Steady State Modeling and Analysis of a De-Coupled Fuel Cell – Gas Turbine Hybrid for Clean Power Generation

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What?? Why??

• What is a solid oxide fuel cell?
  – Direct conversion of chemical energy to power

• What is a heat engine?
  – Combustion → Heat → Spins something → Power
    • Loses efficiency at each step
What is a FC-GT?

- Combination of systems
  - Improve on existing systems
  - Heat generated by fuel cell drives turbomachinery
- Fuel Cell (Heat) $\rightarrow$ Spin something $\rightarrow$ Power
Outline

• Background
• Literature Review
• Modeling Considerations
• Results
  – Design Space Investigation
  – Economic Analysis
• Conclusions
Real World Examples

GE 2003

UC Irvine – Siemens/Westinghouse

Mitsubishi
De-Coupled FC-GT

Fuel Cell → **Power** → Combustion → Heat → Spin Something → **Added Power**
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Literature Review

• Fuel Cell Modeling Approaches
  – Fuel cell modeling
    • Bulk/Spatially Resolved \(^1, 2\)
      – Simplest
    • Equivalent Circuit/Physical
      – Black Box \(^3\)
      – Nodal \(^4\)

Literature Review Cont..

• Gas Turbine Modeling
  – Brayton Cycle
    • Isentropic Relations
  – Refined w/ real world data
    • Compressor/Turbine maps


FC-GT Hybrids

• Modeling studies cite balance of of mass and energy into systems\textsuperscript{7, 8}
  – Maintaining thermal tolerance of SOFC
  – Mass flow of GT

• Most modeling based on system configurations\textsuperscript{9}
  – Bottoming cycle
  – Topping cycle

Topping Cycle: Benefits and Challenges

- **Benefits:**
  - Higher pressure ratios – higher OCV\(^8\)

- **Drawbacks:**
  - GT operates at constant mass flux – temp changes
    - Surge Margin \(^9\)
  - FC temp constant – changing mass flux
  - FC pressurization within turbine
    - No way to control temperature gradient – Tightly coupled\(^{10}\)

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Solutions

- Decoupling the system?\(^{11}\)
  - Additional control
  - Reduce risk
  - Hard to accomplish
- Thermal management\(^{12}\)
  - Internal reformation\(^{13}\)
    - Eliminate auxiliary systems

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Models using First Principles

• Compressor/Turbine:
  – Isentropic Relations:
    • \( \dot{W} = \dot{m}(h_{in} - h_{out}) \)
    • \( \eta_C = \frac{h_s - h_{in}}{h_{out} - h_{in}}, \eta_T = \frac{h_{In} - h_{out}}{h_{in} - h_s} \),
OTM Modeling

- OTM:
  
  \[ Q_{\text{Preheat}} = \dot{m} (h_{800^\circ C} - h_{C,\text{out}}) \]

  \[ R_T = 1 - \frac{(1 - X_{\text{feed}}) \cdot P_{\text{OTM}}}{X_{\text{feed}} \cdot (P_{\text{in}} - P_{\text{OTM}})} \]

  \[ \dot{n}_{O_2} = \alpha R_T \cdot X_{\text{feed}} \cdot \frac{\dot{m}_{C,\text{out}}}{M} \]

\[ P_{\text{in}} \quad O_2, N_2 \]

\[ P_{\text{OTM}} \quad \alpha O_2, N_2 \]
Fuel Cell Modeling

- Heat generated = Cooling of Steam Reforming
  \[ \Delta E = \dot{Q}_{Gen} - \dot{Q}_{Reform} \]

- Nernst Equation:
  \[ E(x) = \frac{-\Delta G_{rxn}}{2F} - \frac{RT}{F} \ln \left( \frac{X_{H_2O}(x)}{X_{H_2}(x) \cdot X_{O_2} \cdot \left( \frac{P_{GT}}{100\,kPa} \right)^{\frac{1}{2}}} \right) \]

- Mass Balance
  \[ X_{H_2}(x) = 1 + \frac{\varepsilon_{WGS}}{3} - \frac{2\dot{n}_{O_2} \cdot r}{3\dot{n}_{CH_4}} - \frac{W(1-r)}{6F \cdot \dot{n}_{CH_4}} \int_0^x i(x) \, dx \]
  \[ X_{H_2O}(x) = \frac{2\dot{n}_{O_2} \cdot r}{3\dot{n}_{CH_4}} - \frac{1+\varepsilon_{WGS}}{3} + \frac{W(1-r)}{6F \cdot \dot{n}_{CH_4}} \int_0^x i(x) \, dx \]

- Define current distribution along \((x)\)
  \[ i(x) = \frac{E(x) - V}{ASR} \]
## Nodal Fuel Cell

<table>
<thead>
<tr>
<th>Average Current Density (A/cm²)</th>
<th>Operating Voltage (V)</th>
<th>Hydrogen Utilization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>.77</td>
<td>.488</td>
</tr>
<tr>
<td>1.37</td>
<td>.791</td>
<td>.510</td>
</tr>
<tr>
<td>1.23</td>
<td>.815</td>
<td>.536</td>
</tr>
<tr>
<td>1.09</td>
<td>.840</td>
<td>.568</td>
</tr>
<tr>
<td>0.950</td>
<td>.863</td>
<td>.603</td>
</tr>
<tr>
<td>0.810</td>
<td>.887</td>
<td>.642</td>
</tr>
<tr>
<td>0.669</td>
<td>.910</td>
<td>.685</td>
</tr>
<tr>
<td>0.528</td>
<td>.936</td>
<td>.731</td>
</tr>
<tr>
<td>0.387</td>
<td>.951</td>
<td>.777</td>
</tr>
<tr>
<td>0.246</td>
<td>.965</td>
<td>.815</td>
</tr>
<tr>
<td>.105</td>
<td>.973</td>
<td>.831</td>
</tr>
</tbody>
</table>

### Graph

Graph showing the relationship between Current Density A/cm² and Length (cm) for various operating voltages and hydrogen utilization percentages.
Combustor Model

- Energy balance with products from OTM and FC

\[- \Delta E = \dot{n}_{\text{air}} h_{\text{air}} + \dot{n}_{\text{Anode}}(h_{\text{Anode}} + X_{\text{CO}}(L)) \cdot \]
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Design Space Investigation
Sensitivity Analysis

- Current Density: 55% of 82%
- OTM Back Pressure: 70% of 78%
- GT Pressure Ratio: 69% of 76%
- Compressor Efficiency: 74% of 76%
- Turbine Efficiency: 70% of 76%
- Turbine Inlet Temperature: 71% of 76%

75% FTE
## Results

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Value</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Density</td>
<td>0.50</td>
<td>0.105 – 1.5</td>
<td>A/cm²</td>
</tr>
<tr>
<td>Turbine Press.</td>
<td>1.5</td>
<td>0.3-2.5</td>
<td>MPa</td>
</tr>
<tr>
<td>Permeate Press.</td>
<td>50</td>
<td>50-250</td>
<td>kPa</td>
</tr>
<tr>
<td>η&lt;sub&gt;C&lt;/sub&gt;</td>
<td>80</td>
<td>70-85</td>
<td>%</td>
</tr>
<tr>
<td>η&lt;sub&gt;T&lt;/sub&gt;</td>
<td>88</td>
<td>75-90</td>
<td>%</td>
</tr>
<tr>
<td>Turbine Inlet</td>
<td>1200</td>
<td>1000-1700</td>
<td>K</td>
</tr>
<tr>
<td>ASR</td>
<td>.25</td>
<td>.18-.30</td>
<td>Ω·cm²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFC Voltage</td>
<td>0.936V</td>
<td>0.77-0.97V</td>
</tr>
<tr>
<td>Hydrogen Utilization</td>
<td>74.0%</td>
<td>48.8-83.1%</td>
</tr>
<tr>
<td>Anode Recirculation</td>
<td>59.6%</td>
<td>85.1-53.6%</td>
</tr>
<tr>
<td>Oxygen Recovered</td>
<td>49.7% of R_T</td>
<td>16.5-82.5%</td>
</tr>
<tr>
<td>dFC-GT Efficiency</td>
<td>75.4%</td>
<td>55.0-82.1%</td>
</tr>
</tbody>
</table>
Micro Turbines

Allows for high efficiency at lower pressure ratios!
# Potential Hydrogen Recovery

<table>
<thead>
<tr>
<th>SOFC Operating Voltage (Volts)</th>
<th>SOFC Exhaust H₂ Concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.972</td>
<td>9.10</td>
</tr>
<tr>
<td>0.951</td>
<td>16.4</td>
</tr>
<tr>
<td>0.910</td>
<td>28.7</td>
</tr>
<tr>
<td>0.863</td>
<td>39.7</td>
</tr>
<tr>
<td>0.815</td>
<td>48.4</td>
</tr>
<tr>
<td>0.770</td>
<td>55.0</td>
</tr>
</tbody>
</table>
Hydrogen Recovery
Economic Analysis

- **Cost Assumptions:**
  - Fuel - $4.50/therm
  - Grid - $0.05/kWh
  - Demand - $3.00/kW

- **Emission Assumptions:**
  - Fuel – 879 lb/therm
  - Grid – 116.39 lb/MWh
Meeting Peak Demand

• Efficiency Curves
  – Peaker vs dFC-GT
  – Varying efficiencies

• Operation at near design conditions > 95% of time
### Economic Conclusions

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capital Financing Costs</th>
<th>On-Site Fuel Costs</th>
<th>Grid energy &amp; demand costs</th>
<th>Total annual costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid dependent</td>
<td>-</td>
<td>-</td>
<td>$7,059,206</td>
<td>$7,059,206</td>
</tr>
<tr>
<td>Base-load CC + grid</td>
<td>$953,825</td>
<td>$2,249,604</td>
<td>$2,666,855</td>
<td>$5,870,285</td>
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<tr>
<td>‘Peaker’ GT</td>
<td>$1,192,281</td>
<td>$5,685,589</td>
<td>-</td>
<td>$6,877,871</td>
</tr>
<tr>
<td>dFC-GT</td>
<td>$2,384,563</td>
<td>$3,236,865</td>
<td>-</td>
<td>$5,621,428</td>
</tr>
</tbody>
</table>

### Technology

<table>
<thead>
<tr>
<th>Technology</th>
<th>On-Site Emissions of CO2 (tons)</th>
<th>Grid related Emissions (tons)</th>
<th>Total Emissions (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid dependent</td>
<td>-</td>
<td>55,336</td>
<td>55,336</td>
</tr>
<tr>
<td>Base-load CC + grid</td>
<td>29,254</td>
<td>19,888</td>
<td>49,142</td>
</tr>
<tr>
<td>‘Peaker’ GT</td>
<td>73,879</td>
<td>-</td>
<td>73,879</td>
</tr>
<tr>
<td>dFC-GT</td>
<td>42,079</td>
<td>-</td>
<td>42,079</td>
</tr>
</tbody>
</table>
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Outlook/Next Steps

• Pressurized/Pure Oxygen cathode tests:
  – Currently being worked on at CESI Lab

• Steam Reformation Tests:
  – Internal steam reformation able to thermally balance pressurized FC

• OTM Tests:
  – Ability to operate at lower pressure ratios
  – Pre-heating

• Transient Response
  – Dynamic modeling
Conclusions

• dFC-GT:
  – Retro-Fit capable
  – De-Coupling – Extra Control
  – Highly efficient hybrid – 75.4% FTE
    • .936V FC Operating Voltage
    • 74% H₂ utilization
  – Micro-Turbine Scaling
  – Economically feasible
    • Lower investment
    • Lower fuel costs

• The future is bright!

• QUESTIONS?
Thank You!