Pilot Testing of a Highly Efficient Pre-combustion Sorbent-based Carbon Capture System
(Contract No. DE-FE-0013105)

Gökhan Alptekin, PhD
Ambal Jayaraman, PhD
Matt Cates
Mike Bonnema
David Gribble
Jim Dippo

2019 DOE/NETL CO₂ Capture Technology Meeting

August 28, 2019
Project Summary

• The objective is to develop a new sorbent-based pre-combustion capture technology for Integrated Gasification Combined Cycle (IGCC) power plants

• Demonstrate techno-economic viability of the new technology by:
  1) Evaluating technical feasibility in 0.1 MW\textsubscript{e} slipstream tests
  2) Carrying out high fidelity process design and engineering analysis

• Major Project Tasks
  ✓ Sorbent Manufacturing
    ✓ Performance validation via long-term cycling tests
  ✓ Reactor Design
    ✓ CFD Analysis and PSA cycle optimization/adsorption modeling
  ✓ Fabricate a Pilot-scale Prototype for Demonstration
  • Evaluations at various sites using coal-derived synthesis gas
  • Techno-economic analysis
    • High fidelity engineering analysis and process simulation
Project Partners

Project Duration
• Start Date = January 1, 2014
• End Date = September 30, 2019*

Budget
• Project Cost = $9,929,228
• DOE Share = $7,943,382
• TDA and its partners = $1,985,846

* 12 month no cost time extension is requested from DOE
TDA’s uses a mesoporous carbon with surface functional groups that remove CO₂ via strong physical adsorption

- CO₂-surface interaction is strong enough to allow operation at elevated temperatures
- Because CO₂ is not bonded via a covalent bond, energy input for regeneration is low

**Heat of CO₂ adsorption is 4.9 kcal/mol for TDA sorbent**

- Net energy loss in sorbent regeneration is similar to Selexol; much higher IGCC efficiency can be achieved due to high temperature CO₂ capture

**Favorable material properties**
- Pore size is tuned to 10 to 100 Å
- Mesopores eliminates diffusion limitations

US Pat. Appl. 61790193, Alptekin, Jayaraman, Copeland “Pre-combustion CO₂ Capture System Using a Regenerable Sorbent”
Integration to the IGCC Power Plant

Advantages

- Higher mass throughput to gas turbine – higher efficiency
- Lower GT temperature – Reduced need for HP N₂ dilution hence lower NOₓ formation
- Elimination of heat exchangers needed for cooling and re-heating the gas
- Elimination of gray water treatment problem
- Potential for further efficiency improvements via integration with WGS
Operating Conditions

- CO₂ is recovered via combined pressure and concentration swing
  - CO₂ recovery at ~150 psia reduces energy need for CO₂ compression
  - Small steam purge ensures high product purity
- Isothermal operation eliminates heat/cool transitions
  - Rapid cycles reduces cycle time and increases sorbent utilization
- Similar PSA systems are used in commercial H₂ plants and air separation plants

**Adsorption**
- Syngas Inlet 240°C, 500 psia
- 40% CO₂
- $P_{CO_2} = 200$ psia

**Desorption**
- Regen. Exit 240°C, 150 psia
- 50% CO₂/Steam
- $P_{CO_2} = 75$ psia

- Regen. Inlet 250°C, 158 psia
- 100% H₂O
- $P_{CO_2} = 0$ psia

Source: Honeywell/UOP
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tests</td>
<td>Bench-scale tests at NCCC</td>
<td>0.5-1 kW tests at Wabash River IGCC</td>
<td>Sorbent Scale-up</td>
<td>0.1 MW tests at NCCC</td>
<td>Integrated with WGS Tests with Praxair</td>
<td>0.1 MW Tests at Sinopec/Yangtze Chem. Nanhua Plant</td>
<td></td>
</tr>
</tbody>
</table>
Primary Focus

- 0.1 MW$_e$ evaluation in a world class IGCC plant to demonstrate full benefits of the technology
  - Testing with high pressure gas
- Demonstrate full operation scheme
  - 8 reactors and all accumulators
  - Utilize product/inert gas purges
  - H$_2$ recovery/CO$_2$ purity
- Evaluations at various sites using coal-derived syngas
  - Field Test #1 at NCCC – Air blown gasification
  - Field Test #2 at Sinopec Nanhua Petro-chemical Plant, Nanjing, Jiangsu Province, China – Oxygen blown gasification

<table>
<thead>
<tr>
<th>Nanhua Plant Syngas Supply</th>
<th>Composition</th>
<th>mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H$_2$</td>
<td>32.493</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>0.546</td>
</tr>
<tr>
<td></td>
<td>CO$_2$</td>
<td>24.715</td>
</tr>
<tr>
<td></td>
<td>H$_2$S</td>
<td>0.083</td>
</tr>
<tr>
<td></td>
<td>COS</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>C$_1$</td>
<td>0.021</td>
</tr>
<tr>
<td></td>
<td>N$_2$</td>
<td>0.128</td>
</tr>
<tr>
<td></td>
<td>AR</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>NH$_3$</td>
<td>0.069</td>
</tr>
<tr>
<td></td>
<td>HCN</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>HCL</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>H$_2$O</td>
<td>41.895</td>
</tr>
</tbody>
</table>

Nanhu Plant Syngas Supply

- Temperature, $^\circ$C: 265.6
- Pressure, MPaG: 4
Field Test Unit Installed at NCCC

- Fabrication is completed in 2016
- Installation with all the hook-ups were completed in March 2017
- Testing initiated in April 2017
A successful 30 day (707 hrs) evaluation was completed at NCCC

- Design flow at NCCC operating conditions was 1,420 SLPM (50 SCFM)
- 97.3% capture @ 1,500 SLPM
- 93% @ 1,800 SLPM
- 90% @ 2,100 SLPM
- Pressure drop through the gas conditioning skid prevented flowing more than 2,100 SLPM of syngas through the PSA skids
Sorbent Performance

- Sorbent/PSA system maintained slightly higher CO₂ capacity than the earlier field tests at NCCC at ~60X scale
- At Sinopec we expect to achieve higher capacity than in the previous oxy-fired gasification tests at Wabash River IGCC power plant
- Total Pressure – 340 vs 500 psia
  - CO₂ Partial pressure <2X due to lower N₂ content and high syngas P
Sorbent Evaluations – Multiple Cycles

- Long-term cycling of the scaled-up sorbent has been completed with stable performance over 60,000 cycles

<table>
<thead>
<tr>
<th></th>
<th>Synthesis Gas</th>
<th>Simulated Gas</th>
<th>Steam Purge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>200°C</td>
<td>200°C</td>
<td>200°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>500 psig</td>
<td>200-500 psig</td>
<td>50-300 psig</td>
</tr>
<tr>
<td>Composition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂</td>
<td>42.8%</td>
<td>53.4%</td>
<td>50.0%</td>
</tr>
<tr>
<td>CO₂</td>
<td>30.0%*</td>
<td>30.0%</td>
<td>-</td>
</tr>
<tr>
<td>H₂O</td>
<td>26.6%</td>
<td>26.6%</td>
<td>50.0%⁺</td>
</tr>
<tr>
<td>CO</td>
<td>0.6%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*adjusted for purge with 100% steam at 150 psia
• Working with GTI, we developed a CFD model to support reactor design
• The model was tuned using the data from 1 kW and 0.1 MW systems evaluated at Wabash River IGCC Plant and NCCC field tests
• CFD simulations reached steady state in 6 cycles and the working capacity matched the data sets
• CFD model will be further tuned using data from Sinopec field datasets
Cycle Optimization

• Cycle Schemes D, E and F that use pressure equalizations and co-current blowdown met DOE targets of 90% capture and 95% CO₂ purity
Minimization of Energy Penalty

- Configuration F: 10-step PSA cycle with three pressure equalizations: 95.7 kWh/tonne of CO₂ captured at productivity of 3.3 mol CO₂/m³/s
- Configuration D: 6-step PSA cycle with one pressure equalization and a co-current blowdown: 140 kWh/tonne of CO₂ captured at productivity of 5.2 mol CO₂/m³/s
- OPEX/CAPEX trade-off is being evaluated for a fully optimized PSA cycle
Different reactor concepts have been evaluated

Multiple train vertical reactors with internal flow distribution are selected for final design

<table>
<thead>
<tr>
<th>GE Gasifier</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Syngas flow, kmol/h</td>
<td>34,747</td>
</tr>
<tr>
<td>Sorbent needed, kg</td>
<td>1,115,903</td>
</tr>
<tr>
<td></td>
<td>1,859,838</td>
</tr>
<tr>
<td>Cycle time, min</td>
<td>8</td>
</tr>
<tr>
<td>Ads. GHSV, h⁻¹</td>
<td>1,117</td>
</tr>
<tr>
<td>Total Beds</td>
<td>16</td>
</tr>
<tr>
<td>Bed. Volume, L</td>
<td>116,240</td>
</tr>
</tbody>
</table>

**Bed Dimensions**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, ft</td>
<td>14</td>
</tr>
<tr>
<td>Length, ft</td>
<td>30.1</td>
</tr>
<tr>
<td>Vessel wall thickness, in</td>
<td>5.0</td>
</tr>
<tr>
<td>L/D</td>
<td>2.30</td>
</tr>
<tr>
<td>Particle size, in</td>
<td>1/8</td>
</tr>
<tr>
<td>Bed Pressure drop, psid</td>
<td>3.6</td>
</tr>
</tbody>
</table>

World-class PSA systems used in H₂ purification produces up to 400,000 m³/hr H₂ (compared to ~780,000 m³/hr flow rate used in TEA base case)
Full-scale System Design

Major Units
- 8 beds x 2 = 16
- 2 accumulator X 2 = 4
- Cycling Valves
  - 6 x 8 x 2 = 96
- 2 recycle compressors
- 2 isolation vales x 2 per train = 4
### Techno-economic Analysis

<table>
<thead>
<tr>
<th>Gasifier</th>
<th>E-Gas</th>
<th>GE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Capture Technology</td>
<td>Cold Gas Cleanup</td>
<td>Warm Gas Cleanup</td>
</tr>
<tr>
<td>TDA’s CO₂ Sorbent</td>
<td>Selexol™</td>
<td>TDA’s CO₂ Sorbent</td>
</tr>
<tr>
<td>CO₂ Capture, %</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Gross Power Generated, kW</td>
<td>710,789</td>
<td>670,056</td>
</tr>
<tr>
<td>Gas Turbine Power</td>
<td>464,000</td>
<td>425,605</td>
</tr>
<tr>
<td>Steam Turbine Power</td>
<td>246,789</td>
<td>244,450</td>
</tr>
<tr>
<td>Syngas Expander Power</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Auxiliary Load, kW</td>
<td>194,473</td>
<td>124,138</td>
</tr>
<tr>
<td>Net Power, kW</td>
<td>516,316</td>
<td>545,917</td>
</tr>
<tr>
<td>Net Plant Efficiency, % HHV</td>
<td>31.0</td>
<td>34.1</td>
</tr>
<tr>
<td>Coal Feed Rate, kg/h</td>
<td>220,549</td>
<td>212,265</td>
</tr>
<tr>
<td>Raw Water Usage, GPM/MW</td>
<td>10.9</td>
<td>10.3</td>
</tr>
<tr>
<td>Total Plant Cost, $/kW</td>
<td>3,464</td>
<td>3,102</td>
</tr>
<tr>
<td>COE without CO₂ TS&amp;M, $/MWh</td>
<td>136.8</td>
<td>122.3</td>
</tr>
<tr>
<td>COE with CO₂ TS&amp;M, $/MWh</td>
<td>145.7</td>
<td>130.4</td>
</tr>
<tr>
<td>Cost of CO₂ Capture, $/tonne</td>
<td>43</td>
<td>30</td>
</tr>
</tbody>
</table>

- IGCC plant with TDA’s CO₂ capture system achieves higher efficiencies (34.5% and 34.1%) than IGCC with Selexol™ (32.0% and 31.0%) for E-Gas™ and GE gasifiers.
- Cost of CO₂ capture is calculated as $31 and $30 per tonne for GE and E-Gas™ gasifiers, respectively (16-30% reduction against Selexol™).
- Cost of CO₂ capture is calculated as $40 and $28 per tonne for Shell and TRIG gasifiers, respectively (15-28% reduction against Selexol™).
Sinopec Field Test Update

- 2 skids and 2 containers (containing sorbents, catalyst, analyzers, supplies, toolboxes) are shipped to China in December 2017
- Both skids and one of the containers were delivered to the site on April 2018
- One skid held up due to the hazardous nature of the WGS catalyst and regulations on some of the power equipment
- Catalyst, transformer, fiber optic cable etc. were procured locally
Installation Work at Sinopec

• Because of the delays getting all equipment to site, the test setup had to be moved to a different location in the plant
• An existing super-structure at the new site added complexity to installation
  • Skids were pipe rolled over berm and into place
  • Vessels were loaded manually via socks and buckets
Carbon Bed Filling

- Stainless mesh screens and Denstone deltaP media are added to the beds (not available in NCCC tests)
  - The inert ceramic beads eliminated some of the dead volume in the reactor top and bottom
  - Heavy Denstone beads also limits material movement in the bed during cycling
Pipework and Utility Connections

- Sinopec completed all needed site modifications and installations in the plant
  - Syngas Inlet Line – 120 m insulated line
  - Syngas Return Line – 120 m insulated line (high emphasis on reserving as much H₂ as possible)
  - Exhaust/flare lines – 120 m
  - High and Low P nitrogen – 100 m
  - Instrument air – 100 m
  - Cooling water lines inlet and return – 15 m
  - Electrical connections – 400 m
    - 400VAC to 480VAC transformer procured from China was installed
    - Fiber optic lines from the control room to the skid PC – 450 m
Pilot Plant Installed at Sinopec
Shakedown Tests

- All leak checks were completed
  - Long road trip from NCCC Alabama to Los Angeles, ocean travel to Shanghai, followed by another road trip to Nanjing
  - Skids were lifted several times China (one improperly despite having a specified lift plan)
- Pressure decay testing was performed at 4.0 MPag
- All heaters, heated lines were tested
Very Early Results

- Testing started on 8/27/2019 at 21:50 MST
- High syngas flow, high T, low P during start-up to avoid water/tar condensation in the system
- 2500 SLPM Syngas Flow
- ~85% CO₂ removal efficiency
- ~110 kg/hr CO₂ removal rate
Next Steps

- A fiber optic cable with adapters to Ethernet at both ends will be installed to allow monitoring the equipment from the USA and for data transfer
  - The distance from the skids to the control room is roughly 400m
- Training of plant personnel is underway
- Within 2-3 weeks of routine operation, TDA will let Sinopec/Yangtze employees to run the unit (basic maintenance etc.)
- 6 to 9 month evaluation is planned
Acknowledgements

- DOE/NELT funding under the DE-FE-0013105 project
- Project Manager, Andy O’Palko
- Chuck Shistla, GTI
- Ashok Rao, UCI
- Arvind Rajandran, UOA
- Frank Morton, NCCC
- Chen Chaomei and Ruan Tian, Sinopec
- Yang Xujie, Yangtze Petrochemicals Nanhua Plant