MEMBRANELESS PURIFICATION OF HEAVY METAL CONTAMINATED WATER BY ION CONCENTRATION POLARIZATION

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ABSTRACT

The lethal threats to human health from heavy metals are associated with untreated ground water. We developed a high throughput single step heavy metal purification process based on Ion Concentration Polarization mechanism. Instead of microfluidic channel networks, the plastic prototype made of plastic meshes and Nafion nanoporous material was built so that the manufacturability and cost efficiency were maximized. Modeled heavy metal contaminated water was filtered below the safe concentration. Based on the demonstration, one can expect to achieve a 100mL/min throughput from a 2.5inch portable system which is capable of desalting seawater, purifying heavy metals and disinfecting biological contaminants.

KEYWORDS

Water purification, seawater desalination, ion concentration polarization, nanoporous membrane, nanofluidics, electrokinetics

INTRODUCTION

Groundwater contamination by heavy metal compounds is a significant problem in many countries [1]. Arsenic (As), cadmium (Cd) and lead (Pb) ions in drinking water can cause serious illness such as skin cancer, kidney damage and gastrointestinal uptake. Current methods for heavy metal removal rely on coagulation-precipitation of metal contaminants, induced by adding chemical coagulants, followed by filtration of solids. While this technique is widely used and could potentially be implemented relatively inexpensively [2], different coagulant chemical should be used for different metal contaminants. Membrane processes (such as reverse osmosis) are widely used for seawater desalination and purification, but requires expensive water purification and delivery infrastructures and therefore cannot be easily implemented in a rural, resource-limited areas. Previously, we have demonstrated a novel microfluidic desalination [3] / disinfection [4] method, which have the potential to be built into a portable and self-powered system. The separation mechanism is based on the Ion Concentration Polarization (ICP) phenomenon [5]. ICP is a fundamental electrochemical phenomenon that describes the behavior of ions in an electrolyte solution near nanoporous membrane under DC electric field [5, 6]. Due to the nano-scale pores in the membrane, it has a perm-selectivity so that the membrane allows only counter-ion to transport through itself. Thus, ionic concentrations dramatically decreases and increases at anodic and cathodic compartment in the system, respectively. Especially, the ultra-low concentration zone (a.k.a. ion depletion zone) at the anodic side of the membrane rejects any ionizable species including salts, biological contaminants (protein and cell) and metal ions so that continuous extracting the fluid from ion depletion zone enables water purification / seawater desalination from highly contaminated source waster. However, the flow rate of fresh water was around ~10uL/min in a single microfluidic channel, too small to be useful for any practical application.

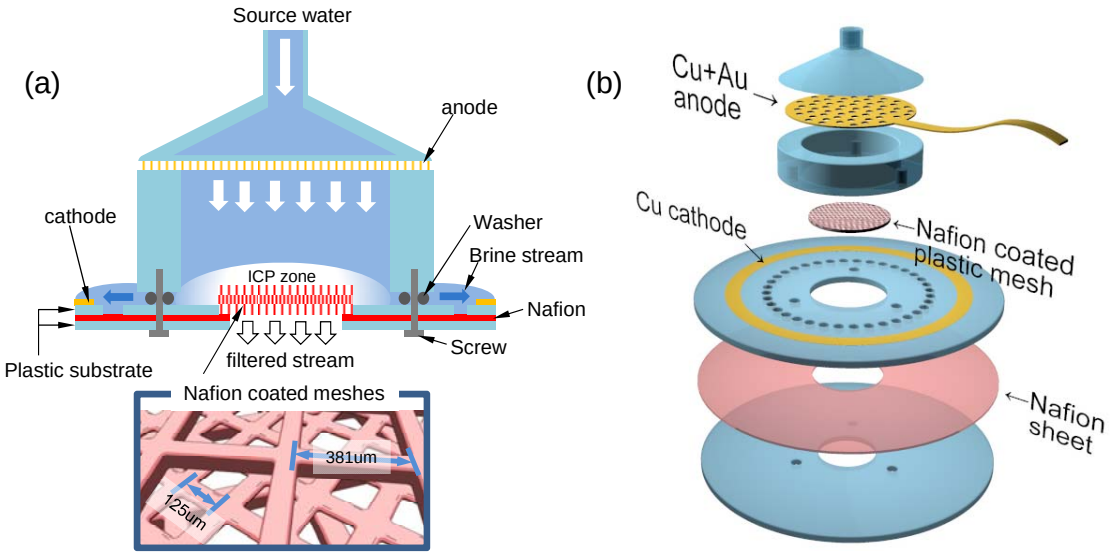

Figure 1. ***ICP purification scheme****. (a) Schematic diagram of ICP desalination / purification system utilizing industrial degree plastic meshes structure and (b) Exploded view of prototype.*

EXPERIMENT

In this work, we demonstrate a high throughput (~1mL/min), single step heavy metal purification / desalination system utilizing the same ICP desalination principle. Source water is fed vertically from the top, which will meet the ICP zone created by the plastic mesh coated with Nafion as shown in the schematics of Figure 1(a) and the exploded diagram of the multiplexed system is shown in Figure 1(b). Purified water (desalted stream) will pass through ICP zones and mesh holes, falling down to the bottom, while brine stream flows away toward the rim of chamber. The mesh structure consists of a fine mesh (~125um mesh holes) sandwiched by two coarse meshes (~381um mesh holes), which creates a dense array of holes where desalted water can pass through, while the brine (salts) are hindered from entering due to the ICP zones created. The fluidic resistance through a hole is proportional to the length and inversely proportional to the square of cross-sectional area. To balance 1:1 separation of brine and desalted flow, a fluidic resistance through the meshes (# of holes × hole area / hole length) should be equal to a fluidic resistance through the gap between top plastic substrate and upper tube part (indicated "gap for brine flow" in Figure 2(a)). For this purpose, three 200um thick washers were inserted at the bottom of the tube. Instead of microfluidic channel networks, commercially available low-cost and off-the-shelf materials were used for the system, so that the manufacturability and cost efficiency were maximized (actual material cost of the prototype was ~$0.5 excluding labor, software and machines). Final assembled prototype is shown in Figure 2.

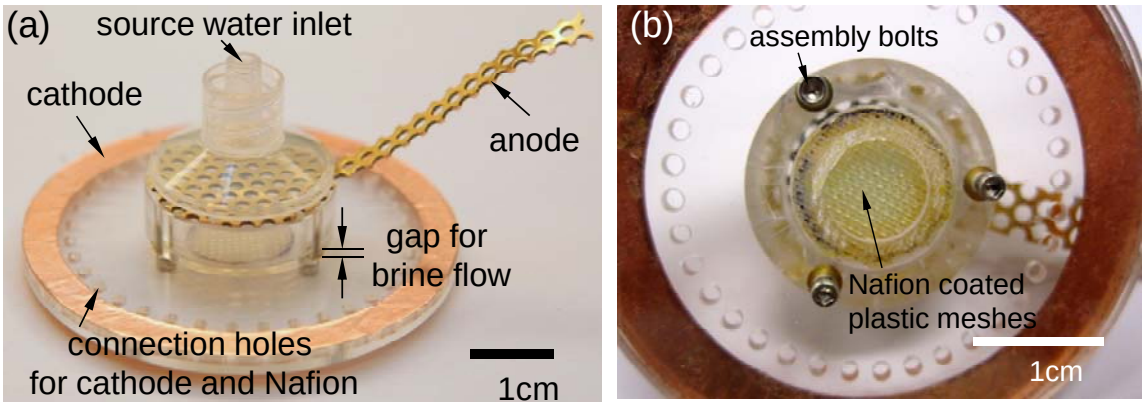

Figure 2. ***Assembled prototype****. Assembled prototype made of transparent plastic substrate and plastic meshes stack. (a) Perspective view and (b) bottom view.*

A water sample modeled after Bangladeshi ground water (As (500ppb), Cd (200ppb) and Pb (200ppb)) was filtered by this prototype, and after a single pass heavy metal contamination levels were brought below the safety limit (As<10ppb, Cd<5ppb and Pb<15ppb: suggested by World Health Organization) as shown in Figure 3. Quantitative analysis of filtered sample was conducted by both inductively coupled plasma-mass spectrometer and laboratory test kit.

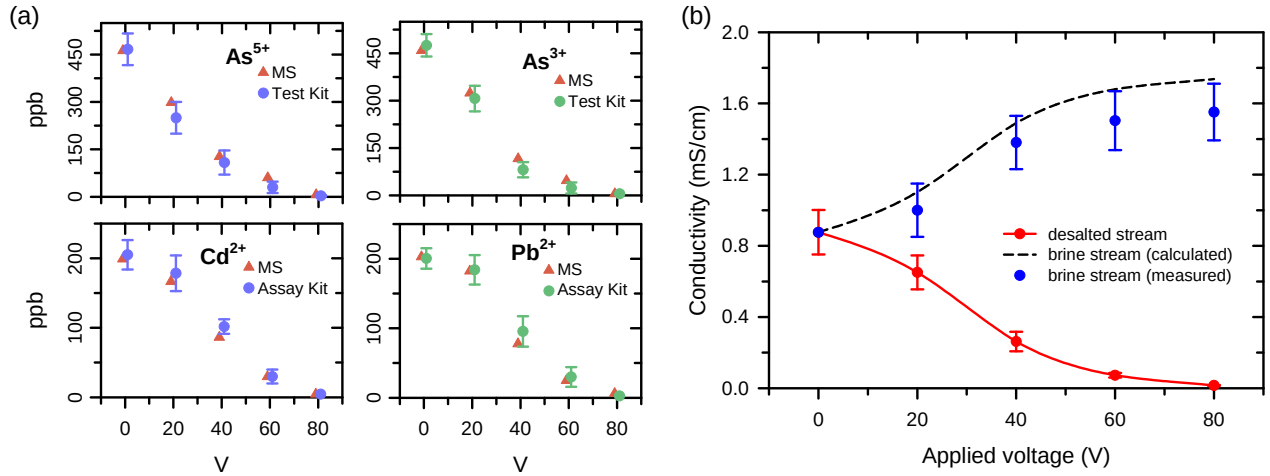

Figure 3. ***Quantitative analysis of ICP purification.*** *(a) The concentration drop of each heavy metal species from filtered samples as a function of applied electrical voltage and (b) the conductivity changes as a function of applied electrical potential at both desalted and brine stream.*

Majority ion concentrations (such as Na^+ and Cl^-) were monitored by conductivity measurement as shown in Figure 3(b), which showed a precipitous drop once the electric voltage was applied. On the other hand, the conductivity increased at the brine stream, confirming that actual separation of salts from the desalted stream into the brine stream

has occurred. In addition, a higher concentrated source water (NaCl: 30,000TDS, seawater level salinity) was also successfully desalted to fresh water at the power efficiency of ~5Wh/L.

In our prototype device, there are approximately 1800 holes in a 3/8 inch diameter (~0.7 cm^2) circular mesh structure, which supports desalination flow rate of 0.5mL/min (0.7mL/min/cm^2). In contrast, reverse osmosis membranes typically operate at the rate of ~0.05mL/min/cm^2 with ~25% recovery rate. Our current prototype device could be operated in parallel, providing scalable water desalination capability that is appropriate both for small scale (e.g. personal / household) and larger municipal scale (e.g. ships and small town). Conclusively, the manufacturability, power efficiency, cost, and salt / heavy metal removal efficiency of this system will make this technology viable for portable water purification system in various areas of the world where water / power infrastructure are not readily available.

ACKNOWLEDGEMENTS

This work was mainly supported by SMART Innovation grant, as well as NSF (CBET-0854026). S. J. Kim was partially supported by Research Settlement Fund for the new faculty of Seoul National University. B. Kim was supported by Mid-career Researcher Program through NRG grant funded by the MEST (No. 2011-0027528). The authors deeply appreciate the help by Dr. Amir Liba (Agilent Technologies), who carried out the heavy metal trace analysis from the water sample purified using our system.

REFERENCES

[1] World Health Organization, Environmental Health Criteria, http://www.who.int/ipcs/publications/ehc/en/

[2] D. Sutherland, O. Kabir, N. A. Chowdhury, paper presented at the International Workshop on Technologies for Arsenic Removal from Drinking Water, (2000).

[3] S. J. Kim, S. H. Ko, K. H. Kang and J. Han, *Direct seawater desalination by ion concentration polarization*, Nat. Nanotech., **5**, 297-301 (2010).

[4] R. Kwak, S. J. Kim and J. Han, *Continuous-flow biomolecule and cell concentrator by ion concentration polarization*, Anal. Chem., **83**, 7348-7355 (2011).

[5] S. J. Kim, Y. C. Wang, J .H. Lee, H. Chang and J. Han, *Concentration polarization and nonlinear electrokinetic flow near nanofluidic channel*, Phy. Rev. Lett., **99**, 044501 (2007).

[6] R. F. Probstein, *Physicochemical hydrodynamics: an introduction*, chapter 7, Wiley-Interscience (1994).

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