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

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Project Start Date: February 1, 2009
Project End Date: June 30, 2015

Overall Objectives

Use microchannel processing techniques to:

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

Fiscal Year (FY) 2014 Objectives

Demonstrate 2-liter Modular Absorption Tank Insert (MATI)

Technical Barriers

This project addresses the following technical barriers from 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 3 technical targets for the Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage project are shown in Table 1.

TABLE 1. Project Technical Targets

Characteristic	Units	2014 Project Milestones	Status
MATI Weight	Kg	9.4	6.0
MATI Volume	Liter	4.2	3.0

Accomplishments

Key developments and technical accomplishments for the reporting period are:

- Completed design and assembly of the 2-liter MATI prototype (Barriers A and E).
- Completed assembly of the test facility for the 2-liter MATI (Barriers A and E).
- Completed model development for the charge and discharge cycle for the 2-liter MATI to prototype (Barriers A and E).

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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 to 10 over conventional designs, while attaining substantially higher heat and mass transfer efficiency. We are developing micro-technology based advanced adsorption tank inserts (MATI) for high media utilization and enhanced heat and mass transfer during charge and discharge of adsorbent hydrogen storage systems.

APPROACH

Our technical approach to meet Phase 3 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 (1) optimizing the performance of a single unit cell, i.e., an individual microchannel, and then "numbering up" using appropriate simulation tools that we then validate by experimental investigation; and (2) developing microlamination methods as a path to numbering up by low-cost, high-volume manufacturing.

RESULTS

In Phase 3 we are focused on the demonstration of high-value applications of microchannel technology: MATI for cooling during charging, heating during discharging, and hydrogen distribution. The MATI concept integrates storage media, microchannel heat exchangers, and microchannel hydrogen distribution plates in such a way that allows convenient use of densified adsorption media in excess of 94% of the tank volume. The concept separates the cooling process from the charging process, allowing flexibility in cooling strategies; in addition, 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 (see Figure 2).

At the end of Phase 2, MATI was selected for inclusion in Phase 3 of the Hydrogen Storage Engineering Center of Excellence research scope. In Phase 3 we are engaged in demonstration of MATI, specifically, in the design, assembly, and testing of a multi-cell MATI contained in a 2-liter pressure vessel. Testing will measure heat removal rates, hydrogen distribution, and durability. After acceptance testing at OSU, MATI will be supplied to Savannah River National Laboratory (SRNL) for independent testing. Progress to date on the development of the microchannel-based tank insert includes:

- Completed design and assembly of the 2-liter MATI prototype. The design of the 2-liter MATI prototype was completed during the reporting period (see Figure 2). The prototype will have five unit cells, each consisting of two cooling plates, two "pucks" of densified metal-organic framework-5 (MOF-5), and a hydrogen distribution region. The design includes (1) a pressure vessel developed in collaboration with Hexagon Lincoln, (2) the monolithic densified MOF-5 or "puck" developed in collaboration with Ford and University of Michigan, (3) the microchannel cooling plate, and

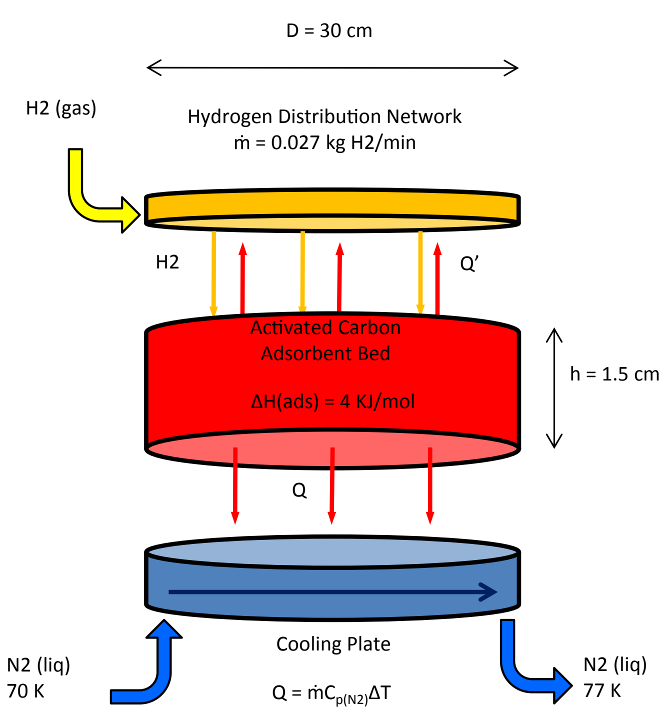

FIGURE 1. MATI Concept

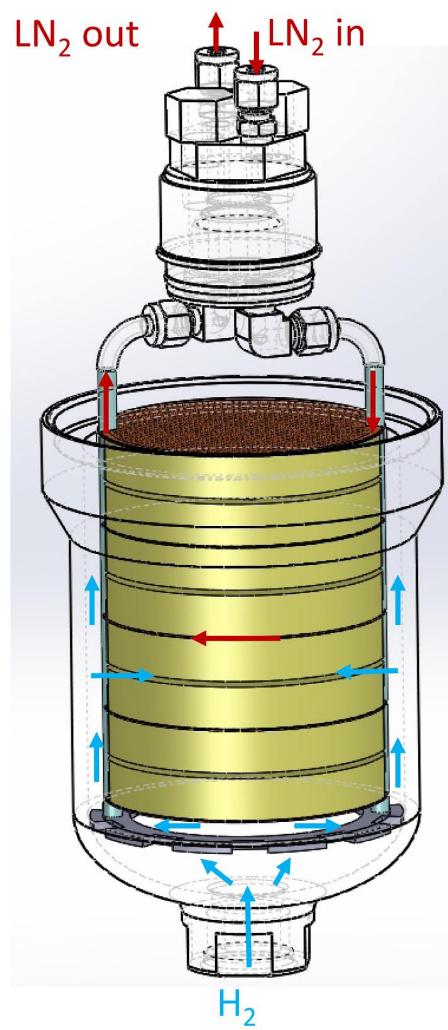

FIGURE 2. 2 Liter Prototype MATI Design

4) the headers for distributing the liquid nitrogen to the cooling plate. The design of the cooling plates was based on our Phase 2 design yet modified to achieve improved flow distribution. Based on both simulation and flow visualization, we have achieved the desired degree of uniform flow distribution in the cooling plate. Figure 3 shows the results of simulation of the flow distribution in a typical cooling plate. The design of the 2-liter MATI prototype was the subject of an external design review conducted by other center members, and recommended design modifications were incorporated into the prototype. Fabrication techniques for bonding the headers to the cooling plates have been developed and demonstrated. Initially we had difficulty brazing the cooling plates to the headers, but after investigating alternative approaches, we are now able to braze the cooling plates to the headers with a high degree of confidence. Figure 4 shows a complete unit cell with cooling plates, headers, and MOF-5 pucks. We are currently assembling the first 2-liter MATI prototype, and this will be used to start up our acceptance test apparatus.

- Completed assembly of the test facility for the 2-liter MATI. OSU will conduct limited testing on the 2-liter MATI prototype to ensure that it is functioning properly before shipping the device to SRNL for comprehensive testing. To facilitate testing, a cryogenic acceptance testing apparatus was designed, and a test plan was developed for acceptance testing. The test apparatus includes both the system for testing MATI and the conditioning systems for cooling the inlet hydrogen and liquid nitrogen to the appropriate inlet conditions. The design and test plan were the subject of an external design review conducted by other center members, and recommended design modifications were incorporated into the test apparatus and test plan. The apparatus will be used for experimental investigations of charging and discharging a 2-liter prototype MATI. Acceptance 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. We have completed assembly of the test apparatus and will be starting up the device in the next month.

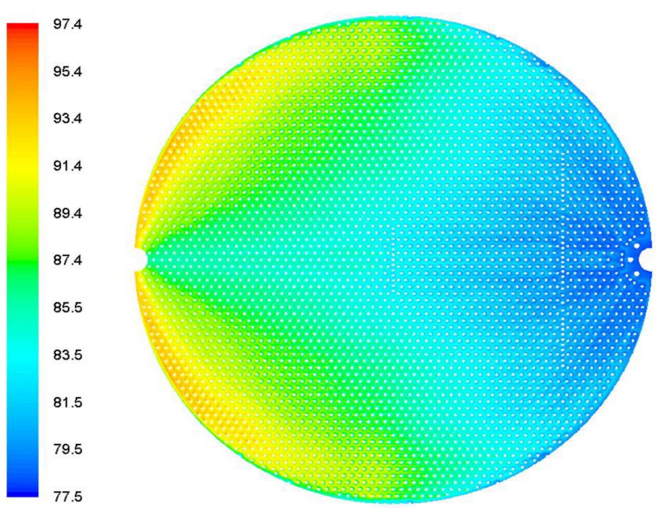

FIGURE 3. Simulation Results for Flow Distribution in a MATI Prototype Cooling Plate

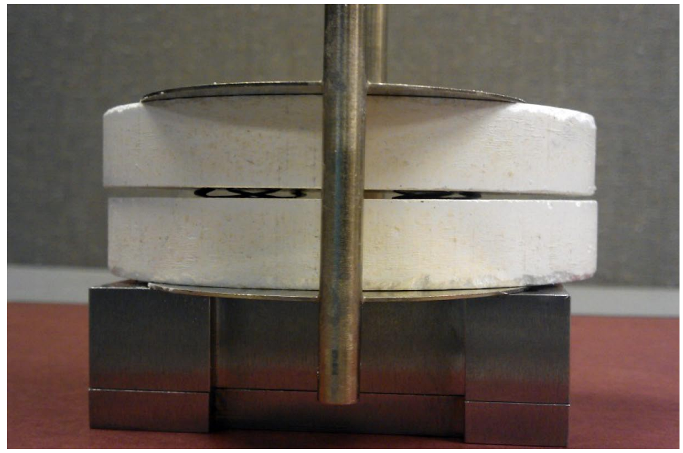

FIGURE 4. Assembled MATI Unit Cell

- Completed model development for the charge and discharge cycle for the 2-liter MATI to prototype. Simulation models have been developed to model all relevant phenomena associated with the charging and discharging of the MATI. During Phase 2 the models were validated against the experimental results of our integrated testing. 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 validation results, we were confident that we could accurately model the adsorption and desorption behavior of a single puck. However, to further improve our modeling capability, we worked with SRNL to incorporate several advanced features used by SRNL. With these modifications we have reduced the average error in our comparison with experimental data from 5.9% to 3.5%. We have completed the assembly of an eight-zone model that will model the complete MATI, including the pressure vessel during both the charge and discharge cycles. As data become available from the SRNL comprehensive testing, we will use the eight-zone model for model validation and support of the experimental investigations being conducted at both OSU and SRNL.

Extending beyond the formal Phase 3 scope of work, OSU made promising advances in commercializing the microchannel combustor/heat exchanger concept for a number of heating applications, with the inventor winning the Transformational Idea award at the FLoW competition at Caltech on May 7, 2014. This technology was developed for hydrogen storage applications in earlier phases of the project.

CONCLUSIONS AND FUTURE DIRECTIONS

Key conclusions resulting from our research are as follows.

- The use of the modular adsorption tank insert allows convenient use of densified adsorption media in excess of 94% of the tank volume. The concept separates the cooling process from the charging process, allowing flexibility in cooling strategies, and 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 design of the 2-liter MATI has been completed and peer reviewed, as have the design of the test apparatus and our test plans.

The next step in our research is to complete the demonstration of MATI that includes (1) final assembly of the test article at OSU, (2) acceptance testing at OSU, (3) comprehensive testing at SRNL, and (4) model validation. In addition, if monolithic densified media, "pucks," are available with conduction enhancements, these will be tested in FY 2015.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

Mohammad Ghazvini, a post-doctoral researcher in OSU's School of Mechanical Industrial and Manufacturing Engineering, won the Transformational Idea award at the FLoW competition at Caltech on May 7, 2014, for the microchannel combustor/heat exchanger developed as part of this project. The $5,000 award is given to groundbreaking pre-commercial research with large potential impact on energy sustainability and efficiency. The FLoW competition is held every year in Los Angeles, California, and is supported by the Department of Energy. FLoW's mission is to support the development of entrepreneurial talent within American universities and to accelerate the movement of leading-edge technologies out of the lab and into the marketplace

FY 2014 PUBLICATIONS/PRESENTATIONS

1. E. Rasouli and V. Narayanan, "Single-phase cryogenic flows through microchannel heat sinks," Proceedings of ICNMM2014-21275, ASME international conference of nanochannels, microchannels, and minichannels, Chicago, Illinois, 2014.

2. C. Loeb and G. Jovanovic, "Improved storage capacity of a MOF-5 hydrogen storage system using a novel microchannel heat exchange device," 23rd International Symposium on Chemical Reaction Engineering and 7th Asia-Pacific Chemical Reaction Engineering Symposium, Bangkok, Thailand, 2014.

3. C. Loeb, A. Truszkowska, 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, 2014 (in review).

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