Oxy-Fuel Process for Hard Coal with CO₂ Capture
A Part of the ADECOS Project

by:

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Presented by Alfons Kather

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Partners:
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26th and 27th January 2007, Windsor (CT) USA

Oxy-Fuel Process – Simplified Process Scheme

Air Separation Unit

Flue Gas Recycle

Flue Gas Drying

CO₂ Separation Unit

all percentages as molar percentage

Introduction
Objective

Identification of key factors that are decisive for the
- feasibility
- economic efficiency

particularly with regard to realistic design boundaries

Current Research Projects at the TUHH

Flue Gas Recycle
Flue Gas Recycle Design Considerations

Low-dust recycle
- using high-efficiency axial-flow fan
- temperature limited to 190 °C, 270 °C with fixed blades
- mill-internal coal drying (300 °C)?
- today’s feed water temperature at 300 °C → heat sink for cooling?
- sensitive to load fluctuations (fixed blades)
- very large dust precipitator and long recycle ducts

High-dust recycle
- requires low-efficiency radial-flow fan
- more robust than axial-flow fans
- very stable with respect to load fluctuations
- small dust precipitator and short recycle ducts
- no increased wear of boiler expected
- temperature up to 350 °C possible
- mill-internal coal drying

Factors influencing the Recycle Requirement

• Condition:
  \[ t_{\text{adiabatic}} = t_{\text{adiabatic, Air}} - t_{\text{O}_2 - \text{Recycle}} \]

• Underlying assumptions:
  \begin{align*}
  t_{\text{Air}} &= 320 \, ^\circ\text{C} \\
  t_{\text{O}_2} &= 25 \, ^\circ\text{C} \\
  t_{\text{Coal}} &= 40 \, ^\circ\text{C} \\
  O_2\text{-excess} &= 15 \% \\
  O_2\text{-purity} &= 98 \%
  \end{align*}

<table>
<thead>
<tr>
<th>Composition (in % by mass)</th>
<th>NCV</th>
<th>( t_{\text{SLHV}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>H</td>
<td>O</td>
</tr>
<tr>
<td>65.93</td>
<td>3.63</td>
<td>7.25</td>
</tr>
<tr>
<td>58.70</td>
<td>4.43</td>
<td>8.82</td>
</tr>
</tbody>
</table>
**Oxygen Concentration in the Combustion Atmosphere**

**First approach:** Oxygen and recycled flue gas are mixed completely prior to the combustion.

The *oxygen concentration*:
- rises by reducing the recycle,
- is always above 21% vol (in the range of interest),
- is a function of both recycle rate and oxygen excess.

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**Combustion**

Air → Air Separation Unit → Flue Gas Recycle → Flue Gas Drying → CO₂ Separation Unit

- Air
- N₂
- O₂
- Coal
- Flue Gas Recycle
- Flue Gas Drying
- Ash
- H₂O
- CO₂
- Ar, N₂, O₂...
- CO₂ Separation Unit
- Exhaust gas
- Almost pure CO₂
Oxygen Concentration in the Combustion Atmosphere of the first Combustion Experiments

Coal: Bituminous Coal
\( O_2 \)-purity from ASU = 99.5 %
\( t_{\text{adibatic}} = 2126 \, ^\circ\text{C} \)

Overall averaged \( O_2 \)-Concentration in the combustion atmosphere

First combustion experiments (+)

Flue Gas Treatment and CO\(_2\) Separation

Air Separation Unit

Flue Gas Recycle

Flue Gas Drying

CO\(_2\) Separation Unit

Air

O\(_2\)

N\(_2\)

exhaust gas

almost pure CO\(_2\)

Ar, N\(_2\), O\(_2\), ...

Coal

Ash

H\(_2\)O

\( \lambda = 1.10 \)

\( \lambda = 1.15 \)

\( \lambda = 1.20 \)
Impurities in the Flue Gas

- **O₂, NOₓ, SO₂**
  - They may influence negatively the geological storage of the injected CO₂ by changing transport properties or by causing geochemical reactions
  - The maximum permissible concentrations for these impurities are still to be defined

- **N₂, Ar**
  - They are inert components which have no significant impact underground
  - They increase auxiliary power demand during liquefaction of the CO₂ (other impurities cause the same, too)
  - Removing them during air separation (to achieve purer O₂) increases the auxiliary power demand of the air separation unit
  - Need for optimization between air separation and CO₂-liquefaction (considering also air leakage)

Impact of Impurities on the CO₂-Concentration

- Fuel's nitrogen and sulfur
- Oxygen excess
  - 3 – 3.5% / 4.5 – 5% O₂-residue
- Air separation unit
  - 98% O₂-purity: 2% Ar
  - 95% O₂-purity: 3.8% Ar + 1.2% N₂
- Air leakage
  - approx. 3 % of flue gas flow for a new conventional power plant
  - up to 10 % over the years for power plants in use
  - Air leakage is a major source for impurities and needs to be reduced by appropriate design
Phase Equilibrium of Argon – CO₂

Phase Equilibrium of SO₂ – CO₂
Phase Equilibrium of $O_2 - CO_2$

Multi-Component Phase Equilibrium $O_2 - N_2 - CO_2$
Flue Gas Treatment for Low Purity Requirements

- For low purity requirements of the liquefied CO₂
  - DeNOx and FGD treat only 3 – 4% of the total flue gas volume (referred to the total flue gas before the recycle branching)

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>N₂</th>
<th>Ar</th>
<th>O₂</th>
<th>SO₂</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue Gas, dry</td>
<td>89.1</td>
<td>5.0</td>
<td>0.6</td>
<td>5.0</td>
<td>0.3</td>
<td>597 ppm</td>
</tr>
<tr>
<td>CO₂</td>
<td>98.8</td>
<td>0.3</td>
<td>450 ppm</td>
<td>0.4</td>
<td>0.4</td>
<td>439 ppm</td>
</tr>
<tr>
<td>Stack Gas</td>
<td>47.3</td>
<td>25.2</td>
<td>2.9</td>
<td>24.6</td>
<td>34 ppm</td>
<td>&lt;1 ppm</td>
</tr>
</tbody>
</table>

Flue Gas Treatment for Higher Purity Requirements

- For higher purity requirements of the liquefied CO₂
  - DeNOx and FGD prior to CO₂ capture
  - DeNOx and FGD treat now 30% of the total flue gas volume (referred to the total flue gas before the recycle branching)

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>N₂</th>
<th>Ar</th>
<th>O₂</th>
<th>SO₂</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue Gas, dry</td>
<td>89.4</td>
<td>5.0</td>
<td>0.6</td>
<td>5.0</td>
<td>47 ppm</td>
<td>60 ppm</td>
</tr>
<tr>
<td>CO₂</td>
<td>99.2</td>
<td>0.3</td>
<td>449 ppm</td>
<td>0.4</td>
<td>57 ppm</td>
<td>43 ppm</td>
</tr>
<tr>
<td>Stack Gas</td>
<td>47.3</td>
<td>25.2</td>
<td>2.8</td>
<td>24.6</td>
<td>&lt;1 ppm</td>
<td>&lt;1 ppm</td>
</tr>
</tbody>
</table>
Flue Gas Treatment for Highest Purity Requirements

- For highest purity requirements of the liquefied CO₂
  - DeNOx is now needed before recycle branching
  - Even higher purity requirements would result in processes like a distillation plant with still higher power demands

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<tr>
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<th>NOₓ</th>
</tr>
</thead>
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<td>89.4</td>
<td>5.0</td>
<td>0.6</td>
<td>5.0</td>
<td>47 ppm</td>
<td>29 ppm</td>
</tr>
<tr>
<td>CO₂</td>
<td>99.2</td>
<td>0.3</td>
<td>449 ppm</td>
<td>0.4</td>
<td>57 ppm</td>
<td>20 ppm</td>
</tr>
<tr>
<td>Stack Gas</td>
<td>47.3</td>
<td>25.2</td>
<td>2.8</td>
<td>24.7</td>
<td>&lt;1 ppm</td>
<td>&lt;1 ppm</td>
</tr>
</tbody>
</table>

All values as molar-%

Test CO₂ Separation Plant at the Institute of Energy Systems

- Up to now: Phase Equilibria
- This test plant: Kinetic Behavior
Overall Process

- Simulation of the overall process
  - Definition of the global parameters supported by subprojects and industry
  - Commercial software: Ebsilon®, Aspen®
  - Continuous integration of the results of the subprojects
  - Use of state of the art technology

- Objectives
  - Feasibility
  - Process optimization (overall energetic efficiency)
  - Clarification of important details (e.g. CO₂ purity, part-load behavior)
  - Economic efficiency
p-T-diagram for Single-Stage Cryogenic CO₂ Liquefaction

Conditions:
- Air leakage: 2.0 %
- O₂-purity: 99.5 %

Temperature (°C)
Pressure (bar)
Capture Rate

-90% CO₂
-95% CO₂
-98% CO₂
Purity

Range of interest

90% CO₂
95% CO₂
98% CO₂

133.5 kWh/t CO₂
133.7 kWh/t CO₂
136.5 kWh/t CO₂

Capture Rate

Temperature (°C)
Overall Energy Demand

Requirements: 90% capture rate and CO₂-purity > 95%

Comparison of Different Processes
(1% Leakage, Capture Rate 90%, Purity > 98.5%)
Thank you for your attention!