ASU and CO₂ Processing Units for Oxyfuel CO₂ Capture Plants

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THE COAL RESEARCH FORUM.
23rd ANNUAL MEETING AND MEETING OF THE COMBUSTION DIVISION
Oxyfuel Combustion Requires...

- Air Separation Units
- Steam Boiler & Turbine
- CO₂ Purification & Compression
- CO₂ Transport & Sequestration
Air Separation Processes

• Adsorption
  – Pressure swing (PSA) and Vacuum swing (VSA)
  – Small scale, up to ~200 tonnes/day $O_2$ single train
  – Limited purity $O_2$ (~93%)

• Cryogenic distillation
  – Most flexible – higher purity, liquids
  – Large scale, up to ~5000 tonnes/day $O_2$

• Other
  – Ion Transport Membrane – in development at ~100 tonnes/day $O_2$
Overview Of The Process

Main and Boost Air Compression
Air Cooling and Pretreatment
Cryogenic Separation
Storage

Air

Oxygen

Heat

Heat
Cryogenic Heat Exchange

- Brazed aluminium plate fin exchangers
- Cools air streams against product streams to recover refrigeration
- Ambient to cryogenic temperatures
Aluminium Plate-Fin Heat Exchanger
Completed Core
Distillation Technology

• Structured Packing
  – Lower pressure drop – saves up to 10% of air compressor power
  – Better turndown
  – Higher plant capacity

• Sieve trays
  – Shorter columns
Structured packing
Oxygen Requirements for Oxycoal CO$_2$ Capture

- Oxygen pressure is low
  - Boiler runs close to atmospheric pressure
- Oxygen purity is low (<97%)
  - Air leaks into boiler, impurities must be removed from CO$_2$
  - Easier to remove argon from CO$_2$ than from O$_2$
- Oxygen demand is large
- 500MWe power plant needs ~10,000 tonnes/day O$_2$
- No use for co-products
- High efficiency and low capital desirable
  - New opportunities to optimise the ASU
Low Purity, Low Pressure Dual HP Column Cycle for Oxyfuel
Oxycoal “Reference ASU” Cycle

• Integration is not always required or desirable
• With no integration, three column cycle is best
  – Minimum power input, high $O_2$ recovery
• But three column cycle still ideal for integration
  – Adiabatic compression with heat recovery
  – Optional $N_2$ at 2.5 bar(a) if it can be used
• So Reference ASU based on three column cycle
ASU Machinery and Drives

- Significant part of ASU cost (capital and power)
  - Critical to optimise efficiency vs. capital cost
- Likely to reach referenced machinery limits
  - Can use multiple trains for a single cold box
- Centrifugal or axial air compressors
  - Centrifugal up to ~5000 tonnes/day O2
  - Axial up to ~8000 tonnes/day O2
- GT derived units will be even larger
- Electric Motor or Steam Turbine drive (GT unsuitable)
  - Motors simplify operation but may have starting issues
  - Steam turbines more efficient for power generation than mechanical drives – balances extra electrical losses
Oxycoal “Reference ASU”

- Designs developed for a scalable reference plant
- Column diameters within manufacturing capabilities (referenced to 7000 te/d)

<table>
<thead>
<tr>
<th>Size te/d O₂</th>
<th>Machinery options</th>
<th>Power MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,000 – 4,000</td>
<td>Centrifugal 1 or 2 train or axial 1 train</td>
<td>22-33</td>
</tr>
<tr>
<td>4,000 – 5,500</td>
<td>Centrifugal 1 or 2 train or axial 1 train</td>
<td>30-45</td>
</tr>
<tr>
<td>5,500 – 7,000</td>
<td>Centrifugal 2 train or axial 1 train</td>
<td>41-58</td>
</tr>
<tr>
<td>7,000 -10,000</td>
<td>Centrifugal or axial 2 train</td>
<td>53-82</td>
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Oxycoal ASU Flexibility

• Turndown limited by compressors not cold box
  – Normally 75-100%
  – Can increase range with efficiency penalty
  – More compression trains or multiple plants give wider, more continuous range
• Rapid ramping possible
  – Dynamic modelling: 5% / minute within ± 2% purity
  – Model predictive control (MPC) will be used
• Instantaneous back-up system
  – For plant trip and peak shaving
  – ASU make liquid for tank refill
Conclusions

• Air Products Oxycoal ASU has low specific power
  – with or without power cycle integration
• Integration needed to get lower specific power
  – boiler modification & novel expanders
• Single cold box to 10,000 te/d O₂ - modest scale-up
• Single train machinery up to about 8,000 te/d O₂
• Rapid load change possible
• Heat integration beneficial – depends on specifics
Oxyfuel CO₂ Purification

- Oxyfuel combustion of coal produces a flue gas containing:
  - CO₂ + H₂O
  - Any inerts from air in leakage or oxygen impurities
  - Oxidation products and impurities from the fuel (SOx, NOx, HCl, Hg, etc.)
- Purification requires:
  - Cooling to remove water
  - Compression to 30 bar: integrated SOx/NOx/Hg removal
  - Low Temperature Purification
    - Low purity, bulk inerts removal
    - High purity, Oxygen removal
  - Compression to pipeline pressure
Air Products Oxy-Fuel CO₂ Capture and Purification – with Air Products PRISM® Membrane

Boiler Steam Cycle

Heat Recovery

Sour Compression & AP Acid Gas Column

Condensate Collection

Raw Flue Gas

Process Condensate

Major Utilities
- Cooling Water
- Electric Power

O₂ and CO₂ Rich [To Boiler]

CO₂ Compression

Auto-Refrigerated N₂, Ar, O₂ Removal Process

Optional APCI PRISM® Membrane

Mercury Removal

TSA Unit

Product CO₂

Product CO₂

Offgas [To Atmosphere]

Expander

Cooling Water

Electric Power
Air Products’ CO₂ Purification and Compression Technology for Oxyfuel

**Sour Compression SOx, NOx, Hg Removal**
- SOx/NOx removed in compression system
  - NO is oxidised to NO₂ which oxidises SO₂ to SO₃
  - The Lead Chamber Process
- FGD and DeNOx systems
  - Optimization
  - Elimination
- Low NOx burners are not required for oxyfuel combustion
- Hg will also be removed, reacting with the nitric acid that is formed

**Auto-Refrigerated Inerts Removal Ar, N₂, O₂**
- Removal minimises compression and transportation costs.
- Optional O₂ removal for EOR-grade CO₂
- CO₂ capture rate of 90% with CO₂ purity >95%
- CO₂ capture rate depends on raw CO₂ purity which depends on air ingress

**Air Products’ PRISM® Membrane For Enhanced CO₂ + O₂ Recovery**
- Inerts vent stream is clean, at pressure and rich in CO₂ (~25%) and O₂ (~20%)
- Polymeric membrane unit – selective for CO₂ and O₂ – in vent stream will recycle CO₂ and O₂ rich permeate stream to the boiler.
- CO₂ capture rate increases to >97% and ASU size/power reduced by ~5%

SOx/NOx, NO is oxidised to NO₂ which oxidises SO₂ to SO₃, optimization, elimination, low NOx burners are not required for oxyfuel combustion.
Compression Options to 30 bar

- Axial Compressor (plus inline radial)
  - Higher compression ratios
  - Higher outlet temperature
    - So better integration options
  - Simpler configuration
    - No intercoolers
  - But higher power consumption
    - Offset with integration opportunities
  - Can be single train to ~8-900 MWe

- Integrally geared compressor
  - Lower power consumption
  - Less opportunity for integration
  - Might need multiple trains for >500 MWe plants
CO₂ Compression and Purification System – Inerts removal and compression

- Flue Gas Vent
  - 1.1 bar
  - ~25% CO₂
  - ~75% inerts

- Flue Gas Expander
  - Flue Gas Heater
  - Aluminium plate/fin exchanger
    - -55°C

- Driers
  - 30 bar Raw CO₂
  - Saturated 30°C
  - 75-85% CO₂

- CO₂ product
  - ~96% CO₂
  - ~4% Inerts
  - -60°C dp
**CO₂ Purity and Recovery**

- -55°C is as cold as we can make the phase separation
- CO₂ purity depends on pressure
  - With 75% CO₂ in the feed, at 30 bar and -55°C, CO₂ purity is 95%
  - Higher pressure gives lower purity CO₂
- CO₂ recovery depends on pressure
  - Lower pressure gives lower CO₂ recovery
  - At 15 bar and -55°C, CO₂ recovery is 75%
  - At 30 bar and -55°C, CO₂ recovery is 90%
- CO₂ recovery depends on feed composition
  - Increases from zero at 25mol% to 90% at 75mol%
  - Reducing air ingress increases CO₂ capture rate
Compression Options from 30 bar to Pipeline Pressure

- Integrally geared compressor only feasible option

- Expander wheels can be integrated onto compressor bull wheel
Can we improve on ~90% CO₂ Capture?

Vent stream is at pressure and is CO₂ (and O₂) rich

- Flue Gas Vent
  - 1.1 bar
  - ~25% CO₂
  - ~25% O₂
  - ~50% N₂

-Driers-

- Flue Gas Expander

- Flue Gas Heater

- Aluminium plate/fin exchanger

- CO₂ product
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30 bar Raw CO₂
Saturated 30°C
75-85% CO₂
Air Products Oxy-Fuel CO$_2$ Capture and Purification – with Air Products PRISM$^\text{®}$ Membrane

- Flue Gas Expander
- Flue Gas Heater
- Aluminium plate/fin exchanger
- Driers
- 30 bar Raw CO$_2$
  - Saturated 30°C
  - 75-85% CO$_2$
- CO$_2$ product
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- CO$_2$ product
  - ~96% CO$_2$
  - ~4% Inerts
  - -60°C dp
Advantages of Air Products’ CO$_2$ Purification Technology for Oxyfuel

- Vent stream is clean, at pressure and rich in CO$_2$ (~25%) and O$_2$ (~20%)
  - Polymeric membrane unit – selective for CO$_2$ and O$_2$ – in vent stream will recycle CO$_2$ and O$_2$ rich permeate stream to boiler.
  - CO$_2$ Capture increase to >97%
  - ASU size/power reduced ~5%
Path to Large-Scale Demonstration

160 kW$_{th}$ oxy-coal rig

15 MW$_{th}$ oxy-coal combustion unit

30 MW$_{th}$ oxy-coal pilot plant

DOE Project
Host: Alstom, Windsor, CT

VATTENFALL
Schwarze Pumpe, Germany

1 MW$_{th}$ slip stream

0.3 MW$_{th}$ slip stream

6 kW$_{th}$ slip stream

Batch

London

Renfrew, Scotland

London

Imperial College

Doosan Babcock Energy

Photo courtesy of Imperial College

Photo courtesy of Doosan Babcock

Photo courtesy of Vattenfall

Photo courtesy of Vattenfall

Photo courtesy of Imperial College

Photo courtesy of Alstom

Photo courtesy of Alstom

Large-Scale (~300 MW) Demo
The effect of Pressure on SO₂ and NO Conversion (1 sl/min, 7 and 14 barg)

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<tr>
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<th>14 bar g</th>
<th>7 bar g</th>
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<tbody>
<tr>
<td></td>
<td>Inlet (Point A)</td>
<td>After Compressor &amp; Receiver (Point C)</td>
</tr>
<tr>
<td>ppm SO₂</td>
<td>900</td>
<td>20</td>
</tr>
<tr>
<td>ppm NOₓ</td>
<td>520</td>
<td>50</td>
</tr>
</tbody>
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DOE Project: Air Products’ Sour Compression PDU – Key Results

- For the overall process, total SO$_2$ removal was 20-100 % (based on gas compositions).
- For the overall process, total NOx removal was 60-90 % (based on gas compositions).
- The effects of variations in the SO$_2$/NOx feed ratio, column pressure, gas flowrate and liquid recirculation on the reactor performance were explored. Process performance was most sensitive to SO$_2$/NOx feed ratio, over the range of parameter values investigated.
- SO$_2$ was removed from the flue gas through both sulfite and sulfate mechanisms.
The Vattenfall – Air Products Oxyfuel CPU Pilot Plant

Air Products’ Proprietary Technology Joins World’s First Full Demonstration of Oxyfuel CO2 Capture and Sequestration at Vattenfall

LEHIGH VALLEY, Pa. (March 31, 2009) - Air Products (NYSE: APD) today announced it will play a key role in the world’s first full demonstration of oxyfuel carbon capture and sequestration with the signing of an agreement with Vattenfall AB, one of Europe’s leading energy companies. Air Products will install its proprietary carbon dioxide (CO2) capture, purification and compression system at Vattenfall’s research and development facility in Schwarze Pumpe, Germany, which is viewed globally as the preeminent CO2 oxyfuel project. Air Products will focus specifically on the purification and compression of oxyfuel combustion flue gas. The two companies also executed a joint research and development agreement related to the project. Air Products’ pilot plant is to be operational at Schwarze Pumpe in December 2010.
Air Products’ CO₂ Purification Unit (CPU) Pilot Plant at Vattenfall’s Schwarze Pumpe

- Raw Flue Gas
  - Sour Compression
  - Condensate Collection
  - Process Condensate

- TSA Unit

- Mercury Removal

- Auto-Refrigerated Inerts +O₂ Removal Process
  - CO₂ Returned To OxPP
  - O₂ and CO₂ Rich [To OxPP]
  - Inerts Vent [To OxPP]

- Air Products PRISM® Membrane
50/50 Flue Gas Mix From Before and After OxPP FGD
Conclusions

• First demonstration of Sour Compression in representative equipment

• First demonstration of auto-refrigerated inerts removal

• Learned many lesson relevant to full scale plant design and operation

• Purification of the CO$_2$ from oxyfuel-fired coal power plants is a technology ready for commercialisation

• Several advances in CPU technology have been described which will improve the performance of the CPU and the power plant

• Air Products is developing commercial offerings for CPU plants on demonstration plants
Thank you

www.airproducts.com