III.6 Active Magnetic Regenerative Liquefier

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Objectives

This project has several well-defined objectives intended to experimentally demonstrate highly efficient hydrogen liquefiers. These include:

- Develop validated engineering design data for active magnetic regenerative liquefiers (AMRLs) for liquefied hydrogen (LH_2) (or liquefied natural gas) to meet or exceed DOE's liquefaction targets for both capital and energy efficiency.
- Analyze, design, fabricate, and test one or more liquefier prototypes to experimentally demonstrate this technology and answer numerous questions such as how to design optimized layered magnetic regenerators with bypass flow of the heat transfer fluid.
- Validate the high figure of merit (FOM) predicted by our unique numerical simulation model used to analyze and design AMRL prototypes.
- From June 2009 through May 2010 our focus has been to analyze, design, fabricate, and test our first AMRL prototype with a target of spanning from ~290 K to ~120 K with a high FOM.

Technical Barriers

This project addresses the following Delivery barrier from the Fuel Cell Technologies Multi-Year Research, Development and Demonstration Plan:

(C) High Cost and Low Energy Efficiency of Hydrogen Liquefaction

Technical Targets

Conventional hydrogen liquefiers at any scale have a maximum FOM of ~0.35 due primarily to the intrinsic difficulty of rapid, efficient compression of either hydrogen or helium working gases (depending on the liquefier design). This novel AMRL project uses regenerative magnetic refrigeration with solid working refrigerants to execute an efficient thermodynamic liquefaction cycle that avoids the use of gas compressors. Detailed modeling of the AMRL technology indicates it has promise to simultaneously lower installed capital costs/unit capacity and to increase thermodynamic efficiency from a FOM of ~0.35 toward ~0.5 to ~0.6. Results from experimental prototypes should support the design and deployment of hydrogen liquefier plants that meet the DOE 2010 hydrogen production and delivery targets:

- Delivery cost of LH_2 at <$1.00/kg;
- $40 MM capital cost for a turn-key plant with a capacity of 30 te/day; and
- Operational efficiency of a complete liquefier plant of 75% as defined by DOE and commensurate with a liquefier FOM of ~0.6.

Accomplishments

- Finished design five subsystems of a 290 K to 120 K AMRL prototype including:
  - The 7-T solenoidal superconducting magnet subsystem;
  - Cold box including the annular access tube subsystem;
  - Gifford McMahon cryocooler subsystem;
  - Cryogenic structural subsystem; and
  - Cryogenic instrumentation and LabVIEW control subsystem.
- Procured all components and completed the assembly of the five subsystems above.
- Successfully tested the five subsystems after diagnosing/fixing several vacuum leaks, sensor electronic noise, and cryocooler performance to obtain ~1.5 W of cooling at 4 K.

- Began the design of remaining three subsystems for our first AMRL prototype:
  - Wrote Mathcad programs for design of efficient active magnetic regenerators by optimizing heat transfer, pressure drop, and longitudinal thermal conduction.
  - Began to design heat transfer fluid subsystem to match requirements of the AMRL prototype and keep pressure drop low for required flow rates.
  - Analyzed force imbalance due to dual magnetic regenerators reciprocating in/out of the 7-T s/c solenoidal magnet to design the mechanical drive subsystem.
  - Used our AMRL performance simulation code to calculate the impact of the thermal mass differences due to temperature and magnetic field dependence of ferromagnetic refrigerants using controllable bypass heat transfer fluid flow rates.

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Introduction

AMRL technology promises cost-effective and efficient liquefaction of hydrogen because it eliminates the compressors, the largest source of inefficiency in Claude-cycle liquefiers. However, as with any innovative technique, many questions have to be investigated and understood before commercial applications happen. Since the mid 1970s, magnetic refrigeration technology has been investigated with increasing understanding of magnetic cycles and magnetic refrigeration prototype designs. The seminal patent on the 'active magnetic regenerator' was issued in 1982. Only in the last decade or so has there been significant engineering effort on two applications; non-chlorofluorocarbon refrigeration near room temperature using permanent magnets and cryogenic liquefiers for hydrogen and natural gas.

The AMRL project funded under this DOE contract is an extensive engineering effort to analyze, design, fabricate, and test several natural gas and hydrogen liquefier prototypes. Successful demonstration of AMRL prototypes will enable use of advanced liquefiers into various hydrogen infrastructure projects to cost-effectively provide LH_2 energy storage/delivery for gaseous hydrogen produced by electrolysis at renewable energy stations such as wind or solar. The AMRL technology readily scales up or down in capacity so it could be scaled to DOE's target of 30 te/day to a vehicular refueling station size (~2-3 te/day) where gaseous hydrogen is produced via steam methane reformation, liquefied/stored and supplied as LH_2 and/or as compressed hydrogen produced from liquid hydrogen.

Approach

During the past year our approach was to analyze, design, build, and test our first AMRL prototype that will eventually span from ~290 K to ~120 K. The experimental data will validate our numerical simulation model. It will also guide the design of the second AMRL prototype.

Results

A block process flow diagram of a complete turn-key LH_2 facility was created and is illustrated in Figure 1. The function of various modules is shown. The AMRR is combined within a cold box with a process heat exchanger to produce LH_2 from a gaseous feedstock stream. Also shown are nominal compositions, flow rates, heat/work flows, and other features of a safe operational plant.

The mechanical design of a reciprocating design of a 290 K to 120 K AMRR prototype required numerous calculations of the thermodynamics, heat transfer, fluid dynamics, structural loads, and many related items. One of the more challenging design features was the support of the 4 K superconducting magnet that has to be structurally capable of withstanding large magnetic forces between the magnetic materials in the regenerators and the magnetic field of the magnet. The large magnetic forces impact the design of mechanical drive mechanism; i.e., an AMRR cycle takes ~0.1 seconds to magnetize/demagnetize by moving the dual regenerators ~26 cm along the vertical z axis of the solenoid. The regenerators stop for dwell periods of ~0.4 seconds while the heat transfer fluid flows from hot to cold or cold to hot through the regenerators. Figure 2 illustrates the calculated magnetic forces on a single gadolinium cylindrical regenerator with ~5" outer diameter and ~5" length at 7 Tesla. The same figure includes the force reduction that is possible when two identical magnetic regenerators are balanced as much as possible. This force imbalance is several times larger than the net magnetic force required to provide the work input for the thermodynamic cycle and suggests a future rotary AMRL choice.

Figure 3 shows a two-dimensional mechanical design of the prototype that includes the superconducting magnet, the Gifford McMahon (GM) cryocooler to conduction cool the magnet and thermal shield, the elaborate support structure, and the top plate to mount the prototype in the double-walled Dewar that serves as the cold box. The center access tube through the magnet is insulated from the magnet to enable the dual regenerators to operate between ~290 K and ~120 K.

Figure 4 presents a photograph of the partially assembled AMRR prototype with the bottom heat shield

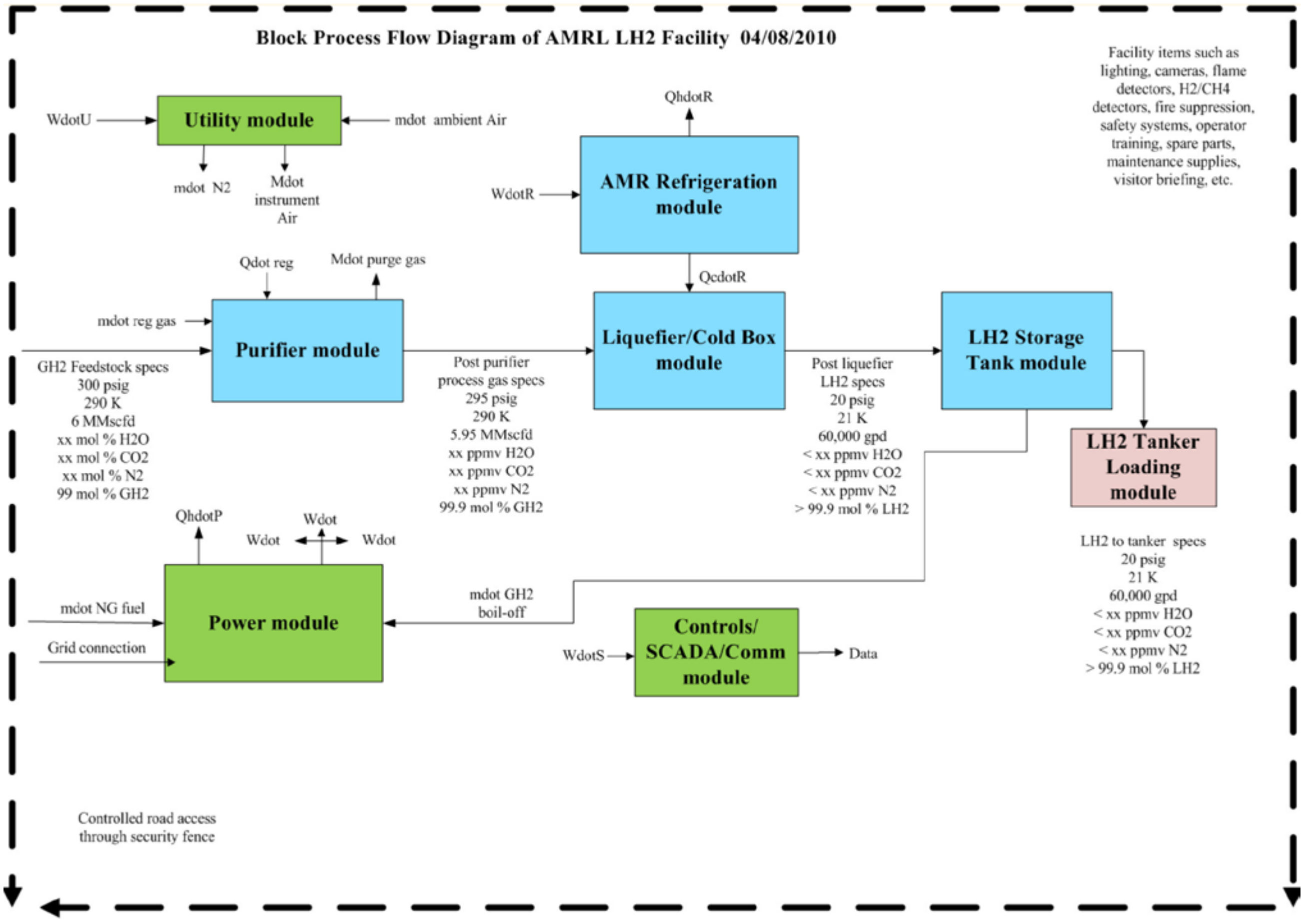

FIGURE 1. Block Process Flow Diagram of AMRL Hydrogen Liquefier Plant

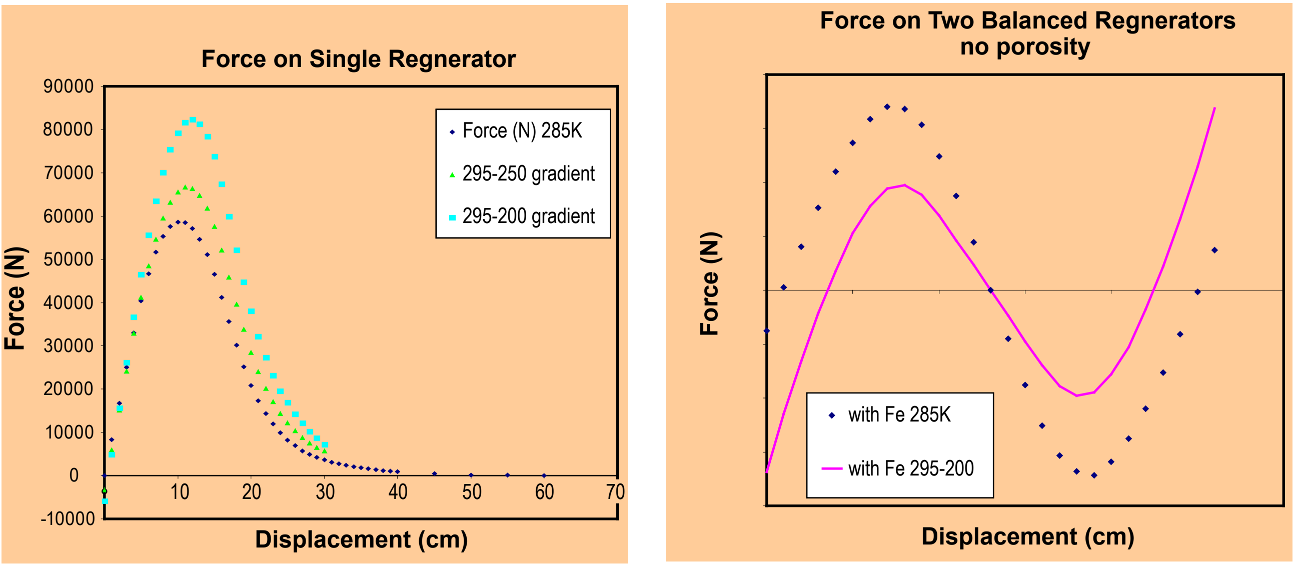

FIGURE 2. Calculation of Magnetic Forces between S/C Magnet and Magnetic Regenerators

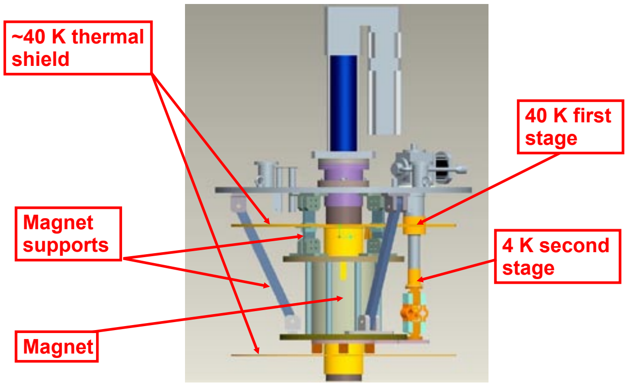

FIGURE 3. Mechanical Design of the 290 K to 120 K AMRL Prototype as Built

FIGURE 4. Photograph of the AMRL prototype just before being inserted into the cold box.

ready to be raised and attached to the ~40 K thermal shield. The prototype has been instrumented with numerous sensors and connected to a LabVIEW-based data acquisition system. The cold box was evacuated to ~1 x 10^{-7} torr for excellent thermal isolation from the surroundings. The GM cryocooler cooling power on the first and second stage was measured and found to be better than the manufacturer's specifications. The GM cryocooler successfully cooled the magnet before it was charged with a proper power supply designed for high current, low voltage and operated in persistent mode. The magnetic field profile was measured as was the adiabatic temperature change in a sample of gadolinium. Both of these measurements gave results that agree very well with calculated values.

Conclusions and Future Directions

Heracles/Prometheus is making excellent progress toward completion of its first AMRL prototype spanning a large temperature span from near room temperature to the temperature of liquefied natural gas. Five subsystems of the first lab-scale prototype have been designed, built, and successfully tested. The designs of the remaining three subsystems of the prototype are in progress; when the resultant subsystems are completed and integrated with the first five subsystems, full prototype testing will be done. The results will experimentally answer key questions regarding the best design for layers of magnetic materials in regenerators with varying amounts of bypass flow of the heat transfer fluid. We expect that ~15% of bypass flow should significantly improve the thermodynamic performance. The measurements will include the temperature span, cold thermal cooling power, hot heat rejection power, and thermodynamic efficiency (as FOM) as a function frequency, heat transfer fluid flow rate, applied magnetic field, hot temperature, bypass flow, layering technique, etc. The experimental results will be analyzed and compared to performance simulations to further validate the numerical performance model. Assuming the progress on this project is sufficient for a "GO" decision for additional funding, we expect to use results from the first AMRL prototype to design a multi-stage, ~290 K to ~20 K AMRL to make ~10-15 kg/day of LH_2. Results from the second prototype will be used to establish an engineering database for larger AMRL designs. Such a prototype will be the world's first AMRL to make LH_2. The report obligations for this project are completed when due.

FY 2010 Publications/Presentations

1. Technical seminar to U. of WA entitled "An introduction to magnetic refrigeration"; Proprietary presentation to Paul Bakke during site visit on October 27th/28th 2009.