Electrohydrodynamic Thermal Oscillators for Waste Heat Harvesting Applications

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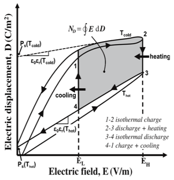
Abstract

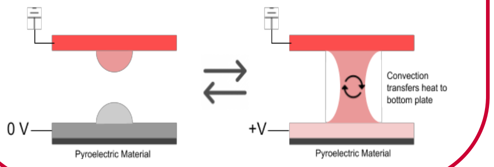
Pyroelectric materials generate electrical power when exposed to an oscillating heat source. This work attempts to design and test the efficiency of a novel liquid based thermal oscillator which utilizes electrohydrodynamic (EHD) capillary bridging and debridging to periodically heat a pyroelectric layer. Preliminary testing of various liquids was conducted in order to determine which liquids were able to successfully form and break capillary bridges. High molecular weight fatty acids/triglycerides, usually unsaturated and with polar groups were most effective. Contact angle of the liquid droplets were measured at different temperatures, durations and during bridging to understand surface interactions. Finally, thermal tests were conducted with the pyroelectric layer and liquid droplet EHD switches, resulting in efficient thermal cycling of 0.35-0.5C and a power density of 12.15 W/m² produced through the Olsen cycle. These liquid thermal oscillators show potential in future waste heat harvesting applications.

Background

It is estimated that conversion of waste heat into electricity can reduce US energy needs by 12% and CO2 production by 13%.[1] One method of waste heat recovery that has seen recent success is through use of pyroelectric materials. Pyroelectric materials have a crystal structure that produces a temporary voltage when a temperature change is applied. However, to efficiently produce electrical power using pyroelectrics, a thermal oscillator must be used to periodically heat and cool the pyroelectric layer. This thermal oscillation, along with a small applied voltage, allows the pyroelectric material to generate power through the Olsen Cycle.

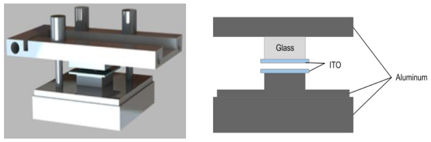


Our work involves the development and testing of a novel liquid based thermal oscillator, which utilizes electrohydrodynamic capillary bridging to rapidly heat and cool a pyroelectric layer. The general device we have developed consists of two parallel plates with one or more droplets in between. When a voltage is cyclically applied between the parallel plates, the droplets alternate between a bridged and debridged state, transferring heat from the hot plate to the pyroelectric material periodically, allowing for power generation.



Methods

Design and Modification of Testing Setup

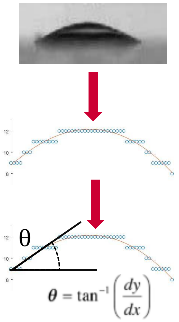


Gen 1 (Top): Used mainly for initial liquid EHD tests

Gen 2 (Bottom): Added PZT (pyroelectric material) with Olsen voltage, extended aluminum frame for better heat transfer to top ITO, better thermocouple placement

Contact Angle (CA) Analysis

Effects of silane surface modifications were measured using contact angle analysis in MATLAB



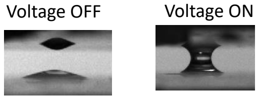
$$\theta = \tan^{-1}\left(\frac{dy}{dx}\right)$$

Testing of optimal liquid for EHD capillary bridging

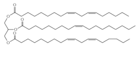
Various liquids were tested for the ability to form stable capillary bridges under electric field and break these bridges once E-field is turned off. Various combinations of gap widths between 0.5-1.75mm and voltages of 0-5kV were tested

Liquids Tested:

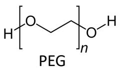
- Water
- Silicone Oil - 5 cSt
- Silicone Oil - 350 cSt
- N-Methyl-2-pyrrolidone
- Triton X-45
- TritonX-100
- EMIMBF4*
- Hexadecane
- Glycerol
- α-Terpineol
- Polyethylene Glycol
- Glyceryl triacetate
- Glyceryl caprylate
- Glyceryl trioleate
- Canola Oil
- Castor oil
- Oleyl Alcohol
- Dielectric Oil**



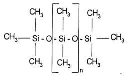
Examples of Compounds Tested:



Triglycerides and fatty acids



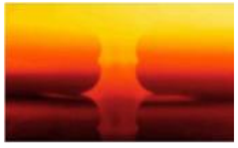
PEG



Silicone Oils

EHD x Thermal Tests

EHD tests were conducted with the top Al frame heated to 80°C and an array of droplets to maximize heat transfer



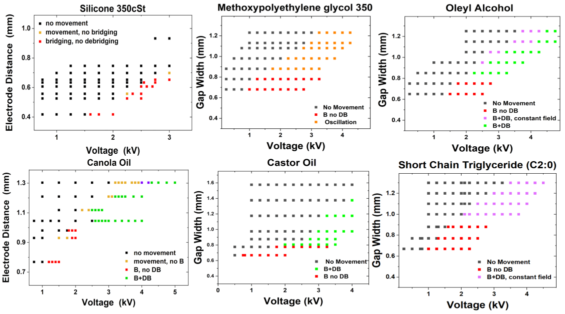
Temperature fluctuations were measured using IR camera and power produced by PZT through Olsen cycle was plotted in MATLAB

Results

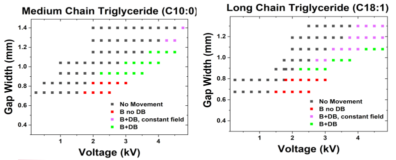
Optimal Liquids for EHD

5 possible outcomes for each test

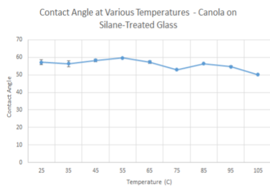
1) B+DB: bridge when voltage on and debridge when voltage off (desired)
2) B+DB, constant field: droplet bridges and debridges while voltage still on
3) B no DB: droplet bridges, but doesn't debridge when voltage turned off
4) Oscillation: droplet moves up and down in place, but never bridges
5) No Movement

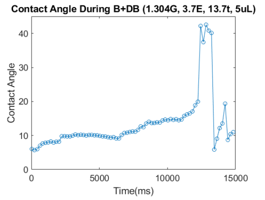


- Most liquids (Silicone oils, Triton, PEG) displayed no movement at low voltages, B no DB at low gap widths and oscillatory behavior at higher gap widths
- Vegetable oil, and more generally triglycerides and fatty acids with double bonds and polar groups exhibited most consistent B+DB behavior at high voltage and gap width
- In triglyceride fatty acid chain length test, medium and long chain successful, short chain ineffective



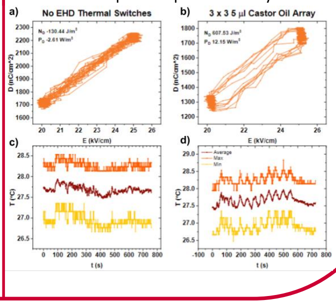
Contact Angle Studies





EHD x Thermal Tests

Thermal oscillations due to castor oil droplet bridging resulted in consistent temperature oscillations and positive power density



Discussion

- EHD tests with various liquids showed that high molecular weight, unsaturated (double bonded) fatty acids and triglycerides exhibited optimal capillary bridging behavior
- Contact angle studies showed that CA was stable at high temperatures and durations
  - Effect of lowered viscosity at high temperatures is more significant than any slight changes in CA
- Contact angle starts to increase as soon as voltage turned on and reaches ~40° during bridging (canola)
- Successful thermal oscillations of 0.35-0.5°C were observed with 3x3 castor oil droplet array
- Positive energy/power density produced by pyroelectric material shows effectiveness of thermal oscillator

Future Work

- Use inkjet printer to print larger arrays of droplets with smaller volumes to maximize heat transfer and minimize gap width/voltage required
- Analyze capillary bridge profile
- Ensure repeatability of EHD x Thermal test by being more careful with synchronization process in MATLAB

References

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