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Water purification by shock electrodialysis: Deionization, filtration, separation, and disinfection ☆

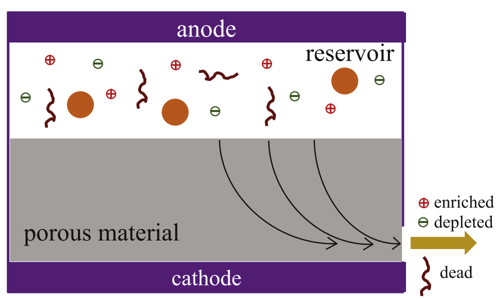
Daosheng Deng [a,2], Wassim Aouad [a,1], William A. Braff [b,3], Sven Schlumpberger [a], Matthew E. Suss [a,4], Martin Z. Bazant [a,c,*]

[a] Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[b] Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[c] Department of Mathematics, Massachusetts Institute of Technology, Cambridge, MA, USA

HIGHLIGHTS

- Experiments demonstrate the multi-functionality of shock electrodialysis.
- Besides deionization and filtration, nano-particles can be separated by charge.
- Bacteria in the feedwater are either filtered or killed by large electric fields.

GRAPHICAL ABSTRACT



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ABSTRACT

The development of energy and infrastructure efficient water purification systems is among the most critical engineering challenges facing our society. Water purification is often a multi-step process involving filtration, desalination, and disinfection of a feedstream. Shock electrodialysis (shock ED) is a newly developed technique for water desalination, leveraging the formation of ion concentration polarization (ICP) zones and deionization shock waves in microscale pores near to an ion selective element. While shock ED has been demonstrated as an effective water desalination tool, we here present evidence of other simultaneous functionalities. We show that shock ED can thoroughly filter micron-scale particles and aggregates of nanoparticles present in the feedwater. We also demonstrate that shock ED can enable disinfection of feedwaters, as approximately 99% of viable bacteria (here *Escherichia coli*) in the inflow were killed or removed by our prototype. Shock ED also separates positive from negative particles, contrary to claims that ICP acts as a virtual barrier for all charged particles. By combining these functionalities (filtration, separation and disinfection) with deionization, shock ED has the potential to enable highly compact and efficient water purification systems.

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* Corresponding author.
E-mail address: bazant@mit.edu (M.Z. Bazant).
[1] Present address: St Edmund's College, University of Cambridge, Cambridge, UK.
[2] Present address: School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA.
[3] Present address: Giner Inc., Newton, MA, USA.
[4] Present address: Faculty of Mechanical Engineering, Technion - Israel Institute of Technology, Haifa, Israel.

1. Introduction

The purification of sea or brackish water is an increasingly important process in areas suffering from water stress or scarcity [1]. State of the art water purification is performed primarily by reverse osmosis (RO) plants and in some cases by electrodialysis (ED) plants [1,2]. In RO and

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ED plants, the complete water purification process can be roughly divided into three sequential steps: i) upstream feedwater processing, ii) salt removal (desalination), and iii) downstream processing of the product water [3–5]. In RO plants, to perform desalination, the feedwater is pressurized to above its osmotic pressure, and then flows through an RO membrane which inhibits the transport of salts. In ED, feedwater is flows through an open channel between an anion and cation exchange membrane, and an appropriately directed ionic current is applied to the system, removing anions and cations (dissolved salts) from water [6,7]. Many upstream steps are required in both RO and ED purification system to prevent membrane fouling, including filtration to remove silt (membrane foulants), and pH adjustments of the feedwater [8]. Downstream processes include disinfection of the desalted water through the use of chemical additives such as chlorine [8]. Modern RO plants typically require roughly 4 kWh/m^3 of energy to purify sea water to potable water [3,5], but nearly one third of this total energy is devoted to upstream and downstream processes rather than the desalination itself [4,5]. In some cases, there can also be economic benefits of combining ED and RO in a hybrid desalination process [9].

Shock electrodialysis (shock ED) is a new technique for water desalination that differs from classical ED in several key aspects [10,11]. The theory behind shock ED is a subject of active research [11–17], so here we briefly summarize the basic concepts needed to understand our experiments. In its current realization, a shock ED cell consists of two ion selective elements (ion exchange membranes or electrodes) between which feedwater flows through a charged porous medium with thin double layers that acts as a "leaky membrane" [11,15,16] (Fig. 1). Like ED, when current is passed through the shock ED cell, an ion depleted zone is formed along an ion selective element (the cathode in Fig. 1). As the applied voltage is increased, ion concentration near this element approaches zero, and the system can reach the classical diffusion-limited current [6]. However, unlike ED, in shock ED the presence of a surface charge along the porous media's internal surfaces can enable transport of ions faster than diffusion. There are two theoretically predicted mechanisms [14]: surface conduction by electromigration through the electric double layers of the pores [14,18], which dominates in submicron pores, and surface convection by electro-osmotic flow vortices in the depleted region [14,17–19], which dominates in micron-scale or larger pores. Experiments in microchannels or pores of different sizes have recently demonstrated and visualized the surface conduction [20] and electro-osmotic flow [11] mechanisms, as well as the transition between them [21]. As a result of this "over-limiting current", the depletion zone can be propagated through the pores as a shock wave (i.e. with a sharp boundary between the depleted and undepleted zones) [12,13,15,16,22,23]. Water flowing through the depletion zone is separated and emerges from the cell as desalinated water [11]. In shock ED [10,11], an ion enrichment or brine zone is formed at the opposite ion selective element, and the formation of enriched and depleted zones at opposite ends leads to strong ion concentration polarization (ICP) [6,7].

Previously, we developed a shock ED prototype using a porous silica glass frit with micron-scale pores as the porous medium, a copper electrode as the anode-side ion selective element, and a Nafion ion exchange membrane as the cathode-side ion selective element [11]. With this device, we demonstrated the deionization of a copper sulfate solution by reducing its concentration by roughly 4 orders of magnitude in two passes (to 10 μM). Further, our measurements of overlimiting conductance suggested that the overlimiting current mechanism in our prototype device was electroosmotic flow rather than surface transport [11]. Compared to recently-developed microfluidic approaches leveraging ICP for water desalination [24,25], shock electrodialysis is a more scalable technology, as its use of porous media can enable high throughput without requiring the fabrication of many parallel microfluidic systems [11]. Another unique feature of shock ED is the ability to propagate the depletion zone controllably through micron-scale frit pores, enabling a tunable ion depletion zone which can extend to millimeters or larger in length to further increase throughput.

In this work, we demonstrate that our shock ED cell can perform a number of functions in addition to (and simultaneously with) water desalination, including filtration, disinfection, and ion separations (see Fig. 1). Both filtration and disinfection are important processes in modern water purification plants [3,8]. With our cell, we demonstrate the

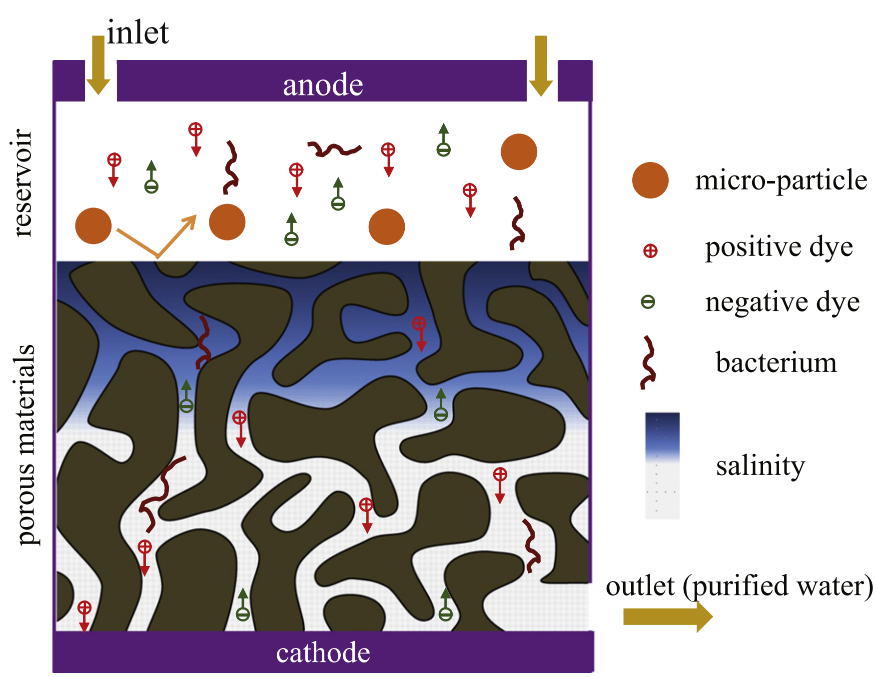

Fig. 1. Schematic demonstrating water purification with our shock ED device. Our shock ED cell consists of two ion selective elements (electrodes or ion exchange membranes) between which is placed a porous media. By passing an ionic current between the ion selective elements, a salt depletion zone is formed near to the cathode. In addition to leveraging the depletion zone to produce desalinated water, the device demonstrates other unique functionalities, including filtration of particulates, spatial separation of species by valence sign, and disinfection.