IV.D.10 Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

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Fiscal Year (FY) 2011 Objectives

Use microchannel processing techniques to:

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

Technical Barriers

This project addresses the following technical barriers from the 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 I technical targets for the Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage project are:

- Complete identification of the highest value applications of microchannel-based technology.
- Complete experimental investigations and modeling to collect data that will support the Go/No-Go decision to proceed to Phase II.

The Phase I Go/No-Go Criteria associated with these technical goals are:

- Identify and demonstrate, through experiment and simulation, one or more high-priority applications where the application of microchannel technology can make a significant contribution to meeting DOE 2015 performance goals.
- Develop specific performance, weight, and size goals for each application included in the OSU Phase II scope of work.

FY 2011 Accomplishments

Key developments and technical accomplishments for the reporting period are summarized in the following.

- Completed system design of a modular adsorption tank insert that facilitates the use of densified storage media while providing cooling for charging, heating for discharging, and hydrogen distribution (Barriers A and E).
- Initiated experimental investigations to validate key design assumptions used in the design of the modular adsorption tank insert (Barriers A and E).
- Completed system design and production cost estimate for a microchannel combustor/heat exchanger to heat oil using catalytic combustion of discharge hydrogen from storage (Barrier H).
- Completed experimental validation of performance and size estimates used in developing the microchannel combustor/heat exchanger (Barrier H).

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Introduction

Hydrogen storage involves coupled heat and mass transfer processes that are significantly impacted the 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 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 and mass transfer during charge and discharge of metal hydride and adsorbent hydrogen storage systems; and 2) microchannel-based thermal balance of plant components such as combustors, heat exchangers, and chemical reactors.

Approach

Our technical approach to meet the Phase I goals involves: 1) OSU will focus on simulation and experimental investigations to identify and prioritize opportunities for applying microscale heat and mass transfer enhancement techniques; and 2) working with other team members, OSU will identify the highest value applications and conduct experimental investigations and modeling to collect data necessary to support the Go/No-Go decision to proceed to Phase II.

For each high-priority component, we plan to use microchannel technology to reduce the relevant barriers to heat and mass transfer. Our 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.

Results

With respect to our Phase I technical targets, we identified two high-value applications of microchannel technology. The first is the development of a modular microchannel tank insert for cooling during charging, heating during discharging, and hydrogen distribution. The tank insert can be used with either metal hydride or cryogenic adsorbing material; however, we have focused on 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 on-board oil heating during discharge of a metal hydride hydrogen storage system. Results relative to these two applications are summarized below.

Microchannel-Based Tank Insert – A tank insert that integrates storage media, microchannel heat exchangers, and microchannel hydrogen distribution plates may provide improved charging of the storage system, rapid startup, and quicker response to changing driving conditions. Progress-to-date on the development of the microchannel-based tank insert includes:

- Cooling Plate Fabrication and Performance Validation – During the reporting period, we completed the assembly and testing of a 5-cm diameter cooling plate that includes two sets of microchannel cooling channels and microchannels for the distribution of hydrogen. The resulting cooling plate is on the order of 1-mm thick. The overall conclusion from these experiments is that the pressure drop through the microchannel heat exchanger and hydrogen distributor plates is reasonably small (15 kPa at a flow rate of 0.15 l/min). Furthermore, the above experiments indicate that the major pressure drop in the cooling subsystem will be located in the coolant feed and in exit lines. These components can be redesigned to further reduce pressure drop.
- Insert Design Development – Figure 1 shows the design of a multi-module tank insert including the headers to distribute cooling fluid. Figure 2 shows

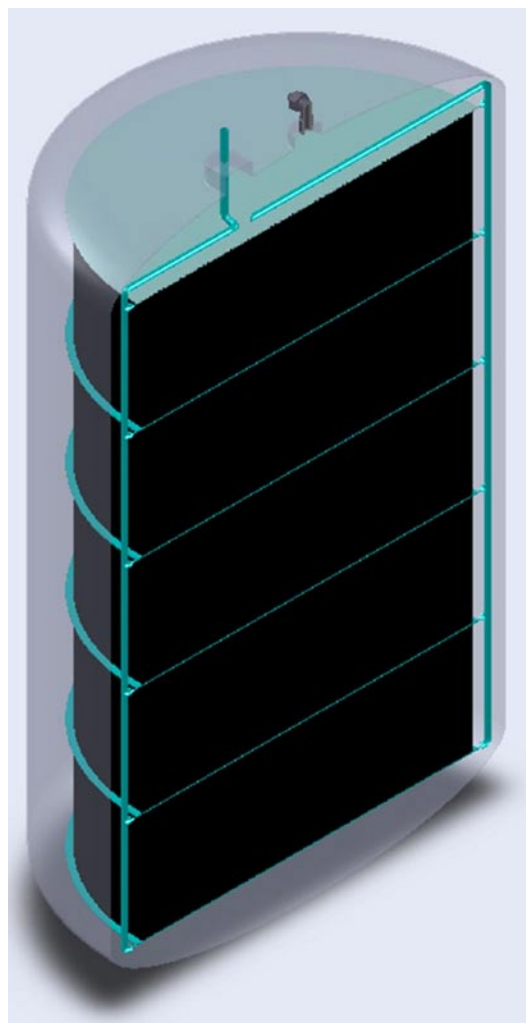

FIGURE 1. Schematic Diagram of Modular Adsorption System including Five Modules and Cooling Fluid Headers

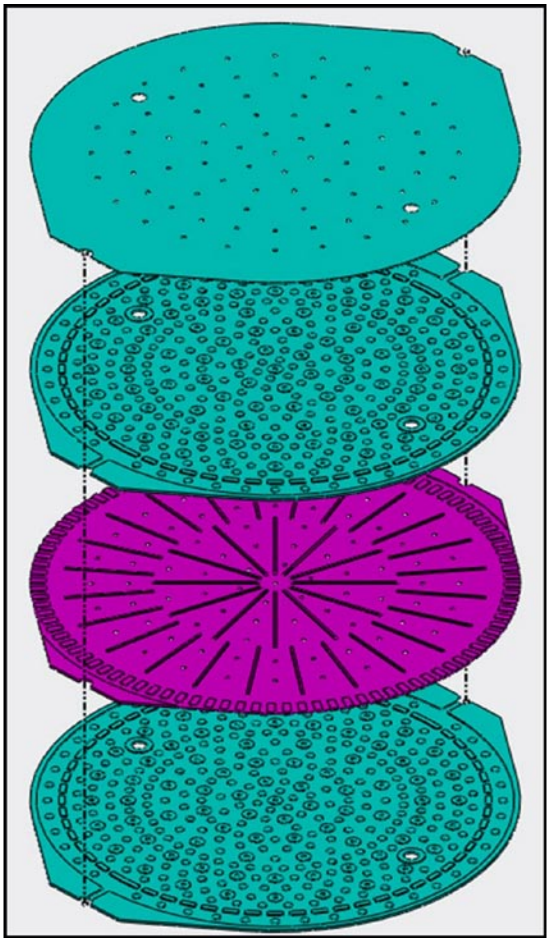

FIGURE 2. Schematic Diagram of Cooling plate including One Hydrogen Distribution Lamina (Purple) and Two Cooling Fluid Lamina (Teal)

the design of one cooling plate with one lamina used for hydrogen distribution and two laminae used for cooling. An individual module will consist of two cooling plates with media located between the cooling plates. Computational fluid dynamics (CFD) modeling was used to predict cooling fluid pressure drop and flow distribution both across one cooling plate as well as for a multi-module system. Overall pressure drop from the cooling fluid system inlet to outlet was predicted to be on the order of 1 bar. CFD modeling showed that flow maldistribution between plates in a single cooling plate was not a problem.

- Insert Fabrication and Weight Analysis – The system design described above was used as the basis for developing a fabrication approach and an estimated system weight. The fabrication strategy is amenable to high-volume production. The weight analysis for a cryo-adsorption hydrogen storage system capable of storing 5.6 kg of hydrogen and being filled in 4 minutes was on the order of 9 kg. This is based on a cooling plate spacing of 5 cm and assumes that the insert if fabricated from aluminum.

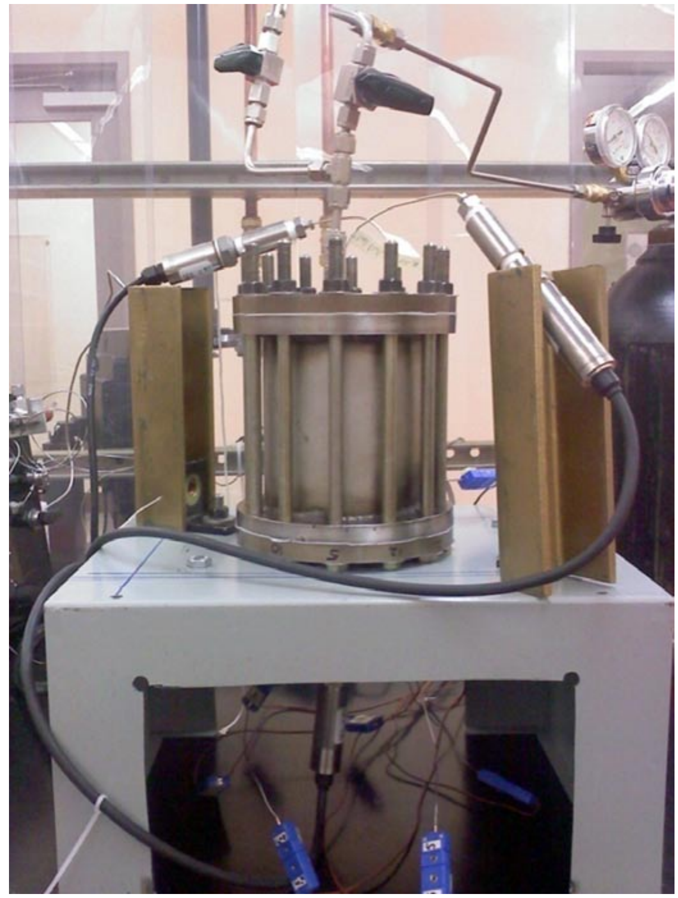

FIGURE 3. Modular Adsorption System Test Apparatus

- Experimental Investigations – We are currently starting up our test apparatus, shown in Figure 3, which will allow the testing of a cooling plate and media. The system is being converted to be able to operate at cryogenic temperatures so that we can test a 5-cm diameter module with liquid nitrogen cooling and hydrogen adsorption. The existing pressure vessel is limited to hydrogen pressures of 50 bars.

Integrated Microscale Combustor/Heat Exchanger (μCHX) – The microscale combustor/heat exchanger (μCHX, Figure 4) will be used to safely and efficiently produce heated oil, which is used to discharge hydrogen from the storage bed. Combining the combustion and heat exchanger systems and the use of microchannels for enhanced heat and mass transfer can drastically reduce the size and weight required for this function, while simultaneously increasing efficiency. A substantial safety benefit of a microscale combustor is that flames cannot be sustained in the sub-millimeter microchannels. Progress-to-date on the development of the μCHX includes:

- μCHX System Design, Weight and Cost Estimate – Previously we used simulation to predict the size, weight, and performance of a single unit cell of the

FIGURE 4. Schematic Diagram of μCHX

μCHX. During the reporting period, we used these results to develop the design of a full-sized μCHX (12 kW to 30 kW heating capacity) including the headers needed to distribute the feed (a mixture of hydrogen and air), combustion products, and oil between a large number of unit cells. The overall system dimensions of a 12 kW μCHX was estimated to be 15.1 cm by 15.6 cm by 4.3 cm with an overall volume of approximately 1 liter. The predicted volume of the μCHX is approximately 10% of the best alternative design. The predicted mass of the μCHX was estimated to be between 1.3 and 3.8 kg with an overall system efficiency of 92% (thermal energy transferred to the oil/chemical energy in the feed stream). Using this design as the basis for a bottom-up cost estimate we predicted a cost for this component of $120 to $200 at an annual production rate of 500,000 units. The production cost assumed that microlamination was used to fabricate the device with chemical etching used for patterning and laser welding used for bonding. Both stainless steel and aluminum were considered for fabrication materials. Simulation suggested that aluminum was a suitable material because material temperatures in the device were well below the temperature limits for aluminum.

- Unit Cell Experimental Validation of μCHX Performance and Weight Estimates – During the reporting period we completed preliminary testing of a single unit cell. The results showed an efficiency of 92%. Our results also showed that 130 to 140 W of thermal energy was being transferred to the oil, which is consistent with our size and weight estimates reported above.

Conclusions and Future Directions

Key conclusions resulting from our research include:

- As shown by the μCHX, when addressing a component that is limited by diffusion (heat or mass transfer), the application of microchannel technology can result in significant reductions in the size and weight of the device. Results also show that the cost of μCHX can be attractive.
- The use of the modular adsorption tank insert allows convenient use of densified adsorption media and is amenable to high volume production.

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

- Complete the demonstration of a 1 kW μCHX demonstrating hindering and overall system performance.
- Complete demonstration of a multi-module 5-cm diameter modular tank insert including heat removal rates, hydrogen distribution, durability, and complete a production cost estimate for the system.

FY 2011 Publications/Presentations

1. Ghazvini, M., and Narayanan, V., "Performance Characterization of a Microscale Integrated Combustor, Recuperator and Heat Exchanger," AJTEC2011-44633, in review, ASME/JSME 2011 8th Thermal Engineering Joint Conference, AJTEC2011, Honolulu, Hawaii.