Innovative Injection and Mixing Systems for Diesel Fuel Reforming

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Outline of Presentation

- Program Goals and Work Scope
- Technical Approach
  - Injector and Mixing Concepts
  - CFD Flow Structure and FE Thermal Analyses
  - Experimental Setup and Equipment
- Results to Date
  - Test Rigs
  - Multipoint Impingement Injector and Mixer
  - Single Point Gas-assisted Injector and Mixer
  - High-Energy Piezoelectric Injector
- Future Plans
Objective – The primary objective is to develop cost-effective injection and mixing concepts to enable development of reliable diesel fuel reforming technology for solid oxide fuel cell power system.

Major Tasks

- Task 1- Evaluate Atomization and Injection Concepts
- Task 2- Develop Effective Mixing Chamber
- Task 3- Construct Test Rig and Perform Laser Diagnostics
- Task 4- Investigate Carbon-resistant Coating Materials and Design features
Technical Issues on Liquid Fuel Reforming

- Adequate atomization over the entire operating range
- High flow rate turndown ratio required
- Minimum inlet pressure of steam and airflow
- Uniform distribution of temperature, velocity and fuel mixture at the entrance of the reactor
- Intrinsically unstable flow
- Recirculation and flow reversal inside mixing chamber
- Autoignition
- Droplet impingement on wall surface
- Quick mixing between feed streams
Technical Issues (continued)

- Thermal management issues (heat shielding, steam condensation and internal coking)
- Pressure loss and plugging due to small passage and orifice
- Diesel fuel difficult to vaporize and prone to pyrolysis
- Coking and metal corrosion problems
- Simple and robust injector/mixer design
- Cost effective and low power consumption
- Easy to integrate with different reactors
- Multi-fuel capability
- Quick startup and rapid response
Survey Results for 10-kW Injector/Mixer Operating Parameters

- **Reformer Types** - ATR, CPOX, ATR/SR
- **Fuel Types** - Diesel, Jet A, JP8
- **Fuel Delivery Requirements** - 0.6 to 8 lbs/hr, 50~145 psig inlet pressure
- **Fuel Turndown Ratio** - 2:1 to 10:1
- **Air Delivery Requirement** - 6 to 40 lbs/hr; temperature 70 ~950°F; maximum inlet pressure less than 2 psig
- **Steam Delivery Requirements** - 3 to 20 lbs/hr; 500~700°F; maximum inlet pressure 10 to 30 psig
- **Packaging Requirements** - 0.5 ~ 1 liter
- **Steam/Carbon Ratio** - 0.5 to 3
- **Oxygen/Carbon Ratio** - 0.8 to 1.3
Difficulties Using Conventional Pressure Swirl Injection Technique

1 psig/1 pph
Jet Fuel SMD>120 µm
Diesel SMD>140 µm

5 psig/2.7 pph
Jet Fuel SMD=80 µm
Diesel SMD=90 µm

20 psig/4.8 pph
Jet Fuel SMD=60 µm
Diesel SMD=70 µm

50 psig/7.25 pph
Jet Fuel SMD=45 µm
Diesel SMD=55 µm
Technical Approach

- Conduct a thorough evaluation of various injection and mixing concepts
- Establish threshold and target performance data
- Perform Design of Experiment (DOE) to map out the operating conditions for the most promising concepts
- Utilize CFD and FEA tools to help predict and understand flow-field structure and injector/mixer performance
- Perform detailed laser diagnostics for performance evaluation and design substantiation
- Incorporate carbon-resistant or coke-tolerant design features
Injection and Mixing Concepts

- Multipoint Impingement Injector
- Single-Point Steam or Air-assisted Simplex Injector
- High-Energy Piezoelectric Simplex Injector
- Preheating Simplex Fuel Injector
- Pulse Modulated Fuel Injection
- Effective Mixing Swirlers and Mesh Screens
- Carbon Tolerant Design Features
Multipoint Impingement Injector Concept
Gas-Assisted Simplex Injection and Mixing Concept

Steam Inlet

Fuel Inlet

Air Inlet
High Energy Piezoelectric Simplex Injector

Fuel

Piezoelectric elements

Electrode

Air inlet

Steam inlet
Experimental Capabilities

- Advanced developmental machine shop
- Test rig representative of 3~10 kW reformer operation
- Phase Doppler Interferometry
- SETscan Optical Patternator
- Fuel Reformer Diagnostic Equipment from NASA Glenn
  - Particle Imaging Velocimetry (PIV)
  - Raman Spectroscopy
  - Gas Chromatography
Injector and Mixer Testing Equipment
Phase Doppler Particle Analyzer

- 5W Argon-Ion Laser
- Beam Splitter and Transmitter
- Sampling area
- Receiver Lenses and Detectors
- Computer
- RSA Signal Processor
- Photo detector Unit
6-Axis SETscan Optical Patternator

spray
Raman Spectrometer
Results to Date
(from October 2004 through March 2005)

- Constructed a hot flow test rig for performance development and concept screening
- Completed the evaluation of the multipoint impingement injector concept in March 2005
- Assembled a gas-assisted simplex injector for detailed performance evaluation
- Fabricated a prototype piezoelectric injector for evaluation of driver electronics and injector operating parameters
- Analyzed various injector and mixing chamber configurations for improved mixing capability and thermal management
- Conducted detailed flow field measurements using phase Doppler interferometry, SETscan optical patternator, Raman spectrometer and porcupine thermocouples.
Injector/Mixer Flow Field Analysis

- Full 360° model
- 3 million grid cells
- Mass Flow Inlet Boundaries
- Pressure Outflow Boundaries
- 2 species (air, steam)
- RNG k-ε turbulence model

Air Inlet

Steam Inlet

Mixing Devices

Pressure Outlet
Multipoint Impingement Injector
Flow Field Analysis

CFD Predicted Axial Velocity Contours (m/s)

Air: 930 °F, 30 lbm/hr
Steam: 550 °F, 12 lbm/hr

Time-averaged axial velocity contours at the outlet boundary
Thermal Analysis for Multipoint Impingement Injector

- SolidWorks model directly imported into ANSYS
- Wetted wall temperature of the fuel circuit must not exceed 400°F.
- Internal wall temperature of the steam circuit must be above saturation temperature at the operating pressure.
- Temperature gradients of the metal must be low enough not to cause undesired thermal growth and stresses.
Porcupine Thermocouples for Temperature Measurements

3” Test Section Spool – TC Layout

Section AA
TC1 – TC9

3” ID
Sch 40

45°

2.60’ dia
1.25’ dia

TC – ●
TYPE K

Note: Spool will use existing TC input channels from 10 kW ATR Reactor (39 available)

Scale: 1.0” = 1.0’
Flanges Not Shown

3” Test Section Spool – TC Layout (Porcupine)

Injector Flow

TC1 – TC9

TC10 – TC1B
TC19 – TC27

3.0”

1.0”

5.0”

3” ID
Sch 40
316SS

A
B
C

Scale: 1.0” = 1.0’
Flanges Not Shown

Total 27 TC’s

TMT 3/1205

TMT 3/1205
### Temperature Uniformity at Downstream Locations

<table>
<thead>
<tr>
<th>Test Point</th>
<th>Section A-A (1” downstream)</th>
<th>Section C-C (5” downstream)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave. (°F)</td>
<td>Max-Min. (°F)</td>
</tr>
<tr>
<td>Pt.1 - Fuel 5 pph, Air 25pph/930F, steam 10pph/550F</td>
<td>525</td>
<td>10</td>
</tr>
<tr>
<td>Pt.2 - Fuel 5 pph, Air 25 pph/930 F, steam 6.5pph/550F</td>
<td>549</td>
<td>26</td>
</tr>
<tr>
<td>Pt.3 - Fuel 5 pph, Air 25 pph/930 F, steam 3 pph/550F</td>
<td>554</td>
<td>21</td>
</tr>
<tr>
<td>Pt.4 - Fuel 1.5 pph, Air 7.5 pph/930 F, steam 3 pph/550 F</td>
<td>551</td>
<td>23</td>
</tr>
<tr>
<td>Pt.5 - Fuel 2 pph, Air 12 pph/930 F, steam 5 pph/550 F</td>
<td>553</td>
<td>20</td>
</tr>
</tbody>
</table>

Uniformity Index  \( \text{UI} = \frac{\text{Max.-Min.}}{\text{Average}} \)

Temperature is considered very uniform for UI less than 5%.
Multipoint Impingement Injector
Effect of Steam Pressure

Cold Flow Tests Using SETscan Optical Patternator

2 pph fuel, 15 pph steam, 15 pph air  
2 pph fuel, 5 pph steam, 15 pph air

Note: Shop air was used in the steam circuit for cold flow patternation tests.
Effect of Operating Conditions on Species Distribution

5 pph diesel, 10 pph steam at 550°F
25 pph air at 930°F (pt1)

Multipoint impingement injector
-2 mixing chamber without mixing devices
Diesel Fuel
Effect of Fuel Properties on Species Distribution

Top Row: Jet-A; Bottom Row: Diesel

-1 mixing chamber with mixing devices
Effect of Steam Temperature on Species Distribution

Diesel Fuel: 5 pph, Air Flow: 25 pph at 930°F, Steam Flow: 10 pph

-2 mixing chamber without mixing devices
Effect of Mixing Devices on Species Distribution

Diesel Fuel: 5 pph, Air Flow: 25 pph at 930°F, Steam Flow: 10 pph at 450°F
-1 chamber with mixing devices
-2 chamber without mixing devices
Summary of Test Results for Multipoint Impingement Injector

- Present investigation allowed us to evaluate the effect of fuel type, mixing chamber configuration, steam temperature and operating conditions on injector performance.
- All test conditions exhibited relatively uniform temperature and species distributions.
- Higher steam temperature appears to provide stronger Raman signals and more uniform mixture distribution in the central region.
- The overall signal strength for diesel fuel is lower than Jet fuel due to different physical properties. Jet fuel distribution also appears to be both more uniform and more repeatable.
- Mixing devices do not appear to provide any noticeable benefit to the multipoint impingement injector concept.
- Species distribution appears to be more scattered as steam/carbon ratio decreases when using mixing devices.
Single Point Gas-assisted Simplex Injector and Mixing Concept

- Simple, more robust design and less prone to internal coking
- Easily adaptable to a different reformer
- Narrow spray angle to minimize carbon deposition on the chamber wall
- Excellent atomization when there is adequate gas inlet pressure
- Mixing devices are required for uniform mixture distribution
Spray Characterization
Impingement Injector Versus
Gas-assisted Injector

Fuel: 5 pph, Steam: 10 pph (using air), Air: 25 pph

Simulated Cold Flow Tests

Measurement Distance: 3 inches from injector discharge
Spray Characterization
Impingement Injector Versus
Gas-assisted Injector

Fuel: 5 pph, Steam: 10 pph, Air: 25 pph

Simulated Cold Flow Tests

Measurement Distance: 3 inches from injector discharge
Gas-assist CFD Analysis

Turbine Fuel Technologies

0.125” hole screens

0.094” hole screens

Steam Inlet

Air Inlet

CFD Model

2.5 million cells
CFD Flow Field Results for Gas Assist Injector/Mixer

Axial Velocity Contours (range set -1 to 10 m/s)
Air: 930 °F 25 lbm/hr, Steam: 550 °F 12 lbm/hr

Before screen 1
Between screens 1 & 2
Between screens 2 & 3
Between screens 3 & 4
Between screens 4 & 5
After screen 5

Between screens 2 & 3
Between screens 3 & 4
Between screens 4 & 5
Prototype High-Energy Piezoelectric Injector Spray

- Excellent atomization for low flow rate applications
- High turndown ratio possible (>10:1)
- Power consumption needs to be minimized
- Drift of operating frequency and spray quality due to changes of temperature and flow rate
- Great potential for pulse modulated injection

2 pph fuel operated at 46 kHz frequency
Future Plans

- Evaluation of the single-point gas assisted simplex injector/mixer concept will be completed in May 2005.
- The high-energy piezoelectric injector will be constructed to meet the third quarterly milestone in June 2005.
- Evaluation of the preheating simplex injector/mixer concept will be completed in September 2005.
- Laser diagnostics will be performed at NASA Glenn using a reformer test rig for two injector concepts in October 2005.
- The effect of pulse modulated spray will be investigated by December 2005.
- Phase I program will be completed and final report submitted to DOE by March 2006.