IV.B.8 Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

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Overall 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

Fiscal Year (FY) 2013 Objectives

- Demonstrate ability to develop and demonstrate a modular absorption task insert (MATI) designed for a system consisting of 100% densified media and capable of allowing less than 3 min. refueling time and H_2 release rate of 0.02 g H_2/(sec. kW) with a mass less than 9.4 kg and a volume less than 4.2 liters (Barriers A and E).
- 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.

Technical Barriers

This project addresses the following technical barriers from the Storage section (3.3.5) of the Fuel Cell Technologies Office 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 for the Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage project are shown in Table 1.

TABLE 1. Phase II Technical Targets

Characteristic	Units	2013 Smart Goals	Status
MATI Weight	Kg	9.4	6.0
MATI Volume	Liter	4.2	3.0
Microcombustor Weight	Kg	0.9	0.29
Microcombustor Volume	Liter	0.65	0.15
Microcombustor Efficiency	%	85	86

FY 2013 Accomplishments

Key developments and technical accomplishments for the reporting period are:

- Completed separate effects and integrated testing of the MATI (Barriers A and E).
- Completed model validation for adsorption and desorption with a single MOF-5 puck (Barriers A and E).
- Completed modeling of the charge and discharge cycle for a full-scale MATI to support the development of conduction enhancements for adsorbing media (Barriers A and E).
- Updated the design and production cost estimate for the MATI (Barriers A and E).
- Completed fabrication and testing of a microchannel combustor/heat exchanger to provide hydrogen preheating in an adsorption hydrogen storage system (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. 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

Our technical approach to meet the Phase II goals is that for each high-priority component, we will use microchannel technology to reduce the relevant barriers to heat and mass transfer. Our approach involves the optimizing the performance of a single unit cell and then "Numbering Up" using appropriate simulation tools that we then validate by experimental investigation.

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. The second application is the development of an integrated microchannel combustor and heat exchanger that can be used for preheating hydrogen that can be used with fuel cell waste heat to preheat hydrogen that is used discharge storage.

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 distributing hydrogen. Progress to date on the development of the microchannel-based tank insert includes:

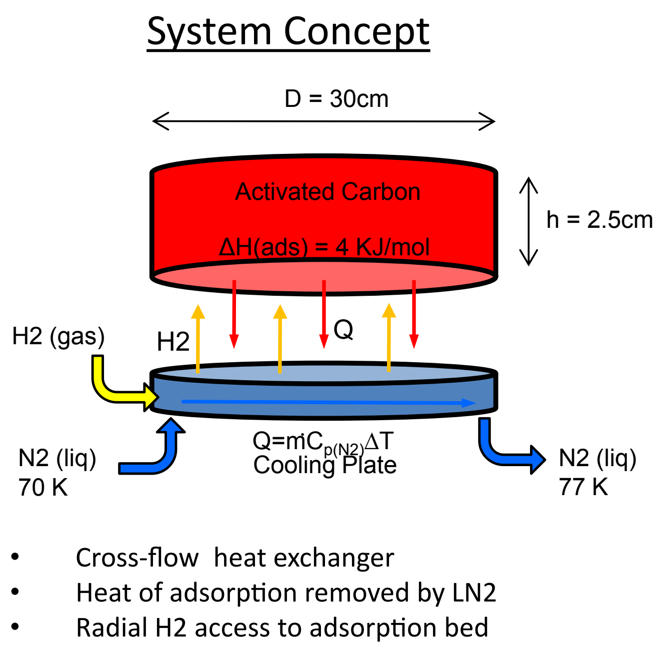

FIGURE 1. MATI Concept

- *Completed separate effects and integrated testing of the MATI*—Cryogenic test apparati have been assembled for experimental investigations of charging and discharging a MATI. 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. Integrated tests were completed in FY 2013. Separate effects testing determined the heat transfer coefficient in the MATI cooling plate for both single- and two-phase flow. The integrated testing initially focused on investigating the absorption and desorption of nitrogen and hydrogen in single pucks of activated carbon and MOF-5. Integrated testing then focused on testing a multi-puck MATI with three cooling plates, two hydrogen distribution plates, and four 1.5-cm thick pucks of MOF-5.
- *Completed model validation for adsorption and desorption with a single MOF-5 puck*—Simulation models have been developed to model all relevant phenomena associated with the charging and discharging of the MATI. During the reporting period the models were validated against the experimental results of our integrated testing. Figure 2 shows typical comparisons of experimental and simulated results for the temperature distribution in a MOF-5 puck. Overall, the average error between experiment and simulation results was between 4% and 5% with the maximum error being between 8% and 9%. Based on these results we are confident that we can accurately model the adsorption and desorption behavior of a single puck, giving confidence that our predictions of system level charging and discharging are valid.

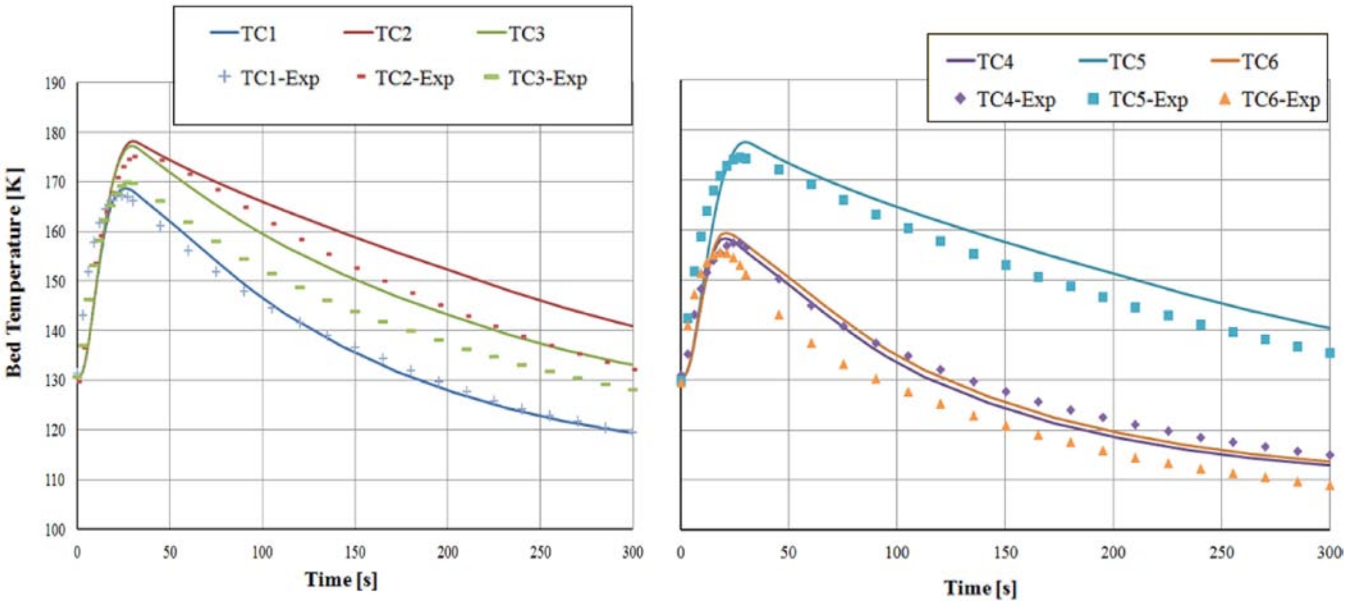

FIGURE 2. LN_2-Cooled Adsorption on MOF-5; Experimental and Modeling Results

- *Completed system modeling of the charge and discharge cycle for a full-scale MATI*—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 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. With this level of conduction enhancement, simulation of the charging cycle showed that the bed could be fully charged with hydrogen in three minutes. Modeling of the discharge cycle showed that the use of fuel cell waste heat for discharge was feasible. In this case the hydrogen from storage is heated using fuel cell heat and returned to the storage system where the hot hydrogen provides the required heating for discharge.
- *Completed demonstration of aluminum fabrication*—Our cost and weight targets require that aluminum be used as our material of construction. During the reporting period we successfully demonstrated our ability to pattern and bond aluminum cooling plates.
- *Updated MATI fabrication, weight, and cost analysis*—Our MATI system design and cost estimates were modified to reflect two key design changes: the use of stamping for the patterning process and the use of micro-pyramidal truss networks to provide the flow structure in the cooling plates and the hydrogen distribution plates. Our current weight and cost estimates are shown in Figure 3.

Integrated Microscale Combustor/Heat Exchanger (µCHX)—The µCHX, shown in 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. During the current reporting period we:

- *Completed design and testing of the µCHX for adsorption system hydrogen preheating*—We have modified the design of the µCHX 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 device has been fabricated and tested. Testing results confirm modeling predictions of performance. The new design is slightly less efficient (90%) and much smaller than the oil heating application described above. This combustor design is shown in Figure 4.
- *Filed a patent on the this concept for automotive and space heating applications*

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

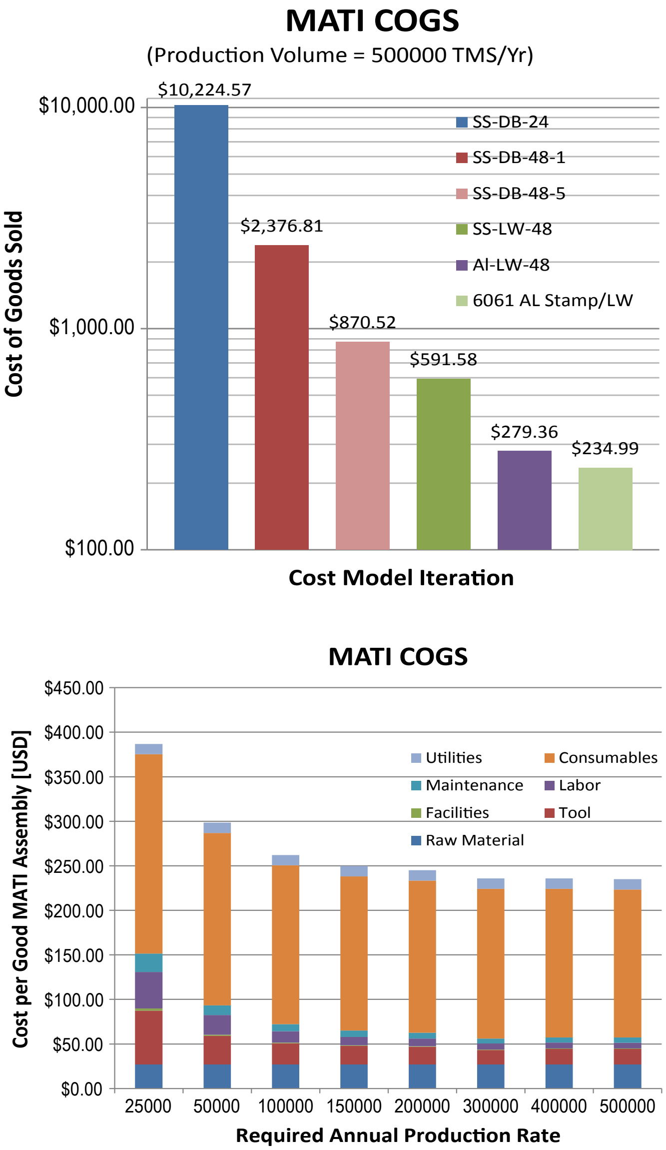

FIGURE 3. Cost of Goods Sold (COGS) of the MATI as a Function of Production Volume

media. The concept separates the cooling process from the charging process, allowing flexibility in cooling 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 µCHX, can provide hydrogen preheating, increasing the flexibility of the storage system with a minimal impact on system weight and size.

The MATI has been selected for inclusion in the third phase of the Hydrogen Storage Engineering Center of Excellence. Our research will focus on the demonstration of the MATI and include completion of the design, assembly,

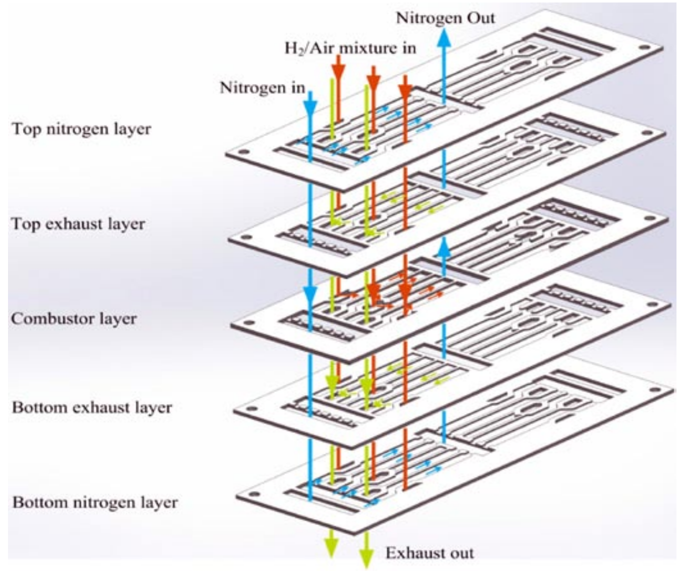

FIGURE 4. Microchannel Integrated Combustor/Heat Exchanger for Hydrogen Heating

and testing of a multi-cell MATI. Testing will measure heat removal rates, hydrogen distribution, and durability. After testing at Oregon State University, the MATI will be supplied to Savannah River National Laboratory for independent testing.

FY 2013 PUBLICATIONS/PRESENTATIONS

1. E.D. Truong, E. Rasouli, and V. Narayanan, "Cryogenic single-phase heat transfer in a microscale pin fin heat sink," Proceeding of SHTC 2013-17660, ASME summer heat transfer conference, Minneapolis, Minnesota, 2013.

2. E. Rasouli, E.D. Truong, and V. Narayanan, "Cryogenic single phase and phase change heat transfer in a microscale pin fin heat sink," Presentation only in ICNMM 2013-73151, 11th International Conference on Nanochannels, Microchannels and Minichannels, Sapporo, Japan, 2013.

3. L.J. Steigleder, "A microchannel-based thermal Management System for Hydrogen Storage Adsorptent Beds," M.S. Thesis, Oregon State University, June 14th, 2013.

4. S.V. Pawar, "Fabrication of Precipitation-Hardened Aluminum Microchannel Cooling Plates for Adsorption-based Hydrogen Storage Systems," M.S. Thesis, Oregon State University, Corvallis, Oregon, March 21st, 2013.

5. M. Ghazvini and V. Narayanan, "Design of A microscale Combustor- Heat Exchanger for Low Temperature Applications," Accepted for *ASME 2013 Summer Conference* (HT2013), July 14–19, 2013, Minneapolis, Minnesota.

6. M.M. Ghazvini and V. Narayanan, "A Microscale Combustor-Heat Exchanger for Low Temperature Applications- Experimental Results," Oral presentation, *ASME 11th International Conference on Nanochannels, Microchannels and Minichannels* (ICNMM2013), June 16–19, 2013, Sapporo, Japan.

7. M. Ghazvini and V. Narayanan, “A microscale combustor recuperator and oil heat exchanger – design and thermofluidic characterization,” *Int J of Heat and Mass Trans,* Vol. 64, pp. 988-1002, 2013.

8. C. Loeb and G. Jovanovic, 2013 “*Cryogenic Hydrogen Adsorption On MOF-5 With Novel Microchannel Thermal Management System - Experiment and Simulation,*” American Institute of Chemical Engineers, San Francisco, CA, USA, 2013 (*in review*).

9. C. Loeb, “*Enhancement and Modeling of Cryogenic Solid-State Hydrogen Storage Systems with a Novel Microchannel Thermal Management Device,* “ Ph.D. Thesis Oregon State University, Corvallis, OR, June 2013 (http://hdl.handle.net/1957/39687)

10. C. Loeb, A. Truszkowska, and G. Jovanovic, “Increasing hydrogen storage in compressed MOF-5 system using a microchannel thermal management device: experiment and simulation,” Advances in Chemical Engineering and Science, 2013 (*in review*).