III.10 Active Magnetic Regenerative Liquefier

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Objectives

This project has several well-defined objectives selected to experimentally prove highly efficient hydrogen liquefiers. The objectives include:

- To collect/create a validated engineering basis for an advanced H_2 liquefier technology that meets or exceeds DOE's targets for both capital and energy efficiency.
  - Identify areas where more applied research is needed.
  - Examples – fabrication techniques for high performance regenerators; different configurations of superconducting magnets; and others.
- To apply our technical knowledge of and experience with active magnetic regenerative liquefaction to sequentially analyze, design, fabricate, and test experimental liquefier prototypes to validate performance simulation model used to design active magnetic regenerative liquefiers (AMRLs).
  - Especially applicable to liquefied hydrogen (LH_2), but also to other cryogens.
- From July 2008 through May 2009, our aim has been:
  - To collect AMRL design literature and create the design basis for the first lab-scale AMRL prototype; and
  - To analyze, design, fabricate, and test an AMRL prototype operating from ~290 K to ~120 K with a figure of merit (FOM) >0.5.

Technical Barriers

This project addresses the following technical barriers from the Delivery section of the Hydrogen, Fuel Cells and Infrastructure Technologies Multi-Year Research, Development and Demonstration Plan:

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

Technical Targets

This project is developing advanced liquefier technology that offers simultaneously lower capital costs and higher thermodynamic efficiency than existing technology. Insights gained from experimental prototypes will be applied toward the design and deployment of hydrogen liquefier facilities that meet the following DOE 2010 hydrogen production and delivery targets:

- Delivery cost of <$1.00/gge;
- $40 MM capital cost for a liquefier with a capacity of 30 tonnes per day (TPD); and
- Operational efficiency of liquefier as defined by DOE of 75%.

Accomplishments

- Created a detailed design basis for 290 K to 120 K lab-scale AMRL prototype including:
  - Solenoidal superconducting magnet subsystem:
    - NbTi multifilament wire; potted; 4 K operation; persistent mode switch.
    - Conduction cooling to 4 K via Gifford McMahon cryocooler; diode quench protection.
    - Low thermal conduction/high electrical conduction leads.
  - Reciprocating drive of dual magnetic regenerators subsystem.
  - Magnetic regenerator subsystem:
    - Rare earth alloys for refrigerants; layered materials per model.
    - Matched regenerator design; aspect ratio 1-2; 10,000 m^2/m^3.

    - Low pressure drop; low longitudinal thermal conductivity.
  - Regenerator heat transfer fluid subsystem:
    - Pressurized He gas; closed-loop circulator with reversing switch for reciprocating flow; bypass flow controls.
    - Anchored at 290 K at input to hot end of regenerators.
  - External process stream:
    - Anchored at 290 K at heat sink; controllable flow.
  - Cold box and structural subsystem:
    - Double walled dewar; G-10 structural braces; high vacuum experimental space.
  - Instrumentation and control subsystem:
    - LabVIEW-based data acquisition system (DAS) and control.
    - Full set of temperature, pressure, mass flow, work rate, thermal loads, magnetic field sensor.
- Used the following principles to conceptually design an initial AMRL lab prototype with high FOM:
  - Use an inherently efficient thermodynamic cycle, i.e., the AMR cycle.
  - Use an efficient work input mechanism for magnetic forces.
  - Use an efficient work recovery mechanism, i.e. balanced dual regenerators.
  - Ensure small temperature approaches for all heat transfer between heat transfer and process streams by use of multiple stages.
  - Chose small dimensions of magnetic refrigerants in regenerative heat exchanger geometries to achieve high specific area.
  - Keep pressure drops for heat transfer fluid flow low with many parallel flow channels.
  - Ensure low longitudinal thermal conduction mechanisms by proper material and geometry choices.
  - Minimize frictional and parasitic heat leak mechanisms.
  - For hydrogen, perform ortho-to-para conversion at the highest possible temperature during cooling in process heat exchangers.
- Used well-defined irreversible entropy mechanisms of heat transfer, pressure drop, and longitudinal thermal conduction for high performance passive regenerators to design our active regenerators:
  - New results from AMRL performance simulation modeling show two additional intrinsic irreversible entropy mechanisms must be included:
    - Thermal mass differences during AMRL cycle due to the temperature and magnetic field dependence of the magnetic refrigerants.
    - Unbalanced heat transfer fluid flow requires bypass flow return.
  - Two additional key objectives of 290 K to 120 K prototype tests are:
    - To characterize the performance of an AMRL as a function of thermal mass imbalance; and
    - To characterize the amount of bypass of the heat transfer fluid.
- The status of 290 K to 120 K AMRL lab-scale prototype is:
  - Detailed design and fabrication of magnetic regenerators are preceding well; magnetic materials are selected and raw materials ordered.
  - Superconducting magnet subsystem design is progressing well; the magnet, high temperature superconductor (HTSC) leads, persistent mode switch, diode protection, power supply and sensors are ordered.
  - Conduction cooling subsystem including cold box and Gifford McMahon cryo-cooler are already in our laboratory facilities.
    - High vacuum pump and related equipment in place for AMRL operational space.
    - Structural support members integrated with shield cooling analysis and design is substantially completed.
  - Both the heat transfer fluid and process fluid flow subsystems are in design.
  - Drive subsystem is in design.
  - The piping and instrumentation diagram is being created as the instrumentation and controls choices are made.
  - The LabVIEW DAS in our lab is being upgraded for high speed measurements.

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Introduction

The primary objective of this project is to provide a validated engineering basis for the AMRL technology by analyzing, designing, fabricating, testing, and validating up to three experimental hydrogen liquefier prototypes. Prometheus Energy has extensive technical experience and unique knowledge of magnetic refrigeration technology that it is using to execute this project.

Successful demonstration of this promising technology will provide a strong incentive for integration of this type of liquefier into various hydrogen infrastructure projects such as creating thermal capacitance for hydrogen produced by electrolysis at intermittent renewable or off-peak electricity plants. It could also be easily scaled to a vehicular refueling station size where the hydrogen is produced via steam methane reformation and supplied as LH_2 and/or compressed hydrogen produced from liquid hydrogen.

Approach

We plan to model, design, build, test, and validate fully instrumented systems. The first prototype under development during the first year of this project is a single-stage active magnetic regenerative liquefier spanning from ~290 K to ~120 K.

Results

We have done extensive performance modeling with a proprietary numerical simulation code for an AMRL. An example of results of these calculations is illustrated in Figure 1. These results with a 6.4 tesla (T) magnetic field change and a heat rejection temperature of 290 K show the temperature span of a particular AMRL with two layers of magnetic refrigerants. The upper (hottest) refrigerant in the regenerator is Gd metal and the second is a homogeneous alloy of Gd with Dy whose Curie temperature was varied by choice of composition. These results show that the temperature span peaks when the Curie temperature of the second magnetic refrigerant is ~250 K. The relative efficiency is also illustrated in Figure 1; it also shows a broad maximum in efficiency near the same Curie temperature. Similar modeling for the AMRL predicts that with reasonable design choices it is possible to achieve relative thermodynamic efficiency for the first stage AMRL of ~70-80% of ideal. This is an important requirement for achieving the high FOM of a hydrogen liquefier.

In addition to modeling the effects of layering of magnetic refrigerants in the magnetic regenerators, the effects of bypass flow of the heat transfer fluid on the performance of the magnetic liquefier stage has been predicted. These analyses are summarized in Figure 2 that illustrates the concept and the substantial predicted improvements in performance due to bypass flow. This is the expected result because the bypass flow is returned to the hot end of the regenerator in counterflow with the process stream. The resultant reduction in temperature approach in the cold heat exchanger significantly reduces the irreversible entropy produced by cooling the process stream. This design feature is unique to AMRLs and is a very important means to improve the FOM of a hydrogen liquefier.

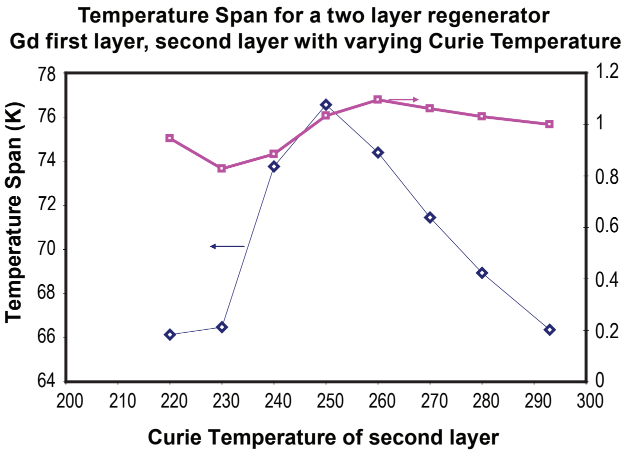

FIGURE 1. Calculation of the Influence of Curie Temperature on Performance of an AMRL Regenerator with T_{hot} = 290 K and ΔB_a = 6.4 T

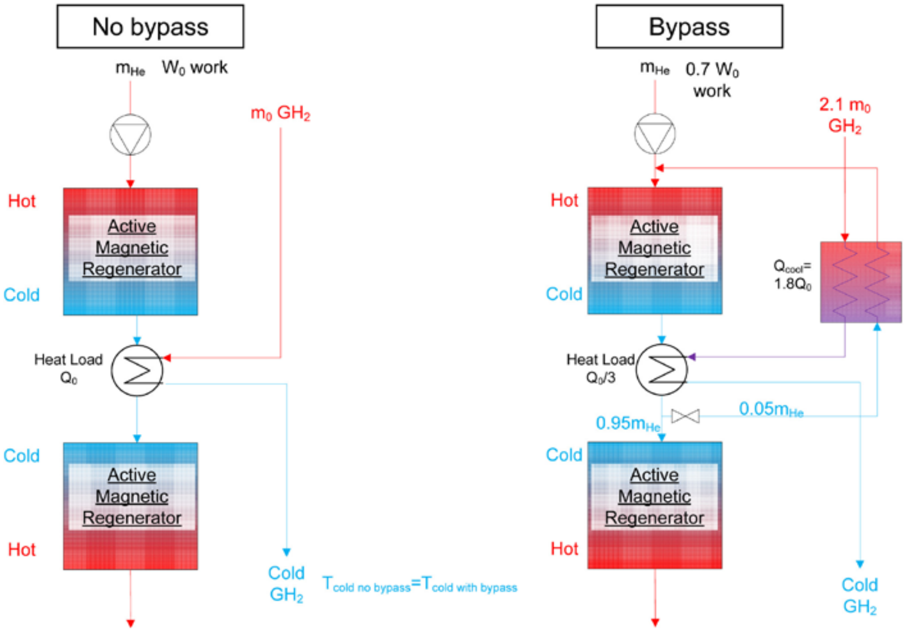

FIGURE 2. Calculation of Influence of Bypass Flow of Heat Transfer Fluid on AMRL Performance

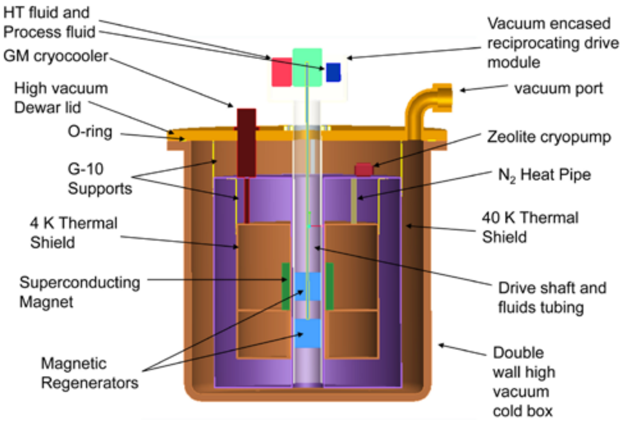

FIGURE 3. Schematic Diagram of the 290 K to 120 K AMRL Lab-Scale Prototype

FIGURE 4. The AMRL cold box on the left is a double-walled Dewar. The cryocooler on the right is a proven two-stage Gifford McMahon model used for conduction cooling of the magnet and thermal shield.

The mechanical design of the 290 K to 120 K lab prototype is being done based on the performance predictions from the numerical AMRL simulation code. The initial design of the prototype based on the design basis completed after the numerical modeling was completed. Figure 3 schematically illustrates a cross-section of the AMRL prototype with the arrangement of the various components of the AMRL. These include the superconducting magnet, the Gifford McMahon cycle cryocooler for conduction cooling of the magnet and thermal shield, the dual magnetic regenerators, the heat transfer fluid circulator, the process stream, the drive, the support structure, and the double-walled dewar that serves as the cold box. The actual cold box (dewar) and the two-stage Gifford McMahon cryocooler cold head in our lab are shown in Figure 4. This prototype will be an excellent test device to understand the new features of the design of a magnetic regenerator with both layering and bypass.

Conclusions and Future Directions

Heracles/Prometheus is developing the first AMRL prototype spanning this large temperature span in the world. The first lab-scale prototype is being designed to operate between ~290 K and ~120 K. It 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. It will allow measurement of the temperature span and thermodynamic efficiency (FOM) as a function of operating parameters such as frequency, heat transfer fluid flow rate, applied magnetic field change, hot temperature, percentage of bypass flow, layering technique, and other performance measures. The experimental results will be analyzed and compared to performance simulations to further validate the numerical performance model.

Future directions of this project include using the results of the first AMRL prototype tests and validated model to design the lab-scale prototype of a multi-stage AMRL to make ~10-15 kg/day of LH_2. The prototype spanning from ~290 K to ~20 K will be tested. It will be the first AMRL to make liquid hydrogen. We anticipate this prototype will be in testing and analysis before September 30, 2010. These results will be used to establish an engineering database for larger AMRL designs. The report obligations for this project will be completed as they become due.