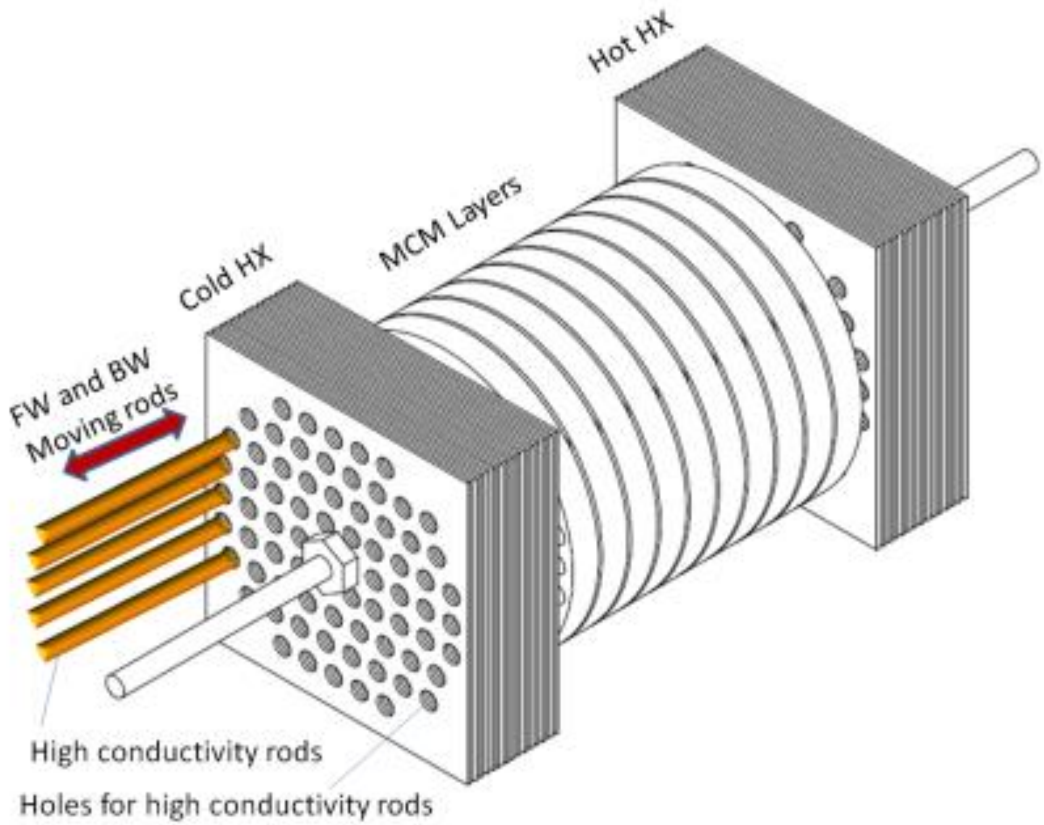
Solid State Magnetocaloric Air Conditioner

2016 Building Technologies Office Peer Review



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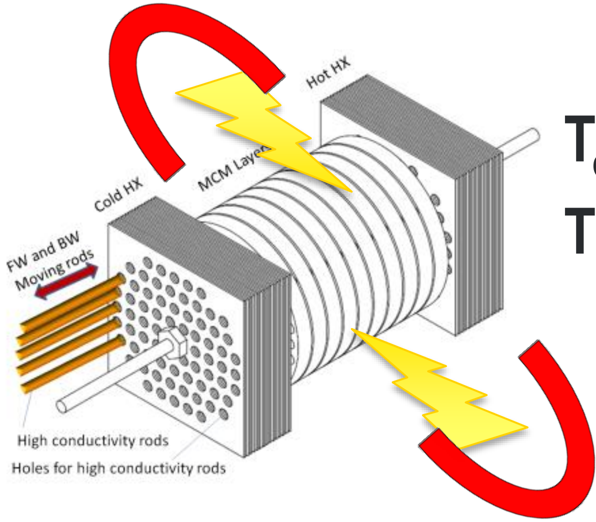
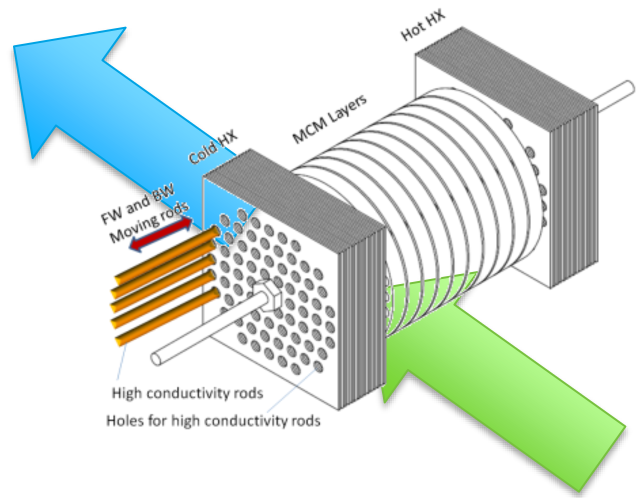
Cooling Effect: Solid State Magnetocaloric Air Conditioner



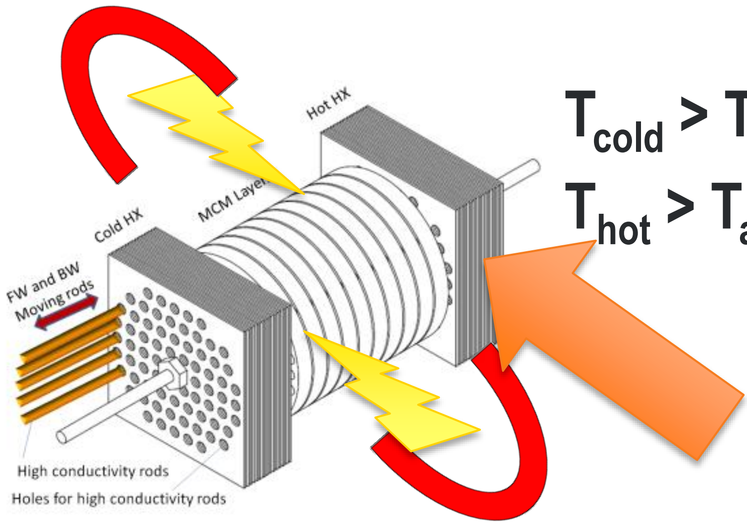
$T_{cold} \sim T_{supply}$

$T_{hot} \sim T_{amb}$



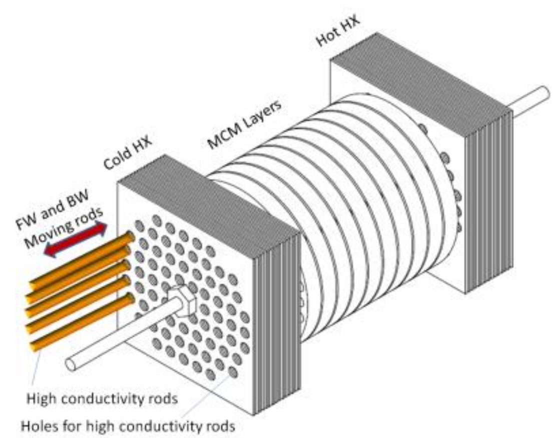
$T_{cold} < T_{supply}$

$T_{hot} < T_{amb}$



$T_{cold} > T_{supply}$

$T_{hot} > T_{amb}$



$T_{cold} < T_{supply}$

$T_{hot} < T_{amb}$

Project Summary

Timeline:

Start date: 10/1/2015

Planned end date: 09/30/2017

Key Milestones

1. Development of a first-order modeling tool that predicts the performance of AMR heating and cooling cycle, 03/31/2016
2. Submit report documenting the performance of the first-generation prototype with analysis of the performance trends. (M12)

Budget:

Total Project $ to Date:

- DOE: $1,400k
- Cost Share: $340k

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Key Partners: (list key partners)

Vacuumschmelze GmbH & Co. KG

VACUUMSCHMELZE

Project Outcome:

- Develop a fully solid state magnetocaloric AC that will result in significantly improved system efficiency and environmental friendliness (i.e., no use of GWP refrigerants)
- Eliminate the need for many expensive system components such as rotating valves and hydraulic pumps.
- Reduce the amount of required MCM mass and hence will achieve a higher magnetic flux than conventional AMR systems.
- Small-scale demonstration prototype (500W nominal capacity).

Purpose and Objectives

Problem Statement:
Create next generation technology that revolutionizes the heating, ventilation, air-conditioning and refrigeration (HVAC&R) industry by creating unprecedented opportunities for non–VC systems.

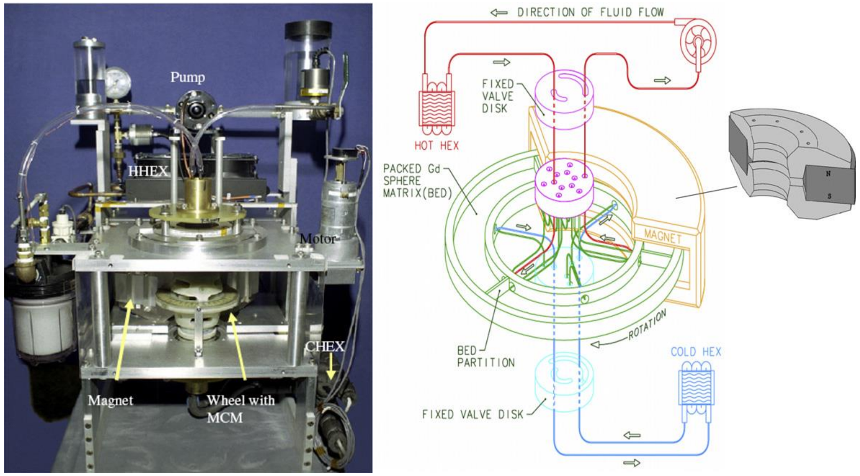
Target Market and Audience: residential and commercial HVAC&R
- Initial market for this project is window AC

Impact of Project:
- The proposed system would theoretically offer 8 times higher heat transfer rates and cost ~ 50% less than a conventional Active Magnetic Regeneration (AMR) systems.
- Create opportunities for other applications, including water heaters, heat pumps, dryers, and dehumidifiers.
- Save 1 quad of energy for space heating and cooling in the US residential sector alone.
- Maintain US leadership in advanced HVAC&R technologies and create jobs in innovative technology.

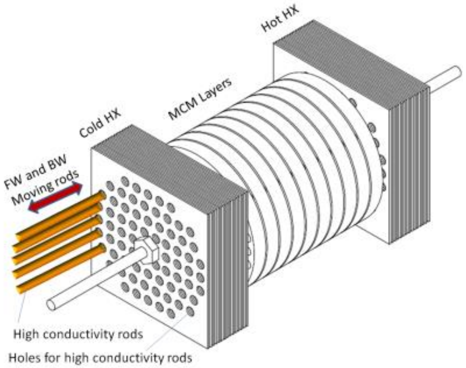
Approach

Approach:

- Develop next-generation technology using innovative concept
  - Fully solid state magnetocaloric air conditioner
- Eliminate the need for expensive system components such as rotating valves and hydraulic pumps.
- Significantly reduce the amount of required magnetocaloric material (MCM) mass and achieve a higher magnetic flux compared with conventional AMR systems.



The "world's first rotary magnetic refrigerator" with permanent magnets built by Zimm and his collaborators at the Astronautics Corporation of America (Zimm et al., 2005, 2006).



Fully Solid-State concept – no valves; simple design

Approach

Key Issues:

- Magnet design (expensive, bulky)
- Impact of increased frequency on balance of system
- Magnetic material machining – need for high surface finish tolerances

Distinctive Characteristics:

- Replace the heat transfer fluid with high-conductivity moving rods to exchange heat. This will provide exceptional heat transfer characteristics, which cannot be achieved otherwise, and eliminate the need for a pump or rotating valve.
- Capitalize on the strength of the industrial partner Vacuumschmelze GmbH & Co. KG.

Progress and Accomplishments

Accomplishments:

- Reviewed previous work on active magnetic refrigeration system designs and materials
- Established contract with Vacuumschmelze
- Developed 1-D discrete model

Market Impact:

- Vacuumschmelze to develop advanced material processing and fabrication techniques for this project – would benefit other AMR systems
- Up to 25% energy savings in window AC performance compared to minimum efficiency units

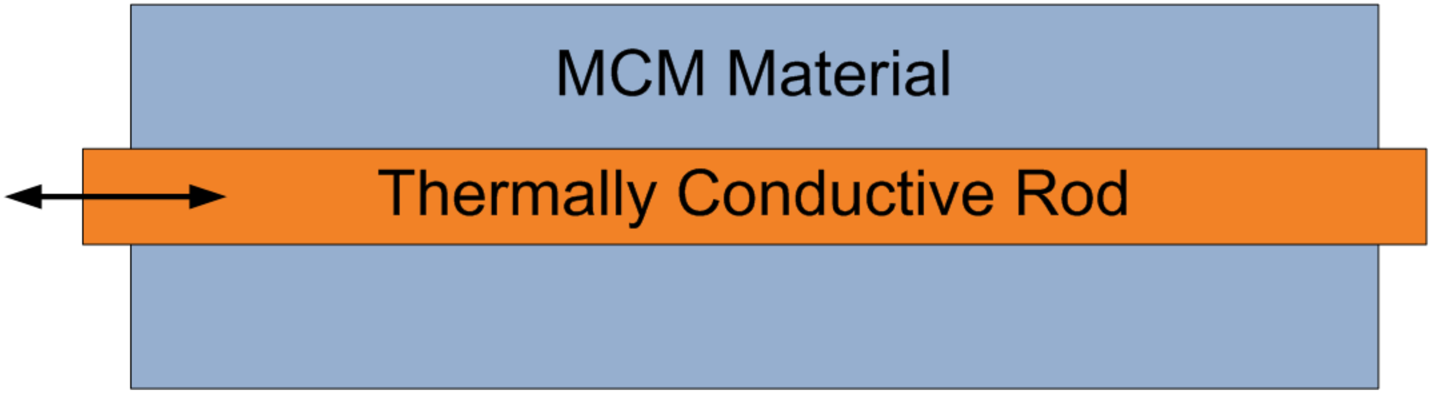
Awards/Recognition: NA

Lessons Learned:

- Long lead time for custom built magnet designs
- Parameters for solid-state modeling are empirical and require additional investigations

Development of One-Dimensional Discrete Model

- Porosity = volume of brass / total volume
- High capacity material would reduce porosity and improve utilization



One-Dimensional Solid State Model

Coupled equation:

- $(h_c + h_g)a_c(T_s - T_r) + (1-\varepsilon)k_r\frac{\partial^2 T_r}{\partial x^2} = (1-\varepsilon)\rho_r c_r\frac{\partial T_r}{\partial t}$, (1)
- $-(h_c + h_g)a_c(T_s - T_r) + \varepsilon k_s\frac{\partial^2 T_s}{\partial x^2} = \varepsilon\rho_s c_s\frac{\partial T_s}{\partial t} + \varepsilon\rho_s c_s u\frac{\partial T_s}{\partial x}$, (2)
  - a_c: contact area
  - ε: porosity
  - u: velocity of solid state rod
  - T: temperature
  - ρ: density
  - k: thermal conductivity
  - c: specific heat
  - h_c: contact conductance between regenerator and brass rod
  - h_g: conductance of the thermal grease.

subscripts r and s indicate regenerator and solid state heat transfer material, respectively.

Contact Conductance

$$h_c = \frac{1.25 m k_m}{\sigma} \left(\frac{P}{H}\right)^{0.95}$$

- *P*: Apparent pressure on the interface;
  - higher *P* improves the contact conductance: better contact
  - Higher *P* results in increased pressure in moving the rods
  - Need to identify the trade-off and determine optimum *P*
- *H*: hardness of the softer material
- *k*: harmonic mean thermal conductivity
- σ: effective surface roughness
- *m*: effective absolute surface slope

$$k_m = 2k_r k_s/(k_r + k_s)$$

$$\sigma = \sqrt{\sigma_r^2 + \sigma_s^2}$$

$$m = \sqrt{m_r^2 + m_s^2}$$

[1] K. Negus and M. Yovanovich, "Correlation of the Gap Conductancg Integral for Conforming Rough Surf aces," *J. Thermophys. heat Transf.*, no. July, pp. 44–46, 1988.

Thermal Grease Conductance

$$h_g = k_g / Y$$

- k_g: thermal conductivity of the thermal grease
- Y: effective gap thickness

$$Y = 1.53\sigma(\frac{P}{H})^{-0.097}$$

V. Antonetti and M. Yovanovich, “Thermal contact resistance in microelectronic equipment,” Int. J. Hybrid Microelectron., 1984

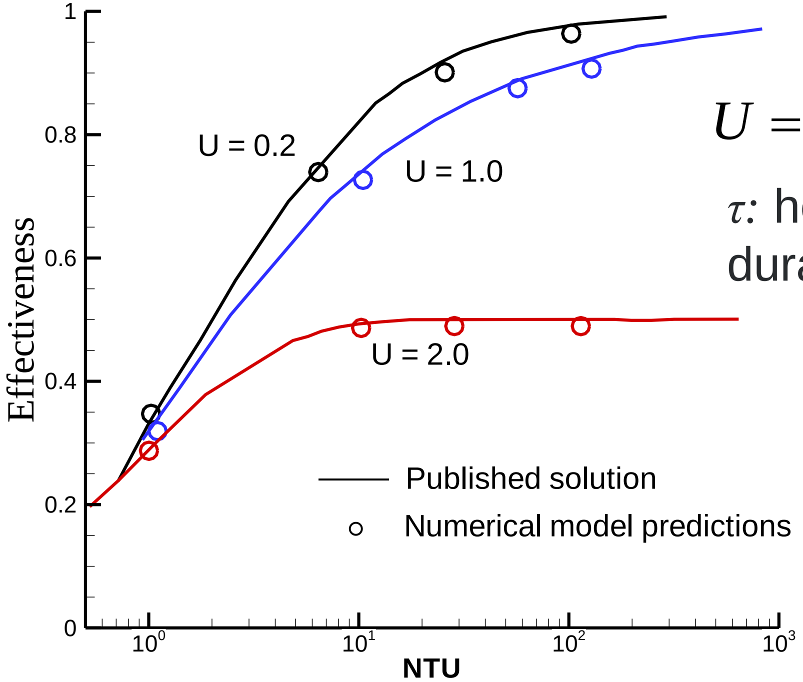
Magnetic Field Impact Simulations

- The magnetocaloric effect (MCE) is implemented by applying the adiabatic temperature change, ΔT_{ad}, to the regenerator during the processes of magnetization or demagnetization as

$$T_{final} = T_{initial} + \Delta T_{ad}$$

- T_{final}: temperature after the step change in magnetic field
- $T_{initial}$ initial temperature before applying magnetic field

Code Validation without Considering Magnetic Effect



$$U = \dot{m}_f c_f \tau / m_s c_s$$

τ: hot/cold blows durations

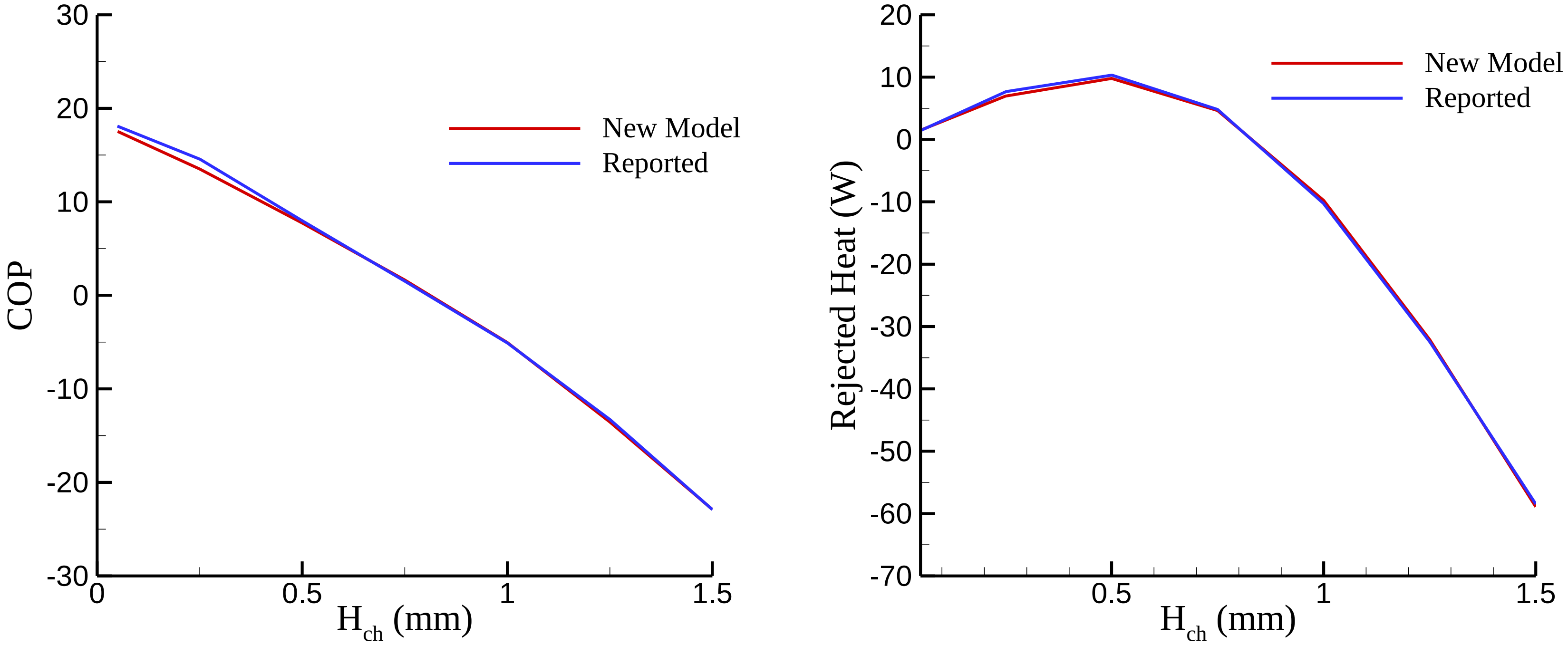
Analytical results versus numerical solutions

NTU: Number of transfer Units and

U: utilization ratio

K. Engelbrecht, A numerical model of an active magnetic regenerator refrigerator with experimental validation. 2008.

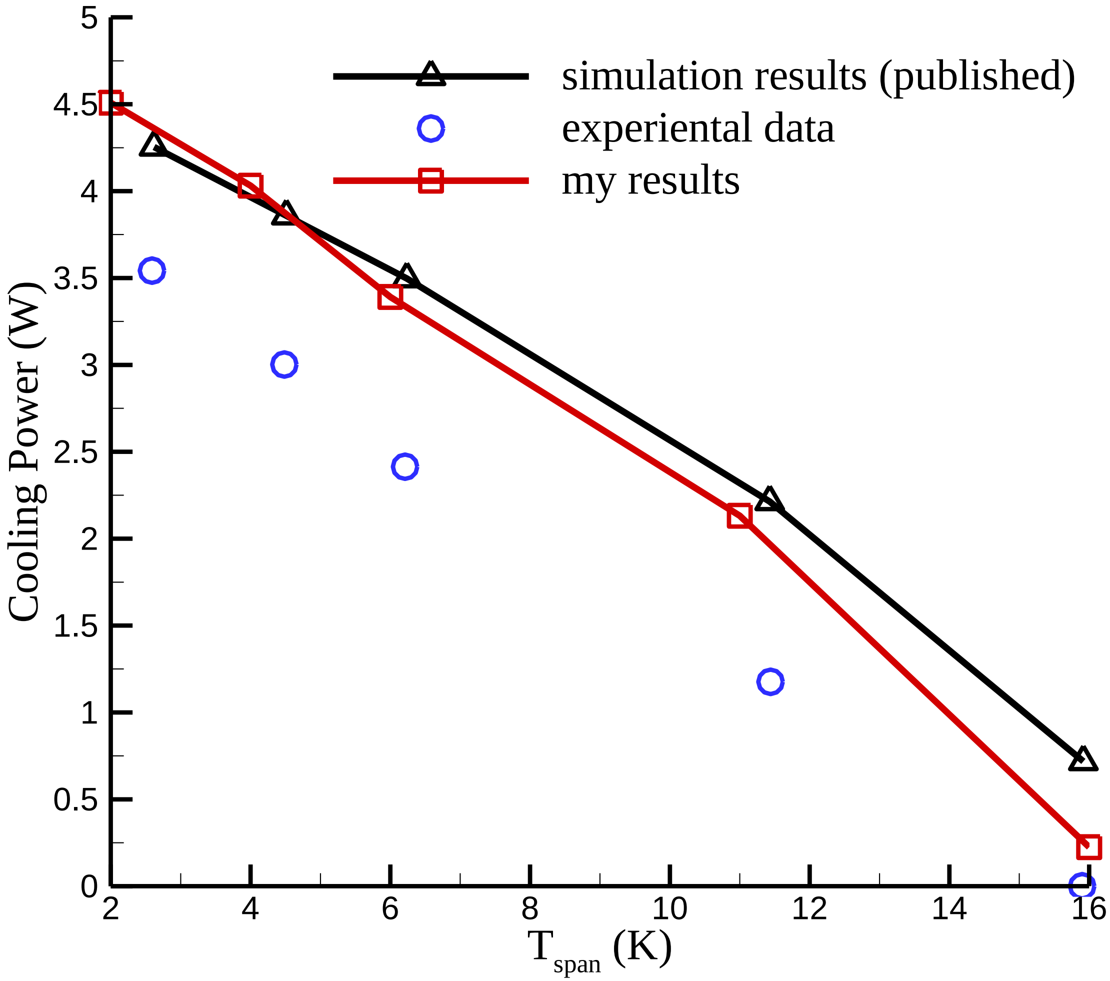
Code Validation Considering Magnetic Effect



H_{ch}: thickness of MCM material.

T. F. Petersen, K. Engelbrecht, C. R. H. Bahl, B. Elmegaard, N. Pryds, and A. Smith, "Comparison between a 1D and a 2D numerical model of an active magnetic regenerative refrigerator," J. Phys. D. Appl. Phys., vol. 41, no. 10, p. 105002, 2008.

Code Validation with experimental data



Engelbrecht, K., Tušek, J., Nielsen, K., Kitanovski, A., Bahl, C., Poredoš, A., 2013. Improved modelling of a parallel plate active magnetic regenerator. J. Phys. D. Appl. Phys. 46, 255002

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2-D/3-D Discretized Simulation

- ANSYS will be used to create models and run simulations for 2-D/3-D solid state AMR modeling. The procedure of the simulation will be as following,
  - The 2-D/3-D solid state AMR model will be generated using SpaceClaim, a model generation module of ANSYS.
  - A high quality mesh will be generated using ANSYS meshing.
  - The ANSYS FLUENT will be employed to run the simulation. In the modeling, the heat transfer for solid state rod as well as MCM will be solved by the built-in heat transfer models in FLUENT. The MCE will be introduced as an instantaneous temperature change (ΔT_{ad}) in the regenerator, which will be implemented using user-defined function, a C language interface of FLUENT.
  - The post-processing will be conducted either using CFD-post in ANSYS or other post-processing software (e.g. tecplot)

Project Integration and Collaboration

Project Integration:

- ORNL will collaborate closely with Vacuumschmelze to develop required system and material specifications
- ORNL is already holding discussions with GE appliances for potential collaboration and integration of this concept on their conceptual refrigerator design

Partners, Subcontractors, and Collaborators:

- Vacuumschmelze is the main project partner
- Subcontractors:
    - Arnold magnetics design and fabricate permanent magnets

Communications:

- Abstract accepted for the Purdue AC&R conference
- Abstract submitted for the upcoming Thermag conference

Next Steps and Future Plans

Next Steps and Future Plans:

- Continue planned activities
- Reach out to OEM and appliance manufacturers to establish commercial interest and eventual product commercialization

REFERENCE SLIDES

Project Budget

Project Budget:
- Federal Funds: $1400k
  - ORNL: $980k
  - Vacuumschmelze : $420k
- Cost Share
  - Vacuumschmelze: $340k

Variances: NA

Cost to Date: $73k

Additional Funding: NA

Budget History					
(past)		FY 2016 (current)		FY 2017 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
NA	NA	$1,400k	$340k	NA	NA

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Project Plan and Schedule

	Task Mode	Task Name
1		**Establish Subcontract with Vacuumschmelze GmbH & Co. KG**
7		**Kick-Off Meeting**
11		**Modeling Framework**
12		**Develop a Model for system design and optimization**
13		Conduct literature review
14		Submit report documenting literature review summary on previous prototype designs and materials
15		**Develop 1-D discrete model**
16		Review codes developed by Ayyoub
17		Make required changes
18		Validate Model using experimental data from literature
19		Write a journal paper
20		Milestone: validated 1-D discrete model for solid state MCM AC
21		**Investigate finite element modeling approach**
25		**Develop a first-order model for fully solid state AMR system**
31		**Develop system-level model for annual performance evaluation**
34		**Couple the system model with optimization tools**
38		**Validate the model using experimental data**
43		Write report documenting the model validation results
44		Submit report documenting the model validation results
45		**Fabricate and test first-generation unit**
75		**Develop Commercialization Plan**
82		**Go/No-Go Decision**
88		Develop techniques to optimize dynamic performance under varying outdoor conditions
89		**Fabricate and test second-generation unit**
114		**Analyze system cost at various sales volumes**
120		**Technology-to-Market Strategy & Commercialization Plan**
125		**VAC subcontract**
126		**Improve MCM manufacturability**
127		**Develop techniques to improve MCM surface quality**
131		**Develop post-treatment process for recovering the desired MCM properties**
135		Producing MCM with surface roughness less than 50 microns, in required shapes
136		Alternate engineering solution becomes suitable for the application and is accepted by DOE
137		**Develop/identify next-generation MCM to accommodate both heating and cooling applications**
144		**Develop optimized shaping procedure for LaFeSi-based parts**