Performance Evaluation of a Supercritical CO₂ Power Cycle Coal Gasification Plant

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Principal Technical Leader

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- Brayton Power Cycle
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Introduction

- Supercritical CO₂ Cycles offer the potential for high net efficiency of 48.9% (HHV) \(^1\) from coal

- Advanced IGCC design, novel plant components

  - Investigation of sCO₂ Brayton coupled to a ‘conventional IGCC gasifier design’

  - IGCC Plant based on EPRI report 1015699 (2009) \(^2\)

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\(^1\) – R.J. Allam et al, “High efficiency and low cost of electricity generation from fossil fuels while eliminating atmospheric emissions, including carbon dioxide” GHGT-11 - 18th-22nd November 2012, Kyoto International Conference Center, Japan

Background - Base Case IGCC Plant

- Shell Syngas Cooler (SGC) design
- Medium pressure technology (43 barg)
- Oxygen purity 95% v/v
- Pressurized dry gas feed
- No CO shift or CO$_2$ removal
- Selexol acid gas removal
- GE 7FB combustion turbine + HRSG
Gasification with sCO₂ Brayton Power Cycle

- Coal gasified
- Resultant ‘Syngas’ processed
- Syngas compressed to >300 bara
- Combusted at low excess O₂ levels
- Supercritical CO₂ working fluid
- Expanded to produce power
- Recuperative heat exchanger
- Moisture condensed out
- CO₂ Gas Recompressed / Pumped
- Semi - Closed Loop
  - Export CO₂ available at high pressure
‘Closed’ Brayton Cycle

![Diagram of Closed Brayton Cycle]

- **Combustion Heat**
  - CO
  - H₂
  - O₂

- **Recovered Heat**
  - ~700°C
  - ~760°C

- **Pressure (bar)**
  - 0 to 400

- **Heat Rejection**
  - 0 to 2000

- **Specific Enthalpy (kJ/kg)**

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Plant Design Basis

- Conventional gasification system
- PRB Fuel
- 273 tonnes/hr feed (1470MWth HHV)
- \(\text{NH}_3, \text{COS, H}_2\text{S, Mercury removal}\)
- Steam Cycle 565°C / 125 bara
- Max 700°C \(\text{CO}_2\) feed to burner
- Turbine Inlet Temperature \(~1150°C\)
- Max 760°C gas turbine exhaust
- Heat Exchanger min 20°K approach
- \(\text{CO}_2\) delivered pressure \(~150\) bara
- 3 cases developed:
  - 1 Conventional Nitrogen Transfer Fluid
  - 2 Carbon Dioxide Transfer Fluid
  - 3 Case 2 except with High Purity Oxygen
Case 1 – N2TF

- Nitrogen transfer fluid (as before)
- Gasification plant – Syngas production unchanged
  - New power block – ultra high pressure gas turbine
  - Syngas cooler – complete boiler unit
  - ASU capacity increased, oxygen purity 95% v/v
  - Moderator steam remains

IGCC Output: Syngas Product

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition</th>
<th>v/v(w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>58.32%</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>27.91%</td>
<td></td>
</tr>
<tr>
<td>CO2</td>
<td>1.56%</td>
<td></td>
</tr>
<tr>
<td>N2</td>
<td>11.21%</td>
<td></td>
</tr>
<tr>
<td>Ar</td>
<td>0.86%</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>0.15%</td>
<td></td>
</tr>
</tbody>
</table>

Massflow: 375407 kg/hr
Case 2 – CO2TF

- Transfer Fluid sourced from CO₂ working fluid
- Nitrogen content reduced over 90% from Case 1
- Gasifier process changed – increased CO content
- No moderator steam, syngas CO₂ content higher
- Lower hydrogen content
- Oxygen purity at 95% v/v

<table>
<thead>
<tr>
<th>IGCC Output: Syngas Product</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO</td>
</tr>
<tr>
<td></td>
<td>H₂</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
</tr>
<tr>
<td></td>
<td>N₂</td>
</tr>
<tr>
<td></td>
<td>Ar</td>
</tr>
<tr>
<td></td>
<td>Others</td>
</tr>
</tbody>
</table>

Massflow: 388165 kg/hr
Case 3 – CO2TF (HPO)

- Similar to Case 2 except:
  - ASU Oxygen purity increased to 99.5% v/v
  - Nitrogen content reduced further by over 50%
  - Argon content very low

<table>
<thead>
<tr>
<th>IGCC Output: Syngas Product</th>
<th>Composition</th>
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<tbody>
<tr>
<td>CO</td>
<td>69.59% v/v(w)</td>
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<tr>
<td>H2</td>
<td>22.71% v/v(w)</td>
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<tr>
<td>CO2</td>
<td>6.94% v/v(w)</td>
</tr>
<tr>
<td>N2</td>
<td>0.50% v/v(w)</td>
</tr>
<tr>
<td>Ar</td>
<td>0.17% v/v(w)</td>
</tr>
<tr>
<td>Others</td>
<td>0.09% v/v(w)</td>
</tr>
<tr>
<td>Massflow</td>
<td>380393 kg/hr</td>
</tr>
</tbody>
</table>

Massflow: 380393 kg/hr
Compression Analysis – Pure CO$_2$

Power (kJ/kg) vs. Inlet Pressure (bara)

- **Diatonic Gas**
- **Gas-like**
- **Dense Phase - 'Liquid-like'**
- **Incompressible: Liquid**

Critical Pressure: 73.8 bara

$\rho = 750$ kg/m$^3$
Compression Analysis – Case 1

CO2 80.05% v/v(w)
N2 15.89% v/v(w)
AR 3.30% v/v(w)
O2 0.58% v/v(w)
H2O 0.18% v/v(w)

Dense Phase - 'Liquid-like'

\( \rho = 200 \text{ kg/m}^3 \)

Inlet Pressure (bara)

Power (kJ/kg)
Compression Analysis – Case 2

CO2 93.19% v/v(w)
N2 2.23% v/v(w)
AR 3.83% v/v(w)
O2 0.57% v/v(w)
H2O 0.18% v/v(w)

Dense Phase - 'Liquid-like'

\( \rho = 280 \text{ kg/m}^3 \)

Critical Pressure 73.8 bara

Gas-like

Incompressible: Liquid

Power (kJ/kg)

Inlet Pressure (bara)
Compression Analysis – Case 3

Dense Phase - 'Liquid-like'

ρ = 405 kg/m³

Inlet Pressure (bara)

Power (kJ/kg)

CO2 98.06% v/v(w)
N2 0.68% v/v(w)
AR 0.48% v/v(w)
O2 0.59% v/v(w)
H2O 0.18% v/v(w)
Performance Results - Product Purity

- Case 1 N2 TF: Min CO2 Purity = 90% (within range)  
- Case 2 CO2 TF: Min CO2 Purity = 90% (within range)  
- Case 3 CO2 TF HPO: Min CO2 Purity = 90% (within range)
Performance Results - Power

- Low purity CO$_2$ working fluid delivers more power but not within product specification.
- Case 3 (HPO) meets specification and achieves near 100% capture with similar power output.
Performance Results

<table>
<thead>
<tr>
<th>Case</th>
<th>IGCC w/o Capture</th>
<th>sCO₂ Case 1</th>
<th>sCO₂ Case 2</th>
<th>sCO₂ Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer Fluid</td>
<td>N₂</td>
<td>N₂</td>
<td>CO₂</td>
<td>CO₂</td>
</tr>
<tr>
<td>Oxygen Purity</td>
<td>v%</td>
<td>95</td>
<td>95</td>
<td>95</td>
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<tr>
<td>Fuel Input</td>
<td>MWth</td>
<td>1470</td>
<td>1470</td>
<td>1470</td>
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<tr>
<td>GT/Expander Power</td>
<td>MWe</td>
<td>464</td>
<td>922</td>
<td>864</td>
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<tr>
<td>Steam Turbine Power</td>
<td>MWe</td>
<td>235</td>
<td>52.3</td>
<td>58.4</td>
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<tr>
<td>CO₂ Compression</td>
<td>MWe</td>
<td>-</td>
<td>95.0</td>
<td>86.3</td>
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<tr>
<td>CO₂ Pumps</td>
<td>MWe</td>
<td>-</td>
<td>113.6</td>
<td>87.2</td>
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<tr>
<td>Fuel Compression</td>
<td>MWe</td>
<td>-</td>
<td>46.6</td>
<td>43.4</td>
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<tr>
<td>Oxygen Supply (ASU/Comp)</td>
<td>MWe</td>
<td>74.4</td>
<td>91.1</td>
<td>90.7</td>
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<tr>
<td>Gasifier Auxiliary</td>
<td>MWe</td>
<td>16.2</td>
<td>16.2</td>
<td>16.2</td>
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<tr>
<td>Plant Auxiliary</td>
<td>MWe</td>
<td>19.3</td>
<td>14.7</td>
<td>14.9</td>
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<tr>
<td>Net Power Exported*</td>
<td>MWe</td>
<td>587.9</td>
<td>596.0</td>
<td>582.4</td>
</tr>
<tr>
<td>Overall Plant Efficiency</td>
<td>% HHV</td>
<td>40.0</td>
<td>40.5</td>
<td>39.6</td>
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<tr>
<td>Capture Rate</td>
<td>%</td>
<td>0</td>
<td>99.5</td>
<td>99.3</td>
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<tr>
<td>CO₂ Emission</td>
<td>lb/MWh</td>
<td>1770</td>
<td>11.6</td>
<td>12.9</td>
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<tr>
<td>CO₂ Emission</td>
<td>g/kWh</td>
<td>803</td>
<td>5.3</td>
<td>5.9</td>
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<tr>
<td>CO₂ Product Flow</td>
<td>lb/h</td>
<td>-</td>
<td>1,211,335</td>
<td>1,092,124</td>
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<tr>
<td>CO₂ Product Flow</td>
<td>kg/h</td>
<td>-</td>
<td>549,483</td>
<td>495,407</td>
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<tr>
<td>CO₂ Product Purity</td>
<td>v% wet</td>
<td>-</td>
<td>80.1</td>
<td>93.2</td>
</tr>
</tbody>
</table>

...with near 100% capture, performance close to IGCC without capture!
Technical Risks

- Higher Pressure Gasification
- Exchanger and Piping
- Combustor Design – ultra low oxygen
- Expander Design
  - Integrally cooled HP blades
  - High temperature materials
- High & low temperature corrosion
- CO₂ Product Purity (oxygen)
- Ultra high pressure CO₂ Safety
Conclusions and Recommendations

- Superior low carbon performance
- Proven gasification technology
- Near 100% capture
- Opportunities to improve efficiency

Future areas of investigation
- sCO$_2$ turbine development
- Combustion performance
- Heat exchanger cost reduction
- Economic cycle optimization
- Product gas purity improvement
Together...Shaping the Future of Electricity