

Yasamin Salamat
Mechanical and Industrial Engineering
Department,
Northeastern University,
334 Snell Engineering Center,
360 Huntington Avenue,
Boston, MA 02115
e-mail: s.salamat@neu.edu

Carlos A. Rios Perez
Mem. ASME
Mechanical and Industrial Engineering
Department,
Northeastern University,
334 Snell Engineering Center,
360 Huntington Avenue,
Boston, MA 02115
e-mail: c.riosperez@neu.edu

Carlos Hidrovo¹
Mem. ASME
Mechanical and Industrial Engineering
Department,
Northeastern University,
207 Snell Engineering Center,
360 Huntington Avenue,
Boston, MA 02115
e-mail: hidrovo@neu.edu

Performance Characterization of a Capacitive Deionization Water Desalination System With an Intermediate Solution and Low Salinity Water

In recent years, more efforts have been made to improve new and more efficient nonmembrane-based methods for water desalination. Capacitive deionization (CDI), a novel technique for water desalination using an electric field to adsorb ions from a solution to a high-porous media, has the capability to recover a fraction of the energy consumed for the desalination during the regeneration process, which happens to be its most prominent characteristic among other desalination methods. This paper introduces a new desalination method that aims at improving the performance of traditional CDI systems. The proposed process consists of an array of CDI cells connected in series with buffer containers in between them. Each buffer serves two purposes: (1) averaging the outlet solution from the preceding cell and (2) securing a continuous water supply to the following cell. Initial evaluation of the proposed CDI system architecture was made by comparing a two-cell-one-buffer assembly with a two cascaded cells array. Concentration of the intermediate solution buffer was the minimum averaged concentration attained at the outlet of the first CDI cell, under a steady-state condition. The obtained results show that the proposed CDI system with intermediate solution had better performance in terms of desalination percentage. This publication opens new opportunities to improve the performance of CDI systems and implement this technology on industrial applications. [DOI: 10.1115/1.4032427]

1 Introduction

Population growth, improvement in the standard of living, and increasing demand for clean and potable water have led to fresh water shortage in different regions all around the world. As a matter of fact, water resources per capita in Africa and Asia happen to be very low (less than 10^4 m³/yr person⁻¹ comparing to 8×10^4 m³/yr person for Australia and about 2.4×10^4 m³/yr person for South America) [1]. Additionally, over 97% of earth's water is either seawater or brackish water [2–7]. As a consequence, more attention has been focused on unconventional water supplies and using different desalination methods to convert seawater and brackish water into drinkable water [3–7].

Current desalination methods can be categorized into three major groups, based on their procedure for separating the dissolved ions from water: membrane based, thermally based, and electrically based. Membrane-based methods, such as reverse osmosis and membrane electrodialysis, pass the salty solution through a set of water-permeable membranes. Thermal methods like multistage flash distillation, multi-effect distillation, and mechanical vapor compression purify water by means of distillation. Finally, electric-based methods, including electrodialysis and CDI, remove ions from the solution using an electrical field. Despite of the popularity of membrane and thermal methods, they have important drawbacks. These disadvantages, such as large input energy and membrane fouling, resulted in going through cost-effective techniques for water desalination [3,4,6,7].

¹Corresponding author.

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CDI is an innovative and relatively new electric-based desalination method for water treatment. During this process, water flows between a pair of porous electrodes while an external electric field is applied between them using a relatively low DC voltage. The electric field sustained drives positive ions toward the negative electrode and negative ions to the positive electrode. Adsorption of the ions at their respective counter electrode and the corresponding solution salinity reduction through the desalination cell are limited by saturation of the electrodes. At this point, it is required to regenerate the adsorption capacity of these porous materials. Regeneration of the adsorbing electrodes allows recovering part of the energy consumed during the desalination process. This ability to recuperate a fraction of the consumed energy has made CDI a unique method for water desalination [1,3]. Figure 1 depicts desalination and regeneration cycles in a CDI cell.

Significant progress has been made in CDI since this water treatment method was proposed in the 1960s. However, commercialization of this technique requires further research and development as CDI's performance depends not only on the electrode material's properties but also on various operational parameters [8–11]. In this regard, intensive research has been dedicated to evaluate and characterize the adsorption capacity of different porous materials used for the electrodes, such as activated carbon, carbon aerogel, carbide-derived carbon, and carbon nanotubes [9,12,13]. The effect of other operating parameters, such as solution flow rate and applied electric field, was also evaluated [14]. Additionally, varying the timing for desalination and regeneration processes has been investigated [8].

Presented herein is a new method for water desalination, based on CDI technology. To lower the salinity of brackish water to a desired level, a single and large CDI desalination cell may not be adequate. Experimental studies have been conducted regarding

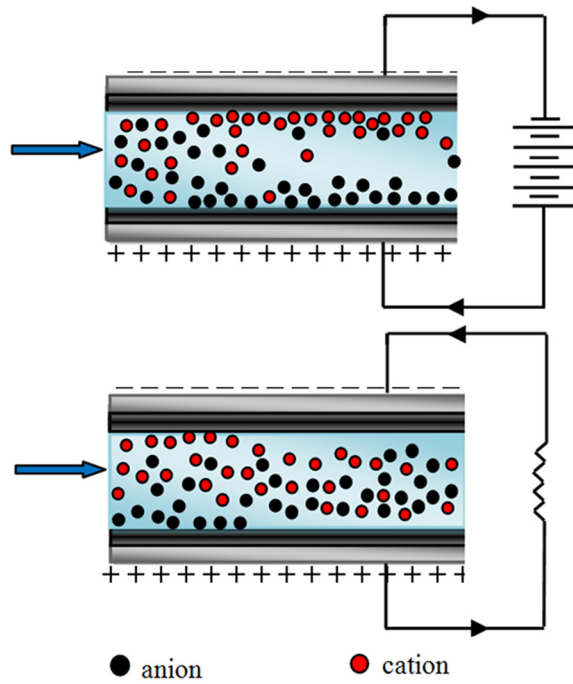


Fig. 1 Schematic of desalination (top) and regeneration (bottom) processes in a sample CDI system. By employing a voltage difference between the porous electrodes, positive and negative ions are adsorbed at their counter-charged electrodes. After the electrodes' saturation, regeneration takes place by short circuiting the electrodes.

the performance of CDI-based water desalination, using multiple successive CDI cells [10,13,15,16]. Moreover, Demirel et al. investigated the effects of the CDI cell size on its performance [8]. However, desalinating in a steplike manner using an array of cells in series with intermediate buffer solutions has not been discussed.

Placing a solution buffer between two cells has two effects. First, it makes the outlet solution concentration from the preceding cell uniform and secures the solution supply for the following cells. Second, it allows operating each cell independently with parameters that maximize its performance, improving the desalination of the whole CDI system. Numerous publications suggest models for studying the underlying physics of electro-adsorption based systems [17–25]. Perez et al. presented a model analyzing the electro-adsorption mechanism for low salinity water in a CDI cell [18]. For dilute solutions, saturation of the electrodes can be neglected, and it can be considered that the outlet concentration remains constant after reaching a minimum value. Under this presumption and steady-state condition, the ratio of the minimum outlet concentration to the inlet concentration in developing convective–diffusive layer regime is calculated as

$$\frac{C_{\text{exit-bulk}}}{C_0} = 1 - \left(\frac{w \cdot L \cdot \overline{v_{\text{ads-ref}}}}{Q^{2/3} \cdot Q_{\text{ref}}^{1/3}} \right) \quad (1)$$

where w (m) and L (m) are, respectively, the width and length of the cell; $\overline{v_{\text{ads-ref}}}$ (m/s) is the average net adsorption velocity at reference flow rate Q_{ref} (m^3/s); and Q is the flow rate in the system (m^3/s). The average net adsorption velocity can be expressed as

$$\overline{v_{\text{ads-ref}}} = 0.776 \left(\frac{3}{2} \right) \left(\frac{D_{\text{eff}}}{H} \right)^{2/3} \left(\frac{Q_{\text{ref}}}{L \cdot w} \right)^{1/3} \quad (2)$$

where D_{eff} (m^2/s) is the effective diffusion coefficient, including both electric potential difference and molar diffusion effects on

the ions movement, and H (m) is the space between the electrodes.

In order to evaluate the effect of the solution buffer on the minimum outlet concentration, performance of a two-cell buffered system versus an arrangement with two cascaded CDI cells can be analyzed. The inlet concentration of the second cell in the buffered system can be considered as the minimum exit concentration of the first cell. Substituting Eq. (2) in Eq. (1), ratio of the minimum exit concentration for a two-cell buffered system, each having the length of L , to that of two cascaded CDI cells, with the total length of $2L$, can be calculated as

$$\frac{C_{\text{exit,buffered}}}{C_{\text{exit,not buffered}}} = \frac{(1-B)^2}{1-2^{2/3}B} \quad (3)$$

where

$$B = \frac{w \cdot L \cdot \overline{v_{\text{ads-ref}}}}{Q^{2/3} \cdot Q_{\text{ref}}^{1/3}} \quad (4)$$

For simplification, it was assumed that effective diffusion coefficient and the space between the electrodes in both systems are equal. Conclusively, for the buffered system to be effective, the ratio in Eq. (3) requires to be less than 1. Therefore, B should be less than 0.413. In other words, the following equation should be satisfied:

$$Q \geq \left(\frac{w \cdot L \cdot \overline{v_{\text{ads-ref}}}}{0.413 \cdot Q_{\text{ref}}^{1/3}} \right)^{3/2} \quad (5)$$

Perez et al. calculated $\overline{v_{\text{ads-ref}}}$ as 4.90×10^{-6} m/s for the reference flow rate of $10 \text{ cm}^3/\text{min}$. Therefore, for the buffered CDI system to outperform a nonbuffered system, for a given cell geometry, the flow rate must be above a certain value

$$Q \geq \left(\frac{w \cdot L}{k} \right)^{3/2} \quad (6)$$

where the constant of k equals to $4.64 \times 10^2 \text{ s}^{-2/3}$. The flow rate used for driving the flow in the CDI systems for this study satisfied the aforementioned criterion.

The proof of concept of the proposed buffered arrangement was performed employing one cell at the time with different initial solution concentrations. For this paper, the operational conditions of the proposed buffered system aim to maximize the desalination percentage of the system. As the first step for investigating the performance of this new method, operation of a CDI system with one solution buffer was evaluated.

2 Methodology

2.1 Experimental Setup. All the desalination experiments were conducted in Multiscale Thermal Fluids Laboratory, at the Northeastern University. Two CDI cells were manufactured for this investigation. The case of each cell was composed of two acrylic parts. This material was selected because of its low electric conductivity. A groove with rectangular cross section was machined on one side of each cell-half for the solution flow. These grooves were covered by highly conductive and corrosion-resistant titanium foils as current collectors. Two pieces of activated carbon ($25 \times 250 \text{ mm}$) from Material Methods served as the porous electrodes for ion storage. Finally, a 2-mm thick polymer mesh was placed between the electrodes to prevent their contact.

An Aqua Lifter AW-20 pump drove the solution of a known concentration through the desalination cell. The instrumentation used in this work consists of a LS32-1500 Sensirion flow meter, one ET908 eDAQ flow-thru conductivity electrode, and an

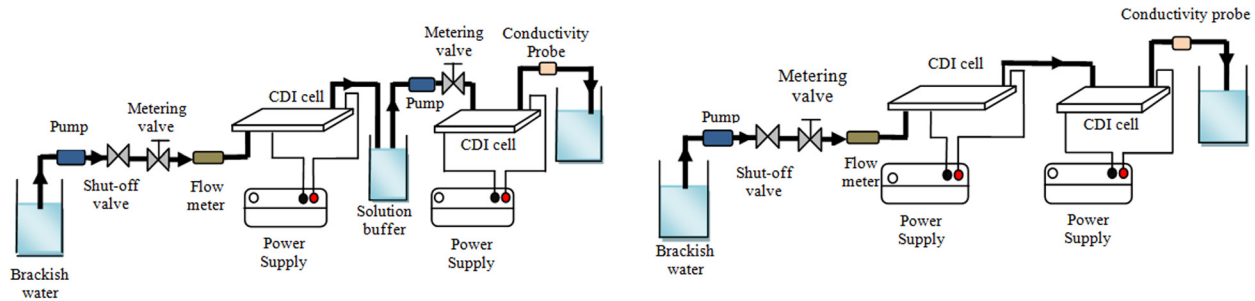


Fig. 2 The experiment setup for two CDI systems. The buffered system (left): A steady desalination test was performed with a single CDI cell. Afterward, the minimum average outlet concentration of that test was used as the inlet concentration of another desalination test with one CDI cell. The cascaded system (right): Two CDI cells cascaded with no intermediate solution buffer.

Agilent E3647A power supply. This last device not only supplied the constant voltage required for the electrical field but also measured the electric current consumed by the system.

2.2 Experimental Procedure. Before starting the tests, recordings for the outlet conductivity were checked to be steady and constant. This would ensure that any change in the outlet conductivity is because of the ions adsorption and not the variation in the inlet concentration. Constant voltage of 1 V was applied across the CDI cells with Agilent E3647A power supply, for all the tests. The minimum required voltage for water electrolysis at 298 K and 1 atm is 1.23 V, and as the pressure increases, the required voltage insignificantly increases [26–29]. Hence, setting the applied voltage below this limit, any electrodecomposition of water during the desalination was obstructed. Prior to initiating a test and recording data, each cell was thoroughly cleaned with distilled water with the maximum flow rate. Simultaneously, every component of the experimental setup was tapped to make sure no bubble is tangled in the system.

Two types of systems were set-up and compared for this paper. Evaluation of both, a buffered and a cascaded system, was performed with the same flow rate ($5.0 \text{ cm}^3/\text{min}$) and initial NaCl concentration ($0.05 \text{ mg}/\text{cm}^3$) for all the tests.

(a) *Buffered system:* The proof of concept for the proposed buffered arrangement was conducted by evaluating the combined performance of two desalination experiments using one CDI cell and two different inlet solution concentrations: $0.05 \text{ mg}/\text{cm}^3$ and the buffer concentration. The buffered concentration was determined to maximize the desalination of the system. For this, a long-term steady test for one single CDI cell with a nominal inlet salinity of $0.05 \text{ mg}/\text{cm}^3$ was performed. The collected data were analyzed to determine the variation of the average concentration in the outlet solution with respect to time. Average outlet concentration at each point can be calculated as

$$C_{\text{ave}} = \frac{1}{t} \int_0^t C \cdot d\tau \quad (7)$$

where C is the outlet solution concentration (mg/cm^3), and t is the time at which the measurement took place (s).

The minimum average concentration was used as the buffer concentration (inlet concentration of the second desalination experiment). The time to achieve this minimum average concentration was assigned as the operation time of the first cell in a buffered system to determine the volume processed and energy consumed. Then, another test was conducted with the second cell and with the same constant flow rate of $5.0 \text{ cm}^3/\text{min}$.

(b) *Cascaded system:* Here, two consecutive CDI cells with no intermediate buffer were employed. As mentioned before, the inlet concentration for this setup was also $0.05 \text{ mg}/\text{cm}^3$, and the flow rate of the solution was $5.0 \text{ cm}^3/\text{min}$. The schematic of both setups for this work is illustrated in Fig. 2.

2.3 Evaluation Criteria. The criteria used to evaluate the performance of the proposed buffered arrangement were: maximum desalination percentage, total volume treated, and total energy consumed. The desalination percentage for the aforementioned CDI systems was calculated by

$$\text{Desalination percentage} = \frac{C_o - C_{\text{ave,min}}}{C_o} \times 100 \quad (8)$$

where C_o is the initial concentration (mg/cm^3), and $C_{\text{ave,min}}$ is the minimum average concentration (mg/cm^3).

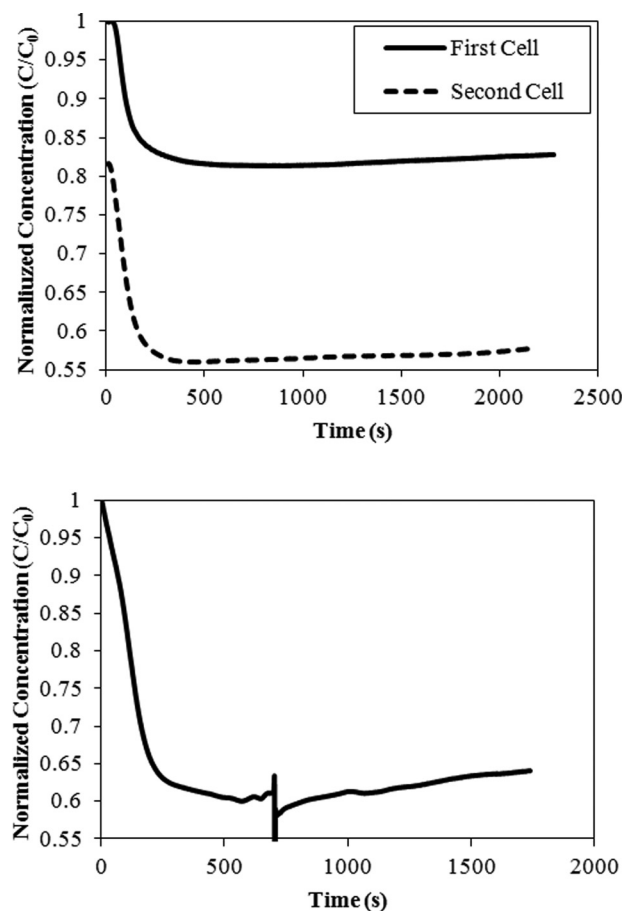


Fig. 3 Normalized concentration for the first and second cells in the buffered desalination system, normalized with the inlet concentration of the first cell (top) and normalized concentration for the two-cell cascaded system (bottom)

Table 1 Summary of the results obtained from the tests for two desalination systems: (a) two-cell buffered system and (b) two-cell cascaded system with no solution buffer

		Minimum average concentration (mg/cm ³)	Purified water (cm ³)	Energy consumption (J)	Desalination percentage (%)
System A	Cell 1	0.0443	190	8.20	
	Cell 2	0.0309	182	9.19	
	Overall	0.0309	182	17.39	42.22
System B		0.0321	145	20.60	36.01

Likewise, the volume of the solution treated and the amount of input energy were estimated by

$$V_{tw} = \frac{t \cdot FR}{60} \quad (9)$$

$$E_{in} = \int_0^t V \cdot I \cdot d\tau \quad (10)$$

where V_{tw} is the volume of the treated water (cm³), t is the instant of the measurement (s), FR is the flow rate during the process (cm³/min), E_{in} is the energy input to the system (J), V is the applied voltage, and I is the electric current at each instant.

3 Results and Discussion

To reduce the experimental noise, the data collected were averaged every 2 s. Figure 3 illustrates the averaged and normalized concentration changes over time before reaching the minimum average outlet concentration. The concentration is normalized with the initial concentration for both systems. Sudden concentration drops recorded correspond to gas bubbles leaving the CDI cell. Despite of our efforts to remove the bubbles while priming the CDI cells before each test, it is believed that these bubbles were trapped within the system before every experiment. Due to the relatively low voltage applied, these gas bubbles were not corresponded to electrodecomposition of water molecules.

The results obtained are listed in Table 1. As it is indicated, the desalination percentage in the proposed buffered system is higher than the other system. Note that the desalination percentage for the buffered system is computed based on the inlet concentration for the first cell. Additionally, the volume of the water purified by the buffered system is about 1.3 times more. Moreover, the total amount of energy consumed to reach the minimum average concentration in this setup happens to be lower. It is also proposed that the number of cells operating in a buffered system could be increased to improve the amount of energy consumed per unit volume of solution treated for a certain period of time. Two or more cells working in parallel could be connected to the same solution buffer, decreasing the amount of energy consumed per unit volume of solution treated. It is important to note that the instant at which the minimum outlet solution concentration was reached does not correspond to the time when the desalination percentage is maximum as previously discussed by Demirel et al.

4 Conclusion

A new approach for CDI water desalination was presented. The performance of the new system, a two-cell setup with an intermediate solution, was compared to one without any buffer solution. The experimental results indicate that in regard to desalination percentage, energy consumed, and amount of water purified, employing the intermediate buffer solution happens to improve the efficacy of the CDI water desalination. Hence, one may use the buffered system with the intermediate solution to achieve a lower salinity level in the outlet with lower amount of energy consumption. Additionally, in order to improve the efficiency of the process in terms of energy input per volume of the treated water

or total amount of time required for water purification, one can use two or more cells after the solution buffer. Further experiments aim to explore these alternative architectures.

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Nomenclature

- C_o = inlet concentration (mg/cm³)
- $C_{exit-bulk}$ = bulk solution concentration at the exit (mg/cm³)
- $C_{exit, buffered}$ = bulk solution concentration at the exit of the buffered system (mg/cm³)
- $C_{exit, non buffered}$ = bulk solution concentration at the exit of the nonbuffered system (mg/cm³)
- D_{eff} = effective diffusion coefficient (m²/s)
- E_{in} = energy input to the system (J)
- FR = flow rate in the system during the experiment (cm³/min)
- H = separation between electrodes (m)
- I = electrical current (A)
- L = length of the CDI cell (m)
- Q = solution flow rate within the cell (m³/s)
- Q_{ref} = reference flow rate (m³/s)
- t = instant of the measurement (s)
- V = applied voltage (V)
- $\overline{v}_{ads-ref}$ = average reference net adsorption velocity (m/s)
- V_{tw} = volume of the purified water (cm³)
- w = width of the CDI cell (m)

References

- [1] Oren, Y., 2008, "Capacitive Deionization (CDI) for Desalination and Water Treatment—Past, Present and Future (A Review)," *Desalination*, **228**(1–3), pp. 10–29.
- [2] McGlade, J., Werner, B., Young, M., Matlock, M., Jefferies, D., Sonnemann, G., Aldaya, M., Pfister, S., Berger, M., Farrell, C., Hyde, K., Wackernagel, M., Hoekstra, A., Mathews, R., Liu, J., Ercin, E., Weber, J. L., Alfieri, A., Martinez-Lagunes, R., Edens, B., Schulte, P., Wirén-Lehr, S. V., and Gee, D., 2012, *Measuring Water Use in a Green Economy*, UNEP, Paris.
- [3] Anderson, M. A., Cudero, A. L., and Palma, J., 2010, "Capacitive Deionization as an Electrochemical Means of Saving Energy and Delivering Clean Water. Comparison to Present Desalination Practices: Will It Compete?" *Electrochim. Acta*, **55**(12), pp. 3845–3856.
- [4] Klausner, J. F., Li, Y., Darwish, M., and Mei, R., 2004, "Innovative Diffusion Driven Desalination Process," *ASME J. Energy Res. Technol.*, **126**(3), pp. 219–225.
- [5] Kowalski, G. J., Modaresifar, M., and Zenouzi, M., 2014, "Significance of Transient Energy Terms in a New Tray Design Solar Desalination Device," *ASME J. Energy Res. Technol.*, **137**(1), p. 011201.
- [6] Farahbod, F., Mowla, D., Jafari Nasr, M. R., and Soltanieh, M., 2012, "Investigation of Solar Desalination Pond Performance Experimentally and Mathematically," *ASME J. Energy Res. Technol.*, **134**(4), p. 041201.
- [7] Farahbod, F., and Farahmand, S., 2014, "Experimental Study of Solar-Powered Desalination Pond as Second Stage in Proposed Zero Discharge Desalination Process," *ASME J. Energy Res. Technol.*, **136**(3), p. 031202.
- [8] Demirel, O. N., Naylor, R. M., Perez, C. A. R., Wilkes, E., and Hidrovo, C., 2013, "Energetic Performance Optimization of a Capacitive Deionization System Operating With Transient Cycles and Brackish Water," *Desalination*, **314**, pp. 130–138.

- [9] Li, H., Gao, Y., Pan, L., Zhang, Y., Chen, Y., and Sun, Z., 2008, "Electrosorptive Desalination by Carbon Nanotubes and Nanofibres Electrodes and Ion-Exchange Membranes," *Water Res.*, **42**(20), pp. 4923–4928.
- [10] Mossad, M., and Zou, L., 2012, "A Study of the Capacitive Deionisation Performance Under Various Operational Conditions," *J. Hazard. Mater.*, **213–214**, pp. 491–497.
- [11] Ryoo, M.-W., and Seo, G., 2003, "Improvement in Capacitive Deionization Function of Activated Carbon Cloth by Titania Modification," *Water Res.*, **37**(7), pp. 1527–1534.
- [12] Porada, S., Weinstein, L., Dash, R., van der Wal, A., Bryjak, M., Gogotsi, Y., and Biesheuvel, P. M., 2012, "Water Desalination Using Capacitive Deionization With Microporous Carbon Electrodes," *ACS Appl. Mater. Interfaces*, **4**(3), pp. 1194–1199.
- [13] 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**(10–11), pp. 2605–2617.
- [14] Dermentzis, K., and Ouzounis, K., 2008, "Continuous Capacitive Deionization–Electrodialysis Reversal Through Electrostatic Shielding for Desalination and Deionization of Water," *Electrochim. Acta*, **53**(24), pp. 7123–7130.
- [15] Welgemoed, T. J., and Schutte, C. F., 2005, "Capacitive Deionization TechnologyTM: An Alternative Desalination Solution," *Desalination*, **183**(1–3), pp. 327–340.
- [16] Farmer, J. C., Bahowick, S. M., Harrar, J. E., Fix, D. V., Martinelli, R. E., Vu, A. K., and Carroll, K. L., 1997, "Electrosorption of Chromium Ions on Carbon Aerogel Electrodes as a Means of Remediating Ground Water," *Energy Fuels*, **11**(2), pp. 337–347.
- [17] Johnson, A. M., and Newman, J., 1971, "Desalting by Means of Porous Carbon Electrodes," *J. Electrochem. Soc.*, **118**(3), pp. 510–517.
- [18] Perez, C. A. R., Demirer, O. N., Clifton, R. L., Naylor, R. M., and Hidrovo, C. H., 2013, "Macro Analysis of the Electro-Adsorption Process in Low Concentration NaCl Solutions for Water Desalination Applications," *J. Electrochem. Soc.*, **160**(3), pp. E13–E21.
- [19] Biesheuvel, P. M., Limpt, B. V., and Wal, A. V. D., 2009, "Dynamic Adsorption/Desorption Process Model for Capacitive Deionization," *J. Phys. Chem. C*, **113**(14), pp. 5636–5640.
- [20] Zhao, R., Biesheuvel, P. M., Miedema, H., Bruning, H., and van der Wal, A., 2009, "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), pp. 205–210.
- [21] Bazant, M. Z., Thornton, K., and Ajdari, A., 2004, "Diffuse-Charge Dynamics in Electrochemical Systems," *Phys. Rev. E*, **70**(2), p. 021506.
- [22] Suss, M. E., Biesheuvel, P. M., Baumann, T. F., Stadermann, M., and Santiago, J. G., 2014, "In Situ Spatially and Temporally Resolved Measurements of Salt Concentration Between Charging Porous Electrodes for Desalination by Capacitive Deionization," *Environ. Sci. Technol.*, **48**(3), pp. 2008–2015.
- [23] Porada, S., Borchardt, L., Oschatz, M., Bryjak, M., Atchison, J. S., Keesman, K. J., Kaskel, S., Biesheuvel, P. M., and Presser, V., 2013, "Direct Prediction of the Desalination Performance of Porous Carbon Electrodes for Capacitive Deionization," *Energy Environ. Sci.*, **6**(12), pp. 3700–3712.
- [24] Biesheuvel, P. M., Fu, Y., and Bazant, M. Z., 2012, "Electrochemistry and Capacitive Charging of Porous Electrodes in Asymmetric Multicomponent Electrolytes," *Russ. J. Electrochem.*, **48**(6), pp. 580–592.
- [25] Biesheuvel, P. M., Fu, Y., and Bazant, M. Z., 2011, "Diffuse Charge and Faradaic Reactions in Porous Electrodes," *Phys. Rev. E*, **83**(6), p. 061507.
- [26] Roussak, O. V., 2012, *Applied Chemistry a Textbook for Engineers and Technologists*, Springer, Heidelberg, Germany.
- [27] Matsushima, H., Nishida, T., Konishi, Y., Fukunaka, Y., Ito, Y., and Kuribayashi, K., 2003, "Water Electrolysis Under Microgravity: Part 1. Experimental Technique," *Electrochim. Acta*, **48**(28), pp. 4119–4125.
- [28] Roy, A., Watson, S., and Infield, D., 2006, "Comparison of Electrical Energy Efficiency of Atmospheric and High-Pressure Electrolysers," *Int. J. Hydrogen Energy*, **31**(14), pp. 1964–1979.
- [29] Turner, J., Sverdrup, G., Mann, M. K., Maness, P.-C., Kroposki, B., Ghirardi, M., Evans, R. J., and Blake, D., 2008, "Renewable Hydrogen Production," *Int. J. Energy Res.*, **32**(5), pp. 379–407.