IV.D.1j Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

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Objectives

Use microchannel techniques 1) to demonstrate reduction in storage system size and weight, 2) for improvement of charge/and discharge rates, and 3) to 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

This project focuses on optimization of the performance characteristics and reduction in the size, weight, and cost of metal hydride and adsorption hydrogen storage systems. We will achieve these goals through careful design of thermal integration to efficiently harness "waste heat", and by applying microscale techniques to enhance heat and mass transfer. More efficient heat transfer through microscale combustors, heat exchangers and recuperators allows for substantial reductions in the size and weight of balance-of-plant components. Microchannel-based hydrogen storage systems offer enhanced heat and mass transfer, possibly allowing more rapid charging and startup, quick response to changing driving conditions. In addition, the excellent heat transfer control achievable with microscale components allows for efficient removal of thermal energy generated during charging. These experimental and simulation studies are expected to guide the design of high-efficiency metal hydride and adsorption-based hydrogen storage systems toward meeting the following DOE 2010/2015 targets:

- System gravimetric capacity: 1.5/1.8 kWh/kg
- System volumetric capacity: 0.9/1.3 kWh/L
- Charging/discharging rates: 1.2/1.5 kg/min, 5–15 sec start time to full flow

Accomplishments

- Completed preliminary design of ~1 mm-thick microchannel-based tank insert plate for liquid-cooling and hydrogen distribution. A unit cell in the model in-tank system consists of two of these liquid-cooled distribution plates, separated by adsorbent or metal hydride. (Barriers A and E)
- Completed design and fabrication of a test apparatus that will be used to test the tank insert unit cell. (Barriers A and E)
- Completed simulation tool and a preliminary design of a microchannel combustor/heat exchanger to heat oil used to discharge hydrogen from storage. High-efficiency (>90%) microscale device integrates a flame-proof combustor, oil heat exchanger and thermal recuperator. (Barrier H)
- Completed simulation tools to support the experimental investigations of the tank insert and microchannel combustor/heat exchanger. (Barriers A, E and H)

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Introduction

Hydrogen storage involves coupled heat and mass transfer processes that significantly impact the size, weight, cost, and performance of system components. Micro-technology devices that contain channels of 10 to 500 microns characteristic length offer substantial heat and mass transfer enhancements, by greatly increasing the surface to volume ratio, and 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 the conventional designs, while attaining substantially higher heat and mass transfer efficiency. In cooperation with the OSU Microproducts Breakthrough Institute and groups at Pacific Northwest National Laboratory, Savannah River National Laboratory (SRNL) 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; 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 2.

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 and which are validated by experimental investigations; and 2) developing microlamination methods as a path to "numbering up" by low-cost high-volume manufacturing.

Results

Relative to our Phase 1 technical targets, we identified two high value applications of microchannel technology. The first application is the development of a microchannel tank insert for cooling during charging, heating during discharging and hydrogen distribution. The tank insert can be used with either metal hydride or adsorbing material. The second application is the development of a microchannel combustor/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:

- A test apparatus for a tank insert unit cell that includes the storage media, microchannel cooling and microchannel hydrogen distribution has been designed, and is being assembled. This system, expected to be operational in August 2010, will support experiments to determine the kinetics of adsorption and desorption of hydrogen on metal hydrides and carbon-based adsorbents, and also serve as a testbed for developing an optimized hydrogen storage unit cell.
- A microchannel unit cell for metal hydride and adsorbing materials has been designed and the integrated microchannel cooling and hydrogen distribution plates have been fabricated (Figure 1).
- Computational simulation of the unit cell is being performed in parallel with the physical experiments. A multi-phase flow simulation in FLUENT, incorporating full Navier-Stokes equations and sodium alanate reaction kinetics (provided by

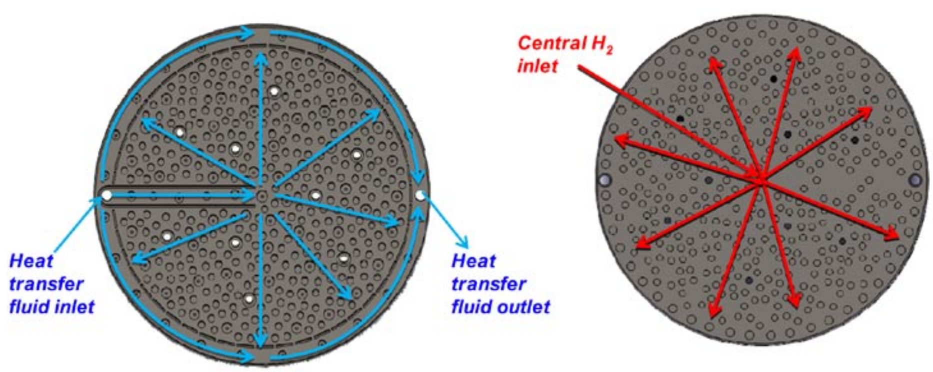

FIGURE 1. Schematic design of ~1 mm-thick high-efficiency microchannel-based storage tank insert, with integrated liquid-cooled heat exchanger (left), and H_2 distribution (right) systems.

SRNL), was used to model hydrogen flow in the porous storage medium. The simulation was validated by comparison with published data [1]. The results indicate that particle size is a major factor, and that multi-phase flow components must be included in simulations dealing with small (<2 µm) particles. This and related computational models are also being used to simulate adsorption/desorption processes on single-particle and whole-bed scales, and further validation and optimization studies for the test bed integrated microscale unit cell are currently under way.

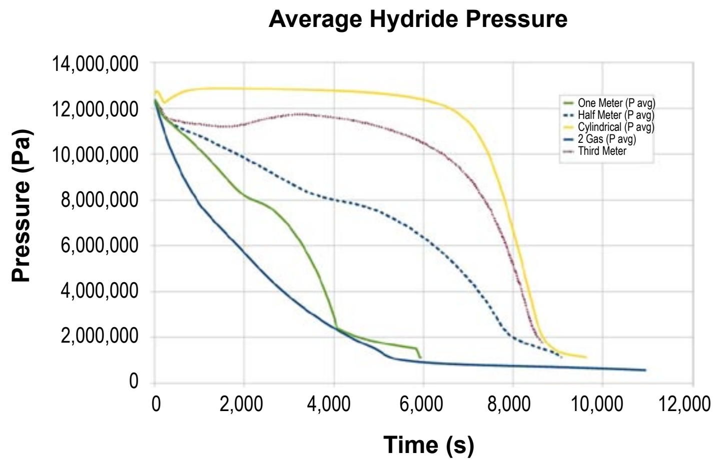

FIGURE 3. Simulation results for desorption of hydrogen from a cylindrical tank of sodium alanate. The highest and most uniform discharge rate is attained with a hydrogen sink and a heat source at each end of the tank (solid dark blue line).

Integrated Microscale Combustor/Heat Exchanger (µCHX) - The microscale combustor/heat exchanger (µCHX, Figure 2) 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:

- A simulation of the µCHX has been completed, including a detailed model of the kinetics of the combustion reactions. The code has been used to predict the performance of the device and current results suggest the µCHX will be significantly smaller, lighter and more efficient then current compact combustion systems.
- A design of the test apparatus and a µCHX unit cell test article has been completed. Currently, we are assembling the test apparatus and having the µCHX unit cell test article fabricated.

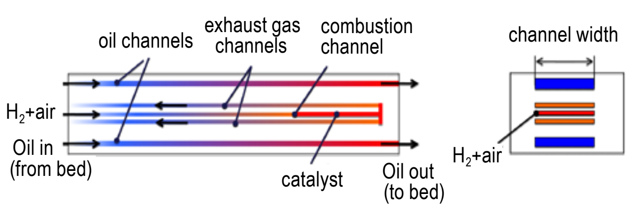

FIGURE 2. Preliminary design of integrated micro-scale combustor, recuperator and oil heater for discharge of hydrogen from storage bed.

- A FLUENT-based two-dimensional computational simulation of hydrogen desorption rates has been completed and used to model the desorption process. A 1 m long, 15 cm radius tank containing 75 kg of sodium alanate bed was modeled, using literature data and accounting for thermal effects on physical properties. The results suggest that two sources of thermal energy one located at each end of the tank, produces acceptable desorption (Figure 3).

Conclusions and Future Directions

- Complete the assembly of the tank insert unit cell test apparatus, assembly of unit cell test articles for metal hydride and adsorbing materials, and validate simulation models and unit cell performance.
- Develop a conceptual design and identify high volume, low cost fabrication approaches for the tank inset.
- Complete the assembly of the µCHX test apparatus and µCHX unit cell test article, and validate simulation model and unit cell performance.
- Provide support for other center partners on applications where microchannel technology can provide significant improvement over existing technology.

References

1. D.E. Dedrick; M.P. Kanouff; R.S. Larson; T.A. Johnson, S.W. Jorgensen , (July 26–29, 2009). "Heat and Mass Transport in Metal Hydride Based Hydrogen Storage Systems" *Proceedings of the ASME 2009 Heat Transfer Summer Conference*, San Francisco, CA, USA.