GEOLOGICAL SEQUESTRATION TRAINING & RESEARCH PROGRAM IN CAPTURE AND TRANSPORT: DEVELOPMENT OF THE MOST ECONOMICAL SEPARATION METHOD FOR CO$_2$ CAPTURE

Project No.: DE-FE0001953; Project Manager: Dawn Deel

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Tuskegee University
TUSKEGEE UNIVERSITY

- PhD granting private institution
- About 3000 students with 5 colleges
- College of Engineering, & Physical Sciences has about 600 students and 50 faculties
- Chemical Engineering Department has 130 students and 7 faculties
DOE Funding
$ 296,511

Period of Performance
December 1, 2009 – November 30, 2012

Team Members
Nader Vahdat, PI
Pamela Tomski, EnTech Strategies, Consultant
Kiara Moorer, Research Assistant
Marially Jean-Jacques, Research Assistant
BACKGROUND INFORMATION ON CO$_2$ CAPTURE

- **1970s – 1980s**: Separation of CO$_2$ from flue gas for EOR using MEA absorption
- **1996**: First CO$_2$ capture plant
- **1997-Present**: tremendous amount of research
- Many different technologies have been proposed
MEA Absorption Process

- Requires high energy for solvent regeneration
- Has high equipment corrosion rate
- Has high solvent degradation rate
- Has high capital cost

It is an expensive process
Typical Absorption System

Clean Gas → Absorber → Lean Solvent → Regenerator → Rich Solvent → Flue Gas

CO₂
Two Different Route to Reduce Cost

1. Modify the MEA absorption process
2. Develop new technologies
MODIFICATION OF OLD TECHNOLOGY

- Add new heat recovery equipment to reduce energy cost
- Change concentration of solvent or use inhibitors to reduce corrosion
- Use other solvents
- Use mixture of solvents
- Use stainless steel to reduce corrosion
- Change operation conditions to reduce solvent degradation
DEVELOPMENT OF NEW TECHNOLOGY

- Adsorption
- Membrane Separation
- Ionic Liquids
- Chemical Looping
- Cryogenics
- Microbial / Algae
SUMMARY OF CARBON CAPTURE

- Very active area of research
- Many different modification of the absorption process
- Many different technologies for CO$_2$ capture

The Goal is to Minimize Cost of CO$_2$ Capture
A large number of CO$_2$ captured methods are available

Complete design and cost estimation is expensive and time consuming

An screening technique is needed to identify potential systems that should be studied in more detail.
OBJECTIVES

1. To develop simple mathematical models to screen different separation methods for possible use for $\text{CO}_2$ capture

2. To provide training that introduces the latest technologies and deployment issues to the university community
THREE PHASES OF PROJECT

1. Absorption Systems
2. Membrane Systems
3. Adsorption Systems
FIRST PHASE

Development of a simple method to evaluate absorption systems for CO$_2$ capture and identify potential solvents for further study
EVALUATION OF ABSORPTION SYSTEMS

Develop a method to optimize absorption processes and to estimate the minimum cost per tonne of CO$_2$ captured by manipulating the process variables.
PROCESS VARIABLES

Absorber and Stripper
- Liquid to gas ratio
- Vapor velocity
- Recovery
- Temperature and pressure

Heat Exchangers
- Temperature of water coming out
Cost per tonne of CO2 captured = \left[ \frac{\text{Annual fixed cost} + \text{operating cost}}{\text{annual tonne of CO2 captured}} \right]
TOTAL COST PER YEAR

Cost per year = (Fixed Cost)(Depreciation Factor) + Operating Costs

Fixed Cost = Initial Investment

Operating Costs = Energy Cost + Raw Material Cost + Maintenance Cost + Labor Cost
LIST OF EQUIPMENT

- 1). Absorption column
- 2). Heat exchanger
- 3). Stripping column
- 4). Reboiler
- 5). Condenser
- 6). Pump
- 7). Cooler
- 8). Compressor
Assumption

- Equilibrium curve for solvent-CO2 system is not a straight line. An average value for the slope of each curve is calculated and used for columns.
EQUILIBRIUM DATA FOR MEA-CO2 SYSTEM AT 120 °C
**FIXED CAPITAL**

- Installation 47% of equipment cost
- Instrumentation 36% of equipment cost
- Piping 68% of equipment cost

Total 151% of equipment cost

**Fixed Capital = 2.51 (Total Equipment Cost)**
Annual fixed cost = \frac{Fixed Cost}{Useful life of process}
Operating Cost = Utilities + Make up solvent + Maintenance + Labor

Utilities Cost = Steam cost + Electricity cost + Water cost
Maintenance Cost = (Fixed Capital).( Factor)

For carbon steel: “Factor” is large
For stainless steel: “Factor” is small
Flow rate of make-up solvent needed is proportional to the rate of circulation of solvent

Rate of make-up solvent = \( f_s \cdot (\text{circulation rate}) \)
A user friendly spread sheet was developed to estimate the cost per tonne of CO₂ captured for a carbon steel and stainless steel processes
## INPUT DATA NEEDED

<table>
<thead>
<tr>
<th>Flue Gas</th>
<th>Flow rate, mole fraction of CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent</td>
<td>Molecular weight, density, heat of absorption, equilibrium data, prices, data on degradation and corrosion</td>
</tr>
<tr>
<td>Plant Operation</td>
<td>Temperatures and pressures, recoveries, utility costs, labor cost, Chemical Engineering Cost Index</td>
</tr>
</tbody>
</table>
# INPUT DATA FOR ANALYSIS

<table>
<thead>
<tr>
<th>Input Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours of operation per year</td>
<td>8,000</td>
</tr>
<tr>
<td>Labor requirement</td>
<td>3.3</td>
</tr>
<tr>
<td>Chemical Engineering Cost Index</td>
<td>541.8</td>
</tr>
<tr>
<td>Useful life</td>
<td>20</td>
</tr>
<tr>
<td>Price of cooling water, $/m³</td>
<td>0.04</td>
</tr>
<tr>
<td>Price of electricity, $/KWh</td>
<td>0.05</td>
</tr>
<tr>
<td>Price of steam, $/1000 Kg</td>
<td>7.5</td>
</tr>
<tr>
<td>Repair factor for carbon steel</td>
<td>2.5</td>
</tr>
<tr>
<td>Repair factor for stainless steel</td>
<td>0.5</td>
</tr>
<tr>
<td>Wages, $/h</td>
<td>33</td>
</tr>
<tr>
<td>Cost of packing, $/ft³</td>
<td>23.9</td>
</tr>
</tbody>
</table>
# Absorption Systems Studied

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Price, $/lb</th>
<th>Make-up factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 M Monoethanolamine (MEA)</td>
<td>0.81</td>
<td>0.1</td>
</tr>
<tr>
<td>3.6 M Potassium Carbonate</td>
<td>1.07</td>
<td>0.05</td>
</tr>
<tr>
<td>4 M n-Methyldiethanolamine (MDEA) – 0.6 M Piperazine (PZ)</td>
<td>1.98 (MDEA)</td>
<td>0.05</td>
</tr>
<tr>
<td>3.6 M Potassium Carbonate – 0.6 M Piperazine (PZ)</td>
<td>1.07 (PC)</td>
<td>0.05</td>
</tr>
<tr>
<td>6.8 M Ammonia</td>
<td>0.13</td>
<td>0.05</td>
</tr>
</tbody>
</table>
MOLAR LIQUID TO GAS RATIO FOR ABSORBER

$/tonne of CO2 captured vs. Molar liquid to gas ratio for absorber

The graph shows an increasing trend in $/tonne of CO2 captured as the molar liquid to gas ratio for absorber increases.
One of CO₂ capture

Molar liquid to gas ratio in stripper

$\$/tonne of CO₂ captured

Molar liquid to gas ratio in stripper

0.4 0.6 0.8 1.0 1.2 1.4
RECOVERY OF CO2 IN ABSORBER

$/tonne of CO2 captured vs. Recovery of CO2 in absorber
TEMPERATURE OF COOLING WATER FROM HEAT EXCHANGERS

Temperature of cooling water exiting heat exchanger, °K

$/tonne of CO2 captured

Temperature of cooling water entering heat exchanger, °K
REPAIR FACTOR

Graph showing the repair factor for carbon steel and stainless steel in terms of $/tonne CO2 captured against the repair factor for carbon steel (% Fixed Capital). The graph indicates a linear relationship with carbon steel having a higher repair factor compared to stainless steel.
One of CO2 capture make-up solvent as percentage of circulation rate.
## Solvents Studied

<table>
<thead>
<tr>
<th>Solvents</th>
<th>Cost per tonne of CO2 captured, $</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 wt% MEA</td>
<td>56</td>
</tr>
<tr>
<td>20 wt% Potassium Carbonate</td>
<td>89</td>
</tr>
<tr>
<td>20 wt% Potassium Carbonate – 0.6 M Piperazine</td>
<td>93</td>
</tr>
<tr>
<td>46 wt% MDEA – 0.6 M Piperazine</td>
<td>31</td>
</tr>
<tr>
<td>12 wt% Ammonia</td>
<td>25</td>
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</tbody>
</table>
PROJECT APPROACH

TRAINING COMPONENT

- CCS short course / Annual Tuskegee CCS Forum
- Facilitate CCS internships
- Establish Tuskegee University Energy Club and CCS Network for professors, students and alumni
Tuskegee will leverage the extensive experience of its expert team to utilize and adapt existing CCS course material and teaching methods into a short course open to the university community. This short course will be conducted under the Annual Tuskegee CCS Forum.
Task 4 – TUSKEGEE CCS NETWORK

Task 4.1 – Development of Outreach Materials
Task 4.2 – Creation of Network Linkages

Activities:
• Creation of the Tuskegee Energy Club /CCS Network and Alumni in Energy
• Web site development
• Recruitment
TASK 5 – CCS TRAINING OPPORTUNITIES

Task 5.1 – Establish Summer Intern Positions

Task 5.2 – Facilitate Student Placement

Task 5.3 – Provide Student Recognition

Activities:
• Exploring intern opportunities through DOE/NETL, support contractors and industry
• Facilitating student participation at the Annual NETL Carbon Sequestration Conference
• Recruiting student intern to assist with Research Experience in Carbon Sequestration (RECS)
• Web site development
2ND ANNUAL TUSKEGEE CCS FORUM

March 29, 2010 at Kellogg Conference Center, Tuskegee University

Program Under Development
## PROJECT TIMELINE

<table>
<thead>
<tr>
<th>Task</th>
<th>First Year</th>
<th>Second Year</th>
<th>Third Year</th>
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<tbody>
<tr>
<td>Task 1. CCS Short Course</td>
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<tr>
<td>Task 2 - Evaluation of CO₂ capture methods</td>
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<tr>
<td>2.1 - Criteria for comparing between methods</td>
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<tr>
<td>2.2 - Absorption method</td>
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<tr>
<td>2.3 - Membrane separation method</td>
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<tr>
<td>2.4 - Adsorption method</td>
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<tr>
<td>Task 3 - Development of mathematical models</td>
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<tr>
<td>Task 4 - Tuskegee CCS Network</td>
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<tr>
<td>4.1 - Development of outreach materials</td>
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</tr>
<tr>
<td>4.2 - Creation of network linkages</td>
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<tr>
<td>Task 5 - CCS training opportunities</td>
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</tbody>
</table>
Thank you