Energy consumption analysis of constant voltage and constant current operations in capacitive deionization

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Abstract

We report our studies to compare energy consumption of a CDI cell in constant voltage (CV) and constant current (CC) operations, with a focus on understanding the underlying physics of consumption patterns. The comparison is conducted under conditions that the CV and CC operations result in the same amounts of input charge and within identical charging phase durations. We present two electrical circuit models to simulate energy consumption in charging phase: one is a simple RC circuit model, and the other a transmission line circuit model. We built and tested a CDI cell to validate the transmission line model, and performed a series of experiments to compare CV versus CC operation under the condition of equal applied charge and charging duration. The experiments show that CC mode consumes energy at 33.8 kJ per mole of ions removed, which is only 28% of CV mode energy consumption (120.6 kJ/mole), but achieves similar level of salt removals. Together, the models and experiment support our major conclusion that CC is more energy efficient than CV for equal charge and charging duration. The models also suggest that the lower energy consumption of CC in charging is due to its lower resistive dissipation.

Key words

Capacitive deionization, energy consumption, constant current and constant voltage.

1. Introduction

Capacitive deionization (CDI) is an emerging technique for water desalination. It is especially promising for treating water with low and moderate salt concentration, also known as brackish water.[1, 2] The key component of a CDI cell is a pair of porous

carbon electrodes. Salt ions are removed from water and held electrostatically at pore surfaces. CDI operates at low voltage (<1.4 V) and low pressure, and has the potential to be cost effective and energy efficient.

Energy consumption is a crucial factor when comparing CDI to state of the art desalination technology, reverse osmosis (RO).[3, 4] A CDI cell can be operated at various charging modes including constant voltage (CV) [5-8] and constant current (CC) [7, 9-15]. Different modes lead to discrepant energy consumption patterns. Zhao et al. [15] and Choi [16] reported lower energy consumption for CC-operation than CV-operation for membrane capacitive deionization (MCDI) cells. Kang et al. demonstrated that CC mode consumed 26% -30% less energy than that consumed in CV mode with the same amount of ions removed.[17] Recently, Han et al. showed that CV mode consumed approximately 50% more energy than CC mode, and only 5.7% of the total energy consumption in charging process in CV mode was recovered in contrast to up to 40% in CC mode.[12] Although these experimental observations have suggested that CC mode is more energy efficient, a thorough understanding of why CC mode consumes less energy than CV mode is missing. Kang et al. attributed lower energy consumption of CC to its overall lower cell voltage [12]. The work we present here will show that the latter argument is ambiguous and strictly inaccurate since the energy saving of CC operation over CV (for equal charge and charging duration) is insensitive to operational voltages of CC. Further, as with most studies, there is no significant effort to make “fair comparison” between the two modes (e.g., charging to same net charge for equal time).

Fundamentally, energy dissipates as currents pass through resistances in the form heat. The underlying reason that CC consumes less energy than CV is that, in CC operation,

the cell dissipates less power through resistive components, as CC has better control of charging currents. Another energy consumption advantage of CC is that CC decreases the time the cell operates under conditions where electrode-to-solution potentials result in parasitic (Faraday) reactions. We also note that all of the aforementioned studies report energy consumption as the amount of electrical energy applied to a CDI cell in charging. Instead, we here define this “Energy input” a value equal to the time integral of charging power (product of charging voltage and current) of the external power source to a CDI cell. Note that it is inaccurate to equate energy input and energy consumption. Only a fraction of the energy input is dissipated/consumed by the cell, a second important fraction is instead stored within the cell as capacitive energy in electrical double layers. This stored energy is recoverable (not part of “energy consumed”). Experimentally, will quantify recoverable energy using a low current discharge. Under low current discharge, energy dissipated by resistances and parasitic reactions in the cell are small compared to the recoverable electrical capacitance. Such recovered energy can be stored externally (e.g. in supercapacitors or batteries) or used by other devices, including other CDI cells. We advocate to the community that energy consumption of CDI processes should be the unrecoverable, dissipated energy during an operation cycle, and should not include stored capacitive energy.

In this study, we present two electrical circuit models to simulate and compare energy consumption of CC and CV operation modes. The first model is a simple RC circuit model, and the second is an experimentally validated circuit model based on classic transmission line theory to simulate a capacitance and resistance network. We validate simulation results by performing experiments with a flow-through CDI (ftCDI) cell made

of hierarchical carbon aerogel monoliths (HCAMs) electrodes, as shown in Figure 1a and 1b. We demonstrate that CC consumes less energy than CV with the same amount of charge transferred and within the identical operation timespan. For our comparison, the two modes also achieve similar charge efficiency. We attribute lower consumption of CC mode to less resistive dissipation in the charging process. As far as we know, our work is the first study centered on the underlying physics of why CC consumes less energy than CV operations for CDI cells. Although we here use ftCDI cell as our model system, our results and conclusions are applicable to flow-between CDI cells and operations. We note that our study might not apply to membrane CDI (MCDI) because other energy loss mechanisms in MCDI, such as energy loss associate with ions overcoming membrane barriers, are not captured by our models and analysis.

Figure 1. (a) Schematic and (b) image of a flow-through CDI cell. The cell consists a pair of 300 μm thick porous carbon electrodes, an 80 μm porous dielectric separator, two metal current collectors and wires. (c) Simple RC circuit model for a CDI cell. (d) Equivalent circuit of a CDI cell based on transmission line impedance model.

2. Energy consumption analysis

2.1. Simple RC circuit analysis

For first-order analysis of energy dissipation in charging, we model a CDI cell as a simple RC circuit: a capacitor C in series with a resistor R , as shown in Figure 1c. This model is perhaps the simplest but still powerful for understanding energy consumption associated with charging and discharging process in CDI. Here, the capacitor C represents the total electrical double layer capacitance for salt adsorption and the resistor R represents an equivalent total resistance of the cell. To create the simplest model which nevertheless offers valuable insight, we here assume that the capacitance and resistance remain the same during charging or discharging process. We consider comparisons where we charge over the same time and equal amounts of charge.

Fundamentally, energy dissipates through the resistive components of a CDI cell in the form of heat. The dissipation power of a CDI cell is proportional to its resistance and the square of response current: $P = I^2 R$. Here the current response I is determined by electrical operation modes, and CC and CV modes have distinguished energy consumption patterns as we further discuss in the paper.

We analyze energy consumption of CV and CC operations under the conditions of finite charging time and the same amount of input charge. For CV operation, the current

response of a CDI cell is

$$I(t) = \frac{V_{CV}}{R} e^{-\frac{t}{RC}}. \quad (1)$$

Here V_{CV} is the constant voltage applied to the CDI cell. R is the total equivalent resistance and C is the total double layer capacitance.

The instantaneous dissipation power is then

$$P(t) = I(t)^2 R = \frac{V_{CV}^2}{R} e^{-2t/RC}. \quad (2)$$

If the cell is charged to finite time t , the charge transferred to a CDI cell and the accumulated dissipated energy are

$$q_{CV}(t) = \int_0^t \frac{V_{CV}}{R} e^{-t/RC} dt = V_{CV} C \left(1 - e^{-\frac{t}{RC}} \right), \quad (3)$$

$$E_{CV}(t) = \int_0^t P(t) dt = \int_0^t \frac{V_{CV}^2}{R} e^{-2t/RC} dt = \frac{1}{2} C V_{CV}^2 \left(1 - e^{-\frac{2t}{RC}} \right). \quad (4)$$

As per Equation (4), for finite charging time and fixed C and V_{CV} , CV energy consumption is a strong function of resistance R and charging time t . We note that if a CDI cell is charged to infinite time, the energy consumption is $CV^2/2$. However, in practical applications, we cannot and would not want to charge a CDI cell for very long times as this leads to very slow salt removal rate and poor water recovery. We here use a total resistance R as 7.64Ω and capacitance C as 3.84 F , based on values characterized for our CDI cell. We plot energy consumption of CV mode as a function of time in Figure S-1a.

For CC operational mode, the dissipated energy of a RC circuit is simply:

$$E_{cc}(t) = I_{CC}^2 R t. \quad (5)$$

For a fair comparison, we charge a cell at CC mode for a duration of time t such that the charge transferred is the same as that in CV mode within the identical timespan. As we later show that electric charge is a good proxy for salt removal, these comparison conditions imply a similar salt removal rate for both CV and CC.

The unique value of equivalent constant charging current I_{CC} is then

$$I_{CC} = \frac{q_{CV}}{t} = \frac{V_{CV} C (1 - e^{-\frac{t}{RC}})}{t}. \quad (6)$$

Here q_{CV} is the accumulated charge and V_{CV} is the voltage applied in the counterpart CV mode to which we compared.

The energy consumption for the equivalent CC mode described above is:

$$E_{CC}(t) = \int_0^t I_{CC}^2 R dt = I_{CC}^2 R \int_0^t dt = \frac{V_{CV}^2 C^2 R}{t} (1 - e^{-t/RC})^2. \quad (7)$$

This equivalent energy consumption is again a strong function of resistance R and charging time t . We plot E_{CC} as a function of time in Figure S-2a.

Combining Equation (4) and (7), the ratio of energy consumption of constant voltage and constant current is

$$\frac{E_{CC}}{E_{CV}}(t) = \frac{2RC}{t} \frac{1 - e^{-\frac{t}{RC}}}{1 + e^{-\frac{t}{RC}}}. \quad (8)$$

Perhaps surprisingly, this ratio is always smaller than unity regardless of the values of resistance R and capacitance C (Figure S-1b). This simple model therefore suggests CC operation always consumes less energy than CV for the same amounts of input charge and for identical timespans. In addition, energy consumption for either CV or CC mode strongly depends on the equivalent total resistance R .

2.2. Transmission-line based circuit model and simulations in LTspice

The resistive and capacitive components in a CDI cell are much more complex than a simple RC circuit. The simple RC circuit is unable to capture the non-uniform charging dynamics of a porous electrode, and it does not include charge loss mechanisms, such as parasitic reactions on electrode surface.[4, 8, 18-20] To further understand the energy consumption in charging process in a CDI cell, we use an equivalent circuit model based on classical transmission line (TL) theory. Transmission line impedance models are commonly used to simulate resistance and capacitance network in porous electrodes.[3, 21-24] In our model, we have a setup resistance (ionic resistance of the solution in the separators and electrical resistance of current collectors and wires), a contact resistance to model the contact between current collectors and porous electrodes, and two porous electrodes each modeled as a TL with 20 resistor-capacitor units (Figure S-2). Each resistor-capacitor unit consists of an EDL capacitor element, an ionic resistance element, an electrode resistance element, and a leakage resistance element which models parasitic reactions. We use a voltage-dependent non-linear relationship that follows Butler-Volmer equation for leakage resistors. We assume constant EDL capacitance and ionic resistance in our simulations because there is no significant ion depletion during charging at the feed concentrations we use in experiments. Further, constant capacitance and ionic

resistance elements generate simulation results which sufficiently well match experimental data (see Results and Discussion). We published a simpler version of this model in our previous study.[3] We here perform simulations with our equivalent circuit model in an integrated circuit simulator LTspice to study dynamic current and voltage responses and evaluate energy dissipations. Simulation conditions are determined by experiments. All the resistive and capacitive values in the LTspice model match those in experiments, as we later describe in Material and methods. Figure 2 compares simulated cell responses to experimental data in CV and CC modes, which shows that transmission line based LTspice model captures charging dynamics of a CDI cell well.

We determine the energy consumption of CC and CV modes in modeling by summing up the dissipation energy of all resistive elements, as shown below:

$$E = \sum_{m=1}^{N_i} \int_{t_0}^{t_l} I_{R_{i(m)}}^2 R_{i(m)} dt + \sum_{k=1}^{N_e} \int_{t_0}^{t_l} I_{R_{e(k)}}^2 R_{e(k)} dt + \sum_{n=1}^{N_{leak}} \int_{t_0}^{t_l} I_{R_{leak(n)}}^2 R_{leak(n)} dt + \int_{t_0}^{t_l} I_{R_s}^2 R_s dt + \int_{t_0}^{t_l} I_{R_{ct}}^2 R_{ct} dt, \quad (9)$$

where t_0 and t_l represent start and end time points of charging process. $R_{i(m)}$ and $R_{e(k)}$ are transmission line resistor elements representing ionic resistance inside pores and electrical bulk resistance of porous materials. N_i and N_e are the numbers of R_i and R_e elements in LTspice simulation, respectively. In our model, we have $N_i = 38$ and $N_e = 40$ (arbitrarily chosen). $R_{leak(n)}$ simulates parasitic reactions across EDL capacitor. N_{leak} is the number of $R_{leak(n)}$ element in the model and we have $N_{leak} = 40$. R_{ct} is the contact resistance between current collector and porous electrode. R_s is the setup resistance as we defined earlier.

Figure 2. (a) Experimental and simulated current responses of a CDI cell under 1V CV operation with charging phase durations of 1, 2, 5, 7.5 and 10 min. (b) Experimental and simulated voltage responses of a CDI cell under equivalent CC operations with charging phase durations of 1, 2, 5, 7.5 and 10 min. Solid blue lines represent experimental data and red dash lines represent simulation results.

3. Material and methods

3.1. Flow-through CDI cell

We fabricated a flow-through CDI cell design using two blocks of hierarchical carbon aerogel monoliths (HCAMs) material [25-28] with area of 2 x 3 cm and thickness of 300 μm , for CV and CC comparison experiments, as shown in Figure 1a and 1b. We used

an 80 μm thick hydrophilic PTFE membrane filter (JCWP04700, EMD Millipore, Billerica, MA) as a separator to insulate between the two electrodes. We used silver epoxy to create intimate electrical contacts between HCAM electrodes and copper wires.[3] The two porous electrodes and a separator were stacked into an assembly and glued on to a polycarbonate frame using epoxy. This assembly was then sandwiched between two 4.2 x 5.0 x 0.6 cm polycarbonate endplates with 630 μm silicone rubber sheets as gaskets. Both endplates were milled to accommodate a tubulation as a port to flow water. The cell was assembled using ten bolts. The cell assembly frame and housing parts were fabricated from polycarbonate.

3.2. ftCDI cell characterization

We characterized capacitance of our ftCDI cell by performing cyclic voltammetry using BioLogic SP-300 potentiostat (Bio Logic Science Claix, France). Apparent capacitances obtained from cyclic voltammetry are well known to depend on scan rates, and slow scan rates generate capacitance readings closer to equilibrium capacitances.[29-31] To accurately evaluate the equilibrium capacitance in a CDI cell, we performed cyclic voltammetry at a slow scan rate of 1.67 mV/s, as shown in Figure 3-S. We then extracted capacitance from cyclic voltammetry data and applied it as an input parameter to LTspice model.

The resistances of the entire CDI cell were characterized by electrochemical impedance spectroscopy (EIS) using a potentiostat.[3] EIS was performed in a two-terminal configuration without a reference electrode since the electrodes of the cell were symmetric. We applied a 10 mV amplitude sinusoidal potential perturbation and scanned

over a frequency range from 700 kHz to 10 mHz at 0 V bias. During electrochemical tests, the cell was filled with 100 mM NaCl. We waited 30 min before performing EIS measurements to allow the cell to equilibrate with the sodium chloride solution. We extracted setup resistance R_s , contact resistance R_{ct} and ionic resistance inside porous electrodes R_i from Nyquist plot of EIS responses (Figure S-4) and then used them as parameters in LTspice simulations.

We characterized parasitic reaction currents by performing constant voltage experiments at 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 V while flowing feed solution through the cell, and recorded leakage currents after 10 min of charging. 10 min is much longer than the CDI cell's RC time constant (about 25s). Therefore, we assume that the currents we observed at 10 min were due to parasitic reactions, not because of EDL charging. We then fitted leakage currents data to obtain a Butler-Volmer equation to characterize voltage-dependent parasitic reactions (Figure S-5).

3.3. Constant voltage and constant current charging experiments

We performed CV and CC experiments using our CDI cell with 100 mM NaCl. With this concentration, there is no significant ion depletion in the cell during charging. We used a Biologic SP-300 potentiostat (Bio Logic Science Claix, France) to supply voltage or current and monitor electrical responses. A flow-through conductivity sensor (Edaq, Denistone East, Australia) was attached to the CDI cell downstream to measure the conductivity of effluent solution. We used a syringe pump (Harvard Apparatus syringe pump, Holliston, MA) to flow feed solution through the cell at 0.24 mL/min. We waited 30 min before starting experiments to allow the cell to equilibrate with sodium chloride

solutions.

We first performed CV experiments at 1V with charging phase durations of 1, 2, 5, 7.5 and 10 min. We obtained the total amounts of charge transferred from potentiostat to the CDI cell by integrating current responses over charging times. To satisfy the conditions of the same input charge and identical timespan, we determined the charging currents for counterpart CC experiments by dividing accumulated charge measured in the CV experiment by total charging time. We then performed counterpart CC experiments for 1, 2, 5, 7.5 and 10 min with the corresponding equivalent currents. For each experiment, we performed two charging and discharging cycles. In both cycles, the charging steps followed preset experiment conditions. For discharging in the first cycle, we drew a very small discharging current (2mA) from the cell to extract an estimate of stored energy in EDL. In second cycle, we held the cell at open circuit state for 15 min after charging to flush desalted water in order to obtain more accurate estimates of salt removal. We then grounded the cell for 10 min to ensure complete regeneration of electrodes prior to the next charging.

4. Results and discussion

4.1. Model validation

As discussed above, the parameters of our LTSpice model are determined using independent experiments using cyclic voltammetry, EIS and leakage current experiments. We then use our LTSpice model to make predictions of the CDI cell in operational modes.

To validate the performance of our LTSpice model, we compared simulated voltage and current responses of the ftCDI cell to experimental data. Figure 2a shows

experimental and simulation data of current responses of the cell under 1V CV operation with 1, 2, 5, 7.5 and 10 min charging phase durations. Figure 2b shows experimental and simulation data of voltage responses of the CDI cell under corresponding CC conditions with the same set of charging phase durations. Simulation results from LTspice model demonstrate fair agreement with experimental data, especially for longer charging times. This agreement validates the use of a transmission line based circuit model to predict electrical charging dynamics and energy consumptions of a CDI cell. Our primary use of this model will be to study the differences between CC and CV energy dissipation.

For our LTspice circuit model, we chose to implement constant capacitor elements. We view this circuit model as the simplest transmission line model which nevertheless sufficiently captures the physics of CDI operation and helps us compare CC versus CV operations. In the Supplementary Information document, we show cyclic voltammetry characterizations (Figure S-3) which explore the net capacitances of our cell. The cyclic voltammetry data capture some voltage dependence of differential capacitance. However, we avoided fitting such data to obtain capacitance versus voltage relations since it is difficult to decouple the effects of capacitance changes versus parasitic reactions in the system. We do not know of a straight forward manner to decouple these confounding effects. Future work could include exploring the relative importance of changes in capacitance versus parasitic reaction effects, and including extending our model to include voltage-dependent capacitances. Our experience so far in exploring this issue is that constant capacitance models are likely sufficiently accurate for operation at higher ionic strengths of the inlet (order 100 mM salt concentration or greater).

4.2. Energy input and energy consumption comparison

We obtain energy inputs to CDI cell by integrating the product of cell voltage and current over charging times, as described by Equation (10):

$$E_{in} = \int_0^t I_{cell} V_{cell} dt, \quad (10)$$

This energy input calculation applies to either CV or CC operation. In CV mode, V_{cell} is fixed and I_{cell} is the cell's current in response. In CC mode, V_{cell} is the measured and I_{cell} is fixed. Figure 3a shows the comparisons of energy inputs of CV and CC modes in experiments and simulations as a function of duration of the charging phase. For each set of data, we first performed CV runs and used measured time-integrated current to calculate electric charge transferred to the cell. We then choose corresponding current values for the CC experiments to source the (unique) applied current to transfer the same charge in the same time as the CV experiment.

Figure 3a presents two sets of simulations results for CC mode. The first set are predictions of the CC circuit model given the applied (experimental) current. These CC current values therefore ensure the corresponding CC and CV *experiments* have identical electric charge transferred in identical charging phase times. As a reference and comparison, we also show CC circuit model predictions for corresponding current values which are predicted by the transferred charge predicted by the CV model. The latter data therefore ensure that the CV and CC *predictions* have identical electric charge transferred in identical charging timespans. Note the discrepancy between the latter prediction and experiments for short charging phase durations. We attribute this to the effect of increased ionic resistance in the cell for CV operation. The residence time of flow in the cell (solution volume inside the cell divided by flow rate) is about 56 s. For charging phase duration of this order (or shorter), the rapid initial ionic charge trapping of the CV

mode results in a short-term rise in ionic resistance; and such changes are not accounted for in the model (which assumes constant resistances). For longer cycle times, the solution inside the cell is well replenished by the flow and the measured time-average resistance loss are closer to those predicted.

We determine energy consumption for both simulations and experiments. In simulations, energy consumption is calculated as the sum of the dissipation energy of all resistive elements in model (i.e., Equation 9) and dissipation of the parasitic reaction circuit elements. In the experiments, we follow cell charging by discharging at a low current to evaluate energy consumptions (as we described in Material and methods). This low-current discharge lets us estimate recoverable output energy. For the experiments, we therefore estimate energy consumption during charging by subtracting from input energy the following three energy values: recoverable output energy, resistive dissipation energy in discharging, and parasitic reaction energy in discharging. The latter is estimated using our Butler-Volmer model for parasitic current (see Section S-5). We can express the estimate for energy consumed during charging in the experiments as follows:

$$E = E_{in} - E_{out} - \int_{t_1}^{t_2} I_{dis}^2 R_{cell} dt - E_{parasitic, dis} . \quad (11)$$

Here, t_1 and t_2 represent start and end time points of discharging phase. E is energy consumption in charging process. E_{in} represents input energy as measured by the potentiostat to the CDI cell. E_{out} is the recoverable output energy from EDL and it is obtained by discharging the cell at a very small constant current. $\int_{t_1}^{t_2} I_{dis}^2 R_{cell} dt$ represents resistive dissipation associated with small current discharging, where R_{cell} is the total equivalent resistance of the CDI cell and I_{dis} is the discharging current (2 mA in our case). $E_{parasitic, dis}$ is the estimate energy consumed by parasitic reactions during discharging.

$E_{parastic,dis}$ is the time integral of the product of parasitic current and cell voltage. Note (potentiostat) voltage is expected to be a good estimate of potential across surface charge layers (and therefore the potential parameter in the Butler-Volmer equation) for such low currents.

Figure 3b shows simulated and experimental energy consumption of CV and CC operations during charging process. With either fast or slow charging rates, CV consumes significantly higher energy than CC under the condition that the same amounts of charge are transferred to the cell within the identical charging timespans. We note here that the salt removals are comparable in CV and CC experiments, as we discuss further in next section. Our model successfully predicts the same major conclusion that CC is more energy efficient than CV for equal charge and charging phase duration. The model results therefore support the hypothesis that the lower energy consumption of CC in charging is due to its lower resistive dissipation. We note that there is some discrepancy between model and experiments for both the CC and CV cases, particularly for charge phase durations of order 100 s or less. As mentioned above, we attribute this discrepancy to the rapid initial rise of ionic resistance associated with CV operation. Our model does not capture such rapid-changing ionic resistance changes.

Figure 3. Comparison of (a) energy input and (b) energy consumption of a CDI cell in CV or CC mode versus charging phase durations of 1, 2, 5, 7.5 and 10 min. CV and CC modes were operated under the conditions of the same input electric charge and identical charging times. The dotdash line with circle markers represents experimental data for CV

operation. The dotdash line with triangular markers represents CC experimental data. The shortdash line is simulation results for CV mode. Black and light gray solid lines are simulation data for CC mode using input current from CV experiments and simulation data for CC mode using input current from corresponding CV simulations.

4.3. Salt removal comparison

We compare salt removals of CC and CV experiments to investigate if there is a trade-off between energy consumption and salt adsorption capabilities. We calculate salt removed from real-time conductivity measurement of effluent stream. Figure 4 shows experimentally measured energy consumption normalized by moles of salt removed as a function of charging phase duration. These data clearly demonstrate that CC consumes less energy per moles of salt removed than CV operation. At a charging duration of 10 min, CC mode consumes energy at 33.8 kJ per mole of ions removed, which is only 28% of CV mode energy consumption (120.6 kJ/mole). The inset figure compares the absolute salt adsorptions of CV and CC. Interestingly, CV and CC remove similar amounts of salts for all five charging phase durations (and so electric charge is here a good proxy for salt removal). These observations reinforce the conclusion that CC mode consumes significantly less energy than CV mode, while also achieving a similar level of salt adsorption.

Figure 4. Energy consumption per mole of salt removal of CV and CC operations from experiments with charging phase durations of 1, 2, 5, 7.5 and 10 min. In the main figure, the dotdash line with blue triangular markers is energy per salt removal of CV operation, whereas the dotdash line with gray circle marker represents CC mode data. Inset figure compares the absolute amounts of salt adsorbed in CV and CC experiments, which indicates similar desalination performance of these two modes.

4.4. Conclusions

We here report our studies on energy consumption of a CDI cell and compare the two most commonly used operation modes: constant voltage (CV) and constant current (CC). The comparison of energy consumption is conducted under the strictly enforced conditions that the CV and CC operations result in the same amounts of input (electric) charge and within identical charging timespans. We have developed a transmission-line

based LTspice circuit model to capture electrical dynamics of CDI charging and investigate energy consumption mechanisms. We found that CC mode consumes much less energy than CV mode but achieves similar level of salt removals, and this is due to less resistive dissipation with CC. We focused on energy consumption during the charging process in order to accurately assess salt removal and avoid salt contamination of the effluent stream caused by ion desorption at the beginning of a standard discharging step. Isolating charging and discharging steps enables precise evaluation of energy cost per unit of ions removed. We hypothesize that our major conclusion regarding energy consumption (that CC is more energy efficient than CV) applies to the discharging phase and to the entire charge/discharge cycle.

Lastly, we note that the CC operation possesses other advantages over CV apart from lower energy consumption, such as producing constant and adjustable effluent concentrations,[9, 10, 32, 33] and limiting charging time spent at substantial oxidizing potentials.[8] Therefore, we advocate the use of CC mode over CV for CDI cell operations to achieve lower energy consumption as well as produce controllable desalted effluent.

ACKNOWLEDGMENT

Yatian Qu would like to thank the Lawrence Scholar program. This work was supported by LLNL LDRD project 15-ERD- 068. Work at LLNL was performed under the auspices of the US DOE by LLNL under Contract DE-AC52-07NA27344. Yatian Qu and Juan G. Santiago also gratefully acknowledge support from the TomKat Center for Sustainable Energy at Stanford University.

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