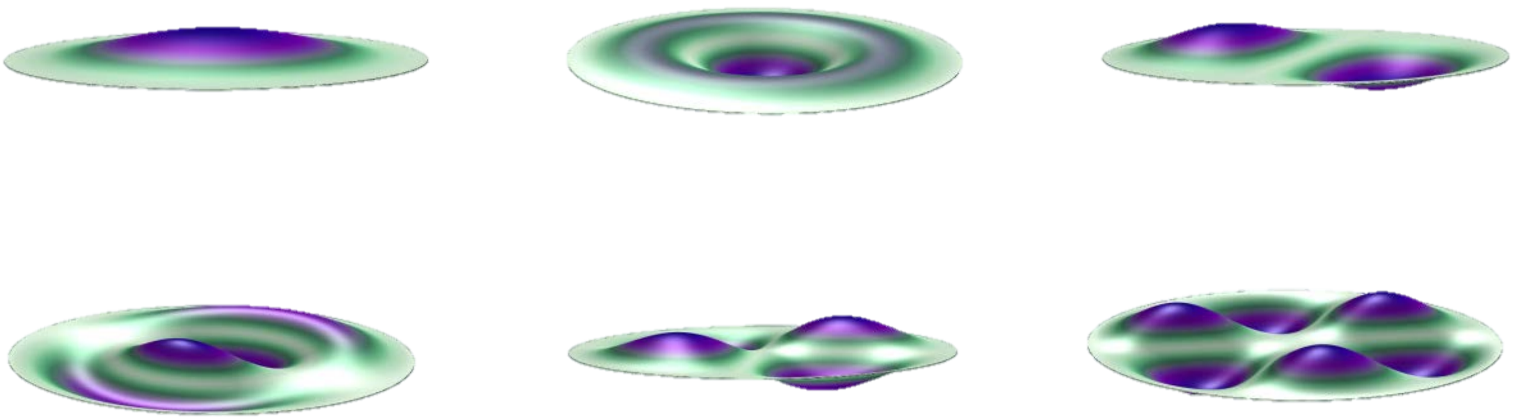
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Mechanical Dehumidification Using High-Frequency Ultrasonic Vibration



Oak Ridge National Laboratory

Ayyoub Momen, Subprogram Manager for HVAC&R, Water Heating, and Appliances

momena@ornl.gov

Project Summary

Timeline:

Start date: 10/1/2017

Planned end date: 9/31/2019

Key Milestones:

Milestone 1: Evaluate absorption and mechanical water ejection rate of piezoelectric/ desiccant, 9/31/2018

Milestone 2: Evaluate first-generation system, 3/31/2019

Budget:

Total Project: $ 556k:

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

Total Project $:

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

Key Partners:

STEMiNC STEINER & MARTINS, INC.

VIRGINIA TECH

Project Outcome:

- This will make the dehumidification process 3-5 times more efficient than in current state-of-the-art vapor compression dehumidifiers.
- Bench-scale stand-alone humidifier module of 0.1 L/day capacity in a laboratory environment will be developed.
- This aligns with MYPP for BTO's dehumidification target.

Team

ORNL Team ⟷ STEMiNC Inc.

ORNL Team

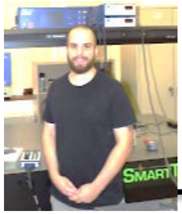
BTRIC

Ayyoub Momen
PI & R&D Staff

Kashif Nawaz
R&D Staff

Viral Patel
R&D Staff

- Exp. Design & Analysis
- Prototype fabrication
- Model development



Eric Dupuis
PhD student

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

Membrane and Separation Team

Brian Bischoff
R&D Staff

- Membrane fabrication

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

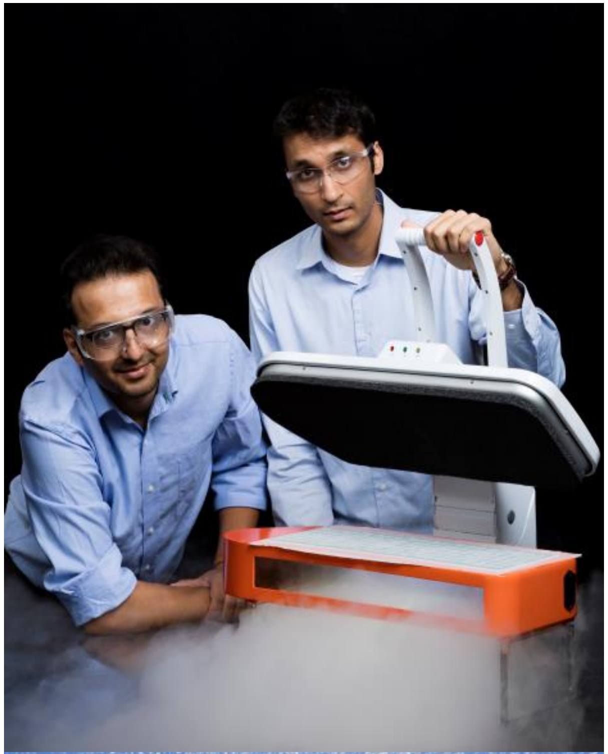
Virginia Tech.

Shima Shahab
Assistant Professor, VT
Piezoelectric energy harvesting,
Acoustics and Dynamics,
and Mechanics of Materials

Technology Background/History

Ultrasonic Clothes Dryer:

- The team invented and developed ultrasonic clothes dryer technology in 2015-17.
- It is shown that high frequency vibration of piezoelectric transducers can mechanically remove water from the wet fabric in the form of the cold mist (bypassing water latent heat of evaporation).
- Drying efficiency improved by 5X (1/5th of power input).

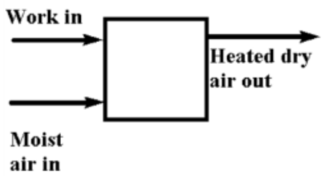


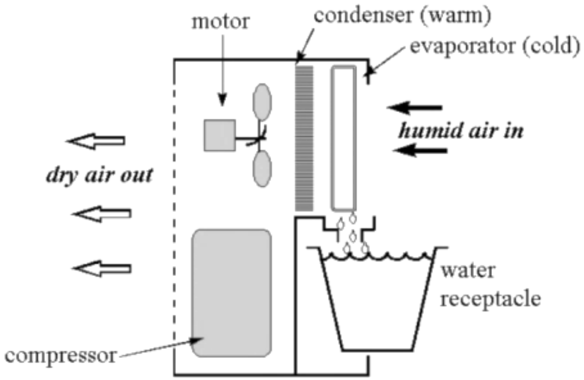
Take-away message:
Don't evaporate water, shake it out

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 the HVAC systems (Separate sensible and latent cooling (SSLC) systems).
- Dehumidification is conventionally achieved by 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 to the VC based systems- Regeneration of the desiccant materials and management of the heat of sorption are critical issues.
- Innovative solution is needed to avoid the intense heat needed for regeneration.



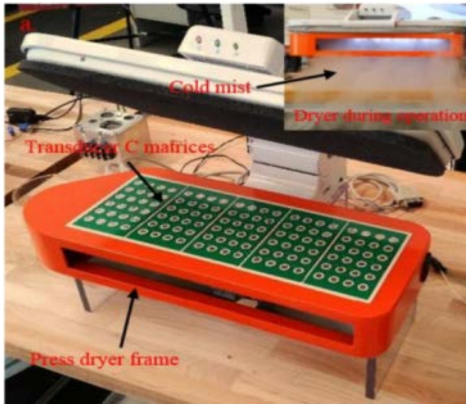


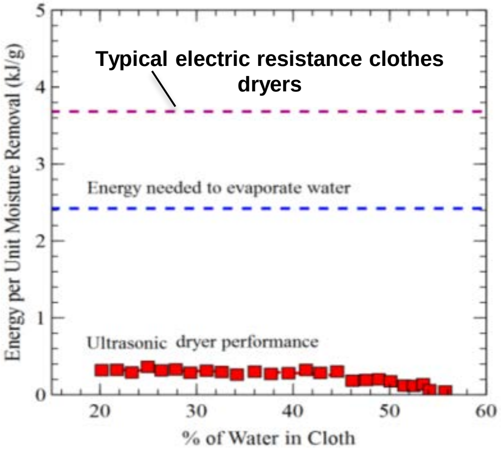
Source: http://chem.engr.utc.edu/Webres/435F/Dehumidifier/Dehumid/R5-435-1.html

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

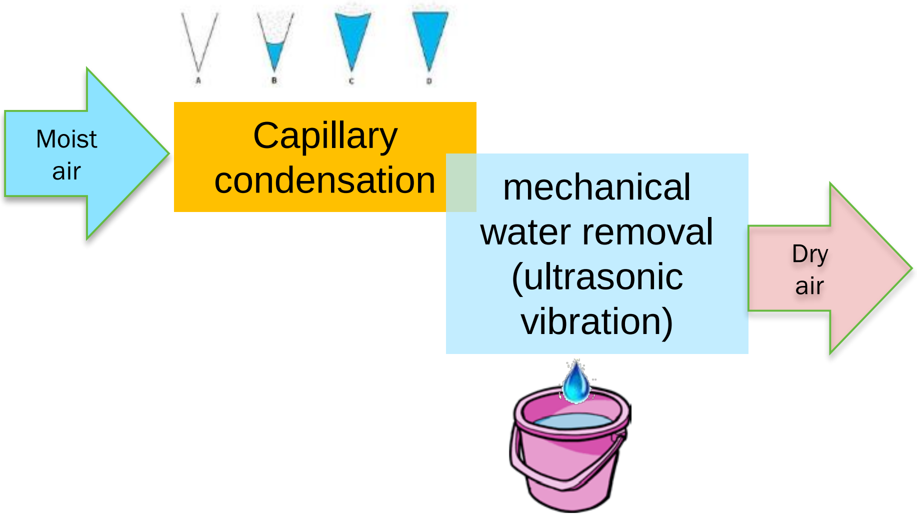
Approach

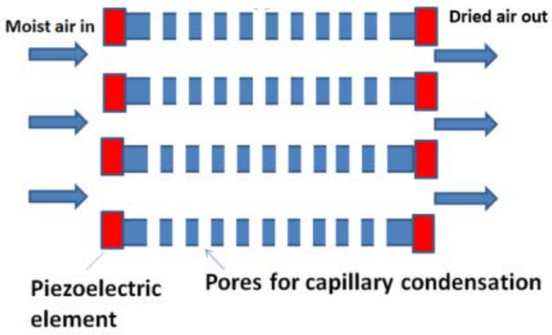
The Solution: Bypassing the heating-based regeneration!





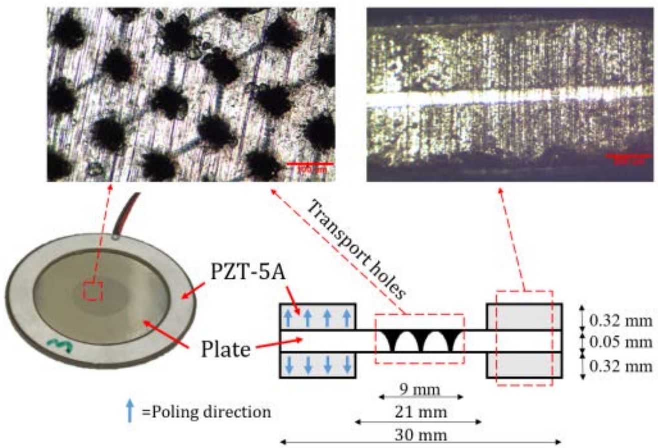
We have already shown that piezoelectric vibration could significantly boost the drying efficiency.



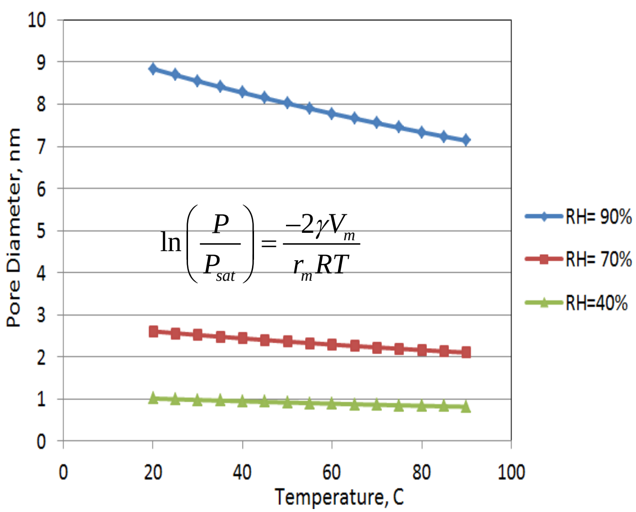


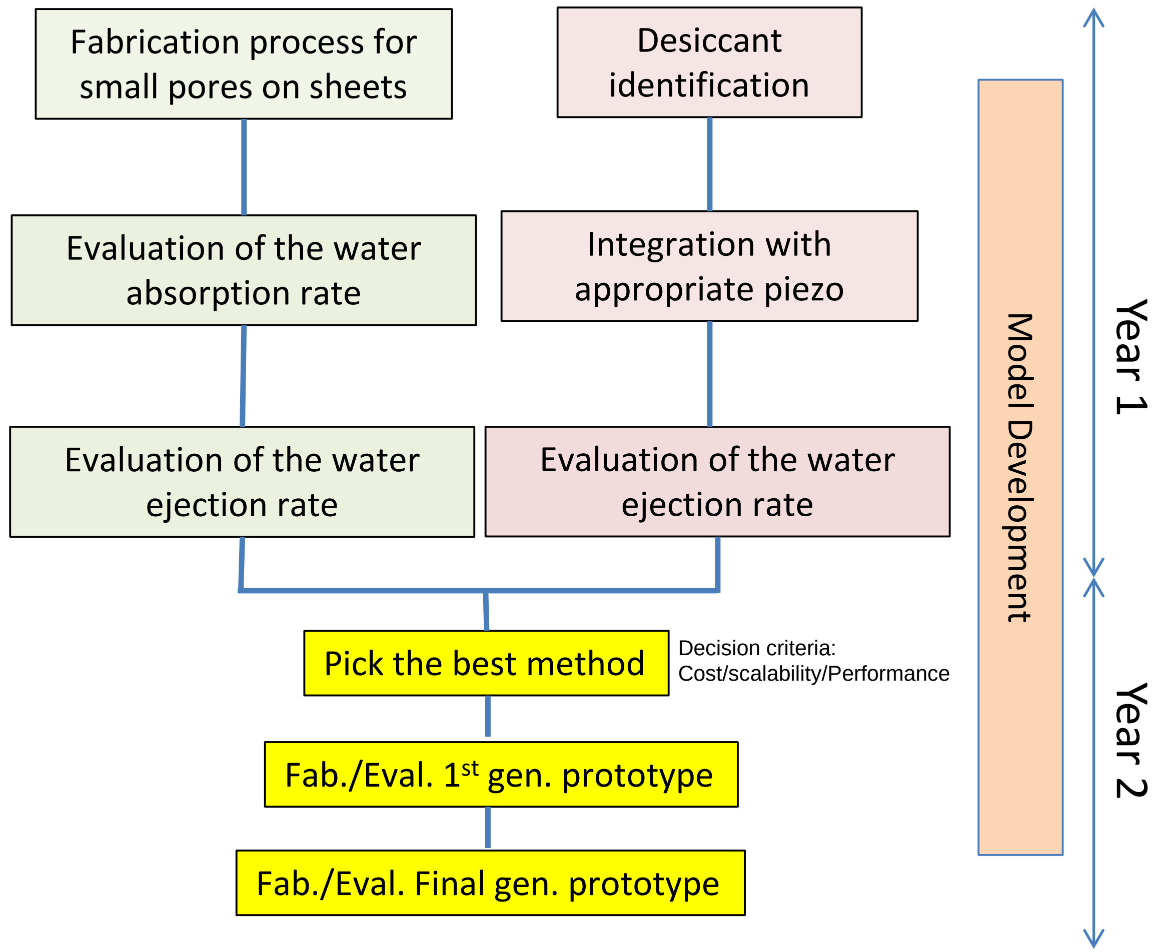
Approach

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



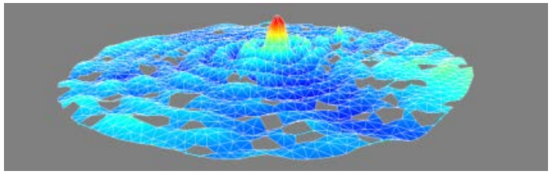
Capillary condensation:

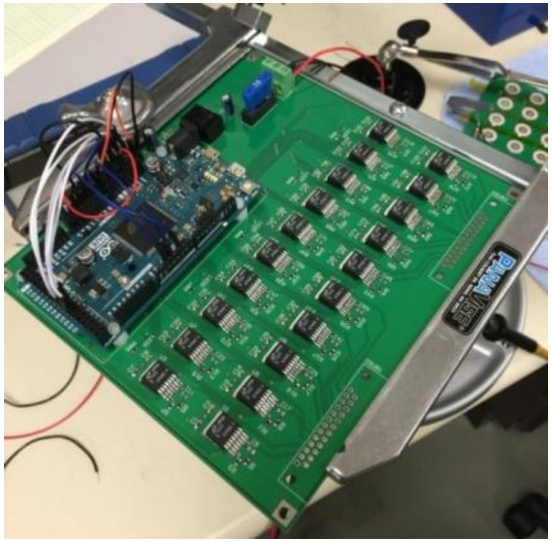




Advantage, differentiation, and impact

- Introducing 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 to 372-3000 kJ/Kg in conventional systems). This translates to 32-85% operating cost savings.
- Grid tie flexibility (eco mode/performance mode) Knobs: voltage, and duty cycle.
- Opens up new opportunities for Separate sensible and latent cooling (SSLC) systems due to 48% enhanced efficiency and 30% compactness.
- The technology can save 715 TBtu of energy annually by 2030.
- This amount of savings would support 6,020 new jobs over 10 years.



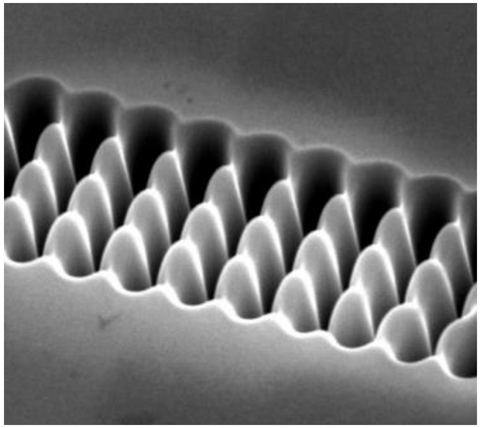


Target Market:

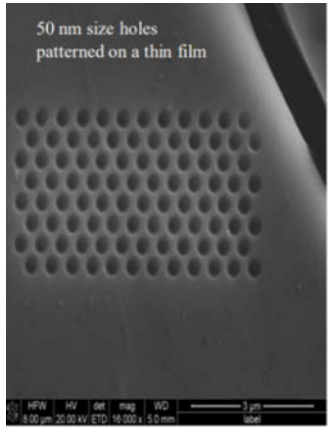
- Short term: Residential and commercial dehumidifiers
- Long term: SSLC for HVAC

Screening the viable manufacturing processes

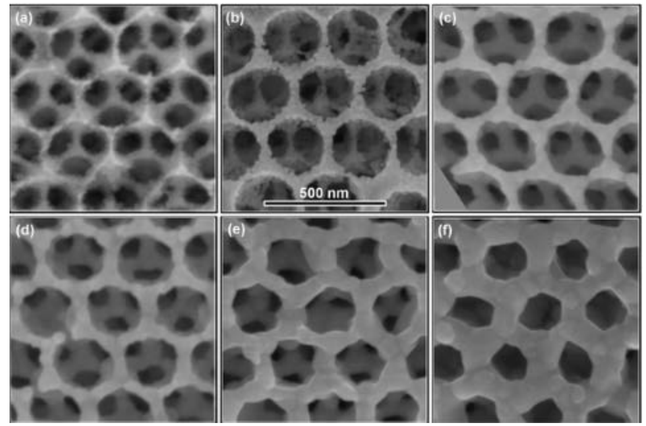
Identified the viable manufacturing processes for fabrication of capillary pores:



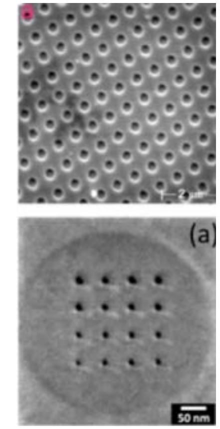
Focused ion beam



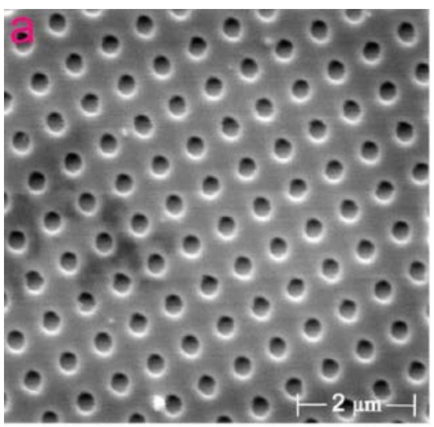
E-Beam Lithography



Atomic Layer Deposition



Helium-ion Milling



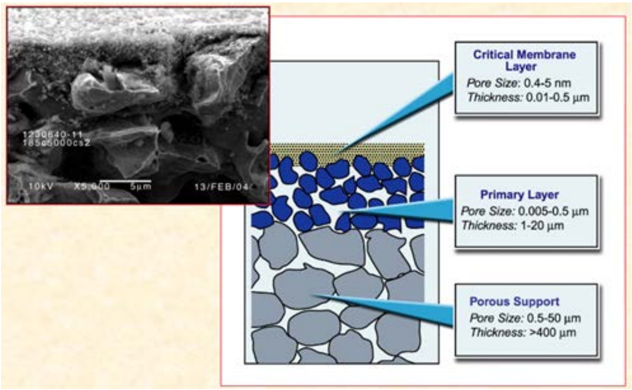
Laser Lithography

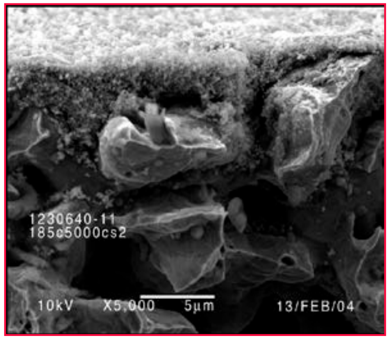
Various micromachining processes and specifications

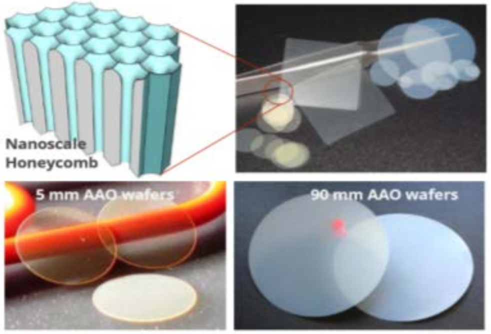
Technology / Feature Geometry	Minimum Feature Size / Feature Tolerance	Feature Positional Tolerance	Materials Removal Rate	Material
Dual-beam SEM/FIB (fused ion beam)	200 nm / 20 nm	100 nm	5 $\mu m^3/s$	Any
3D direct-write fab (LASER lithography)	1 µm / submicron	submicron	40,000 $\mu m^3/s$	Polymers, ceramics, metals
Atomic layer deposition	10 nm / 2 nm	100 nm	NA	Polymers, ceramics, metals
Helium-ion milling	5 nm (10–15× better than fused ion beam)	10–20 nm	5 $\mu m^3/s$	Polymers, ceramics, metals
E-beam lithography	4 nm	10–20 nm	1 $\mu m^3/s$	Metals
Micromilling/ microturning (2D/3D)	25 µm / 2 µm	3 µm	10,000 $\mu m^3/s$	PMMA, Al, brass, mild steel
Micro-EDM sinker or wire (2D/3D)	25 µm / 3 µm	3 µm	25 million $\mu m^3/s$	Conductive materials
LIGA (2D)	0.02–0.05 µm / submicron	~0.3 µm	NA	Cu, Ni, polymer, ceramics

Progress: Paths currently under investigation

Un-organized structures Tubular design	Un-organized structures Coating on the piezo	Organized structures Mesh







Promising initial results

Nano perforated plate of Aluminum Oxide

The transient and steady state response of the sample were recorded using dynamic vapor sorption and were used to calculate the moisture diffusivity of the sample using appropriate model.

Equations:

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

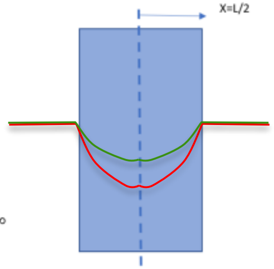
Initial condition:

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

Boundary conditions:

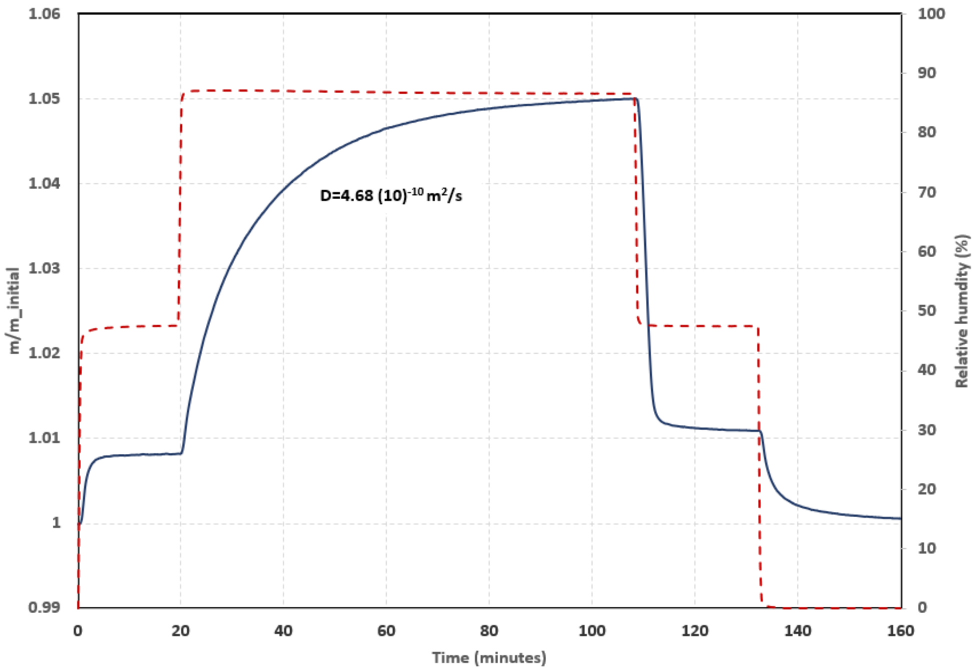
$$\rho(x = L/2, t) = \rho_\infty$$

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



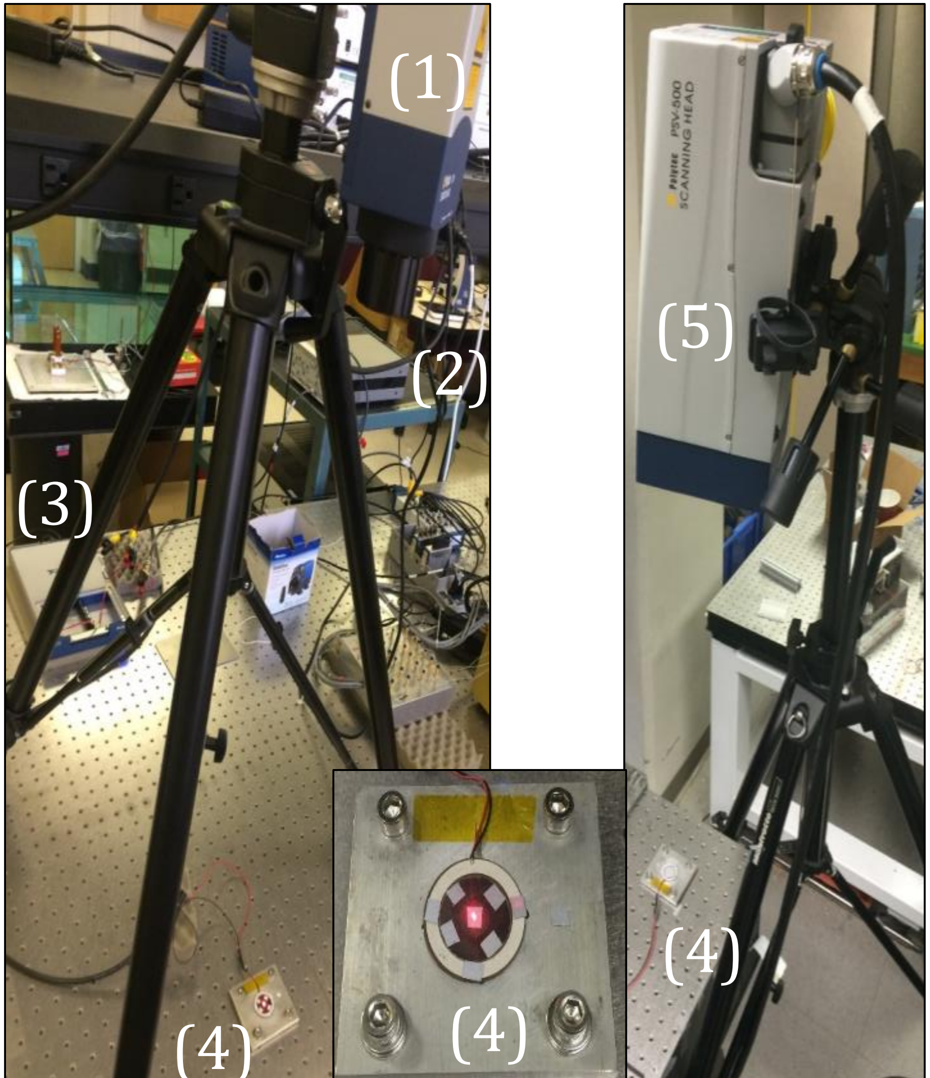
Following important observation were made:

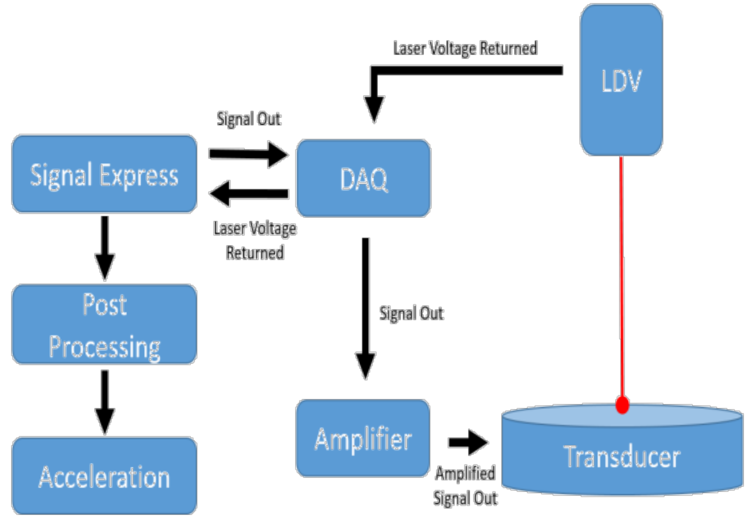
- The desorption rate for the sample is higher compared to the adsorption rate (45% RH to 85% RH compared to 85% RH to 45% RH).
- The sample can absorb around 5.0% of the dry mass under extreme conditions.
- There is a minor hysteresis (0.275%) in adsorption and desorption processes.



Moisture adsorption/desorption behavior of the AAO sample measured by dynamic vapor sorption device.

Experimental Validation





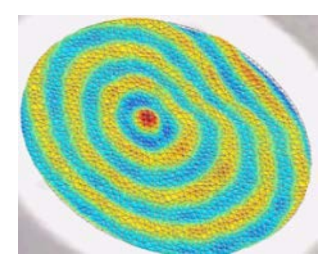
(1) Single-point laser vibrometer

(2) Amplifier

(3) Data acquisition unit

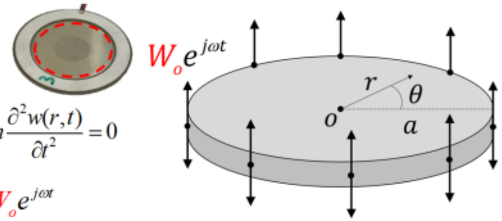
(4) Mounted transducer

(5) Scanning vibrometer



Progress

Plate Model
Distributed parameter method



$$D\nabla^4 w(r,t)+c_s\frac{\partial}{\partial t}\nabla^4 w(r,t)+c_a\frac{\partial w(r,t)}{\partial t}+\rho h\frac{\partial^2 w(r,t)}{\partial t^2}=0$$

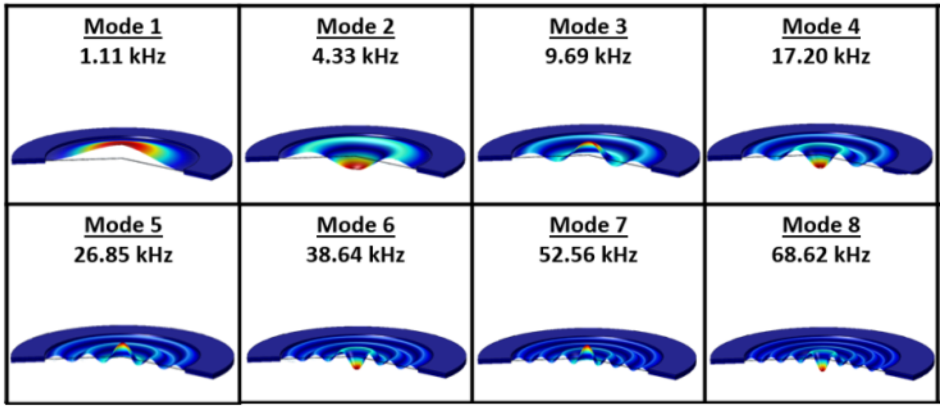
$$w(r,t)=w_b(r,t)+w_{rel}(r,t) \qquad w_b(r,t)=W_o e^{j\omega t}$$

$$w_{rel}(r,t)=\sum_{n=1}^{\infty}\phi_n(r)\eta_n(t) \quad \begin{cases}\phi_n(r)=E_n\left[J_0(\lambda_n r)I_0(\lambda_n a)-J_0(\lambda_n a)I_0(\lambda_n r)\right]\\ \eta_n(t)=A_n e^{j\omega t}\end{cases}$$

$$A_n=\frac{f_n(t)}{\left(\omega_n^2-\omega^2+2j\zeta_n\omega_n\omega\right)e^{j\omega t}}$$

$$w_{rel}(r,t)=\sum_{n=1}^{\infty}\phi_n(r)\frac{2\pi\rho h\omega^2 W_o\int_0^a r\phi_n(r)dr}{\omega_n^2-\omega^2+2j\zeta_n\omega_n\omega}e^{j\omega t}$$

$$f_n(t)=2\pi\rho h\omega^2 W_o e^{j\omega t}\int_0^a r\phi_n(r)dr$$

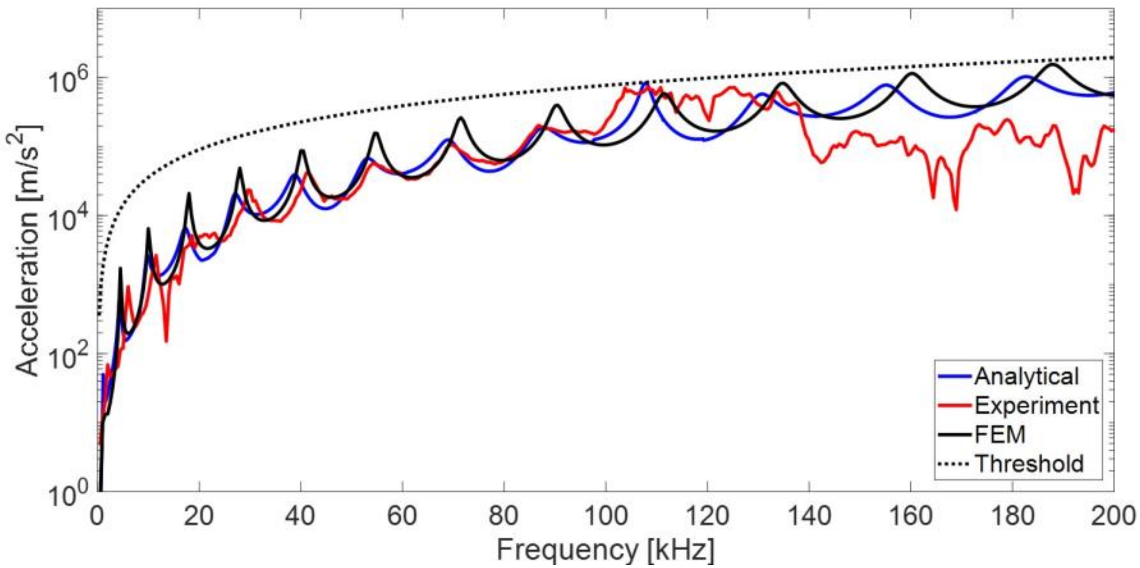


$$a_c \approx 4\, f^{4/3}\left(\sigma/\rho\right)^{1/3}$$

$\rho =$ density [kg/m^3]

$\sigma =$ surface tension [N/m]

$f =$ excitation frequency [Hz]



Eric Dupuis, Ayyoub M. Momen, Viral K. Patel, and Shima Shahaba, *Multiphysics modeling of mesh piezoelectric atomizers*, SPIE, March 2018.

Stakeholder Engagement

Communication:

- Weekly meeting among the ORNL team
- Bi-Weekly meeting with Virginia Tech.
- Bi-weekly meeting with the whole team including the industrial partner

Team members' role:

- ORNL's BERG:
  - Early stage research on Nano structures, Nano pores, viable manufacturing process, rate measurements, integration of the piezo and nano pores.
- ORNL's membrane team:
  - Developing the proprietary membrane to enhanced capillary condensation
- ORNL's GO! PhD student from Virginia Tech:
  - Developing the comprehensive analytical and FEM models
  - Guide the design

Remaining Project Work

Achieved in the last 6 months:

- Develop or identify viable capillary fabrication processes
- Design high-volume-density pores in sheets of material
- Preliminary measurement of the condensation kinetics
- Piezo model successfully developed (both analytical and FEM)

Remaining work for the next 18 months:

- Develop small-scale perforated sheet
- Evaluate absorption and mechanical water ejection rate of piezoelectric/desiccant
- Tie piezo model to the adsorbing material
- Fabricate first-generation system
- Evalu.ate and improve first-generation system

Thank You

Oak Ridge National Laboratory
Ayyoub M. Momen, R&D Staff
momena@ornl.gov

BTRIC

REFERENCE SLIDES

Project Budget

Project Budget: $500K (BENEFIT FOA 2017)
Variances: None
Cost to Date: $136k (Through March 2018)
Additional Funding: No additional direct funding.

Budget History					
10/1/2017		FY 2018 (current)		FY 2019 – 9/31/2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$250K	$28K	$250K	$28K

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									
	FY2018				FY2019				FY2020		
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)	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											
Current/Future Work											
Evaluate the adsorption and ejection rate of the pizeo desccant assembly											
Design and development of the first fgeneration prototype											
Modify the design and achieve the target of 250 kJ/kg											