A study of the capacitive deionisation performance under various operational conditions

Mohamed Mossad, Linda Zou *

SA Water Centre for Water Management and Reuse, University of South Australia, Adelaide, SA 5095, Australia

ABSTRACT

Capacitive deionisation (CDI) has many advantages over other desalination technologies due to its low energy consumption, less environmental pollution and low fouling potential. The objectives of this study are to investigate the effect of operational conditions on the CDI electrosorption efficiency and energy consumption, to identify ion selectivity in multi-ionic solutions and to probe the effect of dissolved reactive silica on the treatment efficiency. A series of laboratory scale experiments were conducted using a CDI unit with activated carbon electrodes. The electrosorption removal efficiency was inversely related to solution temperature, initial total dissolved salts (TDS) concentration and the applied flow rate. CDI energy consumption (kWh/m^3) is directly related to the TDS concentration and inversely related to the flow rate. The kinetics analysis indicated that the electrosorption followed pseudo-first-order kinetics model. Ion selectivity on activated carbon electrodes followed the order of $Fe^{3+} > Ca^{2+} > Mg^{2+} > Na^+$ for cations and $SO_4^{2-} > Br^- > Cl^- > F^- > NO_3^-$ for anions. It was found that the dissolved silica was not removed by CDI; no silica fouling was found. The deterioration of activated carbon electrodes was not observed at any time during experiment.

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1. Introduction

Fresh water shortages affect many countries and communities, principally due to population growth and the increase in the standard of living. Compounding this is the large-scale exploitation and contamination of natural freshwater resources by industry, agriculture and municipalities [1,2]. Over 1 billion people live in regions without clean drinking water and approximately 2.3 billion people (41% of the world population) suffer water shortages [3]. More than 96.5% of earth's water is salty. Therefore, water desalination stands out as one of the most useful tools to resolve the impending water crises. Several desalination technologies have been developed and used based on thermal methods, membrane methods, electrochemical methods and other methods [4]. However, these technologies still have many disadvantages that need to be overcome, such as high energy consumption, membrane fouling, secondary pollution and high expense for operation and maintenance [5–7]. Therefore, there is an urgent need to develop a cost-effective and environmentally friendly desalination technology.

Capacitive deionisation (CDI) is an electrosorption desalination technology that has the potential to avoid most of the critical problems that face the other technologies, namely high energy consumption and membrane fouling [8,9]. CDI operates at a relatively low electrical voltage (typically 0.8–2.0 V) for the removal of ions [10,11]. Further, CDI does not require pressure-driven membranes or high-pressure pumps, thereby avoiding the severe scaling problems that occur with conventional membrane-based technologies for desalination [12,13]. In CDI technology, the feed solution flows through high-capacitive electrodes made from conductive porous materials in which the cations and anions from the feed solution are adsorbed on the oppositely charged electrodes. After a time of operation, the electrodes are saturated with ions and the effluent salinity rises. Regeneration of the electrodes is then required by applying a reverse potential to release the adsorbed ions into the waste stream [14,15].

Much progress has been made in CDI technology. However, research remains to be done before it can be used as a commercial technology. Generally, capacitive electrodes have different electrosorption performance for different ions, depending on the atomic mass, charge and hydrated ionic radius [16,17]. Most of the CDI selectivity studies were conducted using single ion solution instead of a multi-ion solution. Gabelich et al. [16] studied the electrosorption behaviour of carbon aerogel electrodes in different solutions and reported that ion selectivity was based on the hydrated size of the ions and that monovalent ions were preferentially removed from feed solution over multivalent ions. The ion selectivity of CDI electrodes has not been clearly elucidated,

* Corresponding author. Tel.: +61 8 83202 5489; fax: +61 8 8302 3386.
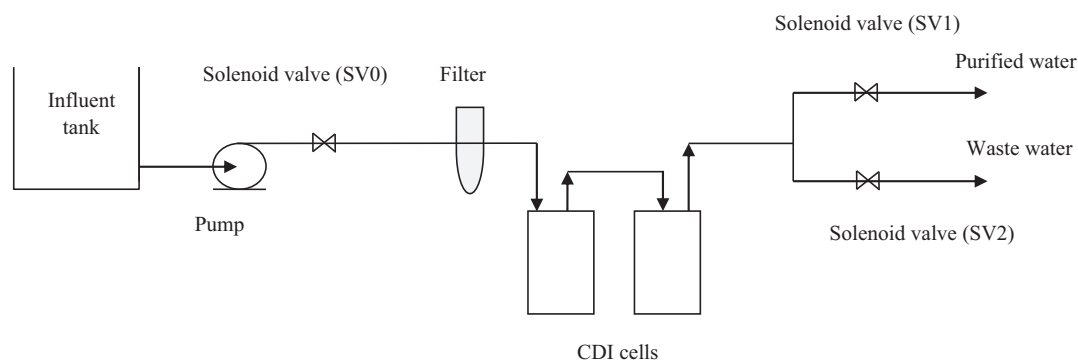E-mail address: linda.zou@unisa.edu.au (L. Zou).

Fig. 1. CDI schematic diagram.

especially in complex multi-ionic solutions that reflect the actual conditions of the feed in inland brackish groundwater. Operational conditions that affect the electrosorption efficiency and energy consumption of CDI need to be investigated to provide guidance for actual site application. For example, silica is always found in seawater and brackish water. Irreversible silica fouling on membrane surfaces is one of the unresolved problems in membrane-based desalination technologies [18]. Therefore, studying the effect of dissolved reactive silica on the treatment efficiency of CDI is necessary because brackish groundwater in inland areas often contains high levels of dissolved reactive silica, and its effect on electrosorption performance is unknown.

In this work, electrosorption experiments were conducted using a CDI unit from AQUA EWP to investigate the efficiency and ion selectivity of CDI in treating brackish water and to evaluate the effect of operational conditions on treatment efficiency and energy consumption. Further, the effect of silica on the treatment efficiency of CDI was determined. The investigation provides an evaluation of the desalting performance of this CDI technology, and contributes to the possibility of actual site operation for inland brackish water desalination.

2. Experimental

2.1. The CDI pilot plant

The CDI pilot plant used in this research was developed by AQUA EWP. Fig. 1 shows a schematic diagram of the CDI unit used. The influent water is pumped from a storage tank through a sand filter for pre-treatment and passes over a flow weir to measure the influent flow into two carbon electrode cells connected in series (see Fig. 2). The CDI pilot system required a 240 VAC, 10 A, single-phase electrical supply. The operating potential was approximately DC 1.5 V per CDI cell, such that no electrolysis reactions occurred. The operational cycle of CDI takes 2.5 min and consists of two main steps: the regeneration mode step and the purification mode step. The regeneration step commences with 30 s, when the effluent solenoid valve (SV1) and the influent solenoid valve (SV0) are closed and the power supply is off, followed by another 30 s when the effluent waste solenoid valve (SV2) and the influent solenoid valve (SV0) are opened and the power is turned on with the opposite polarity of 1.5 VDC. The regeneration step finishes after 60 s. The purification step begins immediately after this and takes 90 s to purify the feed solution. Here, the influent solenoid valve (SV0) and the effluent solenoid valve (SV1) are opened and the power is turned on with the polarity of 1.5 VDC. A heater was inserted into the feed tank to maintain the required temperature for the feed solution.
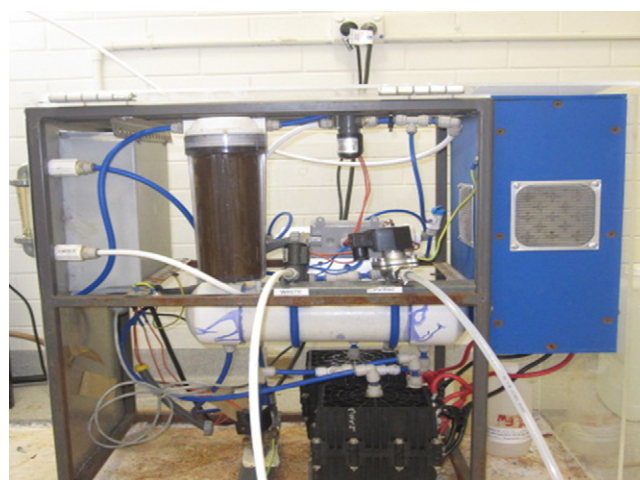

Fig. 2. Side view of the EWP CDI pilot plant.

2.2. Electrode materials and their composition

Fig. 3 shows a schematic diagram of the CDI cell construction. The CDI cell consists of graphite current collectors and porous activated carbon electrodes derived from coconut shells with a specific area of 800 m^2/g [20,21]. The graphite current collectors were alternated by positive or negative bias. Each activated carbon electrode pair was separated by a non-conductive polymeric membrane to prevent short-circuiting. The activated carbon electrodes were coated with anion-exchanging moulded bodies, which were manufactured from the combination of the reactive halogen containing polyether and the inert polymer with the amine component. Anion-exchanging moulded bodies improve the adsorption/desorption
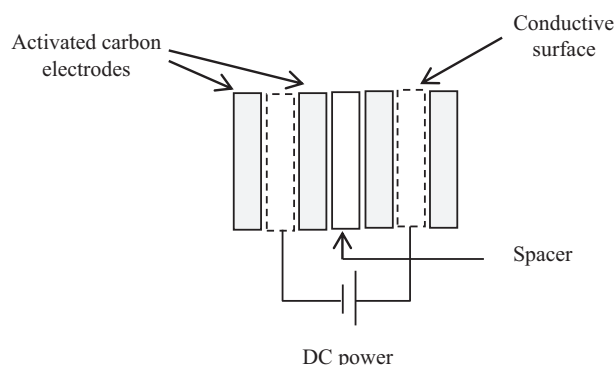

Fig. 3. CDI cell construction schematic diagram.

Table 1
Charge, mass and hydrated radius of test ions [19].

Ion	Charge	Mass (amu)	Hydrated radius (pm)
Sodium	+1	22.99	358
Magnesium	+2	24.31	428
Calcium	+2	40.08	412
Ferric	+3	55.85	457
Chloride	−1	35.45	332
Bromide	−1	79.90	330
Nitrate	−1	62.01	335
Fluoride	−1	19.00	352
Sulphate	−2	96.06	379

Table 2
Initial concentration of ions used to identify the ion selectivity of the carbon electrodes at operational flow rate of 2 l/min and a temperature of 24 °C.

Experiment group	Ions	Feed concentration (mg/l)
Cations selectivity	Na^+	240.1
	Ca^{2+}	72.8
	Mg^{2+}	54.3
	Fe^{3+}	1.78
Anions selectivity	Cl^-	390
	Br^-	8.6
	NO_3^-	6.9
	F^-	2.2
	SO_4^{2-}	186

performance of activated carbon electrodes [22]. Each cell assembly contained 200 sheets of activated carbon (100 cathodes and 100 anodes) with dimensions of 158 mm × 174 mm × 0.3 mm and a total mass of 1354 g of activated carbon. These electrodes are connected to the two sides of the DC power supply. Two cells were installed in the CDI unit used in this study.

2.3. Experimental methods

A series of laboratory experiments was conducted to investigate the effect of operational conditions (TDS concentration, flow rate and temperature) on the CDI electrosorption-removal efficiency and energy consumption. These experiments were conducted as follows: first, the TDS concentration of the feed solution was gradually increased from 500 to 3500 mg/l at a temperature of 24 °C and a flow rate of 2 l/min. Second, the flow rate was gradually increased from 1 to 4.5 l/min at a TDS concentration of 1000 mg/l and a temperature of 24 °C. Finally, the temperature of the feed flow was gradually increased from 20 to 50 °C at a flow rate of 2 l/min and a TDS concentration of 1000 mg/l. The feed solution used in all the experiments was passed through the CDI unit only once, and the conductivity of the feed and the purified water were measured using an electrical conductivity meter (HACH, HQ40d Digital Meter). The obtained results showed the instantaneous electrosorption performance at any time during the experimental period, rather than the accumulated adsorption. In these experiments, sodium chloride (NaCl) was used to prepare the feed solutions with the required concentrations. The electrical energy consumption (kWh) of the CDI unit was measured using a power meter (Todae, MS6115).

In our experiment, the electrosorption removal efficiency (Eq. (1)) was calculated as follows:

$$\text{Electrosorption removal efficiency } (\%) = \frac{C_0 - C}{C_0} \times 100 \qquad (1)$$

where C_0 and C (mg/l) represent the influent and treated stream TDS concentrations, respectively.

Experiments were conducted to identify the ion selectivity of the activated carbon electrodes in multi-ionic solutions. The solution temperature was kept at 25 °C and a flow rate of 2 l/min was applied. The first group of experiments was conducted to identify the cation selectivity by using a solution containing sodium chloride (NaCl), calcium chloride (CaCl$_2$), magnesium chloride (MgCl$_2$) and ferric chloride (FeCl$_3$). The second group of experiments was conducted to identify the anion selectivity by using a solution containing sodium chloride (NaCl), sodium bromide (NaBr), sodium nitrate (NaNO$_3$), sodium fluoride (NaF) and sodium sulphate (Na$_2$SO$_4$). Table 1 shows the charge, atomic mass and hydrated radius for each of the above ions. Table 2 shows the initial ionic concentrations used in the experiments. These were calculated to be close to the actual concentrations in groundwater. The concentrations of cations and anions in the purified stream were measured by means of an Analyst 400 atomic absorption

spectrophotometer (Perkin Elmer) and an ion chromatograph (Dionex 500 IC), respectively. Analyst 400 atomic absorption spectrophotometer was used to determine the concentration of Na$^+$, Ca^{2+}, Mg^{2+}, Fe^{3+} at a wavelength of 589, 422, 202 and 248 nm, respectively. Dionex 500 IC system with conductivity detection utilizing an Ion PAC AS22 column with 4.5 mM Na$_2$CO$_3$/1.4 mM NaHCO$_3$ as the eluent was used to determine the anions concentrations.

To investigate the effect of silica on the CDI electrosorption efficiency, two experiments were conducted. In both experiments, the feed solution TDS concentration was 1000 mg/l and the silica concentration was maintained at 60 mg/l using Na$_2$SiO$_3$·9H$_2$O. The first and second experiments were operated at a flow rate of 2 l/min and 4 l/min, respectively. The purified and waste stream TDS and silica concentrations were measured in every cycle. The silica concentration was measured using the HACH molybdosilicate colorimetric method. A Cary 100 Bio ultraviolet spectrophotometer (VARIAN) was used to analyse the peak absorption of silica at a wavelength of 452 nm.

3. Results and discussion

3.1. Electrosorption and regeneration cycle

The reproducibility and operational performance of the CDI unit were investigated by treating feed water with initial TDS concentrations of 1000 mg/l using sodium chloride. The CDI unit was operated in a single-pass continuous-flow mode with a flow rate of 2 l/min for 3 h treatment at a temperature of 24 °C. The TDS concentration was measured in 10 s intervals for the effluent from the treatment cycle and the regeneration cycle. The effluent TDS, over nine consecutive electrosorption/regeneration cycles, are presented in Fig. 4. This figure clearly shows the treatment and regeneration cycle, which ions are adsorbed into and desorbed from the activated carbon electrodes. The purified stream TDS concentration decreased gradually until it reached a minimum of 90 mg/l after 1 min of each treatment phase. The waste stream TDS concentration decreased gradually from about 3400 mg/l, until it approached feed water level (1000 mg/l) at the end of each regeneration phase. Mass balance calculations show that the regeneration cycle was able to remove more than 99% of adsorbed sodium chloride from the activated carbon. The standard deviation of the TDS effluent concentration of the purified and waste streams was calculated for each phase to illustrate the reproducibility of each treatment and regeneration cycle. The standard deviations of the treatment and regeneration cycles were 1.4% and 1%, respectively. The treatment efficiency of the CDI was nearly the same over 72 cycles of operation, which shows the operational stability of the CDI unit. Throughout the pilot-scale testing, each experiment was conducted by applying 72 consecutive cycles under the same operational conditions. Before starting any new experiment, deionised water was fed to the CDI unit for 30 min to remove any residual salts on the
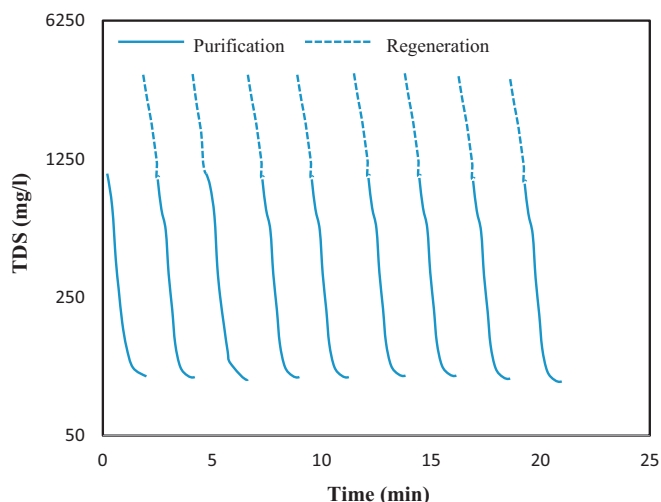
Fig. 4. CDI unit operational performance over nine consecutive electrosorption/desorption cyclesat a flow rate of 2 l/min, TDS concentrations of 1000 mg/l and a temperature of 24 °C.

electrodes. Result discussion was based on the average value of the treatment and regeneration cycles.

3.2. Electrosorptive behaviour under various feed solution temperatures

The electrosorption removal efficiencies of the CDI unit at different temperatures (20, 25, 30, 35, 40, 45 and 50 °C) are shown in Fig. 5. The purified stream TDS concentration can be seen to increase gradually as the solution temperature rises. Further, the electrosorption efficiency follows a decreasing trend from 90.4% to 79.2% when the solution temperature is increased from 20 to 50 °C. Therefore, it can be said that the electrosorption removal efficiency is inversely related to solution temperature. This sorption trend is consistent with results reported by Li et al. [23] using carbon nanotubes and carbon nanofibres electrodes in a batch-mode CDI electrosorption experiment. The obtained electrosorption results seem to follow the physisorption under different temperatures, which could be described by the Langmuir or Freundlich adsorption isotherms. One possible reason for this is that the adsorption capacity of activated carbon decreases by increasing the temperature according to the adsorption isotherms. Further, rising the temperature of the feed solution increases the tendency of the metal ions to escape from the electrode surface to the solution phase, which results in a decrease in adsorption as temperature
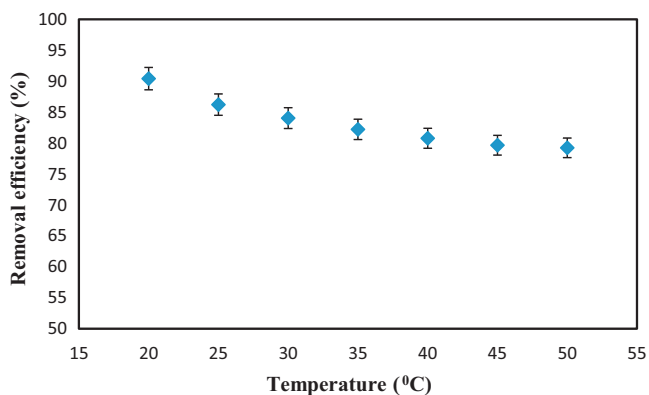

Fig. 5. The electrosorption removal efficiency at various feed solution temperatures at a flow rate of 2 l/min and a TDS concentration of 1000 mg/l.
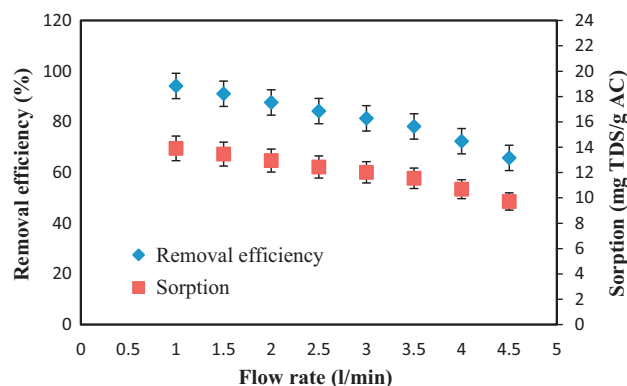

Fig. 6. The electrosorption removal efficiency and electrosorption load on the activated carbon electrodes at various flow rates at a TDS concentration of 1000 mg/l and a temperature of 24 °C.

increases. Another reason may be related to the occurrence of hydrophobic–hydrophilic transition in the structure of interfacial water by decreasing the temperature of the solution, which strengthens the affinity between activated carbon and interfacial hydrated ions [24]. As a result, higher electrosorption removal efficiency at lower temperatures may be related to the transition from hydrophobic to hydrophilic transitions on the surface of the activated carbon.

3.3. Effect of flow rate on electrosorption efficiency and energy consumption

Fig. 6 depicts the variation of the electrosorption removal efficiency and electrosorptive load on the carbon electrodes (that is, feed volume × removed TDS/mass of electrodes) at various flow rates (1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 l/min). It is clearly shown that the purified TDS concentration increases gradually by increasing the flow rate. The electrosorption removal efficiency follows a decreasing trend from 94.2% to 65.8% when the flow rate increases from 1 to 4.5 l/min. The electrosorptive load follows the same decreasing trend as the electrosorption removal efficiency. The electrosorptive load on the carbon electrodes decreases gradually from 13.91 to 9.71 mg TDS per g of activated carbon with the increase in the flow rate from 1 to 4.5 l/min. These results indicate that the higher the flow rates, the higher product TDS is obtained, due to low residual time of the solution inside the cells, which gives less time for the mass transfer required for the purification of the solution. High purification could be achieved at high flow rates by increasing the number of CDI cells connected in parallel, which will give more time for ion transfer from the bulk solution to the CDI electrodes.

Fig. 7 shows the effect of different operational flow rates on the electrical energy consumption in terms of kWh/m^3 and kWh/g of TDS removed. It is seen that as the flow rate increases, the energy consumption decreases. It was noticed that the energy consumption in terms of kWh/m^3 of purified water was decreased from 6.67 to 1.85 kWh/m^3 of purified water by increasing the flow rate from 1 to 4.5 l/min. The unit flow of water per hour is higher at the high flow rate; this results in lower energy consumption in terms of kWh/m^3. Further, the energy consumption in terms of kWh/g of salt removal was deceased from 7.37×10^{-3} to 2.81×10^{-3} by increasing the flow rate from 1 to 4.5 l/min. This may be due to higher sorption rates of ions during higher flow rates. Consequently, both the electrosorption removal efficiency and the energy consumption need to be considered when choosing the optimum operational flow rate. In this study, the optimal flow rate is 4.5 l/min as it consumes the lowest energy compared to other flow rates and the TDS
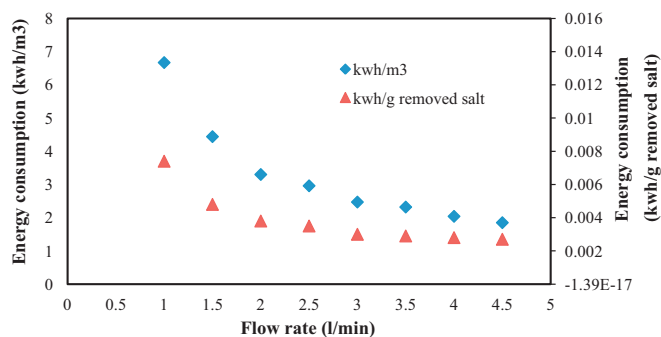
Fig. 7. Effect of operational flow rate on energy consumption at a TDS concentration of 1000 mg/l and a temperature of 24 °C.

concentration of purified stream still remains below the allowable range (less than 500 mg/l) [25].

3.4. Effect of feed solution TDS on electrosorption efficiency and energy consumption

The dependence of salt-removal efficiency and the electrosorption load on the initial feed TDS concentrations (500, 1000, 1500, 2000, 2500, 3000, 3500 mg/l) at a constant flow rate of 2 l/min and a temperature of 24 °C is shown in Fig. 8. It is clear that the TDS removal efficiency decreases gradually with increase in the initial feed TDS. The TDS-removal efficiency was 95.3% and 54.4% when using the initial feed TDS values of 500 and 3500 mg/l, respectively. It was noticed that the increase in the initial feed TDS corresponds to an initially linear increase in electrosorption load on the activated carbon electrodes. After the initial feed TDS reached 3000 mg/l, the electrosorption capacity remained constant, reaching 25.5 mg TDS per gram of activated carbon. This indicated that the electrodes had reached saturation; that is, their full electrosorption capacity had been reached. The diffuse double-layer capacity is one of the factors having an important role in enhancing and improving the electrosorptive capacity of the electrodes. The capacity of the diffuse layer depends mainly on the electrolyte solution concentration as documented by widely accepted models such as the Gouy–Chapman–Stern theory [26]. The diffuse double-layer capacity increases as the electrolyte solution concentration rises [10]. Consequently, the porous electrode capacity for salt storage increases with the increasing electrolyte solution concentration [27,28]. The present study confirms that increasing the feed TDS concentration could enhance the electrosorption of activated carbon through improving the diffuse double-layer capacity.
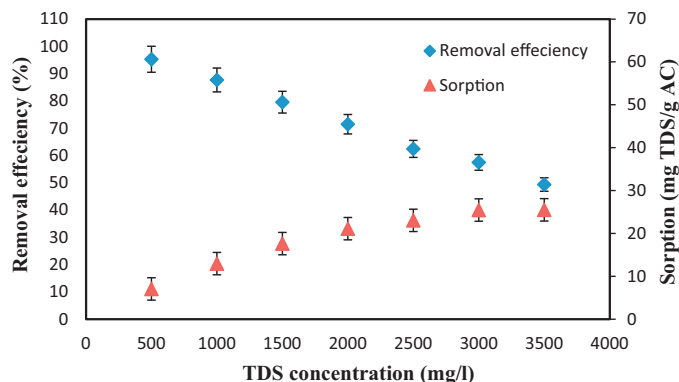

Fig. 8. The electrosorption removal efficiency and sorption load on the activated carbon electrodes at various initial feed TDS at a flow rate of 2 l/min and a temperature of 24 °C.
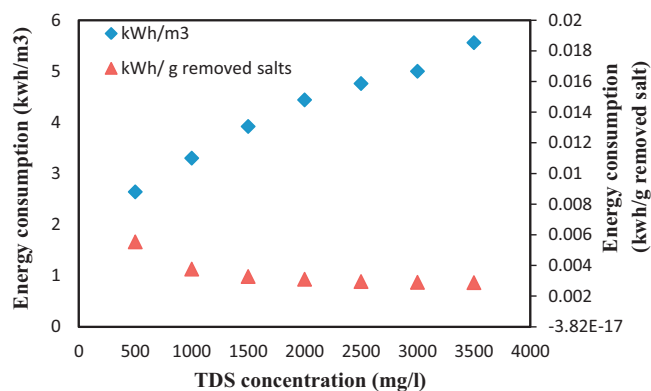

Fig. 9. Effect of TDS feed concentration on energy consumption at a flow rate of 2 l/min and a temperature of 24 °C.

Fig. 9 shows the effect of initial feed TDS concentrations on the CDI unit energy consumption in terms of kWh/m³ and kWh/g of TDS removed. The CDI energy consumption increased gradually from 2.64 to 5.56 kWh/m³ of purified water when the initial feed TDS was increased from 500 to 3500 mg/l at a flow rate of 2 l/min. This may be related to the higher electrosorptive activity resulting from increasing the feed solution TDS concentration, which affects the CDI energy consumption. Conversely, the CDI energy consumption in terms of kWh/g of TDS removed decreased gradually from 5.54×10^{-3} to 2.88×10^{-3} when the influent TDS concentration was increased from 500 to 3500 mg/l. This occurred because electrolyte resistance decreases with the increase of solution concentration. Therefore, sorption rate rises as concentration increases. This implies that when choosing the treatment capacity of a CDI unit, it is important to take both the feed TDS concentrations and power consumption into consideration, as the unit will only be cost-effective when the feed TDS and power consumption are within the optimal range.

3.5. Electrosorption rate constants

Adsorption kinetics – that is, the adsorption rate – is an important characteristic of the adsorbent. To investigate the kinetics of electrosorption of NaCl, the electrosorption rate constant was determined by fitting the pseudo-first-order adsorption kinetics (Eq. (2)). The equation is as follows:

$$C = C_0 \, e^{-kt} \tag{2}$$

where k is the adsorption rate constant (min^{-1}), C and C_0 are the purified solution concentration at time (t) and feed concentration, respectively.

The adsorption kinetics at various TDS feed concentrations were fitted with the pseudo-first-order adsorption kinetics law by regression analysis using the method of least squares (Fig. 10). Table 3 displays the fitting parameters, including electrosorption rate k and regression coefficients R^2. It can be seen that pseudo-first-order was able to fit the experimental data. Further, it can be seen that the solution concentration influences the rate of electrosorption. The rate constants increased gradually as the solution concentration was raised from 500 to 3500 mg/l. The electrosorption rate of 3500 mg/l was increased by 18.18%, compared with the electrosorption rate of 500 mg/l.

3.6. Ion selectivity and electrosorptive capacity of CDI electrodes

The ion selectivity of the activated carbon electrodes is shown in Fig. 11. It follows the order of Fe (98.5%) > Ca (97%) > Mg (92.3%) > Na (83.9%) for cations and SO_4 (98.2%) > Br (97.1%) > Cl (94.1%) > F

Table 3
The electrosorption parameters of the pseudo-first-order kinetics at various solution concentrations at operational flow rate of 2 l/min and a temperature of 24 °C.

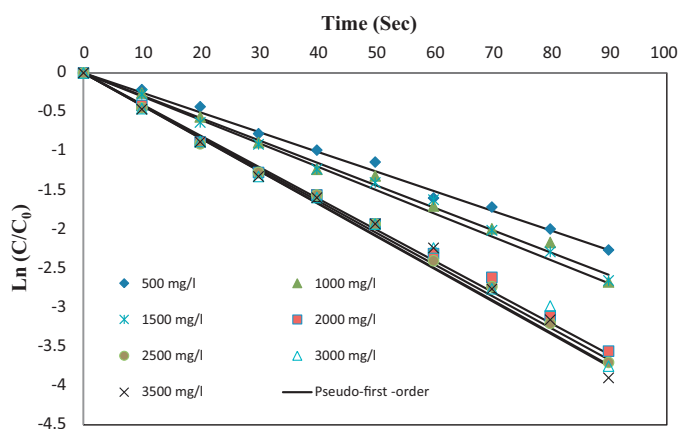| Concentration (mg/l)	500	1000	1500	2000	2500	3000	3500
k (min^{-1})	2.07	2.17	2.20	2.40	2.44	2.49	2.53
R^2	0.9852	0.9725	0.9734	0.9760	0.9741	0.9801	0.9786

Fig. 10. The electrosorption kinetics of CDI at various solution concentrations at a flow rate of 2 l/min and a temperature of 24 °C.
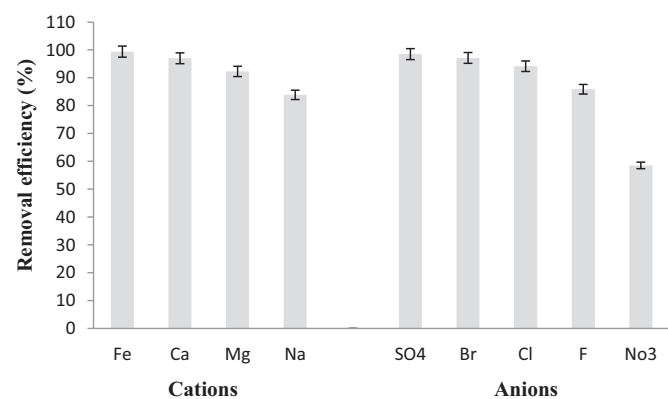

Fig. 11. Effect of ion properties on removal efficiency of CDI at a flow rate of 2 l/min, a TDS concentration of 1000 mg/l and a temperature of 24 °C.

is the largest, while that of Na^+ is the smallest among these cations. However, Fe^{3+} has more selectivity than Na^+ and Ca^{2+} ion has a smaller hydrated radius than Mg^{2+}, but it has higher selectivity than Mg^{2+}. This means that selectivity is not completely dependent on the hydrated radius. In this study, it was observed that ions with greater charge are more easily adsorbed onto the electrode surface under the effect of the electric field applied at the activated carbon electrodes. For ions having the same charge, their hydrated radius plays an important role in selectivity. Ions with smaller hydrated radii are more easily adsorbed onto the electrodes.

The electrosorptive capacity of activated carbon (in mass concentration of ions; that is, mg of ions per gram of activated carbon) follows the order of Na (2.97) > Ca (1.04) > Mg (0.74) > Fe (0.026) for cations and Cl (5.42) > SO$_4$ (2.71) > Br (0.123) > NO$_3$ (0.06) > F (0.03) for anions. These results are consistent with the results reported by Xu et al. [12]. Although sodium and chloride have low affinity for activated carbon electrodes, they occupy a large proportion of the electrosorption capacity of the CDI electrodes due to their high concentration in the feed solution. These results show that the ions with more affinity for the electrodes were electrosorped first, followed by the less selective ions, until the electrodes reached their saturated electrosorptive capacity. The electrosorptive capacity of activated carbon in multi-ionic solutions depends primarily on the initial feed concentrations of ions. Electrosorptive capacity could be used to indicate the selectivity of ions in cases using the same concentrations for all the ions, as reported by Li et al. [7].

3.7. Effect of dissolved reactive silica element on electrosorptive performance

Fig. 12(a) and (b) shows the feed and purified streams of TDS and silica concentrations by a CDI unit at flow rates of 2 and 4 l/min, respectively, with an initial feed concentration of 1000 mg/l and a silica concentration of 60 mg/l. The TDS removal efficiency was about 87.8% and 72.7% at flow rates of 2 l/min and 4 l/min, respectively. By comparing the results with and without silica in feed, it was found that silica does not affect the treatment efficiency of the CDI unit. Silica removal efficiency was very low – in the range of 9% at a flow rate of 2 l/min and decreasing to 3% at a flow rate of 4 l/min. It was also noticed that silica concentrations in the CDI waste stream were in the range of 64 mg/l and 63 mg/l at flow rates
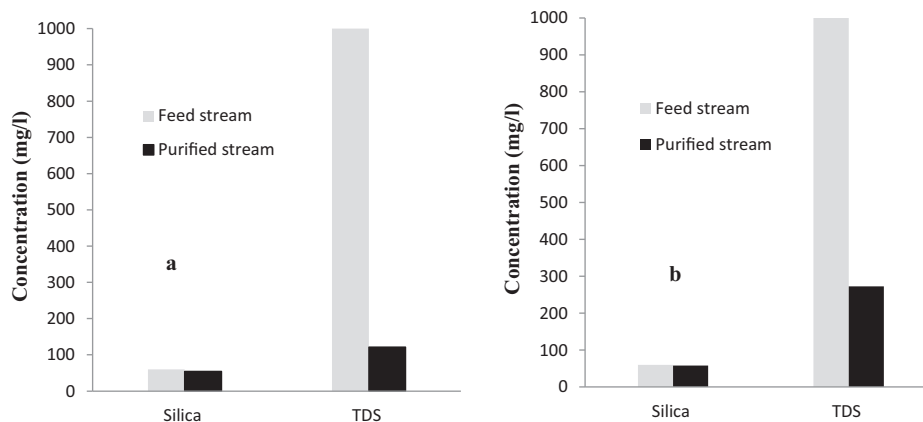
(85.9%) > NO$_3$ (58.5%) for anions. Previous studies reported that for ions having similar feed solution concentrations, the hydrated radius might dictate their selectivity on carbon–aerogel electrodes [16,29]. From Table 1, it can be seen that the hydrated radius of Fe^{3+}

Fig. 12. Feed and purified stream of TDS and silica concentrations at flow rates of 2 and 4 l/min respectively at a flow rate of 2 l/min and a temperature of 24 °C.

of 2 l/min and 4 l/min, respectively, which is higher than the feed solution. This suggests that the removed silica does not accumulate on the electrodes. This is likely due to the undissociated state of silica salt within the operating pH range (7.7–8.0). Consequently, silica does not result in fouling problems for the CDI unit and it will remain in the treated water. Silica in drinking water does not have any harmful effects on human health, may even reduce the risk of developing Alzheimer's disease and protect against impairment of cognitive function in elderly women [30].

4. Conclusions

This research has systematically investigated the desalting performance and energy consumption of a small CDI unit under different operational parameters. It has been found that capacitive deionisation is an effective process to remove salt from water streams without exposing the environment to any harmful impacts. CDI could be a promising alternative for brackish water desalination in inland areas. The operational conditions of CDI can be optimised according to the required water quality. Electrosorption removal efficiency is inversely related to solution temperature, initial TDS concentration and the applied flow rate. CDI energy consumption (in kWh/m^3) is directly related to the TDS feed concentration and inversely proportional to the flow rate. The electrosorptive capacity of activated carbon (in mass concentration of ions) in treated water depends mainly upon the feed concentrations of ions. The ion selectivity of activated carbon electrodes depends upon the properties of the ions, following the order $Fe^{3+} > Ca^{2+} > Mg^{2+} > Na^+$ for cations and $SO_4^{2-} > Br^- > Cl^- > F^- > NO_3^-$ for anions. Dissolved reactive silica in the feed water was not removed by CDI and remained in the purified water. The presence of low concentrations of silica in drinking water does not have any harmful effect on human health [25]. Deterioration of activated carbon electrodes was not observed at any time during the experiment. It is important to choose the treatment capacity of CDI that is suitable to the feed TDS concentrations and power consumption to achieve cost effectiveness in using CDI in inland brackish water desalination and water treatment.

Acknowledgements

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