Thermodynamic cycle and heat management for packed bed CLC-based large scale power plants

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Packed Bed Reactors for CLC

+ No solids circulation → easy operations at high pressures
+ No solids entrainment → simplified high temperature filtration before gas turbine
  — Dynamic non-homogeneous system with high temperature gradients → coupling with turbomachines can be challenging
  — Need of high temperature switching valves
  — Operations with different sequential stages with different durations → many parallel reactors may be needed, influencing cost and footprint
Ilmenite as oxygen carrier

Ilmenite has been selected as oxygen carrier (natural oxygen carrier)

- CO conversion is very slow for T lower than 750°C
- H₂ oxidation with syngas is very fast for T higher than 450°C
- Reduction reaction is slightly endothermic (ΔT is about 10°C)
- Maximum temperature = 1200°C, suitable for power generation
Packed Bed Reactors for CLC

Thermal profile inside the reactor (oxidation + heat removal)

Temperature at reactor outlet

Reaction front faster than the heat front:
- After oxidation, heat is stored inside the reactor.
- Heat removal phase needed, producing high temperature gas suitable for expansion in a turbine.
- After heat removal, bed at the temperature of the inlet gas.
After heat removal, the bed is left at the inlet air temperature (400-450°C)
→ Reduction too slow at that temperature!

→ A different heat management strategy is needed
Heat management – improved configuration

coal → Gasification island → syngas coolers and AGR → syngas

HR, Ox, Red → CO2 cooling

Air → gas turbine → stack

N2 recycle
Reactors are operated with the following strategies:

- **Oxidation phase**: it stops when the reaction front reaches the end of the reactor.
- **Purge phase**: O₂ is removed from the reactor with N₂.
- **Reduction phase**: syngas is fed to the reactor when the bed is at the maximum temperature level.
- **Heat Removal phase**: N₂ the highest part of heat is still stored in the bed after reduction and the maximum temperature has not changed significantly (-10°C).

Complete cycle simulated with 1D model developed at TU/e.

Reactor Design – Heat Management

**B.1 strategy**
(co-current reduction)

- **Time**
  - *Air* → **Oxidation** → *N₂*
  - *N₂* → **Purge** → *N₂*
  - *Syngas* → **Reduction** → *CO₂/H₂O*
  - *N₂* → **Heat Removal** → *N₂*

**B.2 strategy**
(counter-current reduction)

- **Time**
  - *Air* → **Oxidation** → *N₂*
  - *N₂* → **Purge** → *N₂*
  - *CO₂/H₂O* → **Reduction** → *Syngas*
  - *N₂* → **Heat Removal** → *N₂*
B.1 strategy (co-current reduction):
high temperature of CO$_2$ from reduction stage

B.2 strategy (counter current reduction):
Lower temperature of CO$_2$ from reduction stage

V. Spallina, F. Gallucci, M.C. Romano, P. Chiesa, G. Lozza, M. van Sint’Annaland,
Investigation of heat management for CLC of syngas in packed bed reactors, Chem. Eng. J.,
Assumptions for power plants calculation

- Gasification based on entrained flow, oxygen-blown, dry-feed Shell Gasifier:
  - Gasifier temperature/pressure = 1450°C, 44 bar
  - Coal feeding in Lock Hoppers with recirculated CO₂
  - O₂ purity = 95%
  - Recycle gas quenching = 900°C

- H₂S Removal with MDEA chemical absorption

- Power island:
  - TIT = 1200°C
  - β_{comp} = 16.5
  - 3 pressures (144/36/4 bar, 565/565°C) heat recovery steam cycle
  - p_{cond} = 0.048 bar

- Other main assumptions from EBTF report on CO₂ capture technology (D4.9 European best practice guidelines for assessment of CO₂ capture technologies CAESAR project)
Process simulation tools

GS code:
- Modular structure: very complex schemes can be reproduced by assembling basic modules
- Efficiency of turbomachines evaluated by built-in correlations accounting for operating conditions and machine size
- Stage-by-stage calculation of steam and gas turbines
- Sophisticated model for the calculation of expansion in cooled gas turbine stages
- Chemical equilibrium
- Thermodynamic properties of gases → NASA polynomials
- Thermodynamic properties of water/steam → IAPWS-IF97

http://www.gecos.polimi.it/software/gs.php

Aspen Plus:
- CO$_2$ compression
Integrated Gasification CLC Combined Cycle

Coal, CO₂

Gasification Island

DCO SC

Dry solids removal

COS hydr.

To IP drum

from HP ECO (HRSG)

Nitrogen for purge cycle

ASU

Air

O₂

N₂

Nitrogen for purge cycle

Scrubber

saturator water

HR

Q<sub>hr</sub>

recirculating N₂

to wall Gasifier

to HP ECO line

to deaeretor

clean HTR

clean drying

Coal drying

to deaeretor

to HP EVO line

Liquid CO₂

to HP EVO (HRSG)

waste CO₂ at LH

Dried coal

AGR

Lock Hoppers

SCR

e.m.

to wall Gasifier
## Calculated performance

<table>
<thead>
<tr>
<th>Power balance, MW&lt;sub&gt;e&lt;/sub&gt;</th>
<th>IG-CLC-B1</th>
<th>IG-CLC-B2</th>
<th>IGCC</th>
<th>IGCC+Selexol</th>
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<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; capture</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
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<tr>
<td>Gas Turbine Cycle, MW&lt;sub&gt;e&lt;/sub&gt;</td>
<td>174.6</td>
<td>212.9</td>
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<td>Steam Cycle, MW&lt;sub&gt;e&lt;/sub&gt;</td>
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<td>179.9</td>
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<td>Gasification*, MW&lt;sub&gt;e&lt;/sub&gt;</td>
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<td>-38.5</td>
<td>-45.4</td>
<td>-52.1</td>
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<td>CO&lt;sub&gt;2&lt;/sub&gt; capture island + AGR, MW&lt;sub&gt;e&lt;/sub&gt;</td>
<td>-17.7</td>
<td>-17.7</td>
<td>-0.4</td>
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<td>Packed Bed Reactors Aux., MW&lt;sub&gt;e&lt;/sub&gt;</td>
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<td>-3.1</td>
<td>-</td>
<td>-</td>
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<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt; to GT compression, MW&lt;sub&gt;e&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>-34.6</td>
<td>-20.4</td>
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<td>Other Auxiliar., MW&lt;sub&gt;e&lt;/sub&gt;</td>
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<td>-2.5</td>
<td>-3.3</td>
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<td>Net Power, MW&lt;sub&gt;e&lt;/sub&gt;</td>
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<td>Thermal Input, MW&lt;sub&gt;LHV&lt;/sub&gt;</td>
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<td>896.5</td>
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<td>Net efficiency, %&lt;sub&gt;coal_LHV&lt;/sub&gt;</td>
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<td>CO&lt;sub&gt;2&lt;/sub&gt; emission, kg/MWh&lt;sub&gt;e&lt;/sub&gt;</td>
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<td>CO&lt;sub&gt;2&lt;/sub&gt; avoided, %</td>
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* ASU, coal milling, ash handling, recycling syngas blower, etc…

** SPECCA = specific primary energy consumptions for CO2 avoided

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V. Spallina, M. C. Romano, P. Chiesa, G. Lozza, Integration of coal gasification and packed bed CLC process for high efficiency and near-zero emission power generation GHGT-11 (18-22 Nov. 2012 – Kyoto (Japan)
Thank You

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