Final Scientific/Technical Report for DOE/EERE

Project Title:	Advanced Magnetic Refrigant Materials
Covering Period:	September 1st, 2010 to June 30th, 2013
Approved Project Period:	September 1st, 2010 to June 30th, 2013
Submission Date:	September 28th, 2013
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Award Number:	DE-EE0003839
Working Partners:	George Washington University Astronautics Corporation of America
Cost-Sharing Partners:	None

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Executive summary

A team led by GE Global Research developed new magnetic refrigerant materials needed to enhance the commercialization potential of residential appliances such as refrigerators and air conditioners based on the magnetocaloric effect (a nonvapor compression cooling cycle). The new magnetic refrigerant materials have potentially better performance at lower cost than existing materials, increasing technology readiness level. The performance target of the new magnetocaloric material was to reduce the magnetic field needed to achieve 4 °C adiabatic temperature change ($\Delta T_{adiabatic}$) from 1.5 Tesla to 0.75 Tesla. Such a reduction in field minimizes the cost of the magnet assembly needed for a magnetic refrigerator. Such a reduction in magnet assembly cost is crucial to achieving commercialization of magnetic refrigerator technology.

This project was organized as an iterative alloy development effort with a parallel material modeling task being performed at George Washington University. Four families of novel magnetocaloric alloys were identified, screened, and assessed for their performance potential in a magnetic refrigeration cycle. Compositions from three of the alloy families were manufactured into regenerator components. At the beginning of the project a previously studied magnetocaloric alloy was selected for manufacturing into the first regenerator component. Each of the regenerators was tested in magnetic refrigerator prototypes at a subcontractor at at GE Appliances.

Table 1 presents a comparison of the targeted versus achieved properties for the magnetic refrigerant materials developed on this project. The property targets for operating temperature range, operating temperature control, magnetic field sensitivity, and corrosion resistance were met. The targets for adiabatic temperature change ($\Delta T_{adiabatic}$) and thermal hysteresis were not met. The high thermal hysteresis also prevented the regenerator components from displaying measurable cooling power when tested in prototype magnetic refrigerators. Magnetic refrigerant alloy compositions that were predicted to have low hysteresis were not attainable with conventional alloy processing methods. Preliminary experiments with rapid solidification methods showed a path towards attaining low hysteresis compositions should this alloy development effort be continued.

Table 1. Comparison of target versus achieved magnetic refrigerant material properties.

Property	Target (from July 2009)	Final status (June 2013)
$\Delta T_{adiabatic}$ at applied field	> 4 °C at 0.75 Tesla	2 °C at 1.5 Tesla
Magnetic field sensitivity	> 5.33 °C/Tesla	7 °C/Tesla
Thermal hysteresis	< 4 °C	6 °C
Operating temperature range	-23 °C to 40 °C	-23 °C to 77 °C
Operating temperature control	± 1 °C	± 8 °C with one step heat treatment, ± 1 °C with two step heat treatment for some compositions
Corrosion Resistance	<0.1 % mass loss/year	No observable corrosion loss after several weeks in aqueous heat transfer fluid with corrosion inhibitor

Project Activities Summary

Task 1: Project Management Plan

A project management plan was written and submitted in August of 2010.

Task 2: Develop New Magnetic Refrigerant Material

subTask 2.1 Identify Candidate Alloys

Four families of candidate alloys were identified after literature review.

subTask 2.2 Model materials and verify properties (GWU)

The research group of Prof. Larry Bennett at George Washington University completed development of a mathematical model that can analyze magnetocaloric materials that can display mixed-state behavior. This model was applied to all four alloy families screened in this Task. George Washington University also constructed an Active Magnetic Regenerative Testing system that directly measurement the adiabatic temperature change in samples under controlled temperature and magnetic field. This apparatus was used to measure magnetic refrigerant samples provided by GE.

subTask 2.3 Screen and validate alloy candidates

GE Global Research perfomed alloy screening using a high-throughput arc-melting system located in our metallurgical laboratory. Over the course of 8 screening campaigns, approximately 180 samples of 31 total compositions were produced and characterized. Magnetic and structural properties were mapped in each of the four candidate alloy families identified in Task 2.1. One composition was selected from three of the alloy families for manufacturing into regenerators for testing in a prototype magnetic refrigerator.

Task 3.0 Manufacture regenerators

Four regenerators were manufactured in the metallurgical laboratories at GE Global Research. The first regenerator was fabricated from a magnetic refrigerant compostion previously developed by GE. The last three regenerators were manufactured from compositions screened in Task 2.3. The first two regenerators were manufactured to specifications required for testing in a prototype at an external subcontractor. The last two regenerators were manufactured to specifcations required for a prototype at GE Appliances.

Task 4.0 Validate Regenerator in Prototype

Four regenerators were tested in magnetic refrigerator prototypes. The first two regenerators were tested at an external subcontractor. The last two were tested at GE Appliances. No mass loss due to corrosion was observed when the regenerators were tested in an aqueous heat transfer fluid with a corrosion inhibitor. All prototype tests were completed successfuly, however, measureable cooling was not observed in any of the regnerator tests. The cause was insufficient magnetic field availble in the prototype refrigerator needed to overcome the hysteresis of the magnetic refrigerant compositions that were used in the regenerators.

Task 5.0 Reporting

Quarterly reports were submitted for every quarter. Annual project meetings were held at the campus of George Washington University. A technical review with DOE personnel was performed on October 10th, 2012 at GE Global Research.

Publications

1. M. Ghahremani, H.M. Seyoum, H. ElBidweiy, E. Della Torre, and L. H. Bennett, “Adiabatic magnetocaloric temperature change in polycrystalline gadolinium – A new approach highlighting reversibility” AIP Advances 2, 032149 (2012).
2. M. Ghahremani, Y. Jin, L. H. Bennett, E. Della Torre, S. Gu, and H. ELBidweihy, “Design and Instrumentation of an Advanced Magnetocaloric Direct Temperature Measurement System”, IEEE Transaction on Magnetics, 48, 11, 3999 (2012).
3. Y. Jin, M. Ghahremani, S. Gu, V. Provenzano, L. H. Bennett, E. Della Torre, and H. ElBidweihy, “Characterization of the Mixed-State Clusters using Self-Similarity Phenomenon for First-Order Magnetocaloric Metamagnets”, IEEE Transaction on Magnetics, 48, 11, 3992 (2012).
4. H. M. Seyoum, M. Ghahremani, H. ElBidweihy, L. H. Bennett, and E. Della Torre, “Evidence of metastability near the Curie temperature of polycrystalline gadolinium”, Journal of Applied Physics, 112, 11, 113913 (2012).
5. M. Ghahremani, H. ElBidweihy, L. H. Bennett, E. Della Torre, M. Zou, and F. Johnson, “Implicit Measurement of the Latent Heat in a Magnetocaloric NiMnIn Heusler Alloy”, Journal of Applied Physics, 113, 17 (2013).
6. M. Ghahremani, L. H. Bennett, E. Della Torre, and M. Ovichi, “ Cooling Factor for Magnetocaloric Temperature Effect in Polycrystalline Gadolinium”, Physical Review B, (Submitted, 2013).
7. M. Ovichi, H. ElBidweihy, M. Ghahremani, L.H. Bennett, E. Della Torre, F. Jonson, and M. Zou, “Self-similar field dependent curves for a Heusler alloy ”, Physica B: Condensed Matter, (In press, 2013).
8. H. M. Seyoum, M. Ghahremani, H. ElBidweihy, L. H. Bennett, E. Della Torre, F. Johnson, and M. Zuo, “Metastability in the Magnetic Structure of Ni51Mn33.4In15.6 Heusler Alloy”, IEEE Magnetics Letters,Vol 4, 2013, 6550918.

Patents:

1. US Patent Application 13707756, “Novel magnetic refrigerant materials,” filed on December 7th, 2012
2. US Provisional Application No. 61/635,431, “DESIGN AND INSTRUMENTATION OF AN ADVANCED MAGNETOCALORIC DIRECT TEMPERATURE MEASUREMENT SYSTEM”, filed April 19,2012
3. “Bidirectional Magnetic Refrigerator”, filing date pending