

Application of Capacitive Deionization (CDI) Technology for Treating the Brackish Ground Water in Dala, Yangon, Myanmar

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미얀마 양곤 지역 달라 마을의 높은 염도의 우물물 처리를 위한 축전식 탈염기술의 적용 및 평가

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The desalination of brackish water is a necessary process due to seawater intrusion and the scarcity of potable water in Dala township in the Yangon region of Myanmar. The application of capacitive deionization (CDI) was proposed and demonstrated for the desalination of ground water samples from three wells in Dala. During the CDI operation, the ion adsorption characteristics and energy consumption were analyzed. The CDI cell was efficient for the desalination of ground water samples with total dissolved solids (TDSs) of up to 3000 mg/L. Moreover, the energy consumption for the deionization of water samples was about 0.5 kWh/m³ of desalinated water. Therefore, the CDI system could be considered a promising method to address in an energy efficient manner the potable water issue in Dala, Yangon, Myanmar.

미얀마의 양곤 지역 달라 마을에서는 바닷물이 강물과 육지로 침습하는 현상이 지속적으로 발생해 식수 공급이 원활하지 못하므로 식수 공급을 위한 탈염 기술이 필요하다. 이를 위하여 본 연구에서는 축전식 탈염 공정이 달라 마을의 우물물 처리에 적합한지에 대하여 탈염 성능과 에너지 소모량 측면에서 살펴보았다. 실험 결과, 3000 mg/L의 총 용존 고형물질(Total dissolved solid, TDS)을 갖는 유입수를 적절히 탈염할 수 있었다. 이 과정에서의 에너지 소모량은 약 0.5 kWh/m³으로 낮게 측정되었다. 그러므로 축전식 탈염 공정은 미얀마 양곤 지역의 달라 마을에 필요한 식수를 적은 에너지를 이용해 효율적으로 생산할 수 있는 적합하고 발전 가능성이 높은 기술로 사료된다.

KEYWORDS: Brackish Water Treatment, Capacitive Deionization (CDI), Desalination, Energy-efficient, Potable water

Introduction

Seawater intrusion into ground water sources is considered

a serious problem in coastal regions worldwide. Particularly in Myanmar, which has more than 1,930 kilometers of coastline, the rapid population growth and the increased agricultural activities have severely stressed ground water sources. Moreover, there is growing concern about the ground water quality due to the presence of dissolved inorganic

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impurities from the chemical interactions of geological substances with the water. For potable applications, the salinity should be within permissible limits. The salt concentration in water is represented by the total dissolved solid (TDS). Water can be considered fresh drinking water if the TDS value is less than 600 mg/L. However, the water could not be potable once its value is greater than 1000 mg/L (WHO, 2011).

The seawater intrusion and the scarcity of potable water are getting worse in Dala township in the Yangon region of Myanmar. In recent years, the TDS value of the ground water in Dala has been rapidly increasing up to 5000 mg/L. Due to the steep increase in the TDS value, more than 90 percent of the residents have to rely on freshwater ponds for drinking water. However, the ponds dry out seasonally. Thus, in the dry season, local residents have to use either salty ground water or fresh water brought across from the Yangon River. The water shortage affects Dala every dry season (from March to May) and causes diarrhea from drinking dirty water.

The desalination process requires energy to separate the water from the salt and other contaminants. Thermal energy is used in a process-like distillation to evaporate and collect the purified condensate water leaving the salts and solids behind (Shatat and Riffat, 2012). This process generally requires a large area because the sun is an economical source of thermal energy. Mechanical energy is used in a process called Reverse Osmosis or RO to trap the salt and only drive water through a semi-permeable membrane using the high-pressure difference. This method is particularly effective in applications for salt water with a high concentration such as seawater (Shatat and Riffat, 2012) but is not effective in terms of energy because high pressure is required regardless of the salt content.

However, Capacitive Deionization (CDI) is considered an alternative desalination method and has received much attention in recent decades because of its high energy-efficiency. Using a potential difference across a pair of electrodes, salt ions are eliminated by adsorption. CDI requires comparably a small amount of energy for capturing only the salt ions. The electricity demand of the CDI process is lower than that of conventional desalination processes which have a typical energy requirement of about 4 kW/m³ (Anderson *et al.*, 2010). Moreover, a low potential range from 0.8 to 1.4 V is commonly applied to drive the salt adsorption behavior

in the CDI process. At such low potentials, the CDI process can be driven by microbial fuel cells or solar energy (Feng *et al.*, 2013). This concern is important for remote and rural areas, particularly in developing countries like Myanmar where energy resources are limited. Therefore, this method is more efficient at lower salt concentrations such as brackish water (Anderson *et al.*, 2010; Welgemoed and Schutte, 2005). In addition, the CDI reactor can be used sustainably through charge and discharge stages. Thus, the electrical energy could be recovered during the desorption stage (Kang *et al.*, 2016). In this regard, the capacitive deionization (CDI) is one of the most energy efficient and promising methods with much potential for treating the ground water of Dala.

The CDI system involves two porous electrodes placed opposite each other with an electrolyte passing between them. The system separates ions from electrolyte based on the deionization-regeneration cycle. The deionization step occurs when a voltage potential is applied across the electrodes causing a buildup of positive charge on the cathode and a negative charge on the anode. Typical operating voltages for CDI processes are around 1.2 V because electrolysis and the breakdown of water occur at 1.23 V (Farmer *et al.*, 1996; Porada *et al.*, 2012; Welgemoed and Schutte, 2005). Consequently, this induced electric field supplies attractive forces on the positive and negative ions toward the anode and cathode, respectively, resulting in desalinated water. CDI electrodes continually adsorb ions until they are fully saturated. The regeneration step occurs as the cell is short-circuited causing the ions to be released into the main stream of water. Such a step results in a highly concentrated waste stream that is collected and disposed of properly. Thus, the electrode is regenerated, and the desalination cycle is repeated continually. A key advantage of salt adsorption by CDI is that the ions are physisorbed onto the electrode surface minimizing electrode fouling and leading to a longer operational life of the electrodes (Laxman *et al.*, 2015).

This paper demonstrates the potential of the CDI technology for efficient removal of salt from brackish water collected from wells in Dala township in the Yangon region of Myanmar. Synthetic brackish water samples were prepared in accordance to the target feed water quality. For the samples, the ion adsorption properties such as the salt adsorption capacity (SAC) and relative selectivity coefficient (RSC) were investigated. Additionally, emphasis was given to the

desalination performance of the CDI system along with the energy consumption for the deionization of brackish water to potable water meeting drinking water standards.

Materials and Methods

1. Desalination experiments with a CDI cell

The synthetic brackish water samples were prepared by considering the major compositions (Na^+ , Ca^{2+} and Mg^{2+}) of the water collected from three different wells in Dala (Smitha *et al.*, 2002). For the synthesis, NaCl , CaCl_2 , and MgCl_2 (Sigma-Aldrich, USA) were used. The desalination experiments were conducted with a laboratory-scale CDI cell. Figure 1 shows a schematic diagram of the CDI system used in this study. The CDI cell was constructed with a pair of carbon composite electrodes, a pair of graphite sheets as a current collector (thickness = 220 μm), and nylon as a spacer (thickness = 200 μm). A pair of carbon composite electrodes were coated with ion-exchange resin (Innochemtech Co., Republic of Korea). The system was operated in a single-pass mode (fresh feed solution continuously went through between the electrodes), and the experiment was done in a temperature chamber (KCL-2000, EYELA, Japan) at 25°C. The feed solution was supplied to the CDI cell at a flow rate of 10 mL/

min. using a peristaltic pump (Gilson, Inc., USA). Constant voltages of 1.2 and 0 V (each for 2 min.) were applied to the CDI cell using a cycler (WBCS3000, WonATech, Republic of Korea) for charging and discharging, respectively. During the operation, the outlet conductivity was continuously monitored using a flow-type conductivity meter (3573–10C, HORIBA, Japan) (Kim and Yoon, 2013). Water samples were collected every 5 sec during the deionization-regeneration period to measure the ion concentrations throughout the process. All experiments were done in triplicate to assess the reproducibility.

2. Analysis of the salt adsorption characteristics

The ion concentrations in the ground water, the treated water (effluent of the charging step) and the concentrated water (effluent of the discharging step) were determined by ion chromatography (Dionex ICS-1100, USA). One of the important characteristics for evaluating CDI performance is the salt adsorption capacity (SAC) of the electrode. The SAC (q), indicating the amount of salt removed, was calculated by integrating the salt concentration over time during the charging time, multiplied by the flow rate of the feed solution and divided by the weight of the pair of electrodes (Kang *et al.*, 2014):

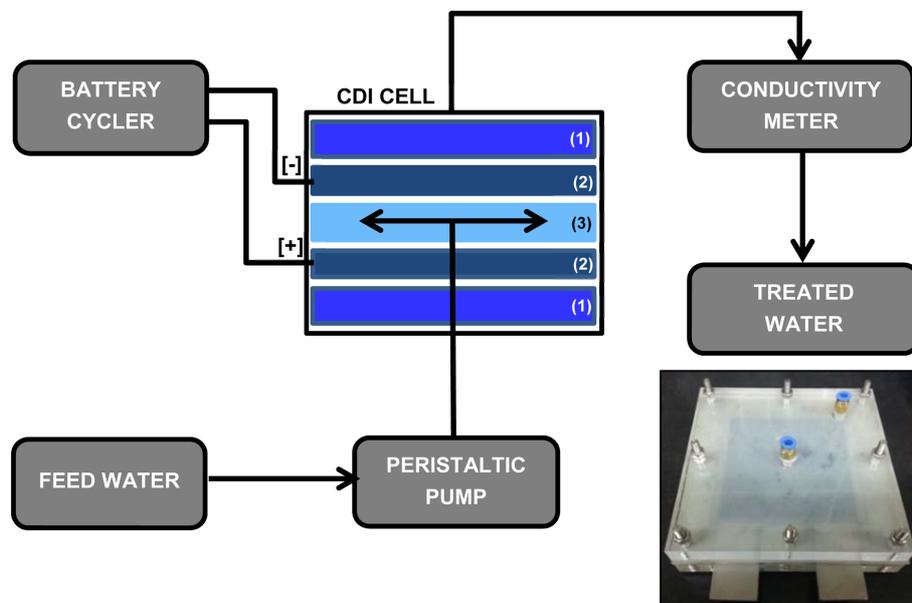


Figure 1. Schematic diagram of the CDI system. The CDI cell consists of (1) a pair of graphite sheets, (2) a pair of electrodes, and (3) nylon as a spacer. A pair of carbon composite electrodes were coated with ion-exchange resin. The photograph shows the CDI cell. The electrode was 10 cm × 10 cm rectangular shape and the flow rate of the feed water was 10 mL/min. The operation time for both deionization step and regeneration step was 2 min.

$$q(\text{mg/g}) = \frac{Q}{M} \int_0^t (C_0 - C) dt \quad (1)$$

, where C_0 and C represent the concentrations (mg/L) at the initial time and any time during the charging; Q is the flow rate of the feed solution (L/min); t is the duration (min) of the deionization stage, and M is the weight of the pair of electrodes (g).

For the performance comparison with different ground water samples and different concentration values, the treated product was expressed as the salt removal efficiency. The overall salt removal efficiency (E) was determined according to the following equation:

$$E(\%) = \frac{1}{C_0 t} \int_0^t (C_0 - C) dt. \quad (2)$$

When multiple coexisting ions are involved in the deionization stage, the competitive salt adsorption behavior can be evaluated by the relative selectivity coefficient (RSC). The RSC was calculated according to the following equation (Fan *et al.*, 2017):

$$\text{RSC} = (q_A/C_A)/(q_B/C_B) \quad (3)$$

, where C_A and C_B indicate the total amount (mg/L) of ions supplied of A and B , respectively, and q_A and q_B indicate the corresponding salt adsorption capacities of A and B .

The energy consumption was calculated based on the values recorded by an automatic battery cyler over the charging (deionization) step.

Results and Discussion

The properties of the ground water samples from the three

Table 1. Properties of ground water samples from three different wells in Dala, Yangon, Myanmar

| Sample | TDS (mg/L) | Na ⁺ (mg/L) | Ca ²⁺ (mg/L) | Mg ²⁺ (mg/L) |
|--------|------------|------------------------|-------------------------|-------------------------|
| Well 1 | 1120 | 412 | 9.2 | 4.4 |
| Well 2 | 2130 | 764 | 43.3 | 20.6 |
| Well 3 | 3280 | 1518 | 75.1 | 50.2 |

different wells in Dala are listed in Table 1. The TDSs of the ground water samples were 1120, 2130, and 3280 mg/L which were much higher than the standard concentration of drinking water. The most concentrated cation in the ground water samples was sodium (Na⁺, 412, 764 and 1518 mg/L), and the other participating cations were calcium (Ca²⁺, 9.2, 43.3 and 75.1 mg/L) and magnesium (Mg²⁺, 4.4, 20.6 and 50.2 mg/L). Heavy metals were not detected in the ground water samples.

1. Desalination performance of the CDI system

The variations in the conductivity of the water samples from the three wells had a similar trend in the CDI processes. Figure 2 shows the desalination performance of the CDI cell for the treatment of ground water (well 2). It shows the variations in the conductivity which exhibited a typical deionization and regeneration behavior. During the deionization step, charged ions were driven by the electric field forces. Therefore, the ions were transferred from the solution to the inner surface of the oppositely charged electrode. The ions were stored in the electric double-layer (EDL) on the electrode/solution interfaces. Therefore, the conductivity sharply decreased from the initial value (3.98 mS/cm) to a lower value (1.28 mS/cm). Afterward, the electrodes became saturated after charging for 120 sec, and the conductivity returned to the initial value.

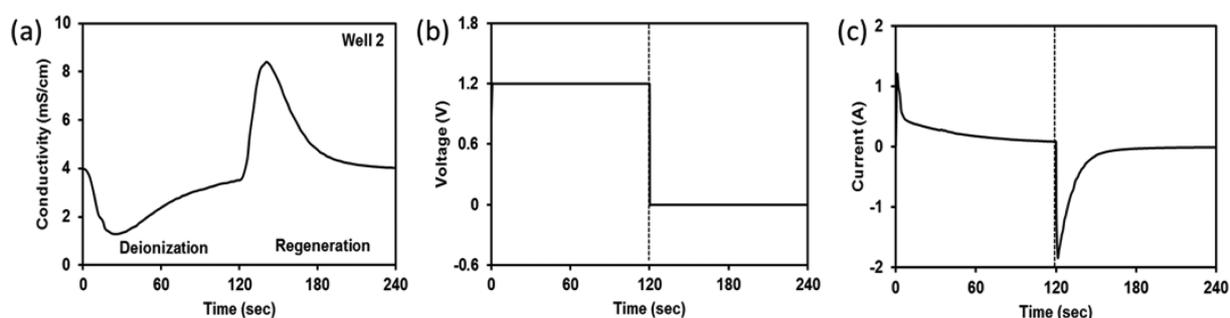


Figure 2. Variations of conductivity (a), voltage (b) and current (c) during deionization and regeneration of CDI process of well 2. The conductivity of effluent was continuously recorded and plotted over time (1.2 V applied in the deionization step and 0 V applied in the regeneration step).

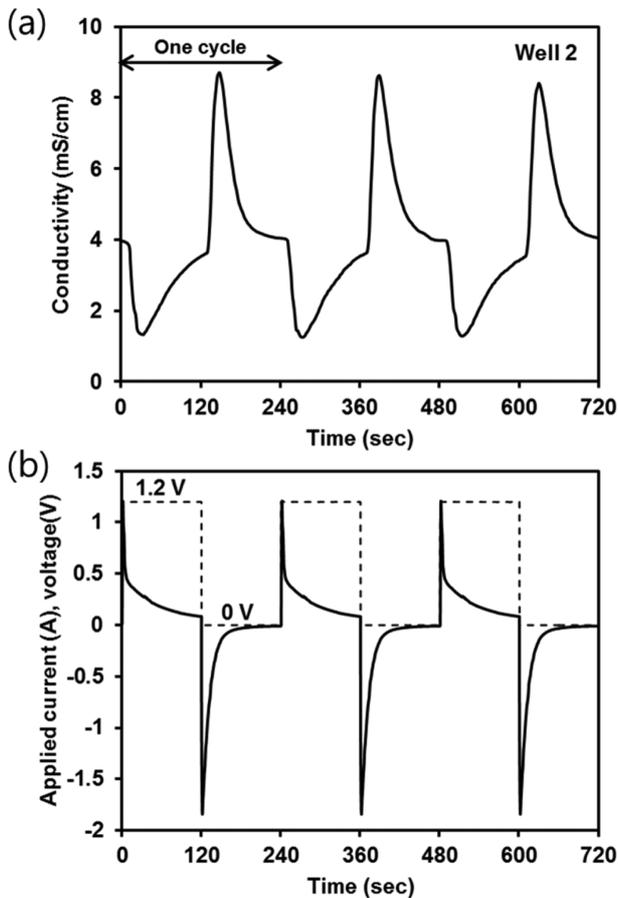


Figure 3. Repeated deionization/regeneration cycles of the CDI process (well 2). The graph suggests the good reproducibility of CDI system. The operation was carried out for 720 sec; 1.2 V for 120 sec (deionization step) and 0 V for 120 sec (regeneration step) and repeated for three times.

Such phenomena indicated that the system reached a pseudo-equilibrium state for deionization in which the ion transport rate became zero (Porada *et al.*, 2012). The system was switched to the regeneration step by applying a potential of 0 V. During this regeneration step, the electric field disappeared, and the stored ions were released from the EDLs into the solution. Initially, the conductivity sharply increased and returned to the initial value suggesting that the electrodes

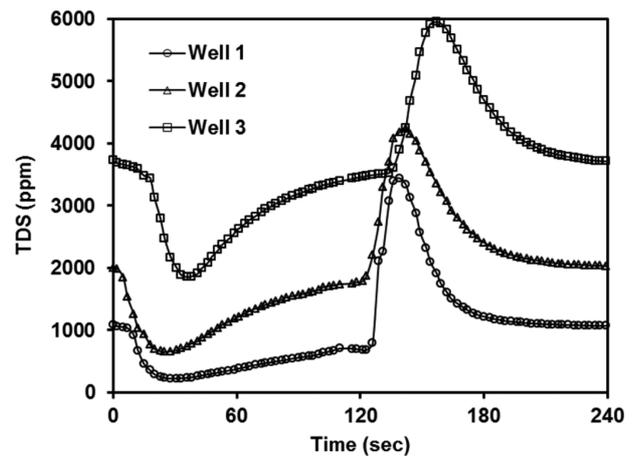


Figure 4. Variations of total dissolved solid (TDS) in CDI process for the water of Dala, Yangon, Myanmar

regenerated completely in 120 sec.

As a repeatability test of the CDI system, continuous deionization-regeneration cycles were performed shown in Figure 3. The electrodes exhibited a good reproducibility which is a critical requirement for the CDI operation. Figure 4 shows the variations in the TDSs for the water samples during the deionization and regeneration steps. As shown in Figure 4 and Table 2, for the water from well 1 with an input TDS of 1120 mg/L, a minimum TDS of 216 mg/L was achieved with an overall salt removal efficiency of 57%. Furthermore, the salt removal ratio decreased as the input TDS increased. For the water from well 2 with an input TDS of 2130 mg/L and a minimum TDS of 648 mg/L, an overall salt removal efficiency of 36% was achieved. For the water from well 3 with the highest input TDS of 3280 mg/L, a minimum TDS of 1843 mg/L was achieved with the lowest overall salt removal efficiency of 26%. Furthermore, the TDS of the effluent after the regeneration cycle was also monitored for each cycle. The additional salt content released after the regeneration matched the amount of salt adsorbed on the electrodes during deionization.

The performance of the CDI system was evaluated by the

Table 2. Overall salt removal efficiency and SAC of CDI system for the water of Dala, Yangon, Myanmar

| Sample | Initial TDS (mg/L) | Minimum TDS (mg/L) | Salt adsorption capacity (mg/g) | Overall salt removal efficiency (%) |
|--------|--------------------|--------------------|---------------------------------|-------------------------------------|
| Well 1 | 1120 | 216 | 7.9 | 57 |
| Well 2 | 2130 | 648 | 9.7 | 36 |
| Well 3 | 3280 | 1843 | 10.7 | 26 |

SAC of the electrodes for the three ground water samples. It was found that the salt adsorption capacities increased as the initial TDS in the ground water increased. Table 2 shows that the increase in the input TDS induced an increase in the SAC of 7.9, 9.7, and 10.7 mg/g for well 1, 2, and 3, respectively. As the amount of salt ions adsorbed onto the adsorbent increases, the exchangeable sites on the adsorbent structure become saturated. This causes a decrease in the salt removal efficiency while the salt adsorption capacities increase with the increase in the concentration due to the elevated mass transfer rate of the salt ions inside the pores (Ahmad *et al.*, 2016).

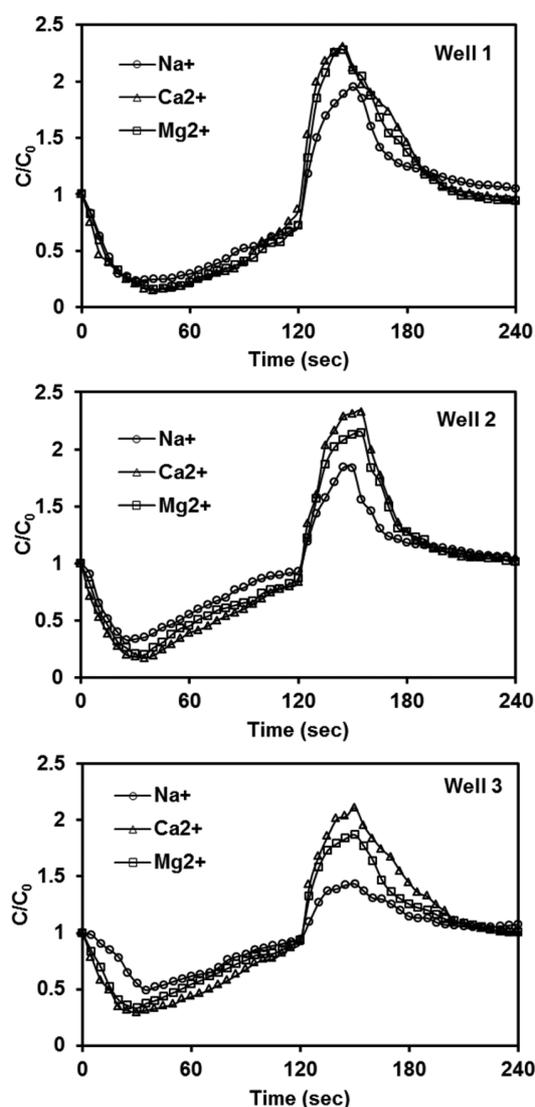


Figure 5. Variations of cation concentration of the effluent in the CDI process for the ground water from three wells of Dala, Yangon, Myanmar

2. Electrosorption of ions in the CDI process

Figure 5 shows the variation in the cation concentration during the deionization and regeneration cycle. As shown in the figure, all cation concentrations were greatly reduced during the early period of the deionization stage. The concentrations of monovalent cations such as Na^+ reached their lowest point after charging for 25 to 35 sec; subsequently, the concentrations increased. This phenomenon may indicate that most of the electrode surface was occupied by charged ions. Simultaneously, the SAC of the electrodes gradually reached saturated conditions. However, the concentration of bivalent cations such as Ca^{2+} and Mg^{2+} decreased continuously for the first 35 to 45 sec of charging. This feature is in accordance with the results obtained in a previous study (Fan *et al.*, 2017).

This result can be attributed to the replacement of monovalent cations by bivalent cations on the electrode surface. The replacement behavior can be explained by the strong competition of the higher valence bivalent cations for the electrode surface over the lower valence monovalent cations (Seo *et al.*, 2010). Therefore, Figure 6 shows that the overall salt removal efficiency of the bivalent cations (61% and 58% for Ca^{2+} and Mg^{2+} , respectively) was higher than that of the monovalent cation (56% for Na^+) for water from well 1. Similarly, the overall salt removal efficiency for Ca^{2+} and Mg^{2+} were 52% and 47% and that for Na^+ was 36% for the water from well 2. The same trends were observed for the water from well 3 with 45% and 38% for Ca^{2+} and Mg^{2+} and 26% for Na^+ .

Accordingly, monovalent cations are easier to transport to

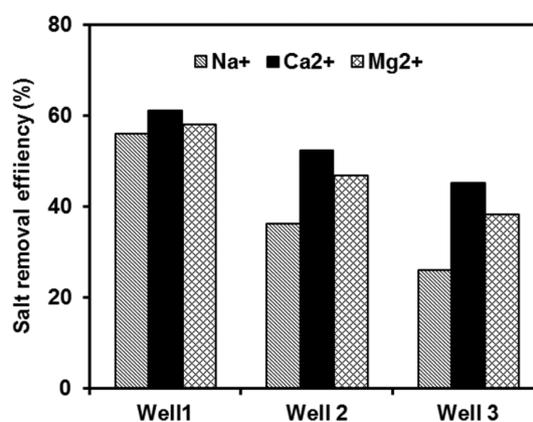


Figure 6. Overall salt removal efficiency of CDI system for cations in the ground water of Dala, Yangon, Myanmar

Table 3. Cation concentrations and salt adsorption characteristics of CDI process for the water of Dala, Yangon, Myanmar

| Sample | Ion type | Cation concentrations (mg/L) | | | Salt adsorption capacity (mg/g) | Relative selectivity coefficient |
|--------|------------------|------------------------------|----------------|-------------------------|---------------------------------|----------------------------------|
| | | Feed water | Treated Water* | Concentrated Effluent** | | |
| Well 1 | Na ⁺ | 412 | 96.3 | 803 | 2.88 | 1.0 |
| | Ca ²⁺ | 9.2 | 1.4 | 21.3 | 0.07 | 1.1 |
| | Mg ²⁺ | 4.4 | 0.7 | 10.0 | 0.03 | 1.1 |
| Well 2 | Na ⁺ | 764 | 251 | 1406 | 3.45 | 1.0 |
| | Ca ²⁺ | 43.3 | 7.4 | 101 | 0.28 | 1.5 |
| | Mg ²⁺ | 20.6 | 4.0 | 44.2 | 0.12 | 1.3 |
| Well 3 | Na ⁺ | 1518 | 747 | 2176 | 4.94 | 1.0 |
| | Ca ²⁺ | 75.1 | 21.8 | 158 | 0.42 | 1.7 |
| | Mg ²⁺ | 50.2 | 16.7 | 93.8 | 0.24 | 1.5 |

*The minimum concentration during charging step. **The maximum concentration during discharging step.

the electrode surface. For this reason, the monovalent cations screen the electrode surface first. Subsequently, when the bivalent cations are transported to the electrode surface, some of the electro-adsorbed monovalent cations are replaced by the bivalent cations due to their higher valence charge (Yoon *et al.*, 2016). Overall, the difference in the concentration variations of the cations is attributed to the different pore accessibility and the valence replacement phenomenon.

The cation concentrations of the feed ground water, treated water (effluent of the charging step), and the concentrated water (effluent of the discharging step) in the CDI process are listed in Table 3. The feed Na⁺ ion concentrations of 412, 764, and 1518 mg/L became 96.3, 251, and 747 mg/L, respectively, after the CDI treatment of the three water samples. Similarly, the feed Ca²⁺ ion concentrations of 9.2, 43.3, and 75.1 mg/L became 1.4, 7.4, and 21.8 mg/L while the feed Mg²⁺ ion concentrations of 4.4, 20.6 and 50.2 mg/L became 0.7, 4.0, and 16.7 mg/L, respectively, after the CDI treatment of the three water samples. It was found that the cation concentrations in the concentrated effluent matched the ion content removed during the deionization.

The SAC of the activated carbon electrodes in the CDI system can be determined by the initial molar concentration, ionic charge, and hydrated ionic radius (Hou and Huang, 2013). In this study, the salt adsorption capacities were strongly dependent on the initial cation concentration. As shown in Table 3, the salt adsorption capacities increased as the initial ion concentrations in the ground water increased. This is consistent with the literature explaining the decrease

of the SAC by the overlapping of the EDL in the micropores (Zhao *et al.*, 2013). According to the literature, the lower the cation concentration of the water is, the thicker the EDL is resulting in a decrease in the effective specific surface area. On the other hand, ions with higher concentrations in the ground water had a higher driving force to be transported from the solution to the pore structure. As a result, the CDI electrode has a good SAC for Na⁺ (2.9, 3.5 and 4.9 mg/g) due to its high concentrations.

3. Water recovery and energy consumption

In this study, deionization and regeneration were conducted alternatively for 2 min each, and the water recovery for the CDI system was 50%. A complete cycle of operation in 4 min with a flow rate of 10 mL/min produced 20 mL desalinated water, and a total time of 200 min resulted in a one-liter output. Extrapolating the water recovery from the laboratory scale to a pilot scale by setting up a CDI module with 400 pairs of electrodes, the water recovery can be extended to 400 L in 200 min. Accordingly, one CDI module can treat 1 m³ of desalinated water in 8.3 h. However, 120 CDI modules will be required to meet the target amount of treated water (346 tons) which is calculated based on the population of Dala (172,857 in 2014, MIP, 2015) and the assumption that each person drinks 2 liters per day.

Table 4 presents the energy consumption for the treatment of ground water. Water from well 1 with an initial conductivity of 2.11 mS/cm was desalinated 57% using 0.35 kWh/m³. The energy consumption was 0.45 and 0.52 kWh/m³ for the treat-

Table 4. Energy consumption for the treatment of ground water from Dala by CDI process

| Sample | Initial conductivity (mS/cm) | Overall salt removal efficiency (%) | Energy consumption for one cycle of operation (Wh) | Energy consumption for one ton of treated water (kWh/m ³) |
|--------|------------------------------|-------------------------------------|--|---|
| Well 1 | 2.1 | 57 | 7.0×10^{-3} | 0.35 |
| Well 2 | 4.0 | 36 | 9.1×10^{-3} | 0.45 |
| Well 3 | 7.4 | 26 | 10.5×10^{-3} | 0.52 |

ment of water from well 2 and 3 whose initial conductivity values were 3.98 and 7.42 mS/cm. These results were in accordance with the results obtained in the literature (Choi *et al.*, 2016). As the conductivity of the input water sample increased, the energy consumption also increased. It shows that the energy consumption is directly related to the ionic strength of the solution being desalinated.

Conclusions

A single-pass-mode capacitive deionization (CDI) cell produced potable water within the acceptable range of drinking water standards from the brackish ground water of Dala, Yangon, Myanmar, and the process was energy efficient. The CDI system reduced the TDS of the water from two of the wells from 1120 and 2130 mg/L to 216 and 648 mg/L using only 0.35 and 0.45 kWh/m³. Although the CDI system reduced the TDS value of the water from a third well from 3280 mg/L to 1843 mg/L, it is not within the acceptable limit of drinking water standards. Therefore, using a one-cell CDI system, water with a TDS up to 2000 mg/L can be desalinated into potable water. However, water with a higher TDS should be treated with a two-cell CDI system to meet the standards. From the analysis of the salt adsorption selectivity, the preference for cation removal could be listed in the order of $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+$. Moreover, it was also observed that monovalent cations can be replaced by divalent cations at the electrode surface in the later period of the deionization stage. Brackish water desalination by CDI technology in Dala is economically feasible and a sustainable solution for the water scarcity problem. The results show that the energy requirement for the desalination of brackish water by CDI technology is much lower than the energy required for treating water with an equivalent TDS by other means. The efficient removal of ions, non-dependence on chemicals, easy regeneration of electrodes, eco-friendliness, and low energy consumption make

CDI a suitable technology for brackish water desalination in Dala, Yangon, Myanmar.

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