LOW ENERGY CO₂ CAPTURE ENABLED BY BIOCATALYST DELIVERY SYSTEM

2015 NETL CO₂ Capture Technology Meeting
Pittsburgh, PA.

Project: DE-FE0012862

June 24, 2014
PROJECT OVERVIEW

Participants, Duration, Funding

- Project awardee and subcontract for TEA:

  [Akermin logo]

  [WorleyParsons logo]

- Enzyme Supply:

  [Novozymes logo]

- Duration: 36 months (Oct 2013 to Sept 2016)

- Funding:

  DOE Funding: $4,053,160
  Akermin Cost share: $1,013,289 (20%)
  Total Project: $5,066,449
PROJECT OBJECTIVES

- Modify existing pilot unit
- Assess performance of a new non-volatile, environmentally benign solvent
- Demonstrate on-stream biocatalyst maintenance
- Complete six-month demonstration at the National Carbon Capture Center (NCCC)
- Meet Techno-Economic Analysis Estimates
  - parasitic power: <220 kWh/t CO₂
  - capital costs reduced by >20%
  - cost of capture reduced by >30%

90% CO₂ capture is assumed for all DOE goals
TECHNOLOGY BACKGROUND

- Chemical absorption of CO₂ in a novel low-energy solvent accelerated by a catalysts, carbonic anhydrase (CA)

\[
\text{CO}_2 + \text{H}_2\text{O} \overset{\text{enzyme}}{\rightleftharpoons} \text{H}^+ + \text{HCO}_3^- \\
\text{B}^- + \text{H}^+ \overset{\text{enzyme}}{\rightleftharpoons} \text{BH}
\]

Challenge: how to make an enzyme evolved in nature work in harsh industrial environments?

- Temperature (40-105 °C)
- Extreme pH
- Impurities (SOx, NOx, etc.)
- Shear Forces
- Multiphasic systems

Enzyme engineering and advanced enzyme delivery systems are critical for solving the problem.

\[k_{cat}/K_M = 10^8 \text{ M}^{-1}\text{s}^{-1}\]
\[k_{cat} = 10^6 \text{ s}^{-1}\]
AKERMIN’S BIOCATALYST DELIVERY SYSTEM

Successful biocatalyst approach enables:
- Non-toxic, non-volatile solvent(s)
- Novel process schemes

High surface area polymers enable higher mass transfer rate

1st generation
Coated packing

options for biocatalyst delivery

2nd generation
Micro-particles

Enzyme
PROOF OF CONCEPT: CATALYST ON PACKING

Two solvents tested: $\text{K}_2\text{CO}_3$ and $\text{AKM}24$ (May – Oct 2013)

3500 Hrs on stream, minimal inactivation in either solvent
REMAINING CHALLENGES: FURTHER REDUCTION OF ENERGY AND IN SITU BIOCATALYST REPLACEMENT

- Introduce new solvent, AKM-24
  - High CO₂ loading
  - Low regeneration energy
  - Non-volatile
  - Thermally stable
  - Highly water-soluble
  - Manufacturing route established
  - Low EH&S risks

- Replace catalyst on packing with catalyst in suspension
## CATALYST RECIRCULATION OPTIONS

<table>
<thead>
<tr>
<th>Within the absorber only</th>
<th>Within absorber and stripper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficient particle separation</td>
<td>No separation is needed</td>
</tr>
<tr>
<td>Moderately thermostable CA</td>
<td>Highly thermostable CA</td>
</tr>
<tr>
<td>Lower rate catalyst inactivation, less frequent catalyst replacement</td>
<td>Higher rate catalyst inactivation, more frequent catalyst replacement</td>
</tr>
<tr>
<td>Fewer performance issues expected</td>
<td>Likely issues with particles in the stripper (inactivation, foaming)</td>
</tr>
<tr>
<td>Standard high temperature stripper</td>
<td>Lower temperature stripper with vacuum; extra stage of compression</td>
</tr>
</tbody>
</table>

- In addition, the economics of both options needs to be considered:
  - Equivalent work of CO2 capture for either option
  - Overall cost of capture (including the enzyme)
TOTAL EQUIVALENT WORK ESTIMATES

Total equivalent work using Aspen after input of thermodynamic and kinetic data

\[
W_{\text{steam}} = 0.90 \left[ 1 - \frac{40^\circ + 273.15}{T_{\text{reb}} + 273.15 + 10} \right] \dot{Q}_{\text{steam}}
\]

\begin{align*}
\text{NETL Case 12.2} & \quad \text{355 kWh/tCO2} \\
\text{(Case 1A)} & \quad \text{265 kWh/tCO2} \\
\text{(Case 2A)} & \quad \text{230 kWh/tCO2} \\
\text{(Case 2B)} & \quad \text{227 kWh/tCO2}
\end{align*}

\begin{itemize}
\item CO2 Compressor
\item Vacuum Blower
\item Reboiler
\item Circulation Pumps
\item ID Fan
\end{itemize}

>35% reduction relative to baseline (Case 12, Rev. 2)
INCREASE IN COST OF ELECTRICITY OVER CASE 11 “NO CAPTURE”

Case-11 (no capture): COE = 80.95$/MWh
assumes 1 year half-life and efficient BRS

~30% reduction in ICOE
COST OF CAPTURE FOR VARIOUS CAPTURE SYSTEMS

-~20% reduction in cost of capture appears achievable

**NetL Case 12.2**
30% MEA

**Case 1A**
AKM-24
60°C Reboiler

**Case 2A**
AKM-24
80°C Reboiler

**Case 2B**
AKM-24
105°C Reboiler

- DOE Goal
$40/tCO₂

- Akermin NETL2 Goal
$39.5/tCO₂

- Milestone
EFFECT OF BIOCATALYST HALF-LIFE ON COE

Minor effect with half-life exceeding 100 days
FLOW DIAGRAM FOR PROCESS WITH CATALYST SEPARATION AND STRIPPING AT 105 °C

Absorber Lean Liquid: $T_L = 30$ to $40°$

Absorber Rich Liquid: $T_R = 50$ to $60°$

Reboiler: $T_{REB} = 105°$
ENHANCEMENT FACTORS FOR ENZYME ON PACKING AND MICROPARTICLES VS. MEA

- 20 wt.% K2CO3, 25°C
- Gen 1A Biocat., 45°C
- 35 wt% AKM24, 25°C
- Gen 2B Biocat. (0.75 wt%), 40°C
- 30 wt% MEA, 0.25 mol/mol, 40°C
- 30 wt% MEA, 0.35 mol/mol, 40°C
CO₂ CAPTURE OVER TIME: CLOSED LOOP REACTOR WITH BIOCATALYST SEPARATION

2 LPM AKM24 @ 30 wt.%, 15 SLPM Gas Flow (13.3% Inlet CO₂), 35-40 °C Column @ 2 psig

Average Capture: 90%
SUMMARY OF PROGRESS TO DATE

- Produced and tested multiple biocatalyst batches on kg-scale
- Installed lab-scale closed loop reactor
- Demonstrated >20X biocatalyst enhancement
- Completed 100-hrs on-stream test, demonstrated avg. 90% capture
- Generated equilibrium and rate data for baseline AKM24 for a range of concentrations, temperatures, and CO2 loadings
- Built enzyme kinetic model in Aspen and validated with data
- Identified cases with total equivalent work < 230 kWh/t CO2
- Identified low cost biocatalyst separation option
- Completed Process Safety Analysis
FUTURE WORK AND NEXT SCALE ACTIVITIES

Commercial scale Biogas treating unit

- Size: 500 Nm³/hr. biogas
  - (50% of avg. commercial unit)
- $7 MM, three year project
- 50% funding through EUDP (Danish Energy Agency)
- Schedule:
  - Project Kickoff – Jan 2014
  - Commissioning – Nov 2015
  - Start Operations – Dec 2015
- 24 months operation and testing

Upgrading biogas to pipeline specification at industrial scale using biocatalyst
DOE/NETL: This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under Award Number DE-FE0004228.

Disclaimer: This presentation was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency.