ADVANCED LOW ENERGY ENZYME-CATALYZED SOLVENT FOR CO$_2$ CAPTURE

John Reardon; Director, Engineering
Project: DE-FE0004228
NETL National CO$_2$ Capture Technology Meeting;
Pittsburgh, PA

July 9, 2013
OUTLINE

- Company profile and project overview
- Technical background & fundamentals
- Progress and current status
- Summary of results
- Future work
AKERMIN INC.

Company profile

- St. Louis-based biotechnology company
  - Developing lower cost, environmentally friendly solutions for CO$_2$ capture for variety of applications
- Integrating proprietary biocatalyst delivery with various solvent systems
PROJECT OVERVIEW

Participants, Duration, Funding

- Project awardee, FFRDC, and Subcontract:

- Enzyme Supply:

- Test Site: (NCCC)

- Fabrication:

- Project duration: 36 months (Oct 2010 to Sept 2013)

- Funding
  - DOE Funding: $3,275,043
  - Akermin Cost share: $2,881,695
  - Total Project: $6,156,738
TECHNICAL BACKGROUND AND FUNDAMENTALS
SCHEMATIC BASIC OPERATION

Indicative temperatures and pressures “simple solvent system”

*Temperatures shown here are indicative of ~ adiabatic scenario using potassium carbonate regenerated at near ambient pressure.

*Vacuum blower: Leverage low quality steam to reduce equivalent work
CORE TECHNOLOGY FOR THIS PROJECT

Coated packing: Akermin’s first generation biocatalyst delivery system

Proprietary formulation achieves high activity and stability
CHEMISTRY: CA-CATALYZED CO$_2$ ABSORPTION

- CA accelerates hydration of CO$_2$ to bicarbonate:
  
  \[
  \text{CA} \quad H_2O + CO_2 \rightleftharpoons H^+ + HCO_3^- 
  \]

- Base captures proton to complete reaction
  
  \[
  B + H^+ \rightleftharpoons BH^+ 
  \]

- Akermin explored numerous CAs

- CA developed by Novozymes is top candidate
  - Highly active
  - Resistant to major impurities in flue gas
  - Thermostable
  - Resistant to high pH (9-10.5)
  - High expression level, few impurities

Key point: CA mechanism is potentially applicable in many basic solvent systems
CATALYST REDUCES COLUMN PACKED HEIGHT

Reducing column height enables certain solvent systems to become feasible

Goal: > 10X overall improvement in packing height
**BENEFITS OF TECHNOLOGY TO THE PROGRAM**

*The most effective and scalable method of CO₂ capture from flue gas is via chemical reaction*

<table>
<thead>
<tr>
<th>Desired Characteristic</th>
<th>Baseline (Amines)</th>
<th>K₂CO₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>No amine aerosol emissions</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>No VOC emissions</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>No toxic air or liquid emissions</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>High Rate</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>High/low ht rxn</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Low regeneration energy potential</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Oxidative stability</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Low viscosity</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Lower corrosivity</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Low or No flue gas polishing needed</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

**Estimated Costs of Greenfield Super Critical PC Power Plant with CO₂ Capture**

- **COE ($/MWh)**, or Cost of Capture ($/t-CO₂)
  - **No Capture**: $0
  - **Optimized Amine**: $68
  - **Akermin**: $53

Both CCS cases include a $5.7 /MWh charge for CO₂ Transport, Storage and Monitoring.

Technology broadens the choice of solvents to be used in CO₂ capture.
TECHNICAL CHALLENGES

- Achieve long-term stability
- Minimize inhibition by flue gas impurities
- Maximize enzyme retention, minimize leaching
- Maximize activity (minimize diffusion resistance)
- Replenishment of enzyme with minimal interruption
PROGRESS AND CURRENT STATUS
BENCH UNIT CURRENTLY OPERATING AT NCCC

Installed at NCCC December 2012

- Sulzer M500X
- 8.33” ID x 26 ft packing
- Gas: 30 Nm³/hr
- Liquid: 275 LPH

Module Design and Fabrication:

Blank testing complete

Immobilized enzyme installed and has been operating since May 2013

Planning to operate through end of September 2013.

Instrumentation and controls:
BENCH UNIT DATA WITH BIOCATALYST

Data at design flow (31.5 Nm³/hr, 275 LPH, XCL ~ 25%)

More than 1250 Hrs On Steam as of 7/09/2013, and continues.
Average CO₂ inlet ~ 12% (dry basis)
90% CO$_2$ CAPTURE TEST (~20 SCMH)

Biocatalyst achieved (average) 90.1% CO$_2$ capture with ~20 Nm$^3$/hr flue gas flow compared to blank estimated ~2.8 Nm$^3$/hr flue gas flow at 90% capture.

~7-fold higher gas flow achieves 90% capture with biocatalyst compared to without biocatalyst in the current column.
QUANTIFIED HEAT STABLE SALT ACCUMULATION

PRELIMINARY (1 week of data), additional results pending

<table>
<thead>
<tr>
<th>Component</th>
<th>HSS (mg/L)</th>
<th>Rate moles/L/year</th>
<th>Loss of Solv. Capacity (%/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrite (NO$_2^-$)</td>
<td>25.1</td>
<td>0.0283</td>
<td>0.83%</td>
</tr>
<tr>
<td>Nitrate (NO$_3^-$)</td>
<td>6.41</td>
<td>0.0054</td>
<td>0.16%</td>
</tr>
<tr>
<td>Sulfate (SO$_4^{2-}$)</td>
<td>36.1</td>
<td>0.0195</td>
<td>1.14%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>67.6</strong></td>
<td><strong>0.0532</strong></td>
<td><strong>1.55%</strong></td>
</tr>
</tbody>
</table>

Preliminary estimate < 2%/year loss in capacity by HSS. Additional data and analytical results are pending.
**QUANTIFIED CO₂ PURITY: ~99.98%**

*NCCC sampled CO₂ product and analyzed purity with Gas Chromatography*

<table>
<thead>
<tr>
<th>Component</th>
<th>Sample #1</th>
<th>Sample #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Ar + O₂</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>N₂</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Net CO₂</td>
<td>99.98%</td>
<td>99.98%</td>
</tr>
</tbody>
</table>

High selectivity is clearly demonstrated with a high purity product
Five Key Areas of Heat Loss Affecting Reboiler Duty (Temperatures displayed in °C)

- Heat loss on riser reduces $T_{\text{rich}}$ feed to STR
- Heat loss on flue gas feed impacts $T_{\text{rich}}$ solution here
- Long steam line with low flows impacts steam quality
- Heat loss from reboiler line results in lower maximum approach temperature

Combined effects of heat loss result in higher reboiler duties than could be achieved under adiabatic conditions (e.g., larger scale)

Reboiler and Stripper Heat Losses ~0.6 kW
This plot used for comparing Aspen prediction and regeneration energy data at test condition.

Aspen model agrees within ~ 2.5% of measured values.
ENERGY & EQUIVALENT WORK VS. REBOILER TEMP.

Using lower grade steam reduces the loss of power-generating capacity for the plant!

- ~3.5 GJ/t\(_{\text{CO}_2}\) with K\(_2\)CO\(_3\), basic flow sheet
- Equivalent work < 150 kWh/ t CO\(_2\) for Steam + VBLR to 1.6 bar
SUMMARY OF RESULTS

- Demonstrated that significant acceleration of CO$_2$ capture is achieved with immobilized CA in the absorber
- Demonstrated 90% capture using K$_2$CO$_3$ salt solution
- Demonstrated > 1200 hours online with no detectible decline in performance
- Negligible heat stable salts accumulation
- >99.9% purity of CO$_2$ product
- Near zero aerosol formation
- 30% - 50% reduction in equivalent work of steam regeneration, including vacuum blower
FUTURE WORK

Outside of this project

- Complete TEA with PNNL (this project)

Beyond this project:

- Scale-up, automate, and optimize manufacture of immobilized enzyme
- Develop and demonstrate second generation replaceable enzyme delivery system
- Demonstrate alternative solvents to further reduce regeneration energy and to lower equivalent work
- Explore alternative biocatalyst-enabled flow sheets

Wrapping up current project with final TEA and report.
ACKNOWLEDGMENTS

- **US DOE-NETL**
  - Andrew Jones, Project Manager

- **Novozymes**
  - Generous supply of carbonic anhydrases

- **National Carbon Capture Center**
  - Test site and on-site operations support

- **PNNL**
  - Charles Freeman, Mark Bearden, James Collette, Dale King

- **Battelle**
  - Bradley Chadwell, Marty Zilka

- **EPIC Systems Inc:**
  - Module design, fabrication, controls programming

- **Emerson:**
  - Instrumentation and controls
DOE/NETL: This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under Award Number DE-FE0004228.

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