High-Efficiency Solid-State Heat Pump Module

2017 Building Technologies Office Peer Review

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Project Summary

Timeline:

Start date: September, 2015

Planned end date: August, 2017

Key Milestones

- ✓ Phase 1: Demonstrate >6.0 °C material-level performance that enables an electrocaloric module COP > 6.0
- ▪ Phase 2: Demonstrate TRL3 solid-state heat pump module performance

Budget:

Total Project $ to Date (through Jan. 2017):

- DOE: $ 854,193
- Cost Share: $284,731

Total Project $:

- DOE: $1,093,845 ($679,393 Phase I)
- Cost Share: $364,615 ($226,464 Phase I)

Key Partners: (none)

Project Outcome:

United Technologies Research Center shall demonstrate a solid state (refrigerant-free), high efficiency, compact, zero direct global warming heat pump which has the potential to replace refrigerant-based vapor compression systems.

TRL 3 demonstration of solid-state heat pump that has the potential to provide primary seasonal COP > 6 at full commercialization.

Purpose and Objectives

Problem Statement:

- Current regulations (both US and European) and market needs, are driving us to systems with lower global warming footprint and higher efficiency
- Electrocaloric heat pumping is a refrigerant-free technology that has the prospect of being more efficient, compact and quieter than current vapor compression systems

Target Market and Audience: The target market is residential and small commercial buildings. Residential heating/cooling uses >4.5 primary quads annually, and small-commercial >1 Quads for a total of ~5.5 Quads.

Impact of Project:

- ≥25% system efficiency improvement and ~2000x direct GWP reduction enabled through:
  - TRL 3 heat pump module demonstration
  - Electrocaloric heat pump with COP > 6.0
  - Elimination of working fluids with global warming potential with reduced noise and maintenance costs
  - Potential for capacity demonstration (2018); system demo (2020)

Approach

Approach:

- ✓ Leveraged UTRC micro-electrocalorimetry capability to demonstrate material performance over required operating envelope
- ✓ Leveraged CFD based multi-physics modeling tools for module design
- Demonstrate module performance through testing and validated models
- Analyze system-level performance using validated dynamic modeling tools
- Collaborate with Carrier to assess techno-economic impact

Key Issues:

- Module construction and integration
- Module test rig losses and electrical actuation

Distinctive Characteristics:

- Novel electrocalorimeter
- Innovative electrocaloric module concept and dynamic models

Progress and Accomplishments

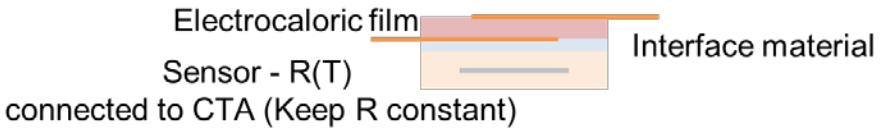
Accomplishments:

- Demonstrated 7.2 °C (5.6 °C without calibration) temperature lift at module-scale (Apr. 2016)
- >6.0 $COP_{electric}$ performance based on dynamic system model w/ module-scale films (June. 2016)
- Successfully passed Go/No-Go review (**Aug. 2016**)
- Designed, fabricated and commissioned test rig for module temperature lift evaluation (**Sep. 2016**)
- Demonstrated first air cooling electrocaloric module concept (**Oct. 2016**)
- Demonstrated 2.5 °C cooling temperature lift across module (Dec. 2016)
- Detailed electrocaloric multi-physics modeling tool validated (Jan. 2016)

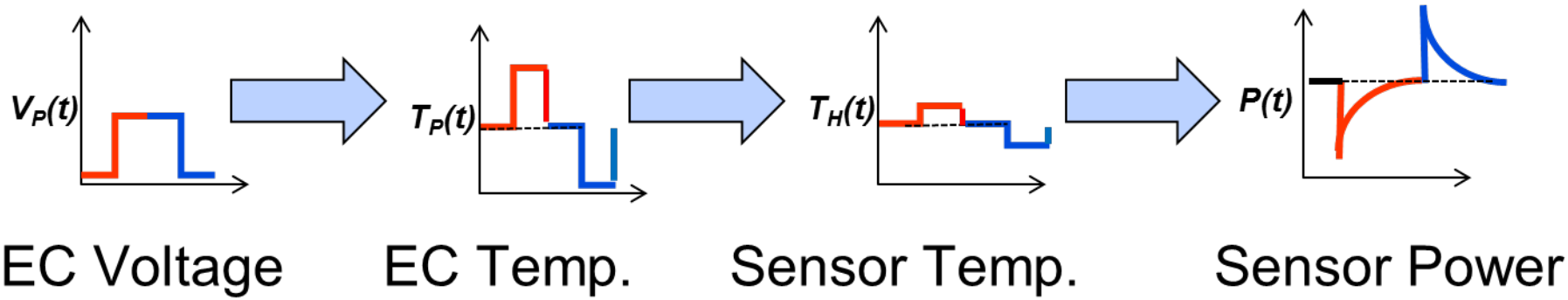
Progress and Accomplishments - Electrocalorimetry

Constant temperature anemometer (CTA) measures energy imbalance

- Concept based on Hot-Wire Anemometer



- Energy Compensation Procedure

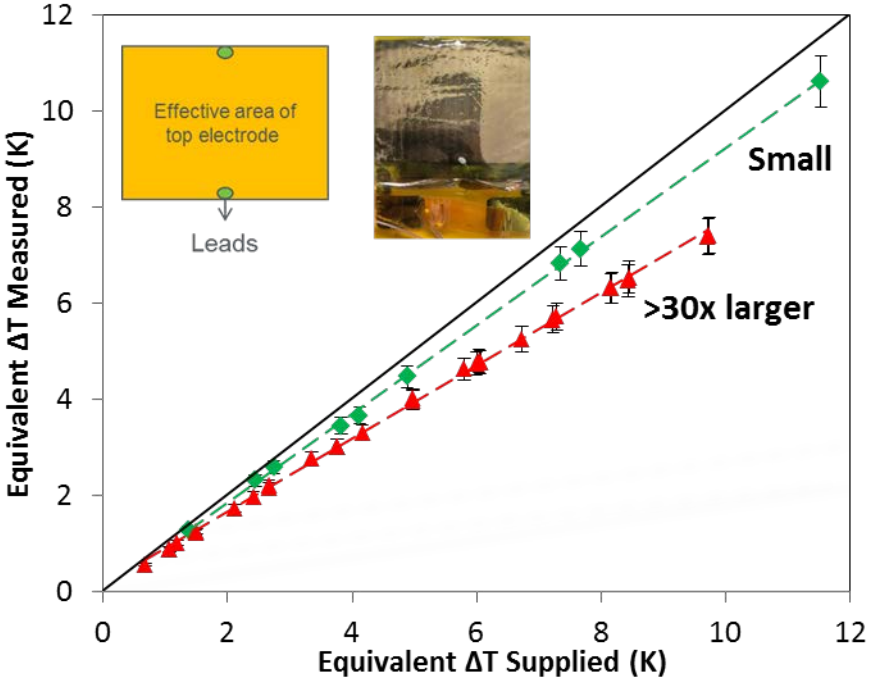


Progress and Accomplishments - Electrocalorimetry

Coupon- and module-scale calibrated measurements are in agreement within experimental uncertainty

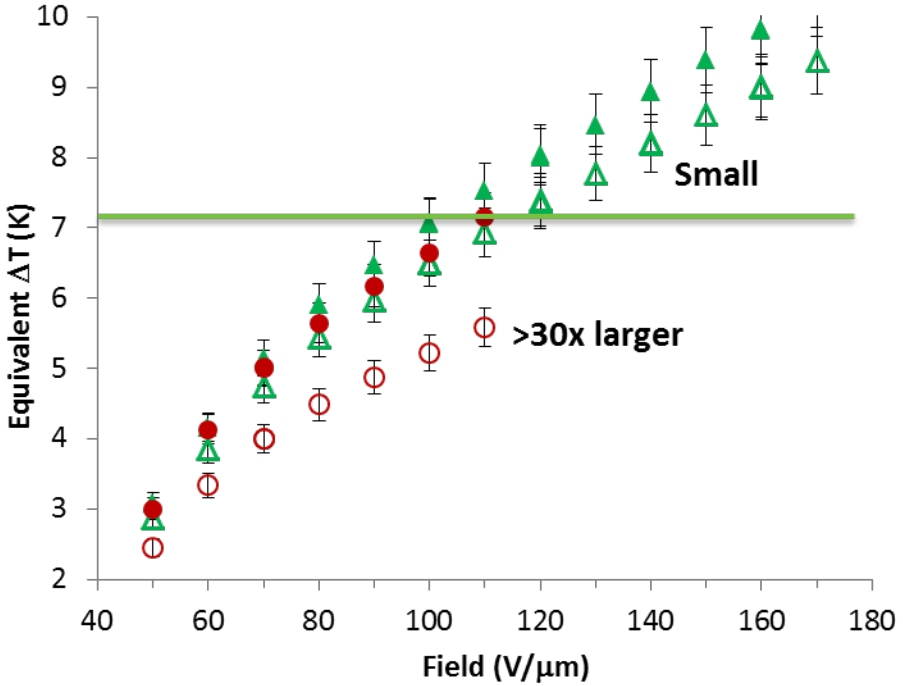
Calibration

- Coupon sensor : <7% loss
- Large sensor (30 x) : 20% loss



Electro-Calorimetry

- Coupon sample : 9 °C lift @170 MV/m
- Large-scale sample: 7.2 °C lift @110 MV/m (5.6 °C without calibration)



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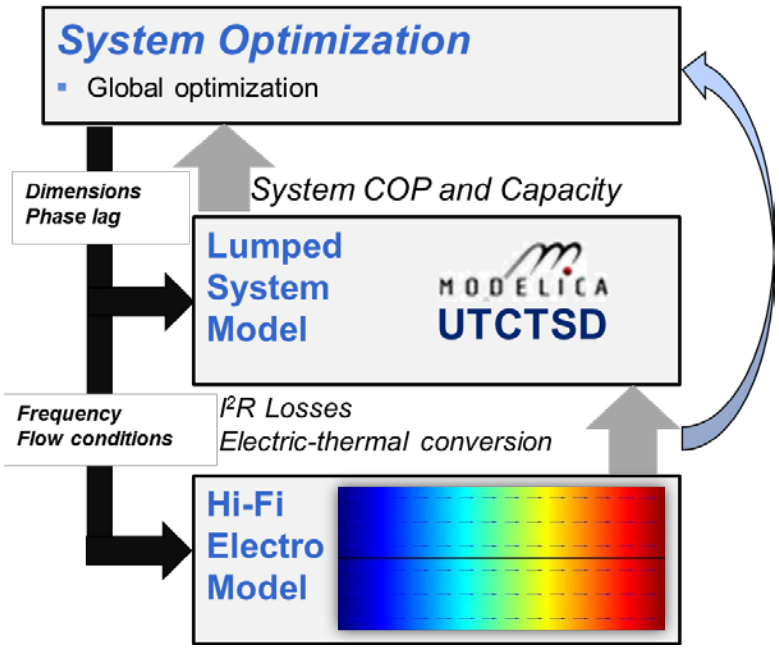
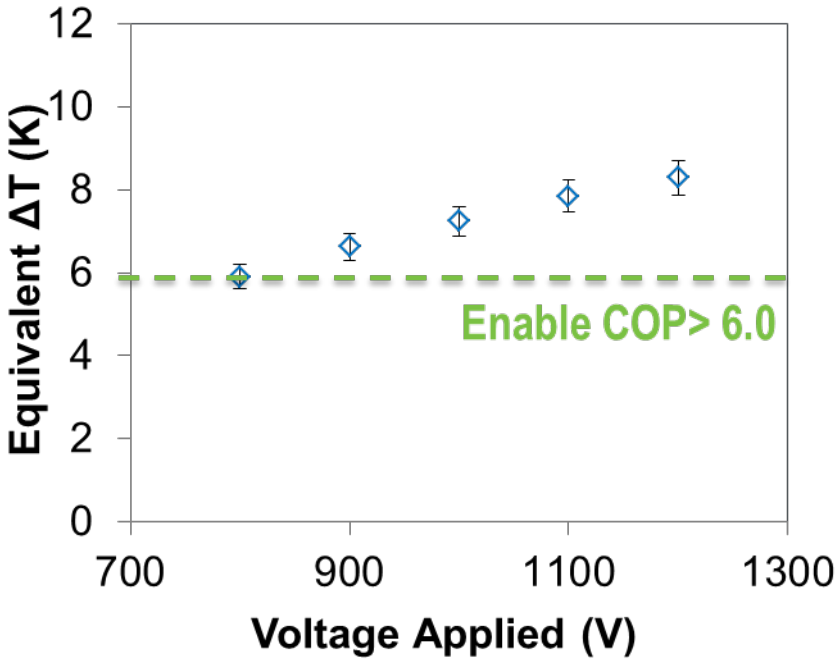
Progress and Accomplishments: : Go/No-Go Review

Go/No-Go Criteria:

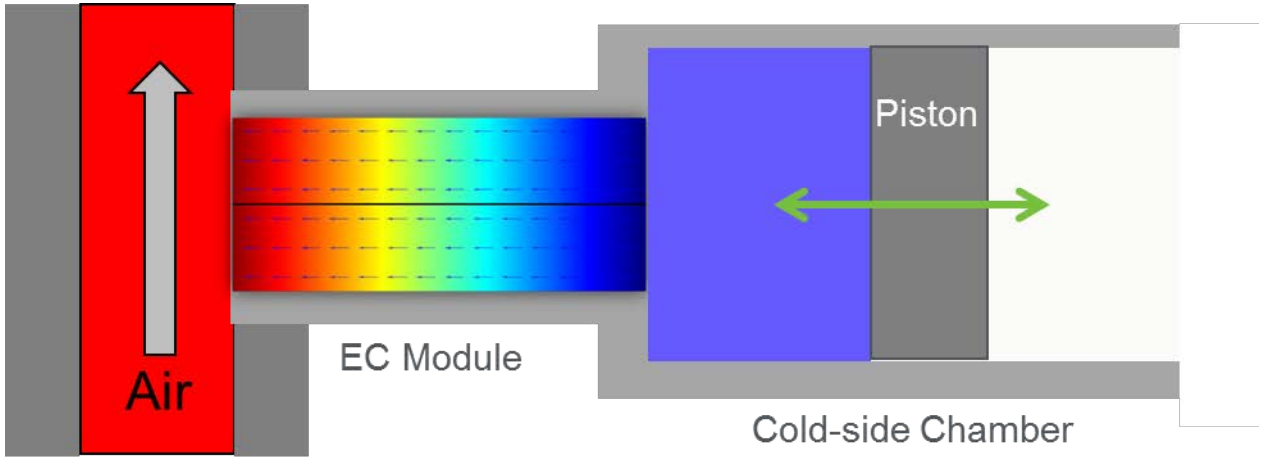
- ✓ Demonstrated 7.2 °C (5.4 °C without calibration) temperature lift at module-scale (>30X)
- ✓ COP > 7.0 shown based on module-scale films



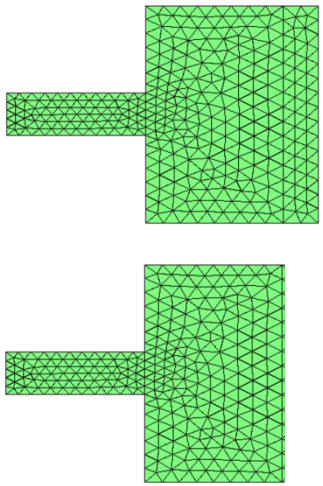


Progress and Accomplishments: Test Rig Design

Cold side moving piston with hot side fixed plenum



Moving Mesh



Constitutive Eqns.

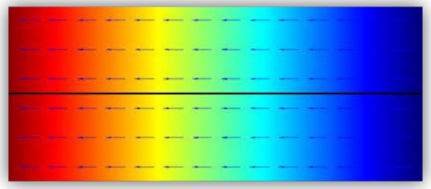
$$\nabla \cdot \left(J + \frac{\partial D}{\partial t} \right) = 0$$

$$D = \varepsilon_o (1 + \chi(\omega)) E + P_s = \varepsilon_o \varepsilon_r E + P_s$$

$$\rho C_E \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q_j - T \left(\frac{dP}{dT} \right)_E \frac{\partial E}{\partial t}$$

Module Details

Channel- and Device-Level: Conjugate Heat Transfer



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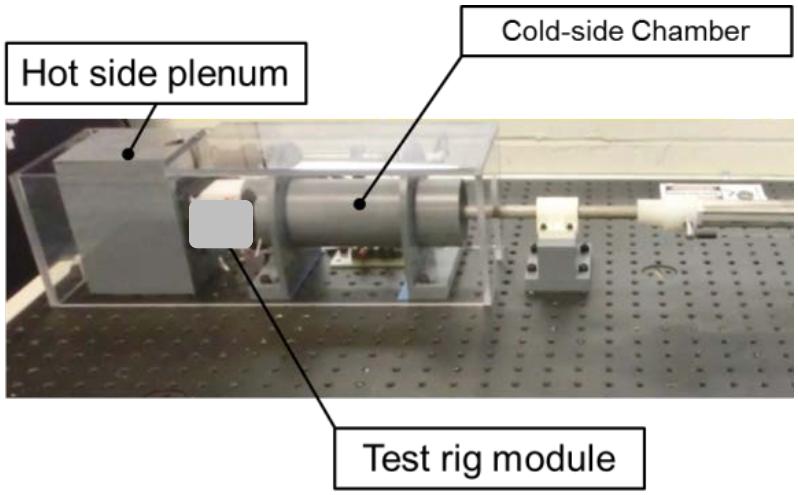
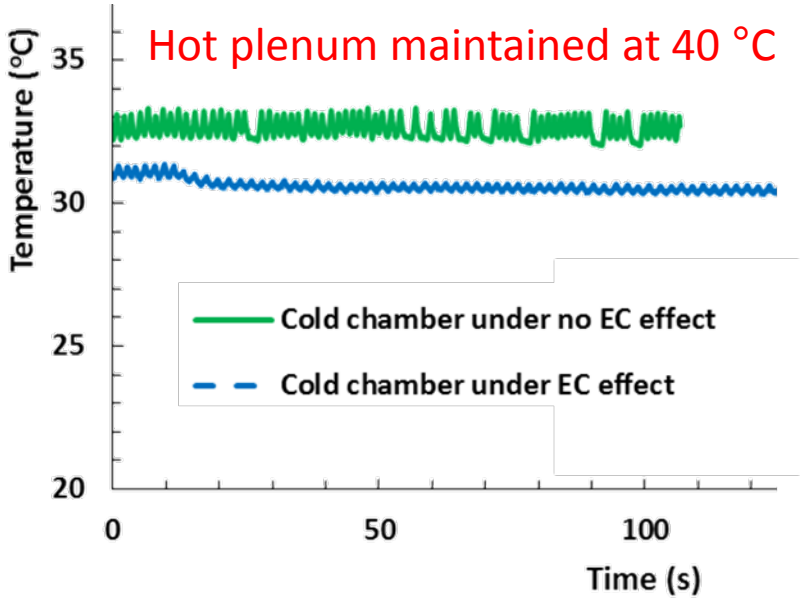
Progress and Accomplishments – Module Demonstration

2.5 °C cooling from module demonstrated; Identified test rig losses





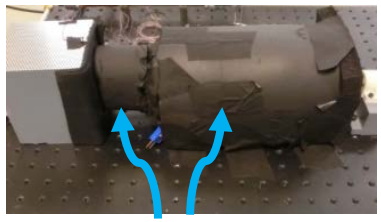
- 50% module degraded during commissioning
- Electric field - 80 V/µm
- Cold side with no field - 33.0 °C
- Cold side with 80 V/um - 30.5 °C

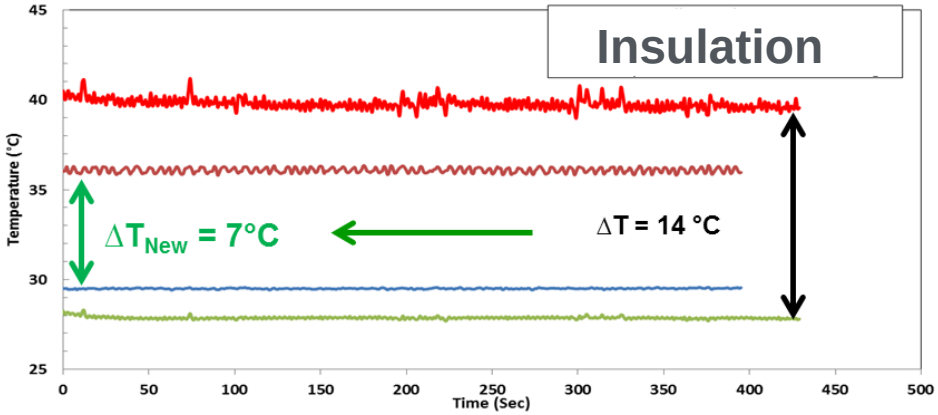
Progress and Accomplishments: Test Rig Improvement

Testing and validated modeling utilized to improve module performance

Effect of Insulation

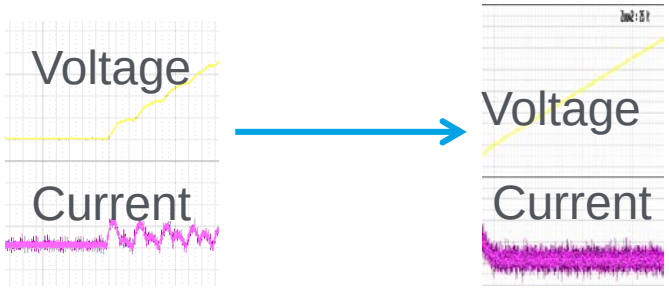
- Steady state
- Transient



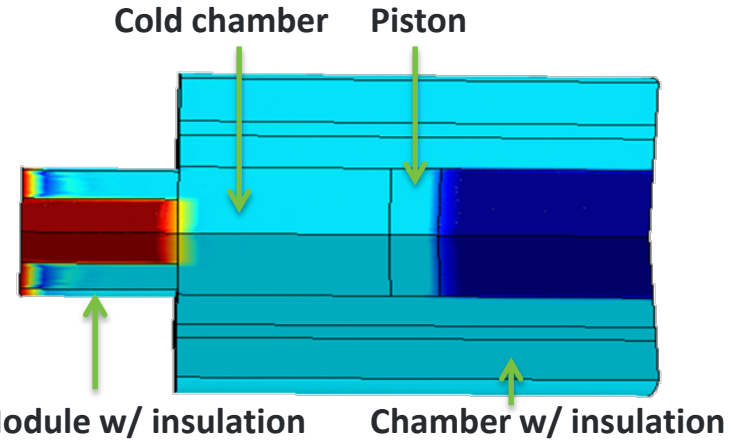


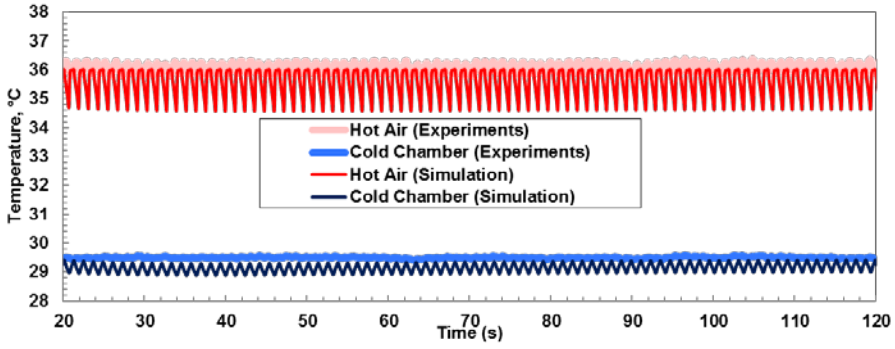
Effect of Amplifier

- Spikes in current damage films



Model-based Analysis





Project Integration and Collaboration

Project Integration:

- Carrier, world's largest manufacturer of HVAC&R equipment, has a long history of developing successfully commercialized products
- Carrier has commercialized HVAC technologies developed at UTRC
- UTRC project team is advised by Carrier product and engineering teams to ensure metrics are met during conceptualization and testing phases

Partners, Subcontractors, and Collaborators: None

Communications:

- MRS Spring 2016: EE11.3.06 Calorimetric Studies of Electrocaloric Polymeric Films: Creating Material Requirements from Sub-Component Level Studies, J. Mantese, **S. Annapragada** et. al.

- ASME IMECE 2016 EPPD Invited Panel on Electrocaloric Cooling (Chairs: **S. Annapragada** (UTRC) and J A Weibel (Purdue), A. Bar Cohen (UMD) : "Electrocaloric Heat Pumping: Creating Material Requirements from Sub-Component Studies," J. Mantese et. al.

- Highlighted to UTC CTO and CEO during annual review

- 1 Invention disclosure submitted to UTC for consideration

Next Steps and Future Plans

Next Steps and Future Plans:

- Phase II: (Sept. 2016 – Aug. 2017)
  - Prototype 2 under construction
  - Prototype 3 based on learning from Prototype 2 (if needed)
  - System performance analysis and techno-economic assessment
  - Develop plans for potential capacity and system demonstrations
  - Final report submission to DOE BTO

REFERENCE SLIDES

Project Budget

Project Budget: $1,458K
Variances: none
Cost to Date: $1,138,924 (FY15-FY17)
Additional Funding: Cost Share 25% UTRC.

- DOE: $ 854,193
- Cost Share: $284,731

Budget History					
Sept. 4, 2015 – FY 2015 (past)		FY 2016 – Jan. 30th 2017 (current)		FY 2017 – Aug. 31, 2017 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$12,028	$4,009	$854,193	$284,731	$239,307	$79,769

Project Plan and Schedule