U.S. DEPARTMENT OF ENERGY

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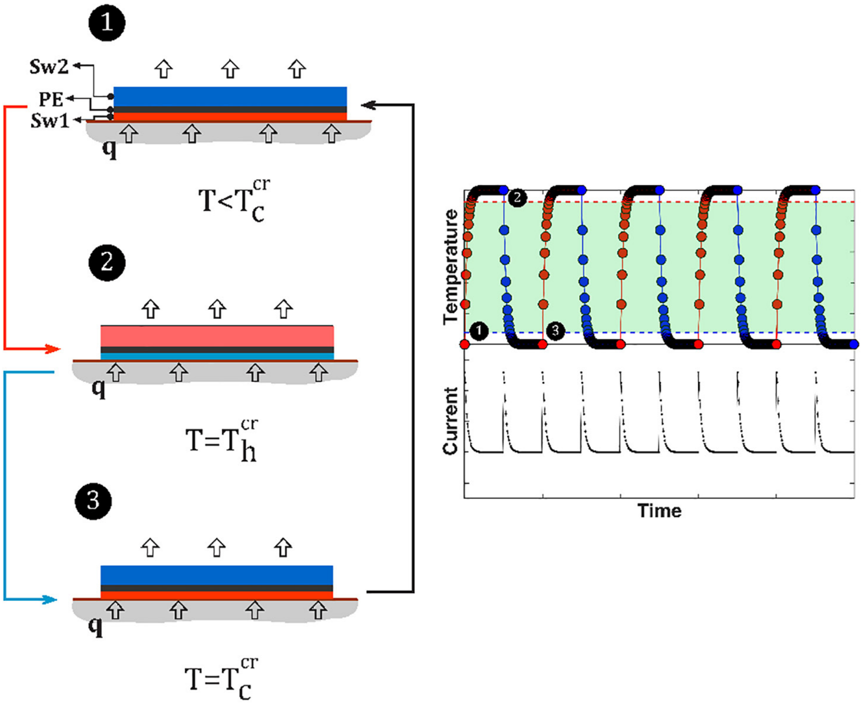
High Efficiency Waste Heat Harvesting Using Novel Thermal Oscillators



(Left) Thermal oscillators Sw1 and Sw2 act in tandem to periodically vary the temperature of the pyroelectric layer. The current output is proportional to the rate of change of temperature (right), shown here schematically using an exponential form.

Graphic credit University of Pennsylvania.

A vast amount of energy consumed in the United States is lost as waste heat, much of which is low-grade waste heat. In industry and manufacturing alone, more than 2,500 trillion Btu of process heating energy is estimated to be lost annually, of which approximately 10%-25% is considered recoverable. Recovering this waste heat provides an opportunity to increase energy efficiency. There have been considerable technological advancements in solid state heat-electricity conversion, particularly in thermoelectric devices that sustain potential differences in response to spatial temperature differences, and vice versa. Improving these devices by utilizing pyroelectric materials, which instead respond to periodic temporal temperature changes at a given heat flux, can help increase waste heat recovery efficiencies.

This project intends to develop novel thermal oscillators to enable practical energy generation from waste heat using pyroelectric materials. These oscillators will be engineered to overcome the current roadblocks to pyroelectric energy harvesting by providing two unique solutions for generating sustained temperature oscillations in thin planar (laminate) devices. The project will begin by verifying the pyroelectric conversion efficiencies with respect to thermal insulation and computer control integration for pyroelectric test devices within a robust test apparatus. These test devices will then be constructed and characterized based on two unique thermal switching solutions: shape memory liquid crystalline elastomer (LCE) switches, and electrohydro-dynamic (EHD) deformation switches. These switches will then be modeled and analyzed using lumped parameter modeling or distributed parameter modeling.

Benefits for Our Industry and Our Nation

The novel thermal oscillators under development are expected to have significant impacts due to their high efficiency and low cost capabilities. In addition, the thermal oscillator designs as well as the pyroelectric system overall are well suited to volume production using simple imprint and film lamination processes. Using state-of-the-art thermal oscillators is expected to have numerous benefits for low-grade waste heat recovery in manufacturing, including:

- Increase efficiency five-fold and reduce cost 50%-90% compared to current approaches that accomplish temperature cycling by fluid pumping

Applications in Our Nation's Industry

This novel thermal oscillator technology will have a variety of benefits to manufacturing industries with extensive process heating requirements. Near-term applications will include energy recovery from waste heat in manufacturing. Other long-term applications include areas beyond manufacturing, such as energy recovery in high performance computing and consumer electronics. In addition, these devices may enable other waste heat harvesting technologies such as thermocapacitive and thermogalvanic energy extraction which are critically reliant on temperature cycles.

Project Description

The project objective is to develop, build, and model novel thermal oscillators for practical energy generation from waste heat using pyroelectric materials. This project aims to accomplish this via two approaches to practical temperature cycling of pyroelectric films based on a constant flux heat source: utilizing shape memory liquid crystalline elastomers (LCEs) to reversibly make and break thermal contact with the heat source, and thermal contact switching using electrohydrodynamic (EHD) deformation.

The project outcomes address current technical challenges currently hindering pyroelectric harvesting usage: (a) demonstration of waste heat conversion in a lab-scale integrated device with a minimum efficiency of 35%, for temperature differences of 100K or less, and a minimum power density of 200 mW/cm^3; (b) development of scalable fabrication strategies to produce energy harvesting laminates at a cost of $1/W or lower; (c) construction of system models that describe thermal oscillations, power output and device efficiency as functions of heat flow, ambient conditions and relevant material parameters; and (d) incorporation of system models for preliminary techno-economic analysis and potential commercialization plans.

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

Pathways

The project is structured to address the key barriers and minimize risk. The ultimate goal is to engineer novel thermal oscillators for practical energy generation from waste heat using pyroelectric materials.

The first project pathway will construct and validate consistent and verifiable results for pyroelectric conversion efficiency. This validation will involve demonstrating effective thermal insulation and computer control integration within the test devices. Each of these laboratory-scale validations and optimizations will be completed in house.

The second pathway will construct and characterize pyroelectric harvesting devices based on either shape memory LCE or EHD thermal switches. These switches will be tested to achieve effective manufacturability as well as a 20% minimum efficiency (with an ultimate target of 35%). In addition, these switches will be fabricated and experimentally validated in-house.

The third pathway will numerically model the thermal switches. The numerical modeling for these devices will be accomplished via working thermal models, particularly the lumped parameter model and the distributed parameter model. This will be done to compare experiments, and optimize the predicted power generation in terms of operating parameters including the magnitude of the heat flux, ambient cooling parameters and slab thickness.

Milestones

This two-year project began in August 2018.

- Determine usable composite composition for reversible EHD cycling at fields relevant to the Olsen cycle (2019)
- Produce consistent and verifiable results for efficiency of pyroelectric conversion for a working single cell device and working thermal models (2019)
- Experimentally verify a functioning pyroelectric harvester with at least 20% efficiency (Carnot) (2020)

Technology Transition

The University of Pennsylvania is partnering with Yale University and Rutgers University for the design and modeling of these novel thermal oscillators. Following successful development, the project team plans to advance the technology towards the market by obtaining additional funding or through licensing of intellectual property.

Project Partners

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