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

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2021 Carbon Management and Oil and Gas Research Project Review Meeting

Point Source Capture — Lab, Bench, and Pilot-Scale Research
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Project Summary

• To develop a new sorbent-based pre-combustion capture technology
• Demonstrate techno-economic viability of the new technology by:
  1) Evaluating technical feasibility in 0.1 MWₑ slipstream tests
  2) Carrying out high fidelity process design and engineering analysis

• Major Project Tasks
  ✓ Sorbent Manufacturing
    ✓ Long-term cycling tests
  ✓ Reactor Design
    ✓ CFD Analysis/PSA cycle optimization
  ✓ Fabricate a Prototype for Demonstration
  ✓ Evaluations at various sites using coal-derived synthesis gas
  ✓ Techno-economic analysis
• Decommissioning and Shipping from China

Project Duration
• Start Date = January 1, 2014
• End Date = March 31, 2022

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

- TDA’s uses a mesoporous carbon with surface functional groups that remove CO$_2$ via strong physical adsorption
  - CO$_2$-surface interaction is strong enough to allow operation at elevated temperatures
  - Because CO$_2$ is not bonded via a covalent bond, energy input for regeneration is low
- Heat of CO$_2$ 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 CO$_2$ capture
- Favorable material properties
  - Pore size is tuned to 10 to 100 Å
  - Mesopores eliminate diffusion limitations

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

- CO$_2$ is recovered via combined pressure and concentration swing
  - CO$_2$ recovery at ~150 psia reduces energy need for CO$_2$ 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 H$_2$ plants and air separation plants

Source: Honeywell/UOP
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

### Nanhua Plant Syngas Supply

<table>
<thead>
<tr>
<th>Composition</th>
<th>mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>32.493</td>
</tr>
<tr>
<td>CO</td>
<td>0.546</td>
</tr>
<tr>
<td>CO2</td>
<td>24.715</td>
</tr>
<tr>
<td>H2S</td>
<td>0.083</td>
</tr>
<tr>
<td>COS</td>
<td>0</td>
</tr>
<tr>
<td>C1</td>
<td>0.021</td>
</tr>
<tr>
<td>N2</td>
<td>0.128</td>
</tr>
<tr>
<td>AR</td>
<td>0.05</td>
</tr>
<tr>
<td>NH3</td>
<td>0.069</td>
</tr>
<tr>
<td>HCN</td>
<td>0</td>
</tr>
<tr>
<td>HCL</td>
<td>0</td>
</tr>
<tr>
<td>H2O</td>
<td>41.895</td>
</tr>
</tbody>
</table>

**Temperature, °C:** 265.6

**Pressure, MPaG:** 4
Slipstream Test Skid - Top View

- CO$_2$ Sorbent Vessels
- Recirculation buffer tanks
- Inlet/Outlet Accumulators
- Trace Contaminant Removal
- 2-Stage (Lead/Lag) Bulk Desulfurizers
- LTWGS Reactor
- 2-Stage HTWGS Reactors
Field Test Unit Installed at NCCC
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
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
  - WGS catalyst, transformer, fiber optic cable etc. were procured locally
- An existing super-structure at the new site added complexity to installation
  - Skids were pipe rolled over berm
  - Vessels were loaded manually via socks and buckets
Pilot Plant Installed at Sinopec
Test 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
Bed Temperatures

- Bed temperature gradients matched our estimates and model predictions
- Larger gradients were evident in the syngas inlet side, while smaller gradients at the CO$_2$ free syngas end
- DeltaT of ~20-30°C was as predicted in the CFD simulations at GTI
Parametric Tests

- ~150 hours of testing with over 1,000 adsorption/desorption cycles were carried out using the same T cycle used at NCCC
  - ~86% CO₂ removal efficiency
  - ~110 kg/hr CO₂ removal rate
- While a higher CO₂ adsorption capacity was observed than the evaluations at the NCCC, the removal efficiency were slightly lower than 90% due to the much higher amount of CO₂ that needed to be removed
  - A new cycle sequence was generated with shorter cycle time to switch the bed positions prior to CO₂ breakthrough, but not implemented
## Summary of Test Results

### Parameters Varied:
- **Syngas Flow = 1500 to 2800 SLPM**
- **Steam Flow = 200 to 1200 SLPM**
- **Bed Temperature = 190 to 290°C**
- **Adsorption Pressure = 130 to 300 psia**
- **Desorption Pressure = 35 to 80 psia**

### System Performance:
- **65-86% CO₂ removal efficiency**
- **Up to 122 kg/hr CO₂ removal rate**
- **3X the CO₂ removal rate compared to our tests at NCCC**

<table>
<thead>
<tr>
<th>feed (SLPM)</th>
<th>steam (SLPM)</th>
<th>syngas product (SLPM)</th>
<th>CO₂ and steam out (SLPM)</th>
<th>ads (°C)</th>
<th>des (°C)</th>
<th>bed T (°C)</th>
<th>Feed (%)</th>
<th>HP product (%)</th>
<th>CO₂ removed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,942</td>
<td>600</td>
<td>1,014</td>
<td>1,272</td>
<td>276</td>
<td>61</td>
<td>213</td>
<td>48</td>
<td>13</td>
<td>86%</td>
</tr>
<tr>
<td>1,983</td>
<td>1,200</td>
<td>1,486</td>
<td>1,262</td>
<td>298</td>
<td>61</td>
<td>192</td>
<td>45</td>
<td>11</td>
<td>83%</td>
</tr>
<tr>
<td>1,953</td>
<td>580</td>
<td>1,029</td>
<td>1,314</td>
<td>293</td>
<td>57</td>
<td>218</td>
<td>45</td>
<td>13</td>
<td>85%</td>
</tr>
<tr>
<td>2,174</td>
<td>892</td>
<td>1,185</td>
<td>1,273</td>
<td>304</td>
<td>36</td>
<td>214</td>
<td>47</td>
<td>14</td>
<td>84%</td>
</tr>
<tr>
<td>2,659</td>
<td>600</td>
<td>1,062</td>
<td>1,761</td>
<td>246</td>
<td>51</td>
<td>183</td>
<td>45</td>
<td>15</td>
<td>86%</td>
</tr>
<tr>
<td>2,648</td>
<td>1,199</td>
<td>1,593</td>
<td>1,513</td>
<td>305</td>
<td>72</td>
<td>225</td>
<td>48</td>
<td>17</td>
<td>78%</td>
</tr>
<tr>
<td>2,752</td>
<td>253</td>
<td>2,060</td>
<td>481</td>
<td>298</td>
<td>59</td>
<td>249</td>
<td>37</td>
<td>17</td>
<td>65%</td>
</tr>
<tr>
<td>859</td>
<td>129</td>
<td>556</td>
<td>128</td>
<td>134</td>
<td>79</td>
<td>288</td>
<td>46</td>
<td>15</td>
<td>78%</td>
</tr>
</tbody>
</table>
Sinopec has completed the extract the rigs from the plant

The pick-up is scheduled (scheduling of cranes and the crew)

All used sorbents and catalysts have been removed from their tanks and will be disposed of by Sinopec

Due to the international shipment bottleneck, our shipment is wait-listed, with the expectation of shipping the units in couple of months
Sorbent Life Tests

- 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.
PSA Cycle Optimization

D. 6-step PSA cycle with CoBLO, purge, PREQ & LPP

E. 8-step PSA cycle with CnBLO, purge, two PREQ & LPP

F. 10-step PSA cycle with CnBLO, purge, three PREQ & LPP

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- Cycle Schemes D, E and F that use pressure equalizations and co-current blowdown met DOE targets of 90% capture and 95% CO$_2$ purity
Reactor Design

- Different reactor concepts have been evaluated
- Multiple train vertical reactors with internal flow distribution are selected for final design

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)

Source: Honeywell/UOP

<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>L</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

| Diameter, ft | 14 |
| Length, ft | 30.1 |
| Vessel wall thickness, in | 5.0 |
| L/D | 2.30 |
| Particle size, in | 1/8 |
| Bed Pressure drop, psid | 3.6 |
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>CO₂ Capture Technology</th>
<th>E-Gas</th>
<th>GE</th>
<th>Shell</th>
<th>TRIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Capture, %</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Gross Power Generated, kW</td>
<td>707,165</td>
<td>669,993</td>
<td>727,416</td>
<td>674,790</td>
</tr>
<tr>
<td>Gas Turbine Power</td>
<td>464,000</td>
<td>425,761</td>
<td>464,000</td>
<td>417,083</td>
</tr>
<tr>
<td>Steam Turbine Power</td>
<td>243,165</td>
<td>244,232</td>
<td>257,250</td>
<td>247,362</td>
</tr>
<tr>
<td>Syngas Expander Power</td>
<td>-</td>
<td>-</td>
<td>6,166</td>
<td>10,345</td>
</tr>
<tr>
<td>Auxiliary Load, kW</td>
<td>194,495</td>
<td>125,755</td>
<td>193,155</td>
<td>121,834</td>
</tr>
<tr>
<td>Net Power, kW</td>
<td>512,670</td>
<td>544,238</td>
<td>534,262</td>
<td>552,956</td>
</tr>
<tr>
<td>Net Plant Efficiency, % HHV</td>
<td>30.8</td>
<td>34.0</td>
<td>31.9</td>
<td>34.4</td>
</tr>
<tr>
<td>Coal Feed Rate, kg/h</td>
<td>220,557</td>
<td>212,265</td>
<td>222,026</td>
<td>213,013</td>
</tr>
<tr>
<td>Raw Water Usage, GPM/MW</td>
<td>11.0</td>
<td>10.7</td>
<td>11.0</td>
<td>10.8</td>
</tr>
<tr>
<td>Total Plant Cost, $/KW</td>
<td>3,466</td>
<td>3,063</td>
<td>3,369</td>
<td>3,160</td>
</tr>
<tr>
<td>COE without CO₂ TS&amp;M, $/MWh</td>
<td>137.3</td>
<td>121.1</td>
<td>133.6</td>
<td>124.0</td>
</tr>
<tr>
<td>COE with CO₂ TS&amp;M, $/MWh</td>
<td>146.3</td>
<td>129.2</td>
<td>142.2</td>
<td>131.9</td>
</tr>
<tr>
<td>Cost of CO₂ Capture, $/tonne</td>
<td>43</td>
<td>28</td>
<td>38</td>
<td>29</td>
</tr>
</tbody>
</table>

- IGCC plant with TDA’s CO₂ capture system achieves higher efficiencies (34.4% and 34.0%) than IGCC with Selexol™ (31.9% and 30.8%) for E-Gas™ and GE gasifiers.
- Cost of CO₂ capture is calculated as $29 and $28 per tonne for GE and E-Gas™ gasifiers, respectively (24-35% reduction against Selexol™).
- Cost of CO₂ capture is calculated as $40 and $28 per tonne for Shell and TRIG gasifiers, respectively (20-33% reduction against Selexol™).
Acknowledgements

- DOE/NETL funding under the DE-FE-0013105 project
- Project Manager, Andy O’Palko
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- Arvind Rajendran, UOA
- Frank Morton, NCCC