Microchannel Fuel Processing

Fuel Cells for Transportation/Fuels for Fuel Cells
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Objectives

- Demonstrate at ~1/10 scale a microchannel-based fuel processing system that meets FreedomCAR performance targets.

- Engage industrial partner(s) to facilitate development of full scale fuel processing system.

- Develop reactors, vaporizers, recuperative heat exchangers, and condensers broadly applicable to other fuel processing options.

Approach

Steam Reformation

- Improve power density, specific power
- Demonstrate fuel flexibility, transient response, 1000-hour durability (catalyst and reactor)
- Redesign for rapid startup

Water Gas Shift Reactor

- Differential temperature design reduces reactor size
- Collaborate on catalyst formulations from industry

Preferential Oxidation Reactor

- Investigate advantages of microchannel design

<table>
<thead>
<tr>
<th>Performance Criteria</th>
<th>Current Performance</th>
<th>2004 FreedomCAR Targets</th>
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</thead>
<tbody>
<tr>
<td>50 kW e System Volume</td>
<td>&lt;1 cubic foot (&lt;28L)</td>
<td>2.5 cubic foot (71 L)</td>
</tr>
<tr>
<td>Power Density, Specific Power</td>
<td>1800 W/L, 320 W/kg</td>
<td>700 W/L, 700 W/kg</td>
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<tr>
<td>System Efficiency</td>
<td>81%</td>
<td>76%</td>
</tr>
<tr>
<td>Durability</td>
<td>&gt;1000 h</td>
<td>4000 h</td>
</tr>
<tr>
<td>Transient Response (10 to 90%)</td>
<td>5 s</td>
<td>5 s</td>
</tr>
<tr>
<td>Start-Up to Full Power, 20°C</td>
<td>30 s (low dP projection), 15 m (current reactor block)</td>
<td>&lt;1 min</td>
</tr>
<tr>
<td>Steady State CO Content</td>
<td>15 ppm</td>
<td>10 ppm</td>
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</table>
### Project Timeline

**FY 1998**
- Full-size gasoline vaporizer/combustor
- R&D100 Award

**FY 1999**
- Fast SR kinetics demonstrated in a microchannel reactor

**FY 2000**
- Designed and built 10 kWe SR with integrated HX network
- Engineered catalyst, reactor development
- Demonstrate rapid startup
- Sulfur management
- Integrated reformer/fuel cell demonstration at ~5 kWe

**FY 2002**
- SR fuel flexibility, durability testing
- WGS/PROX catalyst studies
- Differential temperature reactor concept
- SR/WGS/PROX initial integration
- Full-scale low dP vaporizers delivered

**FY 2001**
- 10 kWe reactor testing
- First “low dP” vaporizers
- Modular test stand established

**Collaborate with industrial partner(s) on manufacturing, field testing, lifetime, controls**
Reactor Volumetric Productivity Improved
(isooctane at 3:1 S:C / GHSV basis: 1atm, 25C, exit conditions, bulk catalyst volume)

Factor of ~3X Increase in Processing Rate

GHSV in Steam Reforming Reactor [hr⁻¹]
Fuel Flexibility Demonstrated

Durability and Transient Response

1000-Hour Reforming Test

5 Second Warm Transient Response

Benchmark Fuel

- 74 wt% isoctane
- 20 wt% xylene
- 5 wt% methyl cyclohexane
- 1 wt% 1-pentene

Response to step changes in liquid fuel and water feed rates of 100% to 10% and 10% to 100% in 51 cc reactor
Water-Gas Shift Development
Approach / Progress

Catalyst Screening

Kinetic Model

Reactor Modeling

Integrate into system

Reactor Prototypes

Air-Cooled Gradient WGS Section
Fuel Vaporizer
Manual Adjustment Valves
Steam & Fuel-Cooled Gradient WGS Section
Reformate Recuperator
Fuel Vaporizer
Catalyst Screening
Kinetic
Coefficient
(mol CO/s.g cat)

\[ y = 34686e^{-10388x} \]

R² = 0.9627

Temperature, C
CO Conversion, %
WHSV = 75393

CO Conversion

Equil CO Conversion

Integrate into system

[Graph showing kinetic coefficient vs. inverse temperature]

[Graph showing CO conversion vs. temperature]

[Graph showing water-gas shift development approach/progress]

Steam Reforming Reactor
HT Air Recuperator

[Diagram of reactor components]
WGS Catalyst Screening
Sud-Chemie Copper-Zinc (T2650) and Precious Metal/Ceria (PMS5)

Low Shift Feed at 0.5 S/G

PMS5 preferred for microchannel WGS development
Water-Gas Shift
Why microchannels? – To control temperature profile

1 Integrated Unit
2.3X Less Catalyst

Conventional 2-stage Adiabatic

Ideal profile

Based on Sud-Chemie PMS5 PM catalyst and SR reformate
Differential Temperature Water-Gas Shift
Reactor volume < 3L projected from experimental results

150,000 GHSV, 0.5 Steam/Dry Gas, 4.6% CO Feed

Differential temperature outperforms isothermal operation

Prototype 7-channel Reactor

Reactor can be operated isothermally or with a temperature gradient

Differential temperature outperforms isothermal operation
Performance of Engineered PROX Catalysts

Stage 1 PROX, Precious and Base Metal Catalysts; 1% CO, O2/CO = 1, GHSV = 400K, S/G = 0.3

Stage 2 PROX Performance of Precious Metal Catalyst in a Single Channel Reactor: 0.1% CO, 100°C, GHSV = 200K; S/G=0.3

- Base metal catalyst preferred for Stage 1; Precious metal catalyst preferred for Stage 2
Industry Interactions

- Formally seeking to engage industrial partner
- Water Vaporizer for 50 kWe ATR designed, built, tested and delivered to McDermott Technology, Inc.
- Water Vaporizer delivered to Gas Technology Institute for boiler-related research, funded by OIT.
- Interaction with Engelhard, Süd Chemie, NexTech, and ANL for catalyst formulations
- Vaporizer and recuperator delivered to Innovatek for Army reformer demonstration

50 kWe Water Vaporizer Panel Size:
dimensions 22.2 cm x 10 cm x 1.8 cm
weight = 2.4 kg

At max operating point:
HX duty = 24.6 kW
HX intensity = 60 W/cm³

Sample Operating Point

Steam
225°C, 425 kPa abs.

Combustion Gas
685°C, 69.1 kg/h

Combustion Gas
157°C, ambient pressure
dP = 5 in. H₂O

Water
23°C, 4.08 g/s
Plans, Future Milestones

- Complete catalyst optimization (FY03)
- WGS, PROX reactor development and integration (FY03)
- High temperature reformation/sulfur tolerance study complete (FY02)
- Demonstrate rapid start-up concepts based on low dP design (FY03)
- Develop sulfur management approach (FY03)
- Engage industrial partner(s) to facilitate development (FY03)
- Demonstrate fast-start, integrated fuel processor at 5 kWe, and operate with a PEM fuel cell (FY04)
Rapid Cold Start Concept for Steam Reformer

- Low combustion gas dP key to rapid startup (30 second start projected)
- Target test system has four reformer stages with one water vaporizer

**Key Data For 30-Second Startup Calculation - 2.4 kWe System**

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
<th>(\Delta P ) at Normal Cond. (~60 SLPM, Air)</th>
<th>(\Delta P ) at Startup (~800 SLPM, Air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reforming Reactor, 650C</td>
<td>720 g</td>
<td>1.6 in H(_2)O (0.4 in H(_2)O, per stage)</td>
<td>21.3 in H(_2)O (5.33 in H(_2)O, per stage)</td>
</tr>
<tr>
<td>(4 stages, 600We each)</td>
<td>(180 g, per stage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Vaporizer (1 stage)</td>
<td>91 g</td>
<td>0.1 in H(_2)O</td>
<td>1.3 in H(_2)O</td>
</tr>
</tbody>
</table>
Responses to Comments from Last Year

- **An effort should be made to test this reformer with methanol:** Tests conducted showed that methanol was the most easily reformed of all fuels evaluated. Productivity is >2x higher than rate for benchmark gasoline, or ~4 kWe/L.

- **Engage an industrial partner to build a complete reforming system:** Formal process underway.

- **More studies evaluating catalyst performance and life:**
  - Completed 1000 hour reformer durability test on benchmark gasoline.
  - Commercial and prototype WGS and PROX catalysts extensively studied in powder and engineered form.
  - Developed single channel reactors that provide flexibility in testing of engineered catalysts, provide data to develop kinetic model.