Active Magnetic Regenerative Liquefier

John A. Barclay

Prometheus Energy Company

June 11, 2008

Project ID
PDP32

Overview

Timeline

- June 2008
- December 2010
- New; ~1 %

Budget

- $2.5 MM
  - DOE: $2.0 MM
  - Prometheus: $0.5 MM
- Funding FY07: $0.0 MM
- Funding FY08: $0.12 MM

Barriers

- Barriers addressed
  - High capital cost and low energy efficiency of current hydrogen liquefaction
  - Delivery cost of <$1.00/gge
  - 30 te/day: $40 MM; 75% η

Partners

- Prometheus Energy is project lead
  - Specialized vendors will be used for different components

Objectives

- To provide a validated engineering basis for an advanced H_2 liquefier technology that meets or exceeds DOE’s targets for both capital and energy efficiency.

- We intend to apply our technical knowledge of and experience with active magnetic regenerative liquefaction to sequentially analyze, design, fabricate, test and validate three experimental H_2 liquefier prototypes.

Milestones

Month/year	Milestone or GO/NO GO Decision
June 2008	Begin Project
March 2009	Test 1st stage lab prototype for ~290 K to ~190 K operation
December 2009	Test lab-prototype for ~290 K to ~20 K operation of a complete AMRL for LH2
Dec. 31, 2009	GO/NO GO decision for engineering-scale prototype of an AMRL for LH2
December 2010	Test and validate engineering-scale prototype of an AMRL for LH2
Dec. 31, 2010	Complete lab-scale and engineering-scale prototype phases of project

Plan and Approach

- Our plan is model, design, build, test and validate three prototypes; a single-stage active magnetic regenerative refrigerator (AMRR) spanning from ~290 K to ~190 K as the first stage of a six-stage AMRL for H_2; a lab-scale AMRL making LH_2; and a engineering-scale AMRL making LH_2
- Task 1 – System design and analysis of an AMRL for LH_2.
  - Establish design basis for mechanical design of prototypes.
- Task 2 – Design, build and test 1st stage AMRR prototype
  - Use existing detailed AMRR performance model code to guide design of layered magnetic regenerators for 290 K to 190 K operation
  - Design and procure all other sub-systems, e.g., s/c magnet for the AMRR prototype
  - Integrate subsystems with DAQ system and test the prototype to validate model
- Task 3 – Design, build, & test lab-scale prototype of complete AMRL for LH_2
  - Use results of task 2 to extend design of five additional AMRR stages for an AMRL
  - Fabricate and test the complete AMRL prototype for making LH_2
  - Results will provide a basis for an informed Go/No Go decision for next step
- Task 4 – Design, build & test engineering-scale prototype of AMRL for LH_2
- Task 4 – Perform reliability and durability testing of engineering prototype
- Task 5 – Project management, documentation, and reporting.

Technical Accomplishments/ Progress/Results-I

- **Updated technical data base on components for magnetic refrigeration and hydrogen liquefaction**
  - **Adiabatic temperature changes as a function of T and B_a; heat capacity as a function of T and B_a; etc.**
  - **Superconducting magnet design and availability as conduction cooled systems**
  - **Gifford McMahon and pulse tube cryocoolers for conduction cooling of s/c magnets**
  - **Status of high temperature superconducting wires for ~6 T magnets**
  - **Data from experimental tests of lab-scale magnetic regenerators with single materials and multiple materials.**

Technical Accomplishments/ Progress/Results-II

- **Updated, extended and validated numerical code for calculating the detailed performance of active magnetic regenerative refrigerators.**
  - **Complexity of coupled partial differential equations describing the time dependent performance of an active magnetic regenerative cycle required numerical solution techniques.**

1 $$\frac{\partial \rho'}{\partial t} + \frac{\partial \rho' u}{\partial x} = 0$$ **heat transfer fluid mass continuity**

2 $$\frac{\partial \rho' u}{\partial t} + \frac{\partial \left(\rho' u^2\right)}{\partial x} + \alpha \frac{\partial P}{\partial x} - \frac{f\rho(1-\varepsilon)|u|u}{d_p} = 0$$ **heat transfer fluid momentum**

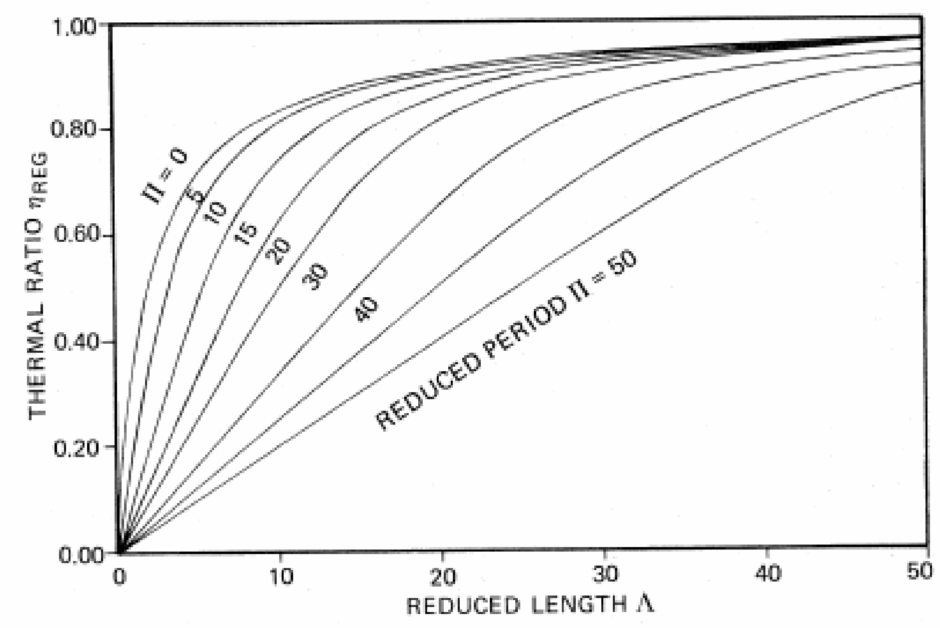
3 $$\frac{\partial \rho' U}{\partial t} + \frac{\partial \rho' u U}{\partial t} + P\frac{\partial (\varepsilon u)}{\partial x} + \frac{6(1-\varepsilon)\alpha_{fs}}{d_p}(T-\theta) + \frac{4\varepsilon\alpha_{fw}}{d_i}(T-\psi) - \frac{f\rho(1-\varepsilon)|u|u^2}{d_p} - \frac{\partial}{\partial x}\left(\lambda_f \varepsilon \nabla T\right) = 0$$

4 $$\rho'_s \frac{\partial U_s}{\partial t} - E_s - \frac{6(1-\varepsilon)}{d_p}\alpha_{fs}(T-\theta) - \frac{4(1-\varepsilon)\alpha_{sw}}{d_i}(\psi-\theta) - \nabla\cdot\left[\lambda_s(1-\varepsilon)\nabla\theta\right] = 0$$

5 $$\rho'_w \frac{\partial U_w}{\partial t} - E_w + \frac{4(1-\varepsilon)d_i}{\left(d_o{}^2 - d_i{}^2\right)}\alpha_{sw}(\psi-\theta) - \frac{4d_i\varepsilon\alpha_{fw}}{\left(d_o{}^2 - d_i{}^2\right)}(T-\psi) - \nabla\cdot\left(\lambda_w \nabla\psi\right) = 0$$

Technical Accomplishments/ Progress/Results-III

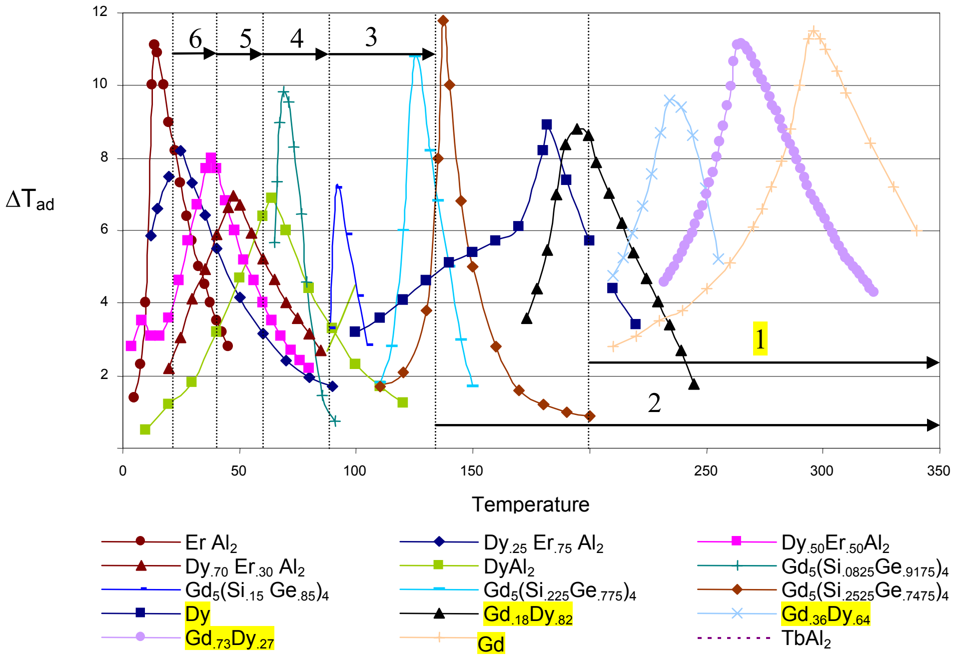
- Predictions of the AMRR code were validated by comparison with analytical pressure drop calculations (MacDonald-Ergun); by temperature profiles from energy conservation for step-change thermal wave propagation through high performance packed particle beds (Schuman); and excellent comparison to well-known passive regenerator performance curves in the literature such as by Schmidt & Willmott and by Hausen.



Technical Accomplishments/ Progress/Results-IV

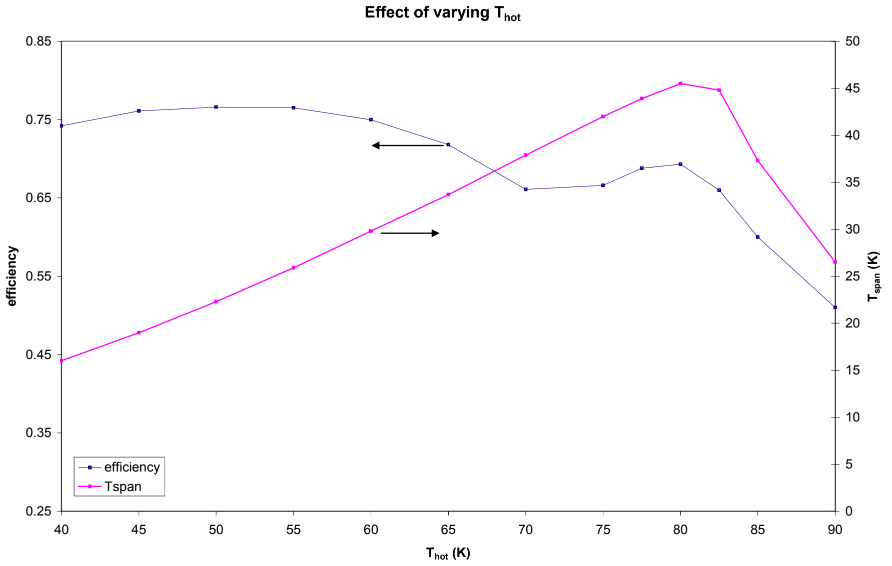
- **Wrote code to calculate magnetic and thermal properties for ferromagnetic refrigerants**
  - **Used Stoner, Debye, and Molecular Field models to obtain magnetization, heat capacity, magnetic entropy, and adiabatic temperature changes for ferromagnetic materials with 2nd order magnetic order phase transitions as a function of applied magnetic field changes and temperature. The code was validated against published experimental data.**

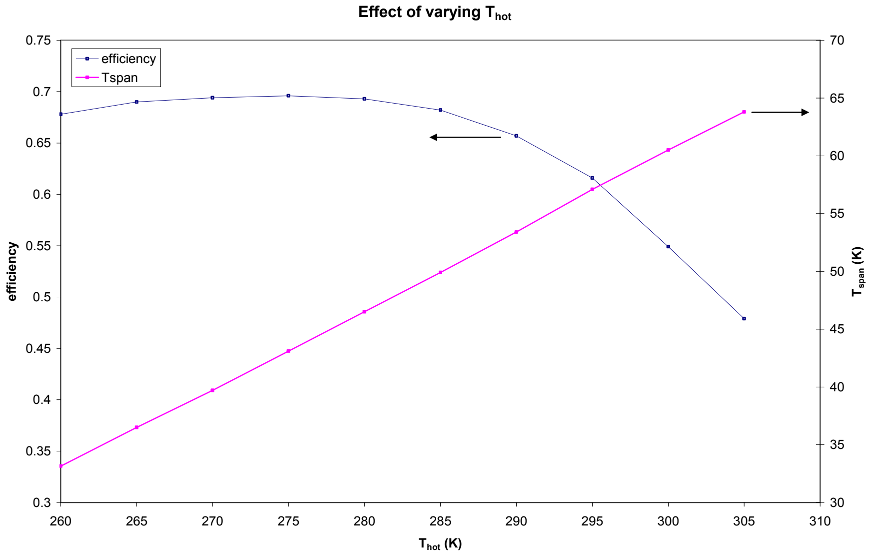
Magnetocaloric Effect at 5Tesla



Technical Accomplishments/ Progress/Results-V

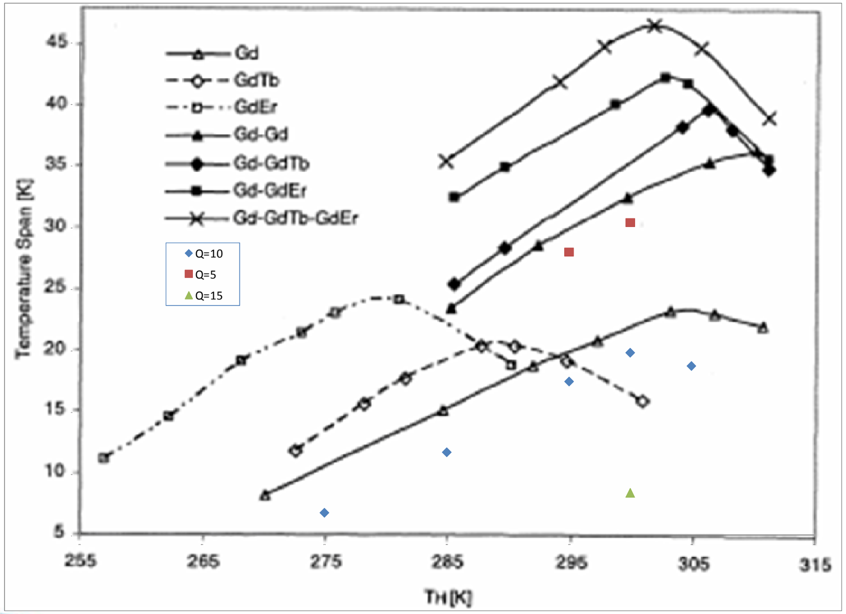
- **The AMRR performance model shows high relative thermodynamic efficiency is achievable in high specific area magnetic regenerator designs with reasonable magnetic field changes as indicated in the results below; GdNi (65 K) on left with 30 W external load; Gd (293 K) on right with 50 W external load; both with 0.5 tesla to 9 tesla field changes.**

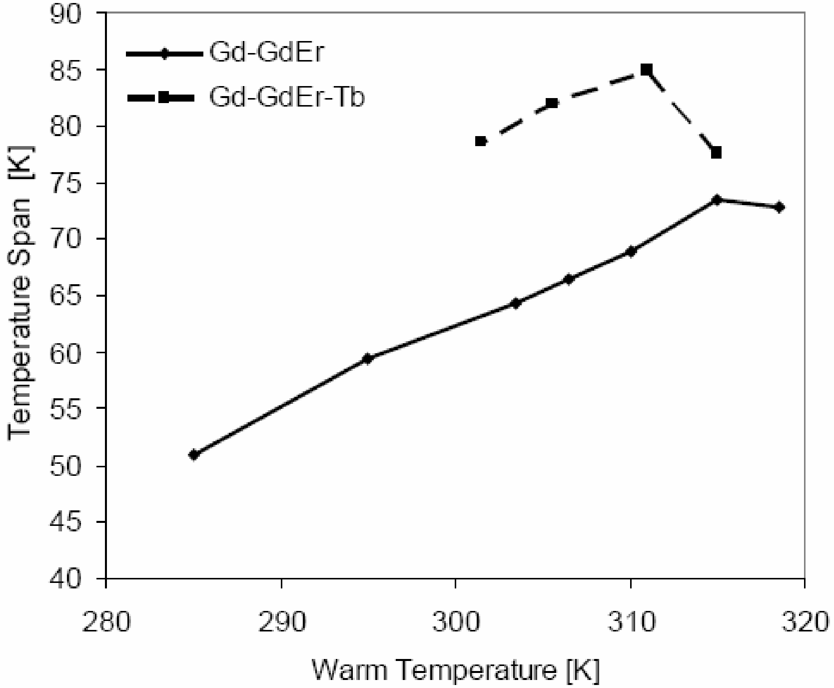




Technical Accomplishments/ Progress/Results-VI

- Performance model enables us to model AMRRs with layered refrigerants with different Curie temperatures and with and without balanced heat transfer fluid flow.
- We have been able to match the recent experimental results of Dr. Andrew Rowe's group at the U. of Victoria; both for Gd at 2 T and for Gd with Gd-GdEr-Tb at 5 T.
  - These impressive results show a no-external load temperature span of ~86 K with a 5-T magnetic field and ~1 Hz operation





Technical Accomplishments/ Progress/Results-VII

- **To prove that the model predictions are valid, we intend to build a complete prototype AMRR operating between ~290 K to ~190 K.**

Magnetic liquefier components:

The AMRL prototype is composed of many sub-systems. The major components or sub-systems are listed below:

1. Magnetic materials and their incorporation into highly effective magnetic regenerators
2. Work input drive system
    - motor and transmission to either magnet or regenerator
    - magnet carriage if it is moved or regenerator gears if it is moved
3. Heat transfer system
    - circulator
    - flow control valves
    - insulated plumbing
4. Magnet assemblies
    - superconducting magnets
    - conduction cooling with a G-M cryocooler and its associated compressor
    - power supplies, high temperature leads, persistent-mode switches
    - cold box (single-walled dewar) and structure for magnets
5. System integration, heat exchanger assemblies
    - cold box for He/H_2 heat exchangers
    - He/H_2O heat exchangers
    - He/H_2 heat exchangers with ortho-to-para hydrogen conversion
    - H_2 supply and LH_2 storage
6. Auxiliary systems
    - electrical power for the AMRL
    - vacuum pumping station and cryogenic pump for long-term operation
7. Instrumentation and control
    - temperature, pressure, magnetic field, velocity, loads, power, and flow rate gauges
    - safety monitors, process stream control, level and pump controls

- control panel, DAQ racks, PC and PC interface/software for LabVIEW DAQ station.

Technical Accomplishments/ Progress/Results-VIII

- The AMRR model with good magnetic material properties and high performance regenerator parameters enables us to design with a high degree of confidence.
- To prove that the model predictions are valid, we intend to build a complete prototype AMRR operating between ~290 K to ~190 K.
  - This is the first stage of a six-stage AMRL for hydrogen.
- We will use the performance model to guide the fabrication of dual magnetic regenerators with ~10 layered ferromagnetic refrigerants with Curie temperatures ~10 K apart over this span.
  - This type of layered regenerator is the first of its kind.
- All our modeling results to date indicate this design should give excellent thermodynamic efficiency.
  - Ability to measure performance with zero bypass to ~25 % bypass.
- This first-stage AMRL prototype also becomes an excellent test apparatus for modified designs should surprises occur.
- Validation of a detailed numerical performance simulation code is essential to design the complex thermodynamic AMRL.

Future Work

- **FY08 (June 2008 through September 2008)**
  - Design and begin to build an active magnetic regenerative refrigerator that has ~20-30 W of cooling power at ~190 K and rejects heat at ~290 K.
- **FY09 (October 2008 through September 2009)**
  - Complete assembly and tests of an active magnetic regenerative refrigerator that has ~20-30 W of cooling power at ~190 K and rejects heat at ~290 K.
  - Measure load curve as a function of cold temperature with other operating parameters fixed
  - Measure temperature span and thermodynamic efficiency as a function of operating parameters such as frequency, heat transfer fluid flow rate, applied magnetic field change, hot temperature, percentage of unbalanced flow, layering technique, and other performance measures.
  - Analyze the results and compare to model predictions to further validate numerical performance model code.
  - Use results of 1st AMRR prototype tests and validated model to design of a lab-scale prototype of a six-stage AMRL that makes ~10-15 kg/day of LH_2.
  - Fabricate the various stages of the AMRL and assemble the prototype into a complete system ready for operation and testing.
- **FY10 (October 2009 through December 2009)**
  - Complete AMRL assembly and test the complete liquefier with hydrogen.
  - Compare measured performance with predicted performance from the simulation model.
  - Review of AMRL lab-prototype results and present recommendations for an informed GO/NO GO decision for an engineering-scale prototype of an AMRL at the end of December 2009.
- **FY10 (January 2010 through September 2010)**
  - Assuming a GO decision, to design, build, and test an engineering-scale prototype of an AMRL for LH_2.
- **FY11 (October 2010 through December 2011)**
  - Complete assembly and reliability, durability testing of engineering prototype of AMRL
  - Document engineering database for larger AMRL designs.

Summary

- The Hydrogen, Fuel Cell and Infrastructure Technologies Plan clearly identifies the need for a break through in hydrogen liquefaction to reduce capital costs and increase energy efficiency.
- This new project is focused on the development of experimental prototypes of one of the few technologies identified as having the potential to deliver such an important break through.
- Members of Prometheus Energy's team have pursued advanced liquefier technology for decades and are poised to apply their extensive knowledge and experience to determine whether magnetic liquefaction can deliver on its promise.
- jbarclay@prometheus-energy.com
- Project # PDP32