IV.B.3 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) 2015 Objectives

- Demonstrate 2-liter modular absorption tank insert (MATI)

Technical Barriers

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

TABLE 1. Phase 3 Technical Targets

Characteristic	Units	2014 Smart Goals	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 as follows:

- Completed assembly of three MATI prototypes and provided two to Savannah River National Laboratory (SRNL) for testing (Barriers A and E)
- Completed testing of conduction enhancement schemes for densified MOF-5 (metal organic framework) pucks (Barriers A and E)
- Initiated model validation 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 the 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 compared to conventional designs, while attaining substantially higher heat and mass transfer efficiency. We are developing micro-technology-based advanced adsorption tank inserts (MATIs) 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 one high-value application of microchannel technology: the 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 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; in addition, the MATI can provide heating during discharge, avoiding the need to use electric energy for discharge heating. The full-sized MATI would consist of a number of cells, along with headers for cooling fluid and distributing hydrogen (see Figure 1).

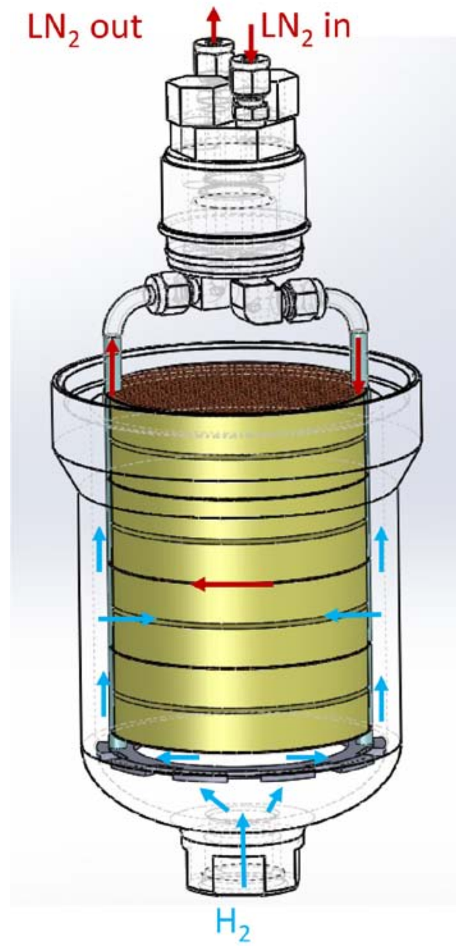

FIGURE 1. Two-liter prototype MATI design

At the end of Phase 2, the 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 the 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. Two prototype MATIs have been supplied to SRNL for independent testing. Progress-to-date on the development of the microchannel-based tank insert includes the following:

- *Completed assembly of three MATI prototypes* – OSU has completed the assembly of three 2-liter MATI prototypes, including the insertion of MOF-5 pucks and sensors for testing. The MATI prototypes were fabricate in two processes. First, stainless steel lamina were chemically etched to form the flow paths and then diffusion bonded forming the cooling plate. Each cooling plate was pressure tested and tested for flow distribution. The cooling plates were then brazed to the distribution tubing, and the complete MATI was pressure tested. The assembly process for the test apparatus is shown in Figure 2. The MATI was first attached to the pressure vessel flange. Two half-pucks were slid in between two cooling plates, and the thermocouple leads were fed through one of the two 3/8" tubes on the flange and inserted into the bed. The assembly process was conducted inside a glove box in order to minimize the bed's exposure to air. Given the use of a glove box and the large number of thermocouples, the assembly process took a significant amount of time. One MATI is being used at OSU for conduction enhancement testing, and the remaining two MATIs have been shipped to SRNL for testing.
- *Completed testing of conduction enhancement schemes for densified MOF-5 pucks* – The time required to charge the MOF-5 with hydrogen can be significantly reduced if the conductivity of the densified MOF-5 pucks can be improved. OSU has conducted preliminary experimental investigations of five approaches to enhancement. These include the insertion of small aluminum pins into the puck and/or the mixing of high conductivity expanded natural graphite (ENG). In addition, unenhanced pucks were included for comparison. Each puck has two thermocouple holes in the same locations and depths of penetration for measuring bed temperature during absorption experiments. The OSU team submerged the

FIGURE 2. Various steps of assembly process and fully assembled flanged pressure vessel

MATI tank within a dewar filled with liquid nitrogen (LN_2) and modeled a charge cycle using nitrogen gas as a proxy for hydrogen. The absorption of nitrogen gas produced thermal energy that was removed from the puck to the liquid nitrogen cooling fluid in the cooling plates. By comparing the performance of enhanced pucks to the unenhanced puck, we were able to get an estimate of the value of the enhancement.

As shown in Figure 3, all of the conduction enhancements performed significantly better than the bare, unenhanced puck. The best performing enhancement (pins without any ENG) reached a steady-state temperature in 1,200 s, as compared to 2,700 s for the unenhanced puck. This is a significant improvement and suggests that puck conduction enhancement is both feasible and could lead to a significant improvement in the rate of charging and discharging of an adsorption bed formed from densified adsorbing material. We investigated a number of charging options, and the multiple experiments conducted during this quarter clearly demonstrated the benefit of conduction enhancement for current MATI design.

- *Initiated model validation for the charge and discharge cycle for the 2-liter MATI 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 percent, with the maximum error being between 8 and 9 percent. 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 percent. We have completed the assembly of an eight-zone model (shown in Figure 4) that will model the complete MATI, including the pressure vessel during both the charge and discharge cycles. The eight-zone model simulated the various processes occurring in a single-unit cell. As data becomes available from the

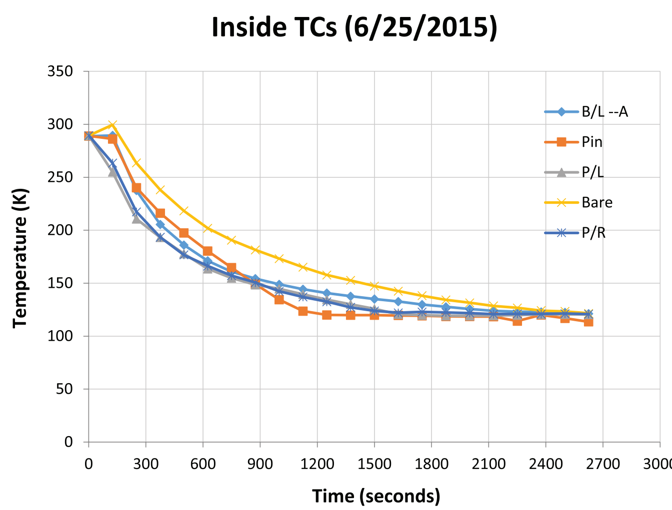

FIGURE 3. Bed temperature profiles for various conduction enhancements with submerged MATI tank

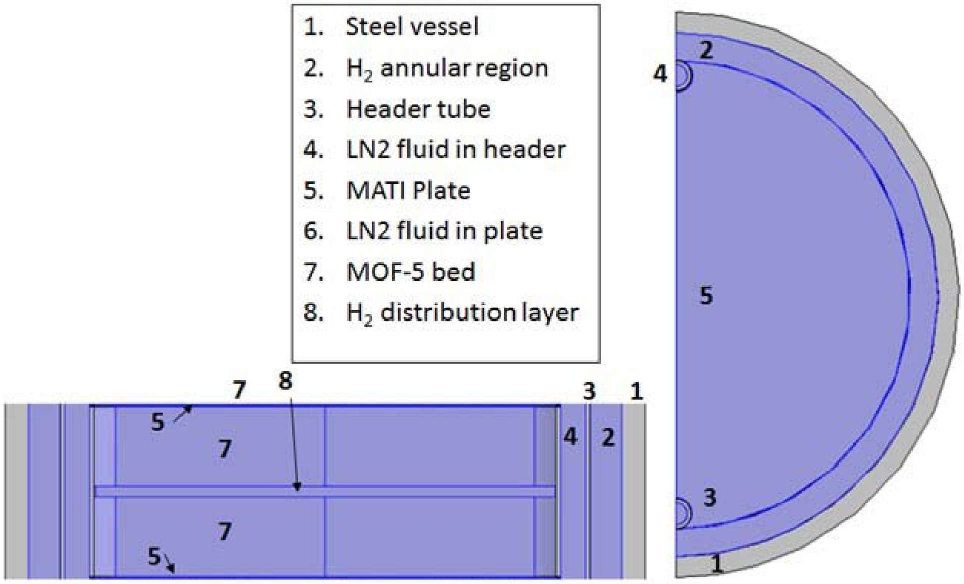

FIGURE 4. Eight-zone computational model for a MATI

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.

CONCLUSIONS AND FUTURE DIRECTIONS

Key conclusions resulting from our research are as follows:

- The use of the MATI 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 both cooling during charging and heating during discharge with a weight less than 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 three prototypes have been assembled and are being tested, demonstrating the technical feasibility of the concept.
- Testing at OSU has demonstrated the feasibility and impact of conduction enhancement of the MOF-5 pucks.
- The computational model has been validated with laboratory data and will be validated with prototype data being acquired by SRNL.

The next steps in our research are to complete the demonstration of the MATI, which includes comprehensive testing at SRNL, and to validate the model. The results of the project will be documented in a comprehensive project report that will include all OSU research activities associated with the Hydrogen Storage Engineering Center of Excellence.