Post Combustion CO$_2$ Capture Technology: Current Status and Future Directions

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Outline

Introduction to Post Combustion Capture Technology

Post Combustion Capture Pilot & Demonstration Plants

Improvements for solvent based Post Combustion Capture Process

2nd & 3rd Generation Post Combustion Capture Technologies
Post Combustion Capture (PCC) Process

- Boiler
- Electrostatic Precipitator (ESP)
- Flue Gas Desulphurization (FGD)
- Air Heater
- Selected Catalyst Reactor (SCR)
- Carbon Dioxide Capture

Source: Mitsubishi Heavy Industries
Why Post Combustion Capture (PCC)?

- Can be easily Retrofitted
- Capture readiness makes relatively easy to incorporate into power plants
- State of Art Technology; Several Pilot demo. projects
- Learning by doing will lead to cost reductions
- It has more operational flexibility in switching between capture – no capture operation mode

Diagram:
- Power plant
- Fossil fuel & air
- Exhaust gas with CO2
- Absorbent & water
- Scrubber Column
- Heat exchanger
- Regenerator
- CO2
- Cooling
- Cleaning exhaust gas
- Energy
Leading PCC Technology is Solvent Based Absorption process
CO$_2$ and Amine based Solvent Reaction

Acid Base, Temperature Dependent, Reversible Reaction

\[ 2R_2NH + CO_2 \leftrightarrow R_2NCOO^- + R_2NH_2^+ \]

- **Fast reaction**
- **Low Temp.**

**Monoethanolamine (MEA)**

**Sterically Hindered**

**Piperazine (Pz)**
## Commercially Available Solvents

<table>
<thead>
<tr>
<th>Solvents</th>
<th>Process Name</th>
<th>Developers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional MEA</td>
<td>Econamine +</td>
<td>Fluor, ABB</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Chilled Ammonia</td>
<td>Alstom</td>
</tr>
<tr>
<td>Hindered Amines</td>
<td>KS-1, AMP, …</td>
<td>MHI, EXXON</td>
</tr>
<tr>
<td>Tertiary Amines</td>
<td>MDEA</td>
<td>BASF, DOW</td>
</tr>
<tr>
<td>Amino Acid Salts</td>
<td>CORAL</td>
<td>TNO, Siemens, BASF</td>
</tr>
<tr>
<td>Piperazine</td>
<td></td>
<td>Uni. Texas at Austin</td>
</tr>
<tr>
<td>HiCapt, DMX&lt;sup&gt;TM&lt;/sup&gt;</td>
<td>Mixture</td>
<td>IFP, France</td>
</tr>
<tr>
<td>Integrated SO&lt;sub&gt;2&lt;/sub&gt;/CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Amines</td>
<td>Shell/Cansolv</td>
</tr>
<tr>
<td>Amine</td>
<td></td>
<td>Aker Clean Carbon</td>
</tr>
<tr>
<td>Chemical solvents</td>
<td>DEAB, KoSol, Calcium based,</td>
<td>HTC, Uni Regina, KEPRI, NTNU, SINTEF, CSIRO, KEPRI, EnBW</td>
</tr>
</tbody>
</table>
Process Economics

- New IEAGHG Base line study for Supercritical Pulverized Coal Power Plant with 90% CO₂ Capture, The Netherlands
- Based on Shell/Cansolv Amine based Post combustion capture process
- 15% Increase in Annual Operational Cost (same coal feed rate)
Post Combustion Capture Pilot & Demonstration Plants
Ferrybridge CCPIlot100+, UK

- PCC demonstration plant using Doosan Power Systems’ technology
- 100 t/day slip stream from a 500MWe unit on SSE’s Ferrybridge Power Station, making it the largest PCC demonstration in the UK
- Two year test programme, fast-tracked build, operating March 2012
- Funded by all project partners
- Lessons learned to be incorporated into future designs

http://www.sse.com/Ferrybridge/TheCarbonCaptureProject/ProjectInformation/
RWE CO\textsubscript{2} Capture Pilot Plant
Niederaussem, Germany

- Flue gas from lignite fired power plant: 1,550 m\textsuperscript{3} N/hr
- CO\textsubscript{2} product: 7.2 t\textsubscript{CO\textsubscript{2}}/day; capture rate 90%
- Absorber / regenerator packing type and height corresponds to full scale
- Commissioning and start-up 2009, availability of 97%
- Budget of RWE for phases I/II: 15 M\texteuro
- 40% funding by German Federal Ministry of Economics and Technology (0327793 A-F)
- Phase III being planned
American Electric Power (AEP): Mountaineer CCS Demo., USA

- Alstom Chilled Ammonia Process (CAP) process for 90% of the carbon dioxide capture from a 235 megawatt electric (MWe) slipstream of 1300MWe Mountaineer coal-fired power plant located near New Haven, West Virginia
- Capture and sequester approximately 1.5 million tons per year of CO₂
- The project is comprised of American Electric Power, Alstom, RWE, NETL, and Battelle Memorial Institute
- Between September 2009 and May 2011, validated successfully the capture and storage technologies

http://www.aep.com/environment/climatechange/carboncapture.aspx
Boundary Dam Integrated CCS Demo. Project, Canada

$1.24-billion partnership involving the Government of Canada, the Government of Saskatchewan, SaskPower, and private industry

In construction and scheduled to begin operation in 2014

1 million tonne CO₂/year captured at 90% emission reduction

Upgrading the unit’s output to help meet the additional power demands of the CCS operation

This project is a component of the new E.ON Maasvlakte Power Plant 3 (MPP3), a 1070 MW (gross) coal- and biomass-based power plant

A 250MWe post-combustion capture unit will be installed at the plant

Approximately 1.1 million tonnes per annum of carbon dioxide (CO₂) would be captured for storage in offshore depleted oil and gas reservoirs

Maasvlakte CCS Project C.V., a joint venture of E.ON Benelux and Electrabel; Project currently is under planning

http://road2020.nl/en
Improvements in Amine based Post Combustion Capture Process
Ideal Liquid Solvent for PCC

- Not only:
  - High cyclic CO$_2$ absorption capacity
  - High rates of CO$_2$ absorption
  - Low CO$_2$ desorption energy requirement

- But also:
  - Resistance to oxidation
  - Resistance to other routes for degradation
  - No impact of O$_2$, SO$_x$, NO$_x$ and fly ash
  - No corrosion issues
  - No concerns around health, safety and environment
Solvent Regeneration Energy

- **Increase**
  - Negative Effect
  - Solve heat of absorption
  - Sensible heat (Heat capacity)
  - Heat for water vaporization

- **Decrease**
  - Positive Effect

**Direct impact on fuel consumption and affects OPEX**

- Increase steam consumption for reboiler, require larger LP steam to produce extra steam.

- Require LP steam turbine to generate electricity from extra steam; Low quality steam is required; require additional energy for compression due to lower regeneration pressure.
Solvent Absorption Kinetics

![Graph showing the relationship between basicity (pKa) and solvent absorption kinetics (k2 in L/mole sec)]

Source: IEAGHG 2013/TR5 Incorporating Future Technological Improvements in Existing CO2 Post Combustion Capture Plants: Technical Review
Absorption Capacity Depends on:
- Base strength (pKa)
- Molecular weight (per NH functionality)
- Viscosity

Solvent Absorption Kinetics

Determine the height of absorber, also impact the power consumption by blower, affects CAPEX and OPEX

Increase
- Positive Effect
  - Require larger LP steam turbine capacity for reduction in steam demand from the capture unit;
  - Require higher electricity due to increase in blower power consumption;
  - Require increase in absorber height

Decrease
- Negative Effect
Solvent Loss: Degradation

2% of initial amine loss per week

Source: IEAGHG 2013/TR5 Incorporating Future Technological Improvements in Existing CO2 Post Combustion Capture Plants: Technical Review
Solvent Loss: Degradation

- Presence of Impurity in Flue gas

- Degradation
  - Affect solvent characteristics, affect solvent makeup cost, OPEX. Thermal degradation affect stripper temperature and pressure

- Increase
  - Negative Effect
    - Increase solvent make-up rate, fouling of system, corrosion rate, reclaimer waste; will also require deeper SOx and NOx removal, require addition pre-treatment column and utilities

- Decrease
  - Positive Effect
    - Reduce solvent makeup cost, reclaimer waste, regeneration at higher stripper pressure and temperature
Solvent Loss: Corrosivity

- Found in the order of MEA > AMP > DEA > MDEA

- Degradation
  - Affected by oxidative and thermal degradation, affects CAPEX
  - Increase in degradation and solvent makeup cost; Increase equipment maintenance cost; Require additional coating to the capture equipment

- Positive Effect
  - Decrease solvent makeup cost, equipment maintenance cost
Process Design

Around 15 different process integrations are reported in Open Publications and Patents

• Inter-stage temperature control
• Split flow process
• Matrix stripping
• Heat integration options like
  • Extracting semi-loaded CO₂ solvent from stripper and heat exchanging it with the hot exhaust gas from boiler or steam condensate from the reboiler
  • Inlet feed gas to pre-heat rich solvent before entering the stripper
  • Stripper overhead gas to pre-heat rich solvent entering the stripper
Multi-Component Column

Reduce energy requirement from pre-treatment column

2-stage quench scrubber

Ref: Reddy 2007; Hakka and Ouimet 2007; Shaw 2009
Multi-Component Column

Reduce energy requirement from pre-treatment column

Additional heat exchanger & 2 pumps

Ref: Reddy 2007; Hakka and Ouimet 2007; Shaw 2009
Inter-stage temperature control process

Increase of temperature during absorption

Ref: Leites 2003; Aroonwilas and Veawab 2007;
Inter-stage temperature control process

Increase of temperature during absorption

Inter-stage cooling is applied to increase CO₂ loading

Ref: Leites 2003; Oyenekan & Rochelle 2006
Inter-stage temperature control process

- Increase of temperature during absorption
- Inter-stage cooling is applied to increase CO$_2$ loading
- Additional heat exchanger & 3 pumps

Ref: Leites 2003; Oyenekan & Rochelle 2006
Vapour Recompression

Reduction in steam for reboiler, stripper size and power cost

Ref: Woodhouse 2008; Jassim and Rochelle 2006; Reddy 2007
Vapour Recompression

Additional pump & flash drum

Reduction in steam for reboiler, stripper size and power cost

Ref: Woodhouse 2008; Jassim and Rochelle 2006; Reddy 2007
Several process integrations focuses on reducing steam consumption in the reboiler, reducing CO$_2$ compression energy, reducing solvent circulation rate, reducing water consumption.

When considering these processes integration, one should focus on following main issues:

- Effect on the power plant performance related to steam requirement, electricity duty, utilities, operational flexibility
- Incorporation of process integration to an existing CO$_2$ capture plant
- Site specific issues like available space for additional units and pipe work, water requirement, ambient conditions
Emission Control

Several options available to reduce emission from amine based PCC process

Water wash

Temp. Control

Absorber

Flue gas

Acid wash

Acid Make-up

Drain

Make-up

Absorber

Flue gas

pH & Salt Conc.

“Dry“ bed
- patented -

“Dry“ bed
- patented -

RWE, BASF

Source: RWE, BASF
2nd & 3rd Generation Post Combustion Capture Technologies
2\textsuperscript{nd} & 3\textsuperscript{rd} Generation PCC Technologies:
Solvents

- Biphasic solvents
- Ionic liquids
- Carbonic Anhydrase
- Enzymes
- Algae
2nd & 3rd Generation PCC Technologies: Solid Sorbents & Membrane

Zeolite

Metal Organic Frameworks (MOF’s)

Hollow Fiber Membrane

Ca-Looping
2\textsuperscript{nd} & 3\textsuperscript{rd} Generation PCC Technologies: Hybrid process

- Immobilized amine sorbent
- Ionic liquid/ZIF-8 mixed-matrix membranes
- Polymer supported amine/enzymes membrane
- Enzymes + Algae Process
In recent years there has been an increase in publications and patents for 2\textsuperscript{nd} and 3\textsuperscript{rd} generation PCC technologies.
Carbonic Anhydrase with Bicarbonate solution is currently tested by AKERMIN at NETL NCCC pilot plant (USA); capture 150 kg of CO$_2$ per day from a coal-based flue gas stream.

IFP (France) DMX-1 Biphasic solvent process planning tests at Enel's Brindisi industrial CO$_2$ Pilot (Italy) in 2015-2016 (Decision will be made in Dec 2013).

Polyvinylamine Fixed site carrier Membrane long term pilot testing in EDP Coal Power Plant Sines, Unit 4 (314 MWe) Portugal: show CO$_2$ permeance and selectivity similar to the lab scale results.
Where to Focus?

➢ Need to consider all → Solvent improvement, Power plant integration, Process flow scheme

➢ Pilot plant data for operational flexibility and emission control technologies

➢ 2nd and 3rd generation technologies → techno economics, environmental impact and detailed pilot plant evaluation

Figure Source: EDF, PCCC2
Thank you

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