FIRST Center Research Perspective:

Title: Electrochemical Flow Capacitor

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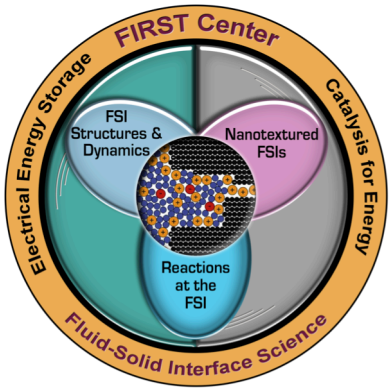

Research Summary: We developed the Electrochemical Flow Capacitor (EFC) concept, which couples the extremely high power density and cyclability of electrical double layer capacitors (EDLCs) with energy storage capacity rivaling battery systems, enabled by storage of a porous carbon-particle suspension in an electrolyte in scalable reservoirs external to the flow-electrode system. We investigated the effect of particle size, shape, and rheological properties of the particle suspensions in aqueous electrolytes as a function of particle concentration, flow channel geometry, electrolyte concentration and pseudocapacitive energy density.

Technical Details:

With the increasing usage of renewable energy, the grid requires highly efficient technologies that can *quickly respond* to large, rapid fluctuations in energy generation and demand. Current grid storage technologies suffer from slow response rates (flow batteries), moderate efficiency at a high cost (Li-ion batteries), limited life (molten salt batteries), and costly scalability (flywheels). The most important metrics for grid storage are \$/kWh/cycle and \$/kWh/year rather than energy density. Therefore, supercapacitors have great potential for these applications because of their rapid charge/discharge ability in the electrical double layer (EDL); however they suffer from high cost and self-discharge.

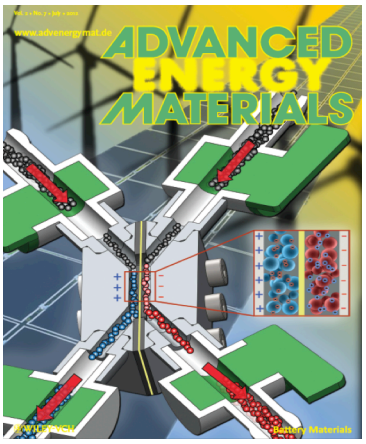

Figure I. In the archetypical EFC, nanoporous, micron-scale carbon spheres (grey, top), suspended in aqueous Na_2SO_4, are pumped into an electrode assembly (inset), where they become positively (blue) or negatively (red) charged by collision with electrode surfaces, inducing EDL charge storage on the particle surfaces. Charged particles are pumped to storage reservoirs, and the EFC is discharged by reversing the process (Presser, 2012).

The EFC concept (**Figure I**), invented at Drexel University with FIRST Center support (patent pending), exploits the characteristics of both EDLCs and flow batteries, enabling rapid charge/discharge *(i.e.* high power density) while decoupling energy storage from power, i.e., offering scalable energy capacity (Presser, 2012; Campos, 2013; Dennison, 2013; Hatzel, 2013). The EFC has the potential to eliminate the major limitations of electrochemical capacitors (ECs) and become an attractive low-cost alternative for grid-scale energy storage. This new concept exploits the characteristics of both ECs and flow batteries and enables rapid charge/discharge (i.e., fast response rates with high power density) while decoupling energy storage from power (i.e., scalable energy capacity). The EFC is envisioned as operating in a similar manner as a redox flow battery. The unique aspect of this concept is **to employ a flowable carbon slurry for capacitive energy storage**, which is pumped between two

electrodes to be charged or discharged. Ion transport between the electrodes occurs through an ion-permeable porous membrane. *In the EFC, the energy storage is determined by the size of the tanks, whereas the power is dictated by the discharge cell. Therefore the energy storage capacity and the power output are decoupled.* The combination of high power, scalable energy capacity, fast charge/discharge, and long lifetime make the EFC well suited for energy recovery and storage in smart-grid and renewable energy applications.

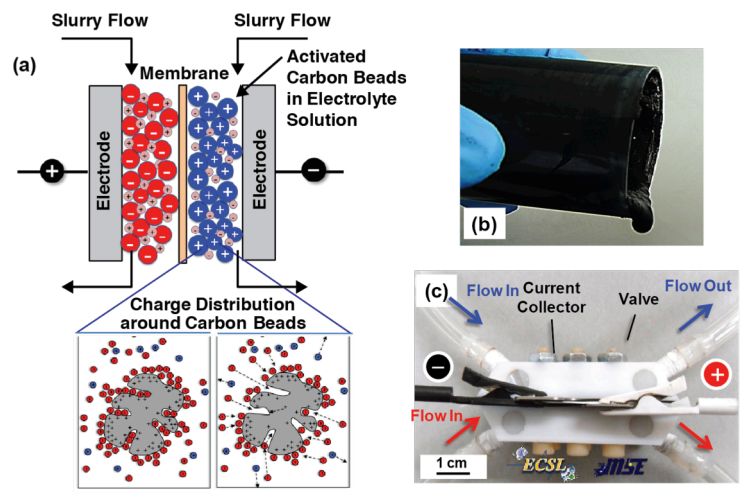

Figure 2. (a) Schematic of operation of EFC and charge distribution in the cell; (b) flowable carbon slurry; (c) Flow capacitor cell design used for initial experiments.

Our team has performed a proof-of-concept study to show the feasibility of the EFC. A lab-scale EFC cell was designed and tested using carbon slurries that consist of activated carbon beads in aqueous, organic, and ionic liquid electrolytes (**Figure 2**). The tested slurry was observed to store and recover energy at a high coulombic efficiency (~98%) at fast charge/discharge rates, while maintaining a specific capacitance (~100 F/g) similar to those seen in static ECs (**Figure 3**). Virtually no loss of efficiency was observed, even after 2200+ cycles (Figure 3), and round-trip energy efficiencies of 94% were measured. Although self-discharge represents one potential issue for EFCs, our initial study suggests that this can be greatly reduced by storing the charged materials in ionically- and electronically-insulated reservoirs to eliminate shunt currents during storage.

To fully develop the EFC concept, several fundamental questions must be addressed. Of central

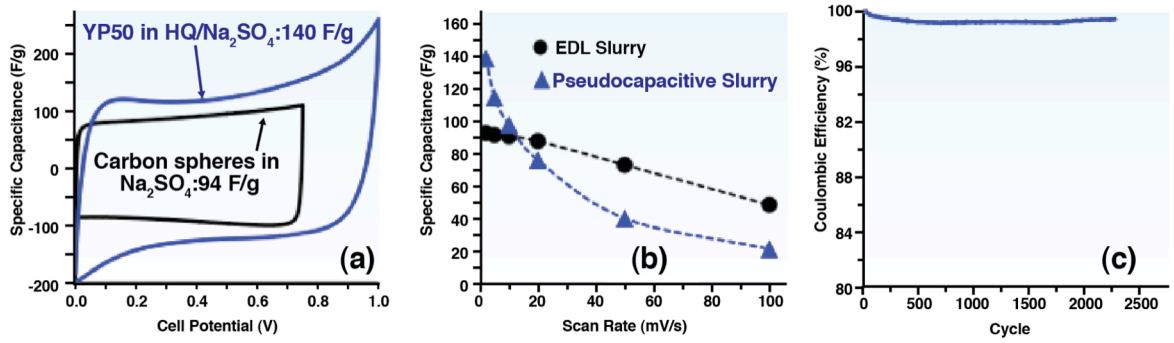

Figure 3. (a) Capacitive behavior of EDLC slurry (carbon in aqueous electrolyte, shown in black) and pseudocapacitive slurry (i.e., YP50 activated carbon in aqueous electrolyte with hydroquinone, shown in blue) at 2 mV/s (Note the rectangular shape of the carbon slurry CV, which is similar to the best conventional EDLCs); (b) Rate performance for the slurries and (c) Coulombic efficiency of EDL slurry over extended galvanostatic cycling.

importance are issues related to charge storage and charge distribution in porous carbon particles

suspended in an electrolyte, and the rheological behavior of the carbon slurry. Motivated by these issues, our research is directed towards a fundamental understanding of how the electrolyte composition and carbon loading affect the system capacitance, charge transport within the carbon particles, and flow characteristics of the slurry. Detailed studies of EFCs with different slurry chemistries are being conducted. Aqueous electrolytes have been tested as a low-cost electrolyte option for initial benchmarking.

In particular, we have addressed the following fundamental issues:

(a) Exploring methods to increase energy density within suspension-type electrodes. This investigation examined methods to increase the capacitance of carbon materials and methods to expand the voltage window.
(b) Understanding the effects of surface functionalization on electrochemical performance. The effect on capacitance and self-discharge have been explored.

Significant Impacts on Science and Technology: The EFC concept combines the characteristics of both EDLCs and flow batteries, enabling rapid charge/discharge *(i.e.* high power density) while decoupling energy storage from power. This is a new approach to scalable energy storage that may find applications in other energy storage and recovery technologies.

Publications and Manuscripts:

1. V. Presser, C. R. Dennison, J. Campos, K. W. Knehr, E. C. Kumbur, Y. Gogotsi, The Electrochemical Flow Capacitor: A New Concept for Rapid Energy Storage and Recovery, *Advanced Energy Materials*, **2**, 895–902 (2012)
2. K. B. Hatzell, M. Beidaghi, J. W. Campos, C. R. Dennison, E. C. Kumbur, Y. Gogotsi, A High Performance Pseudocapacitive Suspension Electrode for the Electrochemical Flow Capacitor, *Electrochimica Acta*, **111**, 888-897 (2013)
3. J. W. Campos, M. Beidaghi, K. B. Hatzell, C. R. Dennison, B. Musci, V. Presser, E. C. Kumbur, Yury Gogotsi, Investigation of Carbon Materials for Use as a Flowable Electrode in Electrochemical Flow Capacitors, *Electrochimica Acta,* **98**, 123-130 (2013)
4. C. R. Dennison, M. Beidaghi, K. B. Hatzell, J. W. Campos, Y. Gogotsi, E. C. Kumbur, Effects of Flow Cell Design on Charge Percolation and Storage in the Carbon Slurry Electrodes of Electrochemical Flow Capacitors, *J. Power Sources*, **247**, 489-496 (2014)