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Energy self-sufficient desalination stack as a potential fresh water supply on small islands

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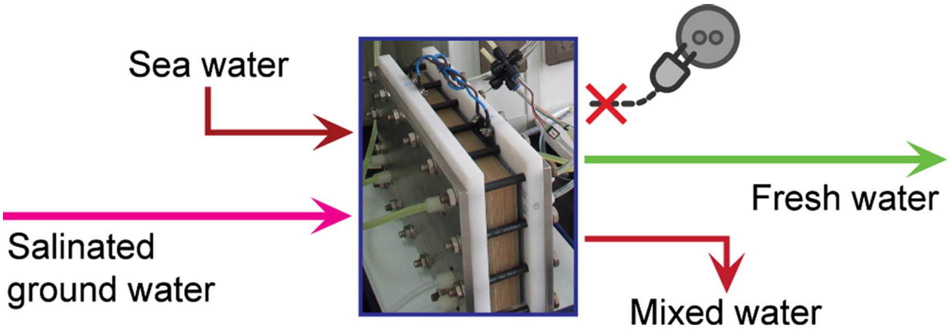
HIGHLIGHTS

- An energy self-sufficient system was built to desalt brackish water on islands.
- Reverse electrodialysis and electrodialysis were integrated in single module.
- Salinity gradient energy was harvested for desalination.
- The system was well optimized for best overall performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Sea water intrusion causes fresh water shortage on small islands, and desalination systems are needed to desalt the salinated water (brackish water) and produce fresh water. Unfortunately conventional desalination technologies can only work properly with stable external power inputs, which are usually not accessible in these rural areas. In this study we propose an integrated self-desalination stack that consists of alternate anion and cation ion exchange membranes and couples the technologies of reverse electrodialysis and electrodialysis. The salinity gradient energy between sea water and brackish water is harvested to demineralize another portion of brackish water directly in the same stack. The overall process is spontaneous and energy self-sufficient with minimum peripheral devices, and it is promising to provide fresh water supply especially for these rural residents on small islands.

1. Introduction

Potable fresh water (FW) is of vital importance for residents on small islands. There are about 1000 populated small islands in Pacific Ocean, and many islanders especially in rural areas are facing the challenge of FW shortage [1–3]. Groundwater is the main source of FW on many of these islands, which exists in the form of FW lenses, namely thin veneers of FW overlying sea water (SW) in highly permeated aquifers [1]. These lenses are very limited and vulnerable because of the mixing and intrusion of SW [1–6]. The boundary between FW and SW is not sharp, and it occurs as a wide transition zone, where the salinity increases as the depth increases. The water in this transition zone is classified as brackish water (BW) [7].

It's widely believed that the first refugees of climate change will come from these islands [2]. The rising seawater levels and abnormal rainfall patterns will further ruin the FW lenses by SW intrusion [1,3]. The maximum salinity of FW is 400–500 mg/L NaCl according to the drinking water guidelines from World Health Organization (WHO) [8]. When salinity exceeds 500 mg/L NaCl, the water will be not drinkable,

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and FW shortage happens. Desalination technologies are the key to resolve this issue [9–11]. Currently available processes such as multi-stage flash (MSF) distillation, multiple-effect distillation (MED), vapor compression (VC) distillation, reverse osmosis (RO) and electrodialysis (ED) are well proven approaches to obtain FW from the SW or BW. Unfortunately the above desalination processes rely on stable power or heat source and economically effective only in large scale plants, while the majority of islanders (~80% in the 14 Pacific Island Countries) are living in rural areas [3] where the power grid is not available. Furthermore, there is no water distribution system in theses areas, so distributed desalination systems are supposed to be close to the end-point household users. Desalination systems integrated with renewable energy technologies such as geothermal, solar or wind [12–14] are more suitable for these islanders, while the energy conversions in these systems are complex and costly. Electricity (as electronic current) must be obtained first and then used for the desalination later, and extra energy storage systems are usually needed to get stable electrical power [15].

According to the local geohydrology conditions, salinity gradient power is a reliable candidate of renewable energy source on these islands [16,17]. SW and BW are always available there, and they mix all the time underground. Reverse electrodialysis (RED) is able to capture this salinity gradient energy as electricity [16,18–23], and theoretically it may provide the energy to meet the needs on these islands. However, RED is not an economic power generator at present because of the limited net power density, and further developments are needed [16,24,25]. Here in this study, we propose a novel architecture of energy self-sufficient desalination stack, in which RED and ED parts are coupled in single module. The ionic current generated in RED portion is the very driving force for ED desalination process, which is able to drive desalination directly and seamlessly within the stack, without any conversion. When compared with other desalination systems integrated with renewable energy technologies, the energy conversion practices reduce remarkably in this integrated stack. The produced FW has much more value than the small amount of energy which can be produced by current RED system alone on these small islands. In contrast with previous works based on the combination of RED and ED [26–30], the stack design in this work is much more applicable on these small islands. The integrated stack here ensures very low hydraulic pumping losses. Only after manually elevating 10 cm to help the feed water flow through the stack naturally, the FW will be produced constantly without any other external energy input. This feature is especially valuable for approaching the final energy self-sufficient goal, because it has the potential to get rid of all energized pumps in the whole system. The self-desalination stack in this study is promising to fill the gap for desalination need in these areas, which is helpful to relieve the FW shortage there.

2. Materials and methods

Fig. 1 presents a design of the self-desalination stack in our lab. There are four independent flow channels (CH1-4, also shown in Fig. S1A) in the integrated stack regulated by special designed spacers and membranes. The energy from salinity difference between BW (CH1) and SW (CH2) is harvested as ionic current in RED cell pairs, which is utilized for BW desalting in ED cell pairs to get FW (CH4) directly. The salinity gradient drives the ion migration needed for desalination in the stack, because the RED and ED subsystems are ionically connected. The electrodes and the short-circuit cable provide a closed loop for the current in the stack. The overall process is spontaneous and no external energy is needed.

Three different ion exchange membranes were used in this work, which were DF-120 anion exchange membranes (AEMs), DF-120 cation exchange membranes (CEMs) and Selemion CMD CEMs. The Selemion CMD CEMs were purchased from Asahi Glass Engineering Co., Ltd. Japan, and other membranes were purchased from Shandong Tianwei Membrane Technology Co., Ltd. China. The main parameters of these membranes are listed in Table S1 in supplementary materials.

The spacers in this study were designed and manufactured in our lab, which had been described in our previous works [31,32]. This kind of spacer has a dimension of 260 mm (length) × 130 mm (width) × 0.9 mm (thickness). The spacer consists of polyethylene (PE) sheet and polypropylene (PP) turbulence accelerating mesh net, with tortuous flow path geometry of 33 mm (width) × 567 mm (length), i.e. 187 cm^2 of effective area. The total flow rates (mL/min) and the flow velocities (cm/s) in stack can be readily converted from geometry of the flow paths. The PP mesh net has a porosity of 72%, and projected shadow effective area of the spacer is 135 cm^2. The specially designed pattern of the spacer enables 4 different flow channels at most, which is shown in Fig. S1.

RED and ED stacks with 2-compartment configurations, and integrated RED-ED stack with 4-compartment configuration, are assembled (shown in Fig. 1) independently. In this study, electrode membranes (CEMs near the electrodes) are Selemion CMD CEMs, and all other membranes are DF-120 CEMs and AEMs respectively. Heavy Selemion CMD CEMs are positioned adjacent to the electrodes, and they completely separate the electrode rinse from other feed streams to avoid potential contaminations. In addition, these heavy CEMs are durable for chemical contaminations, which is essential for the membrane adjacent to an electrode compartment [32]. The well designed components of the stack ensure good performance and no leakage.

Dimension stable electrodes (DSEs, from Suzhou Borui Industrial Material Science & Technology Co., Ltd. China, titanium electrodes with RuO_2–IrO_2 coatings) were used as electrodes in all stack designs in this study. Two different solutions were evaluated as electrode electrolytes. The first is 0.50 mol/L NaCl solution, and the other is mixture of 0.05 mol/L $Na_4Fe(CN)_6$ (sodium ferrocyanide), 0.05 mol/L $K_3Fe(CN)_6$ (potassium ferricyanide) and 0.25 mol/L NaCl [22,33]. All chemicals were of AR grade and purchased from Sinopharm Chemical Reagent Co., Ltd., China. The $Na_4Fe(CN)_6$ and $K_3Fe(CN)_6$ used here are completely nontoxic, and the health hazard ratings are the same as NaCl (rating 1 in NFPA 704). A miniature cell (shown in Fig. S2A) was built to evaluate the voltage loss in real stack. The key parameters, including electrode materials, heavy CEM, electrode rinse flow velocity and spacer thickness, are identical with real stacks. We applied constant current mode and recorded the voltage between electrodes.

Electrical conductivity distributions of the groundwater indicate the degree of SW intrusion on small islands. The salinities of the groundwater in many areas are as high as 1000 mg/L NaCl (1990 μS/cm, see Fig. S3) even on wide islands such as Tongatapu [1], which makes the water significantly unpalatable. The situations on smaller islands are worse and many of them are uninhabited. To evaluate the performance of the above integrated RED-ED stack, we used 1000 mg/L NaCl solution as BW and 30,000 mg/L NaCl solution as SW feed streams in all experiments.

A Keithley 2400 source measure unit (SMU) was used in this study. With the ability of 4-quadrant operation, it was used here as a power source (for ED testing) as well as a sink (electronic load, for RED testing). 4-Wire configurations were involved in all tests to eliminate voltage loss in wires. A home-made console program was designed on a host computer to fully control the SMU via RS232 interface, which was similar to our previous works [34]. LEAD-2 (4 channels, 0–420 mL/min each) and BT-100 (2 channels, 0–48 mL/min each) metering pumps were used in this study, which were purchased from Baoding Longer Precision Pump Co., Ltd., China. The pumps were controlled by our home-made console program via digital TTL and 0–5 V analog signals. The concentrations of NaCl solutions are calculated from their conductivities according to the calibration curve shown in Fig. S3 in this work.

The change in Gibbs free energy of mixing is chosen to describe the energetics in both mixing and desalting processes. For NaCl solutions with relatively low concentrations, the maximum energy obtained by