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# Optimizing Operational Conditions of Pilot-Scale Membrane Capacitive Deionization System

**Bokjin Lee [1], Changseog Oh [1,2], Jusuk An [1,3], Seungjae Yeon [1] and Hyun Je Oh [1,2,*]**

1 Department of Environmental Research, Korea Institute of Civil Engineering and Building Technology (KICT), Goyang 10223, Republic of Korea; bokjinlee@kict.re.kr (B.L.); csoh@kict.re.kr (C.O.); jusuk@kict.re.kr (J.A.); yeon@kict.re.kr (S.Y.)
2 Department of Civil and Environmental Engineering, University of Science and Technology (UST), Daejeon 34113, Republic of Korea
3 Department of Civil and Environmental Engineering, Yonsei University, Seoul 03722, Republic of Korea
* Correspondence: hjoh@kict.re.kr

**Abstract:** In this study, we developed a pilot-scale membrane capacitive deionization (MCDI) system for treating mildly brackish water and examined various operational parameters, including module arrangements, adsorption/desorption times, and flow rates. As we aimed to optimize these parameters to increase total dissolved solids (TDS) removal efficiency, the results revealed that the dual-series mode module arrangement and an adsorption time of 120 s with a flow rate of 10 L/min achieved the highest TDS removal efficiency of 99%. Energy consumption analysis showed that lower flow rates were associated with higher TDS removal efficiencies, highlighting the balance between energy consumption and water quality. This study provides insights into optimizing a pilot-scale MCDI for efficient water supply solutions, offering promise for sustainable and eco-friendly water treatment.

**Keywords:** membrane capacitive deionization; total dissolved solids removal; water treatment; energy efficiency

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**Citation:** Lee, B.; Oh, C.; An, J.; Yeon, S.; Oh, H.J. Optimizing Operational Conditions of Pilot-Scale Membrane Capacitive Deionization System. *Sustainability* **2023**, *15*, 16809. https://doi.org/10.3390/su152416809

Academic Editors: Bhaskar Jyoti Deka, Jehad A. Kharraz and Noman Khalid Khanzada

Received: 29 October 2023
Revised: 11 December 2023
Accepted: 12 December 2023
Published: 13 December 2023

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## 1. Introduction

Clean water supply has been considered a top priority from the past to the present [1]. Owing to climate change and various water quality pollution issues, the demand for the treatment and utilization of seawater (35,000 mg/L of total dissolved solids (TDS)) or brackish water (TDS at 1000–10,000 mg/L) is increasing in areas where freshwater supply is difficult [2–4]. Capacitive deionization (CDI) has attracted significant attention because of its low energy consumption and effective removal of salts from raw water [5–7]. CDI operates at reduced voltages and consumes less energy, making it more energy efficient than traditional desalination methods [8]. This characteristic aligns with the global emphasis on sustainable and eco-friendly technologies. Among the various CDI technologies, such as flow CDI and hybrid CDI, the TDS removal efficiency of membrane capacitive deionization (MCDI), which incorporates ionic exchange membranes, has significantly increased [9,10].

Integrating ion exchange membranes into MCDI systems effectively minimizes the risk of ion rebound, ensuring consistent water quality and enhancing desalination performance [11]. Effective application methods for MCDI include treating saline water to produce potable water for daily use, agricultural irrigation, and drinking in resource-scarce regions. For example, coastal regions with limited freshwater sources can utilize MCDI to convert nearby saline or brackish water into water suitable for crop irrigation [12]. Despite the evident need for real-world applications of the MCDI technology, most studies have been confined to the laboratory scale. Although these laboratory-scale experiments provide valuable insights, they may not directly translate into practical scenarios. To understand and optimize the benefits of MCDI for the abovementioned purposes, conducting research at pilot or operational scales is imperative.

Several key parameters can significantly influence the performance and outcomes of an MCDI system. These include the number and arrangement of the MCDI modules, which can determine the system's overall processing capacity and configuration [13,14]. Additionally, the characteristics of the influent water, such as its total dissolved solids (TDS) concentration and the nature of the ionic species present, play a critical role in determining ion removal efficiency [15]. Flow rates, which represent the volume of water passing through the electrodes per unit time, are directly related to the hydraulic loading of the system, along with the specific times allocated for the adsorption and desorption processes, further modulating the system's ion removal efficiency and energy consumption [16,17]. For MCDI operation, the adsorption and desorption times play a critical role, as the time regulates the attraction of ions to the electrodes and their discharge, which is deeply related to the desalination efficiency.

The TDS removal efficiency is fundamentally associated with the surface area of the electrodes, which facilitates ion adsorption [18]. Therefore, an increase in the number of electrodes can lead to the removal of a greater quantity of ions. Moreover, even with an identical number of electrodes, the TDS concentration of the treated water can differ depending on whether the modules are arranged in parallel or series.

In this study, we developed an MCDI system at the pilot scale to desalinate larger volumes of water than conventional laboratory-scale systems. We aimed to compare the TDS removal efficiencies based on different module configurations within a pilot-scale MCDI system. To determine the optimal operational conditions for the developed system targeted to treat mildly brackish water, we examined the TDS removal efficiency based on (1) the system configuration of the arrangement of MCDI modules and (2) the operating conditions, such as variations in adsorption/desorption time and flow rates. Furthermore, the energy consumption per unit volume of treated water under these experimental conditions was analyzed to enhance the real-world applicability of the MCDI system, paving the way for its broader application in water supplies.

## 2. Materials and Methods

### *2.1. MCDI Modules*

The MCDI modules were purchased from S Company (Seoul, Republic of Korea). Each module consisted of 250 porous bipolar carbon electrodes, and each electrode was placed between an anion exchange membrane and a cation exchange membrane (Figure 1). Nylon net spacers with a thickness of 180 μm were placed between adjacent anion and cation exchange membranes, allowing water to pass through the ionic exchange membranes and electrodes. The diameter of the electrodes, ionic exchange membranes, and spacers was 20 cm.

### *2.2. Experimental Setup*

A pilot-scale MCDI operating system was developed, as shown in Figure 2. The system consisted of four pre-filters (microfilter 1 μm, Toray, Chou, Japan) to remove particulate matter and a compartment for MCDI modules to place them up to 2 × 2 arrays. A DC power supply capable of supplying a constant voltage of 300 V was used to apply a voltage of 1.2 V to the individual cells to prevent the hydrolysis of each module comprising 250 cells. The system was equipped with a power meter, and all of the power used in the system components, including the voltage applied to the MCDI modules, was automatically logged. The capacity of the feedwater tank was 630 L, and a peripheral pump (HBI 4-30, Stairs, Taiwan) was used to stream the feed water into the system at different target flow rates. The solenoid valves were positioned at each line to discharge MCDI-treated water during adsorption and concentrated water during desorption processes, and a PLC controlled the valves. During the experiments, flowmeters (FD-Q32C, Keyence, Osaka, Japan) and TDS meters (3-2822-1 electrode, GF Signet, Irwindale, CA, USA) were placed at the inlet of the feed water and the outlet pipe after the MCDI modules. These instruments were used to measure the corresponding parameters automatically at one-second intervals.

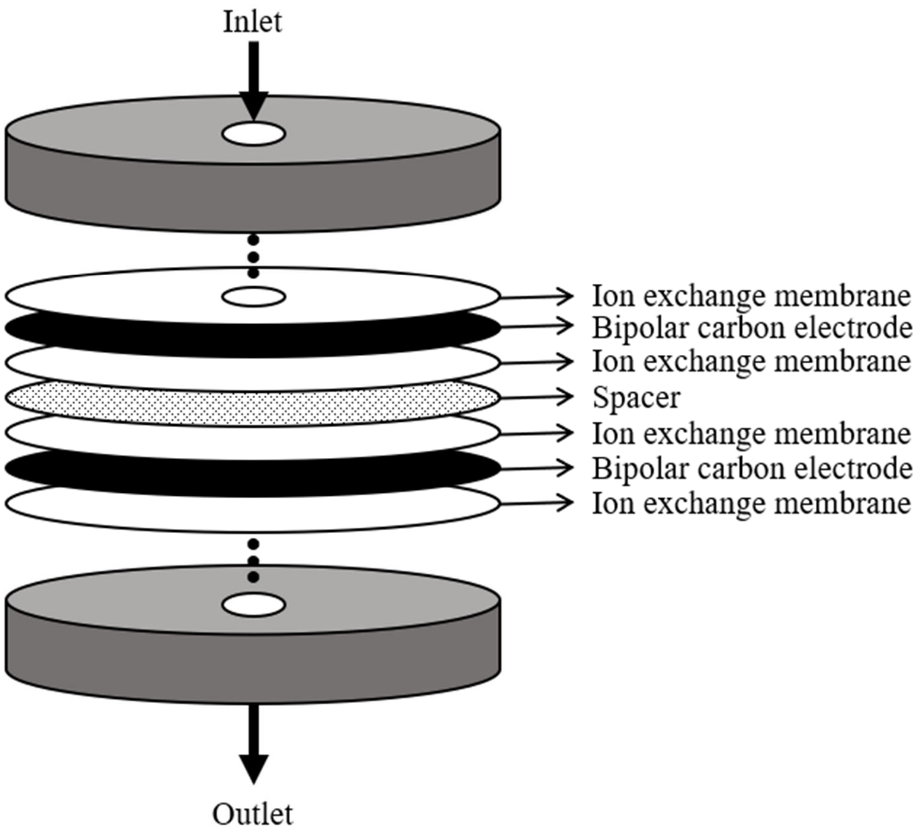


**Figure 1.** Configuration of the MCDI module.

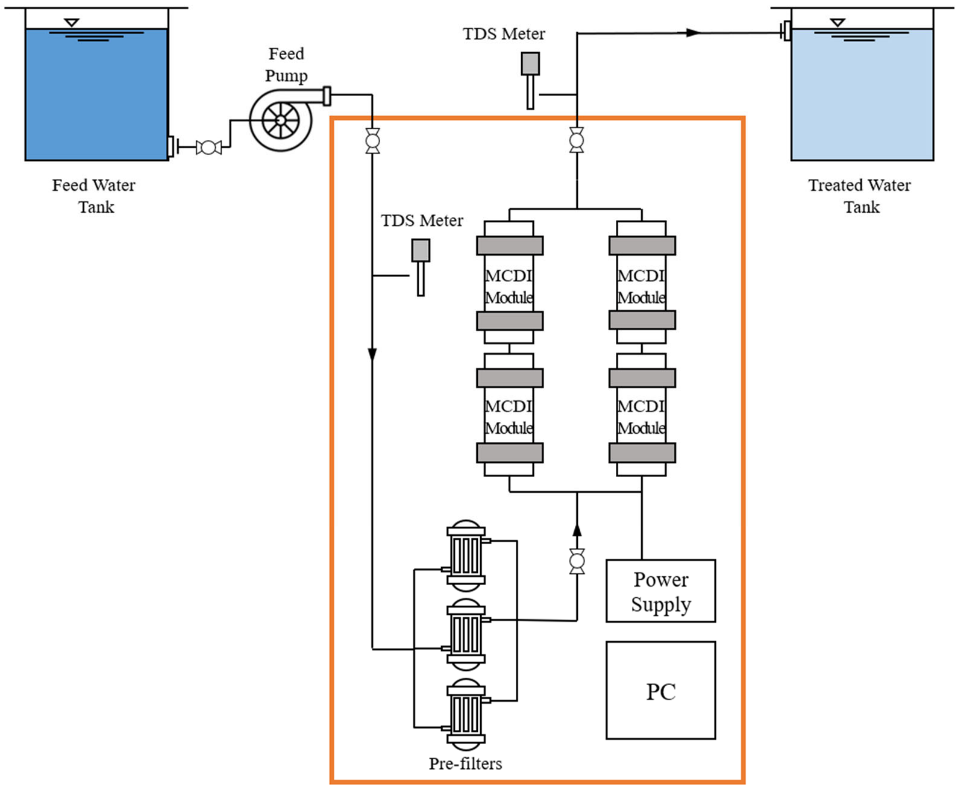


**Figure 2.** Schematic diagram of the pilot-scale MCDI system.

*2.3. TDS Removal Efficiency Test according to Different MCDI Operational Conditions*

The TDS of the feed water was set to 1000 mg/L to reflect the system's performance in the treatment of mildly brackish water and to optimize the operational conditions of the pilot-scale MCDI system. The target concentration was prepared by adding sodium chloride (99.5%, Samchun, Pyeongtaek, Republic of Korea) to the tap water. The same feed water was used for all of the experiments conducted in this study (Table 1).

**Table 1.** Summary of experimental conditions.

| No. | Flow Rate | Adsorption and Desorption Time (s) | Module Arrangement |
|---|---|---|---|
| 1 | 10 L/min | 300 | Single mode |
| 2 | 10 L/min | 300 | Dual (Series) |
| 3 | 20 L/min | 300 | Dual (Parallel) |
| 4 | 15 L/min | 300 | Dual (Series) |
| 5 | 20 L/min | 300 | Dual (Series) |
| 6 | 10 L/min | 120 | Dual (Series) |
| 7 | 15 L/min | 120 | Dual (Series) |
| 8 | 20 L/min | 120 | Dual (Series) |
| 9 | 25 L/min | 120 | Dual (Series) |

Three arrays were tested for the module arrangements: single mode, dual parallel, and dual series. Even though the MCDI system could array 2 × 2 modules, it was excluded because the version of the system at the time of the experiments encountered operational limitations while operating in such an arrangement, which was attributed to momentarily elevated current levels induced by the rapid release of highly concentrated ions during the desorption process.

During adsorption, the top and bottom of the MCDI modules were connected to positive and negative charges, respectively, allowing the upper and lower halves of the electrodes to be given either charge or ions in the feed water, with the opposite charge attracted to the electrodes. When the charge was switched during desorption, the attracted ions were released, and the TDS concentration of the feed water increased. The TDS removal efficiency was calculated using the following equation:

$$\text{Removal efficiency}(\%) = \frac{C_0 - C_A}{C_0} \times 100 \quad (1)$$

where $C_0$ is the TDS concentration of the feed water and $C_A$ is the TDS concentration of the MCDI-treated water during adsorption.

The adsorption/desorption times were controlled under two conditions: 120 and 300 s. Flow rates of 10, 15 L/min, 17.5 L/min, 20, and 25 L/min were used. A summary of the experiments based on these operating conditions is presented in Table 1.

## 3. Results and Discussion

*3.1. Performance of MCDI with Different Module Arrangements*

The same feed water with a TDS of 1000 mg/L was used under the same operational conditions of a flow rate of 10 L/min per module and an adsorption/desorption time of 300 s to compare the TDS removal efficiencies of different module arrangements: single mode, dual-series mode, and dual-parallel mode. A consistent trend of decreasing TDS concentrations during the adsorption process and rapid increases during the desorption process were observed for all three module arrangements (Figure 3a). The initial TDS concentration of 1000 mg/L decreased to 167 mg/L, 121 mg/L, and 13 mg/L after 40 s of adsorption, which were the lowest concentrations for the single mode, dual-parallel mode, and dual-series mode, respectively. In other words, the TDS removal efficiencies were highest after 40 s of adsorption, with values of 83%, 88%, and 99% for the single mode, dual-parallel mode, and dual-series mode systems, respectively (Figure 3b). At the last point of the adsorption process, that is, 300 s, the TDS concentration and removal efficiency were 778 mg/L and 22% for single mode, 717 mg/L and 28% for dual-parallel mode, and 289 mg/L and 71% for dual-series mode adsorption, respectively.

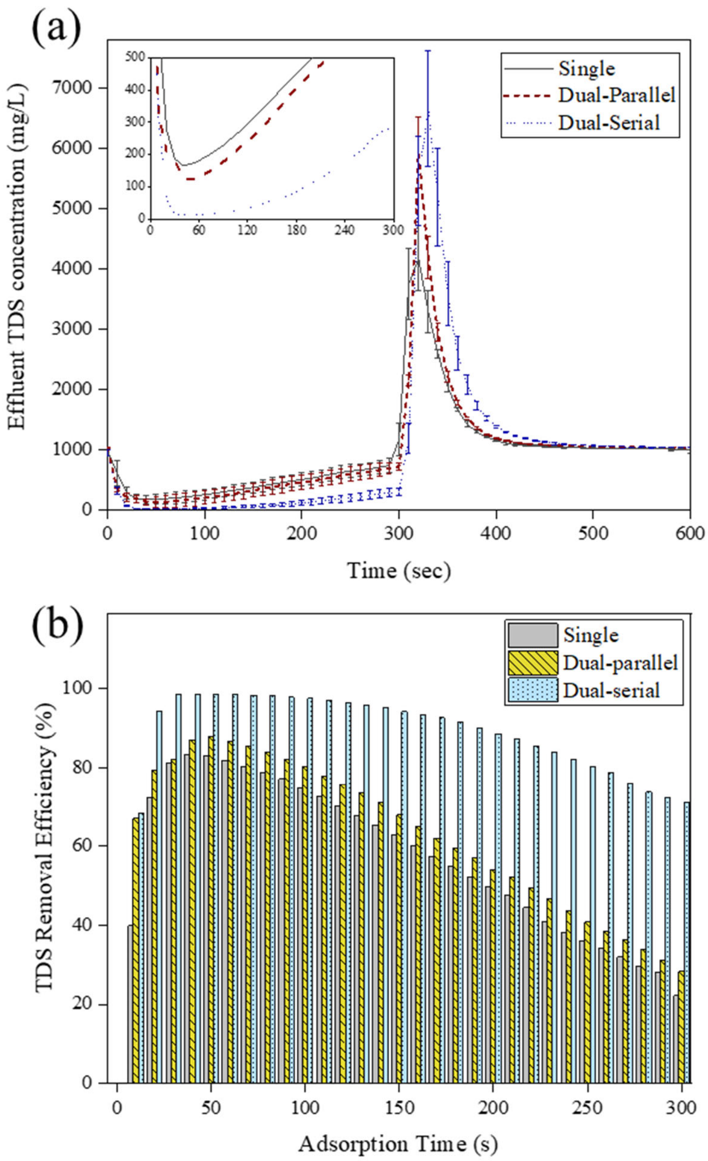


**Figure 3.** Variations in (**a**) TDS concentration and (**b**) TDS removal efficiency during adsorption time according to MCDI module arrangements under the operation condition of 300 s of adsorption/desorption time and flow rates of 10 L/min, 20 L/min, and 10 L/min for single mode, dual-parallel mode, and dual-series mode, respectively.

Because the flow rates were set at 10 and 20 L/min for the single mode and dual-parallel modes, respectively, each module processed 10 L/min. Hence, both arrangements' TDS concentrations and removal rates exhibited similar trends. The dual-series mode exhibited a significantly improved TDS removal efficiency at a flow rate of 10 L/min, implying that the two modules were utilized to treat feed water with the same concentration as the other two arrangements.

During the desorption process, that is, after 300 s, the desorption phase was evident in all configurations characterized by a sharp increase in effluent TDS concentrations, and the highest peaks reached up to 4570, 6395, and 7330 mg/L for the single mode, dual-parallel mode, and dual-series mode configurations, respectively (Figure 3a). The single mode showed a controlled and moderate increase, whereas the dual-parallel mode displayed a more abrupt spike, eventually aligning with the single mode TDS concentrations in the effluent water. The dual-series mode showed a distinct trend, where, though there was a rapid surge in the TDS concentration initially, it managed to stabilize at the lowest level among the three, signifying its superior desorption control and efficient ion-release mechanism. The series arrangement was potentially effective in mitigating ion rebound during desorption. Furthermore, the results highlight the critical influence of the MCDI module configuration on TDS removal efficiency.

Parallel configurations offered an increased surface area for simultaneous separations, ensuring uniform permeate quality [19]. In contrast, series configurations minimized concentration polarization and enhanced cumulative separation. Choosing between these setups can significantly affect performance and operational costs, necessitating careful consideration based on specific needs. However, because most previous MCDI studies were conducted at the laboratory scale, the cell or module arrangements were not subject to the operation parameters. Understanding the implications of the MCDI module arrangement is essential not only for optimizing the efficiency of TDS removal but also for the scalability of the MCDI system. As research continues to bridge the gap between laboratory-scale studies and real-world applications, a strategic configuration of MCDI systems will become instrumental in ensuring their widespread adaptability.

### *3.2. Determination of Optimum Adsorption/Desorption Time and Flow Rate in the Operational-Scale MCDI Operation*

A series of experiments with variations in the adsorption duration and flow rate were conducted to determine the optimal operational parameters for the dual-series mode, demonstrating the highest total dissolved solids (TDS) removal efficiency in the module arrangement experiment. In the module arrangement experiment, an adsorption/desorption time of 300 s was provided to allow an adequate reaction time for each process.

At a desorption time of 300 s, the initial effluent TDS concentrations were the lowest at 13 mg/L for 10 L/min at 40 s, 15 L/min at 30 s, and 24 mg/L at 20 L/min at 20 s. Correspondingly, they showed the highest removal efficiencies of 99%, 99%, and 97%, respectively (Figure 4). As the adsorption progressed, the effluent TDS concentrations continually increased, culminating in 71%, 35%, and 23% removal efficiencies at 10, 15, and 20 L/min, respectively, at 300 s. This decline in efficiency with increasing flow rate suggests that the electrodes were near saturation. The superior efficiency observed at lower flow rates is consistent with the results of previous studies [20]. Notably, while most prior studies utilized a limited number of electrodes and operated under low-flow conditions of less than 100 mL/min, reflecting lab-scale tests, the present study was conducted at a pilot scale using at least 250 electrodes, that is, one MCDI module and flow rates exceeding the former by more than 100 times. Such discrepancies in scale may contribute to variations in MCDI system performance owing to scale-up effects.

During desorption, the effluent TDS concentration increased sharply, reaching peak values of 7, 330, 9005, and 7060 mg/L at flow rates of 10, 15, and 20 L/min, respectively. At 10 L/min, there was a 10 s delay in ion desorption compared to 15 and 20 L/min, yet all flow rates displayed a trend approaching the feed water TDS concentration of 1000 mg/L by 120 s, 420 s into the process. If an adequate desorption time is not provided, chemical reactions such as electrode reactions and electrolysis can occur on the electrode surface [15]. Therefore, to prevent such issues, it is imperative to allocate sufficient desorption time until the effluent TDS concentration decreases to that of the feedwater.

However, the effluent TDS concentration reaching the feed water during desorption implies the discharge of ions adsorbed on the electrodes [21]. Consequently, the MCDI system reached its maximum ion removal capacity, and further desorption did not lead to additional deionization. Continuing the desorption process after that stage can lead to unnecessary energy consumption and reduced efficiency as the system continues to operate without providing any further benefits regarding ion removal. To optimize the efficiency of the MCDI process and ensure energy conservation, it is critical to continually monitor the effluent concentration and make appropriate adjustments to the operation of the MCDI system.

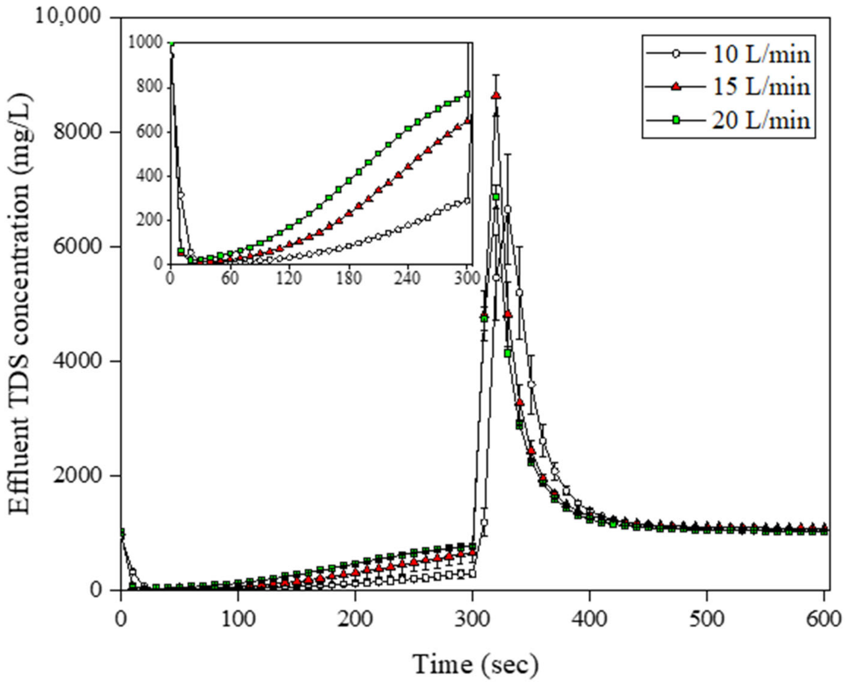


**Figure 4.** Variations in effluent TDS concentrations according to different flow rate conditions of pilot-scale MCDI system operation with 300 s adsorption/desorption time under dual-series mode module arrangement.

The effluent TDS concentration at the adsorption/desorption time of 120 s was lower than that at 300 s, suggesting reduced ion saturation within the electrodes (Figure 5). Observing the variations due to flow rate differences, similar to the 300 s operation, the lower the flow rate, the better the TDS removal efficiency. The results at 10 L/min were the most optimal among the four flow rate conditions, achieving a TDS removal rate of 99% with a concentration of 11 mg/L in just 20 s of the adsorption process and maintaining a high efficiency of 96% at a concentration of 39 mg/L by the end of the adsorption period at 120 s. At the same adsorption end time, the 15 and 20 L/min removal efficiencies were 88% and 84%, respectively. However, at 25 L/min, the efficiency, 76% at 110 s, dropped dramatically to 35% by the end of adsorption, indicating a significant reduction in efficiency during the latter part of the adsorption phase.

In the initial stages of the desorption process, the maximum effluent TDS concentration peak reached a level of 5000 mg/L, with all flow rates exhibiting similar values. At the 140 s mark, 20 s into desorption, the effluent TDS concentrations at flow rates of 10, 15, 20, and 25 L/min were 4870, 3882, 4387, and 2942 mg/L, respectively. In contrast to the adsorption trend, the lowest value was observed at 25 L/min. However, at the termination point of desorption (240 s), the values converged to the feed water TDS concentration, regardless of the flow rate.

A higher flow rate can decrease the contact time between the ions and the electrode surface, reducing adsorption efficiency primarily because of the limited time for ions to migrate and adsorb onto the electrode surfaces [22]. Furthermore, higher flow rates can affect the overall hydrodynamics of the MCDI system, potentially leading to reduced mass transfer rates and increased competition between ions for available adsorption sites. As a result, the overall ion removal efficiency may decrease under high flow rate conditions.

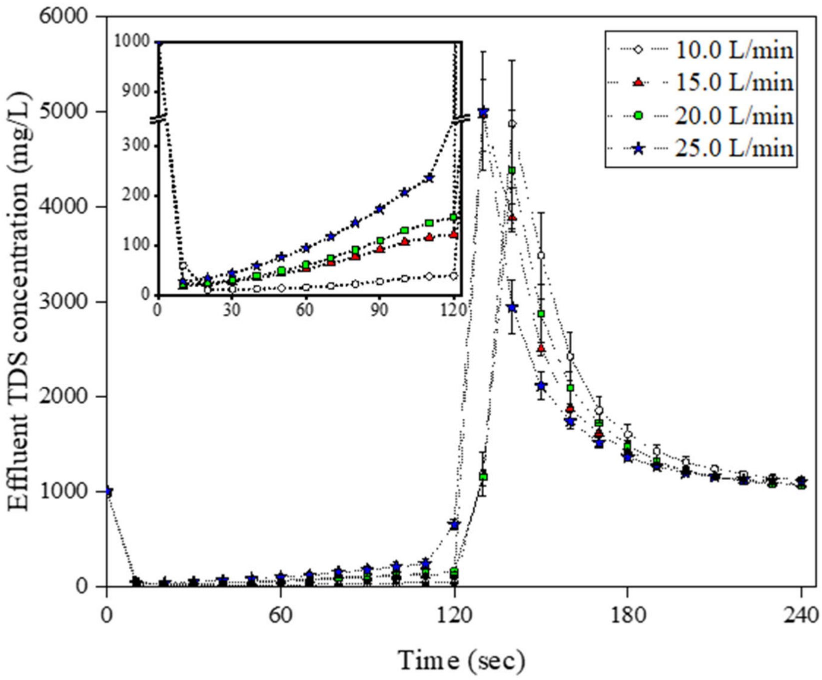


**Figure 5.** Variations in TDS concentrations according to different flow rate conditions of pilot-scale MCDI system operation with 120 s adsorption/desorption time under dual-series mode module arrangement.

Based on a comparison of the results obtained from the 300 s and 120 s adsorption/desorption times, it is evident that selecting the 120 s duration for the dual-series mode is significantly more favorable regarding both TDS removal and energy efficiency. Theoretically, the ratio of treated water to influent water is 50%. Therefore, if the operation time of the MCDI system is 20 h per day, 10 L/min operation will produce 6000 L of treated water per day, which would be 9000 L for 15 L/min, 12,000 L for 20 L/min, and 15,000 L for 25 L/min. This study aimed to derive the optimal operational conditions for removing ions from mildly brackish water with a total dissolved solids (TDS) concentration of 1000 mg/L. Accordingly, the adoption of a flow rate of 10 L/min, identified as the most efficient among the different flow rate conditions during the 120 s adsorption/desorption cycle, is considered favorable. However, in cases with a pre-determined minimum quantity requirement, prioritizing the processing capacity allows for the selection of a flow rate within a satisfactory TDS removal efficiency range.

### *3.3. Energy Consumption Analysis of the Tested MCDI Operational Conditions*

The power consumption (kWh) was calculated based on the logged voltage and current values in the power meter during the experiments conducted under different operational conditions. Integrating these data with the production volume of treated water enabled the computation of energy consumption per unit volume of treated water (kWh/m$^3$).

During the 120 s adsorption and desorption cycle (240 s total), the energy consumption (kWh/m$^3$) demonstrated an increasing trend with higher flow rates, measured at 0.98, 0.99, 0.99, and 0.99 for flow rates of 10, 15, 20, and 25 L/min, respectively (Figure 6). The 300 s adsorption and desorption cycle (600 s total) energy consumption displayed a similar pattern, with values recorded at 0.886, 0.911, and 0.907 for flow rates of 10 L/min, 15 L/min, and 25 L/min, which signifies the influence of flow rate on the overall energy consumed by the pilot-scale MCDI system. The higher energy consumption at elevated flow rates can be attributed to the intensified ion migration and electrochemical processes within the electrodes, leading to enhanced energy dissipation [23]. Moreover, higher flow rates are associated with increased energy demands, highlighting the importance of an in-depth understanding of the fluid dynamics and mass transfer among the electrodes during operation.

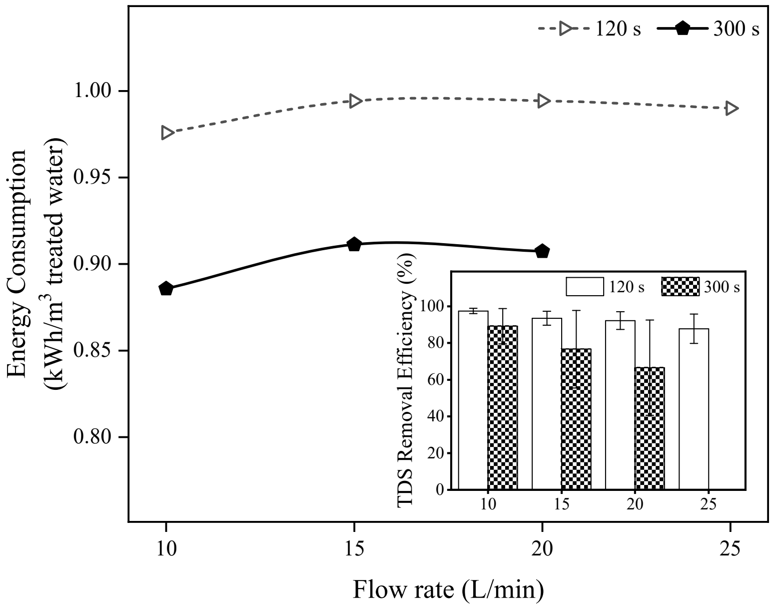


**Figure 6.** Energy consumption per $m^3$ of treated water and TDS removal efficiencies from pilot-scale MCDI system operation in 120 s and 300 s adsorption/desorption time under different flow rate conditions in dual-series mode module arrangement.

The TDS removal efficiencies for an adsorption time of 120 s were 97.4% at a flow rate of 10 L/min, 93.4% at 15 L/min, 92.2% at 20 L/min, and 87.8% at 25 L/min (Table 2). At an adsorption time of 300 s, the TDS removal efficiencies were 89.2%, 76.7%, and 66.5% at 10, 15, and 25 L/min, respectively. This finding agrees with that of [23], where the energy demands in MCDI were influenced by the influent salt concentrations and desired product salinity. Specifically, while MCDI outperformed RO for influent salt concentrations below 3 g/L TDS and a product salinity of 1 g/L, the energy consumption nearly doubled when aiming for 0.5 g/L TDS. Together, these observations emphasize the importance of optimizing the operational parameters in MCDI systems to balance energy costs with TDS removal levels.

**Table 2.** Summary of experimental results of dual-series module arrangement with adsorption and desorption time of 120 s.

| Flow Rate | TDS Removal Efficiency (%) | Energy Consumption (kWh/$m^3$) |
|---|---|---|
| 10 L/min | 97.4 | 0.976 |
| 15 L/min | 93.5 | 0.994 |
| 20 L/min | 92.2 | 0.994 |
| 25 L/min | 87.8 | 0.990 |

Although laboratory-scale tests serve as a preliminary indication of the potential efficacy of a target technology, pilot-scale tests are crucial for assessing the real-world applicability and performance of the technology. Given that the MCDI system was operated at a pilot scale, even though it exhibited greater energy and power demands than laboratory-scale configurations, the ability of the system to produce water with a significantly lower ion concentration indicates its practical significance. Additionally, there are avenues for optimization, such as using fewer electrodes or reducing the flow rate to minimize consumption. Conducting a feasibility study and an economic analysis centered on achieving the target TDS removal efficiency concerning the volume of treated water may elucidate further optimization pathways for the pilot-scale MCDI system.

## 4. Conclusions

Our study demonstrated the effectiveness of MCDI in desalinating water and highlighted the importance of optimizing the operational parameters. The dual-series mode module arrangement outperformed single mode and dual-parallel mode configurations, achieving a TDS removal efficiency of 99%. Moreover, an adsorption time of 120 s and a flow rate of 10 L/min proved to be the most energy-efficient combination, with a TDS removal rate of 96%. We observed that higher flow rates led to a lower TDS removal efficiency, emphasizing the need to balance energy consumption and water quality. Although pilot-scale MCDI systems may have higher energy demands than laboratory-scale setups, they offer the practical advantage of producing water with significantly lower ion concentrations. Further economic analysis is warranted to optimize the efficiency of the pilot-scale MCDI system and achieve the target TDS removal efficiency while considering the specific volume requirements. Our research contributes to understanding MCDI system performance under different operational conditions, paving the way for its broader application in water supplies.

**Author Contributions:** B.L.: formal analysis, investigation, and writing—original draft; C.O.: formal analysis, investigation, and writing—original draft; J.A.: conceptualization, and writing—review and editing; S.Y.: investigation, and writing—review and editing; H.J.O.: funding acquisition, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by Korea Environment Industry & Technology Institute (KEITI) through Project for developing innovative drinking water and wastewater technologies Project, funded by Korea Ministry of Environment (MOE) (2020002700003) and the KICT Research Program (project no. 20230274-001, Development of low-energy/high-efficiency MCDI process and application to Malaysia) funded by the Ministry of Science and ICT.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** All data supporting the findings of this study are provided in this manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

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