HIGH-THROUGHPUT SALT/BIO-AGENT REMOVAL BY ION CONCENTRATION POLARIZATION FOR WATER DESALINATION, PURIFICATION, AND MONITORING

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ABSTRACT

We demonstrate the high-throughput universal platform using ion concentration polarization (ICP) for water desalination, purification and monitoring. Utilizing ICP between two identical cation exchange membranes (CEM), we can relocate ions along a specific portion of fluidic channels, generating salt/bio-agent-depleted flow and salt/bio-agent-enriched flow in one channel. This ICP platform can remove most salt ions in brackish water (10 mM aCl, >97%) with better energy efficiency and current efficiency than electrodialysis (ED). By adjusting the depleted/enriched flow rates, we preconcentrate targets up to 333 fold in fresh water (1 mM aCl) with 120 μL/min sample flow. Moreover, its reciprocal design gives us the solid scale-up strategy, i.e. multi-stacking the unit devices.

KEYWORDS: Ion Concentration Polarization (ICP), Ion Exchange Membrane (IEM), Desalination, Preconcentration

INTRODUCTION

The topics of major technological and societal interest on the water-energy nexus are the development of more scalable, inexpensive, and time/power-economical i) water desalination, ii) purification, and iii) monitoring technologies. When the nonlinear ICP was shown to generate wide depletion zone with extremely low salt concentration near IEMs, the desalting capability of ICP has been recognized as the next-generation electrochemical desalination device$^{1-3}$. While the previous ICP platforms clearly demonstrated the desalination capability of nonlinear ICP, they have three critical challenges. First, the detailed mechanism of ICP desalination was not quantitatively established, and the critical difference between ICP vs. ED were not fully understood. This is important since ICP can also occur in standard ED$^4$. Second, the previous ICP and related platforms$^{5,6}$ had a microfluidic design feature that are not adequate for a high efficiency, robust system. The electrodes were not only connected to the ICP zones with long microchannels creating unnecessary power consumption, they were exposed directly to the desalting flow, which allowed Faradic reaction to affect the quality of desalted water. Last, scaling-up to realistic, macroscopic system is one of the biggest huddles of such microfluidics-based platforms. Therefore, we suggest new ICP platform to overcome these limits by ICP between two identical CEMs. Through visualizing and tracing conductivity, dye concentration, and particle movement, we not only demonstrate the production of purified water and preconcentrated targets, we also quantify the enhancement of ICP desalination over standard ED process.

THEORY

The device is fabricated by slotting CEMs and electrodes into Polydimethylsiloxane (PDMS) (Fig. 1). Through transparent PDMS, we can visualize in situ concentration profiles with fluorescent dyes$^5$. Between two juxtaposed CEMs (termed as ‘2CEM’), ion depletion zone ($d_m$) and ion enrichment zone ($d_e$) are generated under an electric field (Fig. 2a). As cations selectively transfer through the CEMs, anions relocate in order to achieve electro-neutrality, resulting in the concentration drop (increase) in ion depletion (enrichment) zone. The concentration drop (i.e. salt removal) is low and spatially gradual at relatively low voltage or current (i.e. Ohmic regime) (black dotted line in Fig.2a and 2.5V in Fig.3b-c). However, at higher voltage or current (i.e. overlimiting regime), strong electroconvective vortex accelerates cation transport through CEMs, allowing us to “relocate” most salt ions (black solid line in Fig. 2a and 10V in Fig.3b-c). The flat depletion zone occurs with significantly low ion concentration, and corresponding strong electric field in the zone, and charged agents (e.g. proteins and bacteria) are largely depleted from this zone$^5$. As a result, we can separate and collect the desalted/purified flow from brine / preconcentrated flow by bifurcating the channel at the end. To clarify the difference between ICP desalination platform and ED, we also build ED system (Fig. 2b). While cations and anions in ED can move toward the electrodes under the electric field, anions are ‘imprisoned’ between two CEMs in the ICP platform. Therefore, if the internal relocation of anion by ICP does not happen for some reason (e.g. very heavy, immobilized ions), the desalted flow will not be produced.

EXPERIMENTAL

In aCl solution, the fluorescent dye Alexa Fluor 488 (Invitrogen, Carlsbad, CA), is added to visualize ICP. The inter-membrane distance between IEMs is 2mm. The channel height and length are 0.2 and 5-10 mm, respectively. FTCM-E (FuMA-Tech GmbH, Germany), and carbon paper (Fuel Cell Store, Inc., Boulder, CO) are used as CEMs, and electrodes, respectively.
RESULTS AND DISCUSSION

First, real-time conductivity tracing verify the conductivity drop (increase) of desalted (brine) flows by ion relocation (Fig. 4). The desalting performance becomes better as higher voltage or current; when 200μA is applied, 97% of salt ions are removed from 10mM NaCl solution at 10μL/min. We also demonstrate the purification/preconcentration of Alexa Fluor 488 in 1mM NaCl solution (Fig. 5). Here, the microporous membrane is inserted to separate desalt/brine flows fluidically and isolate ICP instability in desalted flow. When sample is pumps with 120μL/min, dyes are preconcentrated up to 333 fold locally. In experiments here, all parameters including current, voltage, and desalt/brine conductivities are saturated and hold the same values, indicating steady and stable operation. Next, to compare ICP (2CEM) and ED systems quantitatively, we calculate two performance metrics: energy per ion removal (Fig. 6a) and current efficiency (Fig. 6b). While energy consumption is an important metric determining the economic viability, it cannot represent the desalination energy efficiency of the system. Current efficiency values in the Ohmic regime might be not accurate, for the measurement error in conductivity can be probably magnified current efficiency (i.e. current)(grey regimes in Fig. 6b). We therefore consider energy consumption to remove a single ion, i.e. energy per ion removal. Energy per ion removal is a parameter representing how efficiently energy is consumed to reject ions. Current efficiency describes the ratio of rejected ions in desalted flow and ions transferred at the electrodes. As can be seen in Fig. 6, ICP system shows better energy per ion removal and current efficiency than ED. This is because that ICP has better salt removal ability at the given conditions. The demonstrated purification/preconcentration technology here can achieve even higher flow rates (few hundred liters per hour) by a simple stacking approach similar to that of the standard electrodialysis (Fig. 7). This high throughput capacity opens a commercial opportunity for efficacious potable water purification/monitoring devices.

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Figure 4. a) conductivities of desalted and brine flows with a conductivity probe (Microelectrodes, Inc, Bedford, NH). Voltage responses show 2.5±0.4, 10.1±1.0, 16.9±1.6, and 38.6±5.6 V at 20, 60, 100, and 200 μA, respectively.

Figure 5. Time response of the preconcentration system: a) fluorescent images, b) fluorescent intensity (dye concentration) curves. With 120 (50) μL/min of sample flow rate, the local dye concentration jumps up to 333.3 (179.5) fold, and the average dye concentration in the preconcentrated flow increases up to 133.8 (76.9) fold from 78 pM (voltage=110 V). The polycarbonate membrane with 1μm pores is integrated between two CEMs.

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