Advanced Combustion Technology: Oxy-Firing to Enable CO₂ Capture

by:

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Advanced Combustion Technology:
OXYFIRING TO ENABLE CO₂ CAPTURE

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ALSTOM Power Inc.
Frank Kluger
ALSTOM Power Boiler GmbH
Fredrik Brogaard
Alstom Power Sweden AB
Oxygen firing: Concept

Fuel is burned in a boiler in a mixture of oxygen and recirculated flue gas (principally CO₂), essentially eliminating the presence of atmospheric nitrogen in the flue gas. The resulting flue gas is comprised of primarily CO₂ and H₂O vapor along with some N₂, O₂, and trace gases like SO₂, and NOₓ. Consequently:

- The flue gas can be processed relatively easily (through rectification or distillation) to enrich the CO₂ content in the product gas to 96-99% percent for use in enhanced oil or gas recovery (EOR or EG), or
- The flue gas is simply dried and compressed for sequestration only

Near-Term Development Horizon

- Most near-term solution -Uses commercially available air fired PC/CFB technology and enabling technologies:
  - O₂ production by commercial cryogenic air separation
  - CO₂ capture, compression, and liquefaction

- Economic analysis looks viable for commercial EOR application
  - Electricity for sale
  - CO₂ sale for oil field stimulation
  - N₂ sale for oil field pressurization

- Required intermediate step leading to the more advanced processes, e.g.:
  - Oxygen Fired PC/CFB with Oxygen Transport Membrane
  - Chemical Looping Combustion
  - Chemical Looping Gasification

Oxygen-Fired PC/CFB Technology - Motivation
Today's Discussion

- Overview
  - Conventional oxy-firing
  - Advanced concepts
  - Economics of recent studies
  - Ongoing test programs

CO₂ Capture Options

Post-combustion capture

Pre-combustion capture

O₂/CO₂ recycle (oxyfuel) combustion capture

Co₂ dehydration, compression, transport and storage

**CO₂ Capture Options**

<table>
<thead>
<tr>
<th>Type</th>
<th>Oxidant</th>
<th>CO₂ Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-combustion</td>
<td>Air Fired</td>
<td>Extract from Flue Gas</td>
</tr>
<tr>
<td>Pre-combustion</td>
<td>O₂ for Gasification</td>
<td>Shift CO to CO₂</td>
</tr>
<tr>
<td></td>
<td>Air for Final Combustion</td>
<td>Extract from Fuel Gas</td>
</tr>
<tr>
<td>Oxyfiring</td>
<td>O₂ for Combustion</td>
<td>Dry and Purify Flue Gas</td>
</tr>
</tbody>
</table>

**Conventional Firing**

<table>
<thead>
<tr>
<th></th>
<th>N₂</th>
<th>CO₂</th>
<th>H₂O</th>
<th>O₂</th>
<th>Rel Vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>75</td>
<td>15</td>
<td>7</td>
<td>3</td>
<td>100</td>
</tr>
</tbody>
</table>
Conventional Firing with Amine Scrubbing

<table>
<thead>
<tr>
<th></th>
<th>N₂</th>
<th>CO₂</th>
<th>H₂O</th>
<th>O₂</th>
<th>Rel Vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>75</td>
<td>15</td>
<td>7</td>
<td>3</td>
<td>100</td>
</tr>
</tbody>
</table>

Conventional Firing using ASU to Produce a Stream of Oxygen

<table>
<thead>
<tr>
<th></th>
<th>N₂</th>
<th>CO₂</th>
<th>H₂O</th>
<th>O₂</th>
<th>Rel Vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>75</td>
<td>15</td>
<td>7</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>100% O₂</td>
<td>5</td>
<td>67</td>
<td>25</td>
<td>3</td>
<td>22</td>
</tr>
</tbody>
</table>
### Conventional Firing with ASU and Drying to Purify the CO2 stream

![Diagram of Conventional Firing with ASU and Drying to Purify the CO2 stream]

<table>
<thead>
<tr>
<th></th>
<th>N₂</th>
<th>CO₂</th>
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<td>5</td>
<td>67</td>
<td>25</td>
<td>3</td>
<td>22</td>
</tr>
</tbody>
</table>

### Three Oxygen-fired firing options

![Diagram of Three Oxygen-fired firing options]
Conventional Firing with ASU produces high combustor temperatures

```
N2  CO2  H2O  O2  Rel Vol
AIR 75  15   7   3    100
O2  5   67  25   3    22
```

Combustor temperatures can be mitigated with upper furnace heat absorption

```
N2  CO2  H2O  O2  Rel Vol
AIR 75  15   7   3    100
O2  5   67  25   3    22
```
Combustor temperatures can be mitigated with flue gas recirculation

<table>
<thead>
<tr>
<th></th>
<th>N₂</th>
<th>CO₂</th>
<th>H₂O</th>
<th>O₂</th>
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<tr>
<td>AIR</td>
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<td>7</td>
<td>3</td>
<td>100</td>
</tr>
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<td>5</td>
<td>67</td>
<td>25</td>
<td>3</td>
<td>22</td>
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</tbody>
</table>

Retrofit option: Recirculate flue gas to a 30% O₂ blend maintains unit performance

<table>
<thead>
<tr>
<th></th>
<th>N₂</th>
<th>CO₂</th>
<th>H₂O</th>
<th>O₂</th>
<th>Rel Vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>75</td>
<td>15</td>
<td>7</td>
<td>3</td>
<td>100</td>
</tr>
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<td>O₂</td>
<td>5</td>
<td>67</td>
<td>25</td>
<td>3</td>
<td>22</td>
</tr>
<tr>
<td>30% O₂</td>
<td>5</td>
<td>67</td>
<td>25</td>
<td>3</td>
<td>64</td>
</tr>
</tbody>
</table>
Retrofit option: Recirculate flue gas to a 30% O2 blend maintains unit performance

Greenfield option: Circulating Fluidized Bed reduces recirculation of flue gas
CFB Heat Duties for Air and Oxy fired systems

AIR
- 20.0% External Heat Exchanger
- 30.4% Conv. Pass
- 48.3% Combustor

70 % O₂
- 68.0%
- 12.5%
- 18.8%

Overview of ALSTOM Studies
Developments Related to Oxy-firing for CO₂ Capture
ALSTOM CO₂ Capture Efforts

1999 - ABB
Technical Feasibility of a CO₂/O₂ Combusion Retrofit to an Existing Coal-Fired Boiler for CO₂ Extraction

1999 - TransAlta
Preliminary Design and Costing of a CO₂/O₂ Combustion Retrofit to an Existing Coal-Fired Boiler for CO₂ Extraction

1999 - ABB
Investigation of Ceramic Oxygen Transport Membrane Processes with Coal-Fired Power Plants

2000 - Sunco
CFB Boiler Integrated with 300 Tonnes per Day CO₂ Removal System for Sunco Thermal Solvent Process Project

2005 - BP Amoco
CO₂ Capture Project: An Integrated, Collaborative Technology Development Project for Next Generation CO₂ Capture, Separation and Sequestration

2001 - ENCAP
EU, DOE, State agencies and utilities
Percentage for

1999 - 200

2001 - 2004
DOE / ALSTOM
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers

2002 - 2003
EU
GRACE - Chemical Looping Combustion - Feasibility Study

2003 - 2004
ADEME / ALSTOM
CO₂ Capture - (cascade cryogenic) - ECS/MSF

2003 - 2004
ADEME / ALSTOM
CO₂ Capture - Calcium Cycle

2003 - 2005
DOE / ALSTOM
Hybrid Combustion Gasification Chemical Looping Coal Power

2003 - 2005
ADEME
EDF - JST

2003 - 2006
EU
ENCAP

2004
EU / IPFP6
Encap (Oxyfiring – Chemical Looping)

2004 - 2006
DOE / ALSTOM
Commercialization Development of O₂-Fired CFBC for Greenhouse Gas Control

2005 - 2006
DOE
CO₂ Capture from Existing Fleet Feasibility Study

2005 - 2006
DOE / Alstom
Pilot Scale Demonstration of LGR Technology on Oxygen Boiler

12 of 18 CO₂ studies focused on O₂ firing: a variety of partners

IEAGHG International Oxy-Combustion Network, Windsor CT USA, 2007

Advanced O₂ Technologies

IEAGHG International Oxy-Combustion Network, Windsor CT USA, 2007
Comparison of plant layouts: 210 MWe Gross

Comparison of plant power output: 210 MWe Gross

ASU requires 18% of net plant output
Advanced Oxygen Separation

Fuel → Compressor → Advanced ASU → Turbine / Generator

Combustion & Boiler System

Cleanup & Cooling

CO₂ Rich Flue Gas

CO₂

O₂ Depleted Air

Air

O₂ + CO₂

Compressor

Advanced ASU

Perovskite materials have the capacity to absorb oxygen from air

Evaluation of Ceramic Autothermal Recovery

Fuel → Bed A → Bed B → Cleanup & Cooling → CO₂ Rich Flue Gas

Combustion & Boiler System

Air

O₂ Depleted Air

Oxidant
Evaluation of Ceramic Autothermal Recovery

Cycle the valves to recharge Bed B while Bed A is used.

Advanced vs. Cryogenic ASU

<table>
<thead>
<tr>
<th></th>
<th>AIR</th>
<th>CRYOGENIC ASU</th>
<th>ADVANCED ASU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Aux Power, % of Gross</td>
<td>8</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>Plant Efficiency, % HHV</td>
<td>35</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Capital Cost, $/kW</td>
<td>1300</td>
<td>2500</td>
<td>2400</td>
</tr>
<tr>
<td>COE, $/kWh</td>
<td>4.5</td>
<td>8.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Summary from DOE Phase I Study * in 2003 dollars
## ALSTOM Economic Studies
### CO₂ Capture with Coal Power

Fourteen economic studies from 1998 – 2006 with a variety of partners: DOE, EU and utilities

<table>
<thead>
<tr>
<th>#</th>
<th>Project Name</th>
<th>Sponsor</th>
<th>Year(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Technical Feasibility of a CO₂/O₂ Combustion Retrofit to an Existing Coal-Fired Boiler for CO₂ Extraction</td>
<td>ABB</td>
<td>1998</td>
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<tr>
<td>2</td>
<td>Preliminary Design and Costing of a CO₂/O₂ Combustion Retrofit to an Existing Coal-Fired Boiler for CO₂ Extraction</td>
<td>TransAlta Corp.</td>
<td>1999</td>
</tr>
<tr>
<td>3</td>
<td>Integration of Ceramic Oxygen Transport Membrane Processes with Coal Fired Power Plants</td>
<td>ABB</td>
<td>1999</td>
</tr>
<tr>
<td>4</td>
<td>CFB boiler feasibility study</td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>5</td>
<td>CO₂-CC project requirements</td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>6</td>
<td>CO₂ Capture in a Coal Fired Boiler: Economic and Performance Sensitivity to CO₂ Capture Percentage for Amine-Based Processes</td>
<td>ALSTOM Power Inc.</td>
<td>2001</td>
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<tr>
<td>7</td>
<td>Engineering Feasibility and Economics of CO₂ Capture on an Existing Coal-Fired Power Plant</td>
<td>DOE/OOE/E NETL</td>
<td>1999-2001</td>
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<tr>
<td>9</td>
<td>GRACE - Chemical Looping Combustion - Feasability Study</td>
<td>EU</td>
<td>2002 - 2003</td>
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<tr>
<td>10</td>
<td>CO₂ capture (cascade cryogenic) - ECS/BUB</td>
<td>ADEME</td>
<td>2003 - 2004</td>
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<tr>
<td>11</td>
<td>CO₂ Capture - Carbon cycle</td>
<td>ADEME</td>
<td>2003 - 2004</td>
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<td>12</td>
<td>LCF - 2015</td>
<td>ADEME</td>
<td>2003 - 2005</td>
</tr>
<tr>
<td>13</td>
<td>CACAP (Oxyfiring - Chemical Looping)</td>
<td>EU / IFPE</td>
<td>2004</td>
</tr>
<tr>
<td>14</td>
<td>OxyCap</td>
<td>EU</td>
<td>2003 - 2006</td>
</tr>
</tbody>
</table>
The graphs depict the Levelized COE (Cost of Energy) for different technologies as a function of CO2 allowance price. The technologies include MEA, Adv.Amine, IGCC, Oxy PC, and Oxy CFB. The graphs illustrate how the cost of energy changes with varying CO2 allowance prices. The reference PC without capture is also shown for comparison.
### Levelized COE

The graph illustrates the levelized COE (Cost of Energy) for different capture technologies as a function of CO2 allowance price. Key technologies include:

- MEA
- IGCC
- Adv. Amine
- Oxy PC
- Oxy CFB
- Advanced Oxy CFB

The y-axis represents the levelized COE in $/kWh, while the x-axis shows the CO2 allowance price in $/ton. The graph highlights the cost savings for technologies with carbon capture compared to a Reference PC without capture.

### CFB Greenfield/Retrofit for EOR

The diagram illustrates a configuration for CFB Greenfield/Retrofit for Enhanced Oil Recovery (EOR) involving:

- Pet Coke
- Air

This setup aims to maximize CO2 capture and utilization in the oil production process.
CFB Greenfield/Retrofit for EOR

Use CO₂ and N₂ for Enhanced Oil Recovery

EOR Economics (210 MWe Gross, Greenfield)

Breakeven COE met with credits
- CO₂: 17 $/ton
- N₂: 4 $/ton

Breakeven COE met with credits
- CO₂: 28 $/ton
CFD as a tool to evaluate
Oxy-firing

**CFD Evaluation**

- **Objective:** Simulation studies with Fluent™ of Conesville #5 to evaluate water-wall heat flux distribution and overall heat transfer in the furnace.
- **Approach:**
  - (1) Calibrate ALSTOM Power Inc.'s version of Fluent™ CFD code with a baseline Conesville #5 coal combustion case
  - (2) Use calibrated code to evaluate impact of the same coal combustion in various CO₂/O₂ ratios.
- **Outputs:**
  - Relative radiation heat fluxes
  - Heat transfer
  - Furnace outlet temperature
  - Unburned carbon
  - NOₓ emissions.
Conesville #5: Base Case CFD Grid

315,000 Cells (Unstructured Mesh)

Conesville #5: Base Case Temperature Contours

Temperature, deg F
ALSTOM Oxy-firing Testing

ALSTOM Oxyfuel Testing

PC Firing

European Universities

ALSTOM Oxyfuel Testing

Small Scale Test Results
Gas Emissions
Concentration Profiles
Ignition and Burnout
Ash Characterization
Temperature Profiles
Radiation Intensity

Test facilities in WP 3.1

100 kW oxyfuel firing at Cranmer
Gas and coal blend

20 kW test rig at U. Bath/uni.
Fluid fluid

ALSTOM Oxyfuel Testing

PC Firing

100 MW

10 MW

1 MW

100 kW

European Universities

10 kW

Burner Tests w/ Recycle


IEAGHG International Oxy-Combustion Network, Windsor CT USA, 2007
ALSTOM Oxyfuel Testing

500 kW test facility at U. Stuttgart

Burner Development with Flue Gas Recirculation

500 kWth at both Cottbus and Stuttgart Universities with ALSTOM participation

ALSTOM Oxyfuel Testing

PC Firing

<table>
<thead>
<tr>
<th>Power Level</th>
<th>Year</th>
<th>Company/Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 MW</td>
<td>2002</td>
<td>Vattenfall Pilot Plant</td>
</tr>
<tr>
<td>10 MW</td>
<td>2004 - 2005</td>
<td>Burner Tests w/ Recycle</td>
</tr>
<tr>
<td>1 MW</td>
<td>Current</td>
<td>European Universities</td>
</tr>
<tr>
<td>100 kW</td>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>10 kW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Vattenfall 30 MWth PC

Schwarze Pumpe Power Station
Brandenburg, Germany

ALSTOM is boiler and firing systems supplier

Vattenfall 30 MWth PC

Complete Oxy-Fired Pilot Plant
Startup in 2008
Vattenfall 30 MWth PC

- Pre-Dried Lignite and Bituminous
- Air Blown Reference Operation
- 21-39% Overall Oxygen Enrichment
- Staged Combustion with Varying Enrichments
- Load Changes and Dynamic Interactions
- CO₂ Compression vs. Inert Levels

Vattenfall 30 MWth PC

- Flame Characteristics
- Gaseous Emissions
- Heat Transfer
- Slagging and Fouling
- Materials Analysis
- In-leakage
ALSTOM Oxyfuel Testing

Fluidized Bed

100 MW

10 MW

1 MW

100 kW

10 kW

WindsorMT

Windsor

F

MTF w/ Advanced ASU

U. Mulhouse

4" CFB

4" Bubbling Bed

2002

2004 - 2005

Current

2008

3 MWth Multiuse Test Facility

• MTF Located at Power Plant Labs
  Windsor, Connecticut

• 9.9 MM-Btu/hr (2.9 MWth)

• Furnace:
  60 feet (18 m) tall
  40 inch (1 m) I.D.

• 42 Test Campaigns since 1998
## 3 MWth Multiuse Test Facility

**CFB Modified for Oxyfiring in 2004 & 2005**

![3 MWth Multiuse Test Facility](image)

### Summary of Concept Validation/Testing – DOE Greenhouse Gas Program

<table>
<thead>
<tr>
<th>Year</th>
<th>April 2004</th>
<th>June 2004</th>
<th>June 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
<td>Medium Volatile Bituminous Coal</td>
<td>Medium Volatile Bituminous Coal and Petcoke</td>
<td>Medium Volatile Bituminous Coal and Petcoke</td>
</tr>
<tr>
<td><strong>Sorbent</strong></td>
<td>Limestone</td>
<td>Aragonite</td>
<td>Lime</td>
</tr>
<tr>
<td><strong>Combustion Medium</strong></td>
<td>Air and 20-30% O&lt;sub&gt;2&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt; Balance</td>
<td>40 - 50% O&lt;sub&gt;2&lt;/sub&gt;, CO&lt;sub&gt;2&lt;/sub&gt; Balance</td>
<td>Air and 30% O&lt;sub&gt;2&lt;/sub&gt;, 70% CO&lt;sub&gt;2&lt;/sub&gt; Balance</td>
</tr>
<tr>
<td><strong>Firing Rate</strong></td>
<td>2.2 - 4.8 MM-Btu/hr (0.64 – 1.41 MW&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>4.2 - 7.9 MM-Btu/hr (1.23 – 2.32 MW&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>9.9 MM-Btu/hr (2.9 MW&lt;sub&gt;t&lt;/sub&gt;)</td>
</tr>
</tbody>
</table>

Two fuels and three sorbents evaluated in air and O<sub>2</sub>/CO<sub>2</sub> mixtures of up to 70% O<sub>2</sub> (by vol.)
Test Results: no show stoppers

- Heat transfer as expected
- No bed agglomeration
- Emissions (SOx, NOx, CO HC and trace monitored)
- NOx lower
- CO somewhat higher
Next Steps

Future
- Oxyfiring
  - ALSTOM plans to demo PC/CFB technologies
  - Vattenfall a 200 MWe PC by 2015
  - ALSTOM scaling CFB technology for demo
- Post combustion technologies
  - Ammonia scrubbing

Conclusion
- Oxy-firing is a relatively near term and cost competitive approach built on current technology