Systems Analysis of Fuel Cell Plant Configurations with Vent Gas Recirculation (VGR)

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Systems Engineering and Analysis
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Outline

• Motivation
• Application of VGR Concept to IGFC and NGFC Utility Scale Systems
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  – Results
• Application of VGR Concept to DG-SOFC Systems
  – Methodology
  – Results
• Conclusions
• Acknowledgments/Contact Information
Motivation

• Solid oxide fuel cell (SOFC) based systems are capable of achieving efficiencies of over 60 percent
  – Based on electrochemical fuel utilization (FU) of 90 percent
  – State-of-the-art SOFC typically operate at FU of less than 80 percent to prevent performance issues such as:
    • Fuel flow mal-distributions
    • Elevated performance degradation rates
    • Increased overpotentials
  – Simply recirculating the anode vent gas dilutes the fuel
    • Lowers electrochemical potential

Motivation

Proposed Solution

**Modified Fuel Cell System with Vent Gas Recirculation**

- Investigation of SOFC systems that feature recirculation of the residual fuel in the vent gas after CO₂ capture/dehydration
- **Concept Advantages:**
  - Allows system efficiency of **GREATER THAN** 70 percent (HHV)
  - Permits nearly 100 percent fuel utilization
  - Improves performance due to increased inlet and average chemical (Nernst) potential
  - Lowers single-pass stack fuel utilization
    - Enables reliable operation at high-system fuel utilization
    - Mitigates fuel mal-distribution concerns
  - Reduces airflow requirements
  - Eliminates the need for an oxy-combustor
Utility Scale IGFC and NGFC with Vent Gas Recirculation Concept
Utility Scale NGFC/IGFC Methodology

- **Applied to utility scale (~550 MWe) SOFC systems for analysis:**
  - Natural Gas Fuel Cell (NGFC) system
  - Integrated Gasification Fuel Cell (IGFC) system

- **A spreadsheet model was developed to discern general advantages of the proposed system:**
  - Recirculation rate, fuel utilization, capture rate, etc.
  - Used to guide Aspen cases

- **Aspen model modifications:**
  - CO level in CO₂ product designed to be less than 35 ppm (per NETL QGESS)
    - Cryogenic CO₂ purification used (auto-refrigeration)
    - WGS reactor or preferential oxidation (PROX) reactor used
  - Pure CO₂ and H₂O separations are assumed

*NETL, QGESS, CO₂ Impurity Design Parameters, August 2013, DOE/NETL-341/011212*
### Baseline Case Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IGFC</th>
<th>NGFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas Reformation</td>
<td>N/A</td>
<td>100% Internal</td>
</tr>
<tr>
<td>Gasifier</td>
<td>Conventional</td>
<td>N/A</td>
</tr>
<tr>
<td>Operating Pressure [atm]</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Overall FU [%]</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Cell Overpotential [mV]</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Degradation Rate [%/1000 h]</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Current Density [mA/cm²]</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Inverter Efficiency [%]</td>
<td>97</td>
<td>98</td>
</tr>
<tr>
<td>Stack Cost [$/kW]</td>
<td>225</td>
<td>225</td>
</tr>
<tr>
<td>Plant HHV Efficiency [%]</td>
<td>42.6</td>
<td>64.7</td>
</tr>
<tr>
<td>Plant COE [$/MWh] (excludes T&amp;S)</td>
<td>104.5</td>
<td>68.8</td>
</tr>
</tbody>
</table>
Utility Scale NGFC/IGFC Configurations

- **Baseline Case**
  - No VGR
  - No water gas shift (WGS) reactor
- **Configuration A**
  - No VGR
  - WGS reactor
- **Configuration B**
  - VGR
  - No WGS reactor
  - Preferential oxidation reactor (PROX)
- **Configuration C**
  - VGR
  - No WGS reactor
  - No PROX reactor
- **Configuration D (IGFC only)**
  - VGR
  - WGS reactor
  - PROX reactor
Results – IGFC Spreadsheet Model

Vent Gas Recirculation Fraction

WGS CO Conversion Efficiency = 30%

No H₂ Membrane
CO₂ Capture Rate = 95%

Source: NETL
Results – NGFC Spreadsheet Model

WGS CO Conversion Efficiency = 30%

Gross SOFC Efficiency with VGR / (Gross SOFC Efficiency without VGR)

No H₂ Membrane
CO₂ Capture Rate = 95%

Source: NETL
## Results Summary (NGFC/IGFC)

<table>
<thead>
<tr>
<th>NGFC System*</th>
<th>VGR Fraction</th>
<th>In-stack FU [%]</th>
<th>System FU [%]</th>
<th>WGS CO Conv. [%]</th>
<th>PROX Use</th>
<th>System Eff. [% HHV]</th>
<th>COE* [$/MWh]</th>
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<tbody>
<tr>
<td>Baseline Case</td>
<td>0</td>
<td>78.6</td>
<td>90.0</td>
<td>0</td>
<td>No</td>
<td>64.7</td>
<td>68.8</td>
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<tr>
<td>Configuration A</td>
<td>0</td>
<td>78.6</td>
<td>90.0</td>
<td>96.5</td>
<td>No</td>
<td>65.7</td>
<td>65.8</td>
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<tr>
<td>Configuration B</td>
<td>0.94</td>
<td>43.3</td>
<td>97.5</td>
<td>0</td>
<td>Yes</td>
<td>71.2</td>
<td>62.3</td>
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<tr>
<td>Configuration C</td>
<td>0.94</td>
<td>58.8</td>
<td>97.5</td>
<td>0</td>
<td>No</td>
<td>71.3</td>
<td>61.3</td>
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<table>
<thead>
<tr>
<th>IGFC System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Case</td>
</tr>
<tr>
<td>Configuration A</td>
</tr>
<tr>
<td>Configuration B</td>
</tr>
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<td>Configuration C</td>
</tr>
<tr>
<td>Configuration D</td>
</tr>
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</table>

* - Reported cost of electricity does not include transport and storage costs, NG price for NGFC cases = $6.13/MMBTU
Potential Impacts on SOFC Operation

- Applying the concept to an NGFC system with complete internal reformation eliminates the need for an air separation unit (ASU)
- The modified SOFC system with the baseline 140 mV overpotential assumption results in nearly the same efficiency as the un-modified system that assumes advanced performance of 70 mV overpotential
  - The modified system enables the SOFC pathways even if the advanced SOFC performance goal cannot be met
  - Conversely, if the performance goals are met, the system can be used to lower the capital cost [$/kW] of the overall system by operating at a higher current density (consequently at a higher power output) corresponding to the 140 mV overpotential
Distributed Generation
Scale NGFC with VGR Concept
The previously discussed investigations were applied to utility scale (≈550 MWe) IGFC and NGFC systems

- Need to explore the advantages of the system with VGR on a distributed generation (DG) SOFC system scale of ≈1 MWe

**Methodology**

- A baseline natural gas based DG-SOFC system was developed is Aspen based on an earlier developed ChemCAD model
  - DG NGFC system with complete internal reforming baseline case
- The baseline system will be extended to include the VGR concept
  - Systems with and without CO₂ capture have been explored
- A cryogenic CO₂ separation system and purification system similar to the utility scale system will be used initially
### Baseline Case Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IGFC</th>
<th>NGFC</th>
<th>DG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas Reformation</td>
<td>N/A</td>
<td>100% Internal</td>
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<td>98</td>
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<td>225</td>
<td>225</td>
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<td>Plant HHV Efficiency [%]</td>
<td>42.6</td>
<td>64.7</td>
<td>61.0</td>
</tr>
<tr>
<td>Plant COE [$/MWh] (excludes T&amp;S)</td>
<td>104.5</td>
<td>68.8</td>
<td>74.9</td>
</tr>
</tbody>
</table>
- Atmospheric SOFC
- 100 percent internal reformation
- Waste heat unutilized

Source: NETL
DG-SOFC System Configuration w/ VGR

- Atmospheric SOFC
- 100 percent internal reformation
- Waste heat unutilized

Source: NETL
DG-SOFC System Configurations

• **Baseline Case:**
  – DG-SOFC system without carbon capture/storage (CCS)

• **Configuration A:**
  – DG-SOFC system without CCS, but with VGR
  – Dehydration of flue gas only

• **Configuration B:**
  – DG-SOFC system with CCS, but without VGR

• **Configuration C:**
  – DG-SOFC system with CCS and VGR
### Results Summary (DG-SOFC)

<table>
<thead>
<tr>
<th>DG-SOFC System Case</th>
<th>VGR Fraction</th>
<th>CO₂ Capture Rate [%]</th>
<th>In-stack FU [%]</th>
<th>System FU [%]</th>
<th>System Eff. [% HHV]</th>
<th>COE [$/MWh]</th>
<th>Selling Price CO₂* [$/tonne]</th>
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<tbody>
<tr>
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<td>0</td>
<td>79</td>
<td>90</td>
<td>61.0</td>
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<td>No VGR, No CCS</td>
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<td></td>
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<tr>
<td>Configuration A</td>
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<td>79</td>
<td>90</td>
<td>57.9</td>
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<td>No VGR, CCS</td>
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<td>Configuration B</td>
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<td>VGR, No CCS</td>
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<td>Configuration C</td>
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<td>VGR, CCS</td>
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</tr>
</tbody>
</table>

- Concept results in lower COE when compared to a DG-SOFC system with CCS
- Efficiency gains and cost reductions are minimal without CCS (dehydration only)

* - To break even with VGR, no CCS Case
Conclusions (Utility Scale NGFC/IGFC)

- The performance and cost of IGFC, NGFC, and DG-SOFC system that incorporated the VGR concepts were investigated.
- A spreadsheet model of the process material flow was developed:
  - Modified fuel cell system has a potential to increase the IGFC and NGFC system efficiencies by up to 30%.
- Incorporation of the VGR concept into IGFC and NGFC cases with CCS demonstrated:
  - An efficiency gain of more than 6 percentage points:
    - Greater than 70 percent in NGFC case
  - A reduction in COE of nearly 10 percent.
  - A high electrochemical fuel utilization of 97.5 percent yet ensuring a reliable fuel cell stack operation with local utilizations potentially below 50 percent.
Conclusions – DG-SOFC System

• DG-SOFC system with VGR and CCS was found to result in a significantly higher performance and lower cost than a DG-SOFC system with CCS but without VGR
  – An efficiency gain of nearly 10 percentage points
  – ≈17 percent reduction in COE (@NG price of $6.13MM/Btu)

• The system performance of the DG-SOFC system with VGR and CCS was even higher than a DG-SOFC system without CCS
  – An efficiency gain of nearly 6 percentage points
  – The system operates at higher voltage and lower in-stack utilization
Conclusions – DG-SOFC System (2)

• The COE of the system with VGR and CCS was ≈$5/MWh higher than a DG-SOFC system without CCS
  – Alternate CCS technology with lower cost and auxiliary load demand than a cryogenic CPU can result in a COE comparable to the COE of the system without CCS
  – Potential applications that can use the captured CO₂ can be used to offset the COE difference
  – The COE differences between the system with VGR and CCS and the system without CCS become smaller as the NG price increases
  – The higher stack fuel flow has a potentially beneficial effect by spreading out the cooling effect of the internal reformation

• Operation of the system with VGR at higher current densities can potentially decrease the capital costs
  – Operation at the same voltage as that of system with CCS nearly doubles the operating current
Acknowledgments

NETL

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• Richard Newby
• Dale Keairns
• Mark Woods

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NETL SOFC Group Posters

• “Phase Field Modeling of Microstructure and Conductivity Evolution in SOFC Electrodes” – Youhai Wen
• “Effects of Humidity on Degradation of Sr-Fe-O Infiltrated Solid Oxide Fuel Cells” – Lynn Fan
• “Catalyst Infiltration of SOFC Electrodes Assisted by a Bio-surfactant” – Ozcan Ozmen
• “Characterization of SOFC Cathode Impedance under Polarization Using Appropriate Counter Electrode Design” – Jay Liu
• “Interpretation of Impedance Spectroscopy Data on Porous LSM Electrodes” – Giuseppe Brunello
• “Representative Volumes in Highly Heterogeneous Fuel Cell Materials” – Billy Epting
• “Ab Initio Modeling of Mn Self-Diffusion in La$_{1-x}$Sr$_x$MnO$_3$ (X=0 and 0.25) for Solid Oxide Electrochemical Cells” – Yueh-Lin Lee
• “Evidence of the Space Charge Layer Evolution at the YSZ Grain Boundaries” – Xueyan Song
Backup Slides
IGFC Pathway Results

All cases include 90% CO₂ capture

Source: NETL

NGFC Pathway Results

All cases include 90% CO₂ capture


Source: NETL
Power Generation Technology Comparison

Performance

Advanced NGFC
Advanced NGCC
Conventional NGFC*
SOTA NGCC
Advanced IGFC
Advanced IGCC
Advanced Oxy PC
Coal-NG Hybrid
Conventional IGFC*
Conventional IGFC*
SOTA PC
SOTA IGCC

Source: NETL

* 0.2% per 1000 h degradation, 70 mV overpotential, CF 85%

All systems with 90% CCS
Power Generation Technology Comparison

Cost of Electricity

- Advanced NGFC: 23 (Capital Charges), 5 (Fixed O&M), 8 (Variable O&M), 32 (Fuel) = 69 (Total)
- Advanced NGCC: 24 (Capital Charges), 5 (Fixed O&M), 3 (Variable O&M), 42 (Fuel) = 75 (Total)
- Conventional NGFC: 28 (Capital Charges), 6 (Fixed O&M), 8 (Variable O&M), 35 (Fuel) = 77 (Total)
- SOA NGCC: 27 (Capital Charges), 6 (Fixed O&M), 4 (Variable O&M), 46 (Fuel) = 83 (Total)
- Advanced IGFC: 37 (Capital Charges), 11 (Fixed O&M), 12 (Variable O&M), 18 (Fuel) = 79 (Total)
- Advanced IGCC: 42 (Capital Charges), 11 (Fixed O&M), 9 (Variable O&M), 25 (Fuel) = 86 (Total)
- Conventional IGFC: 57 (Capital Charges), 11 (Fixed O&M), 12 (Variable O&M), 24 (Fuel) = 104 (Total)
- SOA PC/IGCC: 72 (Capital Charges), 18 (Fixed O&M), 12 (Variable O&M), 31 (Fuel) = 133 (Total)

NG Based @ 6.13 $/MMBtu
Coal Based @ $68/ton

Source: NETL

Advanced fuel cell systems are competitive with NGCC systems