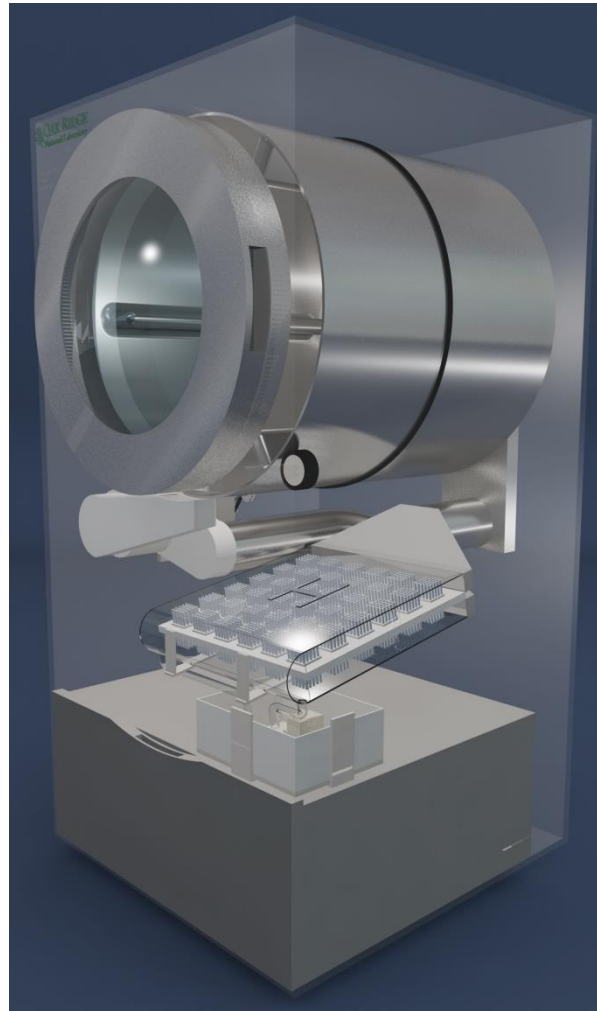


Thermoelectric Clothes Dryer

2016 Building Technologies Office Peer Review



Project Summary

Timeline:

Start date: October 1, 2014

Planned end date: September 30, 2016

Key Milestones

1. Go/No-Go Milestone 1.4: Demonstrate target EF>6 based on combination of modeling and ER prototype test results. **Met** September 30, 2015.
2. Milestone 4.1: Develop water resistant TE modules. **Met** September 30, 2015.

Budget:

Total Project \$ to Date:

- DOE: \$850k
- Cost Share: \$95k

Total Project \$:

- DOE: \$850k
- Cost Share: \$95k

Key Partners:

Sheetak, Inc.	Industry Partner
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Project Outcome:

This project applies innovative solid state heat pump technology to the dryer sector to meet the 2020 MYPP target of EF \geq 6 (EF of 6.2 expected). This leads to primary energy savings of 40% and can position the US as the leader in the clothes drying industry, resulting in job and innovation growth.

Purpose and Objectives

Problem Statement:

Barriers: First cost, long dry time, and perceived risk

TE-based approach: Lower first cost than vapor compression; capable of fast dry times; addresses perceived risk by lacking a “sealed system” or any additional moving parts, leading to higher reliability and consumer desirability

Target Market and Audience:

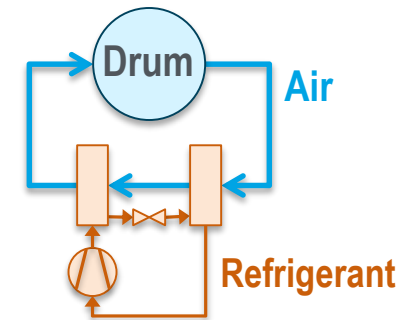
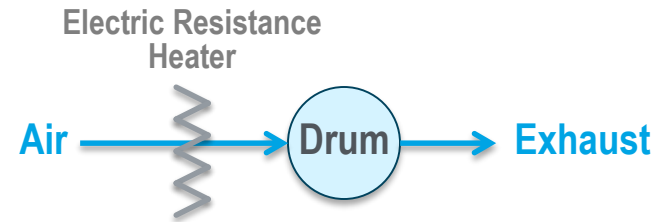
- 638 TBtu/yr: residential electric clothes dryers (2020)
- 5.6 million unit shipments (2008)
- 67.2 million US households (60%) have one

Impact of Project:

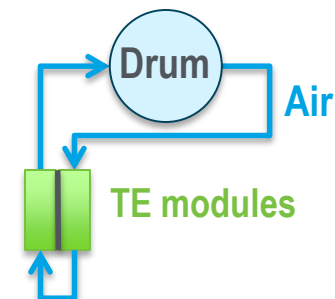
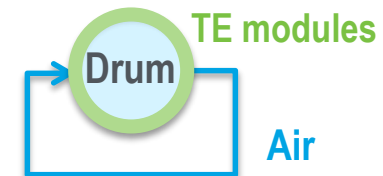
- *During project:* Laboratory prototype will prove performance (EF and dry time), to save 40% primary energy (254 TBtu/yr) in electric clothes drying
- *Intermediate term:* By showing a path to a low-cost approach, product commercialization based on prototype is possible.
- *Eventually:* Position the US as leader in dryer industry, creating jobs and spurring further innovation, and saving TBtu/yr.

Approach – Background

- *State of the art:* Conventional dryers
 - EF/Dry time: 3.73, 15-30 minutes
 - Retail: ~\$350
- *State of the art:* Vapor compression dryers
 - EF/dry time: 4.5 – 8.9; 38 – 72 minutes
 - Products introduced to US market 2015
 - Retail: ~\$1,600



-
- *This project:* Drum-integrated thermoelectric
 - EF 6.2 obtained
 - Dry time longer than vapor compression
 - *This project:* Air-based thermoelectric
 - EF 6.2 expected
 - Target dry time <30 minutes
 - Target retail



Approach

Approach:

- Drum-integrated prototype with drum surface heated by electric resistance (ER) to simulate thermoelectric heat
- TE module development: moisture resistance, low cost
- TE dryer prototype fabrication, development and evaluation

Key Issues:

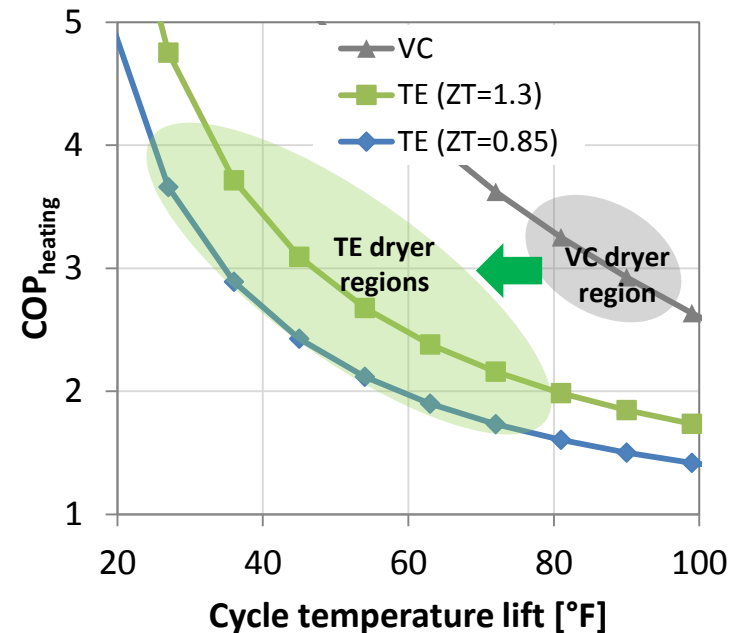
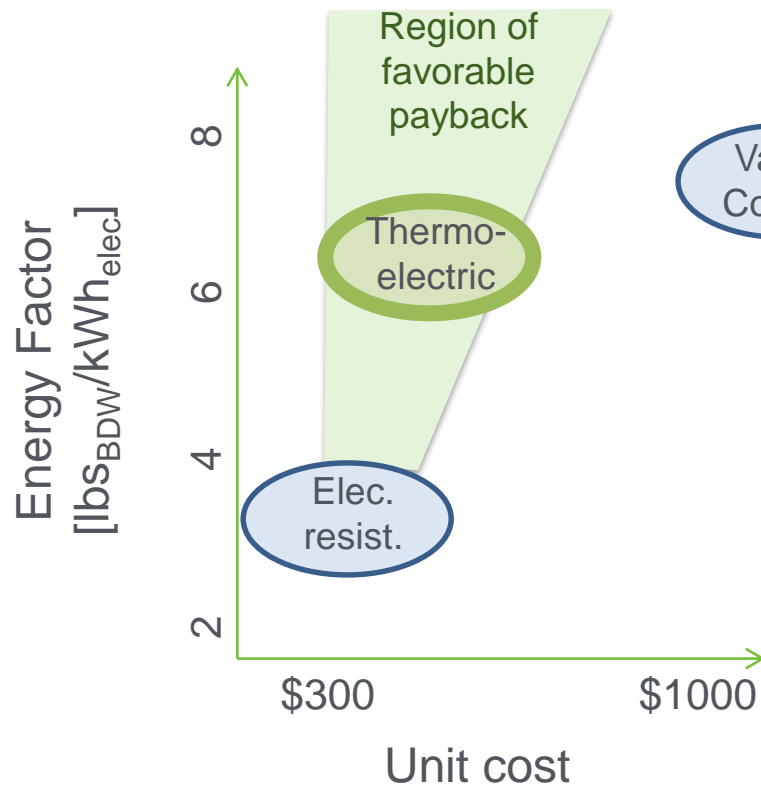
- Drum-integrated approach showed promising efficiency (based on modeling and projected EF) but longer than desired dry time.
- Modeling of air-based TE prototype showed target EF with shorter dry time. Design of prototype was adapted accordingly.

Distinctive Characteristics: High-performance ventless design is achieved at low cost through unique utilization of:

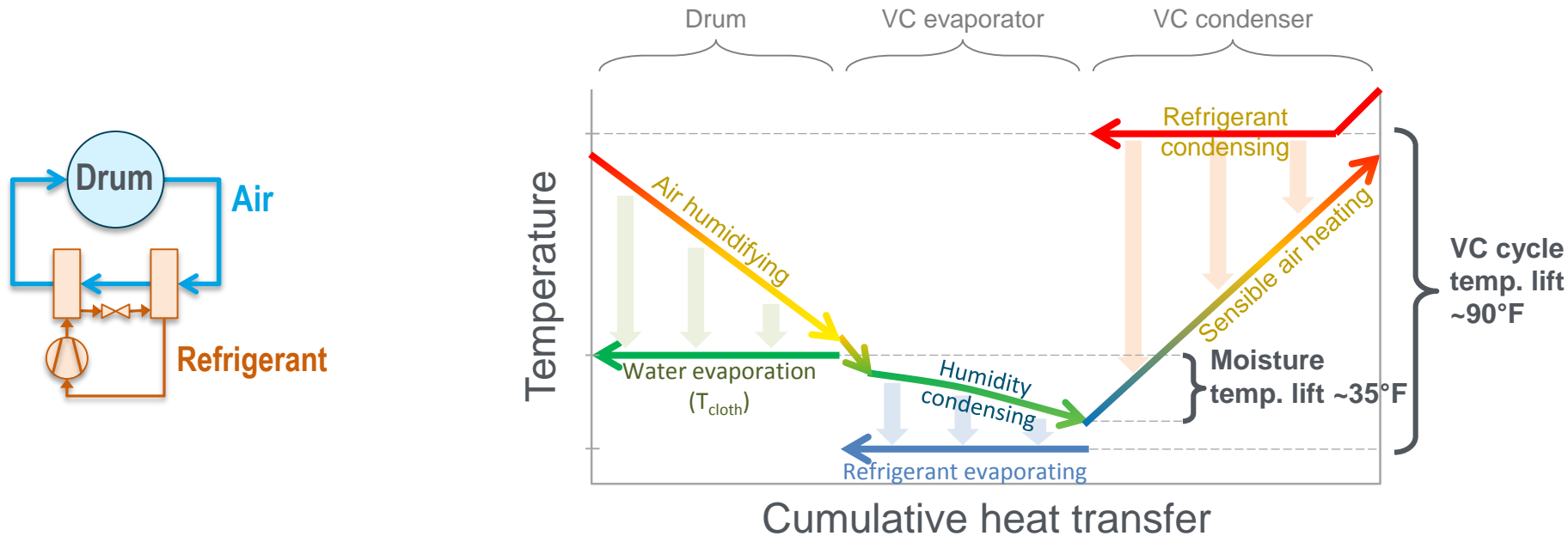
- Novel high volume manufacturing of TE technologies reduce cost of thermoelectric elements
 - Novel spark plasma sintered TE materials with superior mechanical properties, allowing less material be used
 - Novel polymer substrate material eliminates use of expensive ceramics
- Leveraging world-class modeling capabilities, a cost-conscious design optimization of controls, architecture, and psychrometric system design leads to lower cost.

Approach

- Lower cost than vapor compression
- The traditionally inferior efficiency of thermoelectrics is overcome by taking advantage of inherent scalability modularity of TEs

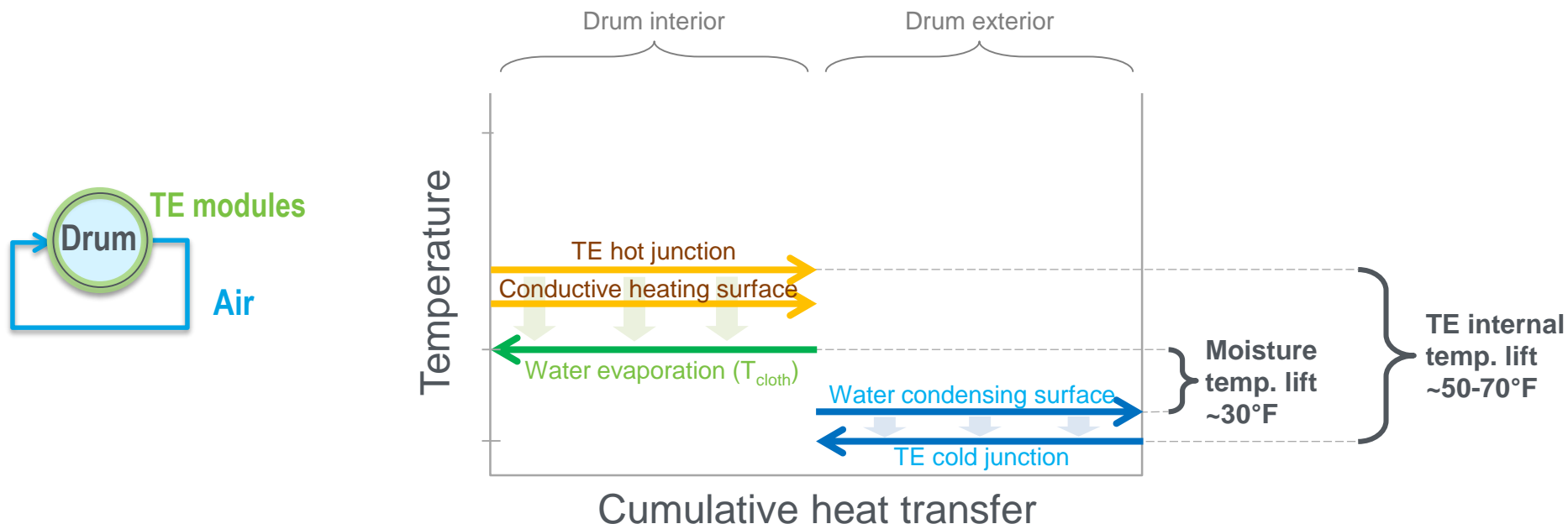


Heat Transfer in Vapor Compression Dryer



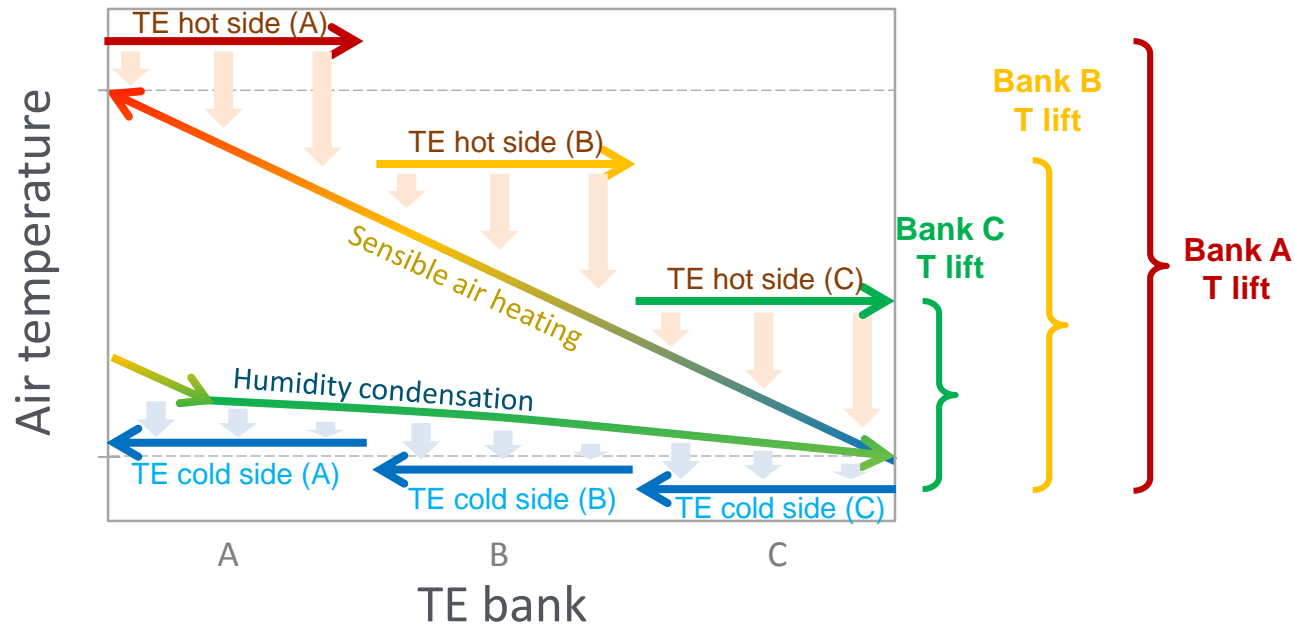
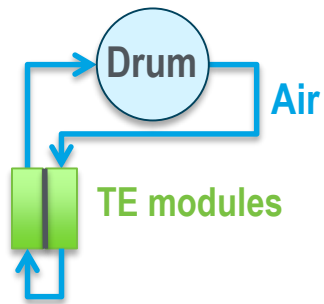
- The vapor compression cycle suffers from large efficiency penalty: effective temperature lift is much greater than the fundamental lift
 - Heat added at temperature above maximum air dry bulb temperature
 - Heat removed at temperature below minimum air dewpoint

Heat Transfer in Drum Integrated Dryer

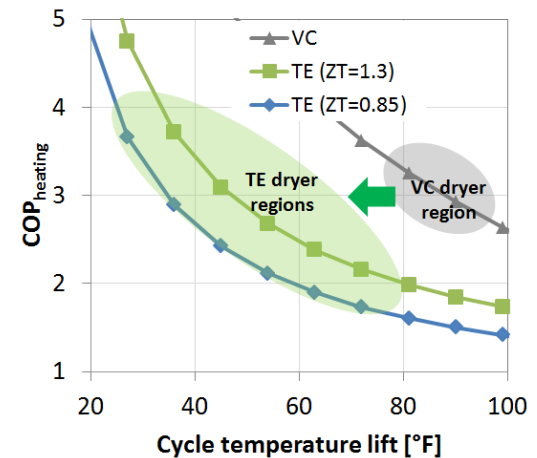


- Effective temperature lift is lower, since heat pumping is accomplished isothermally and closer to the air dewpoint
- However, limited surface area is available for heat transfer
 - Compared to vacuum dryer approach, heat transfer coefficient is higher (air convection can be used)

Heat Transfer in Air-based Thermoelectric Dryer



- Air-based design: inherent modularity of TEs allows most of the heat pumping to be accomplished at lower lift than VCS
- Lower TE lift, for same air temperatures, closes the gap in efficiency between VC and TE



Progress and Accomplishments

Accomplishments:

In Year 1:

- Demonstrated drum-integrated target $EF > 6$ (combined modeling/experimental)
- Designed dryer for thermoelectric integration

In Year 2, Q1 and Q2:

- Fabricated dryer with integrated thermoelectrics
- Obtained preliminary test data on prototype

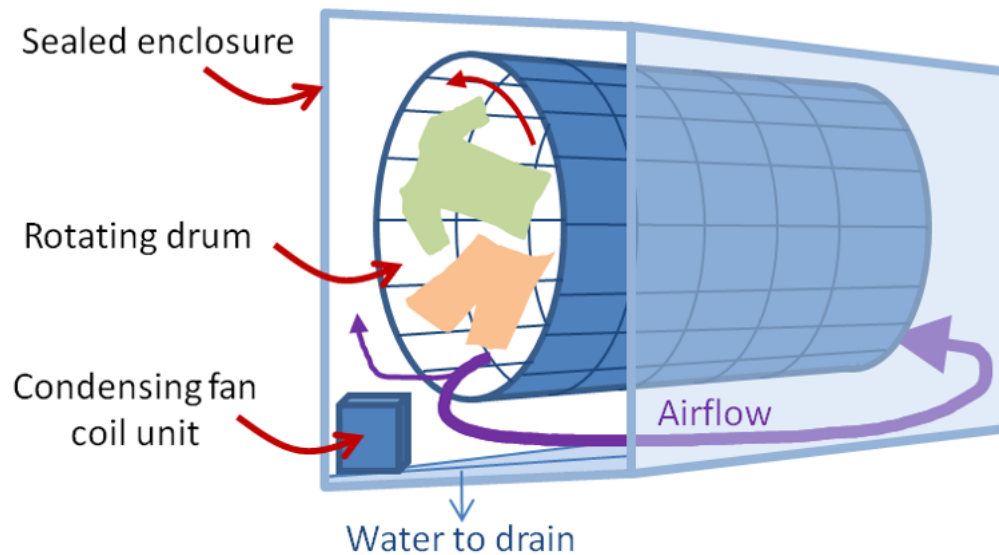
Market Impact: In discussions with appliance commercialization partner. Success of approach could lead to cost effective applications in water heating and other HVAC&R.

Awards/Recognition: None yet.

Lessons Learned:

- Heat transfer limitations result in longer dry time with direct-contact (conduction) heat exchange via the drum surface, limiting the application of this concept.
- High ZT figure of merit TEs are not necessary to achieve dramatic savings over electric resistance dryers
- Blower power matters; selection and optimization of heat sink geometry is critical

Drum-integrated Prototype Design/Fabrication



1

2

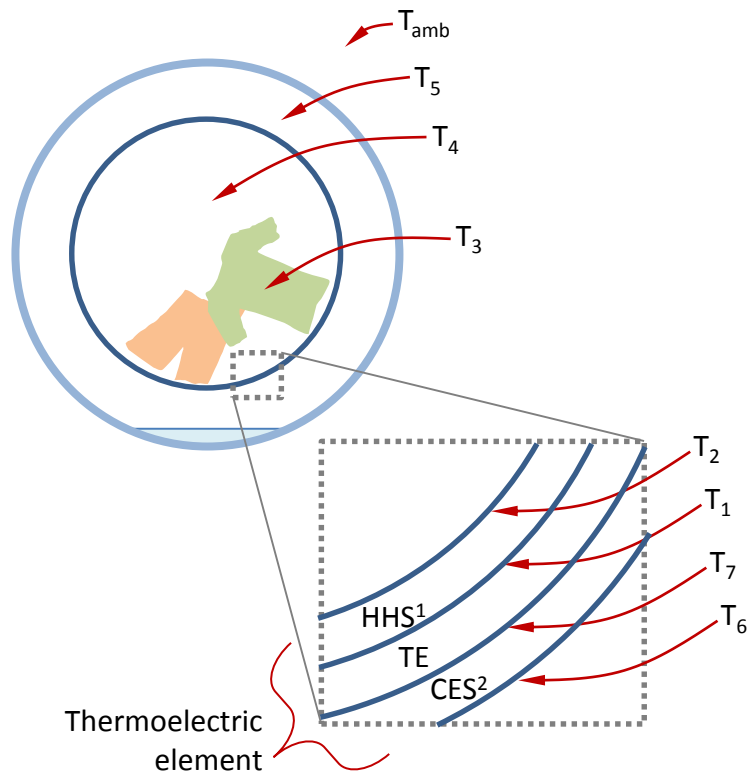
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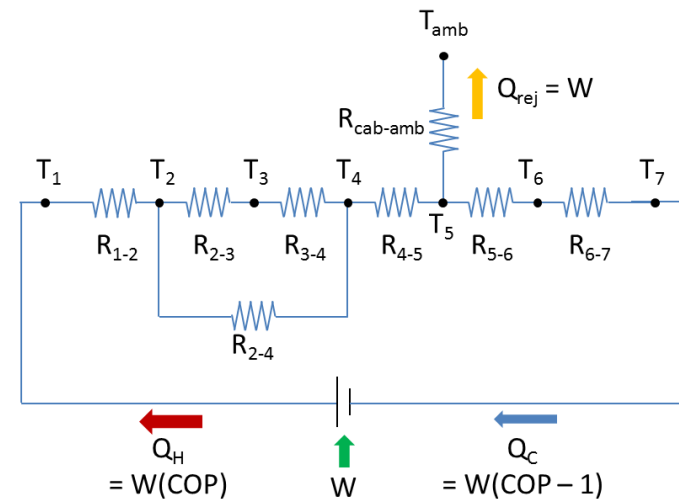
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Drum-integrated Model and Prototype

- Drum-integrated model allowed performance to be inferred from electric resistance prototype results
- EF determined to be 6.4



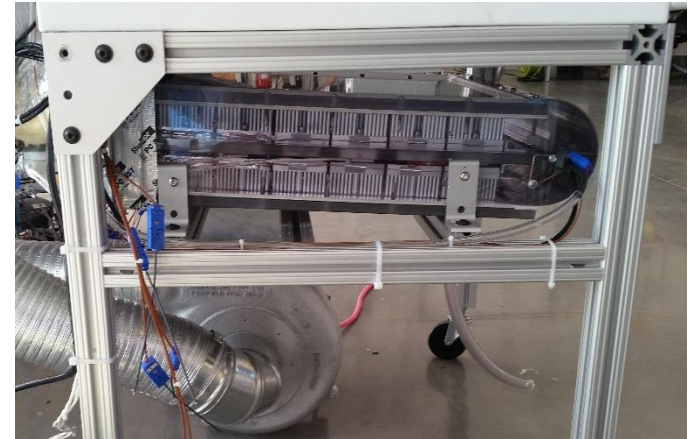
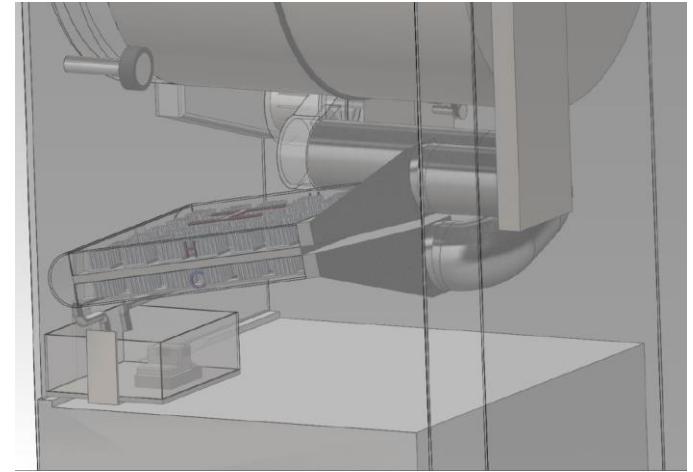
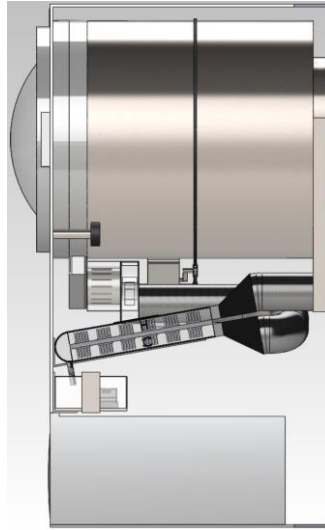
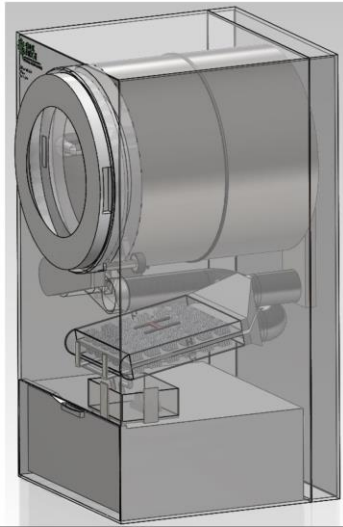
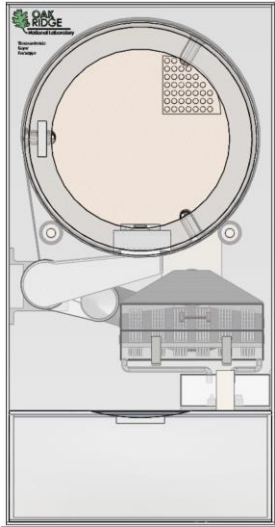
T_1 – hot TE interconnect
 T_2 – hot TE surface
 T_3 – clothes
 T_4 – saturation temperature, inside drum
 T_5 – saturation temperature, outside drum
 T_6 – cool TE surface
 T_7 – cool TE interconnect



¹ HHS: Hot side encapsulation layer and Heat Sink

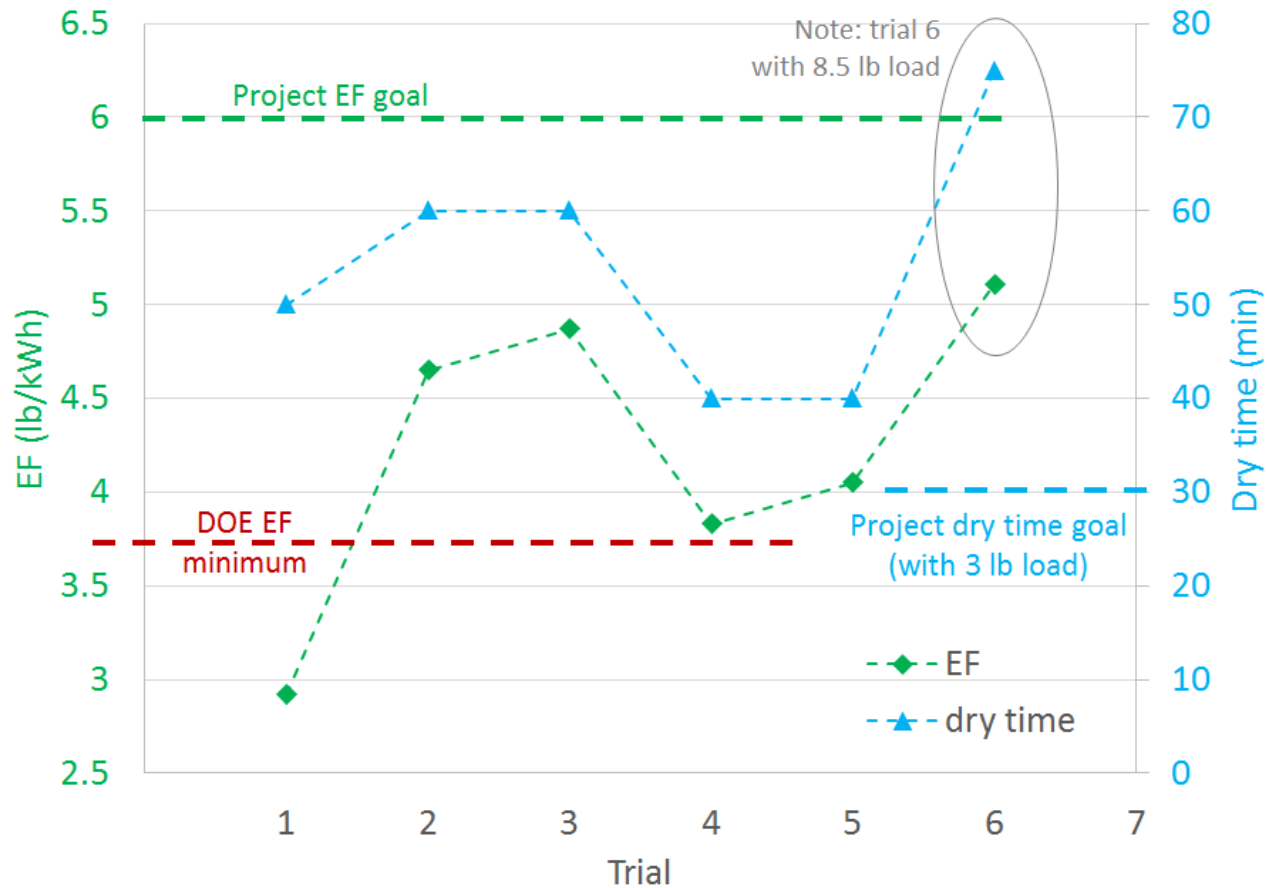
² CES: Cool side encapsulation layer and any Extended Surfaces

Thermoelectric prototype design and fabrication (FY16Q1)



Thermoelectric prototype: preliminary results (FY16Q1)

- Energy factor* and dry time for various TE control schemes, air flow rates and duct implementations



*EF evaluated in development environment near standard conditions

Project Integration and Collaboration

Project Integration: Project partner Sheetak, Inc. is a US manufacturer of thermoelectric modules. The team is in negotiation with appliance manufacturers.

Partners, Subcontractors, and Collaborators: Partners: Ayan Guha, Key Kolle, Uttam Ghoshal from Sheetak, Inc., US-based world leader in advanced TE solid state converters. They have demonstrated high-efficiency (HiE) TE devices with a figure of merit (ZT) exceeding 1.5, and have started volume production of TE heat pumps.

Communications: Abstract accepted at 16th International Refrigeration and Air Conditioning Conference at Purdue University, July 2016:
“Thermodynamic System Modeling of Thermoelectric Heat Pump Clothes Dryer”

Next Steps and Future Plans

Next Steps and Future Plans:

- Improve controls to maximize EF and minimize dry time for current generation prototype
- Identify design changes to improve performance and minimize projected cost of next generation prototype, including heat sink designs

REFERENCE SLIDES

Project Budget

Project Budget: \$850k federal + \$95k cost share

Variances: None

Cost to Date: \$733k federal

Additional Funding: None






Budget History

FY 2015 (first year) (past)		FY 2016 (current)		FY 2017 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
\$425k	\$47.5k	\$425k	\$47.5k	\$0	\$0

Project Plan and Schedule

		FY15				FY16			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	ER Prototype	[Green Bar]							
1.1	Drum-integrated modeling	[Green]							
1.2	Design ER prototype		[Green]						
1.3	Build ER prototype			[Green]					
1.4	Evaluate ER prototype				[Green]				
					[Green Diamond]				
2	TE development		[Green Bar]						
2.1	Water resistant TEs		[Green]						
2.2	Encapsulation method				[Green]				
3	T2M			[Green Bar]					
3.1	Market strategy/comm. plan			[Green]					
3.2	Identify partners/manuf				[Green]				
4	TE Prototype					[Light Blue Bar]			
4.1	Design for TE integration					[Green]			
4.2	Design TE controls						[Light Blue]		
4.3	Build TE prototype							[Light Blue]	
4.4	EF>6 for TE prototype								[Grey]
5	TE module development					[Light Blue Bar]			
5.1	Demonstrate TE modules						[Light Blue]		
5.2	Advanced TE modeling								[Grey]

Legend:

-  Go/No-go: complete
-  Go/No-go: pending
-  complete
-  in progress
-  pending