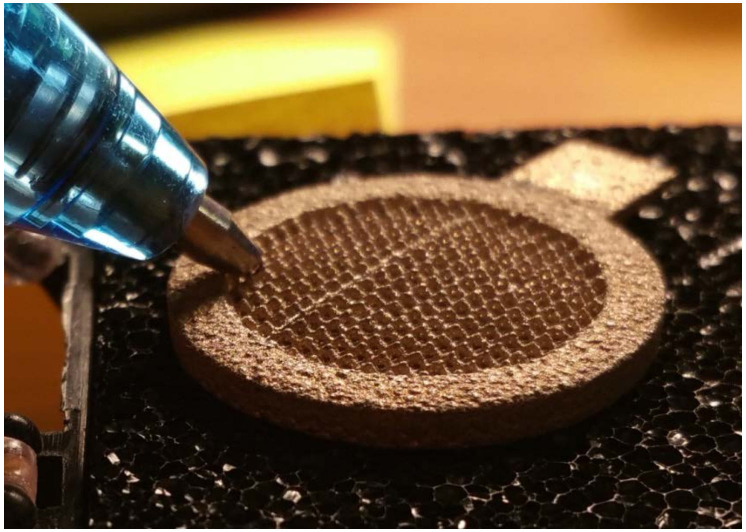
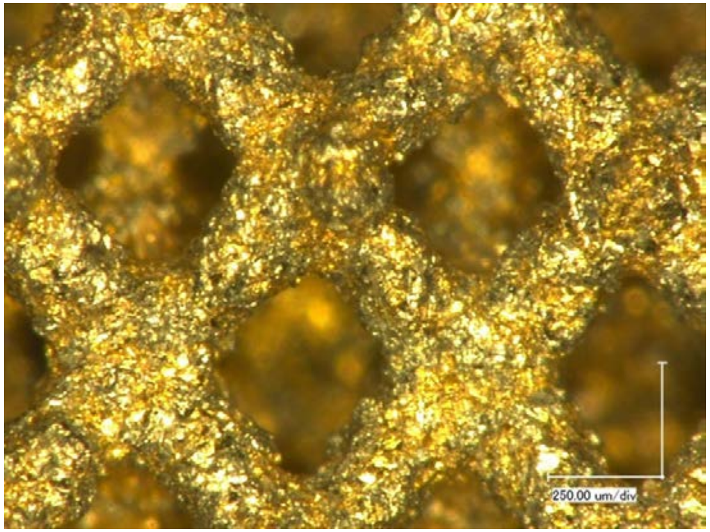
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Magnetocaloric Refrigerator





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

Project Summary

Timeline:

Start date: 11/6/2017 (5 months ago)

Planned end date: 11/6/2020

Key Milestones:

Milestone 1: Reinstate 90% of magnetocaloric effect of the 3D printed microchannel, 11/6/2018

Milestone 2: Fabricate and test 10 stage 3D printed Kagome microchannel 11/6/2020

Budget:

Total Project $ to Date:

- DOE: $0.2M
- Cost Share: $0.2M

Total Project $:

- DOE: $1M
- Cost Share: $0.6M

Key Partners:

General Electric Appliances and Haier Company

GE APPLIANCES
a Haier company

Project Outcome:

- Harnessing the MCE to achieve cooling is among the most promising of the emerging non–vapor-compression technologies. MCE has the potential to reduce energy consumption by 20–30% beyond vapor compression while also eliminating any risk of direct refrigerant emissions to the atmosphere.
- This technology's primary energy savings technical potential is 0.20 quad/yr. in 2030, per DOE-BTO's P-Tool.

Team

ORNL Team ⟷ GE Appliances Team

ORNL Team

- BTRIC
- Additive Manufacturing
- Material Science

Ayyoub Momen
PI & R&D Staff

Amy Elliott
R&D Staff

Jim Kiggans
R&D Staff

Mingkan Zhang
Post Doc

Geoff Ormston
R&D Staff

Seth Newport
Intern

- 3D printing
- Sintering
- Material characterization

- Expert design and analysis
- Prototype fabrication
- Process development
- Model development

GE Appliances Team

Michael Schroeder
Senior Advanced Systems Engineer

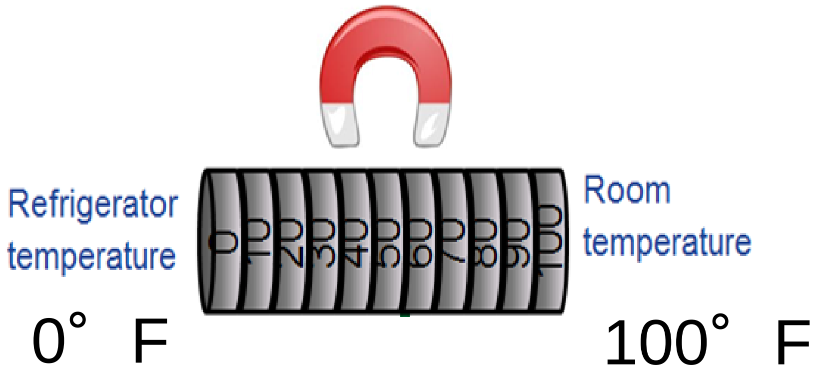
Stephanos Kyriacou
Director, Engineering -
Refrigeration Advanced Systems

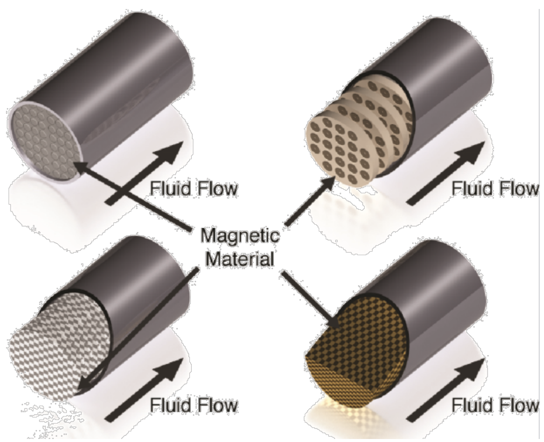
- Bi-weekly review meetings
- Machine development
- Reporting the progress to GEA upper management

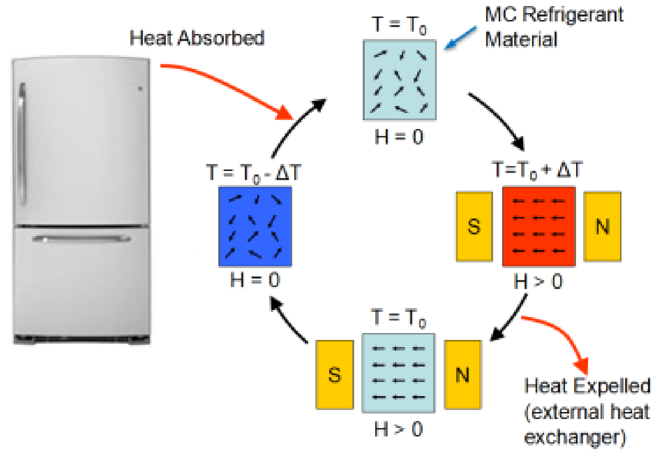
Technology Background

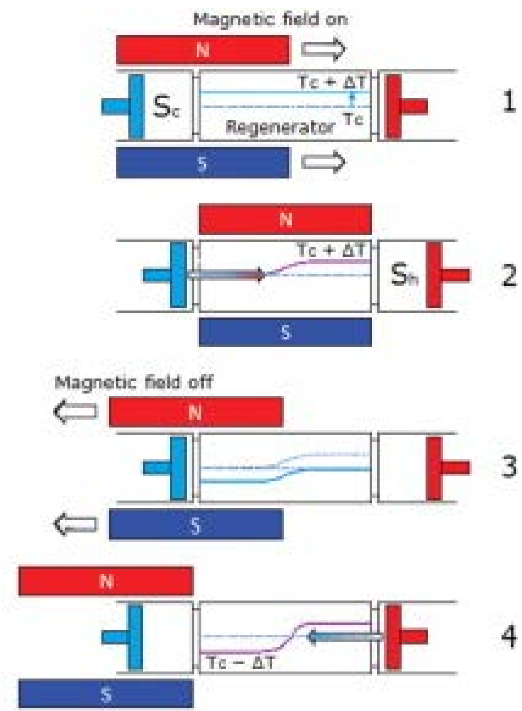
What is the Magnetocaloric effect?

How does the system work?









Significance

Technology Potential:

- There are >200M refrigerators units in U.S.A. In most homes refrigerator is the second largest user of electricity (13.7%) right after air conditioning (14.1%).
- Magnetocaloric refrigeration has the potential to be 20% more efficient than the conventional vapor compression systems.
- According to the recent DOE study on 17 non-vapor compression HVAC technologies, Magnetocaloric refrigeration technology ranked as “very promising” alternatives because they exhibit moderate-to-high energy savings potential, offer significant non-energy benefits, and/or fit well with the BTO mission.

Note:

Early stage R&D is needed to fully utilize the recent and future emerging MCMs. Developing a high performance Magnetocaloric refrigeration system is a very challenging task from system development perspective.

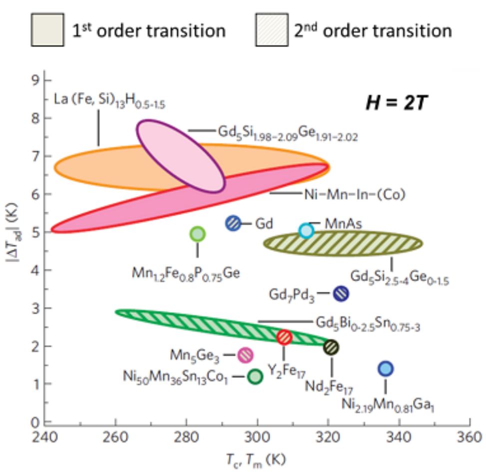
Challenges

Magnetocaloric Refrigeration Challenges

New Material discovery	Processing the material	System integration	Reducing cost

New Material discovery

Not addressed under this project.



Source: J. Liu *et al.* Nat. Mater. 2012

Processing the material

High performance MCM are difficult to be formed, because they are:

- Heat sensitive
- Very reactive
- Brittle

System integration

In the system level Pressure drop across MCM heat exchanger is the main challenge:

- Excessive pressure drop hurting the performance 2 folds.
- Limits the operating frequency.
- Limits the cooling/heating capacity.

Reducing cost

Cost reduction is inversely proportional to system cooling power density.

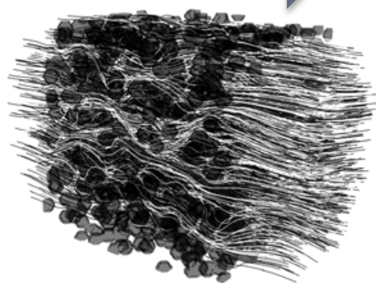
Approach

Pressure drop of MCM particulate regenerator is one of the primary loss sources of the MCM system.

$$COP = \frac{Q_{cool}}{w_{in}}$$

Pressure drop hurts twice

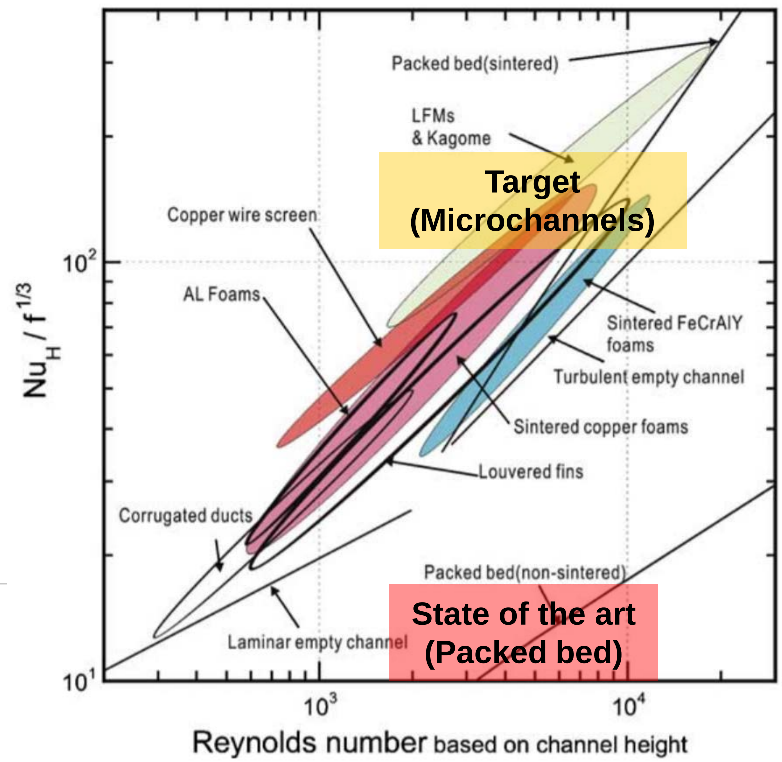
$$COP = \frac{Q_{cool} - \textit{Pump power heat}}{w_{in} + \textit{Pump power heat}}$$



To depart from the state of the art, we need to find develop manufacturing processes to make Microchannels from MCM.

High performance MCM are difficult to be formed or manufactured in shapes (i.e. Microchannel), because they are:

- **Heat sensitive**
- **Very reactive**
- **Brittle**



Source: J. Tian, T. Kim, T.J. Lu, H.P. Hadson, D. T. Quchei llilt, D.J. Sypeck, H.N.H. Hadky.

Approach

MCM Microchannel development R&D

- Advanced Manufacturing
  - 3D Printing
  - Sintering
- Magnetic stabilization (random shape microchannels)
- Fully solid state systems

Machine Design

- GEA 5 generation of cooling machines
- ORNL flexible evaluation platform

Model development

- Identifying loss mechanism
- Model Validation
- Improving machine design

Impact

The magnetocaloric refrigerator :

- ~25% higher efficiency
- Reduced emissions of refrigerators
- **~ 0.23 Quad** of energy saving
- Approximately **6,000 new jobs**

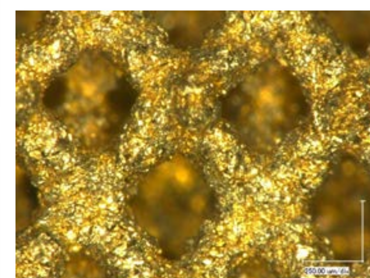
The overall objectives of this project supports the Building Technologies Office goal to reduce building energy use intensity (EUI) by 30% in 2030 vs. 2010 levels, and comply with the Multi-Year Program Plan specific goals for the Emerging Technologies Program.

Innovation is needed to bring Magnetic refrigeration into reality

Demo Magnetic Refrigerator Source: GEA (2015)

Progress: Advanced Manufacturing

- 3D printing of the heat exchangers is a new field and very challenging.
- Additional, complexity is added when we want to do this on the new material (MCM) that does not like to cooperate (reactive, heat sensitive and fragile)!!
- After 18 months of early stage R&D, we fabricated MCM microchannels of 150 μm at 100% MCM full density.
- Variable Parameters Investigated:
  - Particle diameter
  - Binder saturation
  - Print orientation
  - Type of binder
  - Cleanability
  - Curing temperature
  - Pixilation issues.



Progress: Advanced Manufacturing

- Developed MCM 3D printing process
- Developed sintering process
- Identified the flaw in the process
- Currently working to eliminate the C and O_2 pickup during the process.

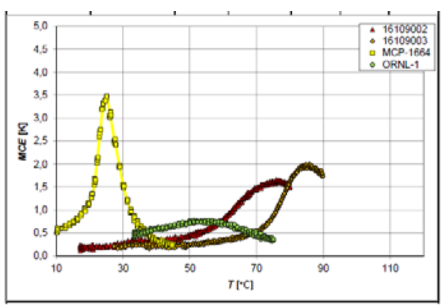
Big challenge to be resolved: Carbon and Oxygen pickup

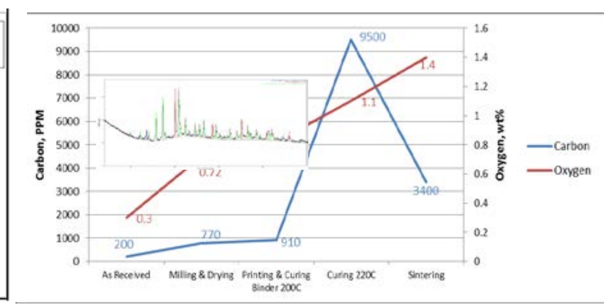
2016
Learn how to print MCM

2016-17
Learn how sinter MCM 3D printed part

2017
Process evaluation Identify the processes flaws

2018-19
Resolving remaining issues 10 stage 3D MCM microchannels for testing in AMR





Progress: Magnetic Stabilization

We invented MCM magnetic stabilization process in 2016.

- No heating is involved
- Scalable process (compared to additive manufacturing)
- Simple and low cost solution
- Significantly reduces the pressure drop
- Provides very high interstitial heat transfer rates
- Random microchannels as small as 20–100 μm
- Enhance magnetization of particles by 10%
- MCE properties intact

2015
Idea developed

2016
Process developed (binder, fludization, magnetization, curing, pressure drop)

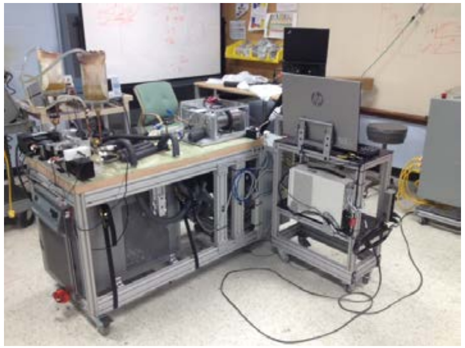
2017
3 Stage AMR developed, evaluated

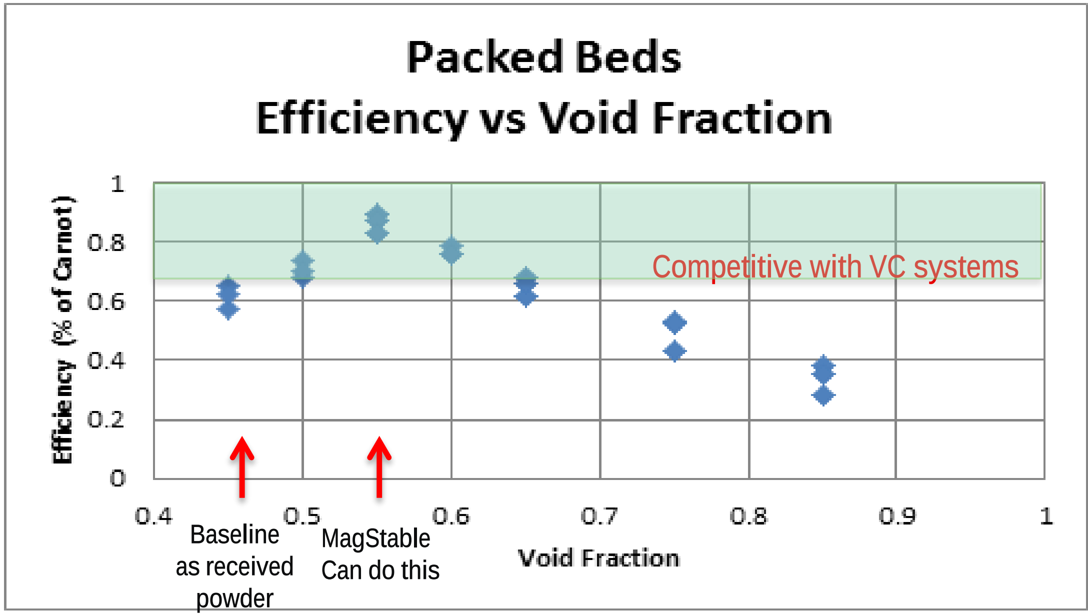
2019
10 Stage AMR Evaluation and fine tuning the process

Progress: Magnetic Stabilization

The process will be refined in FY18-19:

- Improving fabrication process.
- Evaluating the performance of the multistage regenerator.
- Hydrodynamic, HT, Physical inspections.
- Evaluate the performance of 10 stage AMR.
- Finalize the recipe for the Magstable manufacturing process.





Progress: Multistage AMR Model Development

Model development: A paper was published in a Nature family journal on 16-layer regenerator.

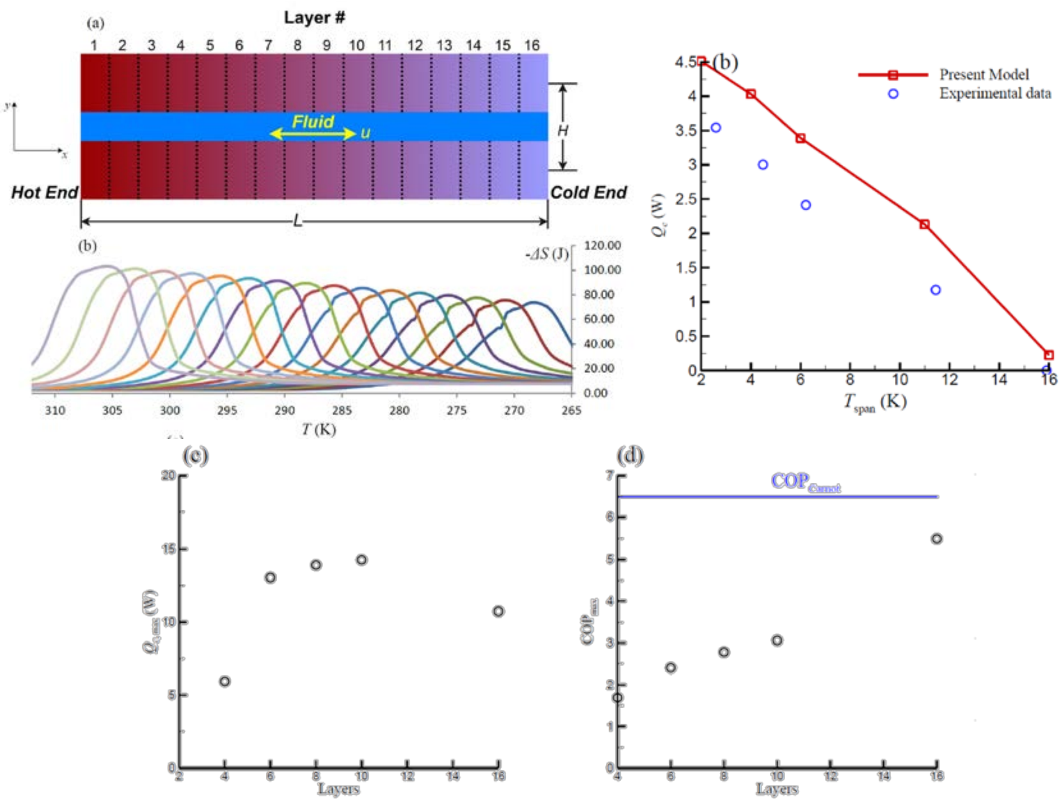
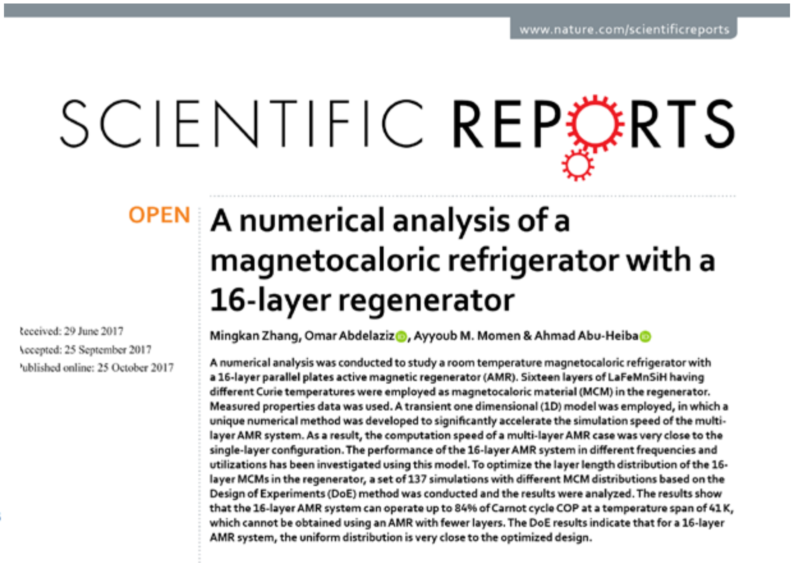


Figure 5. Q_c (a), COP (b), $Q_{c,max}$ (c), and COP_{max} (d)variations with utilization for different N_{layer}.



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A numerical analysis of a magnetocaloric refrigerator with a 16-layer regenerator

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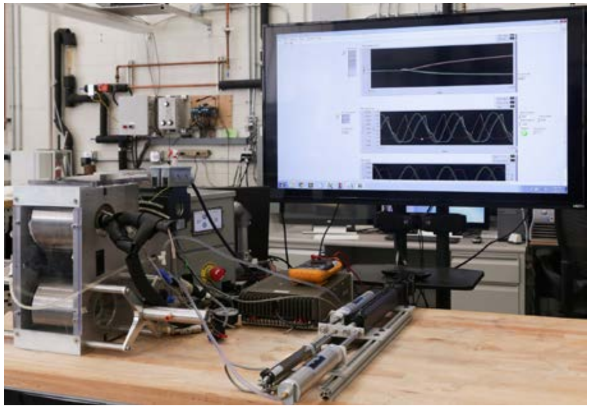
Mingkan Zhang, Omar Abdelaziz, Ayyoub M. Momen & Ahmad Abu-Heiba

A numerical analysis was conducted to study a room temperature magnetocaloric refrigerator with a 16-layer parallel plates active magnetic regenerator (AMR). Sixteen layers of LaFeMnSiH having different Curie temperatures were employed as magnetocaloric material (MCM) in the regenerator. Measured properties data was used. A transient one dimensional (1D) model was employed, in which a unique numerical method was developed to significantly accelerate the simulation speed of the multi-layer AMR system. As a result, the computation speed of a multi-layer AMR case was very close to the single-layer configuration. The performance of the 16-layer AMR system in different frequencies and utilizations has been investigated using this model. To optimize the layer length distribution of the 16-layer MCMs in the regenerator, a set of 137 simulations with different MCM distributions based on the Design of Experiments (DoE) method was conducted and the results were analyzed. The results show that the 16-layer AMR system can operate up to 84% of Carnot cycle COP at a temperature span of 41 K, which cannot be obtained using an AMR with fewer layers. The DoE results indicate that for a 16-layer AMR system, the uniform distribution is very close to the optimized design.

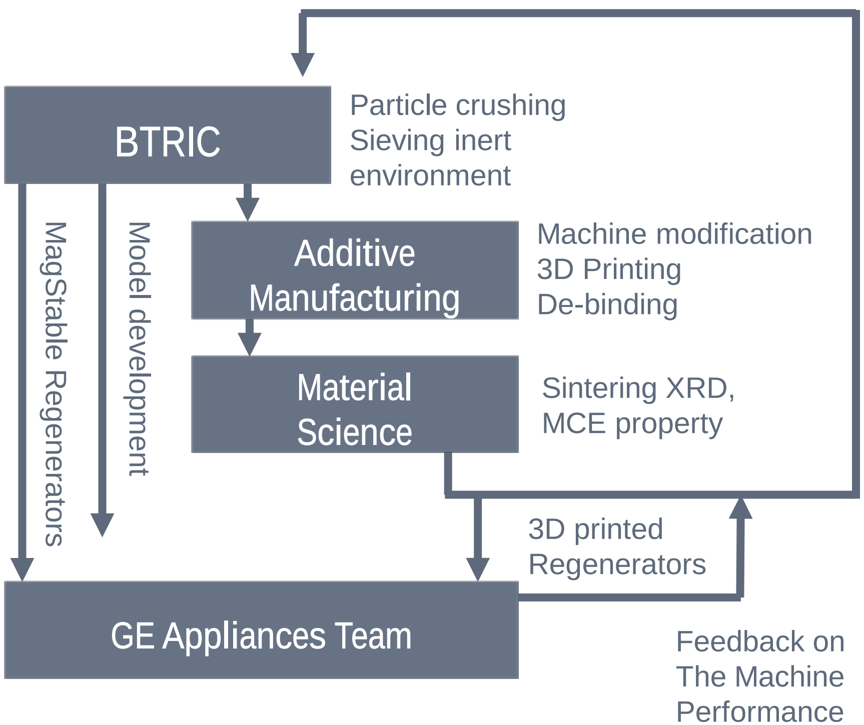


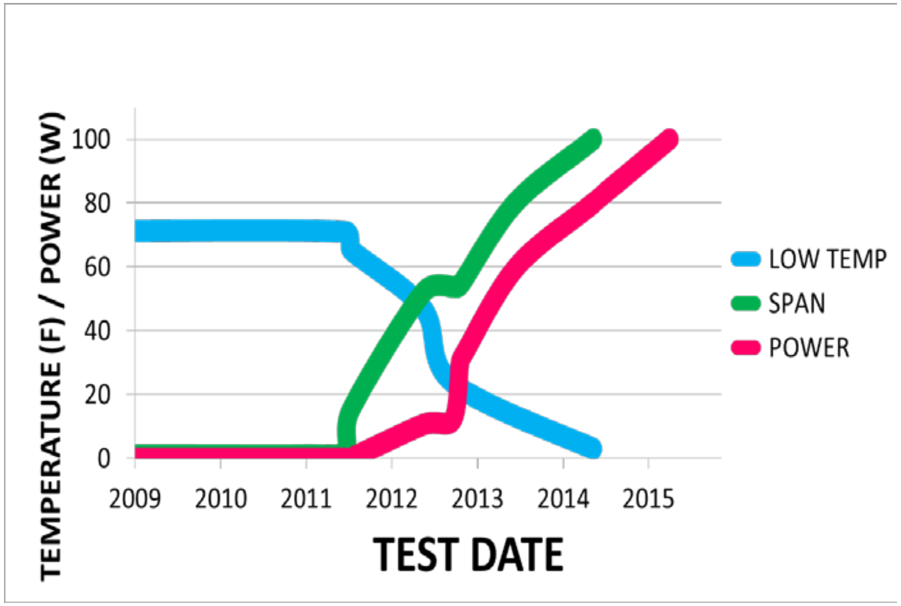
Flexible Characterization Platform for Magnetocaloric Regenerator Performance Evaluation

Currently the model is further developed to identify the main loss mechanisms in the system and being able to be validated against the Magnetically stabilized structure results.

Stakeholder Engagement

- ORNL staff have weekly internal meeting
- ORNL and GEA has bi-weekly meeting
- ORNL and GEA have quarterly site visits
- ORNL submit Quarterly progress report to DOE





Remaining Project Work

- Modeling:
  - Quantify the loss mechanisms for magstablized and 3D printed regenerators.
- Magnetic stabilization:
  - Refine the process, develop 10 stage regenerator, and improve the performance.
- Parameters under investigation:
  - Particle diameter, optimum bed expansion, binding process, draining process, Curing process.
- 3D printing, Sintering:
  - Eliminate the introduction of the C and O^2 into the process.
- Parameters under investigation:
  - Type of binder, type of furnace, process atmosphere.
- COP evaluation:
  - Evaluate the COP of 10 stage magnetic stabilized structure and 10 stage 3D printed regenerator.
- Detailed Cost Model Development by Manufacturer :
  - Develop consumer cost model, Develop manufacturing cost model, market risk and mitigation strategy

Note: Preliminary cost model is currently available.

Thank You

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

REFERENCE SLIDES

Project Budget

Project Budget:

- Phase 1: 2015-2017
- Phase 2: FY18-FY20

Variances: None

Cost to Date: $0.2M FY18 (through March 2018).

Additional Funding: No additional direct funding.

Budget History					
11/6/2017		FY 2018 (current)		FY 2019 – 11/6/2020	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$500k	$200k	$500k	$300k

Project Plan and Schedule

Project Schedule		
Project Start: 11/6/2017		Completed Work
Projected End: 11/6/2020		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missec
		Milestone/Deliverable (Actual) use when met on time

Task	FY2017				FY2018				FY2019		
	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											
Evaluate 3 stage magstable structure											
Validate the model											
Reinstate 90% of MCE properties											
Current/Future Work											
Evaluate the performance of 10 stage 3D printed AMR											
Evaluate the performance of 10 stage Magstable stucture											
Finalize the manufacturing rocess, report COP and market study											