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DESALINATION BY CAPACITIVE DEIONIZATION WITH CARBON-BASED MATERIALS AS ELECTRODE: A REVIEW

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Capacitive deionization (CDI) is a recently developed electrosorption technology for deionization using porous electrodes. The electrode materials play an important role in the efficiency. This paper highlights the current research status of carbon-based materials as the electrode and the adsorption models in the CDI. It includes the types and performances of carbon-based materials and the main influencing factors of the desalination characteristics. Also, operating parameters such as charging voltage, flow rate, concentration of feed solution, treating time and temperature are summarized.

Keywords: Capacitive deionization; carbon-based materials; adsorption models.

1. Introduction

Capacitive deionization (CDI) is an electrochemical desalting technology based on application of an electrical potential difference between two electrodes.¹ Ions can absorb in the electrical double layer of the electrodes when the electrodes are charging, resulting in the removal of salts from the solution. Once the electric potential is removed, the adsorbed ions are quickly released back into the bulk solution, producing ion-concentrated washing water.²

Figure 1 schematically represents CDI process. Carbon-based materials were coated or suppressed on the collectors, which are connected to a direct current power source. Brackish water flows through the space of two electrodes. Anions are adsorbed on the cathode, and cations are adsorbed on the anode during the CDI process.³ Therefore, water is desalted. During the discharging step, the adsorbed ions are subsequently desorbed in water by turning off the potential or changing the polarity.

The CDI process could be traced back to the mid-1960 while carbon electrodes were used to remove salinity from water.⁴ Later, numerous studies on electrode materials in CDI process were performed.^{5–7} The desalting mechanism was attributed to the adsorption of ions in electrical double layers.⁸ During the last decade, CDI technology has gradually matured, and has transited from laboratory to practical application.³

CDI process is operated at a low potential (1 to 2 V)and does not require any additional chemicals to



Fig. 1. Schematic representation of CDI process.

regenerate electrodes.⁹ Compared with other desalination processes, such as ion exchange,² electrodialysis,¹⁰ reverse osmosis² and distillation, etc., it is characterized by the high energy efficiency, high ion removal, easy electrode regeneration and low cost.^{11,12} CDI technology is not only applied to desalination, but also to dyeing wastewater treatment,¹³ pesticides treatment,¹⁴ insulin purification,¹⁵ aniline and phenol wastewater treatment.^{16,17}

This paper will highlight the development and research status of various kinds of carbon-based electrodes used in CDI process, and present the advantages and disadvantages of the electrode materials. Also, the theoretical aspect of CDI for desalination will be summarized.

2. CDI Electrode

Electrode is the core part of CDI process. It is usually prepared by the methods of compression and coating. In the former method, CDI electrode is made by pressing the mixtures of electrode material, binder and conductive agent under a constant pressure. With the latter one, the electrode is made by dispersing first electrode materials, binder and conductive agent in an organic solvent, and then coating the suspension on a current collector and drying at a certain temperature. A CDI electrode module could be assembled with cathode and anode, as shown in Fig. 2. The electrode shape corresponds with that of the modules.

In the preparation of carbon-based electrodes, commonly used binders are poly(vinylidenefluoride) (PVDF) and poly(tetrafluoroethylene) (PTFE). The type and amount of binder used significantly affect the electrochemical characteristics and surface structures of CDI electrodes.³ Recently, some watersoluble polymers such as poly(vinyl alcohol) (PVA) and poly(vinyl acetate) (PVAc) have been used as binders for CDI electrode preparation, which can increase electrode wettability and solution–electrode contact area, and thus increase the adsorption capacity on the electrodes.¹⁸ However, the polymers may be re-dissolved in the bonded electrodes, resulting in breaking of the electrodes.

3. Electrode Materials

Generally, carbon-based materials are profusely used as CDI electrodes for desalination because of their extended specific surface area, high adsorption capacity, reasonable microporous structure and special surface reactivity.³

3.1. Activated carbon powder

The earliest adopters in CDI process was activated carbon powder (ACPs), due to the low cost, good electrochemical stability, high specific surface area $(1000 \sim 3000 \text{ m}^2/\text{g})$ and high adsorption capacity. ACPs could be one of the most potential electrode materials for the commercial industrialization of CDI



Fig. 2. CDI electrode module.

technology.¹⁸ It was reported that with ACP, CDI process dropped the conductivity of NaCl solution from 478 to $51.4 \,\mu s/cm$ at $1.2 \,V$ after 90 min, and the desalination efficiency reached 89.25%.¹⁹

ACPs with large specific surface areas are usually used for achieving high specific capacitance and thus high ion adsorption capacity.²⁰ It was reported that the specific capacitance did not linearly correlate with the surface area. Only part of surface area contributed to the specific capacitance.²¹ In addition, pore size, pore structure and critical aperture also affected the desalination efficiency of CDI process with ACPs as electrodes. For example, the adsorption capacity for methylene blue increased from about 90 to 180 mg/g if the percentage of mesopores in ACPs increased from 33% to 61%.²²

3.2. Activated carbon fiber

Activated carbon fiber (ACF) is a fibrous precursor, which was produced at low temperature (200– $400^{\circ}C$ and then activated by carbonization at 700–1000°C. It features abundant microporous structure, small aperture and narrow pore size distribution, leading to a better ion adsorption and easier electrode regeneration.²³ ACF contains traces of impurity such as O, H, N and S, which results in an excellent adsorption performance.²⁴ Also, ACF is characterized by the high strength and dimensional stability, low thermal expansion coefficient, biological compatibility and fatigue resistance. With ACF as the electrode, an electrosorption capacity of $4.64 \,\mathrm{mg/g}$ was achieved by CDI process at $1.6 \,\mathrm{V}$, which is comparatively higher than that achieved by ACP electrode.²³

However, the high price ACF due to the high production cost limits its commercial applications.

3.3. Carbon aerogels

Carbon aerogel (CA) is obtained from resorcinol and formaldehyde by atmospheric pressure drying method. It is composed of a lot of nano-holes and mesoholes. It features high specific surface area, controllable pore structure, good conductivity and wide density range, leading to an excellent properties for electrosorption.²⁵ CA is considered as an ideal electrode material for electric double layer capacitor. The total capacity of the CA was determined to be 7.0 mg NaCl/g at the flow rate of $250\,\mathrm{mL/min}$ and applied power of $1.3\,\mathrm{V}.^{26}$

However, the high production cost and the difficulty in preparation limited the development of CA as the electrodes in CDI process.

3.4. Carbon nanotubes

Carbon nanotubes (CNTs) have been considered to be an ideal material as electrodes for CDI since 1991.^{27,28} Ideal CNTs are seamless and hollow tube formed by rolling the carbon atom graphene sheet layers. Depending on the number of layers of carbon atoms in the tube, CNTs could be divided into singlewalled nanotube (SWNT) and multi-walled nanotube (MWNT). The nanotubes are generally measured for nanometers to dozens of nanometers in diameter, and microns in length.²⁹ Most of the apertures are more than 2 nm, which is very beneficial to the formation of electric double layers. However, because of the relatively low surface area, about $100 \sim 400 \,\mathrm{m^2/g}$, the capacitance of CNTs is low. The direct method to improve the capacitance of CNTs is to increase the specific surface area.^{30,31}

During the last two decades, numerous reports have concerned CNTs as electrodes for removing hazardous ions from brackish water. CNTs quickly became one of the hot researches in water treatment, due to its unique mechanical, electrical and chemical characteristics.³²

3.5. Graphene

Graphene is a two-dimensional monolayered hexagonal hybridized carbons, and has attracted great attentions due to its unique physical and chemical properties from the one-atom-thick planar structure.³³ Graphene is ideal to be used as electrodes in CDI process, because of the high theoretical specific area of $2630 \text{ m}^2/\text{g}$, the superior theoretical conductivity of 7200 S/m and the excellent mechanical and thermal strength.^{31,34}

Recent studies have demonstrated that graphene nanosheets and their composites such as $MnO_2/graphene$ and polyaniline/graphene have a high potential as electrode materials.^{35,36} Chemical modifications could help graphene nanosheets to improve the electrochemical performance. For example, pristine graphene sheets exhibited a specific capacitance of

Table 1. Desalination of water with CDI process by using different kinds of carbon-based electrodes.

Electrode materials		Feed water $(\mu S/cm)$	Applied voltage (V)	Desalination efficiency	Electrosorption capacity $(\mu mol/g)$	Flow rate (ml/min)	Ref.
AC	1260	400	1.2	92.6%	_	20	18
ACF	712	192	1.6	36.5%	79.32	5	23
\mathbf{CA}	610	101.6	1.7	64.6%	64.3	400	40
CNT	370.7	100	1.2	70%	_	20	31
SWCNT	453	46	2.0	51%	9.35	25	30
Graphene	14.2	50	2.0	22%	31.62	25	41
Graphene	77	46	2.0	93%	7.87	25	30

 $101\,{\rm F\,g^{-1}}$ while the KOH modified graphene sheets achieved $136\,{\rm F\,g^{-1}}.^{37}$

3.6. Other carbon based materials

The mixture of PVA and sulfosuccinic acid (SSA) was reported as a cation-exchange polymer to coat carbon electrode, on which negatively charged ion-exchange groups were impregnated. This composite carbon electrode is suitable for CDI process in terms of its ion-selectivity and electrical resistance.³⁸

A manganese oxide $(MnO_2)/CNTs$ composite was prepared by the layer-by-layer deposition, while polystyrene sodium sulfonate (PSS) was used for the dispersion of CNTs and the growth of MnO₂. This material as electrodes in CDI process could achieve high salt removals from water.³⁹

Table 1 summarizes the results for the desalination of water by using various kinds of carbon-based CDI electrodes with CDI process, which were reported elsewhere.

4. Adsorption Models

At the interface of electrolyte solution and electrode, there exist regions with an excess of opposite electrical charges, termed as EDL.⁴² Under imposed voltage at both ends of electrodes, ions in water migrate because of electrostatic interaction, and are stored in EDL, leading to the reduction of dissolved salt concentration and thus the desalination and purification.⁴³ The models of ionic adsorption in EDL are described in detail as follows.

4.1. Helmoholtz model

The earliest theory of EDL was originally proposed in 1879 by Helmoholtz. The distribution of charges in EDL was described as a capacitor: accumulation of charges on electrode surfaces while the opposite-sign charges are accumulated in the solution. The charges on electrode surface and the ions in solution are closely arranged on both sides of the interface, forming compact layers, as shown in Fig. 3(a). The compact charge density is given by

$$\sigma_H = \frac{\varepsilon \varepsilon_0}{d} \phi, \tag{1}$$

where ε is the dielectric constant of the medium, ε_0 is the permittivity of free space, ϕ is the voltage drop, and d is the interplate spacing. The differential capacity of compact layer, C_H , is expressed by

$$C_H = \frac{d\sigma_H}{d\phi} = \frac{\varepsilon\varepsilon_0}{d}.$$
 (2)

In this case, the potential distribution of EDL presented in a straight line, and the value of differential capacitance is a constant, as shown in Fig. 3(b). This model only considered the electrostatic effect between



Fig. 3. Schemaatic diagram of Helmoholtz model. (a) Charge distribution; (b) Potential variation vs distance and differential capacitance vs electrode potential.

charged solid surfaces and the counter ions, but ignored the thermal motion of the ions.⁴⁴ It did not reflect the differential capacitance changed with electrode potential and solution concentration.

4.2. Gouy-Chapman model

In 1910s, Gouy and Chapman proposed the diffusion model of EDL. In this consideration, ions in solutions are not only influenced by electrostatic attraction, but also by the thermal movement, leading the ions to escape the electrode surfaces and to scatter irregularly in the solutions. Therefore, diffused layer was formed, as shown in Fig. 4(a) The diffuse charge density is given by

$$\sigma_D = (8\kappa T \varepsilon \varepsilon_0 n^0)^{1/2} \sinh\left(\frac{ze\phi_0}{2\kappa T}\right),\tag{3}$$

where κ is the Boltzmann constant, n^0 is the number concentration of each ion in the bulk solution, z is the valence of the ions, ϕ_0 is the voltage drop of diffuse layer, and T is the absolute temperature. The differential capacity, C_D , can be expressed by

$$C_D = \frac{d\sigma_D}{d\phi_0} = \left(\frac{2z^2 e^2 \varepsilon \varepsilon_0 n^0}{\kappa T}\right)^{1/2} \cosh\left(\frac{ze\phi_0}{2\kappa T}\right). \quad (4)$$

The electric potential distribution and C_D were shown in Fig. 4(b).

The Gouy-Chapman model failed to apply to high-concentration electrolytic solution, which might be because ion is not a point charge and that neighbor ions interact each other because of electrostatic and Van der Waals force, leading to a different ion distribution from bulk solutions.



Fig. 4. Schematic diagram of Gouy–Chapman model. (a) Charge distribution; (b) Potential variation vs distance and differential capacitance vs electrode potential.

4.3. Stern model (Gouy-Chapman-Stern model)

In 1924, Stern model was presented, in which the double layer was divided into two regions. One is inner region where ion distribution followed Langmuir's adsorption isotherm, termed as compact layer; another is far from the surface that can be roughly described by the Gouy–Chapman model, termed as diffused layer, (Fig. 5). Gouy–Chapman–Stern (GCS) model successfully explained salt adsorption and charge density on electrodes, which might be close to the real structure of EDL.

Based on the Stern model, total capacitance can be calculated through a series union of compact layer and diffused layer. The differential capacitance includes compact EDL capacitance (C_H) and diffused EDL capacitance (C_D) can be given by

$$\frac{1}{C_d} = \frac{1}{C_H} + \frac{1}{C_D}$$

$$= \frac{x}{\varepsilon \varepsilon_0}$$

$$+ \frac{1}{(2z^2 e^2 \varepsilon \varepsilon_0 n^0 / \kappa T)^{1/2} \cosh(ze\phi_0 / 2\kappa T)}, \quad (5)$$

where x is the thickness of Helmoholtz layer.

However, GCS model is not suitable to the case of ions transporting into porous electrodes. It might be attributed to that the model assumed a diffused layer extending into solution of several times of the Debye length (about 3 nm at 10 mmol/l salt concentration), while micropores in activated carbon electrodes are less than 2 nm, leading diffused layers



Fig. 5. Schematic diagram of GCS model. (a) Charge distribution; (b) Potential variation vs distance and differential capacitance vs electrode potential.

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to be overlapped strongly.⁴⁵ This overlapping effect prevents ions from entering the micropores, resulting in a lower electrosorption capacity.⁴⁶

4.4. Bockris-Devanathan-Muller model

The EDL models stated above are based on interfacial charges on the electrode and ionic species in electrolytic solutions. They might not be suitable to polar solvents such as water that contribute to the potential drop across the electrode/electrolyte interface. Therefore, an innovative model was proposed, which is schematically represented in Fig. 6. Water molecules directly adsorb on electrode surfaces if electric field intensity between compact layer and electrode surface is high. The residual charge in the solution side is positive if electrode charge is negative. The compact layer is composed of water molecules dipole layer and hydrated cation layer, which is termed as outer compact layer. The nearest place to the center of solvated ions is outer Helmoholtz plane (OHP), as shown in Fig. 6(a) with the thickness $x(x = x_1 + x_2)$, which is the distance between electrode surface and hydrated cation center. If electrode charge is positive, specifically adsorbed anions would tightly bound to the electrode surface in the form depicted in Fig. 6(b). The inner Helmholtz plane (IHP) locates at the centers of the anion (x_1) .

Fig. 6. Schematic diagram of BDM model. (a) Charge distribution of negative electrode; (b) Charge distribution of positive electrode.

OHP thickness is different from that of IHP because of the specific adsorption, so that the capacitance of negatively charged compact layer is smaller than that of positively charged layer. In Eq. (5), x is different for the two cases.

4.5. EDL model in pores

In CDI process, EDLs are formed inside pores because microporous or mesoporous electrodes are used. If pore size is less than EDL thickness, the EDL in the pore would overlap and then negatively affect the efficiency of CDI process. An EDL model in pores by considering the overlapping effect was developed for the electrosorption of ions from aqueous solutions.^{25,45}

Regarding a single pore with width ω as a slit formed by two planar plates, as shown in Fig. 7, basic equation for surface potential distribution can be expressed as follows⁴⁷:

$$\frac{d^2\psi}{dx^2} = \frac{2zeN_0}{\varepsilon}\sinh\left(\frac{ze\psi}{kT}\right).$$
(6)

With the boundary conditions according to the distance variable x:

$$\frac{\mathrm{d}\psi}{\mathrm{d}x} = 0$$
 and $\psi = \psi_{\mathrm{m}}$, at $x = 0;$ (7)

$$\psi = \psi_{\rm d}, \quad \text{at } x = \pm \frac{\omega - a}{2};$$
(8)

$$\psi = \psi_0, \quad \text{at } x = \pm \frac{\omega}{2}.$$
(9)

Integrating Eq. (6), the surface charge density is obtained as follows:

$$\sigma_0 = \sqrt{4\varepsilon RTI} \left[\cosh\left(\frac{ze\psi_d}{kT}\right) - \cosh\left(\frac{ze\psi_m}{kT}\right) \right]^{1/2},$$
(10)



Fig. 7. Schematic diagram of EDL model in micropores.

where z is the valence of the ions, e is the electrical charge of electron, N_0 is the total number of the ions in the bulk solution, a is the diameter of hydrated counterion, ψ is the electrical potential, I is the ionic strength, R is the gas constant, ψ_d , ψ_m and ψ_0 are the potentials of diffuse layer, midplane and surfaces, respectively.

The solutions of Eqs. (6) and (10) with the boundary conditions [Eq. (10) can be worked out using the software MatLab] would lead to the surface charge density and then the capacitance of EDL in pores (C_{dl}) as follows:

$$C_{dl} = \frac{d\sigma_0}{d\psi_0}.$$
 (11)

5. Main Parameters of Process

5.1. Electrode material

5.1.1. Pore-size distribution

Porous material can be classified as microporous (pore diameter $d_p < 2 \text{ nm}$), mesoporous ($2 \text{ nm} < d_p < 50 \text{ nm}$) and macroporous ($d_p > 50 \text{ nm}$). As already stated, it is difficult for ions to enter into micropores, while micropores contribute a lot to specific surface area of the electrodes. Therefore, surface area from micropores might be invalid in CDI process. In other words, the use of extremely high surface area carbons might be unprofitable.

Recent studies indicated that CDI capacity significantly related to the charge efficiency of EDL that depends mainly on mesopore volume.⁴⁸ The overlapping effect of EDL would be reduced in mesopores, leading to the increase of electrosorption capacity.²⁵ There are many ways to improve the volume of mesopores of activated carbon. For instance, microwave modification would open blind holes and increase entrances, which would be very helpful of ion adsorption on activated carbon electrodes.⁴⁹

5.1.2. Surface properties

Numerous studies have showed that surface functional groups (SFGs) on carbon materials also greatly influenced the desalination of CDI process. SFGs include carboxyl, carbonyl, phenol, lactone, etc.⁵⁰ SFGs may enhance surface wettability and thus improve the efficiency of surface utilization. Also, SFGs may result

in redox reactions to generate Faradaic pseudocapacitance in the process of charging and discharging, dramatically improving the specific capacitance.⁵¹ The capacitance of Faradaic pseudocapacitance is about 1–5 F/m^2 , while that of EDL in porous carbons is usually 0.1–0.2 F/m^2 .

The property and concentration of SFGs could be modified through post-activation treatments. The common methods are liquid phase oxidation and gas oxidation. The former is realized in liquids, while the latter is realized in gases.

Various chemical reagents, such as nitric acid (HNO_3) , hydrogen peroxide (H_2O_2) , perchloric acid, ammonium persulphate $((NH_4)_2S_2O_8)$, potassium permanganate $(KMnO_4)$ are used for liquid phase oxidation.⁵² For instance, the oxidation with HNO_3 could greatly modify the pore structure, oxygencontained SFGs and capacitance performance of carbon-based materials. Specific surface area and mesopore volume decreased with increasing oxidation temperature, while oxygen-contained SFGs increased. The presence of oxygen-contained SFGs not only brought pseudocapacitance but also enhanced EDL capacitance.⁵³ In addition, it was found that carbonyl and the carboxyl groups in carbon-based materials are helpful for fast Faradic reactions, because of their lower charge transfer resistance than hydroxyl group.⁵⁴

Gas oxidation is a simple and effective method to improve the electrochemical properties of carbon electrodes. Commonly used gases are O_2 , O_3 , SO_2 and H_2S .⁵⁵ Sulfur surface complexes (such as C-S, S-S, C == S and S-O) appeared on carbon based materials treated in SO_2 and H_2S , leading to a great improvement of the adsorption performance on the materials.⁵⁶ Also, gas oxidation with argon plasma and N_2/H_2 and CO_2 plasma could improve the capacitance of carbon materials and avoid collapse of the materials.⁵⁷

5.2. Voltage

According to the EDL theory, the higher the voltage on the electrodes, the thicker the EDL, and the stronger the adsorption of ions. However, a high voltage can cause electrolysis of solution. For instance, water is decomposed to hydrogen ions and hydroxide ions if applied electric field is over 1.2 V, which would change solution pH and oxidize carbon electrodes and thus negatively affects CDI process.⁵⁸ At potentials less than 1.0 V, solution pH rapidly increased until reached a constant as the increase of the potential, which is due to the reduction of dissolved oxygen. However, over 1.2 V, the pH rapidly decreased due to the oxidation of chloride at anodes.⁵⁹ Hence, salt removal would increase with increasing potential in the range of 0.8–1.5 V. In addition, high voltage would increase energy consumption.

5.3. Flow rate

Increasing flow rate would decrease solution resistance and thus increase current density, leading to the increase of salt removal.⁶⁰ On the other hand, increasing flow rate would reduce residence time, so that ions would have less contact time to electrodes to absorb onto the surfaces. The latter is much more remarkable, leading to that flow rate negatively affects salt removal in CDI process.

5.4. Ionic concentration in feed solution

Increasing ionic concentration in feed solution would decrease solution resistance and increase adsorption velocity, and thus increase the capacitance and salt removal.⁶¹ At a high ionic concentration, the increase would cease because of saturation limit.

5.5. Treatment time

Ionic concentration in solution decreases with treatment time, as a part of ions adsorb on electrodes. At the beginning, the concentration dropped down rapidly, indicating a quick adsorption of salts on the electrode. This might be because a large amount of sites are available on electrode surfaces for electrosorption. Later, the sites and ionic concentration reduced, leading the adsorption to slow down until a dynamic equilibrium.⁶²

5.6. Temperature

Salt removal in CDI process decreases with increasing temperature, which has been confirmed in the experiments with carbon nanotubes and nanofibers and activated carbon as the electrodes.⁶³ It might be because the adsorption of salts on carbon-based

materials belongs to physical adsorption, and increasing temperature may result in metallic ions to escape from electrode surfaces into solution. Also, hydrophobic–hydrophilic transition in interfacial water would be stronger at lower temperature, leading the affinity between activated carbon and interfacial hydrated ions to be strengthened.⁶⁴

5.7. Other factors

There are many other factors, such as plate spacing of electrodes and the number of electrode pairs, etc., affecting the desalination efficiency of CDI process. The smaller the distance between electrodes, the stronger the ion adsorption and the shorter the treatment time. The more the electrode pairs, the higher the salt removal.

6. Conclusion

CDI process could be a potential technology for desalination because of low energy consumption, simple operation, multiple electrodes, and environmentfriendly regeneration. Although numerous works in scientific and the technological aspects have been carried out, the commercial application of CDI process has not appeared. CDI process is highly efficient for the desalination of low salinity sources such as brackish, while is not suitable for high salinity such as seawater. The key issues are to develop better porous materials as electrodes and to obtain more understandings of the adsorption of ions on surfaces of pores.

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References

- M. A. Anderson, A. L. Cudero and J. Palma, *Electrochim. Acta* 55 (2010) 3845–3856.
- K. Watson, M. J. Farre and N. Knight, J. Environ. Manage. 110 (2012) 276–298.

- D. D. Caudle, J. H. Tucker, J. L. Cooper, B. B. Arnold and A. Papastamataki, Research and Development Progress Report No. 188 (United States Department of Interior, 1996), p. 190.
- Y. Oren and A. Soffer, J. Electrochem. Soc. 125 (1978) 869–875.
- D. Hall, Y. Oren, Z. Priel and A. Soffer, Sep. Sci. Technol. 22 (1987) 1017–1027.
- J. C. Farmer, D. V. Fix, G. V. Mack, R. W. Pekala and J. F. Poco, J. Electrochem. Soc. 143 (1996) 159–169.
- A. M. Johnson and J. Newman, J. Electrochem. Soc. 118 (1971) 510–517.
- H. B. Li, L. K. Pan, T. Lu, Y. K. Zhan, C. Y. Nie and Z. Sun, J. Electroanal. Chem. 653 (2011) 40–44.
- M. Sadrzadeh and T. Mohammadi, *Desalination* 221 (2008) 440–447.
- J. B. Lee, K. K. Park, S. W. Yoon, P. Y. Park, K. I. Park and C. W. Lee, *Desalination* 237 (2009) 155–161.
- A. Subramani, M. Badruzzaman, J. Oppenheimer and J. G. Jacangelo, *Water Res.* 45 (2011) 1907–1920.
- Y. H. Han, X. Quan, X. L. Ruan and W. D. Zhang, Sep. Purif. Technol. 59 (2007) 43–49.
- O. Kitous, A. Cheikh, H. Lounici, H. Grib, A. Pauss and N. Mameri, *J. Hazard. Mater.* **161** (2009) 1035–1039.
- S. M. Jung, J. H. Choi and J. H. Kim, Sep. Purif. Technol. 19 (2012) 31–35.
- Y. H. Han, X. Quan, S. Chen, H. M. Zhao, C. Y. Cui and Y. Z. Zhao, *J. Colloid Interface Sci.* 299 (2006) 766–771.
- Y. H. Han, X. Quan, S. Chen, H. M. Zhao, C. Y. Cui and Y. Z. Zhao, *Sep. Purif. Technol.* **50** (2006) 365–372.
- B. H. Park, Y. J. Kim, J. S. Park and J. Choi, J. Indus. Eng. Chem. 17 (2011) 717–722.
- C. H. Hou and C. Y. Huang, *Desalination* **314** (2013) 124–129.
- H. Oda and Y. Nakagawa, Carbon 41 (2003) 1037–1047.
- T. C. Wang and H. Teng, *Electrochem. Soc.* 184 (2001) A368–A373.
- K. Sun, J. C. Jiang and D. D. Cui, *Biomass Bioenergy* 35 (2011) 3643–3647.
- G. Wang, C. Pan, L. P. Wang, Q. Dong, C. Yu, Z. B. Zhao and J. S. Qiu, *Electrochim. Acta* 69 (2012) 65–70.
- C. Brasquet, B. Rousseau, H. Estrade-Szwarck and P. L. Cloirec, *Carbon* 38 (2000) 407–422.
- T. Y. Ying, K. L. Yang, S. Yiacoumi and C. Tsouris, J. Colloid Interface Sci. 250 (2002) 18–27.
- P. Xu, J. E. Drewes, D. Heil and G. Wang, *Water Res.* 42 (2008) 2605–2617.
- 27. S. Iijima, Nature 354 (1991) 56-58.
- M. V. Kiamahalleh, S. H. S. Zein, G. Najafpour, S. A. Sata and S. Buniran, *Nano* 7 (2012) 1230002.

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- M. Kumar and Y. Ando, J. Nanosci. Nanotechnol. 10 (2010) 3739–3758.
- 30. A. C. Dillon, Chem. Rev. 110 (2010) 6856–6872.
- H. B. Li, L. K. Pan, T. Lu, Y. K. Zhan, C. Y. Nie and Z. Sun, J. Electroanal. Chem. 653 (2011) 40–44.
- C. J. Yan, L. Zou and R. Short, *Desalination* 290 (2012) 125–129.
- 33. A. K. Geim, Science 324 (2009) 1530–1534.
- T. S. Sreeprasad and T. Pradeep, Int. J. Mod. Phys. B 26 (2012) 1242001.
- M. Kim, Y. Hwang and J. Kim, Chem. Eng. J. 230 (2013) 482–490.
- K. Zhang, L. L. Zhang, X. S. Zhao and J. S. Wu, Chem. Mater. 22 (2010) 1392–1401.
- Y. M. Li, M. V. Zijll, S. Chiang and N. Pan, J. Power Sources 196 (2011) 6003–6006.
- J. S. Kim and J. H. Choi, J. Membr. Sci. 355 (2010) 85–90.
- 39. J. Yang, L. Zou and H. H. Song, Desalination 286 (2012) 108–114.
- H. H. Jung, S. W. Hwang, S. H. Hyun, K. H. Lee and G. T. Kim, *Desalination* **216** (2007) 377–385.
- H. B. Li, T. Lu, L. K. Pan, Y. P. Zhang and Z. Sun, J. Mater. Chem. 19 (2009) 6773–6779.
- 42. C. J. Feng, C. H. Hou, S. H. Chen and C. P. Yu, *Chemosphere* **91** (2013) 623–628.
- E. Avraham, M. Noked, A. Soffer and D. Aurbach, Electrochim. Acta 56 (2011) 6312–6317.
- A. J. Bard and L. R. Faulkner, *Electrochemical Methods: Fundamentals and Applications*, 2nd edn. (John Wiley & Sons, Inc, New York, 2001).
- K. L. Yang, T. Y. Ying, S. Yiacoumi, C. Tsouris and E. S. Vittoratos, *Langmuir* **17** (2001) 1961–1969.
- C. Lin, J. A. Ritter, B. N. Popov and R. E. White, J. Electrochem. Soc. 146 (1999) 3168–3175.
- C. H. Hou, C. D. Liang, S. Yiacoumi, S. Dai and C. Tsouris, J. Colloid Interface Sci. 302 (2006) 54–61.
- Z. H. Huang, M. Wang, L. Wang and F. Kang, Langmuir 28 (2012) 5079–5084.
- X. Jiang, W. J. Jiang, X. F. Zhu and Y. Jin, *Techni*ques Equip. Environ. Pollut. Control 5 (2004) 43–46.
- J. S. Mattson and H. B. Mark, Activated Carbon (Marcel Dekker, New York, 1971).
- M. J. Bleda-Martinez, J. A. Macia-Agullo, D. Lozano-Castello, E. Morallon and D. Cazorla-Amoros, *Carbon* 43 (2005) 2677–2684.
- M. Molina-Sabio, M. A. Muñecas-Vidal and F. Rodriguez-Reinoso, *Stud. Surf. Sci. Catal.* **62** (1991) 329–339.
- D. W. Wang, F. Li, M. Liu and H. M. Ming, New Carbon Mater. 24 (2007) 307–314.
- 54. L. X. Li and F. Li, New Carbon Mater. 26 (2011) 224–228.
- A. Macias-Garcia, V. Gomez-Serrano, M. F. Alexandre-Franco and C. Valenzuela-Calahorro, J. Hazard. Mater. 103 (2003) 141–152.

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- C. Y. Yin, M. K. Aroua and W. M. A. W. Daud, Sep. Purif. Technol. 52 (2007) 403–415.
- D. Tashima, A. Sakamoto, M. Taniguchi, T. Sakoda and M. Otsubo, *Vacuum* 83 (2009) 695–698.
- L. K. Pan, X. Z. Wang, Y. Gao, Y. P. Zhang, Y. W. Chen, Z. Sun, *Desalination* 244 (2009) 139–143.
- 59. J. H. Lee, W. S. Bae and J. H. Choi, *Desalination* 258 (2010) 159–163.
- Y. J. Kim and J. H. Choi, Water Res. 44 (2010) 990–996.
- G. Rasines, P. Lavela, C. Macias, M. Haro, C. O. Ania and J. L. Tirado, *J. Electroanal. Chem.* 671 (2012) 92–98.
- 62. B. P. Jia and L. Zou, Carbon 50 (2012) 2315-2321.
- M. Mossad and L. Zou, J. Hazard. Mater. 213 (2012) 491–497.
- H. J. Wang, X. K. Xi, A. Kleinhammes and Y. Wu, Science **322** (2008) 80–83.