Prototype and Simulation Model for a Magnetocaloric Refrigerator

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Start Date = June 1, 2002 ~
Planned Completion = Dec. 31, 2006

Research Goals and Objectives

- **Evaluate magneto-caloric refrigeration as a viable process for liquefaction of hydrogen**

- **Develop simulation models and thermodynamic models**
  - Numerical evaluation of a composite microchannel heat exchanger
  - Thermodynamic analysis of a magnetic refrigerator
  - Analysis of a magnetic liquefier for hydrogen and compare it with conventional technology

- **Develop key components for prototype magnetocaloric cooling system**
  - Preparation of magnetocaloric materials GdSiGe and its synthesis in different forms with optimal properties
  - Design and development of microfabrication processes for prototype microcoolers
  - Development of in-situ temperature sensors for accurate temperature measurement
  - Demonstration of the microcooler assembly by performing experiments
  - Validation of the model with experimental results

Relevance to Current State-of-the-Art

- Competitive to conventional vapor compression refrigeration technology in terms of overall system performance by using magnetocaloric material GdSiGe.
- Miniaturized magnetocaloric cooling system with Si microstructure
- USF has demonstrated cooling at low magnetic fields (1.7 Tesla).

Relevance to NASA

- Magnetic refrigeration can be useful for heat dissipation in a ZBO cryogenic storage vessel.
- Miniaturization of a refrigeration system: a key technology for future pico-satellites
- High cooling capacity: Realizing micro cryo-coolers that can operate at a wide temperature range with a high cooling capacity
- The small size and lightweight magnetic liquefier developed under this project can be useful to re-liquefy hydrogen in cryogenic storage tanks used for transportation and storage of hydrogen for space missions.

Budget, Schedule and Deliverables

Budget

1 Yr($200,000), 2Yr($109,682), 3 Yr($120,000)

Deliverables

1. Computer simulation programs in an electronic file
2. A prototype MEMS cooling element and its assembly
3. Specific process conditions and process recipes
4. Final report

Schedule

Time table	2003				2004				2005				2006			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Numerical computation fo heat transfer coefficient	■	■	■													
Develop a steady state and a transient state simulation model						■	■	■	■	■	■					
Establish magnetocaloric phases in bulk form			■	■	■	■	■	■								
Microfabrication processes for microchannels	■	■	■	■	■	■	■									
Synthesize required phases for GdSiGe			■	■	■	■	■	■	■							
High temperature diffusion barrier on Si							■	■	■							
Develop in-situ temperature sensors						■	■	■	■	■						
Computational analysis of a large size magnetic cooler						■	■	■	■	■	■	■	▇			
Analysis of heat transfer in a composite Si-Gd microcooler								■	■	■						
Thermodynamic analysis of a magnetic refrigeration system		■	■	■	■											
Conceptual design and analysis of a hydrogen liquefaction system					■	■	■	■	■							
Assembly and Integration of cooling elements										■	■	■	▇	▇	▇	▇
Experimental test setup with electromagent device								■	■	■	■	■	▇	▇	▇	▇
Performing cooling test											■	■	▇	▇	▇	▇
Preparation of components such as valves and heat exchangers													▇	▇		
Construct the full cycle of a magnetic refrigerator														▇	▇	
Automatic valve and magnetic control system													▇			
Test magnetic refrigeration system															▇	▇

Anticipated Technology End Use

Overall integrated technology

- Storage of hydrogen for space missions: zero boil off (ZBO)
- Liquefaction of hydrogen for transportation
- Household refrigerator: environmentally friendly with high efficiency
- Cooling for pico-satellites

Unit technologies

- Design and analysis of micro cooling systems
- Synthesis of magnetocaloric materials
- Temperature sensor: in-situ temperature measurement

Accomplishments and Results (Summary)

❒ **Established a computational magnetic cooler model**

- Made a computational model of a magnetic cooler
- Analysis of heat transfer in a composite microcooler with trapezoidal channels

❒ **Developed magnetocaloric materials**

- Developed the processes to synthesize magnetocaloric material (GdSiGe)
- Established high temperature diffusion barrier (AlN/SiO_2) for GdSiGe films on Si

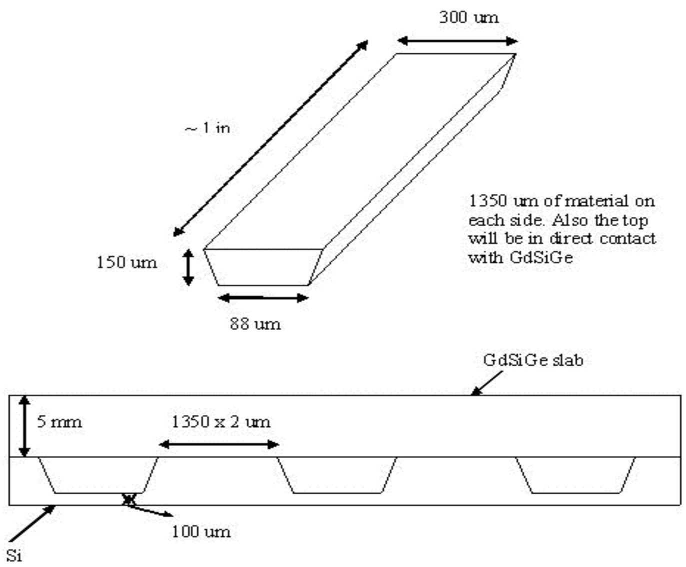
❒ **Developed and tested microcooler**

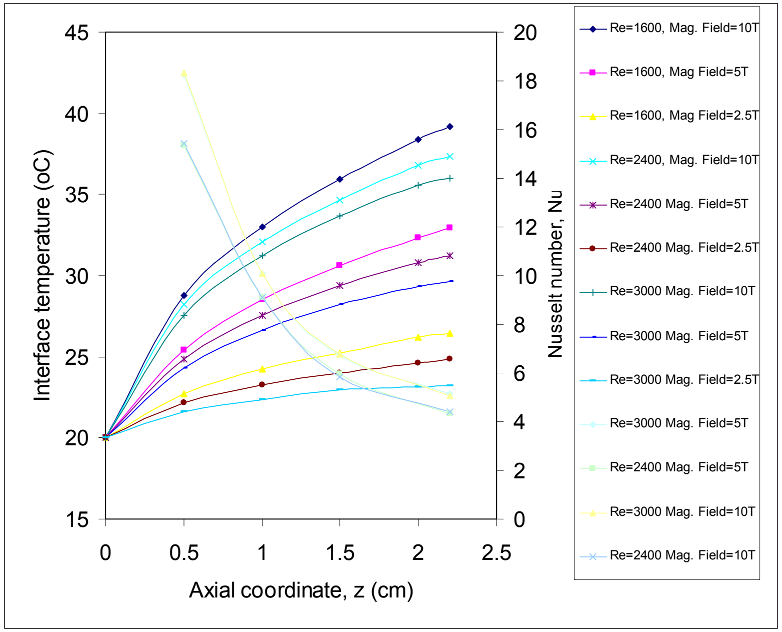
- Developed the fabrication processess and fabricated trapezoidal flow channels in Si
- Made the in-situ temperature sensor through deep impurity diffusion
- Accomplished cooling test and showed the feasibility of the microcooler

❒ **Designed and analyzed a magnetic refrigerator and liquefaction system**

- Analyzed a magnetic refrigeration system
- Made a conceptual design of a hydrogen liquefaction system

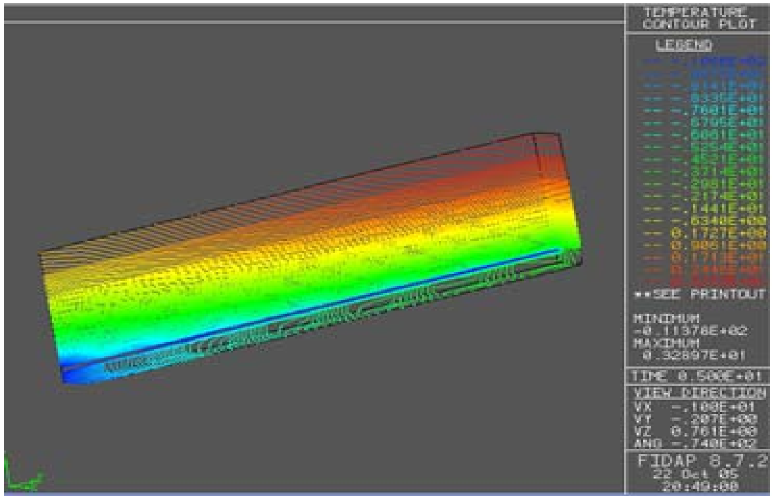
Modeling and simulation of a magnetic microcooler

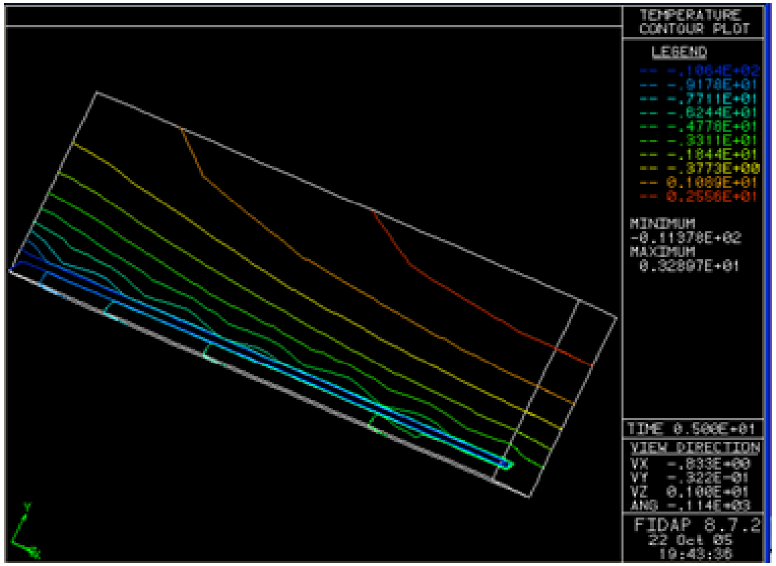


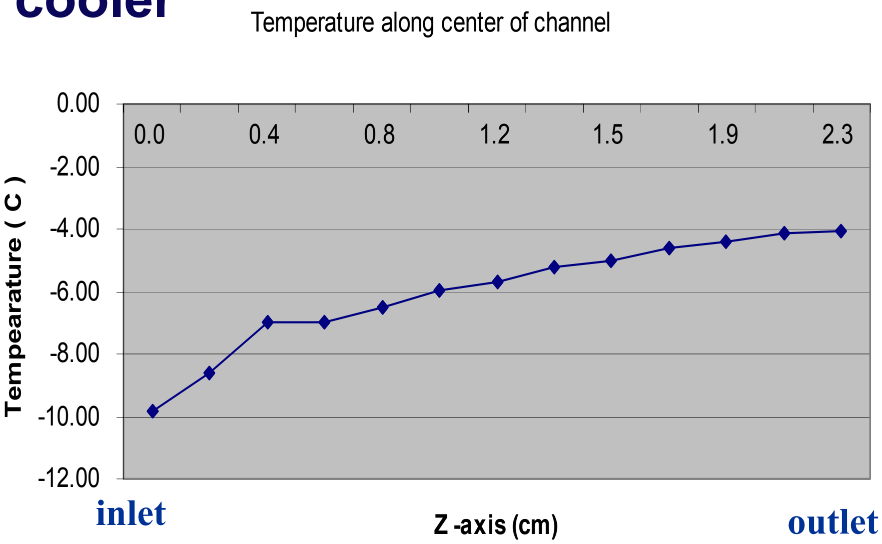


- The peripheral average heat transfer coefficient and Nusselt number decreases along the length of the channel due to the development of thermal boundary layer.
- For the same channel, Nusselt number increases with Reynolds number.
- For same magnetic field, interface temperature increases as the Reynolds number is decreased.
- Nusselt number remains almost constant for different magnetic fields.

Transient response analysis of the cooler



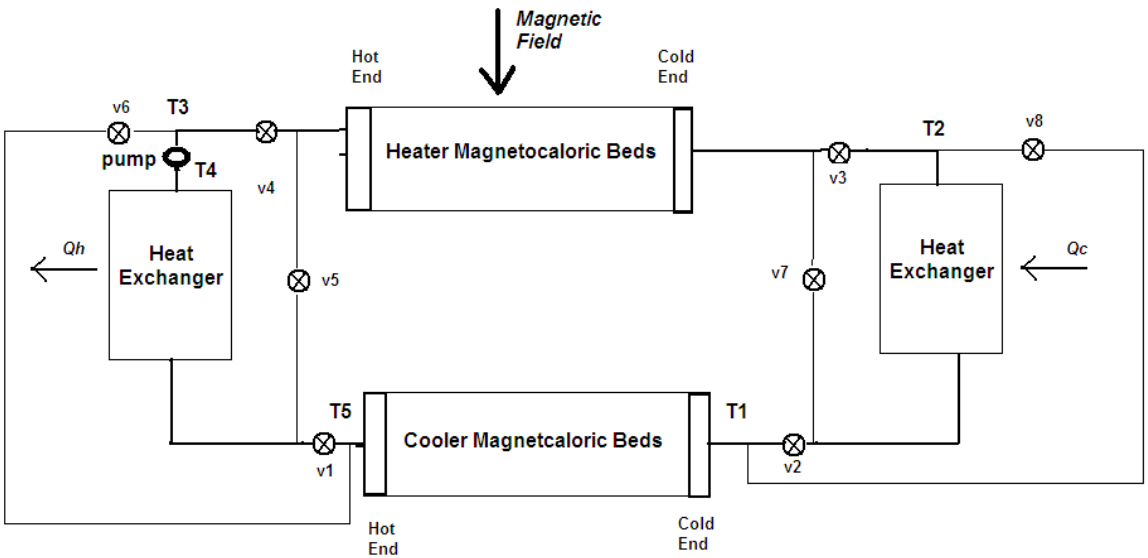




Magnetic Field	1.0 T
Reynolds Number	23.26
Inlet Velocity	337 cm/s
Initial Temperature	**-11 ˚C**
Fluid	60% glycol + 40% water
Material	Gd

- Initial conditions (t=0) for the temperature (-11 °C) for the gadolinium slab, silicon, and fluid.
- The simulation shows inlet and exit channel temperatures during magnetization of the Gadolinium while operating for 60 seconds

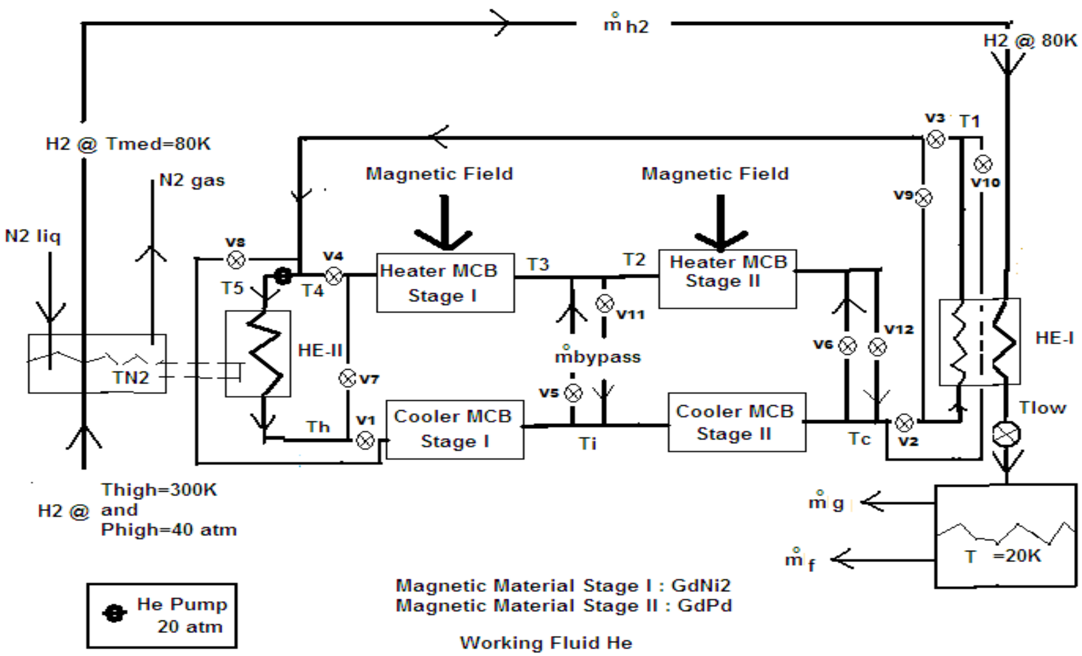
Thermodynamic analysis of a magnetic refrigerator



COP (Typical 18 ft^3 refrigerator)		
Magnetic Refrigerator	Commercial Vapor Cycle Refrigerators [2]	
N/A	R134a	R22
11	2.26	2.29

[2] Vineyard E.A., 1991, “The alternative refrigerant dilemma for refrigerator-freezers: truth or consequences,” ASHRAE Transactions, Vol. 97, Part 2, pp. 955-960.

Analysis of a magnetic liquefier for hydrogen



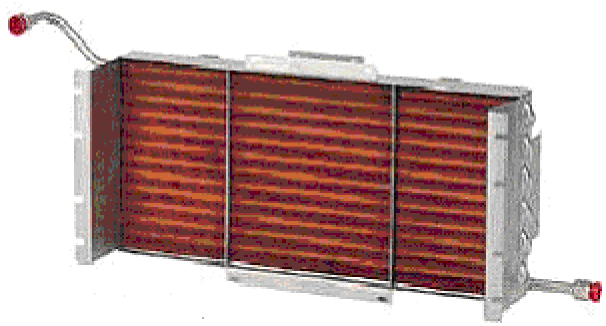
Magnetic H2 Liquefier

Table Liquefaction efficiency comparison

Present Model %	Laboratory magnetic prototype liquefier, % (Iwasaki)	ACA Model [10] %	Conventional reciprocating model, % (Barron [12])
72.4	50	21	33.5

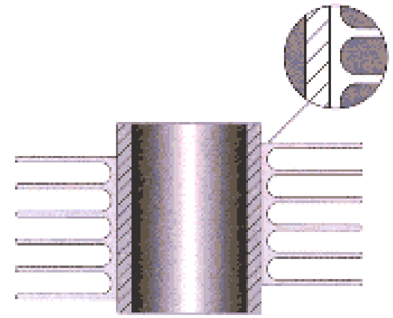
- Liquefaction efficiency of the cycle increases as consequence of an increase in the magnetic refrigerator performance.
- The model showed better performance than that showed by other models.
- Magnetic liquefier exhibits a great potential by showing significantly higher efficiency when compared to small and large scale commercial liquefiers for hydrogen.

Design of refrigerator components

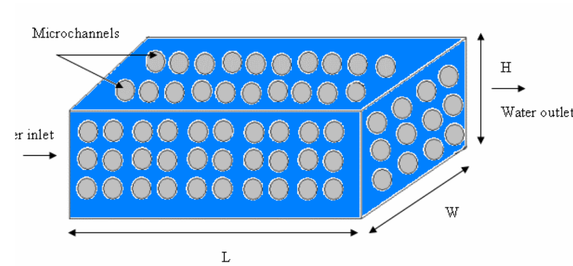


Heat exchanger specifications

Parameter	Range	
Air inlet	85 F	
Air outlet	55 F	
Liquid outlet temp.	278K	
Liquid inlet temp.	273K	
Mass flow rate	1.77 l/min	
Tube OD	0.25 in	0.625 in
Fin height	0.125 in	1.25 in
Fin density	5/in	10/in
Fin thickness	0.3 mm	0.6 mm
Fin material	Al or Cu	
Tube material	Al or Cu	



Detail for the tube and fin section in the heat exchanger



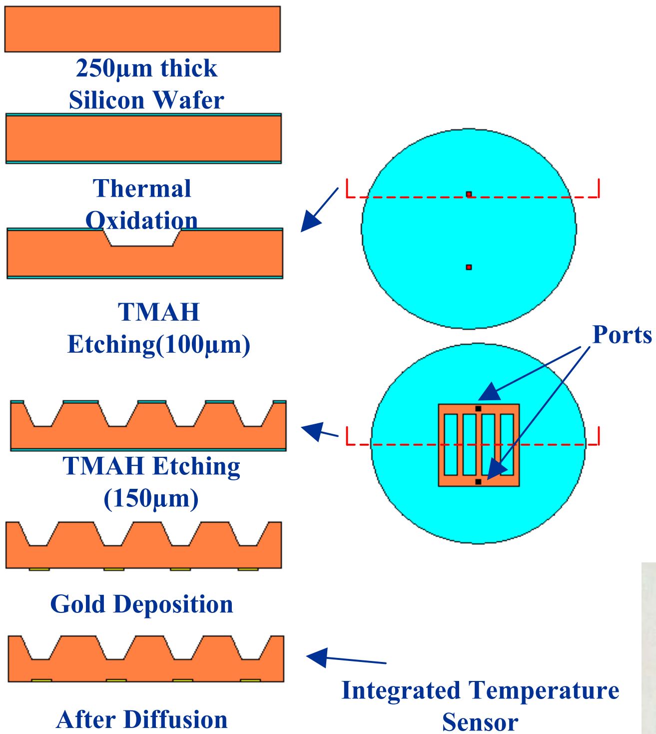
Magnetic bed specifications

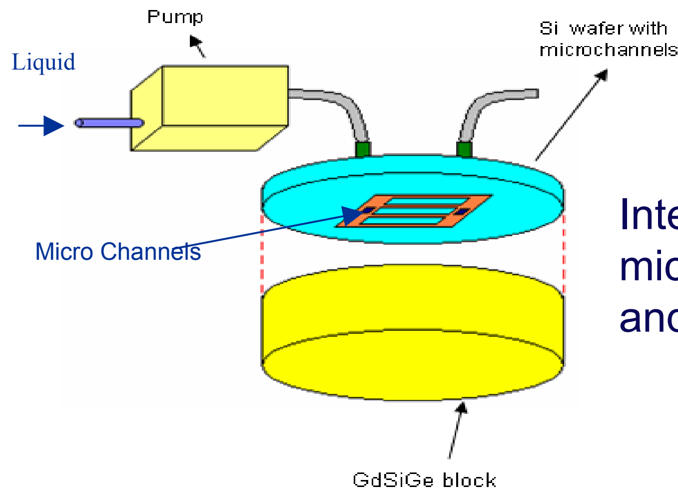
L (m)	W (m)	H (m)
0.18	0.95	0.03
0.2	0.08	0.04
0.22	0.086	0.04

Component	Efficiency [%]	Refrigerator
Evaporator	48.38	Commercial [11]
Condenser	27.8	Commercial [11]
Heat exchanger	12.4	Magnetic
Magnetic bed	53.19	Magnetic

Exergetic efficiency for refrigerator components

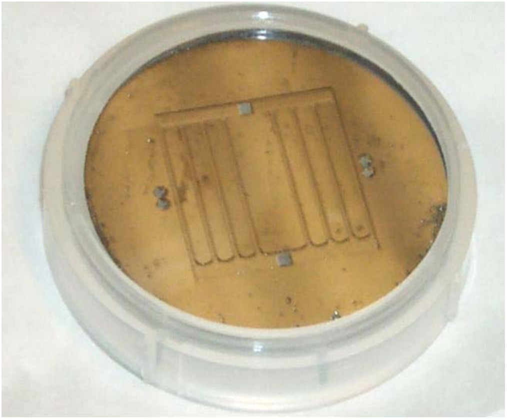
Fabrication of microcooling element



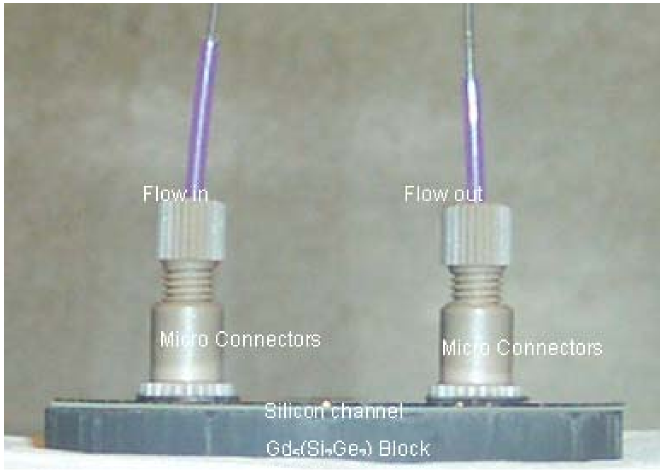


Integration of microcooler element and specification

Estabilished fabrication process for microchannels

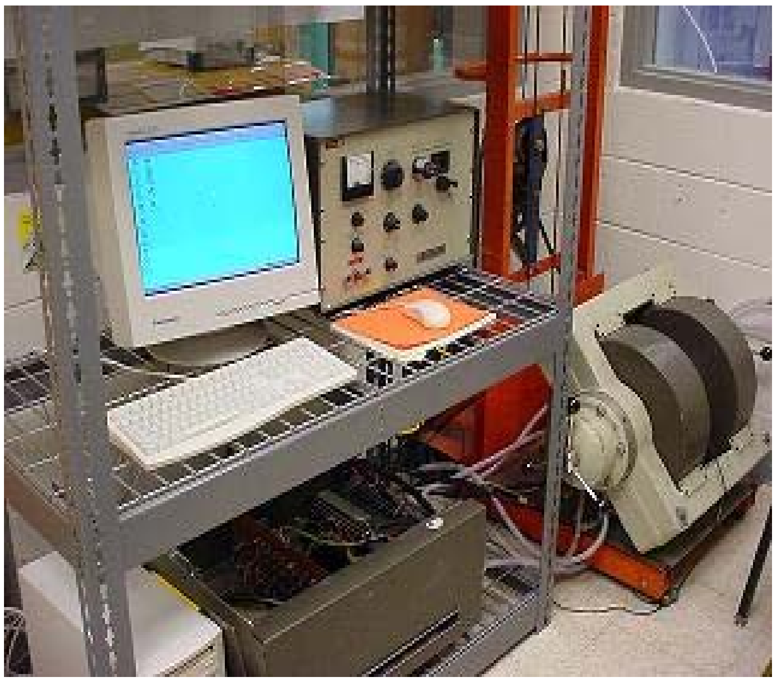


Fabricated microchannels on a 2” silicon wafer

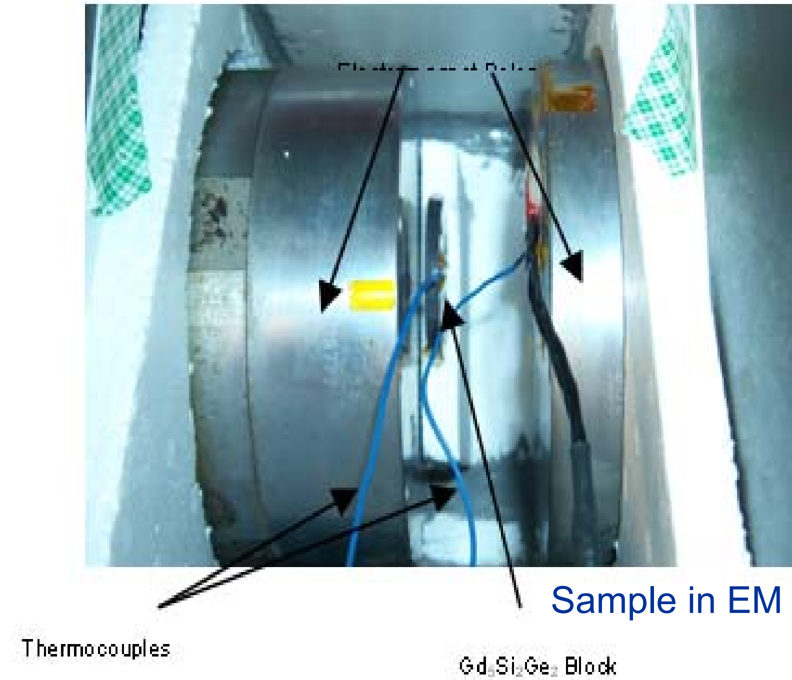


Established cooling test equipment

-Established magnetocaloric cooling experiment
-Test the prototype microcooling system



Cooling test and measurement



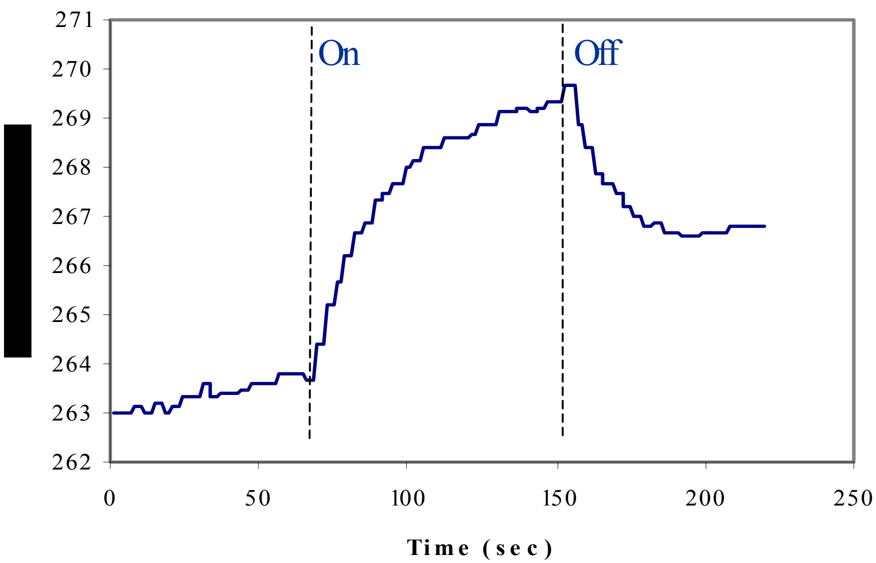
Sample in EM field

Microcooler channel size (WxHxL)	300umx150umx1inch
Channel material	Si (100) wafer, 250um thickness
MCE material	$Gd_5Si_2Ge_2$ (AMES Lab)
MCE block	2inch dia x 1/4 inch thickness
Temp sensor	Diffusion Au @950C
Testing temp	250 K ~ 280 K
Electro-Magent field	~1.7 Tesla (Varian V-3700)

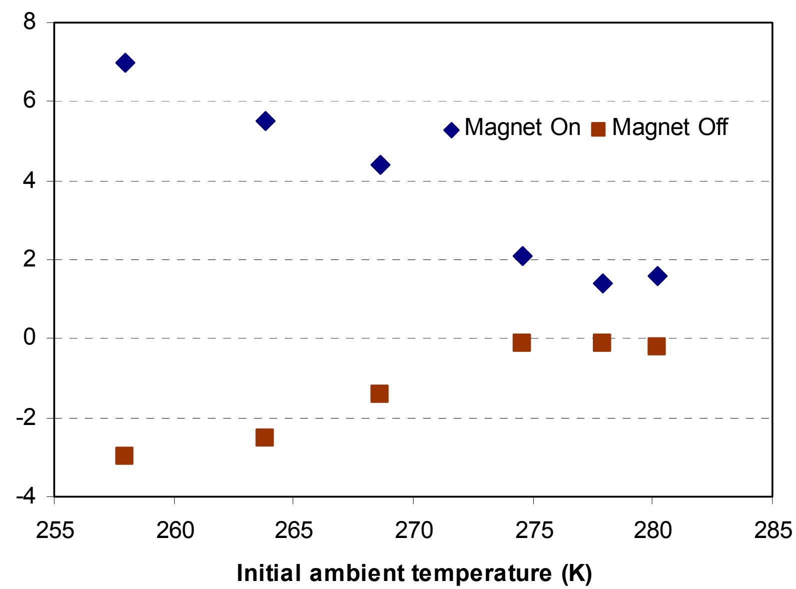
Cooler specification

Cooling test of the MCE block at various ambient conditions

- GdSiGe material was immersed into magnetic field
- Measured temperature on the GdSiGe material surface
- Applied magnetic field = 1.7 Tesla



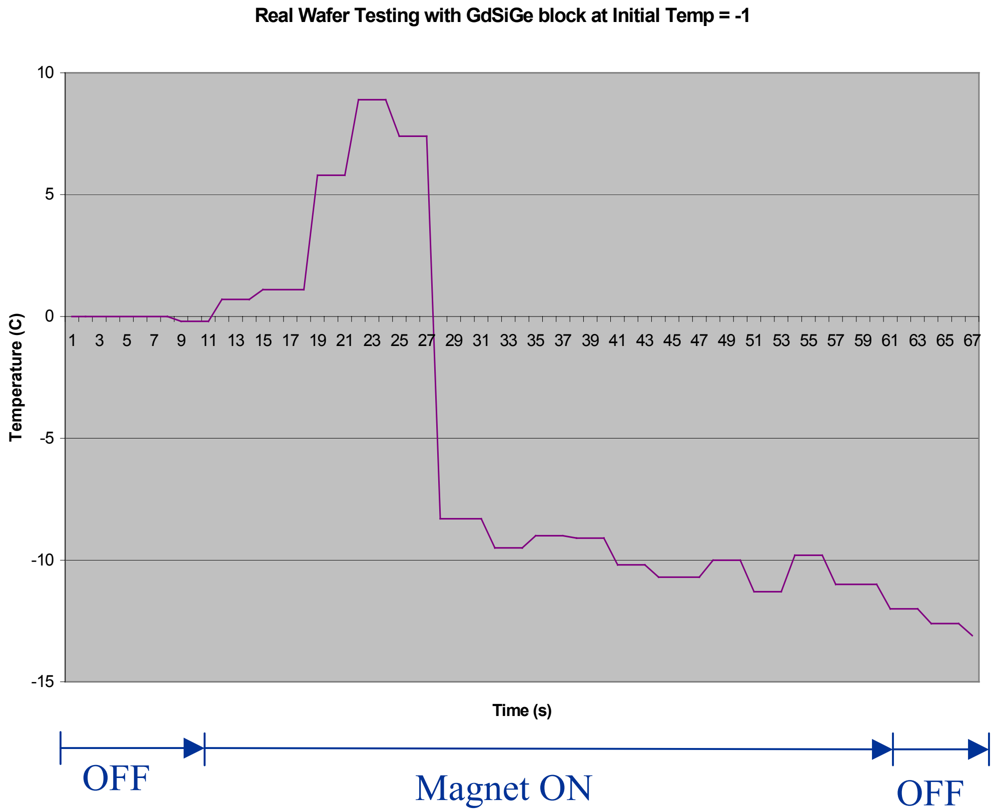
Change in temperature (~ 6K) with time at initial temperature 263.8K



Change in temperature at various initial ambient temperatures

Cooling test with microchannel Si wafer

- Channels were made on Si wafer
- Measured temperature at the inlet and outlet ports using thermocouples

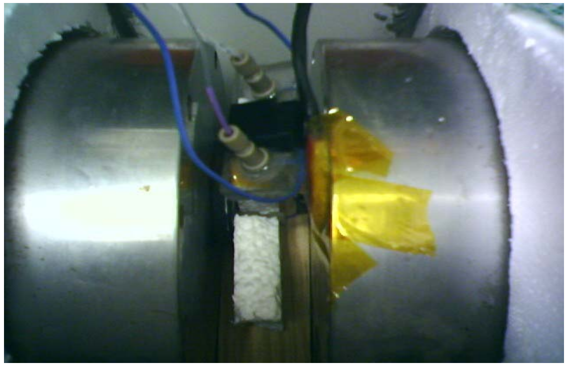


Cooling effect (T_{outlet}-T_{inlet})

- Anti-freeze fluid
  Inhibited Propylene Glycol : water=50:50
- Applied magnetic field: 1.0 Tesla
- Flow rate: 0.83 ml/sec
- The magnet was turned on after 10 sec
- Initial(t=0) chamber temperature: -1 °C.

- Temperature change: 9 °C (at 30sec)

* There was a leaking after 30sec.



Researchers and students involved

- 1 Ph.D student: (Shantanu S. Shevade)
- 3 Master students: Bharath Bethala, Cesar F. Hernandez, and Simone Ghirlanda
- 1 Undergraudate student: Carl Adams
- 3 Postdoctoral fellows: Dr. Sangchae Kim, Dr. Luis Rosario and (Dr. Senthil Sambandam)

Summary of publication papers

2005

1. S. Shevade, M.M. Rahman and L. Rosario, “Second Law Analysis of a Magnetic Refrigerator,” 2005 ASME International Mechanical Engineering Congress and Exposition, Orlando, Florida, November 2005.
2. S.C. Kim, B.Bethala, S. Ghirlanda, S. Sambandam, S. Bhansali, “Design and Fabrication of a Magnetocaloric Microcooler,” ASME International Mechanical Engineering Congress and Exposition, Nov 2005.
3. S. N Sambandam, B. Bethala, S. Bhansali, and D. K Sood, "Search for a Suitable Diffusion Barrier Layer for Annealing Films of Gd-Si-Ge Sputter Deposited on Silicon", Surface Coatings and Technology, 2005 (In print)
4. S.C. Kim, B. Bethala, S. Ghirlanda, P. Khanna and S. Bhansali, “Characterization of Diffusion Barriers for Gd-Si-Ge Films on Silicon Substrate,” 4th International Surface Engineering Congress & Exposition, Aug 2005.
5. P.S.C. Rao and M.M. Rahman, “Transient Conjugate Heat Transfer in a Circular Microtube Inside a Rectangular Substrate,” AIAA Journal of Thermophysics and Heat Transfer, (In press).
6. P.S.C. Rao, M.M. Rahman, and H.M. Soliman, “Numerical Simulation of Steady State Conjugate Heat Transfer in a Circular Microtube Inside a Rectangular Substrate,” Numerical Heat Transfer, (In press)
7. S.N.Sambandam, B.Bethala, S.Bhansali, D.K.Sood, “Search for a Suitable Diffusion Barrier Layer for Annealing Films of Gd-Si-Ge Sputter Deposited on Silicon, International Conference on Metallurgical Coatings and Thin Films, San Diego, California, May 2005.

2004

1. M.M. Rahman and L. Rosario, "Thermodynamic Analysis of Magnetic Refrigerators," Proc. 2004 ASME International Mechanical Engineering Congress and Exposition, Vol. 3, Anaheim, California, November 2004.
2. P.S.C. Rao and M.M. Rahman, "Analysis of Steady State Conjugate Heat Transfer in a Circular Microtube Inside a Substrate," Proc. 2004 ASME International Mechanical Engineering Congress and Exposition, Vol. 1, Anaheim, California, November 2004.
3. S.N. Sambandam, S. Bhansali, V.R. Bhethanabotla, "Study on magnetocaloric GdSiGe thin films for microcooling applications," TMS Annual Meeting, Charlotte, NC, March 14-18, 2004.
4. S.S. Shevade and M.M. Rahman, "Transient Analysis of Microchannel Heat Transfer with Volumetric Heat Generation in the Substrate," Proc. TMS Annual Symposium, Charlotte, North Carolina, March 2004.

2003

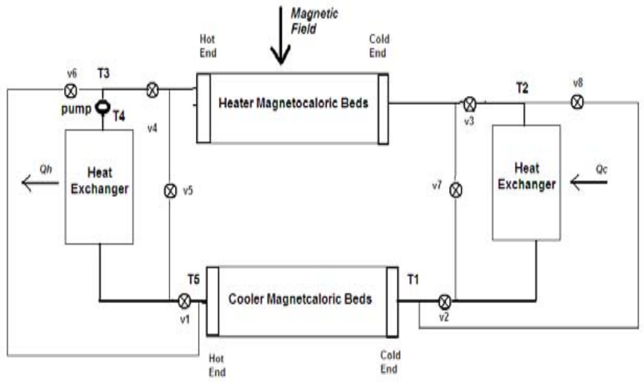
1. M.M. Rahman and S.S. Shevade, "Development of Microchannel Heat Exchanger for Magnetic Refrigeration Applications," Proc. International Conference on Mechanical Engineering (ICME-2003), Dhaka, Bangladesh, December 2003 (keynote paper).
2. M.M. Rahman, S.S. Shevade, and V. Bethanabotla, "Analysis of Transient Heat Transfer in a Microchannel Heat Exchanger During Magnetic Heating of the Substrate Material," Proc. 2003 ASME International Mechanical Engineering Congress and Exposition, Vol. 1, Washington, D.C., November 2003.
3. M.M. Rahman and S.S. Shevade, "Microchannel Thermal Management During Volumetric Heating or Cooling," Proc. First International Energy Conversion Engineering Conference, Portsmouth, Virginia, August 2003.

Establish collaborating structure

- AMES Lab, Iowa state university
- Los Alamos Magnet Lab (NHMFL)
- Analytical Instrument Facility, North Carolina State University
- Constellation technology, Co.

Future Plans

- Construct the full cycle of a miniature refrigerator by connecting two microcoolers



Part List	Number
Electromagnet	2
Air-Cooling and Dehumifying Coils	2
Heat exhanger	2
Magnetic bed	2
Pump	1
Valve	8

- Compact structure with miniaturized components such as valves and heat exchanger
- Application as a house refrigerator or refrigeration system for hydrogen liquefaction