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Optimization of membrane stack configuration in enlarged microbial desalination cells for efficient water desalination

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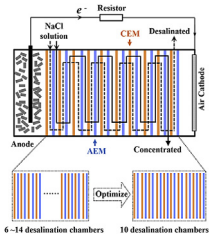
HIGHLIGHTS

- The number of MDC desalination cells was optimized between 6 and 14.
- The 10-desalination-cell reactor achieved the highest TDR (423 mg/h) and CTE (836%).
- TDR is a factor which decreased with time during the desalination process.
- CTE is a factor which was primarily determined by the membrane stack configuration.
- Junction potential significantly increased during the desalination process.

GRAPHICAL ABSTRACT



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ABSTRACT

Microbial desalination cells are considered a low-energy-consumption, clean technology to simultaneously purify wastewater and desalinate saline water by utilizing the *in situ* energy source contained in wastewater. To enhance desalination performance and achieve an optimal membrane stack configuration, an enlarged stacked microbial desalination cell (SMDC) has been developed and tested with 6–14 desalination cells. The cross-membrane area of the enlarged SMDC is 100 cm^2. The anode and cathode volumes are both 200 mL. To reduce internal resistance, the width of desalination cells is kept as <0.5 mm. The optimal configuration with 10 desalination cells achieves the highest total desalination rate (TDR) of 423 mg/h and the highest charge transfer efficiency (CTE) of 836% when treating the 20 g/L NaCl solution. During this process, the junction potential across membranes increases from 0 to 374 mV, and occupies up to 74% of the total potential loss inside the SMDC. This shows that the SMDC used in this work achieves the highest TDR and CTE among the reported studies, and the junction potential should be effectively controlled to achieve the desired desalination performance in future practical applications.

1. Introduction

Lack of fresh water resources has become a worldwide intractable problem [1]. Exploring new techniques to obtain more fresh water from brackish water and reuse wastewater may provide new breakthroughs [2]. Commercial desalination techniques, such as reverse osmosis (RO) or electrodialysis, are typically all energy

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intensive approaches [3,4]. Furthermore, conventional wastewater treatment, involving aerobic/anoxic/aerobic (A^2O) processes, requires large amounts of electricity for aeration. While the bioelectrochemical systems (BESs) in which the electrochemical active bacteria in the anode can oxidize the organics in the wastewater and transfer electrons to the electrode [5,6], is a sustainable technology to treat wastewater. BESs can utilize the chemical energy contained in the wastewater to output current, produce useful substances or drive the directional transport of ions [5–8]. One promising technology in BESs, referred to as microbial desalination cells (MDCs), offers a new way to simultaneously purify wastewater and desalinate saline water [9]. The MDCs that evolved from microbial fuel cells [10–12], can utilize the energy sources contained in wastewater to produce electricity and drive salt ions to migrate across membranes and thus desalinate saline water. MDCs are considered a low-energy-consumption, clean technology to simultaneously purify wastewater and accomplish desalination.

Studies of MDC technologies, aiming at promoting the practical application of this technology, have achieved significant progresses in configuration innovation and operating mode optimization [13]. Air cathode was used in cubic and tubular MDCs to facilitate continuous desalination [14,15]. Ion exchange resins were packed in desalination cells to reduce the internal resistance of microbial desalination cells and achieve efficient desalination of both low and high salinity water [16–18]. Forward osmosis membrane was introduced into the MDC systems and proved beneficial for wastewater volume reduction and saline water dilution [19,20]. In addition to the process of desalination, several versatile MDC configurations can produce valuable chemicals, such as H_2 (by applying voltage) and acid or alkali (by using bipolar membranes) [21–26]. The pH imbalance in electrode chambers has been adequately mitigated by mixing the anolytes and catholytes [27,28]. Several studies have assessed the practical application of MDC technology by treating real wastewater and scaling-up to 105 L [29,30]. To better instruct MDC design and operation, mathematical models were built and improved to synthetically simulate the wastewater treatment and desalination process [31,32]. In these attempts, which focused on improving desalination performance, stacked microbial desalination cell configuration was promising, and has shown the advantages in enhancing the total desalination rate (TDR) and the charge transfer efficiency (CTE) [28,33,34].

In our previous work [28,33], the stacked MDC configuration that contained two desalination cells achieved a TDR of 25.2 mg NaCl/h and a CTE of 223%. In later research, four MDCs with five desalination cells each were operated in series and achieved a TDR of 77 mg NaCl/h (i.e. 19.25 mg NaCl/h per MDC) and a CTE of 430% [34]. In a three-cell-pair multi-anode MDC, a TDR of 107.4 mg NaCl/h was achieved when the anolyte pH was balanced by adding catholyte effluent [35]. A stacked microbial electro-deionization cell, which contained five desalination cells packed with the ion exchange resins, achieved the TDR of 48.0 mg/h when desalinating the 13 g/L NaCl solution [18]. A ten-liter stacked microbial desalination cell (SMDC) with three desalination cells packed with ion exchange resin could desalinate the low conductivity secondary effluent at a rate of 95.4 mg/h and obtain a CTE of ~250% [36]. Furthermore, a ten-cell SMDC achieved a TDR of 91 mg/h and a CTE of 450% (the highest level in the reported works) when treating a 35 g/L NaCl solution. In that study, the desalination performance was further improved by applying a certain level of voltage on the electrical circuit [37].

Based on the above researches, the increase in desalination cell number improved the CTE and TDR of a SMDC. However, in most of the configurations mentioned above, there was little evidence to prove that the chosen desalination cell number was optimal. Moreover, desalination performance is still unsatisfactory: TDRs remained below 100 mg/h, and CTEs remained lower than 500%. Potential loss analysis was used to reflect internal resistance distribution of the SMDC, while the calculation was based on the average current of the SMDC and may not reveal the variation throughout the desalination process.

This study is aimed at promoting the desalination performance of a SMDC and revealing the potential loss variation during the desalination process. Enlarging the SMDC scale and using thin desalination cells could benefit the current production [34,36,37]. However, the increase in the number of desalination cells may not always facilitate desalination owing to the introduction of additional internal resistance [33]. Moreover, in previous studies, the potential loss significantly affected the desalination performance of SMDCs and needs to be investigated further to more effectively instruct the operation of the desalination process. The SMDC configuration in this study has a membrane area of 100 cm^2 (14 times larger than the 7.1 cm^2 membrane area in our previous works [28,33]) and a desalination cell width of 0.45 mm (approximately 22 times smaller than the 10 mm width in those previous works). Desalination cell number has been optimized between 6 and 14 to obtain the highest TDR and CTE, and the change trends of these two factors were investigated within the desalination process. The individual potential losses have been analyzed based on the real current condition to demonstrate the crucial resistance of the desalination process in the configuration of SMDC.

2. Experimental

2.1. Reactor construction

The enlarged SMDC consisted of an anode chamber, membrane stacks containing desalination cells and concentration cells, and a cathode chamber (Fig. 1). The anode and cathode chambers were cube-shaped polycarbonate blocks and each had a 20 × 5 × 2 cm (cross area: 100 cm^2; volume: 200 mL) groove in the center. Granular activated carbon (~1 mm in diameter, ~2–5 mm in length; Beijing Chunqiudingsheng Environmental Science and Technology Co. Ltd., China) [38] acted as anode chamber padding to support biofilm and conduct electrons. A piece of titanium mesh (dimensions: 20 × 5 cm; specification: 28 mesh; titanium wire diameter: 0.25 mm; Hebei Anping Wire and Mesh Co. Ltd., China) was placed against the anion exchange membrane (referred to as AEM; thickness 110 μm, transport number-Na^+ > 0.96; Selemion AMV, Asahi Glass, Japan) to collect and transport electrons to the external circuit. Before use, the granular activated carbon and titanium mesh were washed with distilled water and soaked in 1 M HCl for ~48 h to remove impurities [9]. The cathode was a section of air cathode placed at the end of the cathode chamber. Air cathode was fabricated based on a 50% wet-proofed carbon cloth (dimensions: 20 × 5 cm; E-Tek, Type B, BASF Fuel Cell, Inc., Somerset, NJ, USA), coated with 0.5 mg/cm^2 platinum and three layers of polytetrafluoroethylene (PTFE) [39]. A section of titanium foil which attached to the catalytic side of the air cathode was connected with external circuit. Between the anode and cathode chamber were the membrane stacks which contained several pairs of ion exchange membranes (*n* pairs of membranes constitute *n* desalination cells and *(n−1)* concentration cells). The AEMs and cation exchange membranes (referred to as CEMs; thickness 110 μm, transport number-Cl^- > 0.96; Selemion CMV, Asahi Glass, Japan) were placed alternately from the anode side to the cathode side and were separated by silicone cushions and polypropylene mesh spacers to ensure each chamber had a 0.45 mm width. All the chambers, membranes, silicone cushions and sealing gaskets were clamped together by two 1.5 cm-thick steel plates (the plate on the cathode side had a rectangular hole aligned with the air cathode).