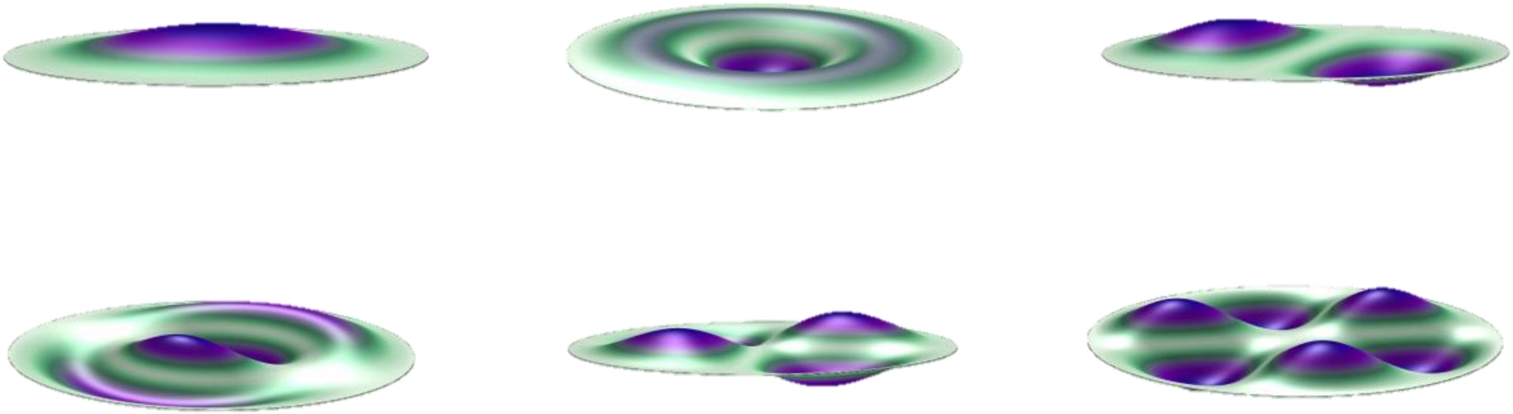
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Mechanical Dehumidification Using High-Frequency Ultrasonic Vibration



Oak Ridge National Laboratory
Ayyoub Momen, R&D Staff
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Project Summary

Timeline:

- Start date: 10/1/2017
- Planned end date: 9/31/2019

Key Milestones

- Evaluate absorption and mechanical water ejection rate of piezoelectric/desiccant, 9/31/2018
- Evaluate first-generation system, 3/31/2019
- Evaluate the improved system, 9/31/2019

Budget:

Total Project: $384K:

- DOE: $384K
- Cost share: $36K

Total Project $:

- DOE: $500K
- Cost share: $56K

Key Partners:

Oak Ridge National Laboratory

STEMiNC Steiner & Martins, Inc.

Georgia Tech

Virginia Tech

Project Outcome:

- Dehumidification process three to five times more efficient than in current state-of-the-art vapor compression dehumidifiers
- Development of a bench-scale stand-alone dehumidifier module with a 0.1 L/day capacity in a laboratory environment
- Alignment with the Multi-Year Program Plan for BTO's dehumidification target

Team

ORNL Team

BTRIC

Ayyoub Momen
PI & R&D Staff

Kashif Nawaz
R&D Staff

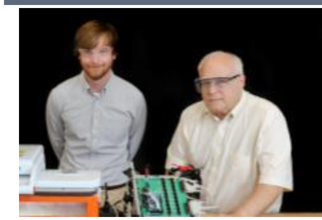
Viral Patel
R&D Staff

- Exp. design and analysis
- Prototype fabrication
- Model development

Eric Dupuis
PhD student

GO! Program PhD student at ORNL
- Modeling and evaluation of piezoelectric transducers

Power Electronics and Embedded Systems



Roger Kisner
Distinguished R&D Staff
Kyle Reed
PhD student

- Power drive/amplifier development

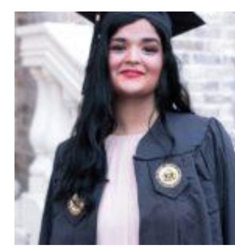
STEMiNC Inc.

Martins Oswalnyr
President, CEO
- Custom piezo fabrication

Virginia Tech

Shima Shahab
Assistant Professor, VT
Piezoelectric energy harvesting, acoustics and dynamics, and mechanics of materials

Georgia Tech



Pri Deo
MSc student

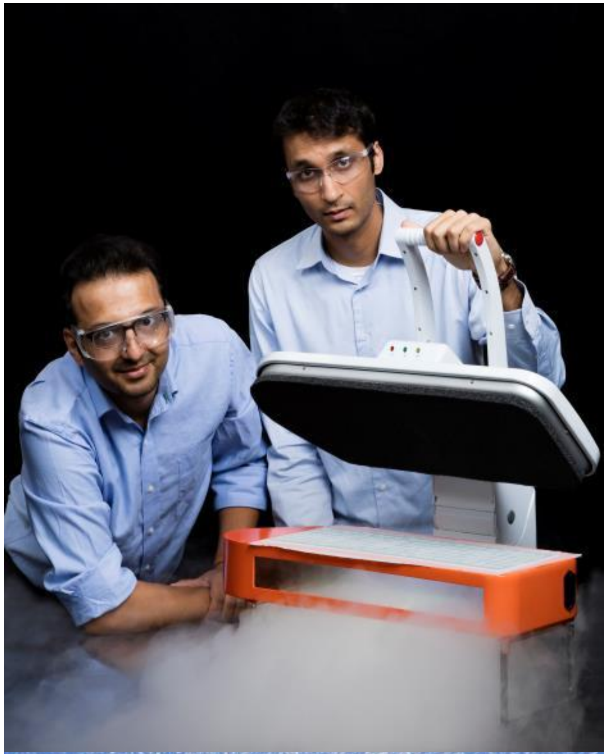
Rate measurements

Samuel Graham
Professor

Technology Background/History

Ultrasonic Clothes Dryer:

- The team invented and developed an ultrasonic clothes dryer technology in 2015-2017
- It was shown that high-frequency vibration of piezoelectric transducers can mechanically remove water from wet fabric in the form of the cold mist (bypassing water latent heat of evaporation)
- Drying efficiency was improved by 5 times (1/5th of power input)
- The technology was exclusively licensed in 2018

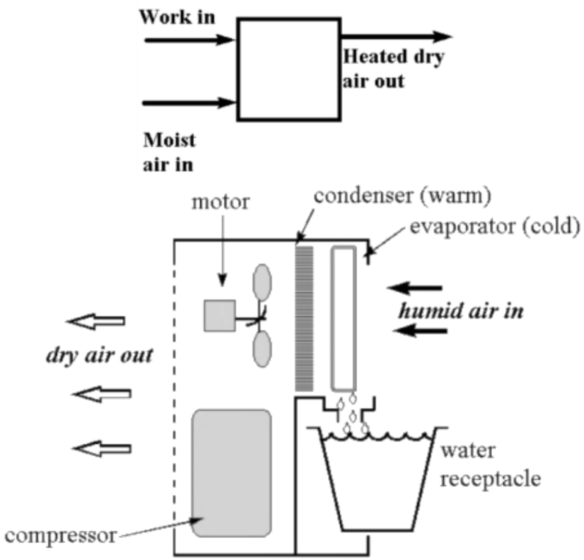


Take-away message:
Don’t evaporate water, shake it out

http://money.cnn.com/2016/06/21/technology/ultrasonic-dryer/index.html
http://www.bbc.com/news/technology-39643452

Challenge

- Latent load ~*40*% of the cooling load of buildings
- Withdrawing moisture from the air can significantly improve the performance of HVAC systems (***separate sensible and latent cooling (SSLC) systems***)
- Dehumidification is conventionally achieved by the vapor compression cycle by ***cooling air below the dew point*** to condense water and reheat—a highly ***inefficient*** process for dehumidification
- Liquid/solid desiccant dehumidification systems are 30–50% efficient compared with VC-based systems. ***Regeneration*** of the desiccant materials and management of the heat of sorption are critical issues.
- An innovative solution is needed to avoid the intense heat needed for regeneration

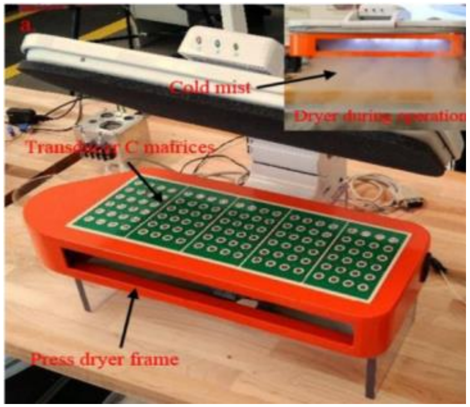


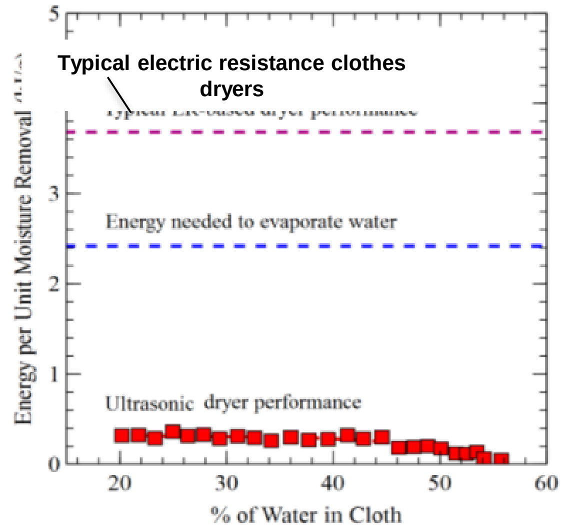
Source: http://chem.engr.utc.edu/Webres/435F/
Dehumidifier/Dehumid/R5-435-1.html

Efficiency: *972–3000 kJ/kg water removal.*

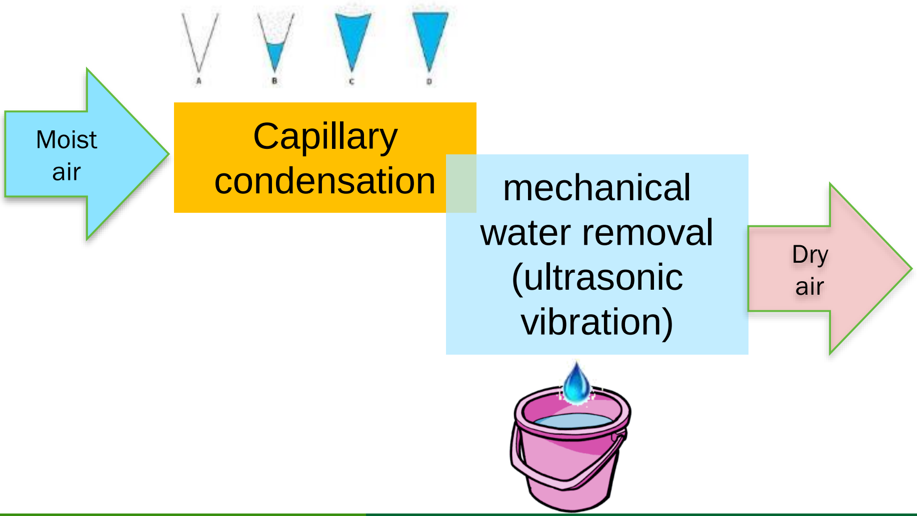
Approach

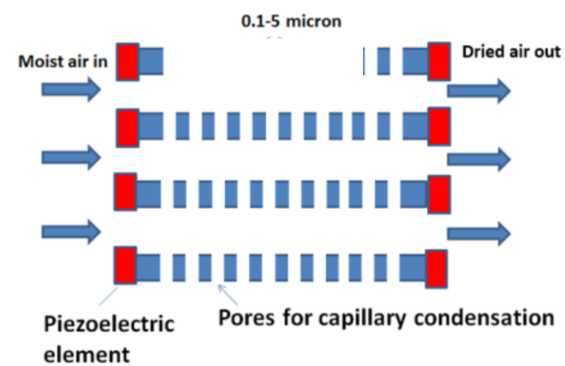
The Solution: Bypassing heating-based regeneration!





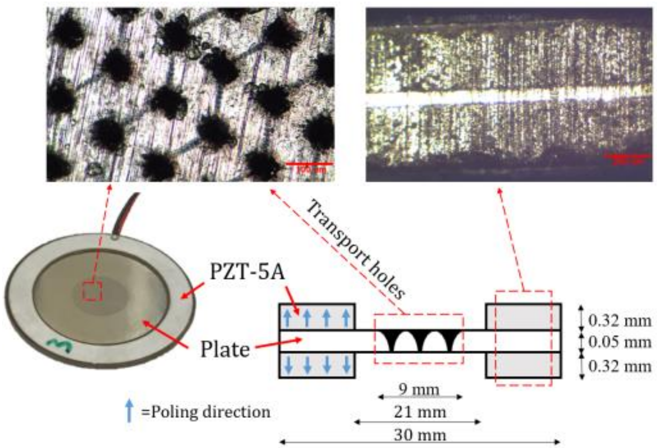
We have already shown that piezoelectric vibration can significantly boost drying efficiency.



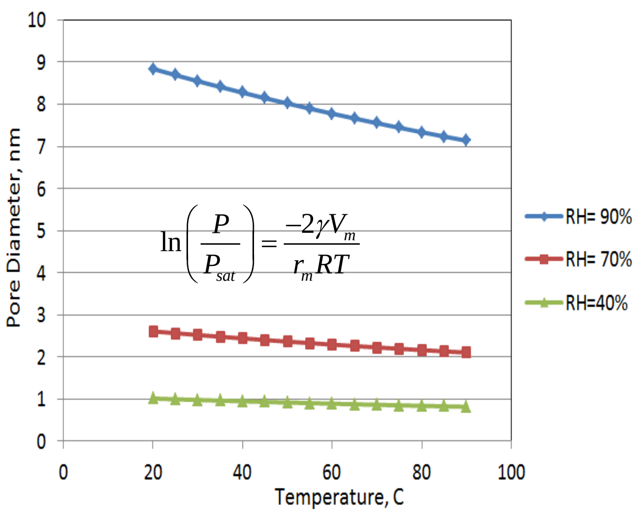


Approach

Step 1: Capillary condense water out of the air
Step 2: Mechanically eject water out



Capillary condensation:



Fabrication process for small pores on sheets → Evaluation of the water absorption rate → Evaluation of the water ejection rate

Desiccant identification → Integration with appropriate piezo → Evaluation of the water ejection rate

→ Pick the best method

Decision criteria: Cost/scalability/performance

→ Fab./Eval. 1st gen. prototype → Fab./Eval. final gen. prototype

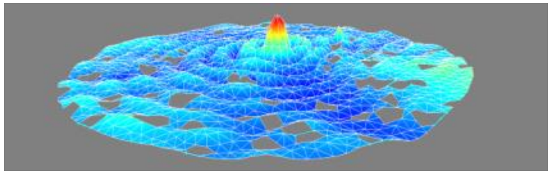
Model Development

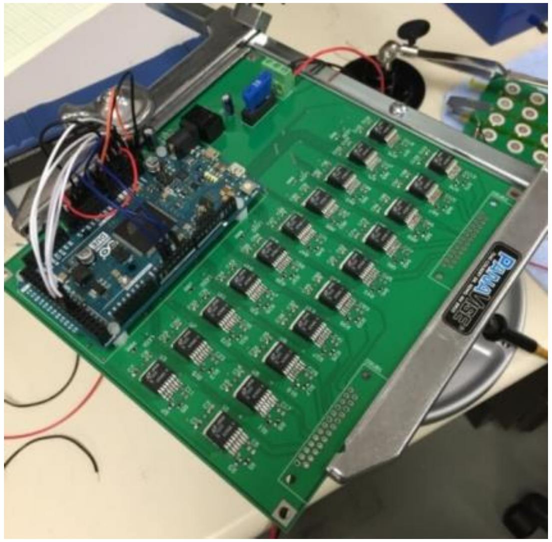
Year 1

Year 2

Impact

- Introduction of a new dehumidification process (proof-of-concept prototype capacity ~0.1 L/day)
- 3–5 times more efficient dehumidification process (~250 kJ/kg of water removal compared with 372–3,000 kJ/Kg in conventional systems); translates to 32–85% operating cost savings
- Grid tie flexibility (eco mode/performance mode) knobs: voltage and duty cycle
- New opportunities for SSLC systems due to 48% enhanced efficiency and 30% compactness
- Annual energy savings of 715 TBtu by 2030
- Savings would support 6,020 new jobs over 10 years



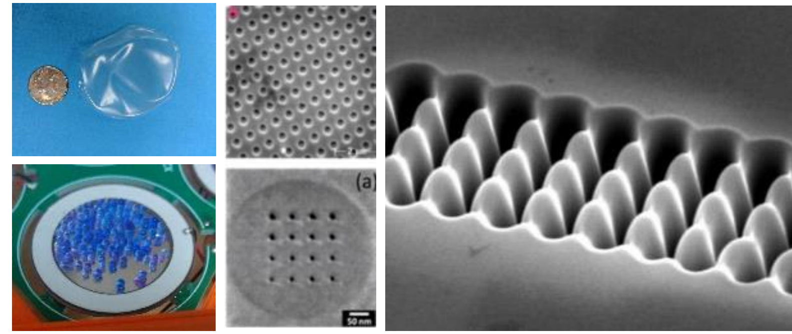


Target Market:

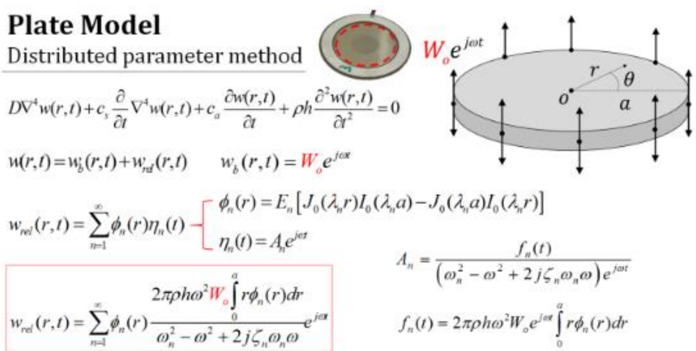
- Short-term: Residential and commercial dehumidifiers
- Long-term: SSLC for HVAC

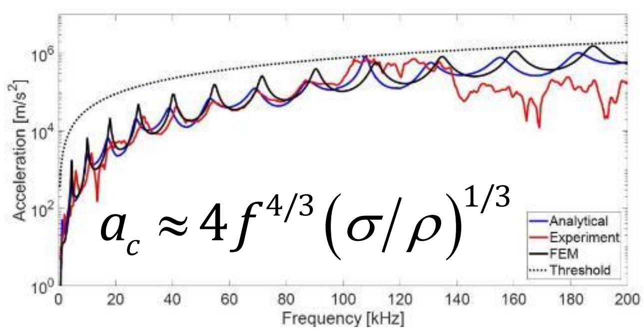
Progress (Reminder of Last Year's Activities…)

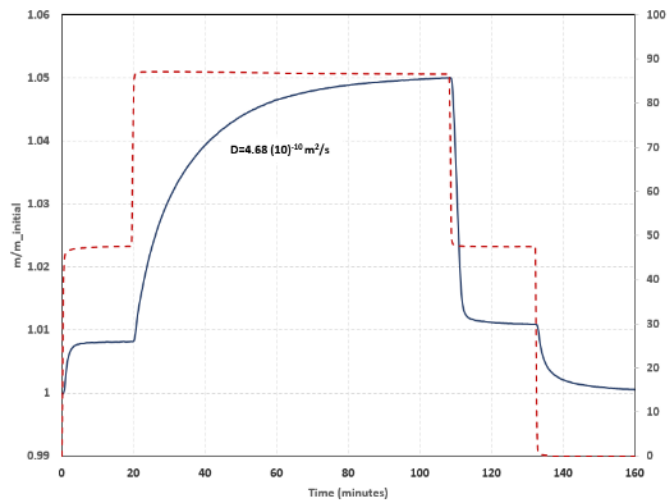
- We Identified the viable material
- We characterized the absorption and desorption rates with heat
- We developed the mathematical vibration model
- We developed the experimental setup (laser vibrometer)



Helium-ion milling   Focused ion beam







Equations:

$$\frac{\partial \rho}{\partial t} = D\left(\frac{\partial^2 \rho}{\partial x^2}\right)$$

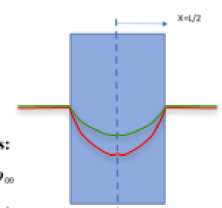
Initial condition:

$$\rho(x, t = 0) = 0$$

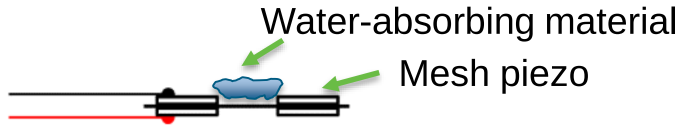
Boundary conditions:

$$\rho(x = L/2, t) = \rho_\infty$$

$$\frac{\partial \rho}{\partial r}(x = 0, t) = 0$$



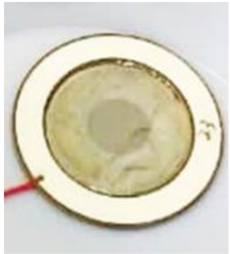
Progress—Recent Activities



Absorption followed by ***mechanical*** desorption rates

Findings:

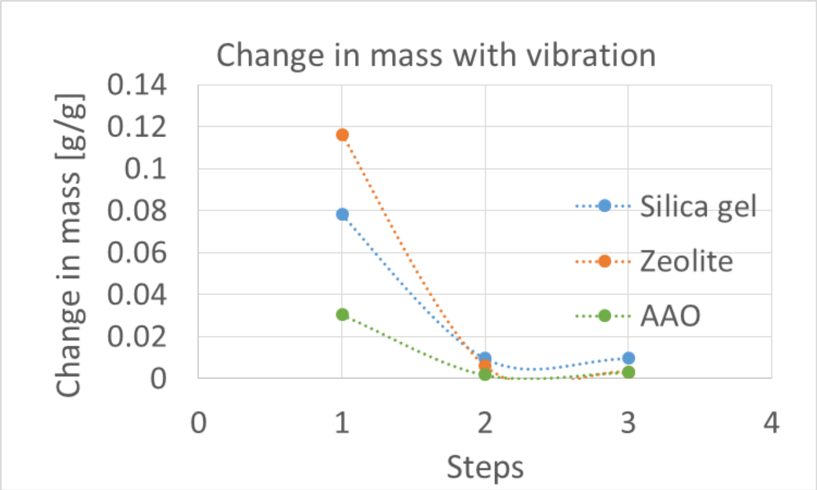
- The desorption rate is highest in the first 20 seconds
- The AAO has a lower mechanical desorption rate than Zeolite or Silica gel. 0.3165 mg/s (Silica gel) and 0.149 mg/s (Zeolite)
- A typical desorption rate profile looks like a decaying exponent—highest at the onset and rapidly dropping after
- The natural desorption/absorption from the air during measurement was subtracted from the data
- The net vibration–based desorption rate is an order of magnitude higher than other parameters
- The absorption/desorption time is being optimized to get the maximum overall performance


Anodized aluminum oxide wafer


Silica gel


RH 98%, K_2SO_4 solutions


Zeolite



Progress—Recent Activities

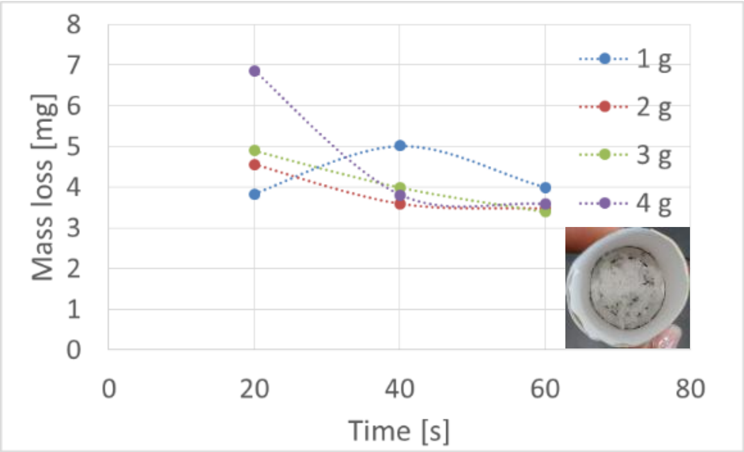
Impact of mass loading:

Findings:

- There is no significant difference between a 1, 2, 3, and 4 g sample on the piezoelectric transducer

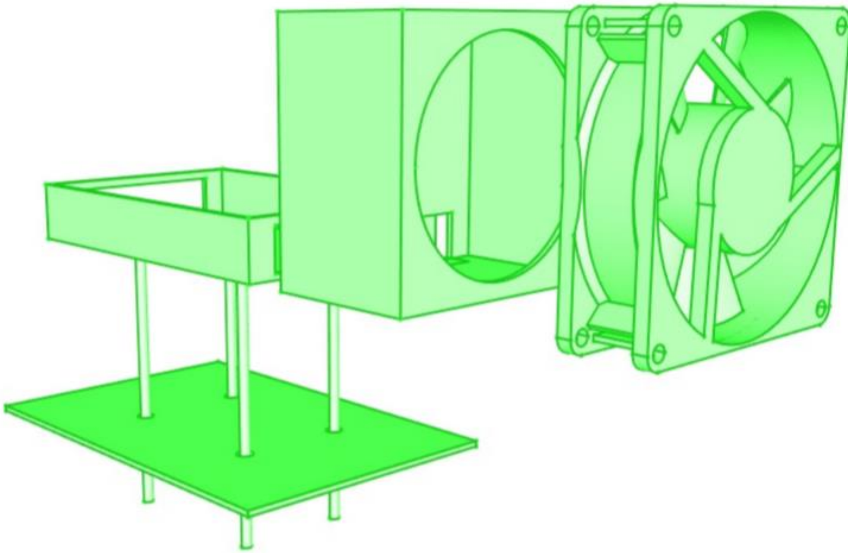
Why?

Mainly because of lack of air movement and poor moisture delivery to the thick sample. This will not be the case for the very well designed machine.

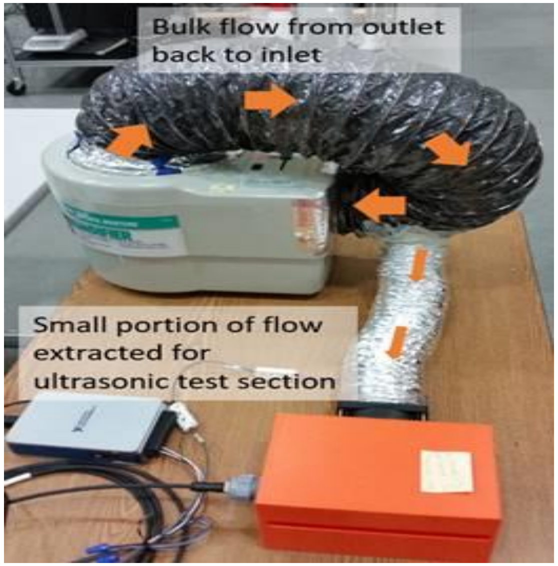


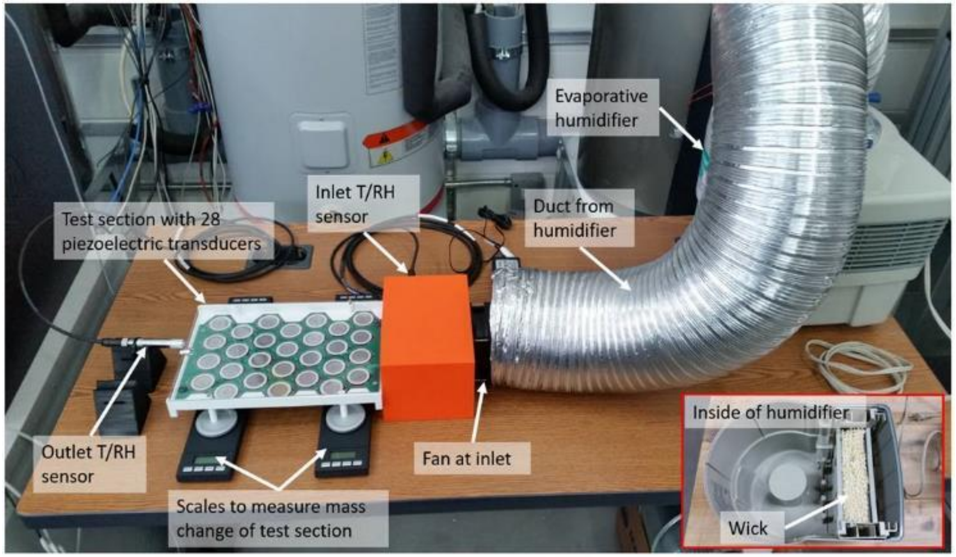
First prototype design:

Considering the absorption and mechanical desorption rates data, it is calculated that only 10 transducers are needed to make a 100 cc/day dehumidification machine.



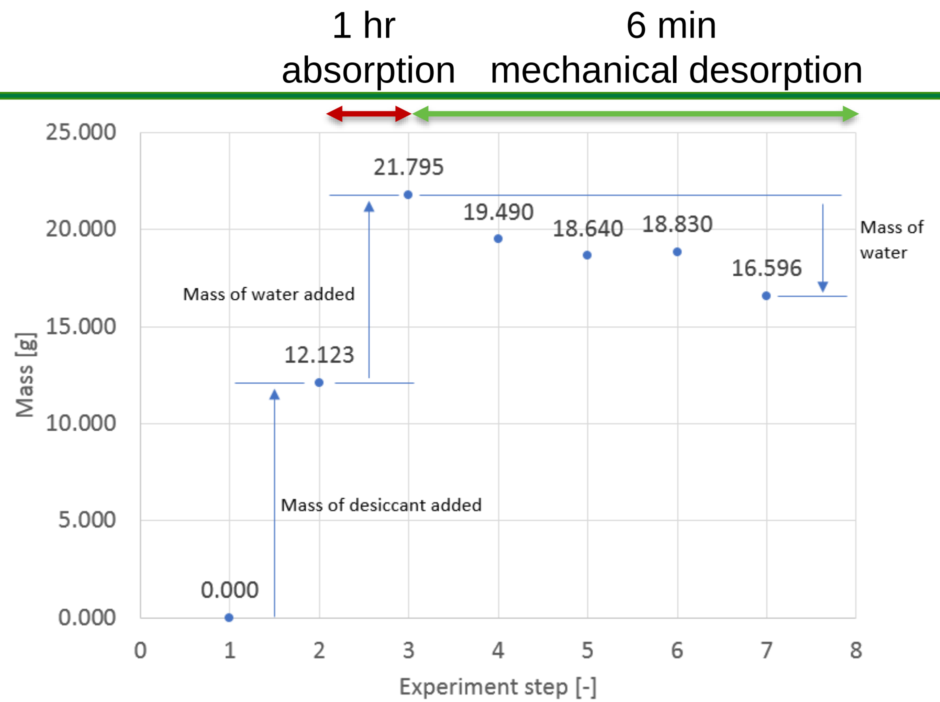
Progress: Prototype Fabrication





Progress: Results

- 12 grams of silica gel placed on the piezoelectric transducers
- One hour absorption
- Six minutes mechanical desorption
- The initial results are encouraging



Stakeholder Engagement

Communication:

- Weekly meeting among the ORNL team
- Biweekly meeting with Virginia Tech and Georgia Tech
- Biweekly meeting with the whole team, including the industrial partner

Team members' roles:

ORNL's BERG:

- ORNL's GO! PhD student from Virginia Tech:
  - Developing the comprehensive analytical and FEM models
  - Guiding the design
- Georgia Tech student:
  - Extracting the kinetics of absorption and mechanical desorption

Invention:

- ORNL holds the IP on this technology

Visitors:

- More than 500 visitors to BTRIC facility

Publications:

- Eric Dupuis, Ayyoub M. Momen, Viral Patel, Shima Shahab, "Ultrasonic Piezoelectric Atomizer: Electromechanical Modeling and Performance Testing," *ASME 2018 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, SMASIS2018-8262, September 2018.
- Eric Dupuis, Ayyoub M. Momen, Viral K. Patel, and Shima Shahab, "Multiphysics modeling of mesh piezoelectric atomizers," *SPIE*, March 2018.

Remaining Project Work

Achieved in the last 15 months:

- Developed or identified viable capillary fabrication processes
- Designed high-volume-density pores in sheets of material
- Took preliminary measurements of the condensation kinetics
- Successfully developed the piezo model (both analytical and FEM)
- Developed small-scale perforated sheet
- Evaluated absorption and mechanical water ejection rate of piezoelectric/ desiccant
- Tied piezo model to the adsorbing material
- Fabricated first-generation system

Remaining work for the next 9 months:

- Evaluate the first-generation system
- Improve the first-generation system

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $500K (BENEFIT FOA 2017)
Variances: None
Cost to Date: $204K (Through March 2019)
Additional Funding: No additional direct funding

Budget History					
FY 2016-2018 (past)		FY 2019 (current)		FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$500k	$28	$0	$28	$0	$0

Project Plan and Schedule

Project Schedule

Project Start: 10/1/2017		Completed Work
Projected End: 9/31/2019		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missec
		Milestone/Deliverable (Actual) use when met on time

Task	FY2018				FY2019				FY2020		
	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)	Q3 (Apr-Jun)
Past Work											
Identify fabricqation process of nano pores											
Design high volume density on the sheet											
Develop a small scale proforated sheet for evaluation											
Evaluate the adsorption and ejection rate of the pizeo desccant assembly											
Design and development of the first fgeneration prototype											
Current/Future Work											
Modify the design and achieve the target of 250 kJ/kg											