



Microscale Enhancement of Heat and Mass Transfer for Hydrogen Energy Storage

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Oregon State University

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Hydrogen Storage Engineering

CENTER OF EXCELLENCE

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Overview

Timeline

- Feb 1st 2009
- Jan 31st, 2014
- 0% Complete

Budget

- Total project funding
 - DOE - \$2,398,935
 - Contractor - \$600,345
- Funding received in FY0 - \$0
- Funding for FY09 - \$300,000

Barriers

- **Barriers addressed**
 - **A)** System Weight and Volume
 - **E)** Charging and Discharging Rates
 - **H)** Balance of Plant

Partners

- **HSECoE Partners** - SNRL, PNNL, LANL, NREL, JPL, United Technologies, TRC, GM, Ford, BASF, Lincoln Composite, HSM, UQTR
- **Center Lead** - SNRL

Hydrogen Storage Engineering Center of Excellence

D. Anton, SRNL
T. Motyka, SRNL

Materials Operating Requirements

D. Herling, PNNL

- Materials Centers of Excellence Collaboration – SRNL, LANL, NREL
- Reactivity – UTRC
- Adsorption Properties – UQTR
- Metal Hydride Properties – SRNL
- Chemical Hydride Properties - LANL

Transport Phenomena

B. Hardy, SRNL

- Bulk Materials Handling – PNNL
- Mass Transport – SRNL
- Thermal Transport – SRNL, OSU
- Media Structure - GM

Enabling Technologies

J. Reiter, JPL

- Thermal Insulation – JPL
- Hydrogen Purity – UTRC
- Sensors – LANL
- Materials Compatibility – PNNL
- Pressure Vessels – PNNL
- Thermal Devices - OSU

Performance Analysis

M. Thornton

- Vehicle Requirements – NREL
- Tank-to-Wheels Analysis – NREL
- Forecourt Requirements - UTRC
- Manufacturing & Cost Analysis - PNNL

Integrated Power Plant/ Storage System Modeling

D. Mosher, UTRC

- Off-Board Rechargeable - UTRC
- On-Board Rechargeable – GM
- Power Plant – Ford

Subscale Prototype Construction, Testing & Evaluation

T. Semelsberger, LANL

- Risk Assessment & Mitigation – UTRC
- System Design Concepts and Integration - LANL
- Design Optimization & Subscale Systems – LANL, SRNL, UQTR
- Fabricate Subscale Systems Components – SRNL, LANL
- Assemble & Evaluate subscale Systems – LANL, JPL, UQTR

Technology Area

Technology Area Lead

- Technology Team – TT Lead
- Technology Team – TT Lead
- Technology Team – TT Lead

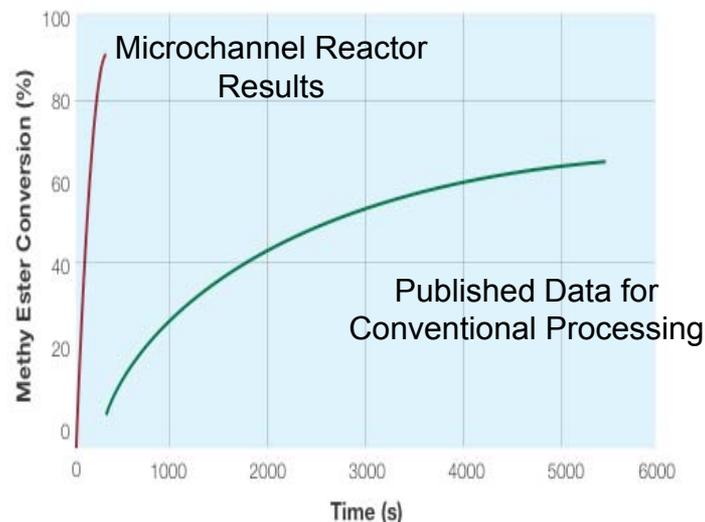
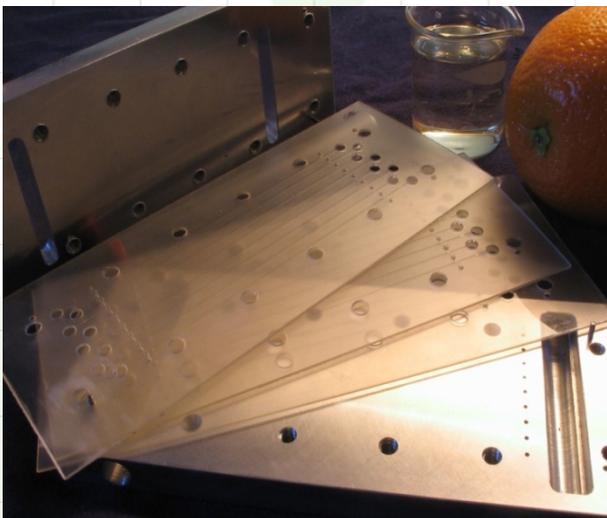


Relevance -Objectives

- **Objective** – Use microchannel technology to ...
 - 1) reduce the size and weight of storage,
 - 2) improve charging and discharging rate of storage
 - 3) reduce size and weight and increase performance of thermal balance of plant components.
- **Barriers Addressed**
 - Reduce system size and weight
 - Charging and Discharging rates
 - Balance of Plant

Relevance – What is microtechnology-based Energy and Chemical Systems (MECS)?

- MECS uses microscale dimensions in flow paths (microchannels) to enhance heat and mass transfer
- For processes limited by diffusion, laminar flow residence time (and to some extent size) decreases as D^2 where D is channel width. **In many energy and chemical systems, diffusion is the limiting phenomena. The use of microchannels addresses this barrier**





Relevance – MECS Features and Hydrogen Storage

- Significant reduction in size and weight when a process is limited by diffusion
 - **Reduce storage size and weight related to heat and mass transfer**
 - **Reduce size of balance of plant thermal components**
 - **Reduce charging time**
- High degree of control over process
 - **Optimize storage for weight minimization**
- Number up rather than scale up
 - **Maintain optimum performance attained in single cell**
- Complexity can be added without increasing cost
 - **Integrate hydrogen distribution in cooling surfaces**
- Low thermal mass and high heat and mass fluxes will allow rapid start-up and response to transients
- In the temperature range of interest, attractive high volume manufacturing options exist.



Approach - Programmatic

- **Phase 1: System Requirements & Novel Concepts**
 - OSU will focus on simulation conducted to identify and prioritize opportunities for applying microscale heat and mass transfer techniques.
 - Working with other team members, OSU will identify the highest value applications and, where necessary, conduct experimental investigations and use modeling to collect data necessary to support the Go/No-Go decision to proceed to Phase 2.
- **Phase 2: Novel Concepts Modeling, Design, and Evaluation**
 - For each high-priority application, OSU will develop predictive models, design and evaluate components, fabricate proof-of-principle test articles, conduct proof-of-principle tests, and use the results to validate the predictive models.
 - With other team members, OSU will select one or more high-priority components for prototype demonstration.
- **Phase 3: Subsystem Prototype Construction, Testing, and Evaluation**
 - For each high-priority component, OSU will design, optimize, and fabricate the component.



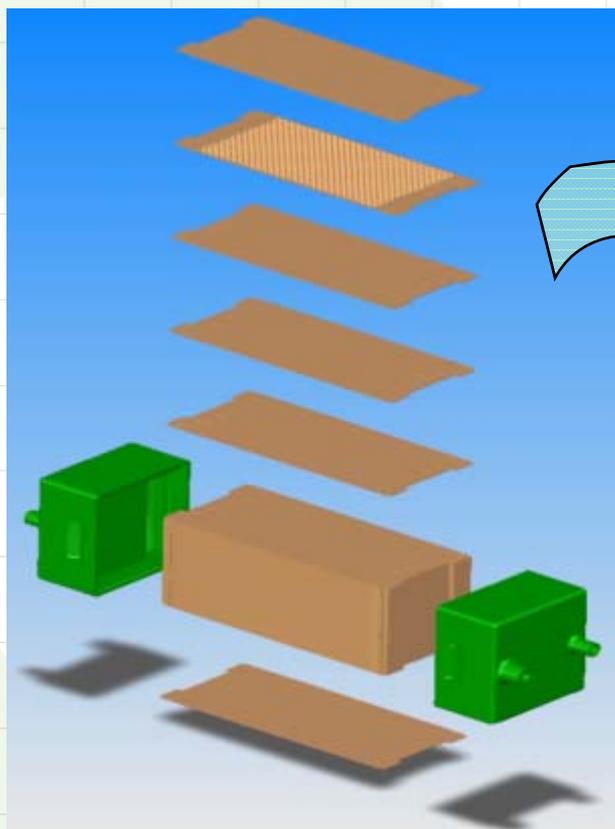
Approach – Technical

- For each high priority component, where possible, use microchannel technology to reduce barriers to heat and mass transfer.
- Optimize the performance of a single unit cell (i.e microchannel) and then “Number Up”
- Use simulation validated by experimental investigations to conduct optimization
- Explore microlamination as a path to low cost high volume manufacturing

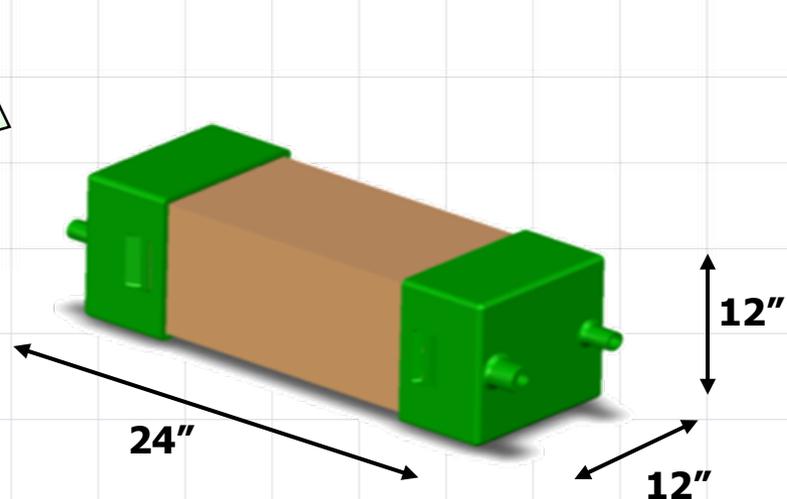


Approach – Fabrication

[Paul et al. 1999, Ehrfeld et al. 2000*]



Microlamination of Reactor



Microchannel Reactor

* W. Ehrfeld, V. Hessel, H. Löwe, Microreactors: New Technology for Modern Chemistry, Wiley-VCH, 2000.



Approach – Second law Analysis

- Energy flows do not have equal value. The useful fraction of an energy flow is exergy (or availability etc.)
- Exergy is destroyed by irreversibility in any real process
- Exergy is a **common currency** that lets us combine the impact of any thermodynamic loss mechanism.
- Example: heat exchangers have two loss mechanisms, viscous dissipation (pressure drop) and heat transfer across a finite temperature difference. How do we combine these?
 - Traditional first law methods for assessing heat exchanger enhancements actually can give the wrong answer!
 - Both heat transfer and viscous dissipation can be evaluated as exergy destruction and combined into a correct figure of merit
- Second Law analysis can give a more accurate picture of sources of losses and hopefully suggest design improvements to minimize losses



Approach – Milestones and Go/No Go Decision Criteria

- **2009/2010 Milestones**

- Complete identification of the highest value applications of microchannel-based technology (2/1/2010).
- Complete experimental investigations and modeling to collect data that will support the Go/No-Go decision to proceed to Phase 2 (11/1/2010).

- **Phase I Go/No Go Criteria**

- 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 2 scope of work.

- **Phase II Go/No Go Criteria**

- Complete successful proof of principle tests for high priority microchannel applications identified in Phase 1 and demonstrate that based, on the proof-of-principle tests, a prototype microchannel component can meet the DOE 2015 goals.



Technical Accomplishments

- This is a new project, funding for this project was available on April 1 2009
- Worked with other center members to identified two applications that merit additional investigation
 - MECS-based structured bed metal-hydride storage
 - Microchannel-based integrated hydrogen combustor/heat exchanger/recuperator plus other BOP heat exchangers
- Outlined fabrication strategy for MECS-based metal hydride storage concept



Proposed Future Work

- MECS Metal Hydride Storage Concept
 - Use simulation to optimize unit cell
 - Experimentally validate simulation
 - Outline fabrication approach and production cost
- Integrated Combustor/Heat Exchanger
 - Use simulation to optimize integrated system
 - Fabricate technology demonstration
 - Experimentally validate simulation
 - Demonstrate rapid start-up and transient performance
- Second Law Analysis
 - Develop 2nd Law analysis tools for system simulation and CFD simulation
 - Use 2nd Law analysis tools to evaluate thermodynamic losses in hydrogen storage and identify design improvements



Collaboration

- Oregon State University is a member (a prime contractor) of the Hydrogen Storage Engineering Center of Excellence (HSECoE) which includes:
 - **Savannah River National Laboratory (Center Lead)**
 - **Pacific Northwest National Laboratory**
 - **Los Alamos National Laboratory**
 - **National Renewable Energy Laboratory**
 - **Jet Propulsion Laboratory**
 - **United Technologies Research Center**
 - **HSM Systems**
 - **Lincoln Composites**
 - **BASF**
 - **Universite' du Quebec a Trois-Rivieres**
 - **General Motors Company**
 - **Ford Motor Company**



Project Summary

- **Relevance:** Microchannel technology can reduce size, weight and charging time of hydrogen storage.
- **Approach:** Use microscale diffusion lengths to improve diffusion limited processes and then “Number Up” rather than “Scale Up” to develop balance of plant thermal components and metal hydride storage bed.
- **Technical Accomplishments:** New Project
- **Collaboration:** Member of HSECoE team.
- **Proposed Future Research:** Develop microchannel-based concept for metal hydride and adsorption storage and key balance of plant thermal components



Supplemental Slides

What is MECS? - Applications

Fuel Processing

Chemical Processing

Heating & Cooling



What is the Microproducts Breakthrough Institute (MBI)

- The MBI is a unique 40,000 sq ft product development laboratory operated by Oregon State University (OSU) and the Pacific Northwest National Laboratory (PNNL)
- The MBI is focused on the application of process intensification to energy and chemical systems miniaturization
- The MBI combines the expertise of the leading industrial (PNNL) and academic (OSU) research programs on process intensification and is a national leader in developing this technology
- The mission of the MBI is to develop and commercialize miniature energy and chemical systems



Why is 2nd Law Analysis Important to Hydrogen Energy Storage

- Hydrogen Storage is an extremely complicated thermodynamic process. For a metal hydride system requiring heating for desorption, the loss mechanisms include:
 - Irreversibility from pressure drop on heat source side of the device
 - Irreversibility from combustion not occurring at equilibrium temperature
 - Irreversibility from heat transfer across a finite temperature difference in heat exchanger and media
 - Irreversibility from desorption reaction
 - Irreversibility from diffusion of hydrogen in storage media
 - Irreversibility from pressure drop on the hydrogen side of the device
- While 2nd law analysis doesn't provide any new physics, it does
 - Give a clear picture of where losses are being generated
 - Provides a valid figure of merit for optimization
 - Our assumption is that the development of hydrogen storage will be accelerated by an accurate picture the magnitude and location of thermodynamic losses