Presentation about MHI CO2 capture technology

September 2017
Takahito Yonekawa
“NRG Energy, JX Nippon complete world’s largest post-combustion carbon capture facility on-budget and on-schedule"
As a global leader in industrial and infrastructure manufacturing, Mitsubishi Heavy Industries is creating commercially viable technology for capturing carbon emissions from coal-fired plants, while enhancing domestic oil production.

**MHI’s Carbon Capture Technologies**
KM CDR – Kansai Mitsubishi Carbon Dioxide Removal – Process®

- Developed in the early 1990s with Kansai Electric
- Similar to other amine-based technologies
- Proprietary features including KS-1™ solvent
- First plant in 1999

KM CDR Process is a registered trademark of Mitsubishi Heavy Industries, Ltd., in Japan, the United States of America, European Union (CTM), Norway, Australia, and China.
KM CDR Process® Development History

From 1991 – 2 TPD Nanko Pilot Plant on Natural Gas Exhaust (Kansai Electric Power Co.)

From 2002 - 1 TPD Hiroshima Pilot Plant on Coal Exhaust (MHI R&D Center)

From 2006 – 10 TPD Matsushima Pilot Plant on Coal Exhaust (J-Power)

From 2008 - 400MWeq Absorber Flow Tests (MHI Mihara)

Engineering HQ (Yokohama)
MHI is the world’s leading large scale post-combustion CO₂ capture technology licensor.
MHI tested various chemicals to develop the KS-1™ solvent for the KM CDR Process®.

- MHI evaluated over 200 solvents and tested 20 solvents at its first CO$_2$ capture pilot plant at KEPCO’s Nanko Power Plant in 1991.
- KS-1™ has exceptionally low corrosivity, high stability, and high CO$_2$ absorption capacity.
- MHI still uses the Nanko pilot plant to develop new solvents, new process schemes, and new equipment.
Impurities Testing for Coal-fired Flue Gas

MHI performed extensive testing to understand the impact of flue gas impurities and to develop countermeasure technologies.

- 2002 – began testing on coal-fired flue gas at Hiroshima R&D Facility.
- 2006 – completed several test programs on a slip stream from a commercial coal fired power plant in Matsushima, Japan.
  - Performed long term operation to verify the impact of coal-fired flue gas impurities on the KM CDR Process®.

| Hiroshima R&D Facility (1 mtpd) | Matsushima Pilot Plant (10 mtpd) |
MHI had extensive experience and resources to ensure successful scale-up of its KM CDR Process®.

- High performance packing is very sensitive to liquid distribution.
- 2008 – tested malfunctions of liquid distributors at Mihara Works.
- Absorber measures ~35 ft x ~15 ft.
- The test program was invaluable to the final design and to guarantee performance for large scale projects.
- Scaling technique is similar to that used on more than 200 commercial FGD systems.
MHI’s CO₂ Capture Technology & Experience

Plant Barry CO₂ Demo Plant – helped prove commercial viability of carbon capture on coal fired flue gas

<table>
<thead>
<tr>
<th>Plant location</th>
<th>Mobile County (Alabama, U.S.A.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant owner</td>
<td>Southern Company subsidiary Alabama Power</td>
</tr>
<tr>
<td>Plant scale</td>
<td>25 megawatts (MWₑq)</td>
</tr>
<tr>
<td>Flue gas amount</td>
<td>116,800 Nm³/h</td>
</tr>
<tr>
<td>CO₂ conc.</td>
<td>10.1 mol%-wet</td>
</tr>
<tr>
<td>CO₂ capture capacity</td>
<td>500 metric ton/day (150,000 ton/year)</td>
</tr>
<tr>
<td>CO₂ removal</td>
<td>90%</td>
</tr>
</tbody>
</table>

Operating data as of 8/31/14:

| Operating time         | 12,400 hrs                      |
| Captured CO₂          | 230,100 metric ton              |
| Injected CO₂          | 115,500 metric ton              |

* Additional technology demonstrations are on-going (HES, ACC).
Applications of CO$_2$ Capture Facilities

CLIMATE

UREA

EOR

METHANOL
Applications of CO$_2$ Capture Facilities

Chemical production has been the main driver of MHI’s 12 commercial projects.

<table>
<thead>
<tr>
<th>Year of Delivery</th>
<th>Country</th>
<th>Flue Gas Source</th>
<th>CO$_2$ Capacity (mtpd)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>Malaysia</td>
<td>NG Fired Furnace</td>
<td>210</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2005</td>
<td>Japan</td>
<td>NG and Heavy Oil Boiler</td>
<td>330</td>
<td>General Use</td>
</tr>
<tr>
<td>2006</td>
<td>India</td>
<td>NG Fired Furnace</td>
<td>450</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2006</td>
<td>India</td>
<td>NG Fired Furnace</td>
<td>450</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2009</td>
<td>India</td>
<td>NG Fired Furnace</td>
<td>450</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2009</td>
<td>Bahrain</td>
<td>NG Fired Furnace</td>
<td>450</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2010</td>
<td>UAE</td>
<td>NG Fired Furnace</td>
<td>400</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2010</td>
<td>Vietnam</td>
<td>NG Fired Furnace</td>
<td>240</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2011</td>
<td>Pakistan</td>
<td>NG Fired Furnace</td>
<td>340</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2012</td>
<td>India</td>
<td>NG Fired Furnace</td>
<td>450</td>
<td>Urea Production</td>
</tr>
<tr>
<td>2014</td>
<td>Qatar</td>
<td>NG Fired Furnace</td>
<td>500</td>
<td>Methanol Production</td>
</tr>
<tr>
<td>2016</td>
<td>USA</td>
<td>Coal-Fired Boiler</td>
<td>4,776</td>
<td>Enhanced Oil Recovery</td>
</tr>
</tbody>
</table>
Increase of Urea Production

To install the flue gas CO\textsubscript{2} recovery unit can realize to maximize urea synthesis by balancing ammonia and CO\textsubscript{2}
Increase of Methanol Production

Case-1: CO2 Recovery - CO2 Injection at Reformer Inlet

NG → REFORMER → COMPRESSION → SYNTHESIS → DISTILLATION → MeOH

FLUE GAS

CO2 RECOVERY

Case-2: CO2 Recovery – CO2 Injection at Reformer Outlet before Compression

NG → REFORMER → COMPRESSION → SYNTHESIS → DISTILLATION → MeOH

FLUE GAS

CO2 RECOVERY
CO$_2$-EOR Supply Chain

Enhanced Oil Recovery drives major North American CCUS projects.

CO$_2$ supply chain

1) Thermal Power Plant
   CO$_2$ is created from combustion

2) Capture System
   CO$_2$ is separated and compressed

3) Pipeline
   CO$_2$ is transported to oil field

4) Oil Field
   CO$_2$ is injected and recycled for oil production

Commercial Plant for CO$_2$-EOR
Petra Nova Project Overview

The world’s largest CO₂ capture plant on coal-fired flue gas began commercial operation on December 2016.

<table>
<thead>
<tr>
<th>Plant location</th>
<th>NRG WA Parish Power Plant in Thompsons, TX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project owner</td>
<td>Petra Nova – partnership between NRG Energy and JX Nippon Oil &amp; Gas</td>
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<tr>
<td>Plant scale</td>
<td>240 megawatts (MWₐq)</td>
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<td>CO₂ conc.</td>
<td>11.5 mol%-wet</td>
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<tr>
<td>CO₂ capacity</td>
<td>4,776 metric ton/day</td>
</tr>
<tr>
<td></td>
<td>(1.4 mil ton/year)</td>
</tr>
<tr>
<td>CO₂ removal</td>
<td>90%</td>
</tr>
</tbody>
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**CO₂ Used for CO₂-EOR**

<table>
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<tr>
<th>Pipeline</th>
<th>12 in diameter, ~81 miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Site</td>
<td>West Ranch Oil Field</td>
</tr>
</tbody>
</table>

CO₂ Captured for Enhanced Oil Recovery (EOR)

- Compressed CO₂ is delivered by an 81 mile CO₂ pipeline to the West Ranch oil field.
- Up to 1.4 million metric tons of CO₂ will be annually injected into the West Ranch formation.
- Oil production could be enhanced from **300 barrels/day to up to 15,000 barrels/day.**

The West Ranch CO₂-EOR Project
WA Parish CO\textsubscript{2} EOR Overall System

Coal fired boiler

Flue gas

\textbf{CO\textsubscript{2} Capture}

\textbf{CO\textsubscript{2} Compression \\& dehydration}

\textbf{Supercritical CO\textsubscript{2}}

\textbf{Pipe line}

\textbf{Oil field}

\textbf{Oil production}

\textbf{Electric power selling}

\textbf{Gas Turbine}

\textbf{Heat Recovery Steam Generator (HRSG)}

Natural gas

Flue gas

Steam

Electric power selling
Petra Nova Project Overview

Quencher and Absorber Construction

Rectangular steel towers and modular construction

→ Speedy and flexible Construction method
Petra Nova Project Overview

Absorber Module Lifting
MHI has been investigating new solvents to further reduce the cost of CO₂ capture.

| New Solvent Testing – Lab Results |
|-------------------------------|------------------|
|                               | KS-1™            | New Solvent |
| Steam Consumption             | 1                | 0.92        |
| Solvent Degradation           | 1                | 0.53        |
| Solvent Emission              | 1                | 0.40        |

• MHI conducted solvent screening in the laboratory and the Nanko pilot plant.
• New solvent has achieved lower steam consumption, solvent degradation, and solvent emissions than KS-1™.
• New solvent may require a higher solvent circulation flow rate which increases electricity consumption.
• Benefits appear to outweigh the higher flow rate.
MHI’s KM CDR Process® can be successfully applied to NGCC power plants.

<table>
<thead>
<tr>
<th>Typical Flue Gas Conditions</th>
<th>Unit</th>
<th>Coal fired Boiler</th>
<th>NG fired GT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol.%</td>
<td>10 - 14</td>
<td>3 - 4</td>
</tr>
<tr>
<td>CO₂</td>
<td>Vol.%</td>
<td>4 - 6</td>
<td>10 - 15</td>
</tr>
<tr>
<td>O₂</td>
<td>ppm(dry)</td>
<td>1 - 50</td>
<td>&lt;0.3</td>
</tr>
<tr>
<td>SOx</td>
<td>mg/Nm³</td>
<td>3 - 10</td>
<td>NA</td>
</tr>
<tr>
<td>PM (Dust)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- MHI operated 1 mtpd pilot plant for 3,000 hrs on simulated NGCC flue gas.
- KS-1™ proved resistant to O₂ degradation despite higher concentration.
- MHI can provide large absorbers to account for lower CO₂ concentration.
- KM CDR Process® requires fewer treatment systems as a result of the minimal SOx and dust in flue gas.
MHI has the capability to investigate advanced NGCC-\(\text{CO}_2\) capture configurations to consider existing and new assets.

Fully optimized integration between NGCC and \(\text{CO}_2\) capture can:

- Take advantage of high efficiency gas turbines
- Reduce parasitic load of \(\text{CO}_2\) capture
- Reduce capital cost of \(\text{CO}_2\) capture
Summary

MHI’s Carbon Capture Technology

- **Tested** MHI proved viability at multiple R&D facilities.
- **Delivered** MHI delivered **eleven (11) operating commercial CO₂ capture plants** prior to the Petra Nova Project.
- **Scaled-up** MHI successfully scaled-up and demonstrated long-term operation at Alabama Power’s Plant Barry.

Commercial Plant for CO₂-EOR

- **Petra Nova** **December 2016** – the world’s largest post-combustion CO₂ capture project on coal-fired flue gas (4,776 mtpd) – completes performance testing.

Continuing Developments

- **New Solvents** MHI is developing new solvents to reduce utility consumption and emissions.
- **NGCC** MHI is ready to optimize CO₂ capture for **NGCC applications**.