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A portable and high energy efficient desalination/purification system by ion concentration polarization

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ABSTRACT

The shortage of fresh water is one of the acute challenges that the world is facing now and, thus, energy efficient desalination strategies can provide substantial answers for the water-crisis. Current desalination methods utilizing reverse-osmosis and electrodialysis mechanisms required high power consumptions/large-scale infrastructures which do not make them appropriate for disaster-stricken area or underdeveloped countries. In addition, groundwater contamination by heavy metal compounds, such as arsenic, cadmium and lead, poses significant public health challenges, especially in developing countries. Existing water purification strategies for heavy metal removal are not readily applicable due to technological, environmental, and economical barriers. This presentation elucidates a novel desalination/purification process, where a continuous contaminated stream is divided into filtered and concentrated stream by the ion concentration polarization. The key distinct feature is that both salts and larger particles (cells, viruses, and microorganisms) are pushed away from the membrane, in continuous flow operations, eliminating the membrane fouling that plagues the membrane filtration methods. The power consumption is less than 5Wh/L, comparable to any existing systems. The energy and removal efficiency, and low cost manufacturability hold strong promises for portable, self-powered water purification/desalination system that can have significant impacts on water shortage in developing/rural part of the world.

Keywords: ion concentration polarization, electrokinetics, micro/nanofluidics, desalination, purification, filtration

1. INTRODUCTION

Fresh water is the vital resource for human life. However, population growth, enhanced living standards, along with expansion in industrial and agricultural activities are urging unprecedented demands on the clean water supplies all over the world. OECD and UN have reported that 0.35 billion people are suffering from the water shortage now in 25 countries, especially in middle-east and Africa as shown in Figure 1, but it will grow up to 3.9 billion people (2/3 of world population) in 52 countries by 2025 [1]. Converting abundant seawater into fresh water can provide the solution to the worldwide water shortage problem, since about 97% of the total water resource on Earth is seawater and only 0.5% of the total is the potable, fresh water. Fresh water is the vital resource for human life. However, population growth, enhanced living standards, along with expansion in industrial and agricultural activities are urging unprecedented demands on the clean water supplies all over the world. OECD and UN have reported that 0.35 billion people are suffering from the water shortage now in 25 countries, especially in middle-east and Africa, but it will grow up to 3.9 billion people (2/3 of world population) in 52 countries by 2025.1,2 Converting abundant seawater into fresh water can provide the solution to the worldwide water shortage problem, since about 97% of the total water resource on Earth is seawater and only 0.5% of the total is the potable, fresh water. However, the areas affected by acute water shortage are often in the poorest, most underdeveloped countries, without any power and water delivery infrastructure necessary. This presents a significant global challenge, since the lack of clean water also presents significant health, energy, and economic challenges to the population in these countries. In addition, groundwater contamination by heavy metal compounds is a significant problem in many countries. 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,

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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. In this sense, small scale or portable water desalination/purification systems with low power consumption and high throughput would be very useful in many important government, civilian and military needs, including humanitarian operations in disaster-stricken area or resource-limited settings.

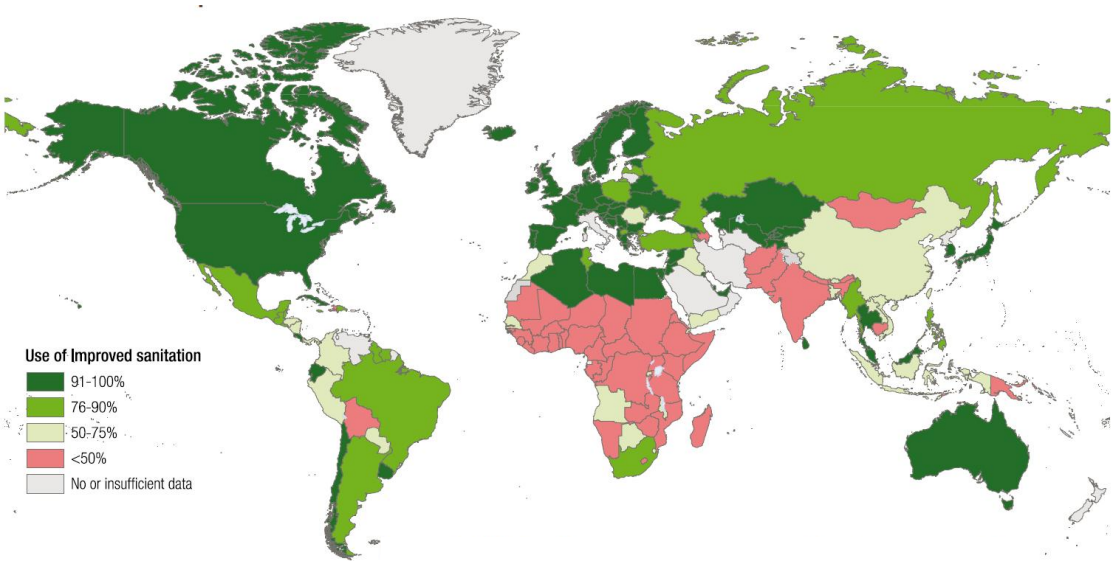

Figure 1. Worldwide use of improved sanitation facilities in 2008

2. ION CONCENTRATION POLARIZATION IN MICROFLUIDIC DEVICE

The objective of this paper is to demonstrate the feasibility of the novel desalination/purification process that utilizes ion concentration polarization (ICP) [2, 3]. ICP is a fundamental electrochemical transport phenomenon that occurs when ion current is passed through ion-selective membranes. Often called as ion depletion or enrichment, this phenomenon is due to the mismatch of charge carriers at the membrane interface. The membrane (either nanochannel or nanoporous membrane) conducts only cations preferentially (cation exchange membrane), which is not matching with the ion conductivities in the bulk electrolyte. As a result, ion concentration gradients are generated on both sides of the membrane. Once ICP is triggered near the cation exchange membrane, the concentrations of both cations and anions decrease on the anodic side of the junction (ion depletion) and increase on the cathodic side (ion enrichment).

In addition, any charged particles, cells, and other small colloids will also be depleted or enriched along with ions. Combined with an external, pressure-driven flow, one could obtain a well-defined stead-state depletion zone forming using the device shown in Figure 2a and 2b. The inlet microchannel had a dimension of 500um width X 100um depths. The Nafion nanojunction was infiltrated and connected two microchannels. Then, using bifurcated channels (the size of each channel was 250 um width X 100 um depth) shown in Figure 2, one can separate the 'desalted' stream from 'salted' one, achieving continuous and steady-state desalination. Strong ICP zones were established even under a high ionic strength condition, because the pore size of Nafion nanojunction is small (~5nm) and therefore remain cation-selective even at 500mM (30,000 mg/L) (seawater) ionic strength [4]. One important characteristic here is that salt ions (and other charged debris) are also driven away from (not toward) the membrane, fundamentally eliminating the potential for membrane (nanojunction) fouling. We experimentally tested direct seawater desalination operation at the single unit device scale. Figure 2b shows the desalination experiment done with natural seawater (obtained from Crane beach, Ipswich, MA, pH=8.4~8.5). Once ICP is initiated, the depletion zone was formed within 1 sec to divert charged ions (represented by dye molecules) into the "salted" stream as shown in Figure 2b. It was also shown that the ICP layer acts as a virtual barrier for any charged particles (both negative and positive), including most solid particles, micro-organisms and biomolecules (proteins, bacteria, viruses, RBCs, WBCs, etc.) found in seawater [5]. This is because most waterborne microorganisms and microparticles have non-zero (usually slightly-negative) zeta potential. Therefore, both small salt

ions and large microorganisms can be simultaneously removed from the output desalted stream, making this process highly attractive for direct seawater desalination from natural sources.

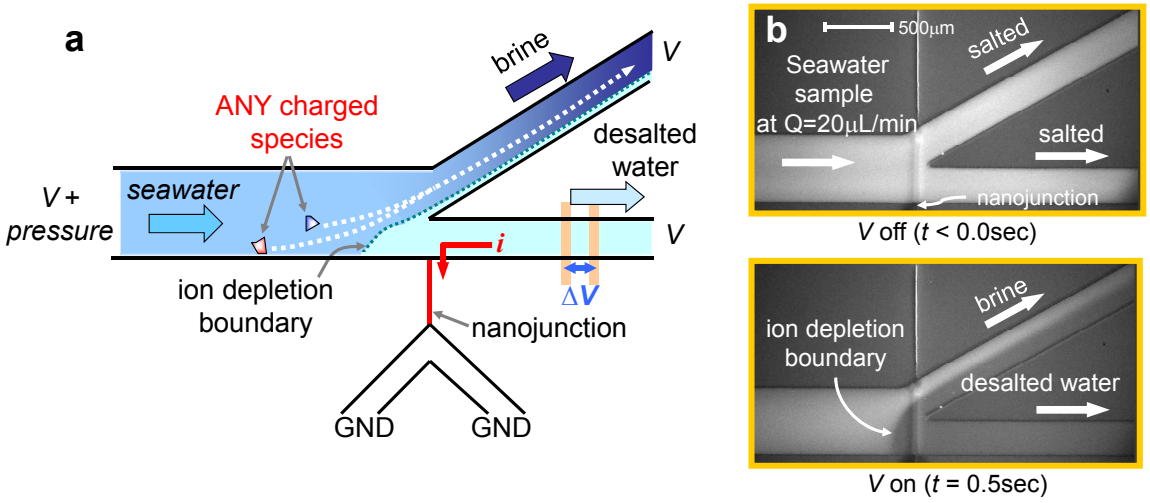

Figure 2. (a) Schematic diagram of ICP desalination process and (b) Experimental demonstration of ICP desalination.

3. SMALL SCALE ICP PURIFICATION DEVICE

Despite of a number of advantages of micro/nanofluidic platform, 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. Here we demonstrate a high throughput (~1mL/min, 1000X enhancement), 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 3a and the exploded diagram of the multiplexed system is shown in Figure 3b.

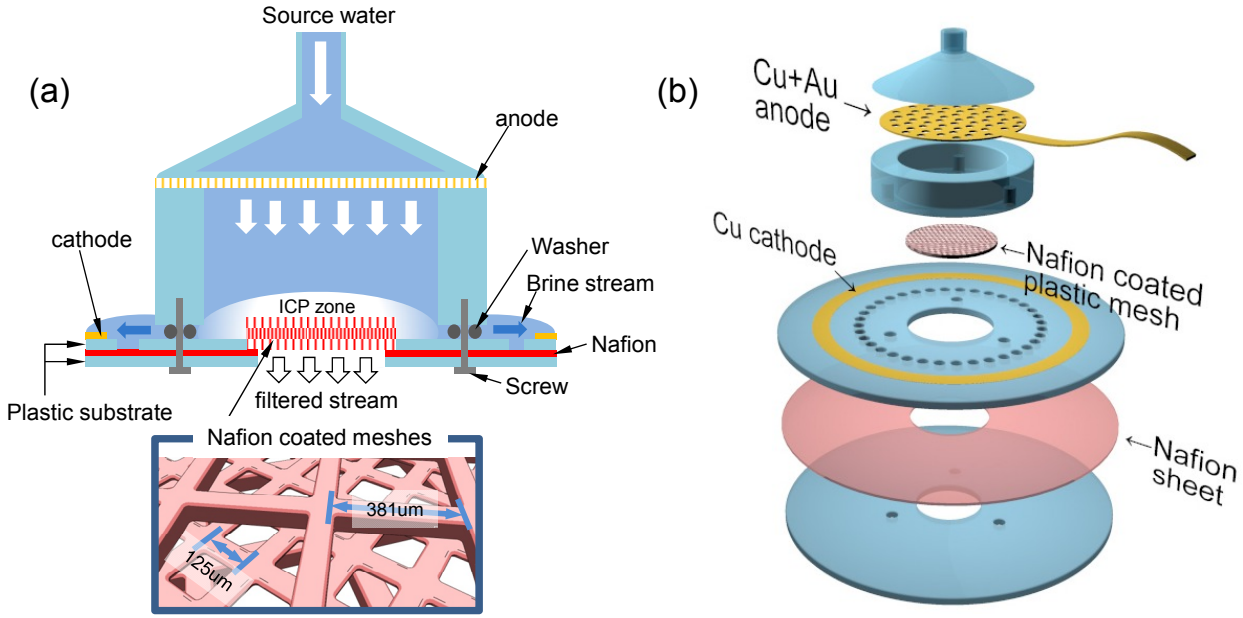

Figure 3. (a) Schematic diagram of ICP desalination / purification system utilizing industrial degree plastic meshes structure and (b) Exploded view of prototype

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 3a. 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 4.

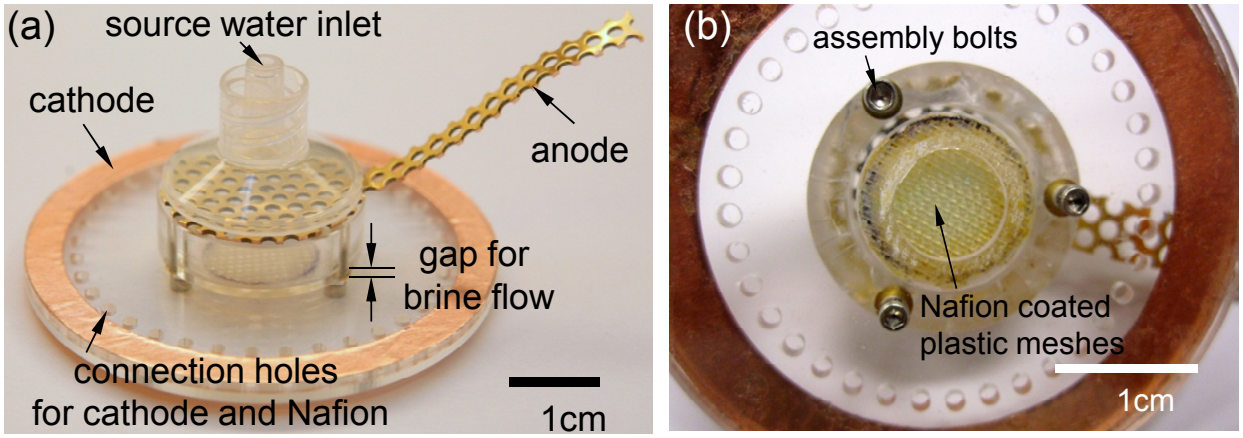

Figure 4. Assembled prototype made of transparent plastic substrate and plastic meshes stack. (a) Perspective view and (b) bottom view.

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 5. Quantitative analysis of filtered sample was conducted by both inductively coupled plasma-mass spectrometer and laboratory test kit.

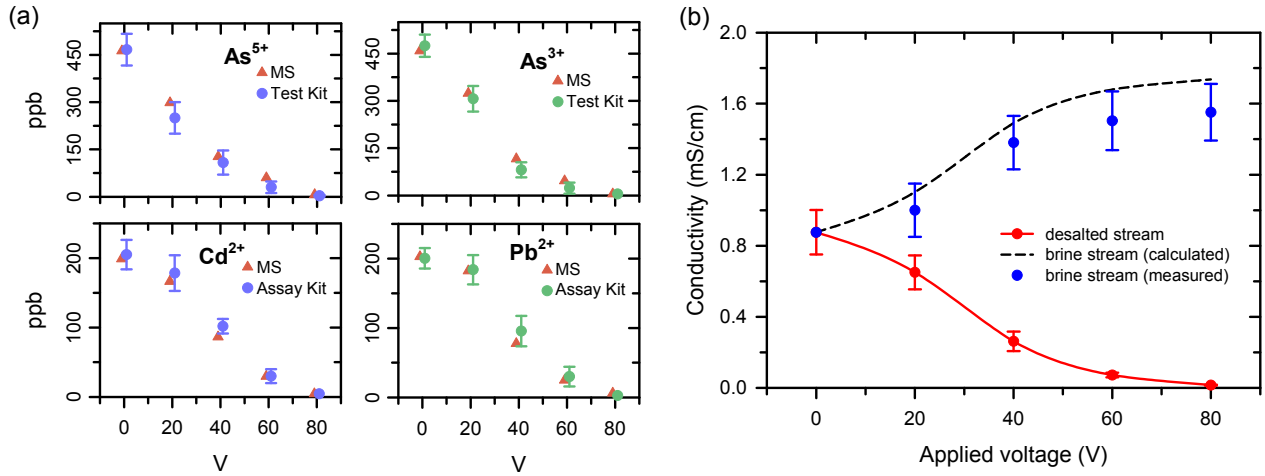

Figure 5. (a) The concentration drop of each heavy metal species from filtered samples as a function of applied electrical voltage and (b) the conductivity changes as a function of applied electrical potential at both desalted and brine stream.

Majority ion concentrations (such as Na^+ and Cl^-) were monitored by conductivity measurement as shown in Figure 5b, 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.

4. CONCLUSION

Conclusively, we developed a low-cost, small-scale ICP desalination / purification device utilizing a novel mesh design, which improves practicality and manufacturability significantly over the previous demonstration. The fresh water production rate was enhanced ~1000 times compared to the previously ICP desalination device, while the cost of the system was decreased down to $0.33. 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. The power requirement and contaminant removal efficiency were similar to the current state-of-art desalination / purification methods. Instead of using sophisticated clean room facilities, we built the prototype entirely out of inexpensive off-the-shelf materials such as plastic meshes and plates, enabling the adoption of this technology even in developing worlds. Since the ICP mechanism can eliminate any ionizable substances regardless of their size by a single separation step, heavy metal contaminants (arsenic, cadmium and lead), a significant public health challenge, were shown to be removed effectively. Seawater desalination was also tested at the same high flow rate condition as well.

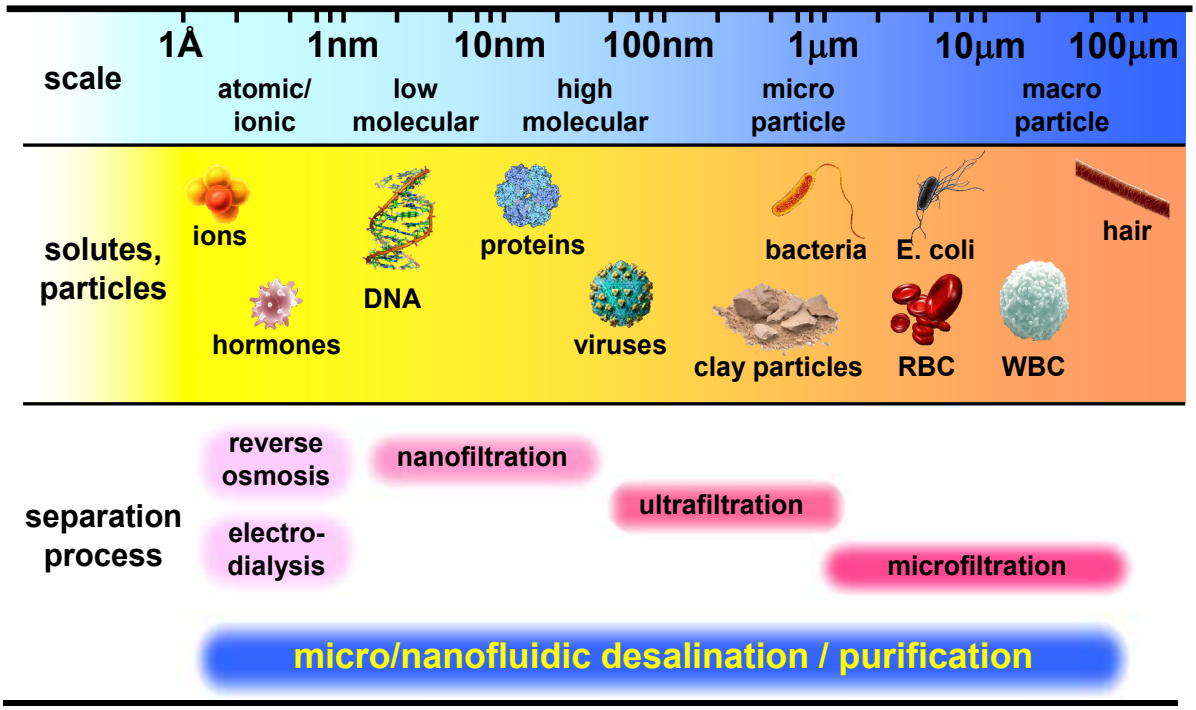

Figure 6. Removal capability of ICP desalination / purification process.

A significant portion of human population is suffering from the shortage of clean water now, especially in poverty-stricken and remote areas. In those areas, infrastructure-based water purification and delivery model is simply not workable, due to economic and other reasons. Desalination and heavy metal removal of water in a large, infrastructure scale would create an environmental challenge of brine / waste management, while a small scale (personal or household), scalable, on-demand water production could relieve much of the water shortages in developing world. The ICP system presented here can (i) desalt from highly concentrated source water like seawater, (ii) remove biological contaminants such as small cells and bacteria as summarized in Figure 6, (iii) eliminate heavy metals possibly dissolved in industrial waste and ground water in some countries, (iv) require low power consumption, enabling off-grid and self-powered operations using solar cells or batteries and (v) be scalable in response to the specific water need, from individual (or

portable) level to small village scale. This combination of capabilities has never been realized in any other previous water purification / desalination systems. We believe the ICP desalination system presented in this work would be a strong contender for future water technologies to solve the global water crisis.

5. ACKNOWLEDGEMENTS

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