

# Effect of Desorption Methods on Electrode Regeneration Performance of Capacitive Deionization

Qihan Yao<sup>1</sup> and Hao L. Tang<sup>2</sup>

**Abstract:** Long regeneration time and substantial water usage in desorption cycles impose potential barriers for practical applications of capacitive deionization (CDI). In this research, a single-pass continuous-flow CDI cell was used to explore the effect of desorption methods on electrode regeneration performance. The results demonstrated effective nature of polarity reversal during electrode regeneration compared to the conventional short-circuit method. A reversed polarity with optimized duration and magnitude of cell voltage while purging with a proper flow scheme exhibited substantial reductions on regeneration time and flush-water usage during the desorption processes of CDI. The beneficial aspects of preferred desorption methods were attributable to minimization of a readsorption effect by limiting the rate of ion transport to the oppositely charged electrode. The results of this research are beneficial for improving the operational efficiency and cost-effectiveness of CDI systems for engineering applications. DOI: 10.1061/(ASCE)EE.1943-7870.0001245. © 2017 American Society of Civil Engineers.

**Author keywords:** Capacitive deionization; Desorption; Electrode regeneration; Polarity reversal; Desalination.

## Introduction

Freshwater, an essential component for human consumption, is facing scarcity with the growth of population and industry. Conventional desalination technologies such as ion exchange, reverse osmosis, electrodialysis, and distillation are among options to produce clean water. However, their disadvantages, including by-product formation and high energy consumption, hinder many applications (Xu et al. 2008). In recent years, capacitive deionization (CDI) has come to be considered a low-polluting, energy-efficient, and cost-effective alternative to conventional water desalination technologies and currently attracts keen interest from worldwide researchers (Suss et al. 2015).

During the adsorption process of CDI, ions are extracted from a water stream and stored within the structures of porous electrodes (Biesheuvel and Bazant 2010). The adsorption capacity depends on intrinsic properties of electrode materials (such as surface area, pore microstructure, pore-size distribution, surface group, etc.) (Gao et al. 2015) and operating conditions (such as cell voltage, electrode distance, retention time, solution conductivity, etc.) (Jande and Kim 2013, 2014; Huang et al. 2016). When the ion storage capacity is reached, a desorption (electrode regeneration) process is needed to release the ions, resulting in a stream concentrated in salt. An adsorption and a desorption step complete a cycle. As the ion transport rate in CDI is potentially limited by the macroscopic transport resistance in the pore microstructure (Suss et al. 2015), for optimum performance, a CDI system must be tuned to achieve faster kinetics of both adsorption and desorption.

Although CDI has been discussed for faster adsorption kinetics (Liu et al. 2015; Bian et al. 2016), few studies have focused on

enhancing its subsequent desorption performance. Some researchers [Gabelich et al. 2002; T. D. Tran and D. J. Lenz, "Alternating-polarity operation for complete regeneration of electrochemical deionization system," U.S. Patent 6346187 (2004); Leonard et al. 2009] used polarity reversal as a desorption method to rejuvenate a CDI system. The beneficial aspect of polarity reversal lies in the fact that a reversed voltage might momentarily expel the adsorbed ions from the electrode. A concern about polarity reversal was also raised by L.-R. Shiue et al. ["Deionizers with energy recovery," U.S. Patent No. 6661643 (2013)] and Biesheuvel et al. (2011): the ions released from one electrode may be quickly adsorbed in the other one. Besides polarity reversal, a short circuit may also be used for desorption. However, it was related with a low efficiency, which was attributed to the slow release of remaining ions trapped in the electrodes' porous structures (Cohen et al. 2013). Because slow desorption during the CDI operation is a potential barrier for its practical applications, enhancement in desorption performance is highly desirable because it reduces the time and volume of water used for regeneration.

Yao and Tang (2016) reported on the occurrence of readsorption during polarity reversal in desorption cycles of CDI. The work described in the present paper was devoted to expedite the desorption process based on the discharge method, reversed charging time, cell voltage, flush flow rate, and type of flush water in a single-pass CDI system. These parameters were examined for their effects on reductions of regeneration time and flush-water usage. As CDI moves into more commercial applications, the results from this study are helpful for water professionals in designing an efficient CDI system for production of desalinated clean water.

## Materials and Methods

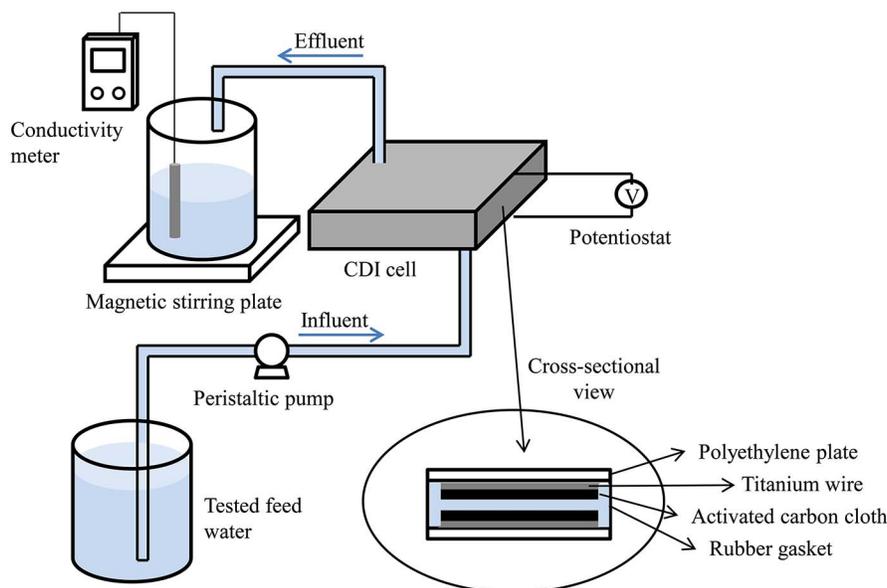
### System Setup and CDI Structure

The CDI system, including a CDI cell, a potentiostat as external power supply, a peristaltic pump with influent and effluent tubes, a magnetic stirring plate, and two containers for influent and effluent storage, respectively, was designed in a continuous single-pass

<sup>1</sup>Research Assistant, Dept. of Water Engineering and Science, Hunan Univ., Changsha, Hunan 410082, China. E-mail: wwttec@gmail.com

<sup>2</sup>Assistant Professor, Dept. of Chemistry, Indiana Univ. of Pennsylvania, Indiana, PA 15705 (corresponding author). E-mail: htang@iup.edu

Note. This manuscript was submitted on February 2, 2016; approved on February 21, 2017; published online on May 10, 2017. Discussion period open until October 10, 2017; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Environmental Engineering*, © ASCE, ISSN 0733-9372.



**Fig. 1.** Schematic diagram of CDI configuration and reactor setup in the desorption mode

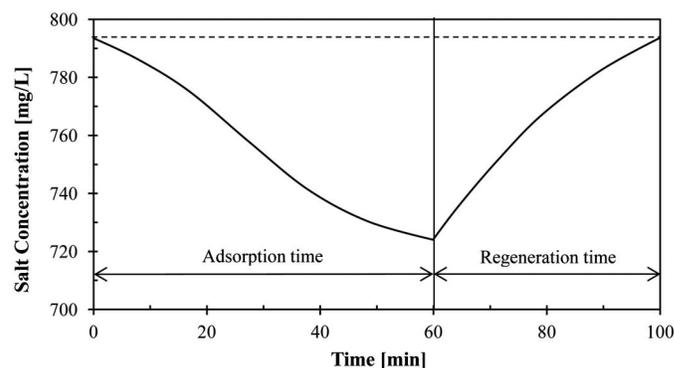
flow mode (Fig. 1). As the saline water was pumped through the CDI cell, the effluent was collected and analyzed via a conductivity meter. The CDI cell, measuring 28.2 cm long, 12.4 cm wide, and 1.6 cm tall, had an effective volume of 450 mL and contained a pair of flow-by electrodes, which were commercially available activated-carbon cloth (ACC) (FM10, Chemviron, U.K.) with a specific surface area of 1,000 m<sup>2</sup>/g and thickness of 0.5 mm. The raw ACC was cut into two pieces with a dimension of 25.6 × 11.8 cm each, weighing 18.4 g total, and was pririnsed with deionized (DI) water until conductivity in the rinsed water became stable and no more ions were released. The channel between the ACC electrodes in the CDI cell was maintained at 8 mm wide via a rubber gasket while titanium wires attached to the ACC were used as current collectors. The channel width was chosen according to the engineering consideration of reducing the short-circuit risk as a result of protruding fibers from the electrodes during prolonged operations. Polyethylene plates were then firmly pressed to seal and immobilize the entire stack of all layers.

### CDI Operation

Analytical-grade NaCl was used to make synthetic raw saline water (1,613 μS/cm, 793 mg/L NaCl solution) for the experiments. Prior to each run, the CDI cell was first equilibrated with the raw water until the effluent conductivity was equal to that of the influent. A cell voltage of 1.2 V was then applied while electroadsorption was conducted in a closed-loop operation. A concentration-time plot of a typical adsorption-desorption cycle during the closed-loop operation is shown in Fig. 2. To ensure that all desorption tests started at the same electrode saturation level, the peristaltic pump recirculated 450 mL of the feed water through the CDI cell until the conductivity reading decreased to 1,499 ± 2 μS/cm, indicating a salt concentration of 737 ± 1 mg/L, and the ACC electrodes reached a salt electroadsorption amount of 1.37 ± 0.03 mg/g. The system was then switched to a single-pass desorption mode, and the original saline water (1,613 μS/cm, 793 mg/L NaCl solution), unless noted otherwise, was used to flush the cell. The effluent was collected during the regeneration for conductivity measurement to determine the concentrations of NaCl in solution. The desorption process continued until all the previously

electrodesorbed salt was released, which was determined by the change of cumulative NaCl concentration in the effluent container. The flush-water usage and time were also recorded corresponding with the conductivity data.

Table 1 indicates the operating conditions of five series of desorption experiments. Series 1 was designed to assess the impact of discharge methods on desorption efficiency. Electrode regeneration took place by power disconnection, short circuit, and polarity reversal with short circuit, respectively. Series 2 was designed to assess the impact of reversed charging time during polarity reversal on desorption efficiency. The examined duration of polarity reversal was from 0 to 14 min. Comparisons were also made between scenarios of flow and no-flow conditions during polarity reversal to explore the potential of the latter condition on reducing flush-water usage. Series 3 was designed to investigate the impact of flush flow rate on desorption efficiency. Flush flow rates of 22.5, 30, 45, and 90 mL/min, which were equivalent to flow velocities of 0.38 × 10<sup>-3</sup>, 0.50 × 10<sup>-3</sup>, 0.76 × 10<sup>-3</sup>, and 1.5 × 10<sup>-3</sup> m/s for the specific system and led to a hydraulic retention time of 20, 15, 10, and 5 min, respectively, in the CDI cell, were explored. Series 4 was used to assess the impact of reversed cell voltage on desorption efficiency. The examined reversed cell voltages were from 0 to 1.2 V. Series 5 was used to evaluate the impact



**Fig. 2.** Concentration-time plot of a typical adsorption-desorption cycle during the closed-loop operation of the CDI system

**Table 1.** Operating Conditions of Five Series of Desorption Tests

| Series | Discharge method | Duration of PR (min) | Flow during PR | Reversed cell voltage (V) | Flush flow rate (mL/min) | Flush-water type |
|--------|------------------|----------------------|----------------|---------------------------|--------------------------|------------------|
| 1      | PD               | N/A                  | N/A            | N/A                       | 30                       | Raw water        |
|        | SC               | N/A                  | N/A            | N/A                       | 30                       | Raw water        |
|        | PR and SC        | 8                    | Yes            | 1.2                       | 30                       | Raw water        |
| 2      | PR and SC        | 0–14                 | No             | 1.2                       | 30                       | Raw water        |
|        | PR and SC        | 0–14                 | Yes            | 1.2                       | 30                       | Raw water        |
| 3      | PR and SC        | 8                    | Yes            | 1.2                       | 22.5–90                  | Raw water        |
| 4      | PR and SC        | 8                    | Yes            | 0.3–1.2                   | 30                       | Raw water        |
| 5      | SC               | N/A                  | N/A            | N/A                       | 45                       | Raw water        |
|        | SC               | N/A                  | N/A            | N/A                       | 45                       | Product water    |
|        | SC               | N/A                  | N/A            | N/A                       | 45                       | DI water         |

Note: PD = power disconnection; PR = polarity reversal; SC = short circuit.

of flush-water type on desorption efficiency. Raw water, product water after CDI treatment, and DI water were investigated.

### Calculation and Data Analysis

Conductivity of the saline water was monitored by a conductivity meter (DDS-307, Shanghai Yueping Scientific Instruments Co. Ltd., Shanghai, China). The relationship between conductivity and NaCl concentration was obtained by preparing a calibration curve prior to the experiments. The desorption percentage at time  $t$  was calculated using Eq. (1)

$$D_t = \frac{m_{d,t}}{m_a} \times 100\% \quad (1)$$

where  $D_t$  = desorption percentage (%) at time  $t$ ; and  $m_a$  (mg) and  $m_{d,t}$  (mg) = mass of adsorbed salt in electroadsorption cycle and mass of cumulative desorbed salt in desorption cycle at time  $t$ , respectively. In the present study,  $m_a$  was determined based on the change of NaCl concentration (mg/L) multiplying the volume (L) of recirculated water used in the closed-loop operation prior to the desorption tests, while  $m_{d,t}$  was determined based on the difference between cumulative effluent concentration (mg/L) at time  $t$  and time zero multiplying the volume (L) of the water in the single-pass desorption.

Regeneration time ( $t_R$ ) was determined based on the time (min) required to achieve complete desorption. Flush volume ( $FV$ ) is a parameter describing the usage of flush water for complete regeneration. It was obtained by normalizing the flush-water volume for regeneration ( $V_R$ , liter) based on the effective volume of the CDI cell ( $V_C$ , liter) [Eq. (2)]

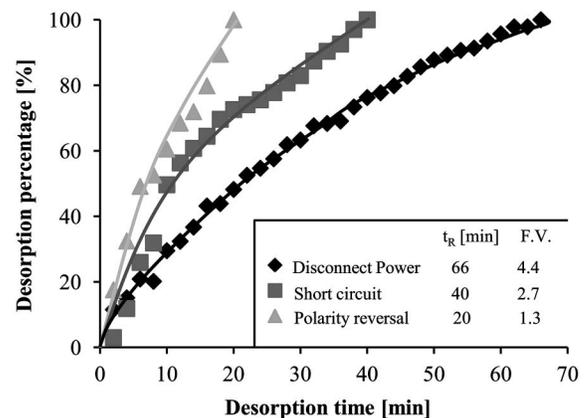
$$FV = \frac{V_R}{V_C} \quad (2)$$

Lower  $t_R$  and  $FV$  values were indicators of preferred desorption methods as a result of faster desorption kinetics and higher water production.

## Results and Discussion

### Effect of Discharge Methods

Fig. 3 presents results of Series 1 experiments showing the effect of three discharge methods on electrode regeneration. The raw water was used to flush the cell during the desorption process and the flush-water flow rate was maintained at 30 mL/min, leading to a 15-min retention time in the CDI. By disconnecting the power

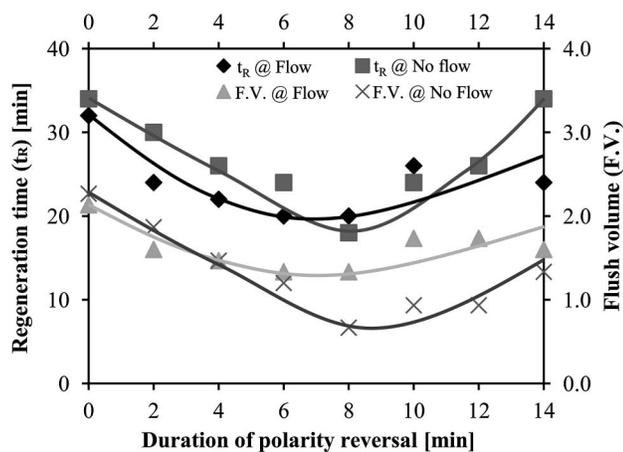


**Fig. 3.** Effect of discharge methods on desorption performance of CDI (operating conditions are shown in Table 1; lines are guides for eyes)

supply, the longest regeneration time ( $t_R = 66$  min) was observed among the three methods. In the meanwhile, the  $FV$  of 4.4 indicated the largest amount of water was consumed to flush the cell. Short circuit resulted in a  $t_R$  of 40 min and a  $FV$  of 2.7, which significantly improved the desorption performance. This was attributable to a faster dissipation of accumulated energy by shorting the capacitor and a quicker reduction of electrostatic forces attracting the electroadsorbed ions. Polarity reversal appeared to be able to further improve the desorption performance, with observed  $t_R$  and  $FV$  reduced to 20 min and 1.3, respectively. The results indicate that the momentary expulsion by the reversed voltage would be beneficial for expedition of desorption and reduction of flush-water usage. Disadvantages regarding the application of reversed polarity mainly lie in a possible readsorption effect; that is, the ions would leave one electrode and then be adsorbed by the other one (Biesheuvel et al. 2011; Yao and Tang 2016). The results of the present study imply that it is possible to regenerate the electrodes at a faster rate while minimizing the effect of readsorption by polarity reversal. Because of the beneficial aspects of polarity reversal on electrode regeneration, the method is further examined for optimization strategies in the following sections.

### Effect of Duration of Polarity Reversal

Fig. 4 illustrates desorption performance achieved at various duration of polarity reversal. To further reduce the flush-water usage, a no-flow condition during polarity reversal was also examined. The no-flow case described a scenario wherein there was no flushing



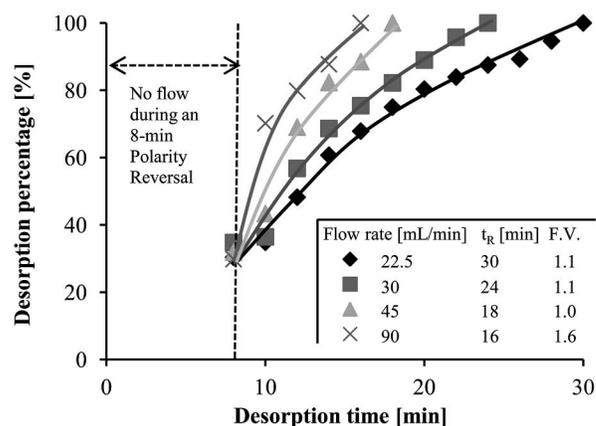
**Fig. 4.** Effect of duration of polarity reversal on desorption performance of CDI (operating conditions are shown in Table 1; lines are guides for eyes)

flow during the temporary phase of polarity reversal. Because a complete desorption procedure here included a temporary polarity reversal followed by a consistent short circuit, the flush volume was generated during the latter short-circuit phase. The raw water was used to flush the cell and the flow rate was maintained at 30 mL/min, leading to a 15-min retention time in the CDI. A V-shape was observed for both  $t_R$  and  $FV$  as the duration of reversed polarity increased from 0 to 14 min. For the specific system, the optimum duration appeared to be 8 min, as judged by the lowest  $t_R$  (18 min) and  $FV$  (0.7) under a no-flow condition. This indicated that with a reversed charging time of 8 min, the influence of re-adsorption was minimum. A longer reversed charging time would lead to a negative impact by moving the ions from one electrode to another, resulting in a drastic decrease in desorption performance.

Furthermore, the no-flow condition reduced the  $t_R$  and  $FV$  from 20 min and 1.3 to 18 min and 0.7, respectively, showing a potential of further improving the desorption efficiency. The results suggested practical operations with stagnant water during polarity reversal prior to purging. In addition, the duration of polarity reversal needs to be adjusted by pilot testing to find an optimum reversed charging time for mostly trapped ions exiting the pores without being trapped again in the pores of the oppositely charged electrode.

### Effect of Flush Flow Rate

Fig. 5 presents results of the Series 3 experiments exploring the effect of flush flow rate on desorption performance of CDI. It was found that a higher flow rate was associated with faster desorption. As the flush flow rate increased from 22.5 to 90 mL/min, a reduction of  $t_R$  from 30 to 16 min was observed. The  $FV$ , however, did not show the same decreasing trend in the range of flow rate between 22.5 and 45 mL/min, and the values appeared to stabilize at  $1.1 \pm 0.1$ . A significant increase in  $FV$  was observed only at the highest tested flow rate of 90 mL/min. Hence, from the practical engineering point of view, a relatively high flush flow rate is preferred to achieve fast desorption kinetics. A higher flow rate leads to a lower residence time of the solution inside the cell (Zhao et al. 2010; Mossad and Zou 2012; Porada et al. 2014), which leaves less time for the ion transport from the bulk solution into the opposite electrode, thus minimizing the re-adsorption effect and resulting in a decreased  $t_R$ . Xu et al. (2008) also reported a shortened regeneration time at a high flush flow rate. Meanwhile, they also reported

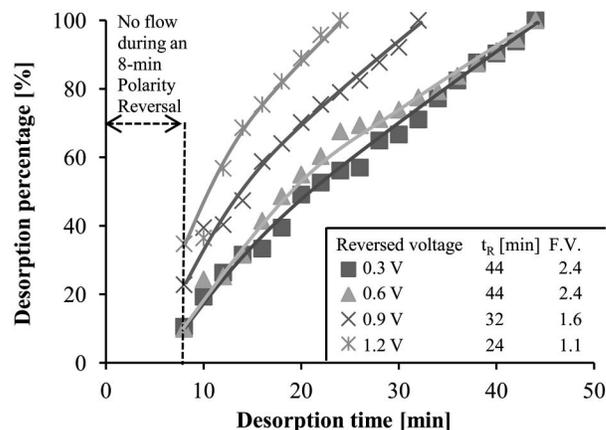


**Fig. 5.** Effect of flush flow rate on desorption performance of CDI (operating conditions are shown in Table 1; lines are guides for eyes)

a rather high volume of brine production. Therefore, it is important to take both  $t_R$  and  $FV$  into consideration because the system will only be effectively optimized when the  $t_R$  and  $FV$  are both optimum.

### Effect of Reversed Cell Voltage

The Series 4 experiments examined reversed cell voltages from 0.3 to 1.2 V for potential impact on desorption performance. It is known that salt adsorption to activated carbon occurs via some kind of affinity between the ions and adsorbing surface, and even without the application of an electric field, the adsorbed ions can still remain on the surface for a period of time (Leonard et al. 2009; Biesheuvel et al. 2014). It is important to apply a reversed cell voltage that is high enough to overcome the affinity of the ions held on the electrodes. By applying a reversed cell voltage  $\leq 0.6$  V with stagnant water during polarity reversal, the resultant  $t_R$  (44 min) and  $FV$  (2.4) were both unsatisfactory (Fig. 6). Significant improvement was observed when the reversed cell voltage increased higher than 0.6 V, with a corresponding  $t_R$  and  $FV$  decreased to 32 min and 1.6 at 0.9 V, respectively. The initial desorption percentage at the start of purging also increased from 10 to 23%. The results indicated that a reversed cell voltage greater than 0.6 V could be high enough to overcome the affinity between

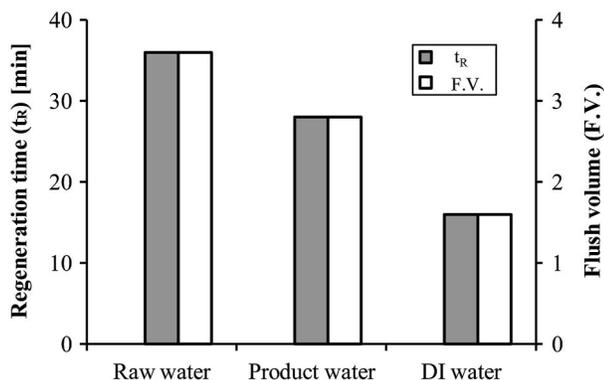


**Fig. 6.** Effect of reversed cell voltage on desorption performance of CDI (operating conditions are shown in Table 1; lines are guides for eyes)

the ions and adsorbing surface. It was also found that a further increase of the reversed cell voltage from 0.9 to 1.2 V resulted in an observed  $t_R$  and  $FV$  reduced to 24 min and 1.1, respectively, indicating that a high reversed cell voltage is preferred. However, a reversed cell voltage of higher than 1.2 V is not recommended because of parasitic concerns of increased water electrolysis and expedited ageing of carbon materials (Ratajczak et al. 2014).

### Effect of Flush-Water Type

T. D. Tran and D. J. Lenz ["Alternating-polarity operation for complete regeneration of electrochemical deionization system," U.S. Patent 6346187 (2004)] suggested the use of DI water as one of options to completely rejuvenate a CDI system. However, purging with DI water may not be practical for large-scale engineering applications. The Series 5 experiments explored the effect of different flush-water types on desorption performance. The raw water, product water, and DI water used in the experiments showed conductivity values of 1,613, 287, and 16  $\mu\text{S}/\text{cm}$ , respectively. In the "Effect of Flush Flow Rate" section, a flow rate of 45 mL/min was found optimal for the system because it was able to achieve both low regeneration time (18 min) and flush volume (1.0), as shown in Fig. 5. Therefore, it would be more meaningful to investigate the effect of flush-water type based on the available optimal condition at a flow rate of 45 mL/min. In order to reduce the potential interference from errors of controlling the exact time during polarity reversal, a short circuit was used as the only discharge method. As shown in Fig. 7, improvement in desorption performance was observed by purging with water of lower conductivity. Because an uncharged carbon pore possesses equal amount of counterions and coions (Suss et al. 2015), purging with product water or DI water changed the equilibrium state of the electrodes by producing a favorable ion concentration gradient and facilitated the release of ions during regeneration. Because ion concentration gradient and electric field were considered as two driving forces for transport of ions in CDI (Biesheuvel et al. 2009), the impact of electric field was removed by short-circuiting the electrodes. Therefore, the improvement in desorption performance was only attributable to the ion concentration gradient caused by purging with a lower conductivity solution. Furthermore, although a  $t_R$  of 16 min and an  $FV$  of 1.6 with DI water (Fig. 7) was the lowest in the short-circuit experiments, similar  $t_R$  and  $FV$  values (Fig. 5) were also observed with raw water by optimization of desorption methods. It is obvious that purging with raw water is considered more practical in engineering applications.



**Fig. 7.** Effect of flush-water type on desorption performance of CDI (operating conditions are shown in Table 1)

### Implications of Optimization of Desorption Methods for CDI

Results of the study are important for the water industry. It was found that it is possible to minimize the potential readsorption effect during polarity reversal by a careful control of operating conditions. Results show that improved regeneration performance could be achieved by optimizing the duration and voltage of reversed polarity and the flow rate of flush water. The conclusions are in accordance with those of Leonard et al. (2009), who reported an increase of regeneration rate when a potential of appropriate sign and magnitude was applied to a CDI system. Considering that the interpretation of these effects was largely empirical, further development of models for the adsorption and desorption principles is needed for quantitative explanation. In recent years, CDI with ion-exchange membranes [a process named membrane-CDI (MCDI)] has been studied as a process to restrict coions from accessing the electrodes, which could also minimize the effect of readsorption during polarity reversal. Although researchers (Li and Zou 2011; Cohen et al. 2011; Kim et al. 2013; Liang et al. 2013) found that the regeneration of MCDI could be more efficient than CDI because the selective shielding of membranes, one should also take into account the disadvantages of using membranes such as the cost of membranes, increases in system volume, added resistance for solution flow and ion transport, membrane fouling and the associated replacement cost, etc. In the present study, optimization of desorption methods were suggested to improve the cost-effectiveness of CDI. Although polarity reversal also has energy consumptions (Dlugolecki and van der Wal 2012; Kim et al. 2015), a tradeoff could be maintained from economic perspectives for best engineering applications.

### Conclusions

This research discussed the effect of desorption methods when regenerating electrodes in a CDI system. The results demonstrated effective nature of polarity reversal during electrode regeneration compared to the conventional short-circuit method. A polarity reversal with optimized duration and magnitude of reversed cell voltage while purging with a proper flow scheme exhibited substantial reductions on regeneration time and flush-water usage during the desorption processes of CDI. The beneficial aspects of preferred desorption methods were attributable to minimization of a readsorption effect by limiting the rate of ion transport to the oppositely charged electrode. The results obtained from this research can promote CDI further by enhancing its operational efficiency and cost-effectiveness for engineering applications.

### Acknowledgments

This research was supported by Minn Water (Minneapolis, Minnesota, United States) under Project No. 1390501914. The authors acknowledge Ningbo Chuanming Electrosorption Equipment Co. Ltd. (Ningbo, China) for assistance on acquiring materials for the bench work and providing accommodation for Q. Yao's stay in Ningbo. H. Tang acknowledges Min Wan and Yanting Li for testing the durability of electrodes.

### References

- Bian, Y., et al. (2016). "Using activated carbon fiber separators to enhance the desalination rate of membrane capacitive deionization." *Desalination*, 381, 95–99.

- Biesheuvel, P. M., and Bazant, M. Z. (2010). "Nonlinear dynamics of capacitive charging and desalination by porous electrodes." *Phys. Rev. E*, 81(3), 031502.
- Biesheuvel, P. M., Porada, S., Levi, M., and Bazant, M. Z. (2014). "Attractive forces in microporous carbon electrodes for capacitive deionization." *J. Solid State Electrochem.*, 18(5), 1365–1376.
- Biesheuvel, P. M., van Limpt, B., and van der Wal, A. (2009). "Dynamic adsorption/desorption process model for capacitive deionization." *J. Phys. Chem. C*, 113(14), 5636–5640.
- Biesheuvel, P. M., Zhao, R., Porada, S., and van der Wal, A. (2011). "Theory of membrane capacitive deionization including the effect of the electrode pore space." *J. Colloid Interface Sci.*, 360(1), 239–248.
- Cohen, I., Avraham, E., Bouhadana, Y., Soffer, A., and Aurbach, D. (2013). "Long term stability of capacitive de-ionization processes for water desalination: The challenge of positive electrodes corrosion." *Electrochim. Acta*, 106, 91–100.
- Cohen, I., Avraham, E., Noked, M., Soffer, A., and Aurbach, D. (2011). "Enhanced charge efficiency in capacitive deionization achieved by surface-treated electrodes and by means of a third electrode." *J. Phys. Chem. C*, 115(40), 19856–19863.
- Długołęcki, P., and van der Wal, A. (2012). "Energy recovery in membrane capacitive deionization." *Environ. Sci. Technol.*, 47(9), 4904–4910.
- Gabelich, C. J., Tran, T. D., and Suffet, I. H. (2002). "Electrosorption of inorganic salts from aqueous solution using carbon aerogels." *Environ. Sci. Technol.*, 36(13), 3010–3019.
- Gao, X., Omosebi, A., Landon, J., and Liu, K. (2015). "Surface charge enhanced carbon electrodes for stable and efficient capacitive deionization using inverted adsorption-desorption behavior." *Energy Environ. Sci.*, 8(3), 897–909.
- Huang, Z., Lu, L., Cai, Z., and Ren, Z. J. (2016). "Individual and competitive removal of heavy metals using capacitive deionization." *J. Hazard. Mater.*, 302, 323–331.
- Jande, Y. A. C., and Kim, W. S. (2013). "Predicting the lowest effluent concentration in capacitive deionization." *Sep. Purif. Technol.*, 115, 224–230.
- Jande, Y. A. C., and Kim, W. S. (2014). "Modeling the capacitive deionization batch mode operation for desalination." *J. Ind. Eng. Chem.*, 20(5), 3356–3360.
- Kim, T., et al. (2015). "Enhanced charge efficiency and reduced energy use in capacitive deionization by increasing the discharge voltage." *J. Colloid Interface Sci.*, 446, 317–326.
- Kim, Y.-J., Kim, J.-H., and Choi, J.-H. (2013). "Selective removal of nitrate ions by controlling the applied current in membrane capacitive deionization (MCDI)." *J. Membr. Sci.*, 429, 52–57.
- Leonard, K. C., Genthe, J. R., Sanfilippo, J. L., Zeltner, W. A., and Anderson, M. A. (2009). "Synthesis and characterization of asymmetric electrochemical capacitive deionization materials using nanoporous silicon dioxide and magnesium doped aluminum oxide." *Electrochim. Acta*, 54(22), 5286–5291.
- Li, H., and Zou, L. (2011). "Ion-exchange membrane capacitive deionization: A new strategy for brackish water desalination." *Desalination*, 275(1), 62–66.
- Liang, P., Yuan, L., Yang, X., Zhou, S., and Huang, X. (2013). "Coupling ion-exchangers with inexpensive activated carbon fiber electrodes to enhance the performance of capacitive deionization cells for domestic wastewater desalination." *Water Res.*, 47(7), 2523–2530.
- Liu, D., Huang, K., Xie, L., and Tang, H. L. (2015). "Relation between operating parameters and desalination performance of capacitive deionization with activated carbon electrodes." *Environ. Sci. Water Res. Technol.*, 1(4), 516–522.
- Mossad, M., and Zou, L. (2012). "A study of the capacitive deionization performance under various operational conditions." *J. Hazard. Mater.*, 213–214, 491–497.
- Porada, S., et al. (2014). "Carbon flow electrodes for continuous operation of capacitive deionization and capacitive mixing energy generation." *J. Mater. Chem. A*, 2(24), 9313–9321.
- Ratajczak, P., Jurewicz, K., and Béguin, F. (2014). "Factors contributing to ageing of high voltage carbon/carbon supercapacitors in salt aqueous electrolyte." *J. Appl. Electrochem.*, 44(4), 475–480.
- Suss, M., et al. (2015). "Water desalination via capacitive deionization: What is it and what can we expect from it?" *Energy Environ. Sci.*, 8(8), 2296–2319.
- Xu, P., Drewes, J. E., Heil, D., and Wang, G. (2008). "Treatment of brackish produced water using carbon aerogel-based capacitive deionization technology." *Water Res.*, 42(10), 2605–2617.
- Yao, Q., and Tang, H. L. (2016). "Occurrence of re-adsorption in desorption cycles of capacitive deionization." *J. Ind. Eng. Chem.*, 34, 180–185.
- Zhao, R., Biesheuvel, P. M., Miedema, H., Bruning, H., and van der Wal, A. (2010). "Charge efficiency: A functional tool to probe the double-layer structure inside of porous electrodes and application in the modeling of capacitive deionization." *J. Phys. Chem. Lett.*, 1(1), 205–210.