Desalination 412 (2017) 20–31

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Partial desalination of hypersaline brine by lab-scale ion concentration polarization device

Bumjoo Kim [a], Hyukjin Kwon [b], Sung Hee Ko [a], Geunbae Lim [b], Jongyoon Han [a,c,d,*]

[a] *Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*
[b] *Department of Mechanical Engineering, Pohang University of Science and Technology, San31, Pohang, Gyeongbuk 790784, Republic of Korea*
[c] *Singapore-MIT Alliance for Research and Technology (SMART) Centre, Singapore*
[d] *Department of Biological Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*

HIGHLIGHTS

- We demonstrate brine (70,000 mg/L) desalination by lab-scale ICP device.
- Power consumption and water cost are calculated for different salt removal ratio.
- Partial desalination is revealed to be more economical than complete desalination.

ARTICLE INFO

Article history:
Received 9 October 2016
Received in revised form 24 February 2017
Accepted 24 February 2017
Available online xxxx

Keywords:
Ion concentration polarization
Desalination
Brine
Electrodialysis
Ion exchange membrane

ABSTRACT

In this paper, technical and economic feasibility of partial desalination of hypersaline brine by ion concentration polarization (ICP) desalination is examined. We engineered a lab-scale ICP desalination system producing flow rate up to 96 mL/min, which represents the largest scale-up of ICP desalination process so far. With highly saline brine feed water (NaCl, 70,000 mg/L of TDS) and utilizing two different cation exchange membranes, we measured electrical responses of unit fluidic cell, and monitored the product water salinity changes over a wide ranges of flow velocities and electric current densities. Based on these, realistic power consumption and expected cost of brine treatment can be calculated, for the economic validation of partial brine desalination by ICP process. For the salt removal ratio of 50%, the optimal water cost is obtained as \$3.08/m^3 while the least power consumption is achieved as 5.6 kWh/m^3. Our results also show that the partial desalination could be more economically preferable than complete desalination for the brine management. Yet, ICP desalination should be further improved and optimized, with significant potential to be applied in many different desalination applications and hybrid scenarios.

1. Introduction

Recent exploration of unconventional gas resources for global energy needs, along with seawater desalination for supply of potable water resources, have generated massive amounts of hypersaline brine waste water, which is increasingly considered as an environmental challenge. Followed by hydraulic fracturing, large volumes of flowback water containing lots of suspended solids and salinity up to 5 times higher than seawater are coming to the surface, while naturally occurring 'produced water' in shale formations flows to the surface throughout the lifespan of the gas well [1,2]. Due to the lack of economical treatment strategies, the brine waste in the gas industry have often been hauled away and deposited in the authorized injection well without further treatment, potentially causing drastic contamination of ground water resources in nearby regions [3,4]. In addition, substantial amounts of hypersaline brine waste are generated in the seawater desalination plants (*e.g.* multi-stage flash distillation, reverse osmosis, *etc.*), often simply discharged back into the ocean. Discharge of high salinity (50,000–85,000 mg/L of TDS) brine could be problematic, since it is reported as one of the reason for increased local (coastal) seawater salinity due to poor mixing (*e.g.* Persian Gulf), resulting in significant ecological

---

[*] Corresponding author at: Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA.
E-mail address: jyhan@mit.edu (J. Han).

http://dx.doi.org/10.1016/j.desal.2017.02.018

impacts on the marine environment system [5–8]. In addition, brine waste from desalination plants contains diverse toxic contaminants such as anti-foulants, anti-scalants, which could damage on marine ecosystems [6,9–11].

Brine desalination should be approached from the perspective of cost-effective waste volume reduction, whereas conventional brackish/seawater desalination is aimed specifically at gaining maximum clean (potable) water efficiently. Since the current state of the art technology (RO) cannot readily deal with hypersaline brine feed, complete desalination of brine waste to produce ultra-purified distilled water requires substantial costs (*e.g.* \$22–39/m^3) in the case of Mechanical Vapor Recompression (MVR), which is often used for brine waste treatment in the gas development [12–14]. Instead of such a near-complete treatment, once brine waste salinity is reduced to near seawater salinity, a range of other technical options open up to treat the wastewater further. For example, there are increasing examples to exploit the salinity-reduced brine waste (10–30 k ppm TDS) as additional water resource in the oil/gas exploration, where partially desalinated wastewater could be productively reused instead of overspending on the complete desalination [15–17]. Similar situations can be observed in the desalination plants, where brine waste water is partially desalinated in order to be fed-back into the seawater desalination unit as feed water [18,19]. For the purpose of minimizing brine waste volume and retaining more feed water resources, therefore, it is worthwhile to examine and develop a viable desalination technology which can desalinate brine wastewater with flexible salt removal capability.

Although electromembrane desalination such as electrodialysis has been used mostly in low salinity water treatment, it should be noted that electromembrane desalination can flexibly control the salt removal ratio of output product (depending on the applied electric energy) without any upper limit of feed salinity [20–22]. Several studies were reported to validate the potential economic viability of electrodialysis for treating highly saline brine, along with emphasizing on the potential economic benefit of partial desalination of electrodialysis [23–25]. While electrodialysis (see Fig. 1(a)) desalinates water employing anion exchange membrane (AEM) and cation exchange membrane (CEM), our group previously proposed ion concentration polarization (ICP) desalination (see Fig. 1(b)) employing only CEM in order to enhance salt removal and energy efficiency [26]. Followed by the study, we examined the ICP desalination to treat the highly saline brine feed (up to 100,000 mg/L of TDS) by presenting trifurcated ICP desalination strategy, which can save energy/cost efficiently (see Fig. 1(c)) [27]. Nevertheless, our previous work on ICP desalination were entirely done in polydimethylsiloxane (PDMS) based miniaturized model devices, with limited diluate product flow rate (<10 μL/min), which was useful only as a technical proof of concept. In this paper, we built up and demonstrate lab-scale ICP desalination for practical throughput (>1000 times larger than microfluidic systems) by stacking layers of membranes and plastic sheets in a similar manner as conventional electrodialysis stacks. Flow rate of diluate product was increased up to 24 mL/min (feed ranges up to 96 mL/min) using the ICP device with 4 membrane stacks. With highly saline brine feed water (NaCl, 70,000 mg/L of TDS) and two different CEMs, we examine the energy consumption/overall cost of this scaled-up ICP device for different salt removal ratios, in order to study the optimal water cost of partial desalination by ICP system.

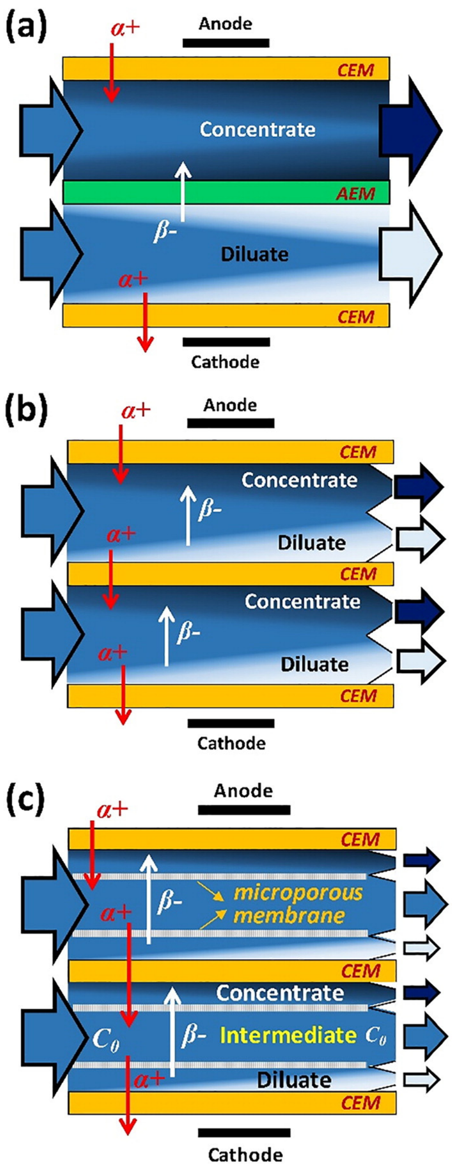

Fig. 1. Schematic view of ion transport in (a) Electrodialysis (ED), (b) Ion Concentration Polarization (ICP) desalination, and (c) lab-scale ICP desalination for multi-stage operation. Red and white arrows indicate the movement of cation $\alpha+$ and anion $\beta-$ by electric field, respectively. Bright and dark colored regions in these schematics represent ion depleted (diluate) and enriched (concentrate) region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Experimental

2.1. Device fabrication

Fig. 2(a) shows schematic view of lab-scale ICP desalination with a single unit cell defined by two CEMs, along with one diluate, concentrate, and intermediate channels as presented in the previous study [27]. For higher flow throughput, we increase the CEM width (W) up to 60 mm, which is 300 times wider than our microfluidic study (200 μm) [26–28]. There are two unique technical issues which should be considered for the lab-scale operation. First, since there might be hydraulic pressure difference between the rinsing and the main channel, straight spacer structures are newly embedded in order to prevent a mechanical deflection of the CEM. Secondly, in order to stabilize the flow stream inside the channel, microporous membranes (polycarbonate membrane filter with 1 μm pore, Sterlitech Co., Kent, WA) are installed in the channel. These issues related to the spacer and microporous membrane will be further discussed in the discussion. Effective length (L) of fluidic channel is 300 mm, and most of fluidic compartments are assembled by multiple silicone rubbers. Multiple fluidic compartments and CEM are stacked up to realize multi-stack ICP configuration. Intermembrane (CEM to CEM) distance is 2.5 mm, which is equivalent to the thickness of single fluidic compartment composed of three silicone rubber layers. Mechanically reinforced