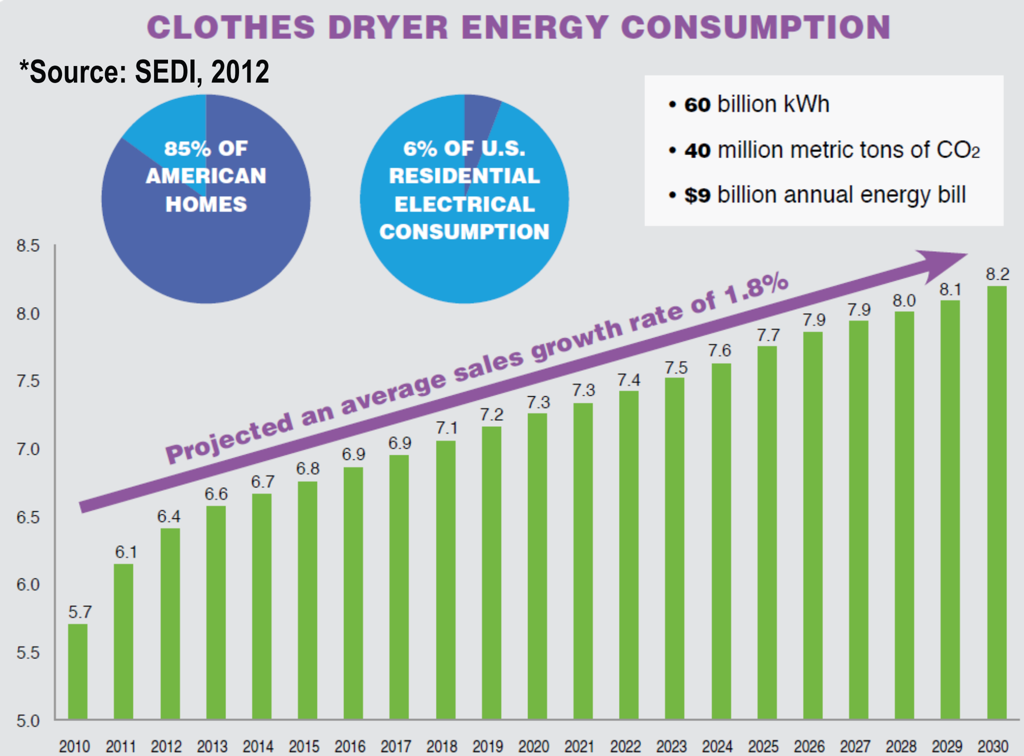
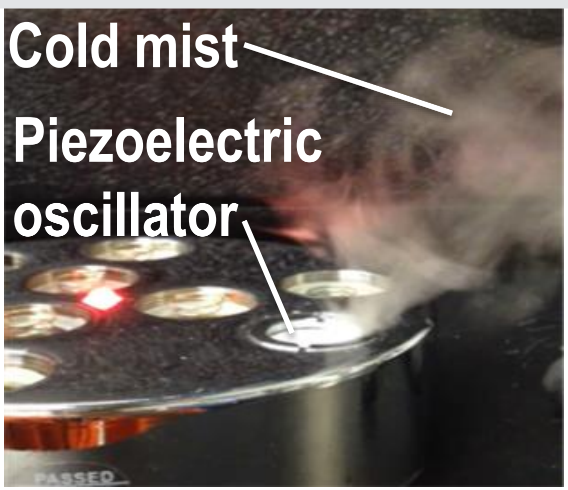
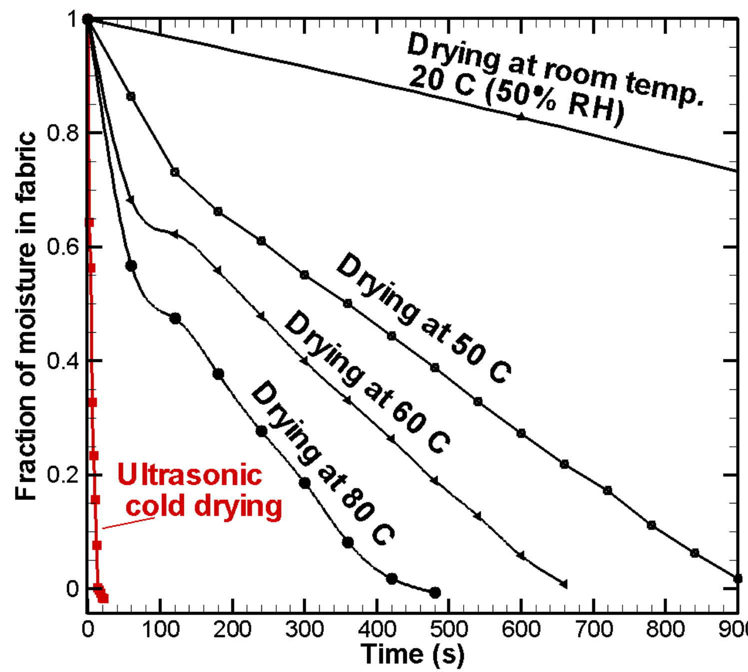


Ultrasonic Clothes Dryer

2016 Building Technologies Office Peer Review





Subcontractor: University of Florida

Industrial Partner: General Electric

PI: Ayyoub M. Momen, momena@ornl.gov
Oak Ridge National Laboratory

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Project Summary

Timeline:

Start date: Sept 1, 2014 (FY 2015)

Planned end date: March 31, 2017

Key Milestones

1. Develop and test a small-scale demo proof of the concept prototype and further validate the model –GO/NO GO(9/30/2015)
2. Design cold mist air carrier flow and mist passage (9/30/2016)
3. Develop the most appropriate full-scale ultrasonic dryer (9/30/2016)
4. Conduct comprehensive testing and refine/finalize the design of the full scale ultrasonic dryer (2/30/2016)

Budget:

Total DOE $ to date: $880K

Total future DOE $: $0

Key Partner:

Industrial Partner:

General Electric Appliances

Subcontractor:

University of Florida

Collaborators:

Project Outcome:

The objective of this project is to develop a clothes dryer prototype using piezoelectric transducers to mechanically extract water and achieve an Energy Factor, EF >10 (lb/kWh) and drying time <20 minutes.

Note:

Resistive heating element dryers: EF~3.5

Heat pump dryers: EF~5-8.5

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Purpose and Objectives

Problem Statement: a) identifying suitable piezoelectric transducer for this specific application; b) identifying the best driving signal; c) integration and scale-up challenges; d) identifying the pros and cons of the technology.

Target Market and Audience: The principal target market is residential/commercial clothes drying processes (can be expanded to other industrial drying processes).

Impact of Project:

Clothes dryers use **1%** of the nation's energy. The proposed technology can be significantly more efficient than current clothes dryers.

According to our market assessment study, ultrasonic dryers are projected to save up to **$900 million** in consumer utility savings over 10 years. Using ACEEE's logic, these savings would support the creation of up to **6,350 jobs**.

1. Final product will be a full scale prototype
2. The success criteria are to achieve an energy factor >10 (lb/kWh) for the large-scale system.
    a) Near-term outcome: Develop a feasible ultrasonic dryer design.
    b) Intermediate-term: Design a dryer
    c) Long-term: Introduce a unit to the market

Approach

Approach:

Research efforts are concentrated in three categories:

a) Identifying, evaluating the right transducer

b) Identifying, evaluating the right power signal

c) Modulating transducers

Key Issues:

a) Operation reliability

b)Performance decay in the scale-up

Distinctive Characteristics:

Research Efforts → **Down-select efficient transducer**; **Identify the efficient operating frequency**; **Modulate the driving signal**; **Develop mist collection mechanism** → Enhanced efficiency, reliability → **Better dryer machine**

Progress and Accomplishments

Accomplishments:
- Appropriate ultrasonic transducer selected (Milestone 2)
- Demo proof of the concept prototype developed (Go/No Go)
- Innovating burst width modulating amplifier developed (significantly improved efficiency over the small-scale system)

Market Impact:

This project can potentially save 1 quad of energy and be the first viable clothes dryer technology with EF>10.

Awards/Recognition:
- Received "Blue status" from BTO: This is the highest level of grading on the project progress that rarely given to the projects (indicating it significantly outperforms on goals and performance measures)
- The project was recognized by EERE assistant secretary Dr. David Danielson
- ORNL Early career award
- Ayyoub M. Momen, Kyle Gluesenkamp, Edward Vineyard, Clothes Dryer Using Ultrasound Phenomena, US provisional patent application 62/158,562, May 8, 2015.

Lessons Learned:
- The cascading failure issues upon modulation of multiple transducers
- The importance of the impedance matching, and amplifier role
- The importance of the drive signals property
- The importance of the geometry and resonance frequency of piezoelectric transducers

Progress and Accomplishments:

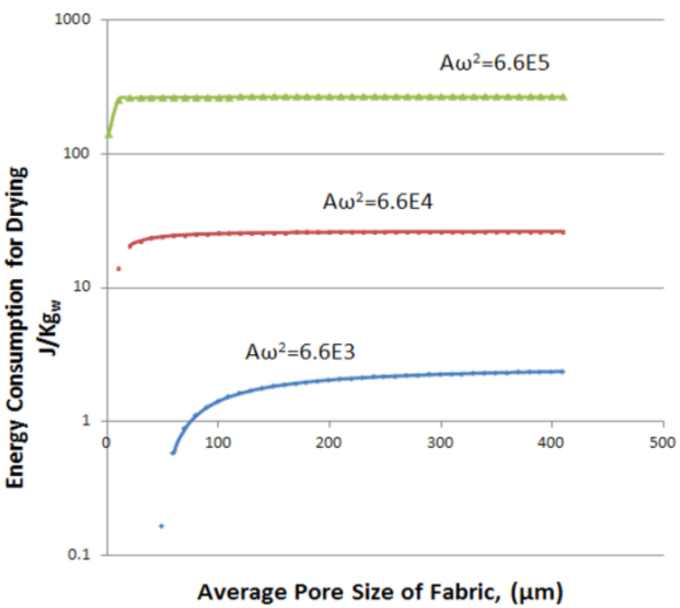
Brief theoretical background

Heat-based drying:

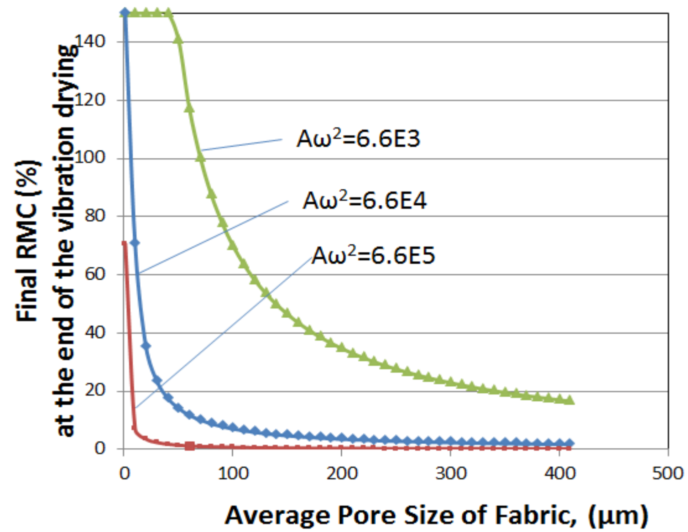
- Conventional evaporation-based dryers must overcome the latent heat of evaporation and thus ideally need about 3.21–3.51 lb_{water}/kWh (or 2453–2257 kJ/kg_w). Considering the losses, existing dryers perform at 54–66% of their theoretical maximum efficiency.

Mechanical drying through vibration of ($y = A\sin(\omega t)$):

- Driving force is mainly inertia of water: $F_{Vib} \sim m_{drop} A\omega^2$
- Resistive force is capillary action: $F_{Cap} \sim \sigma\pi d \cos\theta$
- For a **single** microscopic pore (Orders of magnitude higher performance potential in microscopic scale):



The theoretical minimum energy consumption of vibration based drying for a single pore.



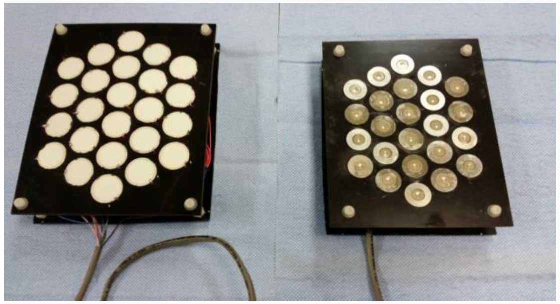
The qualitative minimum theoretical residual moisture content (RMC) of the fabric after vibration under different amplitude and angular frequencies ($\omega = 2\pi f$),

Progress and Accomplishments: Go/No-go Milestone

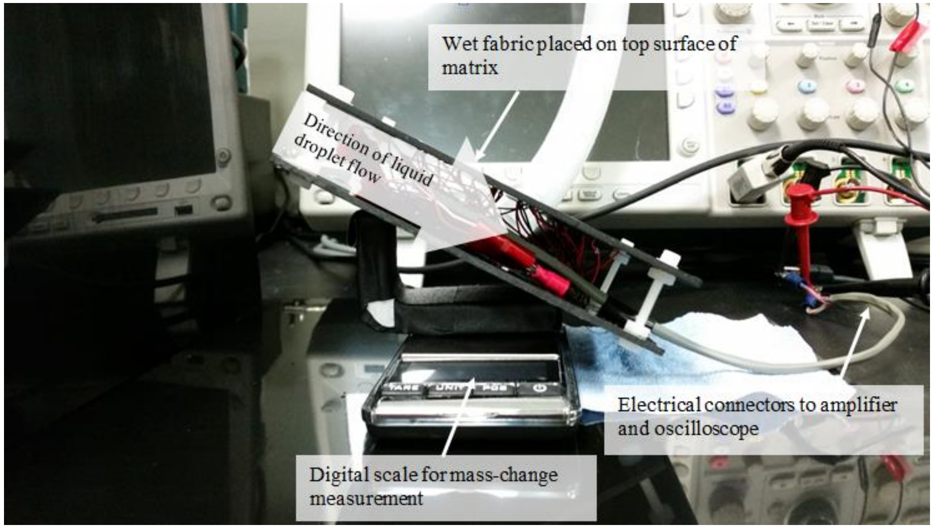
Proof of concept prototype was developed and evaluated; it exceeded the phase 1 goals

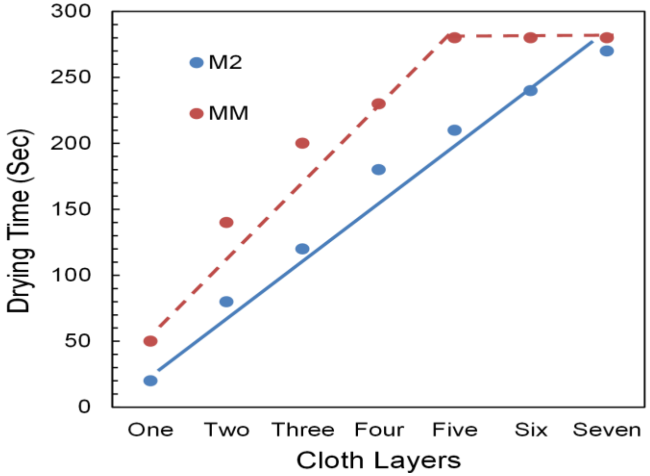
- The best 2 transducers down-selected
- Matrixes containing 24 transducers were developed and evaluated
- Experiments were conducted and the target results achieved
- The effect of number of fabric layers on the drying performance was investigated

Goal	Drying time <20 min	Fabric size > 4 in^2
Achieved	~ 7.5 minutes	~14 in^2



Drying 14 in^2 of fabric on matrix of 24 mesh transducers

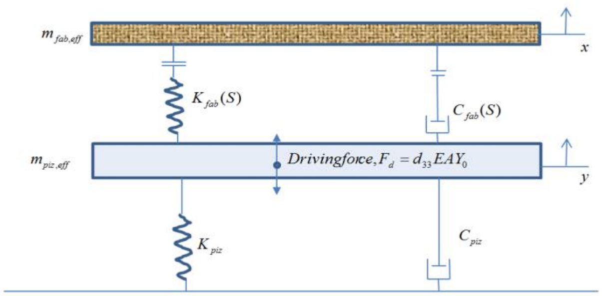


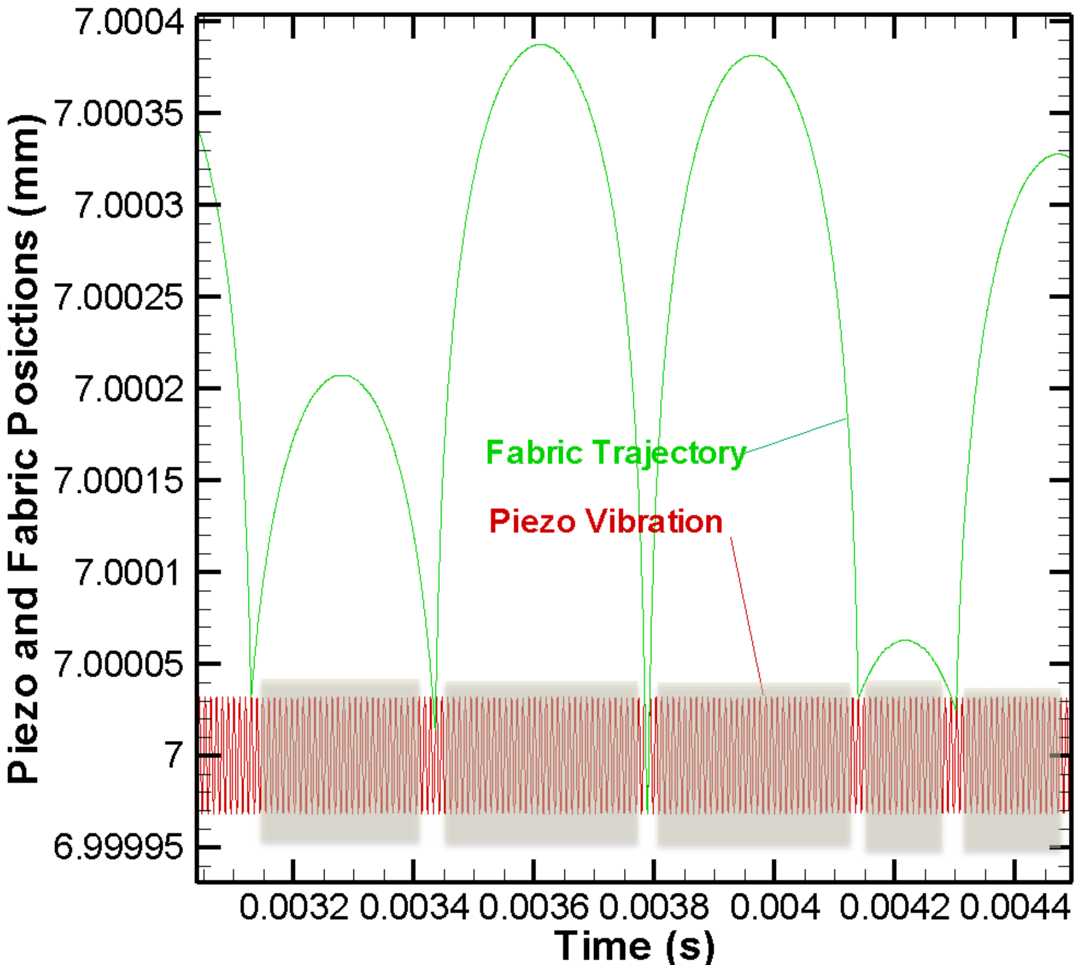


Effect of the number of fabric layers on the performance

Progress and Accomplishments: Our model inspired a game-changing insight

A finite difference–based model for vibration of piezoelectric transducers and fabric vibration has been developed

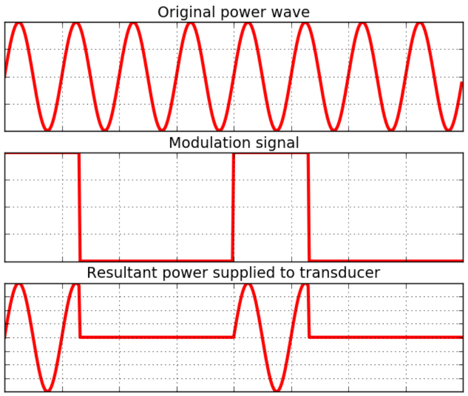




Significant Findings:

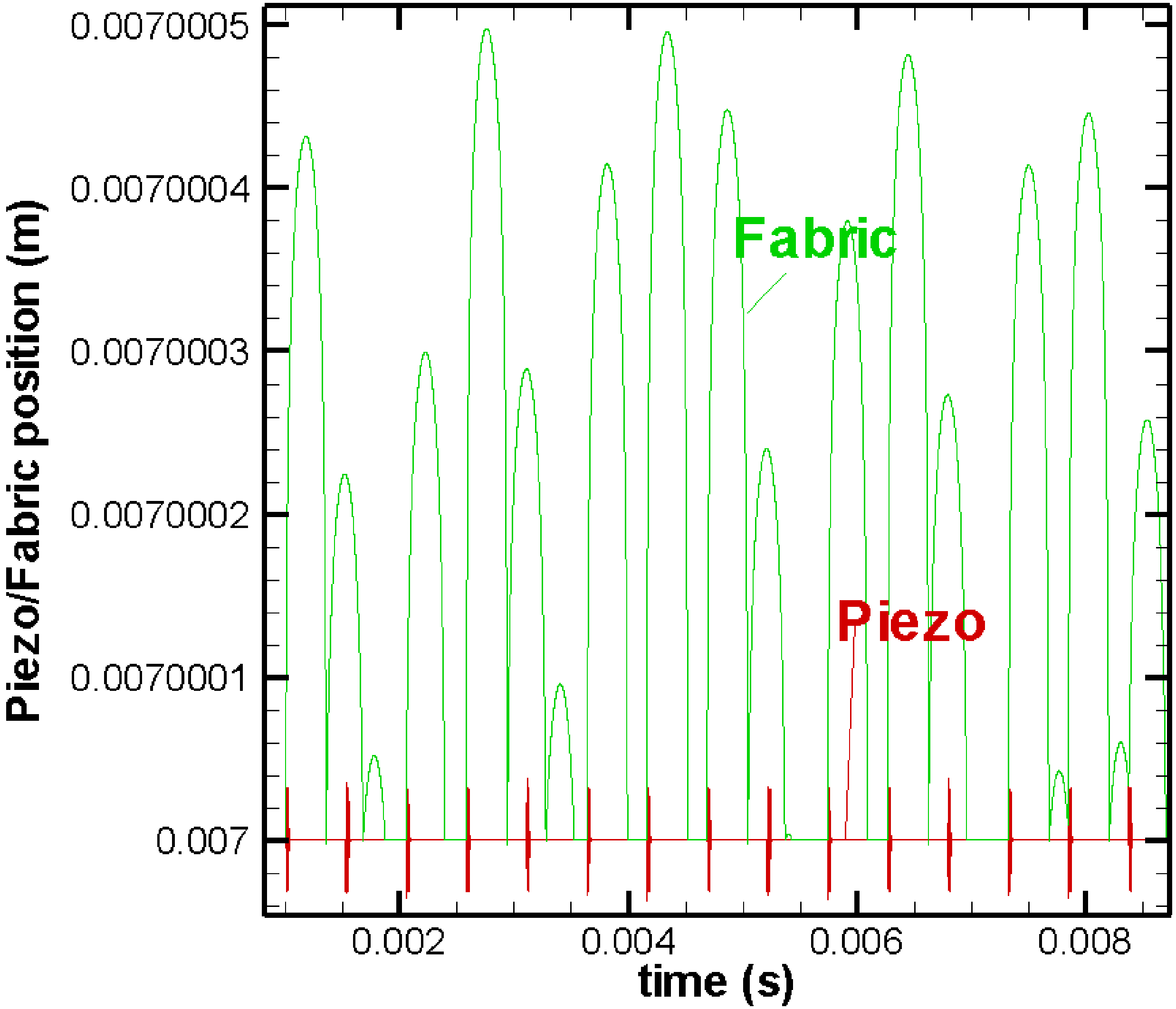
Running at partial duty cycle is better because:

1) No energy is consumed when there is no mechanical coupling between piezo and fabric.
2) The kicks on the fabric (acceleration) will be stronger.

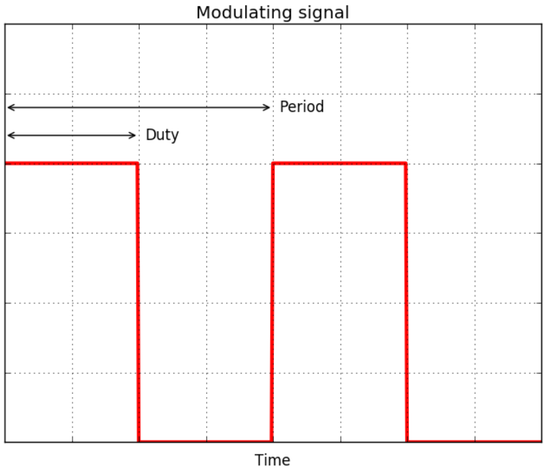


We realized power is not needed when piezo and fabric are mechanically decoupled

Example: Burst Width Modulator Effect on Fabric Vibration/Drying



Example:
- 5% duty cycle,
- 0.0005 millisecond pause



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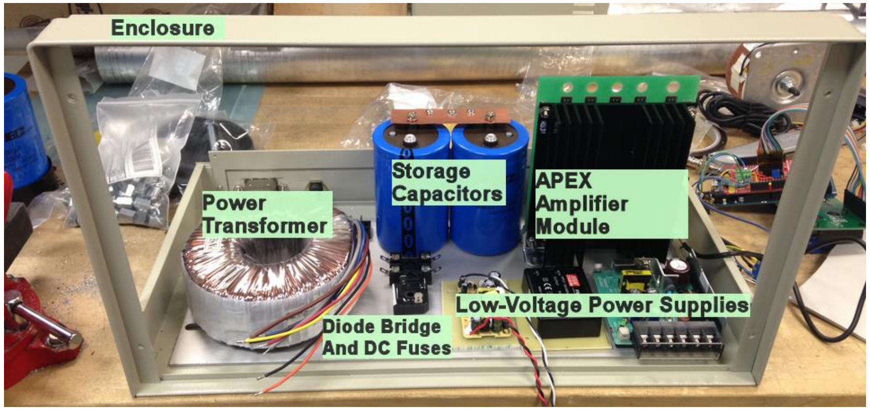
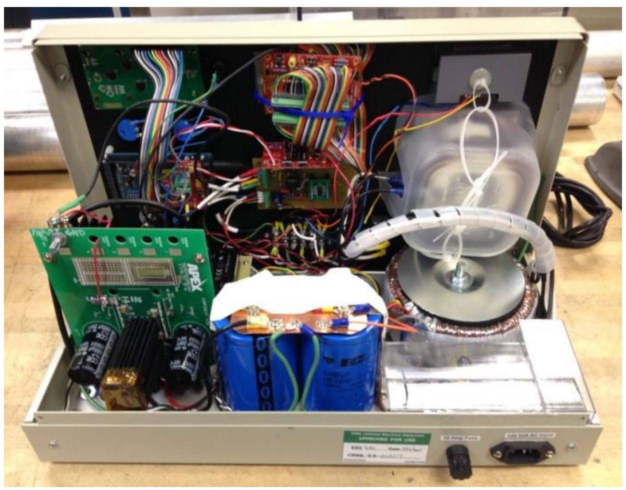
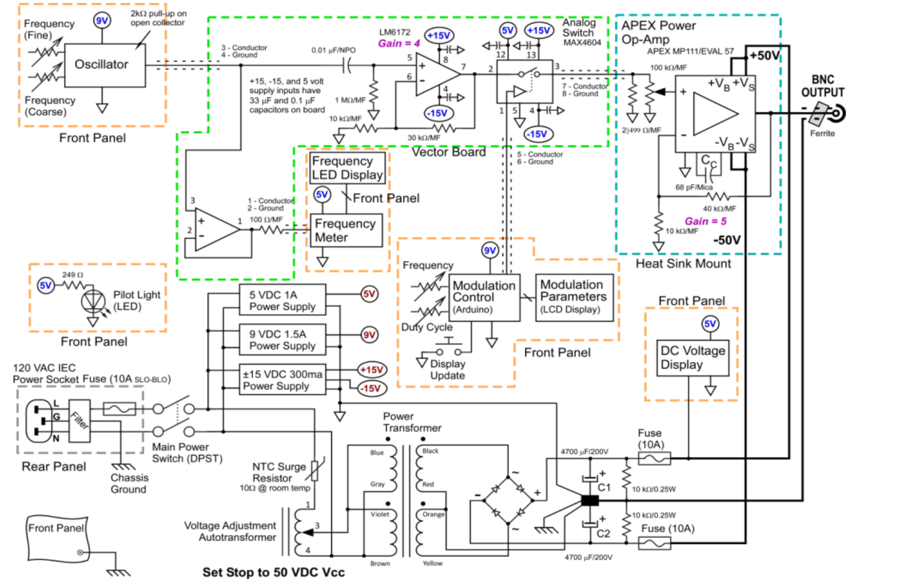
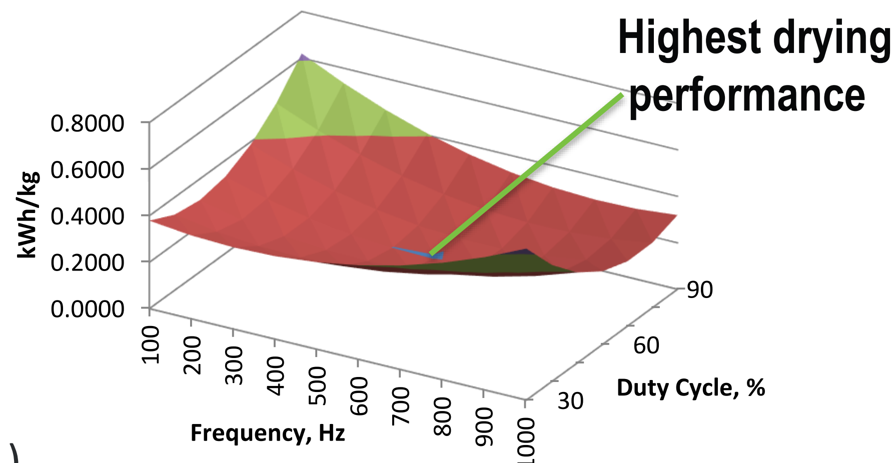
A Custom-made Burst Width Modulator (based on modeling results) Has Been Developed







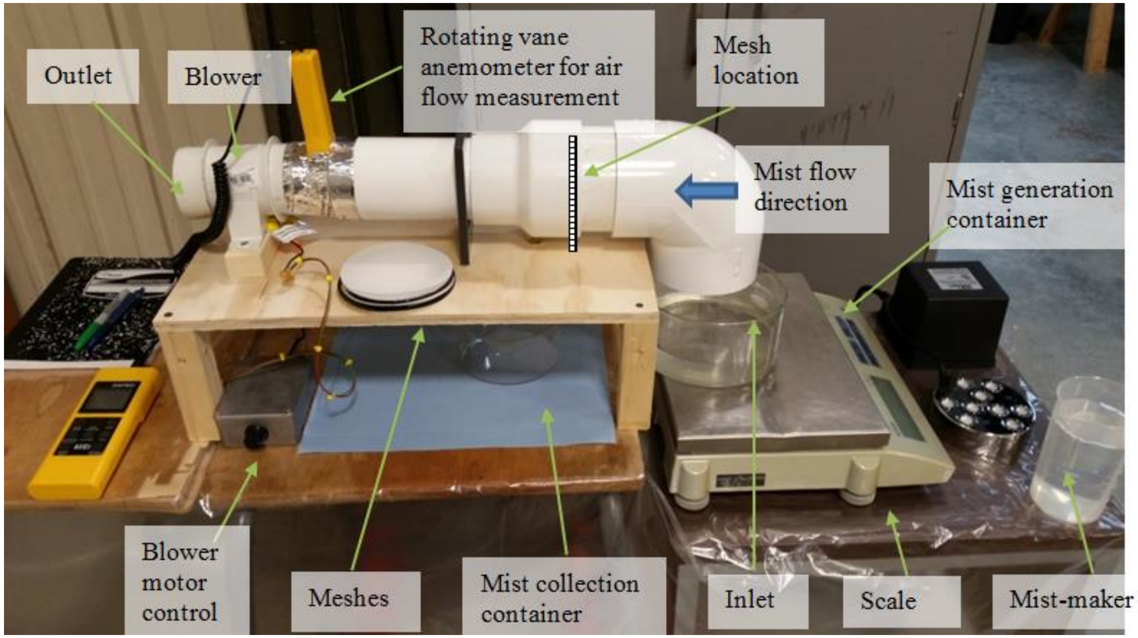


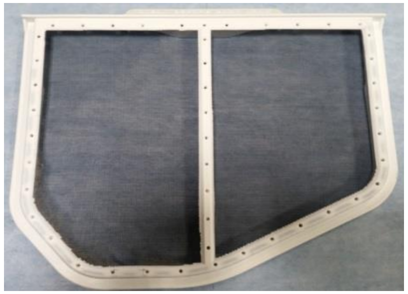
Curve fit on experimental data obtained with this custom amplifier

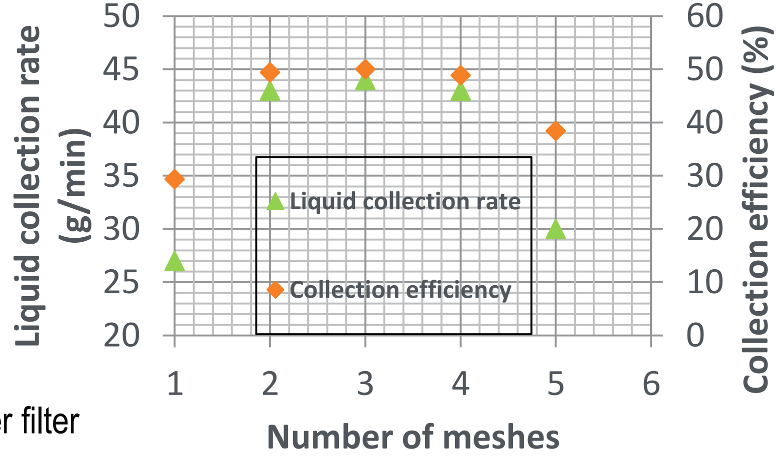
ORNL Findings on 1 cm^2 fabric:

- **The drying efficiency <u>doubled</u> (~712 kJ/kg$_{water}$) modulating the drive signal using the custom amplifier**
- Energy consumption was reduced by five folds compared to conventional dryers

Mist collector design







Finding:

If mist collection mechanism is required, 2-4 layers of the conventional dryer filter can effectively collect the mist from the air stream.

Project Integration and Collaboration

Project Integration:

1) Weekly meetings between ORNL team members
2) Monthly meeting between ORNL/UF and GEA
3) ORNL-GE have quarterly site visits.

Partners, Subcontractors, and Collaborators:

GE Appliances

University of Florida

Communications:

Ayyoub M. Momen, Edem Kokou, Kyle Gluesenkamp, Omar Abdelaziz, Pradeep Bansal, Preliminary Study on the Performance of the Novel Direct Contact Ultrasonic Clothes Dryer, IMECE2015-50479.

Popular Mechanics
Ultrasonic Dryer Does the Laundry in a Fraction of the Time: Vibrations are coming to make laundry day a little less terrible.
http://www.popularmechanics.com/technology/gadgets/news/a16676/dryer-invention-ultrasonic-vibrations/

USA Today
Scientist's cool clothes dryer uses vibration, not heat
http://www.usatoday.com/story/tech/2015/06/23/cold-vibration-ultrasonic-dryer/29160935/

Nashville Public Radio
Oak Ridge Scientists Make Breakthrough In Age-Old Problem: Drying Clothes Faster
http://nashvillepublicradio.org/post/oak-ridge-scientists-make-breakthrough-age-old-problem-drying-clothes-faster#stream/0

Digital Trends
Sick of waiting for the dryer? In a few years, new technology could dry clothes in minutes
http://www.digitaltrends.com/home/ayyoub-momens-new-technology-dries-clothes-super-fast/

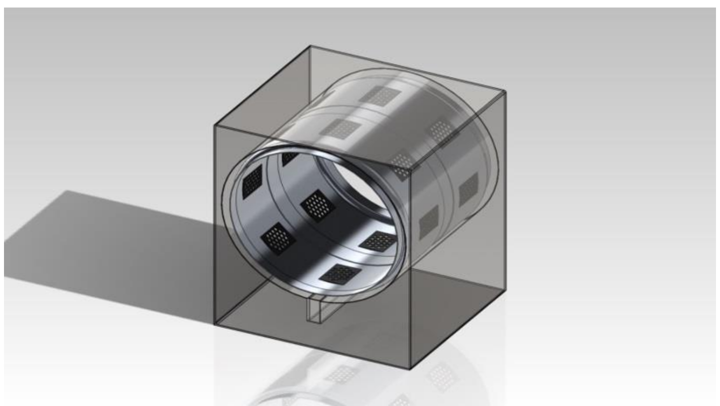
Project video by ORNL
https://www.youtube.com/watch?v=poVwCmqcue8

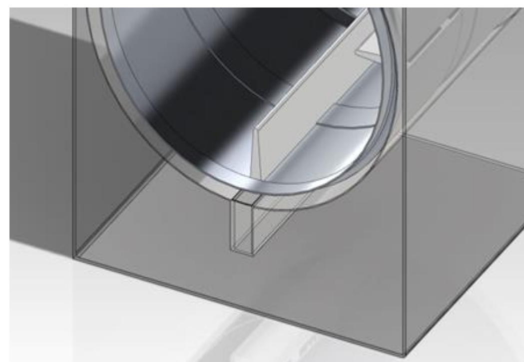
Next Steps and Future Plans

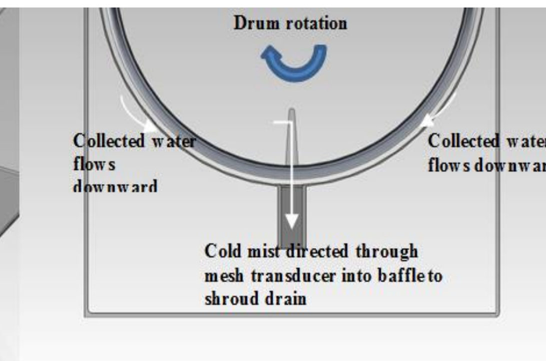
Next Steps and Future Plans:

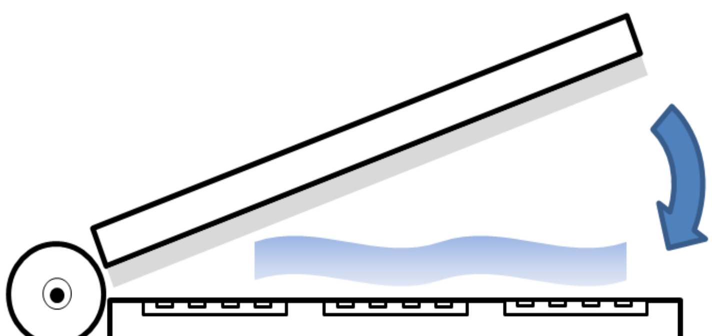
1. Scale up (June 30, 2016)

2. Evaluation/optimization: Target EF >10, drying time <20 minutes (September 30, 2016)









Acknowledgment

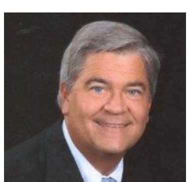
ORNL Team

BTRIC









Sensors and Embedded Systems



University of Florida


GE Appliances Team

REFERENCE SLIDES

Project Budget

Project Budget: DOE total $880K FY 2015– Mid FY 2017
Cost share (GEA): $98K
Variances: None
Cost to Date: $659K
Additional Funding: None

Budget History					
FY 2015 (past)		FY 2016 (current)		FY 2017	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$438K	10%	$437K	10%	$103K	10%

Project Plan and Schedule

Project Schedule												
Project Start: Oct 2014		Completed Work										
Projected End: March 2017		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned) use for missed										
		Milestone/Deliverable (Actual) use when met on time										
	FY2015				FY2016				FY2017			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)		
Past Work												
Appropriate ultrasonic transducer selection												
Complete development of the1st order dynamic model												
Demo proof of the concept												
Market strategy and commercialization plan												
Carrier flow system design.												
Current/Future Work												
Full scale retrofit prototype development and shakedown testing.												
Full scale dryer design & development												
Develop the cost model												
Achieve the target goals in the full scale ultrasonic dryer system												
Pre-commercialization activities												