

Developing desalination techniques

In this insightful discussion, **Drs Juan Santiago** and **Michael Stadermann** explain their development of a flow-through electrode capacitive desalination system, and the opportunities it provides as a viable alternative to traditional water desalination technologies



DRS JUAN SANTIAGO AND MICHAEL STADERMANN

To begin, what are the key objectives of your research?

Our goal is to enable the next generation of technologies for providing fresh water for humanity. We are developing new forms of a technique known as capacitive desalination (CD) whereby ultra-high-surface-area porous carbon electrodes are used to electrically remove salt from water samples. CD is highly scalable, requires lower infrastructure investment than competing technologies, such as reverse osmosis (RO), and can be more energy efficient than RO as salt concentrations approach brackish water levels.

Can you outline some of the key differences between the two systems?

Traditionally, CD systems have used the 'flow-between' approach where water to be desalted is introduced into and extracted from a space between two porous electrodes. This method works, but is inefficient as much of the desalination occurs inside the finite volume of the electrodes, and thus remains inaccessible upon extraction of the water from between (but not within) the electrodes. We advocate the use of 'flow-through' architecture. We minimise the space between electrodes, flow salty water into electrode volumes, electrically desalt, and then flow the desalted water out of the electrodes themselves. This achieves our demonstrated speed-up of desalination and enables extraction of absolute amounts

of salt at levels unprecedented in CD.

How have advances in technology, particularly the invention of erogels, made the project a success and allowed for potential techniques that were not previously possible?

These materials have all of the electrical capacitance advantages of nanoporous electrodes, but offer the ability to achieve flow through method with negligible pumping power. As a substantial bonus, the hierarchy of pore scales offers low electrical resistance (through micron pores) to the sites where most ions are stored (the nanoscale pores). The whole situation is not unlike the evolution of a circulatory system in animals where large conduits transmit over large distances while small vessels help space-fill into tissue volumes.

Is this CD system capable of removing harmful germs in water?

No, all water desalination methods have separate and proven process steps to remove germs. Our fight is to get salt out of the water and our CD systems would leverage known technologies to fight germs.

What are the uses of the system and on what scale do you expect it to be implemented?

Due to its high scalability, robustness, and flexibility with feed water, we expect the method to be implemented over a wide range of applications. At small scale, there are applications to household water polishing (water softening) and personal desalination for outdoor enthusiasts. At a medium scale – eg. carried in the back of a truck – applications

include portable water desalination systems for the military or disaster aid. Large-scale applications include brackish water desalination plants for city water and the treatment of water produced from oil industry processes, such as hydrofracking.

Have you had any interest from other research groups, industry or policy makers so far?

Yes, our research has already been featured in *phys.org*, and has sparked collaborations with researchers at Wetsus in The Netherlands. We have received multiple inquiries from industry, primarily from suppliers for hydrofracking. Our research has also attracted interest from California municipalities and from the military.

Are you collaborating with other stakeholders or researchers to ensure that the system is a success?

So far, our primary collaboration is between Lawrence Livermore National Laboratory and Stanford but we are starting to reach out to other scientist in fields ranging from nanoscale electrokinetics theory to the practical engineering of nanoporous electrodes. These problems are amazingly complex and interdisciplinary and we recognise this.

Could the methods you are developing be useful in crisis situations such as drought?

Yes, CD is ideally suited for producing at small scale (up to a few thousand litres per hour), portable (on a truck bed) plants which can be dispatched to support disaster relief efforts. Unlike RO or multi-stage flash technologies, CD requires no extensive supporting equipment to generate neither high pressure, nor high temperature. Best of all, energy recovery of the charged cell is performed by an electrical circuit. By comparison, RO typically uses hydraulic turbine and electric generators to recover energy from high pressure water streams.



Turning on the water works

As the availability of freshwater declines, researchers at **Stanford University** and **Lawrence Livermore National Laboratory** are working on a water desalination system that works several times faster than existing technologies

AS THE GLOBAL population continues to rise and sources of freshwater become short in supply, water conversion technologies are predicted to emerge as the most common method of meeting the fundamental demand. Today, the most popular approach to convert saltwater to freshwater is reverse osmosis (RO); a method of water desalination that extracts water molecules from saltwater, leaving salt ions behind in the residual brine. However, alternatives do exist. Capacitive desalination (CD) – or capacitive deionisation (CDI) – has shown signs of greater viability and sustainability, operating with more energy efficiency, lower pressures and no membrane components.

A project conducted by researchers at Stanford University and Lawrence Livermore National Laboratory (LLNL) has redesigned the architecture of the common capacitive desalination system. The study has demonstrated desalination rates up to 10 times faster, with concentration reduction up to four times higher, when compared to traditional CD systems. Research findings have been published in *Energy & Environmental Science*.

Developing novel approaches to water desalination is vital given increasing scarcity of freshwater. This pressing need was the impetus for the project's inception. Led by Professor Juan Santiago from the

Department of Mechanical Engineering, Stanford University and Dr Michael Stadermann from the Department of Physical and Life Sciences, Lawrence Livermore National Laboratory, the study began with funding from California Proposition 50 – a government initiative to fund a variety of water projects – helping to improve water management, supply and safety across the state.

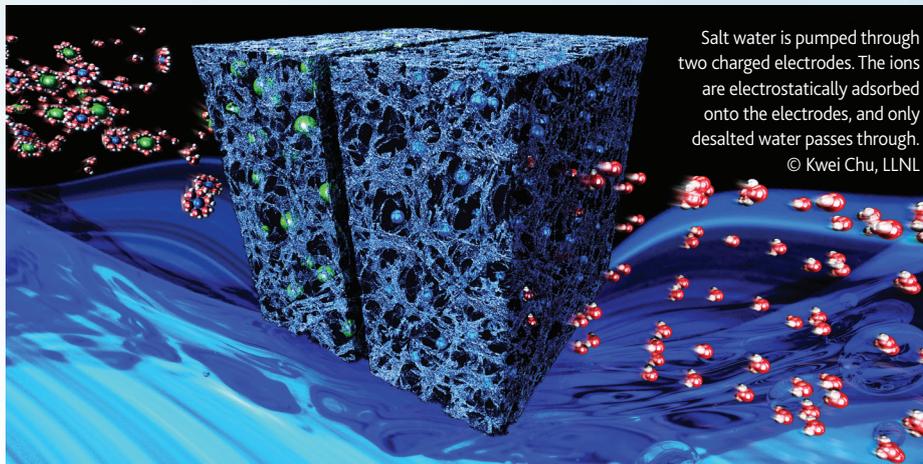
California is increasingly at the mercy of water shortages and droughts. With such water deficiencies comes a growing need for innovative technologies to ensure more economical water desalination. "The current state-of-the-art desalination technology is RO, which requires high pressures to perform water desalination, and does not perform brackish water desalination efficiently – where brackish water forms over 80 per cent of the total desalinated water volume in the US," Stadermann explains. "Capacitive water desalination, in contrast, can desalinate at very low pressures and is potentially significantly more energy efficient for brackish water desalination."

HOW CAPACITIVE DESALINATION SYSTEMS WORK

CD systems are commonly designed to allow salt feed water to travel between two porous electrodes – what experts call a 'flow between' CD system.

Through the application of voltage between these electrodes, ions in the water flow are extracted and kept in the electric double layers (EDLs), located in the micropores of the electrodes. The laws of electrical charge dictate that negatively charged chlorine anions are electrically adsorbed by the positively charged anode. Conversely, positively charged sodium cations are attracted to the negatively charged cathode. When the electrodes reach capacity, desalinated water is ejected from the system by the introduction of new feed water to the system. Removing the voltage from the electrodes releases ions into the residual brine; the brine is then flushed out, allowing the process to restart.

Although the benefits are numerous, the flow-between system also has its limitations. The first such disadvantage is the need for multiple charging steps to desalinate moderately salty water. This is because the system commonly reduces saltwater concentration by under 20 millimolar (mM) per charge. Brackish water (moderately salty water) has a salinity of up to 500 mM, whereas seawater has a salinity of over 500 mM. Therefore, reducing the salinity of even mild saltwater to around 5-10 mM may take multiple charging steps. Furthermore, because each stage of desalination can take 10 times the amount of time of system charge, the entire desalination process can prove time-consuming.



Salt water is pumped through two charged electrodes. The ions are electrostatically adsorbed onto the electrodes, and only desalted water passes through.
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This collaborative project is improving both facets of desalination through a redesign of the CD architecture. The novel process is known as a 'flow-through electrode' CD system. Its design was actually considered as early as the 1970s, but dropped due to insufficient electrode material and small pore size, which resulted in poor performance. Little research into this type of system was subsequently conducted until now.

PROJECT ADVANCEMENTS AND SUCCESSES

Advances in technology, particularly the invention of aerogels, have made the project a success and introduced previously impossible techniques. "The flow-through architecture is normally a losing proposition, given the immense resistance to liquid flow associated with pumping through nanometre-scale pores," Santiago clarifies. "On the other hand, materials with only micron-scale pores have lower resistance but poor surface area. Enter materials with a scale hierarchy. Our high efficiency derives directly from materials engineering by material scientist at LLNL – what we call hierarchical carbon aerogel monoliths (HCAM)."

Carbon aerogels are, essentially, low density polymers that are dried supercritically to maintain their pore structure and then carbonised at high temperature. Indeed, aerogels have long been known to scientists and exist in various forms. The HCAM, as created by LLNL, was developed with a structure of pore scales, giving benefit to both areas: micron scale pores allow high permeability to water flow; nanometer scale components for high surface area and electrical capacitance.

To date, the researchers have shown that their small-scale flow-through prototype has a salt sorption rate between five and 10 time higher, as well as a reduction in concentration, per charge, of between three and 10 times higher than typical flow-between CD systems.

The success of the project thus far has not come without its challenges, and two predominant ones remain. The first is the creation of a scaled-up (though still laboratory bench scale) system,

With water deficiencies comes a growing need for innovative technologies to ensure more economical water desalination

which must achieve efficient desalination of 10-100 litres of water per day. The second obstacle is the optimisation of the electrode pore architecture to abate dispersion; lessen the interspersing of desalted and undesalted streams flowing through the porous electrodes. Minimising this dispersion will improve efficiency of high-salt water desalination.

THE FUTURE OF WATER DESALINATION

The researchers believe that CD systems could have an enormous impact on the process of saltwater desalination, especially on a small scale, such as for truck-bed-sized devices for disaster relief. In the future, the project aims to improve yet another benefit of the flow through system: its ability to operate for numerous stages. "While multiple-stage CD desalination is possible with flow-between, it is usually much harder to achieve than single-stage," Stadermann outlines. "CD has therefore been mostly confined to salinities that can be desalted in a single stage. We think that flow-through CD should be much easier to stage due to easier separation of desalination."

A next step would be to build a multi-stage pilot system that can desalinate water streams with higher salinity and demonstrate desalination of sea water with good energy efficiency. Indeed, the long-term plan is to scale up and lessen the cost of material synthesis, which will hopefully lead to the commercialisation of their innovative technology. Over the next five years, the two researchers are excited by the potential of an explosion of CD technology across the world; establishing it as the main alternative to traditional desalination technologies.

INTELLIGENCE

CAPACITIVE DESALINATION WITH FLOW THROUGH ARCHITECTURE

OBJECTIVES

To develop highly efficient sea and brackish water desalination (ion removal) devices. The group is researching ion concentration shock waves created by concentration polarisation, performing controlled experiments and developing models of key phenomena, which will be utilised to develop highly efficient devices.

FUNDING

National Science Foundation – award no. 0967600

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DR MICHAEL STADERMANN received his PhD in Physical Chemistry from the University of North Carolina at Chapel Hill in 2004. His research focuses on nanostructured materials, such as nanotubes, graphene, aerogels, properties of materials at the nanoscale, and the application of these materials for energy storage, catalysis and desalination. He has authored and co-authored 30 archival publications and two patents.

DR JUAN SANTIAGO received his MS and PhD in Mechanical Engineering from the University of Illinois at Urbana-Champaign in 1995. His research includes the development of microsystems for on-chip chemical and biochemical analysis, methods for sample preparation, miniature pumps and electric-field based deionisation methods. He is a Fellow of the American Physical Society, a Fellow of the American Society of Mechanical Engineering, an Associate Editor of the journal *Lab on a Chip*, co-founder of Cooligy Inc, co-inventor of micron-resolution particle image velocimetry (Micro-PIV) and Director of the Stanford Microfluidics Laboratory.



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