion electrosorption [17, 46].

4.5. Hybrid CDI

A hybrid cell architecture combines a battery electrode (sodium manganese oxide) and a capacitive electrode (porous carbon) in a single desalination cell (**Figure 4E**). Hybrid systems enable high salt adsorption of ~ 31 mg/g as compared to traditional capacitive CDI cells which achieve up to about ~15 mg/g [17, 47–49].

4.6. Desalination battery

In this architecture, CDI cell utilizes two battery electrodes (**Figure 4F**) for better salt adsorption. The Faradaic reactions in electrodes are tuned to consume a single species (such as chloride or sodium) and may not be able to significantly remove (or affect) other present species [17, 47].

4.7. Carbon flow electrodes

In this design, feed water is pumped through electrode compartments for salinity treatment (**Figure 4G–I**). Carbon flow electrodes (FCDI) have two major benefits: first, feed water flowing through a single cell can be desalinated continuously, as the active carbon particle discharge (formation of brine) can occur as a separate process downstream of the cell, and a second major benefit is that FCDI can effectively increase the capacitance available for better

desalination than that of static electrode CDI systems. Therefore, FCDI can desalinate higher salinity streams than static CDI systems. Subsequently, FCDI has to evolve gradually to be economically suitable for sea water desalination [17, 47, 50].

5. ACC-CDI performance analysis

Removal efficiency of the CDI cells has been reviewed and analyzed with respect to many parameters (operating conditions). The effect of the feed flow rate and the initial ionic concentration on the removal efficiency is shown in **Figure 5**. It was found that salt rejections decrease at high flow rate; this is because the separation process requires high contact time between the electrode surface and the salt solution. Furthermore, high feed concentrations would result in reduced removal efficiency but would increase electrosorption capacity (SAC) since high amounts of salts will fill up more carbon pores and yield in higher adsorbed salts per electrode mass. Removal efficiency decreases at higher salt concentrations because it would
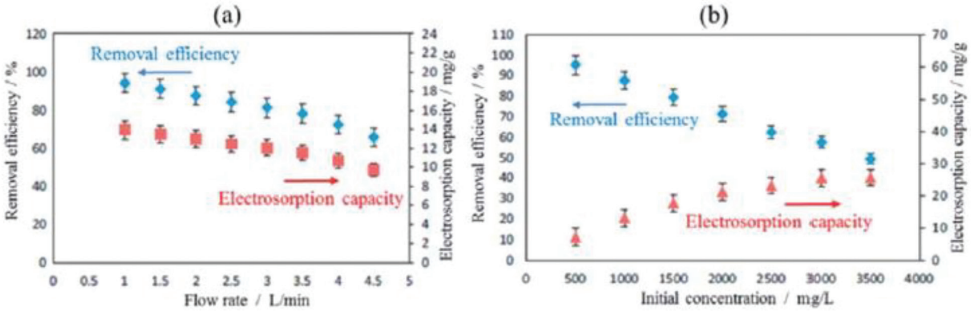

Figure 5. Removal efficiency and electrosorption capacity as a function of (a) flow rate and of (b) initial concentration of NaCl solution [51].
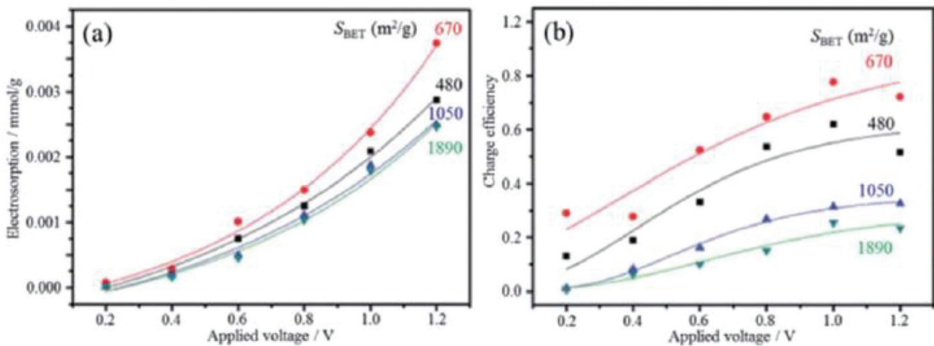

Figure 6. Activated carbon fibers (ACFs) with different S_{BET} (BET surface area): (a) amount of electrosorption and (b) charge efficiency against applied voltage [52].

be difficult to drop a high salinity level by utilizing small electrode mass and dimensions (e.g., 3×3 cm^2 and 0.6 g) which is the case of any CDI designed for lab-scale analysis [51, 52].

Figure 6 shows the effect of applied potential on SAC and charge efficiency at different activated carbon fibers (ACFs) electrodes with various BET surface area (S_{BET}). It was observed that there will be improvements in both SAC and charge efficiency if higher voltages are applied and higher electrode S_{BET} is achieved. The effect of ACC treatment (with KOH or HNO$_3$ for different treatment times) on the removal efficiency has been studied and shown that lower treatment (3 h) is favored to achieve a high CDI performance; see **Figure 7**. Conversely, longer CDI desalination times (4 min) are preferred and the desalination cycle may be terminated
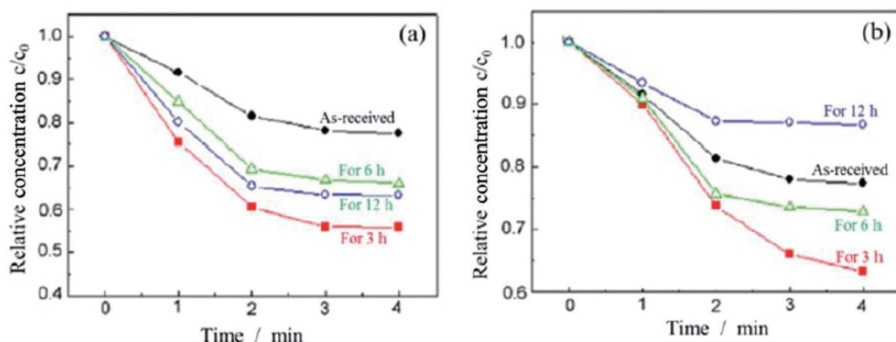

Figure 7. Changes in NaCl concentration (initial conductivity of 2000 mS/cm) with time for ACC. (a) ACC treated in KOH and (b) in HNO$_3$ [53].

Carbon electrode	Specific surface area (m²/g)	Initial salt concentration (mg/L)	Applied voltage (V)	Operation time (min)	Salt Rejection (%)	Salt adsorption capacity, SAC, (mg/g)	Ref.
ACC	984	1000	1.6	7	25	5.4	[31]
	1043	100	1.2	12.5	15	—	[32]
	1980	5844	1	300	18	1.75	[54]
	1200	100	1.2	7	15	5.8	[29]
	1980	5844	0 ~ 1.2	1440	12	—	[55]
ACC/ZnO	1300	100	1.2	7	22	8.5	[29]
	637	1000	1.6	7	15	8.1	[31]
	—	100	1.2	12.5	35	—	[32]
ACC/titania	1180	5844	0 ~ 1.2	1440	50	8.1	[55]
	1890	5844	1	300	40	4.3	[54]
	546	500	1.2	200	45	—	[56]

Table 2. Various activated carbon cloth (ACC) electrodes and their CDI treatment performance.

once we reach a stable product concentration; by doing this, one can estimate the highest achievable rejection for a specific CDI cell; see **Figure 7**.

ACC-CDI performance was evaluated to check for the system feasibility for water treatment by comparing the literature results for different studied ACC-CDI systems. Important parameters associated with the used electrode (e.g., specific surface area), electrolyte solution (e.g., initial salt concentration) and experiment operating conditions (e.g., applied voltage and operation time) were gathered and reported in **Table 2**. Observed salt rejections and SACs were gathered for non-composite ACC and composites ACC/ZnO and ACC/titania electrodes to be compared separately. The highest achieved rejections were 25, 35 and 50% for ACC, ACC/ZnO and ACC/titania, respectively, and the maximum observed SACs were 5.8, 8.5 and 8.1 for ACC, ACC/ZnO and ACC/titania, respectively.

6. Conclusion

CDI technology shows a great potential for brackish water desalination due to its simple design, cheap components, low energy-consumption (fairly low potential and recoverable energy), economical feasibility, high efficiency, safety and environmental friendliness. The classical EDL theory explains the concept behind the CDI which is simply associated with electrosorption of ions at the surface of a pair of electrically charged electrodes; counterions will occupy pores inside the carbon particles due to the presence of the Coulomb force. Salt rejection occurs due to both physical adsorption and electrical adsorption contributions. ACC-CDI systems should have feed water salinity between 100 and 1000 ppm (typically between 5 and 50 mM and/or 0.5 and 5 mS/cm) and applied potential must be in the range 0.6–1.6 V DC (typically 1.2 V). Desalination/regeneration time can have any duration/time, from very short ~ 4 min, with little adsorption, to very long > 90 min, depending on when equilibrium concentration becomes stable. ACC-CDI rejections could reach up to 25 and 35% for plain ACC and ACC deposited with ZnO nanorods.

CDI performance metrics and equations, which identify the system feasibility, have been discussed and included the following: desalination efficiency, charge efficiency, SAC, ASAR, specific capacitance and Langmuir isotherm. Selected parameters when choosing an ideal electrode must involve high specific surface area, high electrical conductivity, high stability, high hydrophilicity, low costs and scalability. It was found that traditional CDI design has advantages over newer designs due to its simplicity and lower costs. However, other CDI architectures showed higher system's efficiency (e.g., MCDI), but with a significant added cost. Generally, removal efficiency increases at low salt concentrations and low flow rates. Though high feed concentrations would result in higher SAC, higher applied potentials, higher surface areas and longer CDI desalination times are favored for better CDI performance. Observed salt rejections and SACs of various non-composite ACC and composites ACC/ZnO and ACC/titania showed that the composite electrodes have much higher numbers. The highest achieved rejections were 25, 35 and 50% for ACC, ACC/ZnO and ACC/titania, respectively, and the maximum observed SACs were 5.8, 8.5 and 8.1 for ACC, ACC/ZnO and ACC/titania, respectively.

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