High Efficiency Waste Heat Harvesting Using Novel Thermal Oscillators

Contract Number: DE-EE0008314

University of Pennsylvania; Rutgers University; Yale University

09/2018-08/2020

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Speaker: Michael Loewenberg, Yale University

U.S. DOE Advanced Manufacturing Office Program Review Meeting
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Overview

Timeline

- Award made: 08/2018
- Project started: 09/2018
- Project Performance period: 09/2018-08/2020

AMO MYPP Connection

- Waste Heat Recovery Systems

Budget

	FY 18 Costs	FY 19 Costs	FY 20 Costs	Total Planned Funding
DOE Funded	_	$480K	$480K	$960K
Cost Share	_	$120K	$120K	$240K
Expenditure (DOE/cost share)	_	$33.6K/$ 28.3K	_	

Barriers

- High performance pyroelectric harvesting of low-grade waste heat requires efficient, simple thermal switching to control heat flows.
- Suitable thermal switches have yet to be developed.

Partners

- University of Pennsylvania (Lead)
  - Materials processing
  - Device fabrication and characterization
- Yale University
  - Materials synthesis; Device modeling
- Rutgers University
  - Device fabrication and characterization

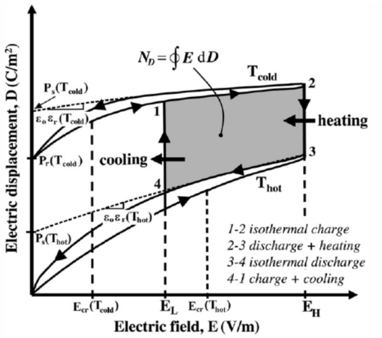
Project Objective(s)

- Pyroelectric (PE) waste heat harvesting is compelling:
  - Current PE materials are intrinsically capable of efficiencies that eclipse current thermoelectric materials.
- PE harvesting requires *periodic* variation of the temperature of a generating device placed in contact with a *steady* heat source.
- Efficient and sustained generation of such temperature variations in PE devices is the critical barrier to practical PE waste heat harvesting.
- **Objective**: Enable practical energy recovery from low temperature waste heat with unprecedented efficiency using pyroelectric materials in manufacturing-relevant settings.
  - Approach: Develop and model switching technology relevant for manufacturing
    - Passive and active switching
  - Target: "Bolt-on" devices; $1/Watt, 35% efficiency (Carnot).
  - Target represents ~5X efficiency improvement.

Technical Innovation

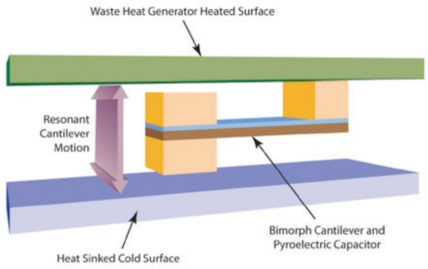
- PE harvesting has been explored largely using MEMS devices and large-scale thermal cycling by pumped fluids.
- **Limitations**:
  - MEMS devices: Complex; costly; not readily scalable.
  - Pumped fluids: Large frictional losses; not easily deployed.
- **Proposed Approach**: Develop simple thin planar devices that can be "bolted on" to warm surfaces
- Thermal switching in planar devices by development of new, scalable thermal management solutions:
  - Shape memory contact switching (passive)
  - Electrohydrodynamic switching (active)
- Critical Innovations:
  1. Scalable fabrication.
  2. Efficient switching.
  3. Geometry enables easy deployment/installation.

Technical Innovation



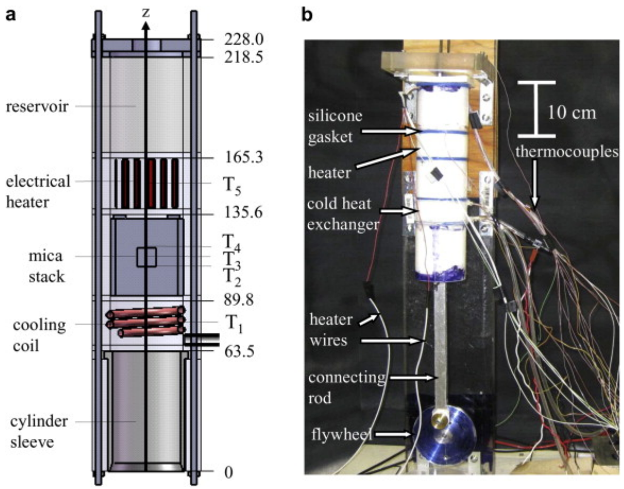
Navid, A. et al. *Int. J. of Heat and Mass Trans.* (2010)

MEMS device



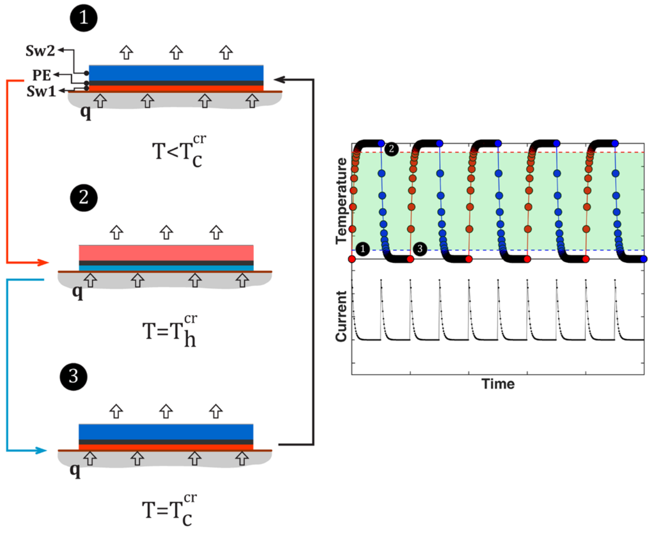
Datskos, P. G. et al. International Society for Optics and Photonics (2011)

Pumped fluid device



Pilon, L. et al. *Applied thermal engineering,* **30**(14): p. 2127-2137 (2010)

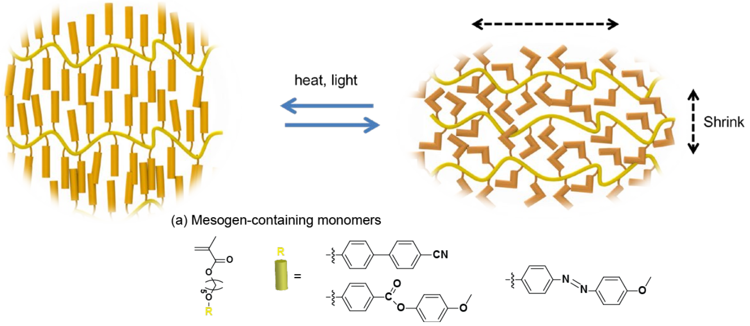
Thermal oscillator planar device

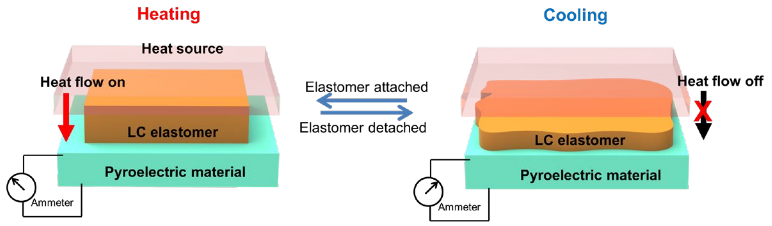


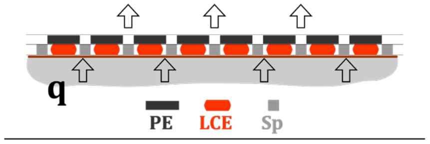
KEY CONCEPTS : Pyroelectric energy generation from waste heat is compelling due to impressive intrinsic efficiencies which far surpass thermoelectric conversion. The inability to readily generate sustained temperature cycles in compact systems represents the single biggest challenge to practical energy recovery using pyroelectric devices today. Prior research efforts have explored MEMS devices and fluid circulators for thermal switching. The proposed work will develop unique "thermal oscillator" switches to enable practical and efficient planar PE energy harvesting devices.

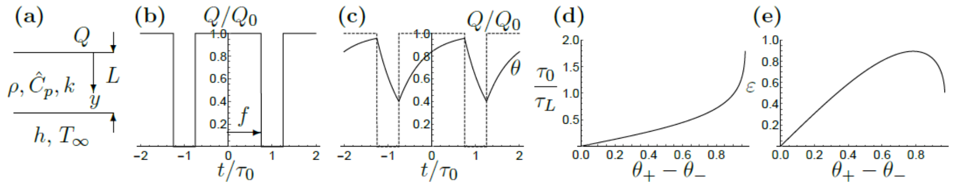
Technical Approach A

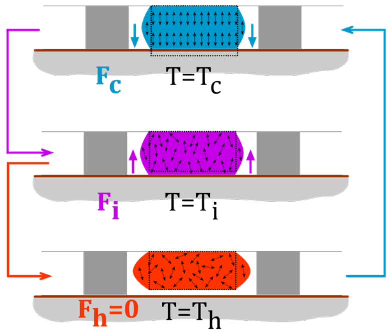
- Thermally actuated shape memory switches











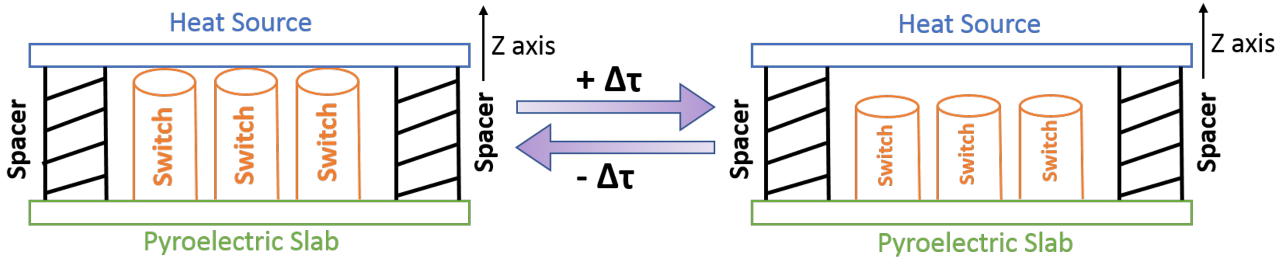
Modeling: *Lumped*, *distributed parameter*, and *multiscale* calculations.

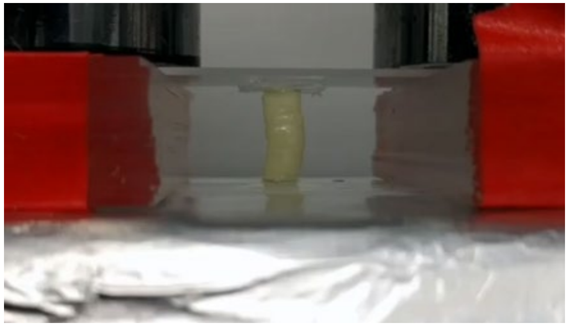
Osuji: Processing of LCEs; Device fabrication and characterization; Thermophysical property optimization.
Zhong: Molecular engineering and synthesis of LCEs; Thermophysical property optimization.
Loewenberg: Modeling of transport properties
Singer: Materials property characterization.

Shape memory passive switching: Shape memory effect (SME) in aligned liquid crystalline elastomers (LCEs) produce reversible dimensional changes on heating and cooling above LC clearing temperatures. **Materials and Methods:** Acrylate LC polymers; cyanobiphenyl and azobenzene mesogens; mechanical and magnetic field alignment. P(VDF-TrFE) and other PEs. Transport modeling. **Shape Memory Thermal Oscillator (SMTO) Challenge:** Engineering shape memory effects to reversibly make and break thermal contacts to control heat flow to a pyroelectric layer.

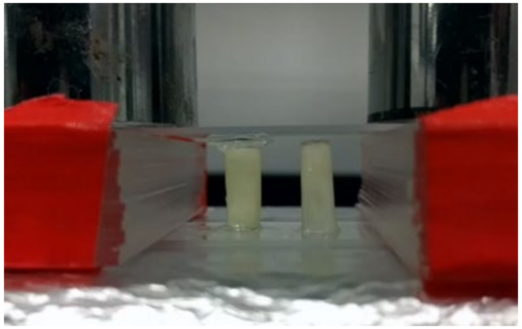
Technical Approach A

- Successfully demonstrated detachment and re-attachment of thermal switch to hot surface utilizing adhesive tab.
- <u>Future</u>: Characterization of switching in test devices.





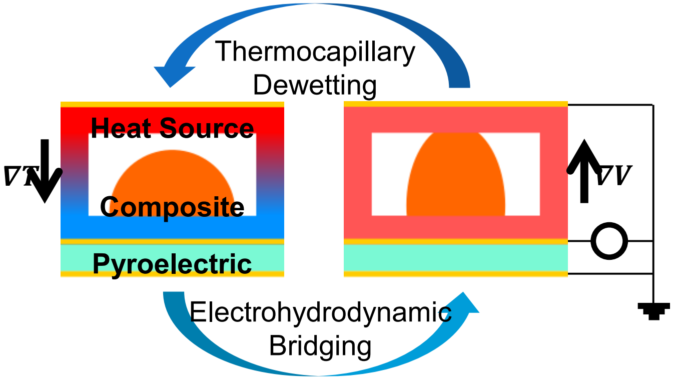
☐ Strong adhesion (PDMS cap)
☐ Snap detachment and reattachment

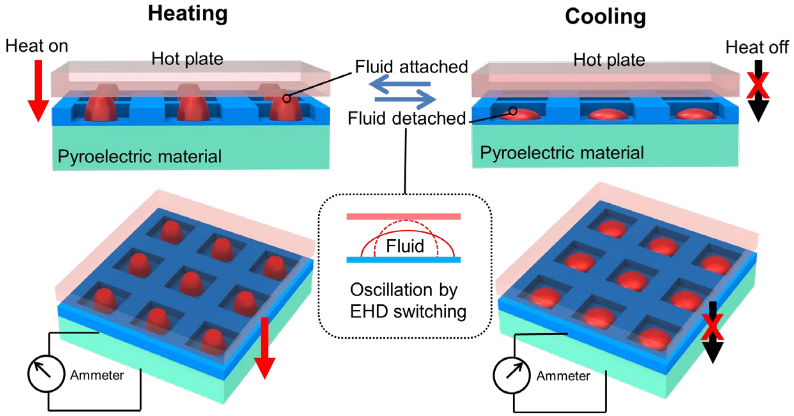


☐ A 2-cycle snap detachment and reattachment
☐ 5 secs delay of detachment compared to the control group (right side)

Technical Approach B

- Electrically actuated thermal fluid switches



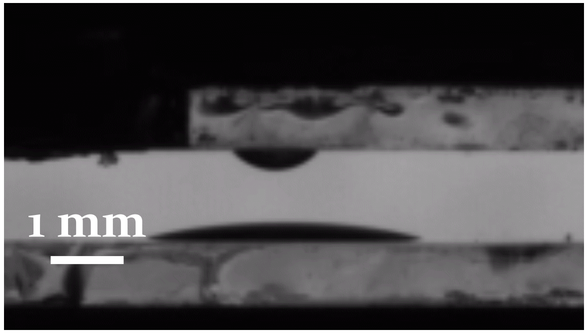


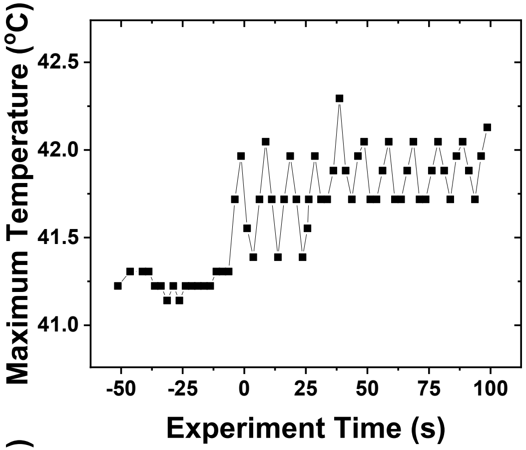
Singer: Formulation of thermal fluids; Device fabrication and characterization; R2R device fabrication; Optimization of thermophysical properties.
Osuji: Characterization of thermal transport.
Loewenberg: Modeling of transport properties.

Electrohydrodynamic active switches: Device utilizes field present in Olsen cycle. Field application drives electrohydrodynamic bridging to make thermal contact with the heat source. Field removal breaks thermal contact due to thermocapillary dewetting.
Materials and Methods: Nanoparticle filled silicone and other fluids for active thermal fluid. P(VDF-TrFE) and other PEs. Transport modeling.
Electrohydrodynamic Thermal Oscillator (EHTO) Challenge: Engineering thermal fluids for desired thermophysical properties and responsiveness.

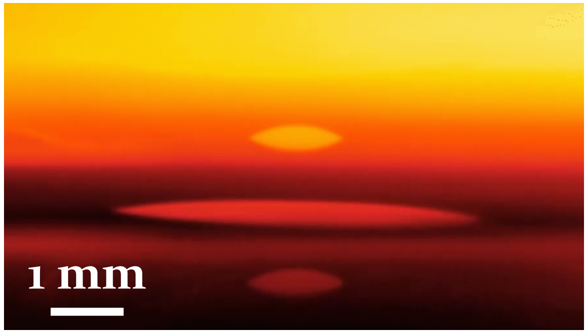
Technical Approach B

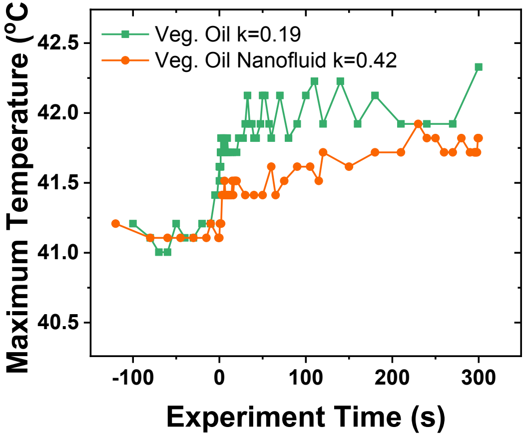
Oscillating Experiments





Static Thermal Comparison



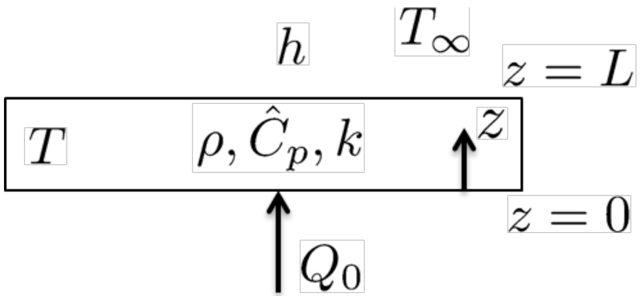


- Demonstrated stable thermal oscillations in EHD bridges by modification of substrate and superstrate surfaces.
- These bridges outperform higher-k bridges of nanofluid due to a proposed TC+EHD convection mechanism.
- <u>Future</u>: Characterization of EHD switches in test devices.

Technical Approach – Modeling

- Analytical results provided for heat transport in lumped and distributed parameter models.
- Figure of merit has been generated that captures the magnitude and rate of temperature changes.
- Overall energy generation efficiency relative to Carnot is provided.
- Future: Model development to incorporate position-varying properties.

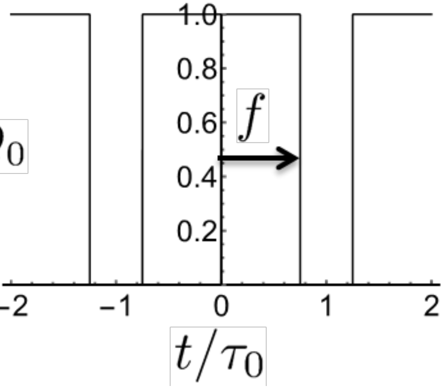
$T < T_+$, contact, heat on:



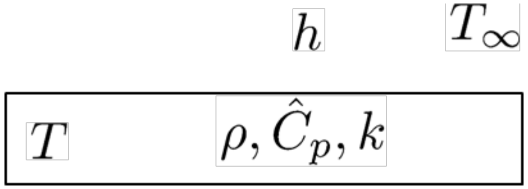
$$\rho \hat{C}_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} \,,$$

$$-k \frac{\partial T}{\partial z} = Q(t) \;:\quad z = 0$$

$$k \frac{\partial T}{\partial z} + h(T - T_\infty) = 0 \;:\quad z = L$$



$T > T_-$, no contact, heat off:



$$\bar{Q}(t) = \frac{Q(t)}{Q_0} = \sum_{k=0}^{\infty} q_k(f) e^{ik\pi t/\tau_0} \,,$$

$$q_k(f) = \begin{cases} \frac{2}{k\pi} \sin(f k \pi) & k > 0 \\ f & k = 0 \end{cases}$$

Results and Accomplishments

Milestone/Tasks	Status
Milestone 1.2.1 (M12/Q4): Proper functioning of computer control – variation in measured thermal transport properties less than +/- 10% and demonstrated ability to execute tests using computer programmed routines.	In Progress
Milestone 2.1.1 (M3/Q1): Identify monomers and synthetic routes for shape memory polymers.	Achieved
Milestone 2.2.1 (M6/Q2): Synthesize 2 or more of the monomers and associated polymers identified in **2.1** at 5-10 g scale.	Achieved
Milestone 2.2.2.1 (M9/Q3): Demonstrate variation of switching temperatures across a 100 ºC range, from 50 ºC to 150 ºC in one or more shape memory polymers.	Partially achieved
Milestone 2.2.4.1 (M12/Q4): Demonstrate variation of adhesion strength by a factor of 10X total (3X higher and lower than base polymer composition).	Achieved with new approach
Milestone 2.3.1 (M12/Q4): Fabrication of shape memory elements from one or more polymers, with shape memory strains of at least 5% actuated by heating and cooling across temperatures in the range of interest.	Achieved
Milestone 2.4.1 (M12/Q4): Assembly of planar device and reliable (normalized variance or standard error less than 0.15) measurement of device efficiency.	In Progress
Milestone 3.2.1 (M8/Q3): Identification of usable compositions – response speeds faster than 1 s at one or more temperatures in the range of interest with thermal enhancement of >2X over the neat polymer.	Achieved
Milestone 3.3.1 (M12/Q4): Reliable characterization (normalized standard error of 0.15 or less) of efficiency of pyroelectric harvesting using Olsen Cycle and EHD switching.	In Progress
Milestone 3.4.1 (M12/Q4): Fabricate a support web consisting of a commercial flexible film and flexible insulating spacer grid.	In Progress
Milestone 4.3.1 (M9/Q3): (M9/Q3): Develop computer simulation of distributed parameter model and explore the model's predictions using representative parameter values.	Achieved
Milestone 4.4.1 (M12/Q4): Solution of distributed parameter model	In Progress

Transition (beyond DOE assistance)

- Technology readiness (TR) level of 4-5 anticipated by project end.
- Intellectual property licensing or recruitment of further development funding beyond 08/2020.