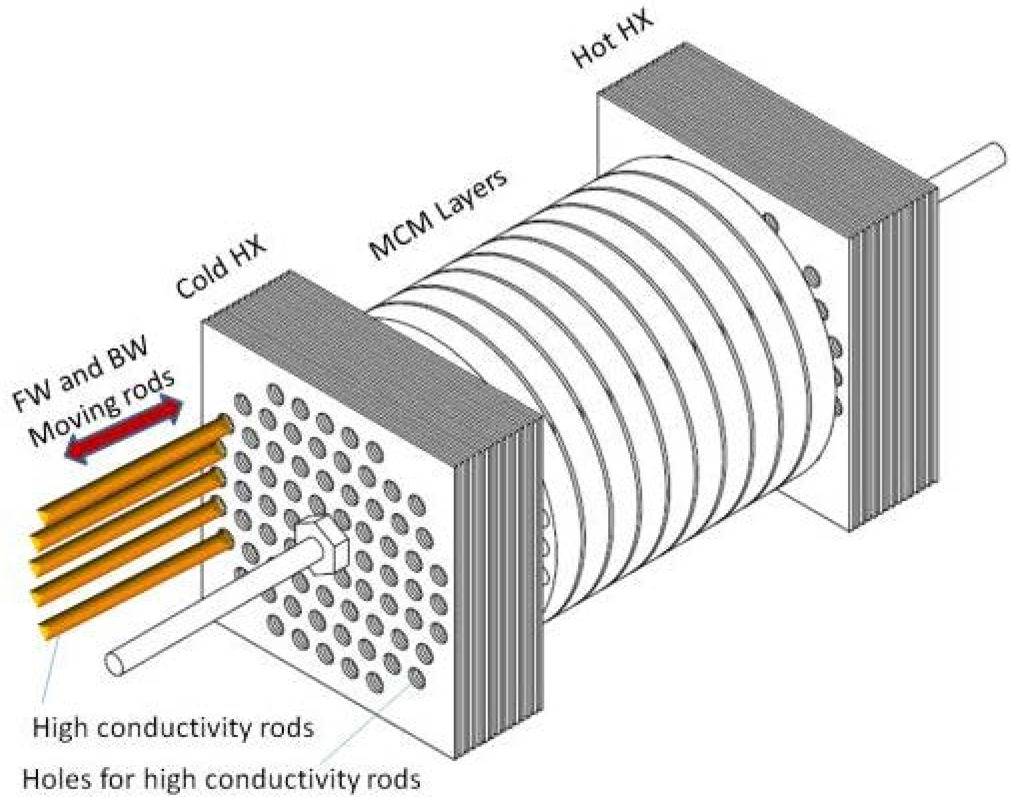
Non-Vapor Compression – Solid State Magnetic Cooling

2017 Building Technologies Office Peer Review



U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Ahmad Abu-Heiba, abuheibaag@ornl.gov
Oak Ridge National Laboratory

Project Summary

Timeline:

Start date: 10/1/2015

Planned end date: 9/16/2017

Key Milestones

1. Improve MCM manufacturability; 9/30/2016
2. Fabricate 2nd generation unit; 8/1/2017

Budget:

Total Project $ to Date:

- DOE: $629,000
- Cost Share: $107,000

Total Project $:

- DOE: $1,360,000
- Cost Share: $340,000

Key Partners:

Vacuumscmelze GmbH & Co. KG

Project Outcome:

Develop fully solid state magnetic air conditioner (AC)

Develop commercialization plan

Purpose and Objectives

Problem Statement: This project supports BTO MYPP HVAC/WH/Appliances Technology Challenges, "Unrealized design potential." The project demonstrates the feasibility of magnetic cooling with reduced complexity and cost relative to conventional magnetic cooling systems.

Target Market:
Currently, room/window AC is the target market sector. It accounts for 161.3 TBTU of primary energy.

Audience:
HVAC&R/Appliances industry manufacturers, MCM manufacturers, energy efficiency organizations.

Purpose and Objectives

Impact of Project: Step change in magnetic heat pumping technology

- Develop new MCM manufacturing methods
- Reduce complexity and cost of magnetic cooling systems

Near-term: Demonstrate feasibility of the technology and develop commercialization plan to identify market barriers and entry points.

Intermediate: Promote the technology into larger capacities and different applications.

Long-term: Adoption of technology on a commercial scale.

Approach

Approach:

- Improve MCM forming and machining techniques and post-treatment methods to produce parts in required shapes and surface roughness.
- System-level design and integration. In parallel, build a system with liquid metal to characterize performance.
- Market assessment to identify opportunities and barriers.

Key Issues:

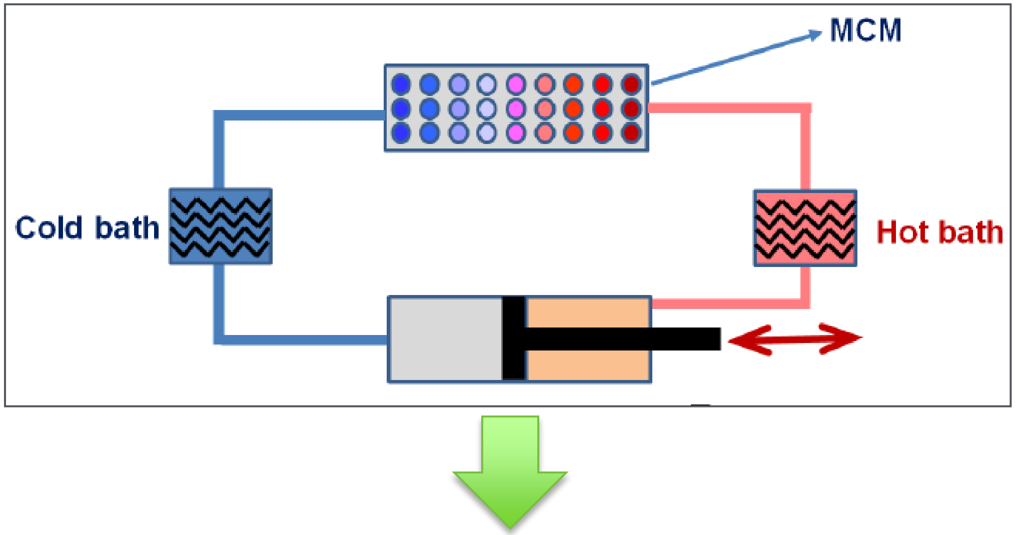
- Manufacturability and post-treatment of MCM
- Mechanical design requirements

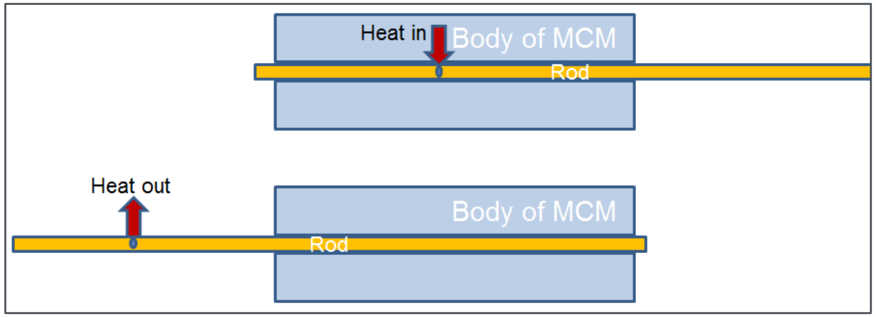
Distinctive Characteristics:

- Increases the heat transfer rate and allows higher operating frequency which results in higher capacity for the same MCM mass (higher volumetric capacity).
- Reduce complexity by eliminating pumping and flow reversal components.

Innovation

- Replacing fluid with solid increases heat transfer rate, capacity and COP.





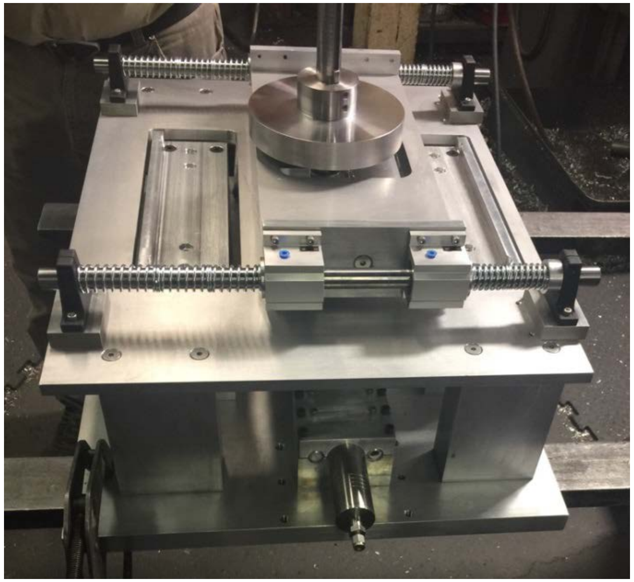
Theoretically $\frac{UA_{rod}}{UA_{fluid}} \approx \frac{k_{rod}}{4 \times k_{fluid}} \approx O(100)$

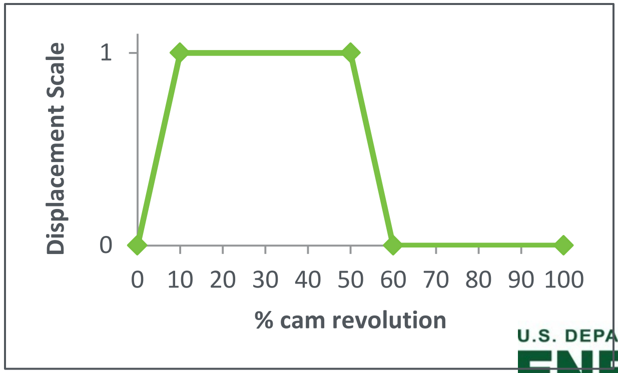
Challenge

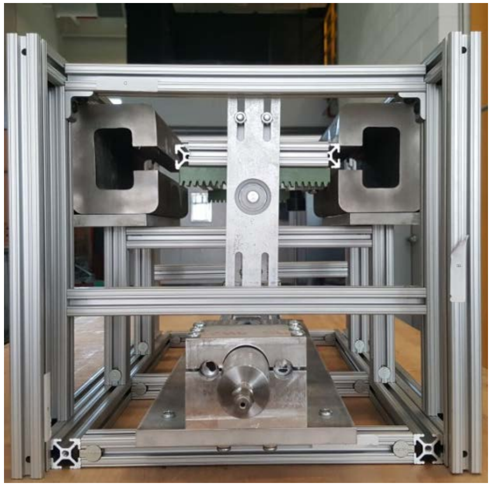
- Because of sliding metal between MCM blocks:
  - Surface roughness must be low (challenging for MCM manufacturing)
  - Air gap is unavoidable (increases thermal resistance)
- Motion profile (long dwells and sharp acceleration)
- MCM that are suitable for heating and cooling in typical heat pump operation range (20° to 40°C)

Prototype 1

- Reciprocating regenerator tubes and C-shaped magnets
- Cam drives and syringe pumps
- Challenging but PROMISING



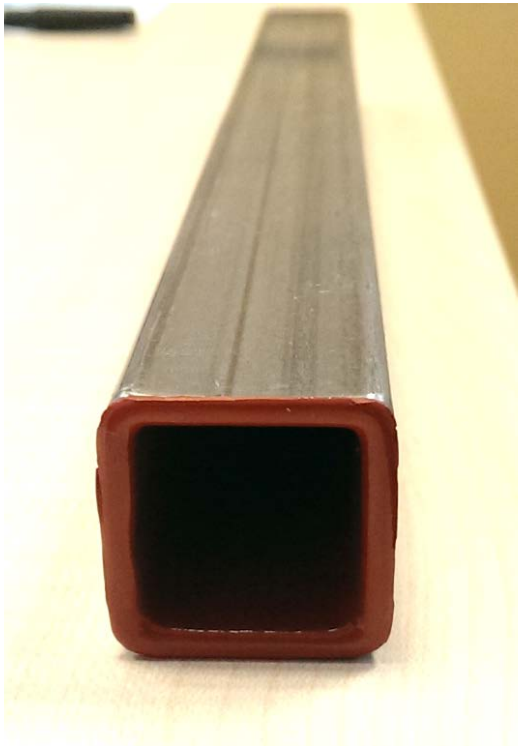


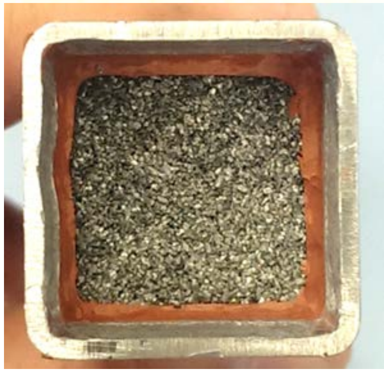


U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Regenerator

- The target was to fill the tube with a bonded powder bed of irregular particles of MCM
- 10 different MCMs, each stage is 1.2” long
- The internal surface was coated for thermal insulation
- Epoxy was cured at 100





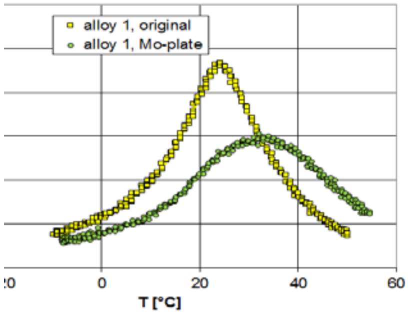
Prototype 2

- Hallbach array magnet with stationary regenerator tube
- Servo motor to control motion
- External pump

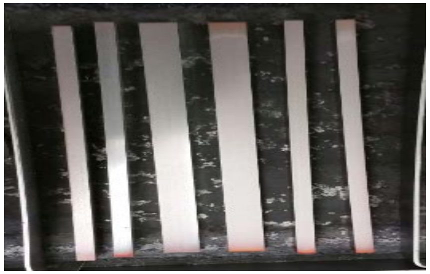
MCM Progress: bottom-up manufacturing – Wire cutting

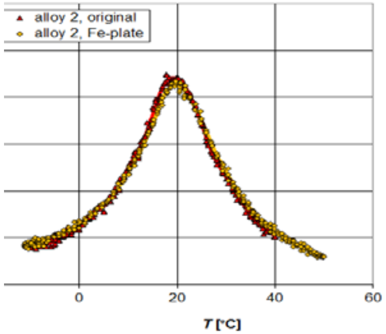
- Produced 10x5x150 mm rods by wire-cutting. Ground, then heat treated (> 1000°C) . Maximum roughness of < 6 μm.
- Reaction between MCM (La-Fe-Si) and Molybdenum reduced MCE.
- Iron lead to significant bowing of the rods.
- For good mechanical and magnetic properties, Mo+Fe supports will be used.

Molybdenum plate



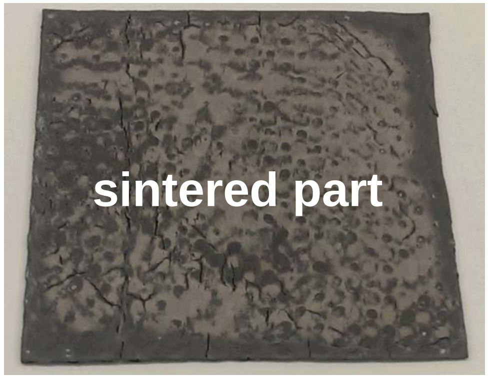
Iron plate

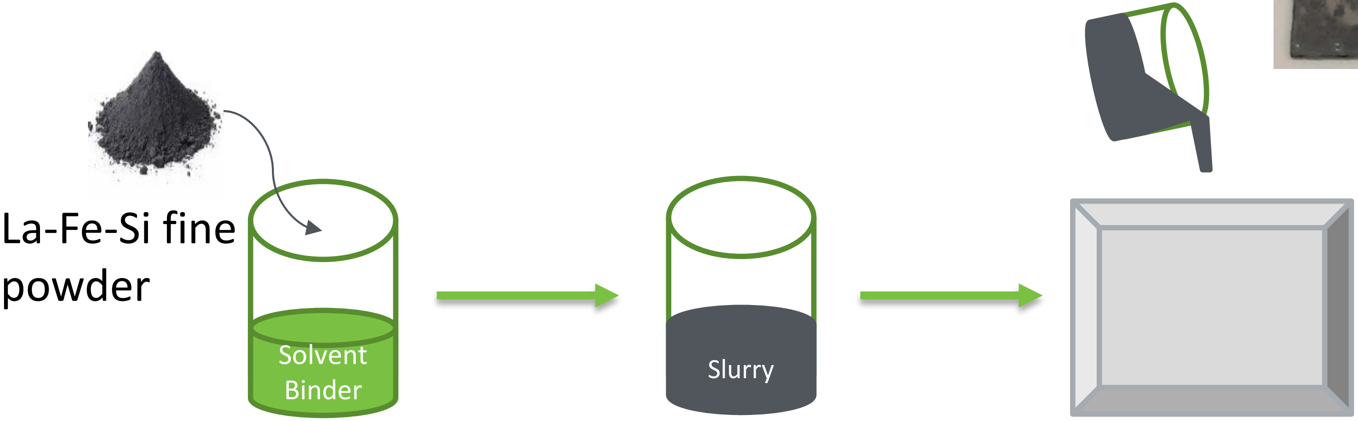




MCM Progress: Bottom-up Manufacturing – Tape casting

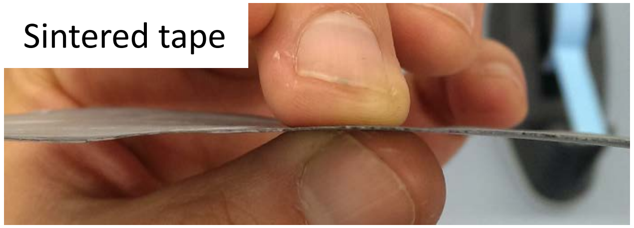
- Preliminary tests have been conducted aiming for La-Fe-Si thin films.
- Work has focused on the formulation of slurries for tape casting.
- First tapes have been hand-casted.

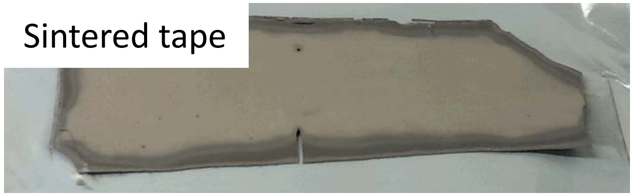




MCM Progress: Bottom-up Manufacturing – Tape casting

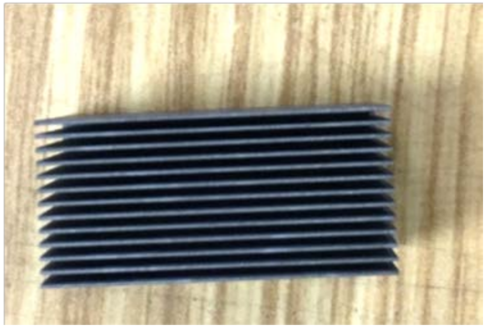
- Tape 0.17 mm thick on average
- Fully dense material achieved after sintering.
- Hydrogenation lead to volume change and cracks.
- Currently investigating slurry formulation.
- Glovebox with connected de-binding furnace was purchased for oxygen-free treatment.





MCM Progress: Top-down Manufacturing

- Blocks of La-Fe-Si were pressed and sintered.
- Parts of La-Fe-Si were cut using wire electric discharge (EDM) machining.
- Geometry can be used to test central hypothesis of this project; Solid state heat transfer between La-Fe-Si and metal part.



Disadvantages:

- EDM machining is slow and the yield is low
- Surface roughness of machines available to VAC typically between 20 – 70 µm

Progress and Accomplishments

Accomplishments:

- Forming of MCM rods with less than 6 μm surface roughness.
- Initial results of MCM tape casting show great potential.
- Analytical model have been developed.

Market Impact:

- Up to 20% higher COP than vapor compression counterparts
- Identified steps toward successful market entry. The report will be published as a milestone report at the end of the project.

Lessons Learned:

- Special attention must be paid to driving system due to large forces.
- Reduction of dead volume is critical.

Project Integration and Collaboration

Partners, Subcontractors, and Collaborators:

- Vacuumscmelze Inc. is a large MCM manufacturer. They supply MCM and develop forming and post-treatment techniques.
- PNNL: Cost modeling of AMR and MCM properties characterization.

Communications:

Zhang, Mingkan; Mehdizadeh Momen, Ayyoub; and Abdelaziz, Omar, "Preliminary Analysis of a Fully Solid State Magnetocaloric Refrigeration" (2016). International Refrigeration and Air Conditioning Conference. Paper 1758.

Inventions:

Ayyoub M. Momen, O. Abdelaziz, and E. Vineyard, "Magnetocaloric Refrigeration Using Solid Working Medium," US Provisional Patent Application, ID 3263.1, Oct 30, 2014.

Next Steps and Future Plans

Next Steps and Future Plans:

- Validate model experimentally.
- Complete cost model and calculate payback.
- Finalize tape casting manufacturing procedure.
- Build fully solid state 500 W heat pump.

REFERENCE SLIDES

Project Budget

Project Budget: $1.74M ($1.4M DOE, $340K Cost Share)
Variances: None
Cost to Date: $689K DOE, $290K Cost Share
Additional Funding: None

Budget History					
10/1/2015– FY 2016 (past)		FY 2017 (current + planned)		FY 2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$583,000	$170,000	$817,000	$170,000	0	0

Project Plan and Schedule

Project Schedule								
Project Start: 10/1/2016		Completed Work						
Projected End: 9/30/2017		Active Task (in progress work)						
		Milestone/Deliverable (Originally Planned) use for						
		Milestone/Deliverable (Actual) use when met on time						
	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)
Past Work								
Q1 Milestone: Review state-of-art								
Q2 Milestone: Develop AMR 1st order model								
Q3 Milestone: Proof of concept AMR unit								
Q4 Milestone: Demonstrate proof of concept								
Q4 Milestone: Post treatment process of MCM								
Q5 Milestone: Optimize hydrogenation of MCM								
Q6 Milestone: Build 2nd generation unit								
Q7 Milestone: Evaluate 2nd generation unit								
Q8 Milestone: Complete cost analysis								