

IV.D.9 Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

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Contract Number: DE-FC36-09GO19005

Project Start Date: February 1, 2009

Project End Date: June 30, 2014

Fiscal Year (FY) 2012 Objectives

Use microchannel processing techniques to:

- Demonstrate reduction in size and weight of hydrogen storage systems.
- Improve charge/and discharge rates of hydrogen storage systems.
- Reduce size and weight and increase performance of thermal balance of plant components.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section (3.3.4) of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

- (A) System Weight and Volume
- (E) Charging/Discharging Rates
- (H) Balance of Plant (BOP) Components

Technical Targets

The Phase II technical targets and Go/No-Go criteria for the Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage project are:

- Ability to develop and demonstrate a Modular Adsorption Tank Insert (MATI) designed for a system consisting of 100% densified media and capable of allowing less than 3 min. refueling time and H₂ release rate of 0.02 g H₂/(sec. kW) with a mass less than 9.4 kg and a volume less than 4.2 liters. (Barriers A and E)
- Ability to develop and demonstrate a 1-kW catalytic combustor to augment partial hydrogen preconditioning by an existing fuel cell radiator with >90% efficiency having a mass less than 0.5 kg and volume less than 0.5 liters. (Barrier H)

FY 2012 Accomplishments

Key developments and technical accomplishments for the reporting period are:

- Developed a technology development road map for the MATI (Barriers A and E).
- Initiated separate effects and integrated testing of the MATI (Barriers A and E).
- Completed modeling to support the development of conduction enhancements for adsorbing media (Barriers A and E).
- Validated Aluminum as a material of construction for the MATI (Barriers A and E).
- Completed a design and production cost estimate for the MATI (Barriers A and E).
- Completed system design for a microchannel combustor/heat exchanger to provide hydrogen preheating in an adsorption hydrogen storage system (Barrier H).



Introduction

Hydrogen storage involves coupled heat and mass transfer processes that are significantly impacted by size, weight, cost, and performance of system components. Micro-technology devices that contain channels of 10-500 microns in characteristic length offer substantial heat and mass transfer enhancements by greatly increasing the surface-to-volume ratio and by reducing the distance that heat or molecules must traverse. These enhancements often

result in a reduction in the size of energy and chemical systems by a factor of 5-10 over conventional designs, while attaining substantially higher heat and mass transfer efficiency. In cooperation with the DOE Hydrogen Storage Engineering Center of Excellence, the OSU Microproducts Breakthrough Institute and groups at the Pacific Northwest National Laboratory, Savannah River National Laboratory, and Los Alamos National Laboratory, we are developing:

- 1) advanced tank inserts for enhanced heat and mass transfer during charge and discharge of adsorbent hydrogen storage systems; and
- 2) microchannel-based thermal balance of plant components such as combustors, heat exchangers, and chemical reactors.

Approach

To meet the Phase II goals, our technical approach is to reduce the relevant barriers to heat and mass transfer within each high-priority hydrogen storage component using microchannel technology. Our specific approach involves:

- 1) The optimization of the performance of a single unit cell (i.e., an individual microchannel) and then “Number Up” using appropriate simulation tools that we then validate by experimental investigation; and
- 2) Develop microlamination methods as a path to “numbering up” by low-cost high-volume manufacturing. We are applying this approach to both the MATI and the microcombustor applied to hydrogen preheating.

Results

We identified two high-value applications of microchannel technology. The first is the development of a MATI for cooling during charging, heating during discharging, and hydrogen distribution. This system will be applying the modular tank insert to cryogenic adsorption hydrogen storage. The second application is the development of an integrated microchannel combustor and heat exchanger that can be used for preheating hydrogen going to the fuel cell to facilitate cold starts and aggressive driving conditions. Results relative to these two applications are summarized in the following.

MATI – A tank insert that integrates storage media, microchannel heat exchangers, and microchannel hydrogen distribution plates allows convenient use of densified adsorption media with in-excess-of 94% of the tank volume being densified media. The concept separates the cooling process from the charging process, allowing flexibility in cooling strategies, and the MATI can provide heating during discharge, avoiding the need to use electric energy for discharge heating. A schematic of a single cell is presented in Figure 1. The full-sized MATI would consist of a number of cells along with headers for cooling fluid and hydrogen distribution. Progress to date on the development of the microchannel-based tank insert includes:

- MATI Technology Development Road Map—The technology development road map included two phases. The first phase involved modifying the hydrogen distribution plates to introduce the stored hydrogen (at 20 to 40°C) at the highest temperature region of the MATI, maximizing cooling impact. The second phase involved, after having identified aluminum as the material of construction, applying aluminum fins in the densified media to enhance conductivity. The second phase involves applying aluminum fins in the densified media to enhance conductivity and using aluminum as the material of construction. The impact of the two phases on weight is summarized in Figure 2.
- Initiated separate effects and integrated testing—Cryogenic test apparatus have been assembled for experimental investigations of charging and discharging a MATI. The separate effects tests focus on testing individual phenomena such as convective heat transfer coefficient and pressure drop during both single-phase and phase-change cooling. Integrated testing involves experimental investigations of the complete charging and discharge cycles including hydrogen distribution and adsorption and the removal of the heat of adsorption using liquid nitrogen. Both the separate effects and integrated test apparatus have been assembled and are now being used to conduct preliminary experimental investigations (Figure 3). Testing will be completed by 6/30/2013.
- Completed modeling to support the development of conduction enhancements for adsorbing media—Simulation models have been developed to model all relevant phenomena associated with the charging

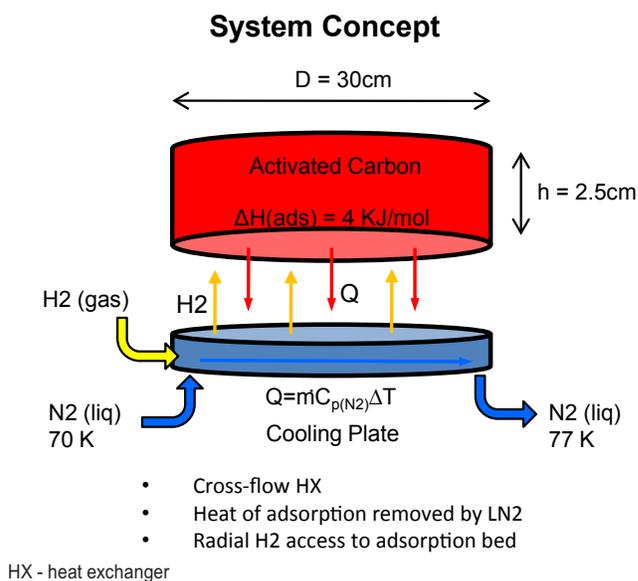
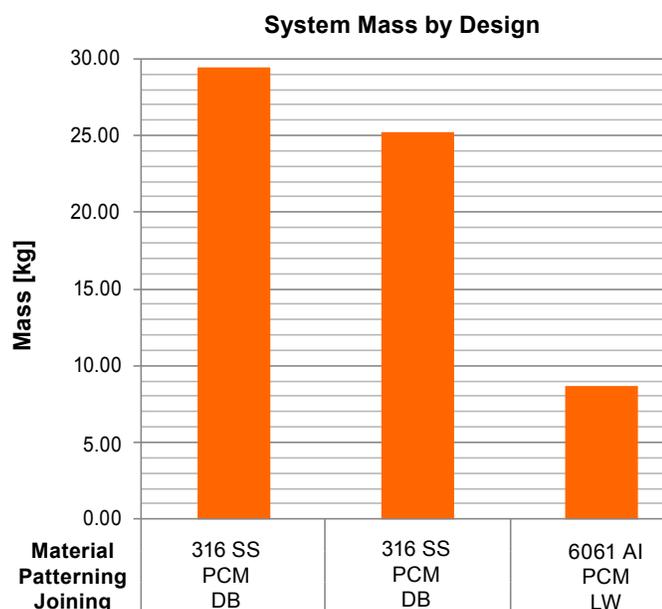


FIGURE 1. MATI Concept

**Development Plan**

Phase 1 – S.S. MATI with combined cooling and H₂ distribution plates produced using photochemical machining (PCM) and diffusion bonding (DB)

Phase 2 – S.S. S.S. with separate cooling and H₂ distribution plates produced using PCM and DB

Phase 3 – Al with separate cooling and H₂ plates and enhanced media conductivity produced using PCM and laser welding (LW)

FIGURE 2. Predicted MATI system weight for the three development phases

and discharging of the MATI. Where possible, these models have been validated against published data. As experimental data becomes available for the MATI, they will be validated against our experimental results. A two-dimensional version of the model has been used to evaluate the required conductivity enhancement of the adsorbent bed, so that we can use a 5-cm spacing between cooling plates. The modeling results show that the average bed conductivity needs to be increased to 3.0 W/mK and that this can be accomplished with the use of embedded aluminum fins in the adsorbing media.

- Validated aluminum as a material of construction for the MATI—We are currently using stainless steel as the assumed material for fabricating the MATI. Stainless steel has been widely used for microlaminated devices and is well understood. However aluminum is significantly lighter and less expensive than stainless steel. Consequently, we have investigated the feasibility of using aluminum as the substrate material for microlamination. Results show that aluminum can be successfully used as a material of construction for microlaminated devices. Both patterning and bonding have been demonstrated.
- MATI Fabrication, Weight, and Cost Analysis—A design of a full-scale MATI has been completed and a fabrication strategy identified. These have formed the

basis for a system weight and volume estimate and a bottoms-up cost estimate. The results of the cost estimate are presented in Figure 4.

Integrated Microscale Combustor/Heat Exchanger

(μ CHX)—The μ CHX (Figure 4) will be used to safely and efficiently preheat hydrogen discharged from the adsorption hydrogen storage system before it enters the fuel cell. In cold conditions, the fuel cell produces insufficient heat to heat the hydrogen to the required inlet temperature for the fuel cell. In these cases a small fraction of the hydrogen will be combusted to preheat the balance of the hydrogen to a temperature appropriate for fuel cell operation. Combining the combustion and heat exchanger systems and using microchannels for enhanced heat and mass transfer can drastically reduce the size and weight required for this function, while simultaneously increasing efficiency. In addition, a substantial safety benefit of a microscale combustor is that flames cannot be sustained in the sub-millimeter microchannels. During the previous reporting period we documented the results of our system design, weight, and cost estimate that showed that the μ CHX System would be perhaps 1/10 the size of the best alternative design with the same heating load, a system efficiency of 92%, and production cost on the order of \$120 per unit for an annual production rate of 500,000 units. During the current reporting period we:

- Completed Unit Cell Experimental Validation of μ CHX Performance and Weight Estimates—We completed a wide range of tests of a single unit cell. The results showed an efficiency of 92% and that 130-140 W of thermal energy was being transferred to the metal hydride heat transfer oil, which is consistent with our size and weight estimates reported above.
- Completed Design of the μ CHX for Adsorption System Hydrogen Preheating—We have modified the design of the μ CHX for the hydrogen preheating application. The significant changes are in heating load (0.5 kW) and application (heating hydrogen initially at cryogenic temperatures). The key design issue was to avoid freezing of the products of combustion (water) in the recuperation section of the device. The new design is slightly less efficient (90%) and much smaller than the oil heating application described above.

Conclusions and Future Directions

Key conclusions resulting from our research include:

- The use of the modular adsorption tank insert allows convenient use of densified adsorption media with in excess of 94% of the tank volume being densified media. The concept separates the cooling process from the charging process, allowing flexibility in cooling

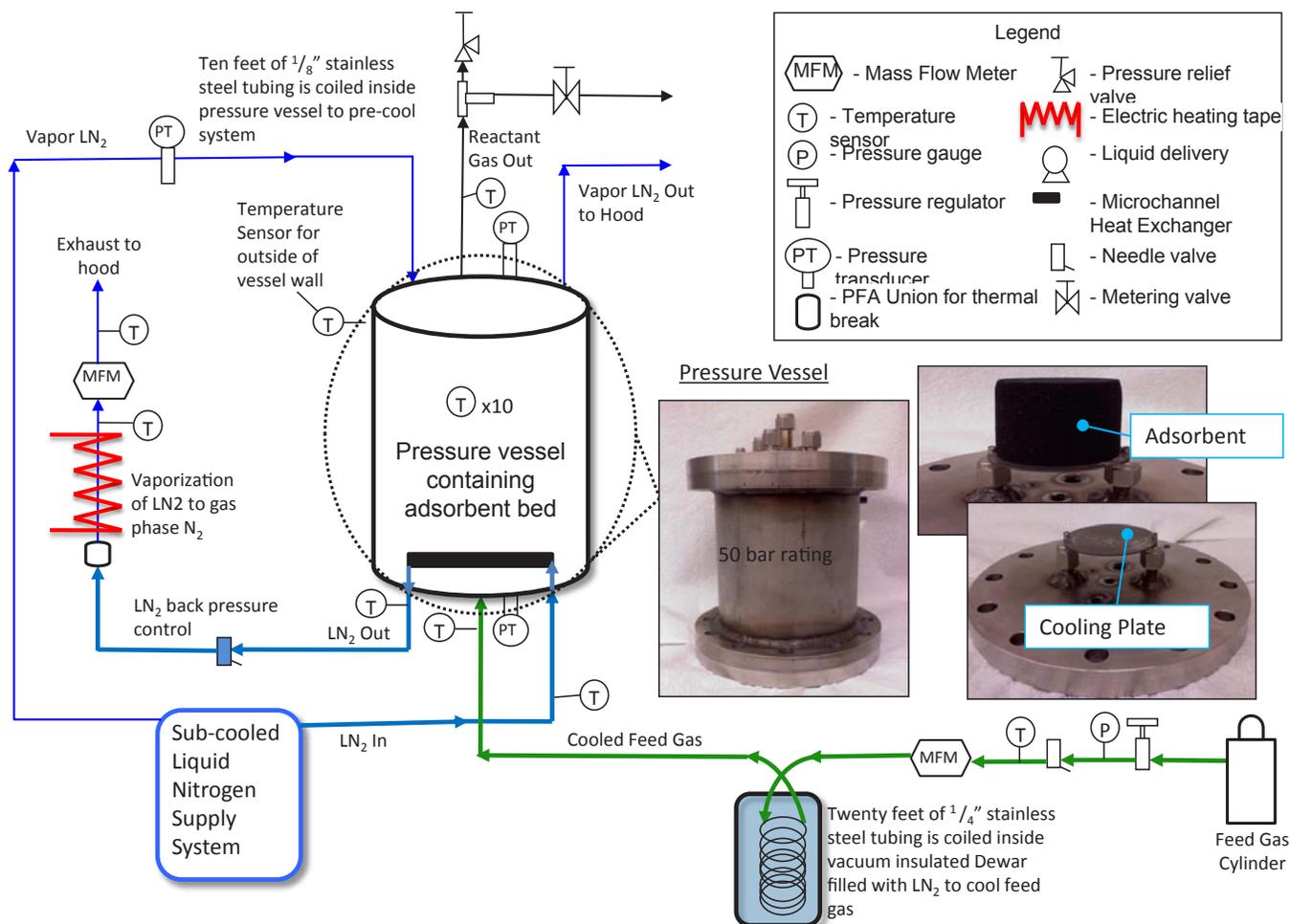


FIGURE 3. Integrated Test Apparatus

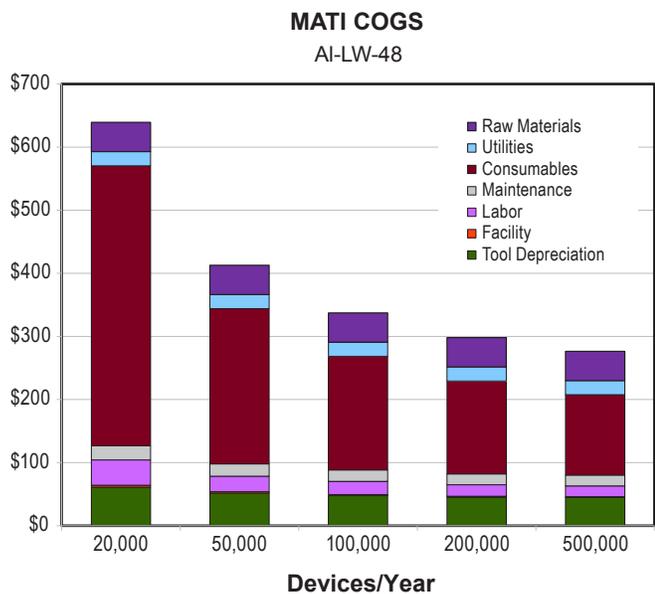


FIGURE 4. Cost of goods sold (COGS) of the MATI as a function of production volume

strategies, and the MATI can provide both cooling during charging and heating during discharge with a weight under 9.5 kg for a hydrogen storage system containing 5.6 kg of hydrogen.

- The μ CHX can provide hydrogen preheating, increasing the flexibility of the storage system in with a minimal impact on system weight and size.

The future direction of our research on the application of microchannel technology to hydrogen storage includes:

- Complete demonstration of a 5-cm diameter MATI including heat removal rates, hydrogen distribution, and durability.
- Complete the demonstration of a .5-kW μ CHX.

FY 2012 Publications/Presentations

- Haley, D.B., and Narayanan, V., 2011, "Performance Characterization of a Microscale Hydrogen Combustor Recuperator and Oil Heat Exchanger," IMECE2011-64176, Proceedings of the ASME 2011 IMECE, Denver CO, November 11–17, 2011.