Electronic Supplementary Information for "Thermo-electrochemical Generator: Energy Harvesting & Thermoregulation for Liquid Cooling Applications"

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1 Stationary thermo-electrochemical (sTEC) and flow thermo-electrochemical (fTEC)

The following schematic shows the stationary and flow electrolyte TECs. In the flowing electrolyte, forced convection assist ion transport between electrodes. In addition the transport of ions is uni-directional.

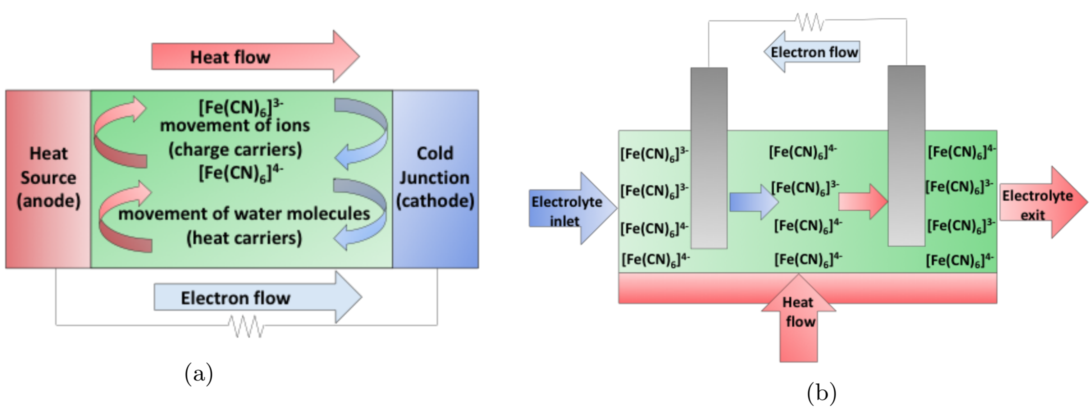

Figure 1: A canonical example of oxidation/reduction at hot and cold anode and cathodes for an *sTEC*(a), and a *fTEC* (b).

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2 COMSOL Simulation

COMSOL Multiphysics model was developed using heat and mass transfer, Butler-volmer, Nernst-planck and Navier stokes equations. The results for the COMSOL simulation for bottom plate at constant temperature boundary condition are shown below:

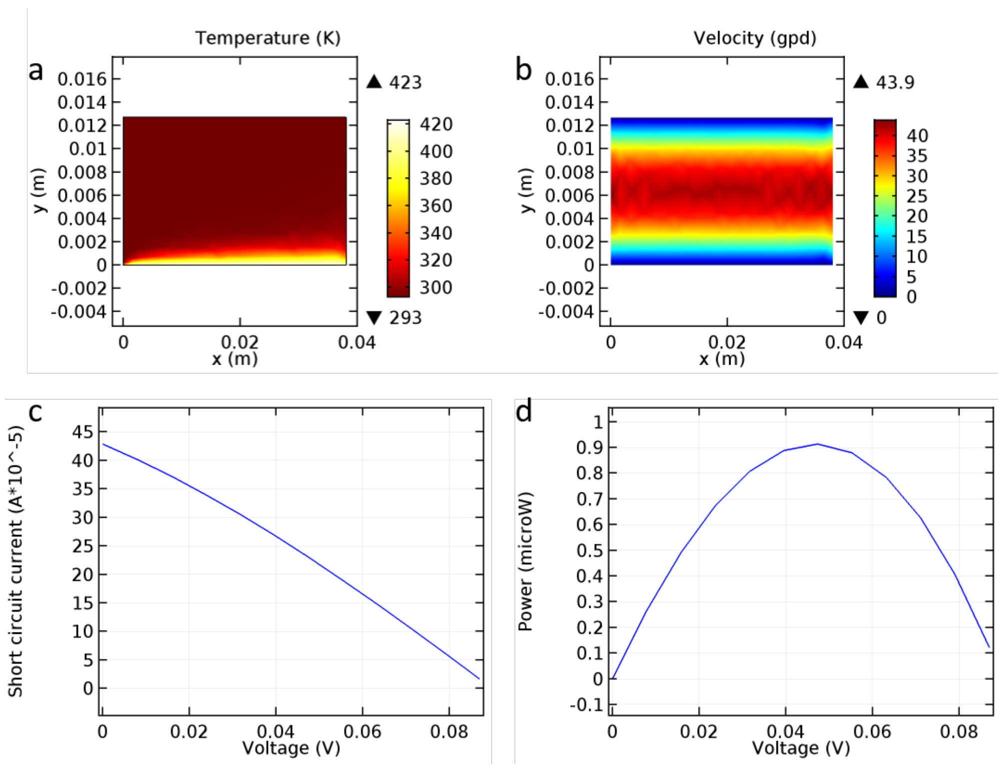


Figure 2: COMSOL modeling for average flow rate of 28.16 gpd and distance between the electrodes of 1.5" (a) Surface plot of temperature distribution (b) Surface plot of velocity distribution (c) Current vs voltage (d) Power vs voltage.

The temperature profile of the electrolyte is shown in Fig.2a. Temperature profile shows that convective fluid is effective in maintaining a high temperature difference. The velocity profile is shown in Fig.2b, shows that the maximum velocity is near the center line and that no-slip boundary condition is at the surface of top and bottom plate. The power performance is given by Fig.2c and Fig.2d.As expected a linear relationship exists between voltage and current. The maximum power corresponds to half open circuit voltage, this is where the internal resistance of thermocell equals the external resistance. As the voltage and resistances are equal, the corresponding current is equal as well and the maximum power is given by equation 15 of the main manuscript.

3 Electrode Configuration that Maximizes P_{out}

In order to maximize P_{out} we need to maximize the temperature gradient in between anode and cathode surfaces without moving them far apart. We simulated the electrode surfaces on the top and bottom of the flow channel, on the plane perpendicular to the direction of heat flux shown in Fig.3. This design will also help establish a direct relationship between the of amount of power produced by cooling with respect to flow rate.

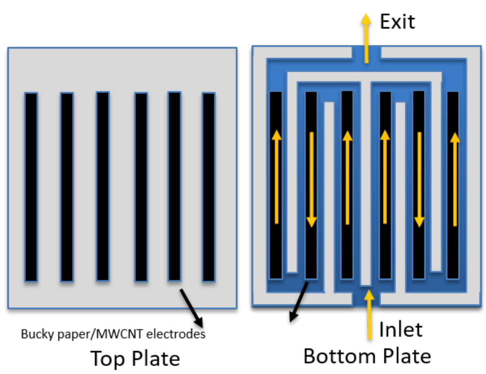


Figure 3: Electrode configuration on top and bottom plate

Having the electrodes located on top and bottom plates will increase the maximum power output due to availability of higher temperature difference. COMSOL simulation was carried out to estimate the increase in power, shown in Fig.4.

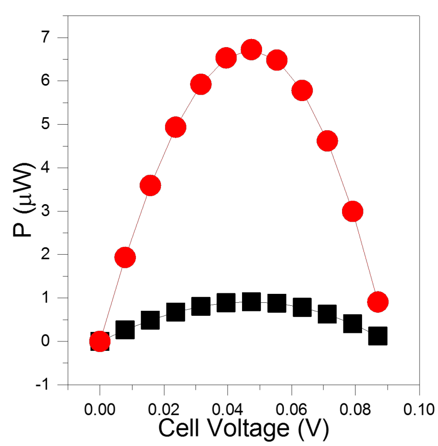


Figure 4: COMSOL simulation, power comparison between electrode on just the top plate (black square) vs those on both the top and bottom plate(red circle). Observe almost a 7x increase in maximum power output.

4 Proposed Design for Harvesting Energy from Waste-heat in an Electric Vehicle Battery Pack

Effective thermal management of batteries is integral for battery safety. By implementing the technology studied in this paper, in the following manner, we can read out a comprehensive temperature distribution of the coolant simply based off of the voltage and power output at different electrode surface pairs as shown in Fig.5. This would complement existing safety features found in these battery packs.

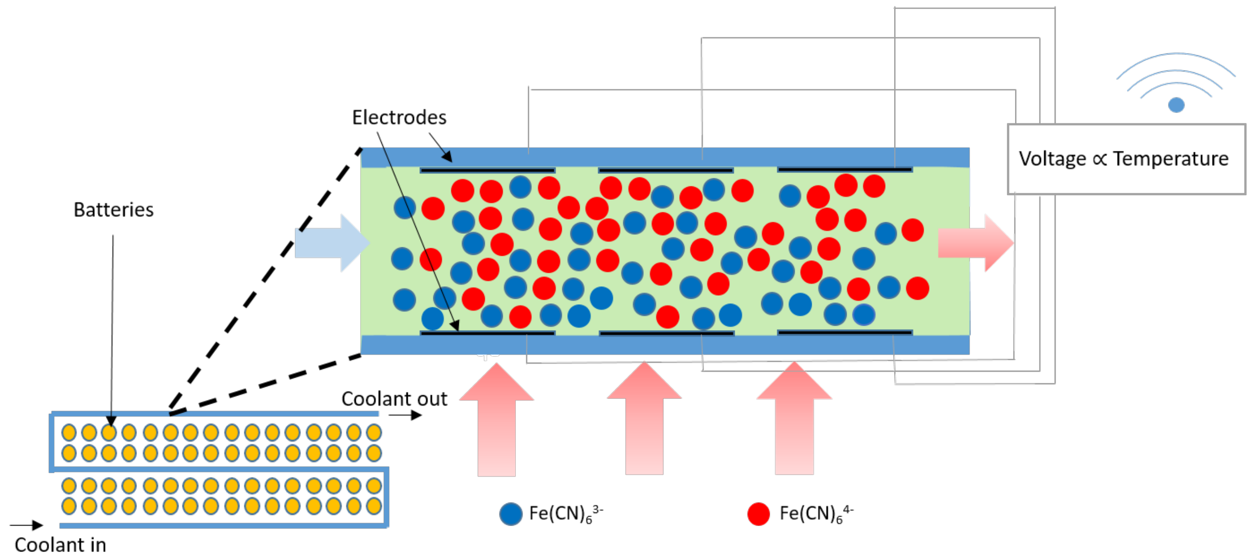


Figure 5: Bottom left is a typical configuration in battery pack used in electric vehicles. Cell are shown surrounded by pipes carrying coolant. The zoomed in portion of the pipe shows a proposed configuration to harvest energy from waste-heat emitted. In doing so we can sense temperature and communicate the information via a wireless signal.

5 Design Considerations

A discussion of the flow cell, electrode, and fluid system design and manufacturing is performed in the following sections. A three dimensional system rendering is seen in Figure 6 and actual plate is see in Figure 7a and 7b . The electrolyte begins in a sealed thermostatic bath, and is pumped through the cold plate system, over the electrode and temperature probes, through a heat exchanger system, and back into the reservoir. Temperature voltage and current outputs between electrodes, as well as the flow rate, were measured and reported. A global schematic of the system is seen in Figure 8.

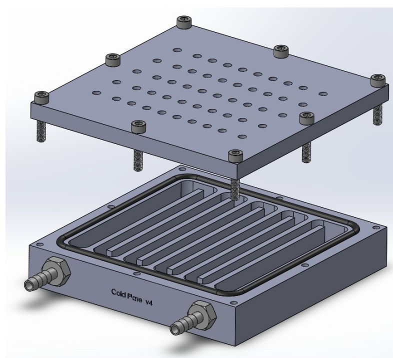


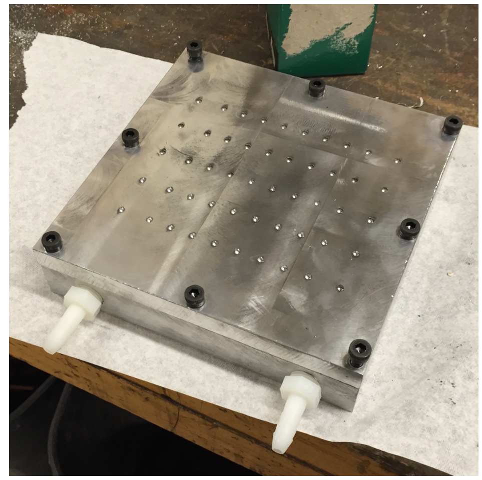
Figure 6: Cold plate design for testing the voltage output of a mass transport of potassium ferri/ferrocyanide using CNT's as electrodes. The NPT fittings on either end were connected to rubber tubing through which the electrolytic fluid flowed. The cold plate is sealed by a silicon gel, which was placed into the ring surrounding the plate. The probes were inserted into the hole matrix according to the experimental design.

5.1 Cold Plate

The cold plate's function is two fold: to draw heat from an external heat source, and to generate a voltage output from the thermal gradient by utilizing an aqueous solution of a redox couple as a working fluid. An aluminum plate was fabricated with a single channel design, to maximize heat transfer away from a heat source, and a sealed variable electrode placement to allow for the study of power output as a function of the inter-electrode distance and electrode temperature. Ultimately, the cold plate serves as a medium through which the electrolyte will flow, so it is imperative that it's design leak-free.

The electrolytic fluid was pumped into the system via two NPT barbed fittings and a peristaltic pump. The range of flow rates that were tested were 28.16-93.87 gal/day. The electronic metering pump set the flow rate directly, without the need for a flow meter. Chemically inert rubber tubing, was connected from the external pump to the barbed fittings, and the fluid flowed through them. In order to extract necessary parameters from

(a)



(b)

Figure 7: (a) The physical cold plate consists of a single channel running along the entire area of the plate. The plate is water tight, and has an inlet and outlet for the fluid. The matrix of holes on the top part of the plate house the electrodes. (b) The system in its operating state.

this system, flow and temperature sensors were added in-line. In-line thermocouples were placed, along with the electrodes, into the electrode holes in order to make fluid temperature measurements.

5.2 Electrodes

The electrodes are critical to the setup, as they are where the ions exchange electrons with the electrodes. As such, they must satisfy certain design requirements: they must be small enough to fit into the electrode holes on the cold plate and they must be electrically isolated from the cold plate. Graphite electrodes were used as electrodes. The electrodes were electrically isolated from the top plate by rubber tubing.

5.3 Fluid System

A closed loop fluid system was desirable for this experiment, as shown in 8. The difference between a closed loop and open loop fluidic system is that in the closed loop, the fluid passes through the flow cell (after having undergone an increase in temperature) and then has its excess heat dissipated through an external heat exchanger, before returning to the fluid reservoir. It is important to note that anodized aluminum plate was used to ensure that electrodes are the only surfaces where potassium ferri/ferrocyanide electrolyte can react. The chemical compatibility between aluminum/304 316 stainless steel proved to be moderate and

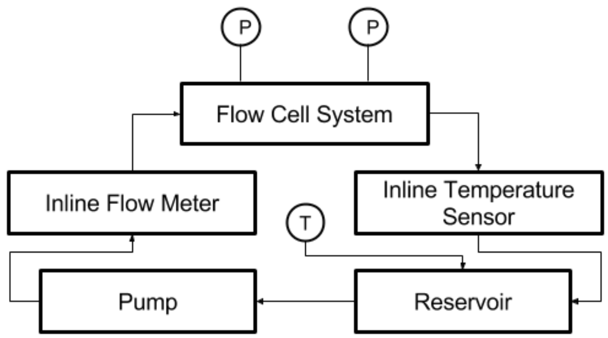


Figure 8: The system consists of a reservoir, in which the redox couple fluid is housed (and maintained at a constant temperature), a pump, and associated sensors. The flow cell system is a cold plate, mounted onto a hot plate. The cold plate contains probes, as specified above.

suitable for this experiment. All connectors are NPT with chemically inert rubber tubing connecting the components of the system. A variable pump was utilized to set and determine the flow rate of the electrolyte through the system. Temperature measurements of the fluid were performed with an in-line K-type thermocouples.

The working fluid for this experiment was a 1:1 potassium ferri/ferro cyanide equimolar solution. For this experimentation, an electrolyte close to saturation, maximizes the kinetics of the chemical reaction, resulting in an increased voltage output. As such, a 0.4 M solution was used, the highest possible redox couple concentration, but still low enough to avoid electrolyte degradation at high concentrations.

Since we desire a 0.4 M solution, utilizing a 5000 mL container, we need $0.4M * 5L = 2$ moles total. The solution should be equimolar ($K_3(FeCN)_6 = 329.24$ g/mol and $K_4(FeCN)_6 = 422.39$ g/mol), therefore we need 2 moles of each solute. This results in

$$\boxed{\text{mass of } K_3(FeCN)_6 = 658.48 \text{ g}}$$

$$\boxed{\text{mass of } K_4(FeCN)_6 = 844.78 \text{ g}}.$$

5.4 Data Collection Methods

The main parameters of interest in the system are the flow rate, the temperature of the fluid at the electrodes, and the voltage/current output at the electrodes for a given electrode distance. The flow rate was set by the pump. To collect electrolyte temperature, in-line K-type thermocouples were utilized at the electrode locations, and a temperature probe was utilized in the reservoir bath to monitor fluid inlet temperature. The electrode voltage and current outputs were measured using a potentiostat.

6 Amount of energy harvested in data center

The amount of energy harvested is estimated by using specification of sever rack used in a typical data center. Each server rack has typically 8-16 cores having CPU of dimension of 54 * 45 mm. For a conservative estimate 8 cores were used for calculation. There are 30 servers present per rack and rack has physical footprint of 11 ft^2. Following table shows the estimate for the amount of energy harvested using thermocell.

	Thermocell Wattage per square meter (A)	Area of CPU in square meter (B)	Wattage per CPU (A*B)	No. of cores Core (C)	Wattage per server (A*B*C)	No. of servers (D)	Wattage per rack (A*B*C*D)	Rack area in square feet (E)	Wattage per square feet(A*B*C*D/E)	Facility size in sqaure feet (F)	Energy harvested in Watts (A*B*C*D*F/E)
Current production	0.049600099	0.00234	0.000116064	8	0.000929	30	0.027855416	11	0.002532311	100000	253.2310519
Best possible	12	0.00234	0.02808	8	0.22464	30	6.7392	11	0.612654545	100000	61265.45455

Figure 9: Estimate of amount of energy harvested from 100,000 square feet facility.