Oxy-Coal Combustion Power Plant with CCS
Current Status of Development

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Cheltenham, UK

39th Clearwater Conference
Florida, USA
May 2014
A transformation is needed...

..and we to have the tools to develop a strategy and be proactive.
Presentation Objectives

• To provide an overview to the current state of development of Oxyfuel Combustion
  • Burners and boiler development
  • Oxygen production
  • CO₂ processing unit

• To provide the highlights of the key developments and identify the critical future direction in R&D
Oxyfuel Combustion for Coal Fired Power Plant with CCS
1980’s
ANL/Battelle/EERC completed the first industrial scale pilot plant

1990 - 1995
EC Joule Thermie Project - IFRF / Doosan Babcock / Int’l Combustion
NEDO / IHI / Jcoal Project

1998 – 2001
CANMET
US DOE Project / B&W / Air Liquide

1990 - 1995
EC Joule Thermie Project - IFRF / Doosan Babcock / Int’l Combustion
NEDO / IHI / Jcoal Project

World’s FIRST 30 MWt full chain demonstration at Schwarze Pumpe

2008
B&W CEDF (30MWt)
large scale burner testing started

2003 - 2005
Vattenfall (ENCAP++)
CS Energy / IHI Callide Project

2007
B&W CEDF (30MWt)
large scale burner testing started

2008
First large scale 35MWt Oxy-Coal Burner Retrofit Test done by International Combustion

2009 – Lacq
World’s first 30MWt retrofitted Oxy-NG boiler w/storage

2012 – Callide
World’s first 30MWt retrofitted Oxy-coal power plant

2012 – CIUDEN
World’s first 30MWt Oxy-CFB Pilot Plant

2003 - 2005
Vattenfall (ENCAP++)
CS Energy / IHI Callide Project

2007
B&W CEDF (30MWt)
large scale burner testing started

1980’s
ANL/Battelle/EERC completed the first industrial scale pilot plant

Can we still achieve our goal to commercialise the technology by 2020???
By 2015-2019
Demonstration of 100–300MWe full scale power plant.

Target: “Commercialised by 2020”

1998 – 2001
CANMET
US DOE Project / B&W / Air Liquide

2007
B&W CEDF (30MWt)
large scale burner testing started

B&W CEDF 2008 30MWth Coal
Alstom Alstom CE 2010 15MWth Coal
Doosan Babcock DBEL - MBTF 2009 40MWth Coal

FutureGen2 - Illinois (PC - 168MWe)
UK: White Rose Project (PC – 426MWe)
China: Shenhua Shenmu Project (PC – 200MWe)
Developments in Burners & Boilers

• We have seen the rapid development of Oxyfuel Combustion in the last 10 years
  • Vattenfall’s Oxyfuel Projects
    o Covering the work from Schwarze Pumpe Large Scale Pilot Plant to Janschwalde’s FEED.
  • Callide Oxyfuel Project
    o Largest mini-demonstration project in the world
  • TOTAL’s Lacq Project
    o First pilot demonstration of CO2 injection from oxyfuel boiler
  • CIUDEN’s Oxyfuel Projects
    o World largest pilot plant for oxy-CFB
Efficiency Improvement with Increasing Steam Conditions

- **1960**: Mature technology
- **1980**: Market intro. by Japan and Europe
- **2000**: USC Materials Consortium & EC AD 700 project (Ni-base)
- **2010**: R&D ongoing USA
- **2012**: COSPL’s 22MWe Callide Oxyfuel Power Plant (42 Bar / 460oC)
- **2013**: CIUDEN’s 200MW Oxy-PC Pilot Plant (30 Bar / 420oC)
- **2010**: TOTAL’s 30MWt Lacq Oxyfuel Steam Generation Plant (60 Bar / 420oC)
- **2017**: FutureGen2 168MW Oxyfuel Power Plant (166 Bar / 538oC / 538oC)
- **2018**: Drax’s 426MW White Rose Project Oxyfuel Power Plant (166 Bar / 538oC / 538oC)
- **20XX**: KOSEP’s 100MW Young Dong Oxyfuel Power Plant (166 Bar / 538oC / 538oC)
- **20XX**: Vattenfall’s 250MW Janschwalde Oxyfuel Power Plant (280 Bar / 600oC / 600oC)
- **20XX**: Vattenfall’s 30MWt Schwarze Pumpe Oxyfuel Pilot Plant (30 Bar / 330oC)
- **2008**: Vattenfall’s 30MWt Schwarze Pumpe Oxyfuel Pilot Plant (30 Bar / 330oC)

S. Santos (16/04/2014) - figure of steam conditions adapted from Alstom’s paper
Large Scale Demo – Progressing

FutureGen 2.0

- Repower Meredosia Energy Center with oxy-combustion and CCS technology
  - Repowered gross: 168 MWe
  - Near-zero emissions
  - CO₂ capture rate: 98%
  - CO₂ capture volume: 1.1 MMT/yr
  - Pipeline transport: ~30 miles
  - Deep geologic storage

<table>
<thead>
<tr>
<th>Design</th>
<th>Construction</th>
<th>Power Production w/ CCS</th>
<th>Post-closure monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>2014</td>
<td>2017</td>
<td>2037</td>
</tr>
</tbody>
</table>

Investment decision to be made before the end of 2014
Large Scale Demo – Progressing

What is making it work? – Delivery

Partner Roles, bringing depth of know-how and resources

OXY-POWER PLANT
- Delivery of Oxy-Power Plant
- Integration of Oxy-Power Plant

Drax
- O&M of Oxy-PP
- Trading Services
- Site Services
- Fuel Supply
- Electrical Connection

BOC-Linde
- Delivery of ASU
- O&M of ASU

CO₂ TRANSPORT & STORAGE
- Full-Chain Integration

National Grid Carbon Ltd
- Delivery of Transport & Storage network
- O&M of Transport & Storage network

Investment decision to be made before the end of 2015
What’s the future landscape of Oxyfuel R&D for boilers & burner development

- **We have learned a lot in the last 10 years**
  - It could be concluded that oxyfuel combustion is ready for demonstration
  - It could be operated very similar to the conventional utility boilers

- **Work in both Oxy-PC and Oxy-CFB will continue.**
  - The pace of development will depend on the market

- **Different fundamental R&D activities will not stop – it is expected to follow the development path of conventional utility boilers.**
  - Fuel characterisation
  - Pollutant formation and reduction
  - Materials development
  - Modelling development

- **Work in opportunity fuels – expected to grow (how fast?)**
  - Biomass, petcoke, and others
Oxygen Production

**Facts:**

- Today, only the Cryogenic Air Separation Unit or ASU is capable of delivering the oxygen demand of a large oxyfuel combustion boiler for power plant with CO$_2$ capture...

- For every 500MWe net output you will require ~10,000 t/d O$_2$
  - Low Purity (95-97%)*
  - Low Pressure (nearly atmospheric)

At 95% purity will have 2% N2 and 3% Ar
Cryogenic Air Separation – Capacity Increase

1902:
5 kg/h
(0.1 ton/day)

2006:
1,250 Mio kg/h
(30,000 ton/day)
Experience - Large ASU Projects and Train Scale-up

- Market drives ASU scale-up
- Proven 70% scale-up
- Quoting 5,000+ MTPD today
Current Status - Cryogenic ASU for Oxyfuel Combustion

• Advances and Development in ASU could result to 25-35% less energy consumption than what could be delivered by the current state of the art ASU today.

• A target of 140 kWh/t O₂ (at ISO condition) is achievable

• These ASU would not be based on the conventional 2 column ASU – but it could be hybrid based on 3 columns design or dual reboiler design.
McCabe Thiele Diagrams

**Double Column**

Equilibrium line

Operating lines

**Single Pressure Side Column Reboiler**

**Cold Compressed Side Column Reboiler**

Nitrogen in vapor vs. Nitrogen in liquid graphs for different configurations.
ASU’s Flexibility & Energy Storage

- Ramping between 1-3%/min the ASU could be designed and adapted without co-production of liquid gases (i.e. air, O₂, N₂)
  - Design of such plant would be strongly dependent on the arrangements of the main air compressors
- With co-production of liquid gases
  - wide ranging flexibility could be achieved.
  - Additionally, the manner on how the ASU will be operated could have a good potential for Energy Storage with CCS.
- Current challenge will be on how to balance between CAPEX and OPEX to achieve the optimised flexible ASU that meets the demand of the power plant
Although the design of the ASUs for Gasification and Oxyfuel Combustion have a lot of differences...

Nonetheless, by building and operating the world’s largest single train ASUs will benefit the Oxyfuel Combustion Technology – i.e. **Demonstrating ASUs of the size needed for Oxyfuel Combustion could be build today.**
What’s the future landscape of Oxyfuel R&D for oxygen production

• Once the world’s largest single train ASUs starts its operation – this will provide a very good basis as a “Reference” to application of oxyfuel combustion.

• Crucial to the improvement of cryogenic ASUs for future oxyfuel combustion applications are:
  • Flexibility of the Main Air Compressor
  • Development of process controls
  • Integration with the boiler island and the CPU.

• Development for alternative oxygen production should continue.
  • It is not expected to dislodge the cryogenic ASU for some time.
CO₂ Processing Unit

• **Key Areas of Development in CO₂ Processing Unit or CPU**
  - Compression and Removal of minor impurities (NOx, SOx and Other Trace elements)
  - Dehydration Unit
  - Cryogenic Separation of Inerts (Cold Box development)
  - Additional capture of CO₂ from the CPU

• **Other key driver to the development is the specification of the CO₂.**
  - Management of CO₂ purity requires good interaction between boiler, flue gas processing and CPU
Overview of Development of CPU over the last 10 years...

- Recognition of the NOx and SOx reaction by Air Products (presented during GHGT Conference – June 2006)
  - This has led to the rapid technology development among the industrial gas producers.
- Identification of potential impact of Hg to the operation of the CPU.
- Development of the use of impure CO₂ as refrigerant driven mostly by reducing energy penalty.
- Work on further recovery of CO₂ in the vent of CPU.
NO\textsubscript{x} SO\textsubscript{2} Reactions in the CO\textsubscript{2} Compression System

- We realised that SO\textsubscript{2}, NO\textsubscript{x} and Hg can be removed in the CO\textsubscript{2} compression process, in the presence of water and oxygen.
- SO\textsubscript{2} is converted to Sulphuric Acid, NO\textsubscript{2} converted to Nitric Acid:
  - \(\text{NO} + \frac{1}{2} \text{O}_2 = \text{NO}_2\) (1) Slow
  - \(2 \text{NO}_2 = \text{N}_2\text{O}_4\) (2) Fast
  - \(2 \text{NO}_2 + \text{H}_2\text{O} = \text{HNO}_2 + \text{HNO}_3\) (3) Slow
  - \(3 \text{HNO}_2 = \text{HNO}_3 + 2 \text{NO} + \text{H}_2\text{O}\) (4) Fast
  - \(\text{NO}_2 + \text{SO}_2 = \text{NO} + \text{SO}_3\) (5) Fast
  - \(\text{SO}_3 + \text{H}_2\text{O} = \text{H}_2\text{SO}_4\) (6) Fast

- Rate increases with Pressure to the 3\textsuperscript{rd} power
  - only feasible at elevated pressure

- No Nitric Acid is formed until all the SO\textsubscript{2} is converted

- Pressure, reactor design and residence times, are important.
# Updated NO\textsubscript{x} - SO\textsubscript{x} Reaction Network

<table>
<thead>
<tr>
<th>Stoichiometry</th>
<th>Phase</th>
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<tbody>
<tr>
<td>2 NO + O\textsubscript{2} → 2 NO\textsubscript{2}</td>
<td>V</td>
</tr>
<tr>
<td>2 NO\textsubscript{2} ⇌ N\textsubscript{2}O\textsubscript{4}</td>
<td>V</td>
</tr>
<tr>
<td>N\textsubscript{2}O\textsubscript{4} + H\textsubscript{2}O → HNO\textsubscript{3} + HNO\textsubscript{2}</td>
<td>L</td>
</tr>
<tr>
<td>2 HNO\textsubscript{2} ⇌ NO + NO\textsubscript{2} + H\textsubscript{2}O</td>
<td>L</td>
</tr>
<tr>
<td>4 HNO\textsubscript{2} ⇌ 2 NO + N\textsubscript{2}O\textsubscript{4} + 2 H\textsubscript{2}O</td>
<td>L</td>
</tr>
<tr>
<td>SO\textsubscript{2} + H\textsubscript{2}O ⇌ H\textsubscript{2}SO\textsubscript{3}</td>
<td>L</td>
</tr>
<tr>
<td>2 HNO\textsubscript{2} + 2 SO\textsubscript{2} + H\textsubscript{2}O ⇌ 2 H\textsubscript{2}SO\textsubscript{4} + N\textsubscript{2}O</td>
<td>L</td>
</tr>
<tr>
<td>2 HNO\textsubscript{2} + 2 H\textsubscript{2}SO\textsubscript{3} → 2 H\textsubscript{2}SO\textsubscript{4} + N\textsubscript{2}O + H\textsubscript{2}O</td>
<td>L</td>
</tr>
<tr>
<td>2 HNO\textsubscript{2} + SO\textsubscript{2} → H\textsubscript{2}SO\textsubscript{4} + 2 NO</td>
<td>L</td>
</tr>
<tr>
<td>2 HNO\textsubscript{2} + H\textsubscript{2}SO\textsubscript{3} → H\textsubscript{2}O + H\textsubscript{2}SO\textsubscript{4} + 2 NO</td>
<td>L</td>
</tr>
<tr>
<td>2 NO\textsubscript{2} + H\textsubscript{2}O → HNO\textsubscript{3} + HNO\textsubscript{2}</td>
<td>L</td>
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</table>

Green – propagates NO\textsubscript{x} redox cycle
Red – terminates NO\textsubscript{x} redox cycle

\[
\begin{align*}
\text{NO + O}_2 & \rightarrow \text{NO}_2 / \text{N}_2\text{O}_4 \\
\text{HNO}_2 + \text{HNO}_3 & \rightarrow \text{H}_2\text{SO}_4 + \text{N}_2\text{O} \\
\text{H}_2\text{SO}_4 + \text{NO} & \rightarrow \text{NO}_2 / \text{N}_2\text{O}_4 \\
\text{H}_2\text{SO}_4 + \text{SO}_2 / \text{H}_2\text{SO}_3 & \rightarrow \text{H}_2\text{SO}_4 + \text{N}_2\text{O}
\end{align*}
\]
Removal of NOx, SOx and others...

CO₂ Compression and Purification System – Removal of SO₂, NOx and Hg

1.02 bar
30°C
67% CO₂
8% H₂O
26% Inerts
SOx
NOx

15 bar

BFW

30 bar to Driers
Saturated 30°C
76% CO₂
24% Inerts

30 bar

Water

CW

Dilute H₂SO₄
HNO₃
Hg

LiCONOX™ Process

Recycle to burner

CaO

NO₂ Scrubber

H₂O

N₂

NH₃

H₂O

Nitrite reduction

Gypsum production

Gypsum

Linde AG: Engineering Division

NOₓ emissions reduction

2 options are possible
- With cryo separation (for low NOₓ content in product CO₂)
- Without cryo separation (NOₓ co-sequestration)

Sulphuric Acid Method

Activated Carbon Method
Capture Rate: Greater than 98% CO₂
What’s the future landscape of Oxyfuel R&D for CO₂ Processing Unit

- **Specification of CO₂ is crucial to the engineering and design of the CPU**

- **We need large scale demonstration – to validate the key results obtained from various pilot plant experience.**
  - Selection of process configurations have several options

- **Also for future R&D will require focus on:**
  - Flexibility of the CPU - this hinged on the CO₂ compressors and pumps performance.
  - Development of process controls
  - Integration with the boiler island and the CPU.
Oxyfuel Combustion with CCS is not only for Power Generation...

- Cement Industry
- Oil Refining Industry
- Oil Refining Industry
- H2 Production
- Steel Industry
- Helium recovery from natural CO2 source
Thank You

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