Fuel Cell Systems Analysis

2004 USDOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review
Philadelphia, PA
May 24-27, 2004

R. K. Ahluwalia, X. Wang, E. Doss, R. Kumar

The submitted manuscript has been created by the University of Chicago as Operator of Argonne National Laboratory (“Argonne”) under Contract No. W-31-109-ENG-38 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

Argonne National Laboratory

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago
Objective

Develop a validated system model and use it to assess design-point, part-load and dynamic performance of automotive fuel cell systems
• Support DOE in setting R&D goals and research directions
• Establish metrics for gauging progress of R&D activities

Technical Barriers Addressed

A. Compressors/Expanders
C. Fuel Cell Power System Benchmarking
D. Heat Utilization
H. Start-up Time

I. Fuel Processor Start-up and Transient Operation
M. Fuel Processor System Integration and Efficiency
R. Thermal and Water Mgmt

FY 2004 Budget: $400 K
Approach

Develop, document & make available versatile system design and analysis tool

- GCtool: Stand-alone code on PC platform
- GCtool_ENG: Coupled to PSAT (MATLAB/SIMULINK)

Validate the models against data obtained in laboratory and at Argonne’s Fuel Cell Test Facility

Apply models to issues of current interest

- Work with FreedomCAR Technical Teams
- Work with DOE contractors as requested by DOE
### Project milestones

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
<th>Complete?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build models for components and systems</td>
<td>12/03</td>
<td>✓</td>
</tr>
<tr>
<td>Analyze data taken at ANL’s Fuel Cell Test Facility</td>
<td>01/04</td>
<td>✓</td>
</tr>
<tr>
<td>Establish efficiency targets for membrane based fuel processors</td>
<td>03/04</td>
<td>✓</td>
</tr>
<tr>
<td>Evaluate thermal and water management requirements and subsystem</td>
<td>07/04</td>
<td></td>
</tr>
<tr>
<td>Assess the effect of humidity on high-temperature membrane FC systems</td>
<td>05/04</td>
<td>✓</td>
</tr>
<tr>
<td>Evaluate performance of PEFC systems for combined heat and power</td>
<td>08/04</td>
<td></td>
</tr>
<tr>
<td>Analyze FC systems for hybrid vehicles</td>
<td>09/04</td>
<td></td>
</tr>
</tbody>
</table>
Reviewers’ comments

Focus on hydrogen fuel-cell systems
• Focus on hydrogen storage options (working with TIAX)
• Resolve benefits of high temperature membranes with regard to efficiency, performance and BOP (presentations to Tech Team and HTMWG)
• Plan verification with subsystem and component data from contractors (Honeywell/Emprise)

Closer communications with FreedomCAR Fuel Cell and Vehicle Teams
• Member of Fuel Cell Tech Team
• Participating in hybridization study with Joint Team
• Seek OEM validation of model results and proposed targets (presentation on Start-up Energy Consumption)
Code development in FY 2004

- Dynamic model of enthalpy wheel humidifier
- Membrane humidifier model
- Dynamic models of catalytic auto-thermal, shift and PrOx reactors

Enthalpy Wheel Model Simulation  Model Validation
Validated models against data taken at ANL’s Fuel Cell Test Facility

Analyzed test data for two systems from Nuvera
- Series SFAA 1A Fuel Cell System: 10 kWe, gasoline powered fuel cell system
- STAR System: 200 kWt

Major conclusions
- Possible to characterize FPS performance in terms of S/C, O/C and COx selectivity
- True efficiency, which includes LHV of fuel burned in TGC, is a better measure of FPS performance
Efficiency of membrane reactor-based fuel processors

- Why membrane reactors for WGS?
  - Eliminate difficult-to-control PrOx reactors
  - Shrink WGS reactor, simplify lay-out, remove HXs
  - Not having to deal with CO in PEFC stack is a plus

---

*Diagram of a membrane reactor-based fuel processor system.*
**Target efficiency needed for H₂ membrane reactor based FPS can be reduced to 68%**

- 100% H₂ recovery not required
- FPS will have to operate at elevated pressure
- Development of new compressor/expander module
- Maintaining efficiency at part load may be a challenge

---

[Graphs showing system efficiency and hydrogen recovery under different conditions.]

**System Efficiency, %**

- O/C=1.04, S/C= 2
- 80% H₂ recovery

**Reformer Pressure, atm**

- P= 12 atm
- P= 10 atm
- P= 8 atm
- P= 6 atm

**Carrier Steam Flow (Equiv. S/C)**

- 0, 1, 2, 3, 4
Thermal & Water Management
Pressurized FCS with condenser and two coolant circuits

- Large radiator (30 kg, 13.6 cm depth) and fan (700 W)
- Large heat duty on air pre-heater (20 kW, 90% RH)
- Difficult to maintain stack at 80°C at low loads

<table>
<thead>
<tr>
<th>FCS Rated Power</th>
<th>Radiator Depth (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 kW</td>
<td>5.4</td>
<td>21.9</td>
</tr>
<tr>
<td>65 kW</td>
<td>12</td>
<td>30.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Front Area</th>
<th>0.6 X 0.5 m²</th>
<th>Pitch</th>
<th>1.25 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator Fan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>700 W</td>
<td>Head</td>
<td>380 Pa</td>
</tr>
<tr>
<td>Coolant Inlet Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HT Radiator</td>
<td>70~80°C</td>
<td>LT Radiator</td>
<td>55~70°C</td>
</tr>
</tbody>
</table>

120 kW FCS for Mid-size Family Sedan

6.5% Grade
600 kg Payload

HT RAD
LT RAD
TIM
Condenser
Air Humidifier / Preheater

Hydrogen, Fuel Cells, & Infrastructure Technologies Program
Thermal & Water Management
Pressurized FCS with enthalpy wheel humidifier

- 5.6”Φ x 6” enthalpy wheel can supply air at 50-70% RH
- Only HT coolant loop needed
- Can maintain stack at 80°C at all loads

P = 1~2.5 atm, 40 rpm
Direct $H_2$ fuel cell system with high-temperature polymer membrane

Stack issues
- Faster ORR kinetics
- Reduced PGM loading
- Higher power density

BOP issues
- Air management system
- Heat rejection system
- Water recovery system

Effect of humidity on system architecture and size
- Analyzed four systems

<table>
<thead>
<tr>
<th>System</th>
<th>Membrane</th>
<th>Air Management</th>
<th>Humidification</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTM-PH</td>
<td>LTM (80°C)</td>
<td>CEM (2.5 atm)</td>
<td>90% RH</td>
</tr>
<tr>
<td>HTM-PH</td>
<td>HTM (120°C)</td>
<td>CEM (2.5 atm)</td>
<td>25% RH</td>
</tr>
<tr>
<td>HTM-PD</td>
<td>HTM (120°C)</td>
<td>CEM (2.5 atm)</td>
<td>Dry</td>
</tr>
<tr>
<td>HTM-AD</td>
<td>HTM (120°C)</td>
<td>Blower</td>
<td>Dry</td>
</tr>
</tbody>
</table>
High temperature membrane system BOP is unattractive if membrane must be humidified

- Why operate dry?
  - Water recovery is difficult at 120°C stack temperature.
  - Stack cannot be maintained at 120°C below 50% of rated power
- Incentive to develop membrane whose ionic conductivity does not depend on moisture
  - Elimination of air and fuel humidifiers, pre-heaters become compact
  - Stack can operate at 120°C at all loads
- HTM option is attractive if FCS is operated at near ambient pressure
  - Replace compressor/expander with blower
  - Stack more compact than in pressurized systems w/o an expander
Fuel economy of hybrid fuel cell vehicles

GCtool-PSAT model of load-following fuel cell vehicles

Results for mid-size family sedan
- 65-kW sustained at 100 mph
- 120-kW peak for Z-60 in 10s
- FCS/ICE FE multiplier 3.0 with 55 kW ESS vs. 2.5 with stand-alone FCS
Drive cycles affect improvement in fuel economy with hybridization

Change in fuel economy

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHDS</td>
<td>3%</td>
</tr>
<tr>
<td>FUDS</td>
<td>30%</td>
</tr>
<tr>
<td>US06</td>
<td>7%</td>
</tr>
<tr>
<td>J1015</td>
<td>34%</td>
</tr>
<tr>
<td>NEDC</td>
<td>19%</td>
</tr>
</tbody>
</table>

Braking energy/traction energy

<table>
<thead>
<tr>
<th>Drive Cycle</th>
<th>Braking Energy/Traction Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHDS</td>
<td>13%</td>
</tr>
<tr>
<td>FUDS</td>
<td>50%</td>
</tr>
<tr>
<td>US06</td>
<td>34%</td>
</tr>
<tr>
<td>J1015</td>
<td>53%</td>
</tr>
<tr>
<td>NEDC</td>
<td>35%</td>
</tr>
</tbody>
</table>
Fuel cell system efficiency at rated power has only a small effect on overall fuel economy

- FCS-1: 50% efficiency (680 mV, 780 W/kg) at rated power
- FCS-2: 40% efficiency (560 mV, 1150 W/kg) at rated power
- Less than 2 mpgge difference in FE on combined cycles
- Differences in fuel economy are even smaller with larger fuel cell systems
**Fuel cell systems for combined heat and power**

Mismatch between thermal and electric demands.
- Summer: High electric but low thermal demand
- Winter: Low electric but high thermal demand

Why heat pump with FC-CHP makes sense?
- Natural gas (NG) furnace, $2/kWh ($0.60/therm)
- Heat pump (HP) with central power (CP), $8/kWh
- Heat pump coupled with fuel cell system (FCS)

<table>
<thead>
<tr>
<th>Ambient Temp</th>
<th>Thermal Efficiency</th>
<th>Relative Energy Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HP</td>
<td>NG</td>
</tr>
<tr>
<td>°C</td>
<td>COP</td>
<td>%</td>
</tr>
<tr>
<td>10</td>
<td>3.6</td>
<td>80</td>
</tr>
<tr>
<td>0</td>
<td>3.0</td>
<td>80</td>
</tr>
<tr>
<td>-10</td>
<td>2.5</td>
<td>80</td>
</tr>
<tr>
<td>-20</td>
<td>2.2</td>
<td>80</td>
</tr>
</tbody>
</table>
Baseline: FCS + NG Furnace
Low utilization: 1.6 kWe peak power
Peak FC thermal eff: 46.9%
Waste heat is insufficient even to meet DHW demand
SH provided by NG furnace
Overall energy efficiency ~80%

Alternative: FCS + HP
High utilization: 5.2 kW peak power
Peak FC thermal eff: 53.3%
Waste heat used for DHW plus 37% of space heating (SH)
63% of SH provided by HP
Overall energy efficiency ~115%
30% fuel saving in winter months
Technology transfer and collaborations

Licensed GCtool to many domestic and international private enterprises, universities, national labs, and government affiliated organizations.

Collaborations and Interactions

- Enthalpy wheel humidifier: Emprise and Honeywell
- Thermal and water management: Honeywell
- Hydrogen storage: TIAX
- Hybrid vehicles: ANL-PSAT, Joint Battery, Fuel Cell and SEAT Tech Team
- High Temperature Membrane FC Systems: FreedomCAR Fuel Cell Tech Team and HTMWG
- Validation: ANL Fuel Cell Test Facility, Nuvera
Future work

- Fuel Cell – Battery Hybridization study with Joint Tech Team
- Initiate joint work with UTRC on ambient-pressure fuel cell systems
- Participate in validation effort
- Initiate study on cold start of fuel cell systems
- Fuel cell systems for combined heat and power
- Support fuel processor engineering projects at ANL
- Continue to support DOE/FreedomCAR development efforts