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

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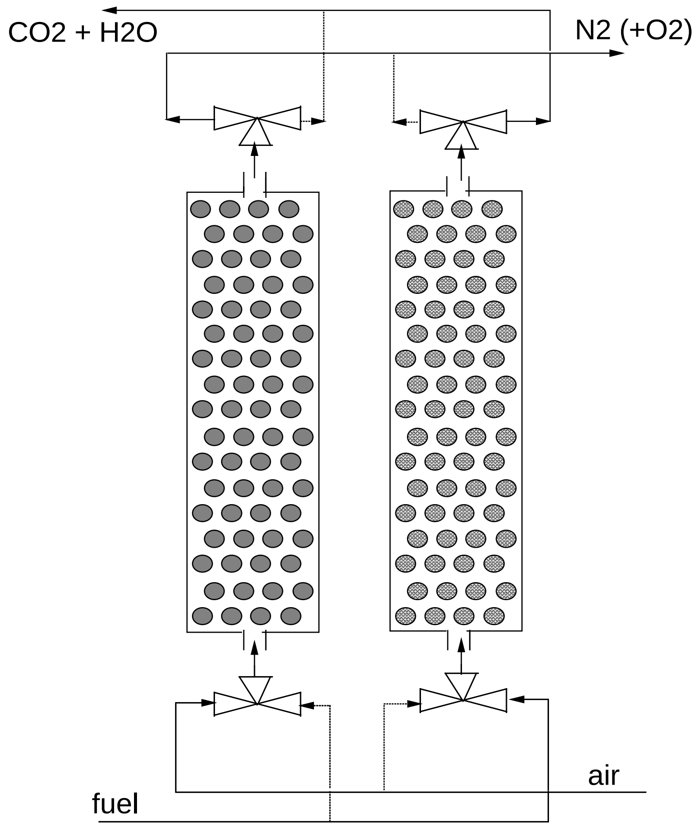
Gecos
Group of Energy
COnversion Systems

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



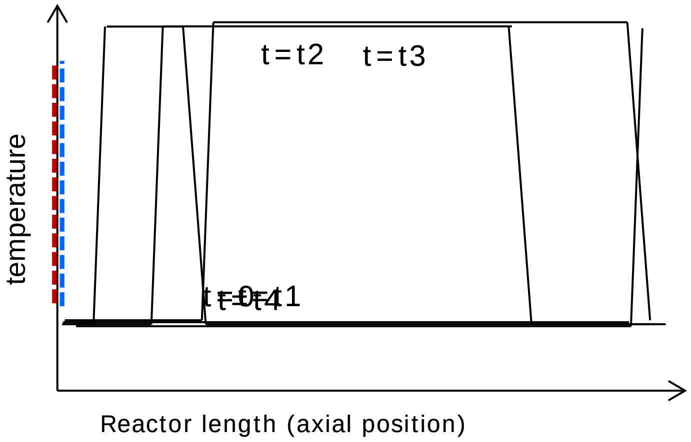
Ilmenite as oxygen carrier

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

- CO conversion is very slow for T lower than 750°C
- H_2 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)



reaction front

heat front

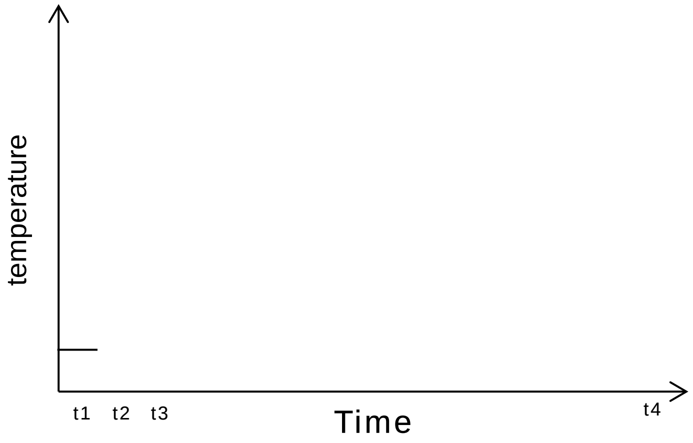
Reaction front faster than the heat front:

- → after oxidation, heat is stored inside the reactor

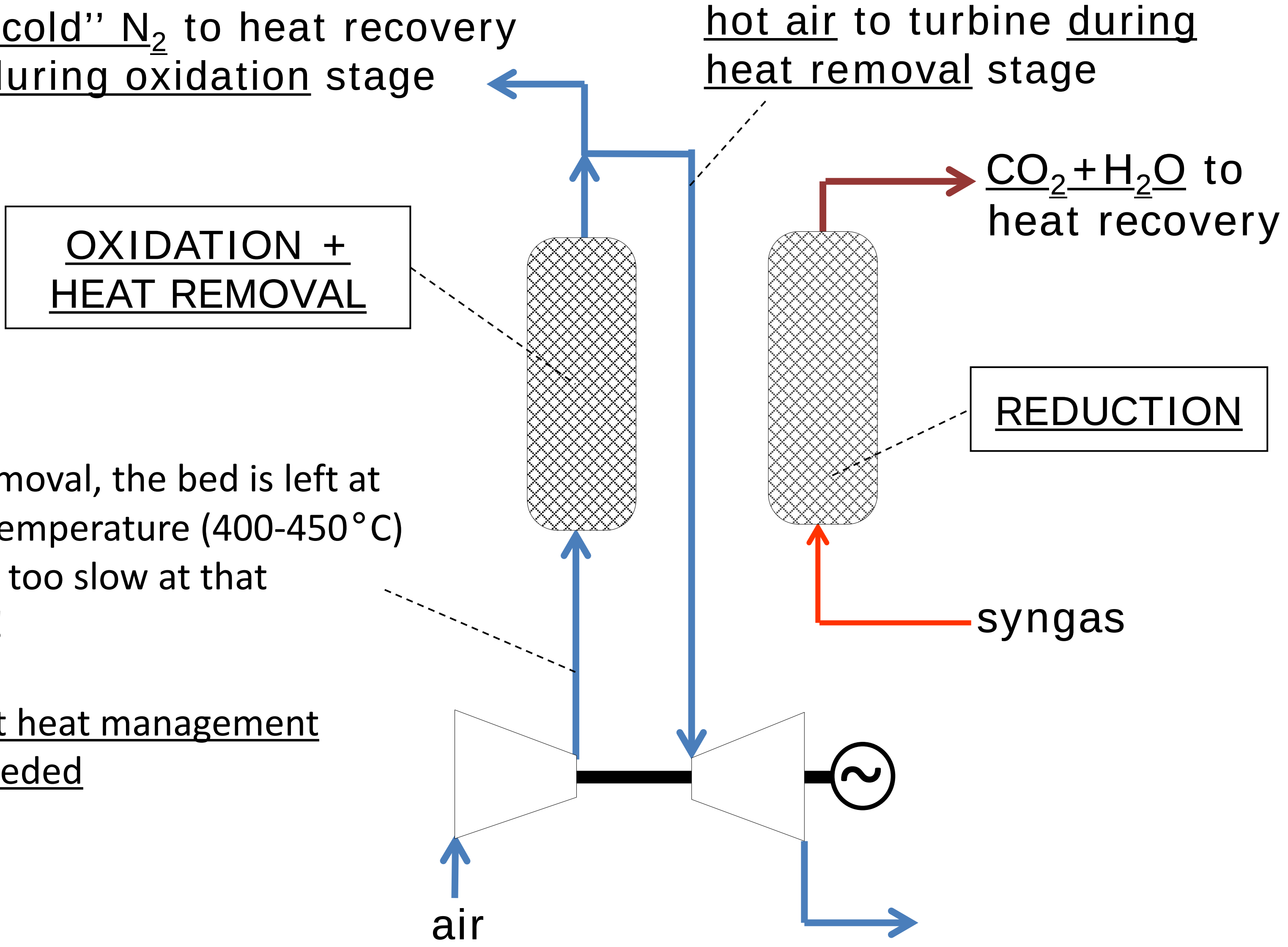
- → heat removal phase needed, producing high temperature gas suitable for expansion in a turbine

- → after heat removal, bed at the temperature of the inlet gas

Temperature at reactor outlet



Heat management – simple configuration



“cold” N_2 to heat recovery during oxidation stage

hot air to turbine during heat removal stage

CO_2+H_2O to heat recovery

OXIDATION + HEAT REMOVAL

REDUCTION

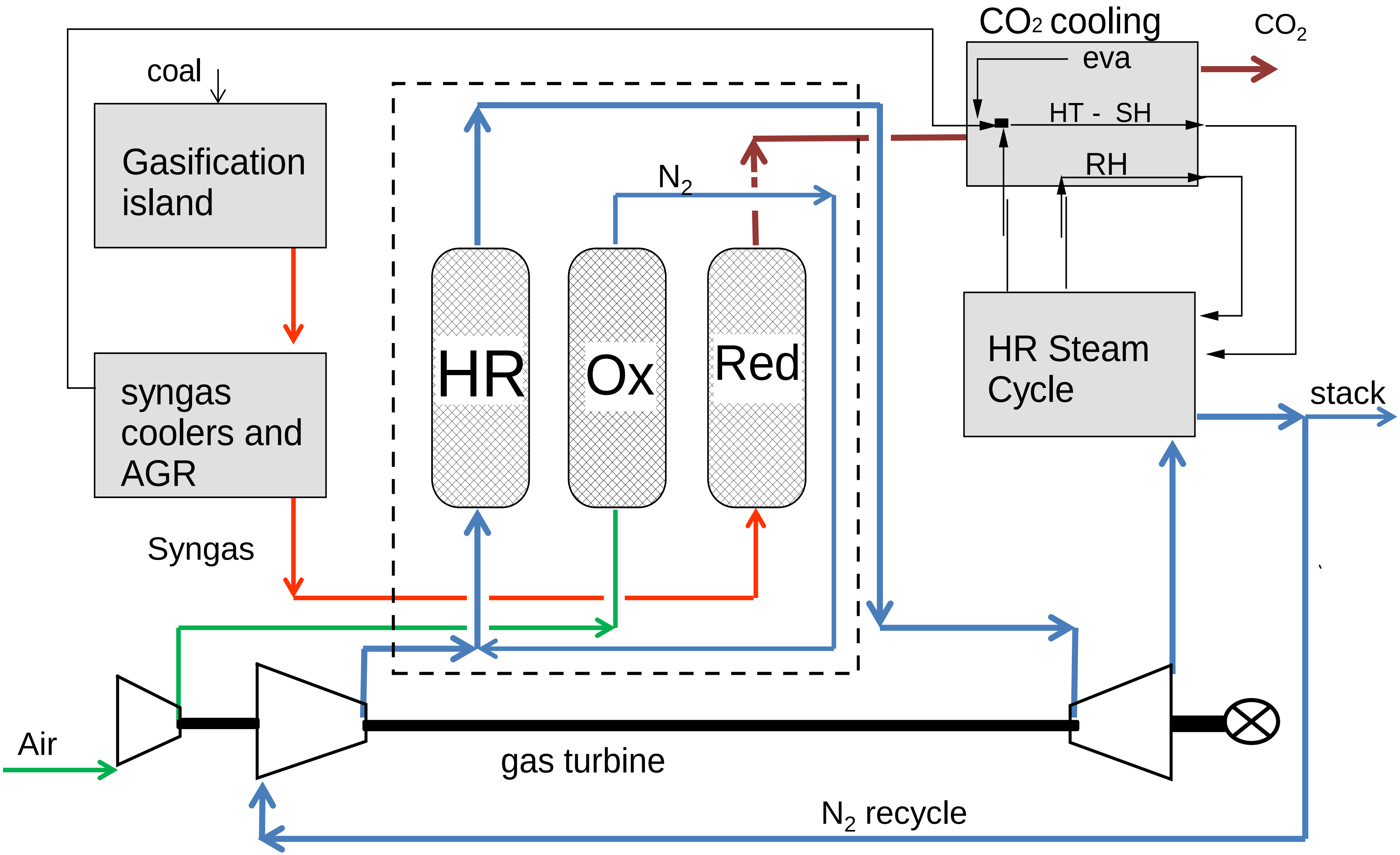
syngas

air

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

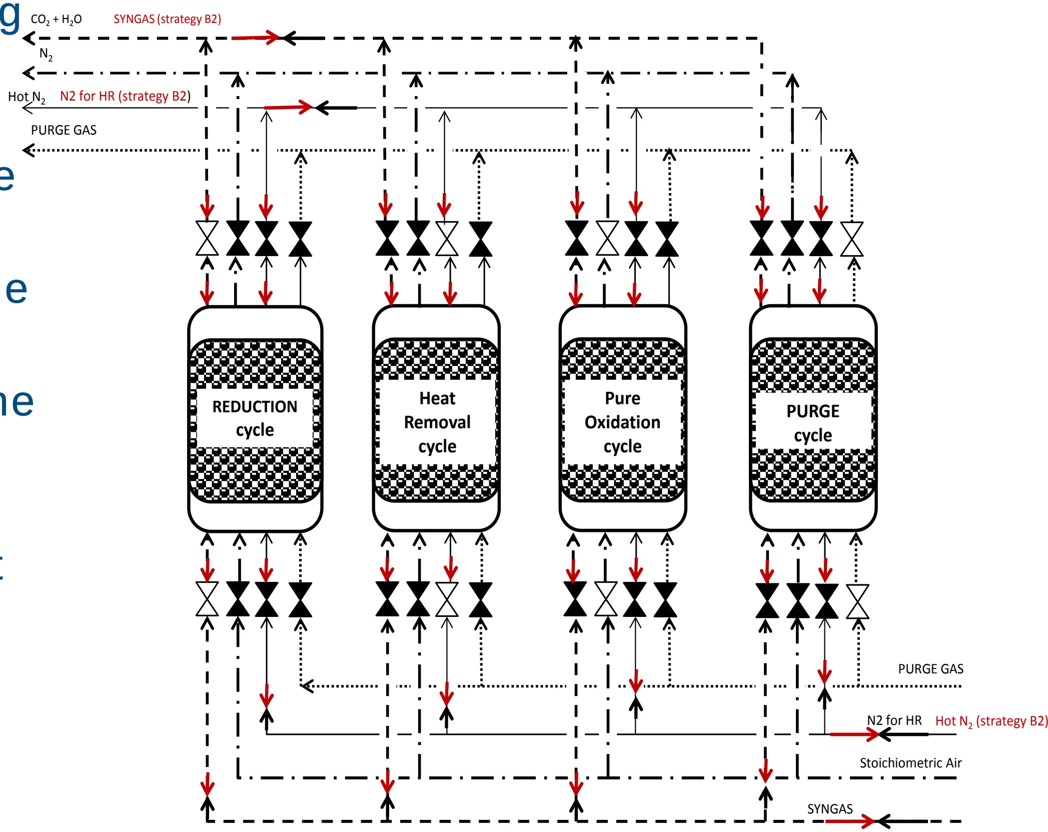
Heat management – improved configuration



Reactor Design – Heat Management

Reactors are operated with the following strategies:

- <u>Oxidation phase</u>: it stops when the reaction front reaches the end of the reactor
- <u>Purge phase</u>: O_2 is removed from the reactor with N_2
- <u>Reduction phase</u>: syngas is fed to the reactor when the bed is at the maximum temperature level
- <u>Heat Removal phase</u>: N_2 the highest part of heat is still stored in the bed after reduction and the maximum temperature has not changed significantly (-10°C)

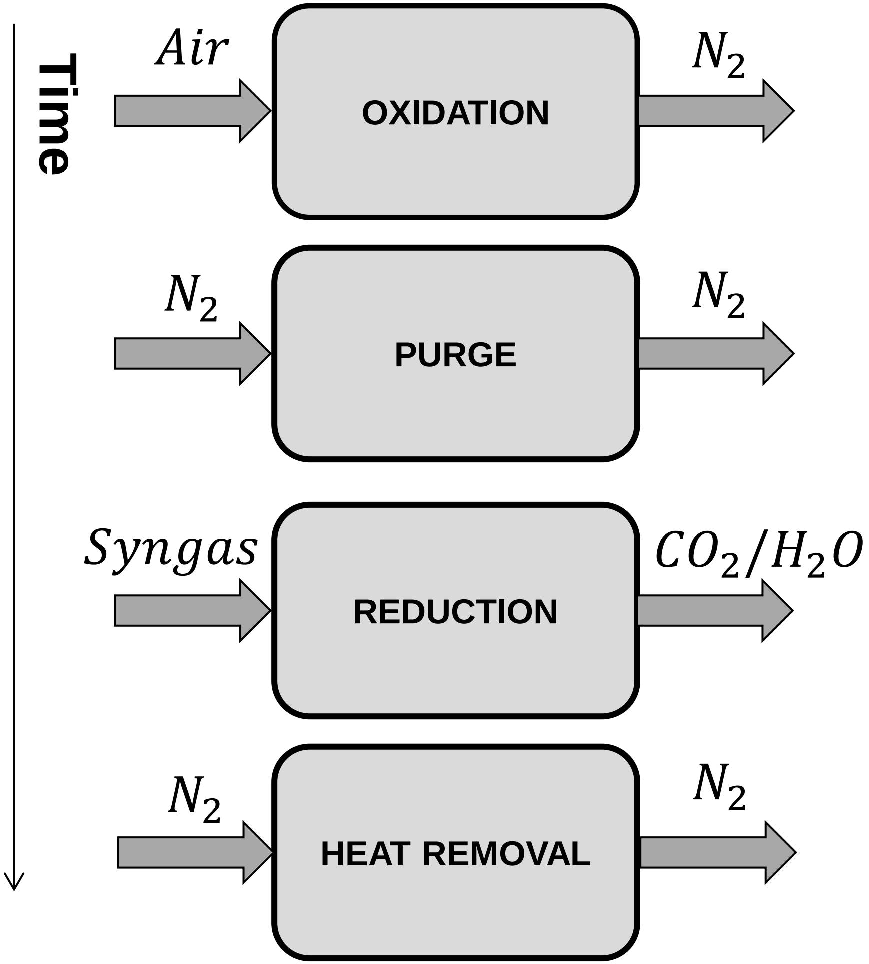


Complete cycle simulated with 1D model developed at TU/e

S. Noorman S, M. van Sint Annaland, H. Kuipers, Packed bed reactor technology for chemical-looping combustion. Ind Eng Chem Res 2007;46:4212-20.

Reactor Design – Heat Management

B.1 strategy
(co-current reduction)



Time

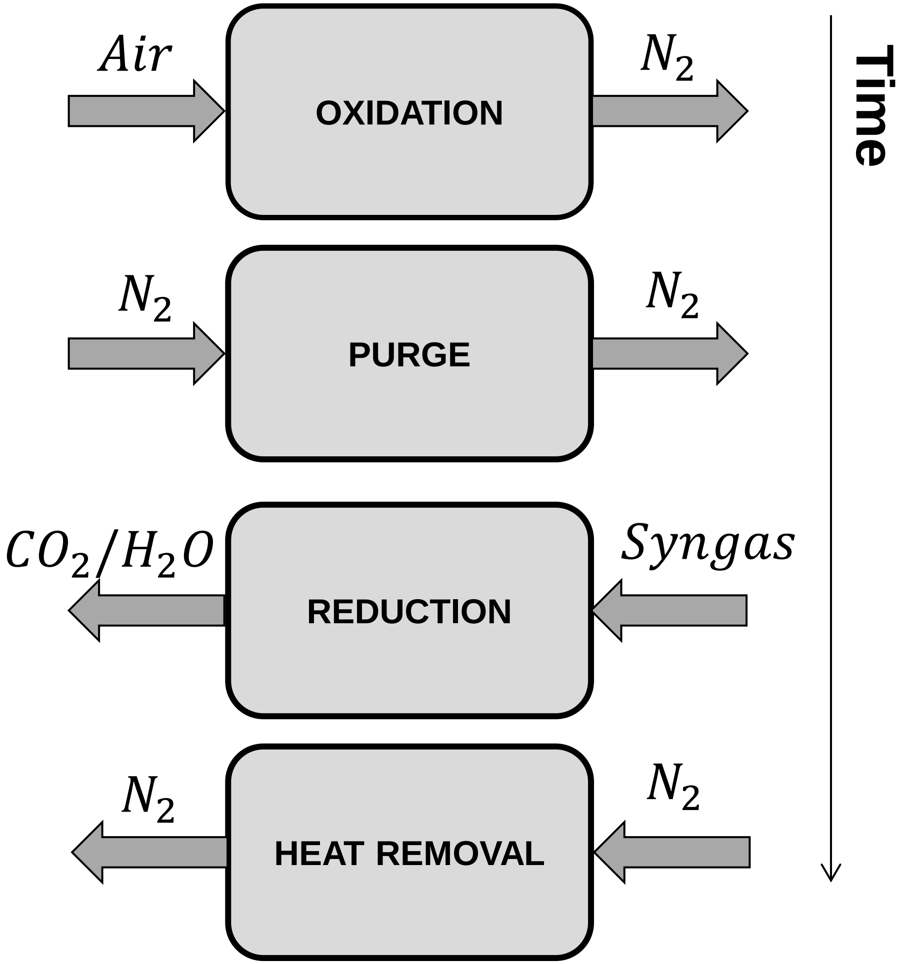
Air → OXIDATION → N_2

N_2 → PURGE → N_2

Syngas → REDUCTION → CO_2/H_2O

N_2 → HEAT REMOVAL → N_2

B.2 strategy
(counter-current reduction)



Time

Air → OXIDATION → N_2

N_2 → PURGE → N_2

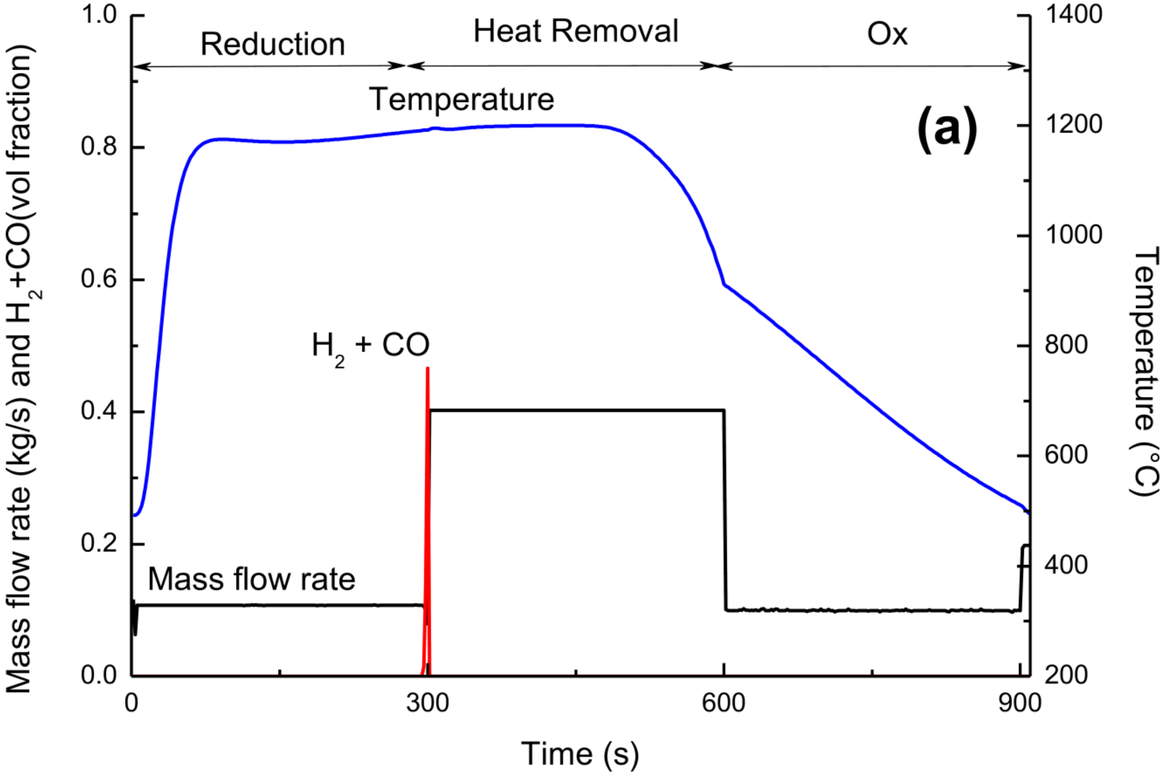
CO_2/H_2O ← REDUCTION ← Syngas

N_2 ← HEAT REMOVAL ← N_2

Reactor Design – Heat Management

B.1 strategy (co-current reduction):

high temperature of CO_2 from reduction stage

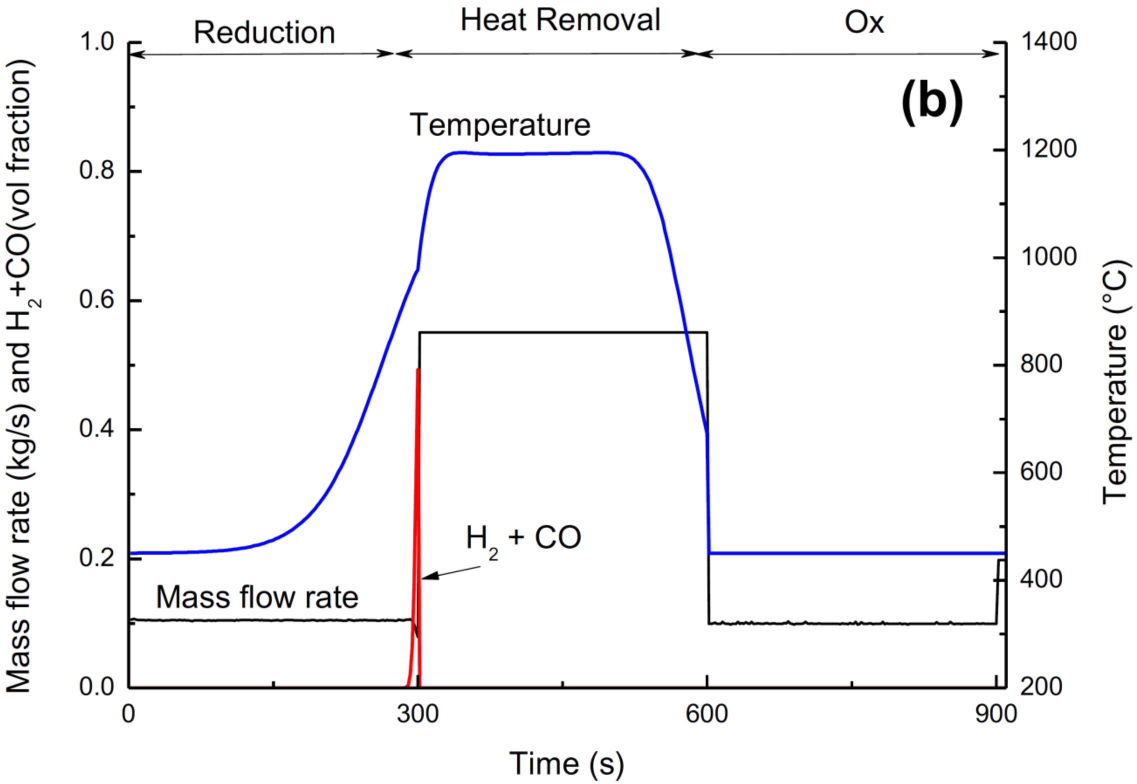


V. Spallina, F. Gallucci, M.C. Romano, P. Chiesa, G. Lozza, M. van Sint'Annaland, Investigation of heat management for CLC of syngas in packed bed reactors, Chem. Eng. J., Volume 225, June 2013, Pages 174–191.

Reactor Design – Heat Management

B.2 strategy (counter current reduction):

Lower temperature of CO_2 from reduction stage



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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 CO_2
  - ✓ O_2 purity = 95%
  - ✓ Recycle gas quenching = 900°C
- H_2S 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 CO_2 capture technology (D4.9 European best practice guidelines for assessment of CO_2 capture technologies CAESAR project)

Process simulation tools

GS code:

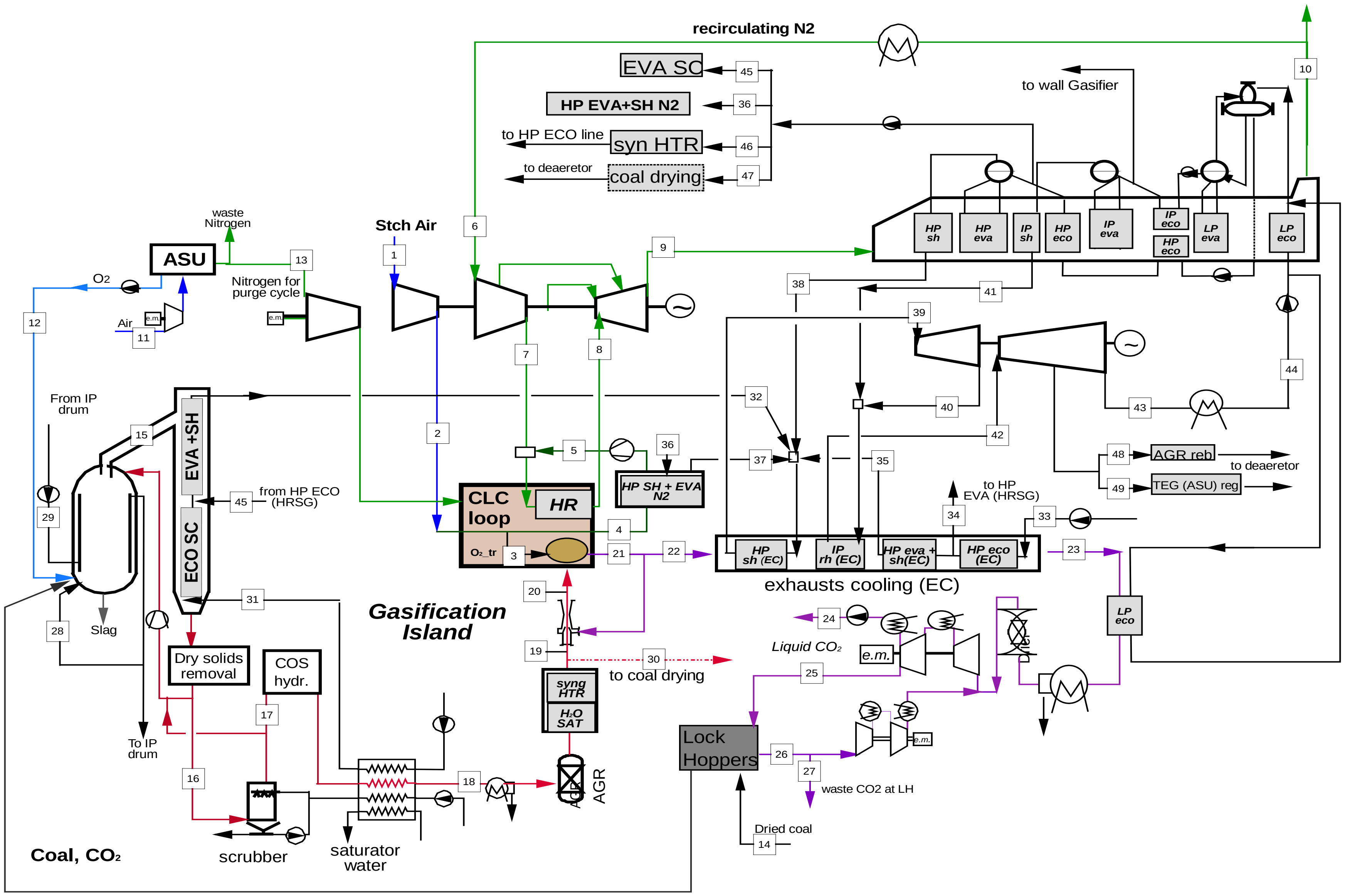
- Modular structure: very complex schemes can be reproduced by assembling basic modules
- Efficiency of turbomachines evaluated by built-in correlations accounting for operating conditions and machine size
- Stage-by-stage calculation of steam and gas turbines
- Sophisticated model for the calculation 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



Calculated performance

REFERENCE PLANTS

Power balance, MW_e	IG-CLC-B1	IG-CLC-B2	IGCC	IGCC+Selexol
CO_2 capture	**Y**	**Y**	**N**	**Y**
Gas Turbine Cycle, MW_e	174.6	212.9	309.4	322.5
Steam Cycle, MW_e	249.0	205.4	190	179.9
Gasification*, MW_e	-38.5	-38.5	-45.4	-52.1
CO_2 capture island + AGR, MW_e	-17.7	-17.7	-0.4	-39.3
Packed Bed Reactors Aux., MW_e	-3.1	-3.1	-	-
N_2 to GT compression, MW_e	-	-	-34.6	-20.4
Other Auxiliar., MW_e	-5.9	-3.05	-2.5	-3.3
Net Power, MW_e	358.4	355.9	421.0	387.1
Thermal Input, MW_{LHV}	896.5	896.5	896.5	1033.1
Net efficiency, $\%_{coal\_LHV}$	**40.0**	**39.7**	**47.0**	**37.5**
CO_2 emission, kg/MWh_e	**18.1**	**18.2**	**677.9**	**97.6**
CO_2 avoided, %	97.5	97.5	-	87.1
SPECCA, MJ_{LHV}/kg_{CO_2}**	**1.9**	**2.13**	**-**	**3.46**

* ASU, coal milling, ash handling, recycling syngas blower, etc…

** SPECCA = specific primary energy consumptions for CO_2 avoided

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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