III.17 Active Magnetic Regenerative Liquefier

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Fiscal Year (FY) 2011 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 AMRL 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 2011 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 technical delivery barrier from the Hydrogen Delivery section of the Fuel Cell Technologies Multi-Year Research, Development and Demonstration Plan, i.e.,

(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). The novel approach of this AMRL project uses solid magnetic working refrigerants cycled in and out of high magnetic fields to execute an efficient active regenerative magnetic liquefaction cycle that avoids the use of gas compressors. Numerical simulation modeling of high performance AMRL designs indicates certain achievable designs have 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 2011 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.
- Operational efficiency of a complete liquefier plant of 75% as defined by DOE and commensurate with a liquefier FOM of ~0.6.

FY 2011 Accomplishments

- Successfully completed the design, fabrication, and test of the dual Gd magnetic regenerators, two pneumatic drives, and the heat transfer fluid subsystems of our reciprocating active magnetic regenerative refrigerator (AMRR) prototype.
- Mechanically and electrically integrated all eight subsystems of our first AMRR prototype into an operational system interfaced to the LabVIEW data acquisition and control program.
- Experimentally demonstrated the first cooling curves of our AMRR and begin to measure its performance under a variety of different operational parameters such as cycle frequency, magnetic field strength, heat transfer fluid flow rate, amount of bypass flow of the heat transfer fluid while measuring work input, temperature span, cooling capability as a function of cold temperature as a function of the amount of bypass flow of the heat transfer fluid for ~290 K to ~240 K temperature span.
- Began to analyze results to compare measured performance data against our numerical process

simulation calculations of this specific reciprocating dual regenerator AMRR prototype.

- Began to incorporate lessons learned from first prototype into the design of the second AMRL prototype with a rotary configuration with the objective to span from ~290 K to ~20 K and produce LH_2 with a FOM of ~0.5.

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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 for applications above 1 K beyond research laboratory use has been investigated with increasing understanding of magnetic cycles, magnetic refrigerants from ~4 K to ~300 K, and practical magnetic refrigeration prototype designs. The seminal patent on the 'active magnetic regenerator' was issued in 1982. The principle of operation this unique refrigeration cycle is illustrated as an AMRR in Figure 1. Only in the last ~15-20 years have there been significant engineering efforts on two commercial applications of magnetic refrigeration: those with small cooling power (~100 W), non-chlorofluorocarbon refrigeration near room temperature using permanent magnets and much larger capacity cryogenic liquefiers for hydrogen and natural gas (~100s of kW of refrigeration).

The AMRL project funded under this DOE award is an extensive engineering effort to analyze, design, fabricate, and test innovative natural gas and hydrogen liquefier prototypes. Successful demonstration of AMRL prototypes will answer a few key design questions and provide a proven knowledge base to enable use of advanced liquefiers for various hydrogen infrastructure projects that cost-effectively provide LH_2 energy storage/delivery for gaseous hydrogen produced by several sources including electrolysis at intermittent wind or solar energy plants. The AMRL technology readily scales up or down in capacity so it could be scaled to reach DOE's target of 30 te/day and down to a vehicular refueling station size of ~2-3 te/day where gaseous hydrogen continuously produced via steam methane reformation, or high temperature fuel cells, or electrolysis could be liquefied, stored and supplied as LH_2 and/or compressed hydrogen produced from liquid hydrogen (LCH_2).

Approach

During the past year our focus has been to complete the design, fabrication, integration and testing of our first AMRR prototype with the objective of spanning from ~290 K to ~120 K with multi-layer regenerators and bypass flow of the heat transfer fluid. We have demonstrated the initial results toward this objective. The experimental results will validate our numerical simulation mode and guide the design of the AMRL prototype spanning from ~290 K to ~20 K.

Results

The completed three-dimensional mechanical design of the first laboratory-scale AMRR prototype with dual regenerators reciprocating in and out of a 7 Tesla (T), large bore superconducting magnet is illustrated in Figure 2. It includes the various components of the eight subsystems required to execute the AMRR cycle. This prototype is designed to operate between ~290 K at the hot end and cold end temperatures down to as low as ~120 K. The design 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 dual regenerators and the magnetic field of the magnet. 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.

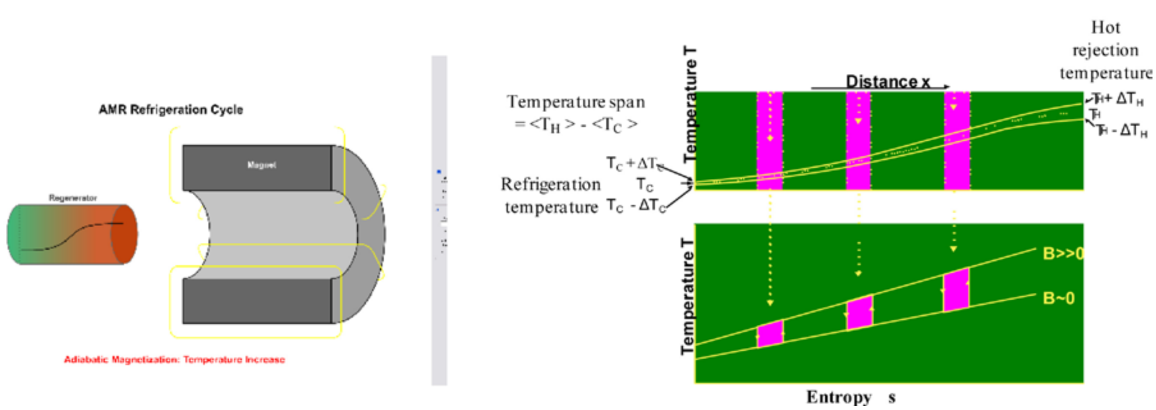

FIGURE 1. Active Magnetic Regenerative Liquefier

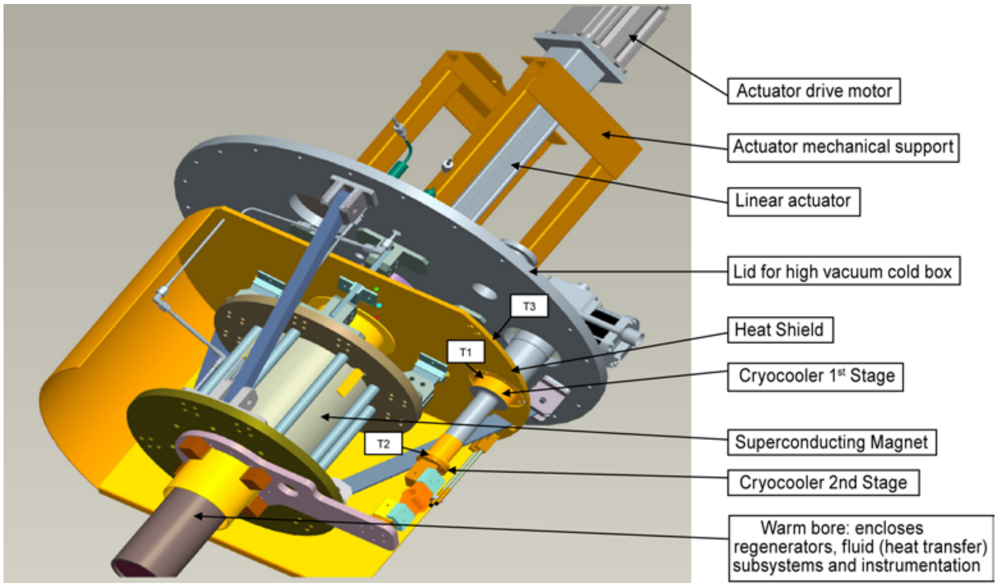

FIGURE 2. Reciprocating AMRR Prototype Design

The dual magnetic regenerators must be strong enough to react large magnetic forces and simultaneously be integrated with the pneumatically actuated mechanical drive mechanism and the helium heat transfer fluid subsystem pressurized to ~250 psia. The heat transfer fluid couples the heating and cooling of the magnetic regenerators to the hot heat sink and the cold heat exchanger between the dual regenerators. Figure 3 illustrates the resultant design of the two identical magnetic regenerators and the heat transfer fluid piping including the path for controlled bypass flow of the cold helium heat transfer fluid. Numerous sensors to measure temperature, helium flow rates, magnetic field strength, etc. are also integrated into these subsystems during the fabrication steps. All these sensors had to have vacuum-tight seals to insure that the high pressure helium did not leak into the high vacuum within the cold box during the AMRR operation. These sensors had to operate at high enough frequency to provide time resolution throughout the entire AMRR cycle. They were connected through high speed modules of a Compact-DAQ LabVIEW control and data acquisition computer.

Figure 4 presents the drive motions as a function of time from the pneumatically-actuated reciprocating drive of the dual magnetic regenerators and the drive motion of the pneumatically actuated positive displacement pump moving the heat transfer fluid as desired. Note that the two reciprocating motions are trapezoidal in time and out of phase with one another as required to properly execute the AMRR cycle.

Figure 5 illustrates a simplified piping and instrumentation diagram (P&ID) for the heat transfer fluid subsystem. It can be used to understand the relatively complex reciprocating flows of the heat transfer fluid during the AMRR operation. Figure 6 shows a photograph of the

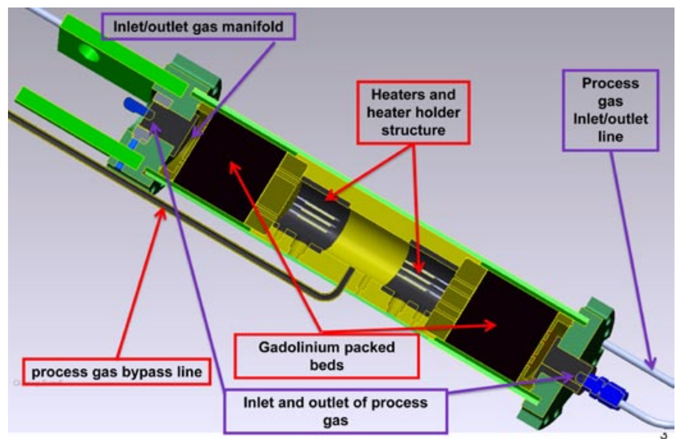

FIGURE 3. Dual Magnetic Regenerator Design Integrates Numerous Subsystems

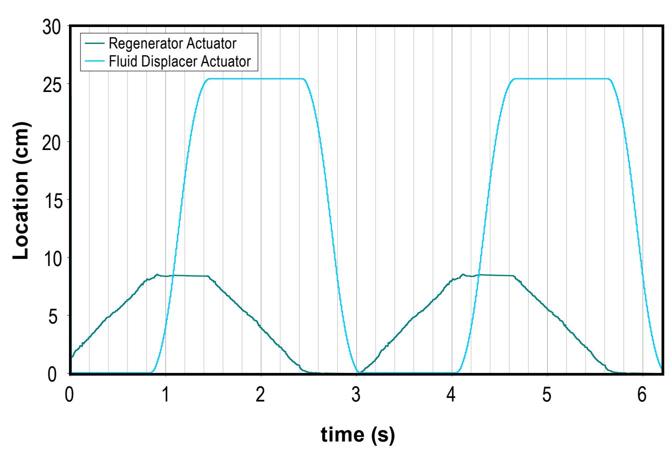

FIGURE 4. The Heat Transfer Fluid Flow and Regenerator Drive Motions for the AMRR Cycle

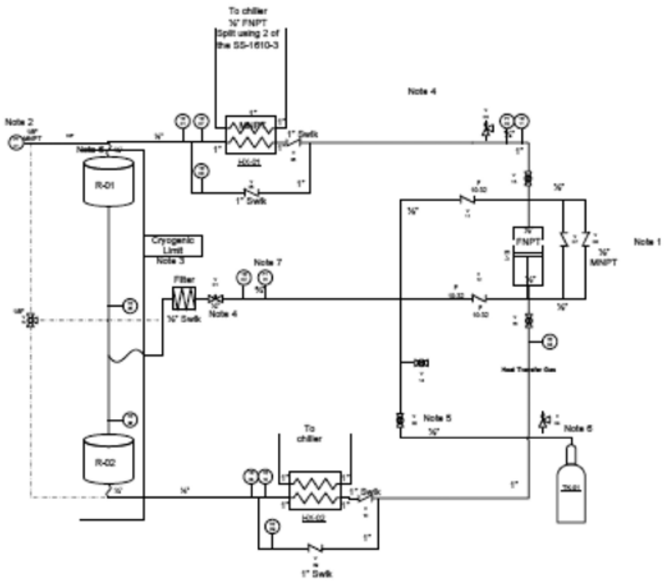

FIGURE 5. The Heat Transfer Fluid Subsystem is Illustrated on this Simplified P&ID

FIGURE 6. Heat Transfer Fluid Subsystem Components

heat transfer fluid subsystem components including the brazed plate frame, counter-flow heat exchangers to couple the hot helium heat transfer fluid to the cold refrigerant from the vapor compression cycle chiller used to ensure a stable hot temperature of the heat transfer fluid during an experimental run of the AMRR. The chiller is located in the center of this photograph.

The initial cooling results from our first AMRR prototype were obtained on May 10, 2011 shortly before the poster was presented at the Annual Merit Review. The test results were not available for this report.

Conclusions and Future Directions

Heracles/Prometheus has made excellent progress and completed the design, fabrication, assembly and initial demonstration of cooling in its first AMRR prototype. All subsystems of the first lab-scale prototype were designed, built, and successfully tested. The initial measurements with the LabVIEW data acquisition program include the temperature span, cold cooling power, hot heat rejection temperature, operating frequency, total heat transfer fluid flow rate, bypass flow, applied magnetic field, etc. The recently obtained initial results spanning from ~292 K to ~240 K are very encouraging but have yet to be analyzed. The operational AMRR prototype enables us to experimentally answer key questions such as the best recipe for multiple layers of different magnetic refrigerants in one or more integrated regenerators with varying amounts of bypass flow of the heat transfer fluid. Our performance simulation model predicts that ~10-15 % of bypass flow should significantly improve the thermodynamic performance but the proof is in the pudding, i.e., measured results from an operational AMRR prototype. To our knowledge, these results will be the first such results for cryogenic liquefiers. We expect to use new insights and knowledge from the experimental results from the first AMRR prototype to validate our performance simulation code, and use that model to guide the design a rotary-type multi-stage AMRL prototype. This larger AMRL prototype should be capable of spanning from ~290 K to ~20 K to make ~25 kg/day of LH_2. This will be the world's first AMRL to make LH_2. The technical and financial report obligations for this project are completed when due.

FY 2011 Publications/Presentations

1. Poster of the project for the AMR in May, 2011.
2. Several papers are being planned based on the impressive test results of our first AMRR prototype using Gd spheres.