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Effects of number of cell pairs on the performance of microbial desalination cells

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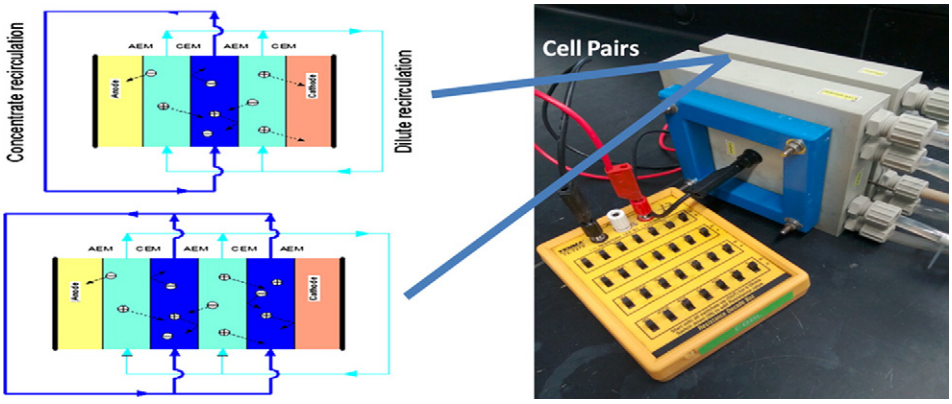
HIGHLIGHTS

- Adding more cell pairs increases charge transfer efficiency in an MDC.
- Salt removal rate in mg h^{-1} also increases with more CPs.
- More CPs result in more water loss and lower water recovery.
- Applying an external voltage can improve desalination and reduce operating time.
- Both water recovery and desalination performance should be evaluated for MDCs.

GRAPHICAL ABSTRACT



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ABSTRACT

Microbial desalination cells (MDCs) are being developed as a low-energy desalination technology. Most MDCs in the previous studies contained one cell pair (CP, a pair of cation and anion exchange membranes) and very few had multiple CPs (<5). The effect of the number of CPs on the MDC performance has not been well understood. Herein we examined the current generation, desalination, and water recovery in a bench-scale MDC containing up to 10 CPs, fed with salt water containing either 35 or 5 g L^{-1} NaCl. It was found that current generation decreased with more CPs, while the charge transfer efficiency increased; the highest value of 450% was achieved with 10 CPs when treating 35 g L^{-1}, which also yielded the highest salt removal rate of 90.8 ± 8.3 mg h^{-1}. Applying an external voltage of 0.8 V greatly increased current generation and salt removal rate, and decreased the desalination time from 12 to 4 h. Water loss tended to be more serious and water recovery became lower with more CPs and/or lower salinity of the salt water. The results suggest that both desalination performance and water recovery should be evaluated when developing the MDC technology.

1. Introduction

Water stress due to increasing population and water pollution makes it urgent to explore new technologies that can efficiently treat water for domestic, industrial and agricultural use. Desalinating brackish water and seawater is a viable approach to provide high quality water [1]. The existing desalination technologies, such as thermal desalination, reverse osmosis, and electrodialysis (ED), are generally energy intensive, resulting in significant economical investment and energy-related environmental impacts [2,3]. To reduce energy consumption during desalination, microbial desalination cells (MDCs) are being

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developed by taking advantage of the bioenergy produced through microbial oxidation of organic compounds. Salts can be separated from saline water in a similar process to ED but the driven force is the current generation within an MDC [4]. An MDC usually consists of a pair of anion exchange membrane (AEM) and cation exchange membrane (CEM), forming a basic cell-pair (CP) structure.

Because of microbial metabolism in the anode, MDCs are able to remove organic contaminants from domestic and many other types of industrial wastes [5,6]. Electrons generated from the organic oxidation promote ion movement. Various MDC configurations have been developed for better wastewater treatment, desalination, and construction flexibility, including three-chamber, tubular, decoupled, and stacked structures [4,7–14]. The use of different separators and/or coupling with resin and capacitive adsorption has been implemented to improve ion migration [15–19]. MDCs have also been combined with microbial electrolysis to produce hydrogen and other valuable chemicals [16,20,21]. It was identified that several limiting factors such as pH imbalance and water loss [22] could affect the performance of MDCs and reduce current generation or water recovery from saline water.

Most MDCs have a single-CP structure containing one pair of ion exchange membranes. MDCs are derived from both microbial fuel cells (MFCs, bioelectricity) and ED (desalination principle). Thus, it is of great interest to investigate whether a multiple-CP structure (which an ED usually has) can also be applied to MDCs and how it will affect microbial processes related to electricity generation. Adding more CPs may improve desalination efficiency; however, the weak electric current generated from microbial activities may not be sufficient to drive salt migration through multiple CPs. The previous studies obtained different results regarding the optimal number of CPs in an MDC. Chen et al. [10] examined the MDCs containing one, two, and three CPs, and found that the salt removal rate could be increased by adding CPs and reducing the external resistance. Their results showed a maximum salt removal rate of 25.2 mg h^{-1} obtained from the MDC with two CPs. They also observed that the MDC with three CPs had an increased internal resistance and a larger salt gradient between the dilute and concentrate chambers compared with the two-CP MDC, resulting in lower electricity generation and salt removal. Their further study focused on the two-CP MDC and used separator coupled circulation to improve the system's stability during a long-term operation [12]. In another study, a stacked MDC consisting of five CPs (6 AEM and 5 CEM) achieved a high current efficiency of 86%; when four of these stacked MDCs were hydraulically connected in series, the system reduced 44% of salinity of the synthetic saline solution containing 35 g L^{-1} NaCl [11]. Those results indicate that the optimal number of CPs is related to the MDC design, especially the inter-membrane distance which can greatly affect the internal resistance and the desalination efficiency [23]. For instance, the inter-membrane distance of the MDCs in Chen's study was 10 mm, much larger than 1.3 mm in Kim and Logan's MDC system. A larger inter-membrane distance can cause a larger internal resistance and decrease both current generation and desalination efficiency. In addition, water loss and recovery could be an important issue in the MDC containing multiple CPs, which create concentrate and dilute chambers that will drive water movement by salt gradients and experience some water loss as concentrate unless further desalination of the concentrate is conducted.

To further understand the effect of the number of CP on MDC performance and water loss/recovery involved in this process, we have conducted a study using a stacked MDC modified from a commercially available lab-scale ED reactor. This MDC contains up to 10 CPs, and the inter-membrane distance is about 0.5 mm (less than half of the smallest inter-membrane distance reported in the MDC studies [11]). Current generation, desalination performance, and water production were examined with different numbers of CP and with two concentrations of salt solution (35 g L^{-1} and 5 g L^{-1} NaCl). To investigate the influence of current generation and its relationship with the numbers of CP, an external voltage of 0.8 V was also applied to boost current generation in some experiments.

2. Materials and methods

2.1. MDC construction

The MDC was modified from an ED-64 002 stack (PCCell GmbH, Germany) by adding a 1-cm thick rubber spacer, which enlarged the anode chamber for an effective liquid volume of ~55 mL. Two 5-cm long carbon brushes (Gordon Brush Mfg. Co. Inc., Commerce, CA, USA) were installed as the anode electrodes after pretreatment [24]. In the cathode chamber (with a liquid volume of ~20 mL), a piece of 8 × 8 cm carbon cloth coated with 0.2 mg cm^{-2} of Pt catalyst was used as the cathode electrode. The cell pairs were installed between the anode and the cathode chambers, as shown in Fig. 1A. The thickness of the ion exchange membrane and the spacer is 0.1 and 0.5 mm, respectively. There were two types of CP installment for the different salinities: when using 35 g L^{-1} NaCl solution as saline water, the MDC consisted of X AEM (X is the number of membrane) and X CEMs with 2X-1 spacers, resulting in X dilute chambers and X-1 concentrate chambers, where X is 2, 4, 6, 8, and 10. Fig. 1B provides an example of the MDC with 2 AEMs and 2 CEMs. For the tests using 5 g L^{-1} NaCl, X + 1 AEM and X CEM with 2X spacers were used and an example can be found in Fig. 1C, which shows the MDC with 3 AEMs and 2 CEMs. When X is 1, only one pair of AEM and CEM formed one desalination chamber similar to those in most MDCs reported previously.

2.2. MDC operation

The MDC was started with one CP and its anode was inoculated with the effluent from the MFCs treating primary sludge from a local wastewater treatment facility [25]. The MDC was operated at room temperature (~20 °C) and the anode was continuously fed with a solution containing (per L of tap water): sodium acetate, 2 g; NH_4Cl, 0.15 g; NaCl, 0.5 g; $MgSO_4$, 0.015 g; $CaCl_2$, 0.02 g; $NaHCO_3$, 0.1 g; KH_2PO_4, 0.53 g; K_2HPO_4, 1.07 g; and trace element, 1 mL [26]. The cathode was operated in a batch mode, and the catholyte, which was phosphate buffer solution (100 mM) containing 5.3 g L^{-1} of KH_2PO_4 and 10.7 g L^{-1} of K_2HPO_4 stored in an external 1-L reservoir, was replaced completely after each cycle (12 h). The catholyte was recirculated at a flow rate of 100 mL min^{-1} between the cathode chamber and the external reservoir. Saline water in the salt chamber was recirculated at a recirculation rate of 2.3 mL min^{-1} per chamber (in a batch mode), and two 100-mL bottles were used to store the dilute and concentrate solutions. The anode and the cathode electrodes were connected by copper wires to an external circuit across the external resistance of 10 Ω. An external voltage (0.8 V) was applied to the circuit in some tests (desalinating saline water containing 5 g L^{-1} NaCl) by connecting the anode pole of a power supply (3644 A, Circuit Specialists, Inc., Mesa, AZ, USA) to an external resistor (10 Ω), then to the cathode electrode of the MDC, and the cathode pole to the anode electrode of the MDC.

2.3. Measurement and analysis

The MDC voltage was recorded every 5 min by a digital multimeter (2700, Keithley Instruments, Inc., Cleveland, OH). The pH was measured using a benchtop pH meter (Oakton Instruments, Vernon Hills, IL). The conductivity was measured by a benchtop conductivity meter (Mettler-Toledo, Columbus, OH). The water loss from the dilute chamber was measured with digital scales to calculate the change of water weight within a period of time. The salt removal rate was calculated in mg h^{-1} or kg m^{-3} h^{-1} (the volume of the total desalination chamber including both concentrating and diluting chambers), based on the correlation between the conductivity and mass concentration of the salt solution (R^2 was 0.9976). The charge transfer efficiency was calculated according