Prototype and Simulation Model for a Magnetocaloric Refrigerator

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University of South Florida

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.
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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/SiO₂) for GdSiGe films on Si

- **Developed and tested microcooler**
  - Developed the fabrication processes 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.
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Transient response analysis of the cooler

Temperature along center of channel

<table>
<thead>
<tr>
<th>inlet</th>
<th>Z-axis (cm)</th>
<th>outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field</td>
<td>1.0 T</td>
<td></td>
</tr>
<tr>
<td>Reynolds Number</td>
<td>23.26</td>
<td></td>
</tr>
<tr>
<td>Inlet Velocity</td>
<td>337 cm/s</td>
<td></td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>-11 °C</td>
<td></td>
</tr>
<tr>
<td>Fluid</td>
<td>60% glycol + 40% water</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Gd</td>
<td></td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>COP (Typical 18 ft³ refrigerator)</th>
<th>Magnetic Refrigerator</th>
<th>Commercial Vapor Cycle Refrigerators [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N/A</td>
<td>R134a</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.29</td>
</tr>
</tbody>
</table>

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

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

Detail for the tube and fin section in the heat exchanger

Magnetic bed specifications

<table>
<thead>
<tr>
<th>L (m)</th>
<th>W (m)</th>
<th>H (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>0.95</td>
<td>0.03</td>
</tr>
<tr>
<td>0.2</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>0.22</td>
<td>0.086</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Exergetic efficiency for refrigerator components

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency [%]</th>
<th>Refrigerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser</td>
<td>27.8</td>
<td>Commercial [11]</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>12.4</td>
<td>Magnetic</td>
</tr>
<tr>
<td>Magnetic bed</td>
<td>53.19</td>
<td>Magnetic</td>
</tr>
</tbody>
</table>
Fabrication of microcooling element

250µm thick Silicon Wafer

Thermal Oxidation

TMAH Etching (100µm)

TMAH Etching (150µm)

Gold Deposition

After Diffusion

Integrated Temperature Sensor

Established fabrication process for microchannels

Fabricated microchannels on a 2” silicon wafer

Integration of microcooler element and specification

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Established cooling test equipment

- Established magnetocaloric cooling experiment
- Test the prototype microcooling system

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcooler channel size (WxHxL)</td>
<td>300um x 150um x 1inch</td>
</tr>
<tr>
<td>Channel material</td>
<td>Si (100) wafer, 250um thickness</td>
</tr>
<tr>
<td>MCE material</td>
<td>Gd₅Si₂Ge₂ (AMES Lab)</td>
</tr>
<tr>
<td>MCE block</td>
<td>2inch dia x 1/4 inch thickness</td>
</tr>
<tr>
<td>Temp sensor</td>
<td>Diffusion Au @950C</td>
</tr>
<tr>
<td>Testing temp</td>
<td>250 K ~ 280 K</td>
</tr>
<tr>
<td>Electro-Magent field</td>
<td>~1.7 Tesla (Varian V-3700)</td>
</tr>
</tbody>
</table>
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

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Cooling test with microchannel Si wafer

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

Real Wafer Testing with GdSiGe block at Initial Temp = -1

- 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.

![Image of cooling test with microchannel Si wafer](image_url)

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

Summary of publication papers
2005
2004


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

<table>
<thead>
<tr>
<th>Part List</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnet</td>
<td>2</td>
</tr>
<tr>
<td>Air-Cooling and Dehumifying Coils</td>
<td>2</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>2</td>
</tr>
<tr>
<td>Magnetic bed</td>
<td>2</td>
</tr>
<tr>
<td>Pump</td>
<td>1</td>
</tr>
<tr>
<td>Valve</td>
<td>8</td>
</tr>
</tbody>
</table>