POLITECNICO DI MILANO

DemoCLOCK Project

CLC based power plant: plant arrangement, heat management and performance assessment

Democlock business brunch, Katowice, December 13th, 2016

Paolo Chiesa, Department of Energy, Politecnico di Milano

SEVENTH FRAMEWORK PROGRAMME

Summary

INTRODUCTION

- Few notes about Politecnico di Milano, Italy

CHEMICAL LOOPING COMBUSTION IN PACKED BED REACTORS

- Heat management
- System operation in power plant and plant performance
- Design and operation of the reactors cluster
- Conclusion

Who we are

Politecnico di Milano is a public technical university located in Milan, at the center of the most industrialized area of Italy

It is the largest School of Engineering in Italy with over 30'000 students enrolled

In the latest QS ranking (year 2016) of the Engineering and Technology universities, Politecnico di Milano ranks 24th in the world, 7th in Europe and 1st in Italy

Support to Democlock project has been provided by the Group of Energy Conversion System (GECOS). GECOS staff includes about 40 people, currently involved in 10 FP7 / H2020 running projects and several research activities privately funded by international companies

GeCOs
Group of Energy COnversion Systems

MAIN REMARKS

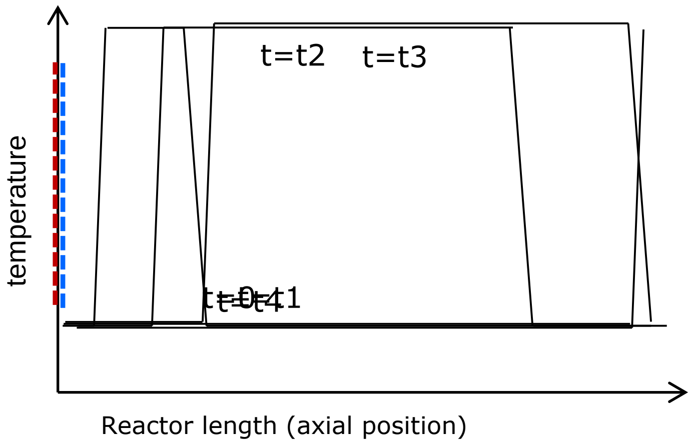
- In Chemical Looping Combustion a metal oxide (acting as oxygen carrier) is placed in contact with a fuel to reduce the metal
- Only CO_2 and H_2O are produced in metal reduction. CO_2 can be easily separated for storage
- Metal is then oxidized with air. Oxidation of a metal is a very exothermic reaction. Heat released in the reaction can be used for power generation

OXIDATION OF METAL IN PACKED BED REACTORS

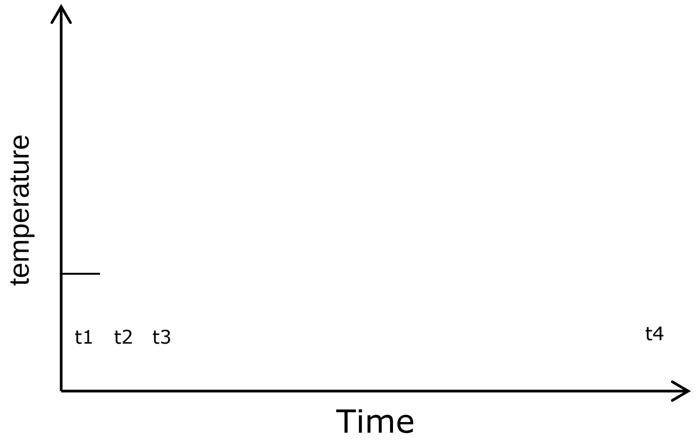
- In packed bed reactors the reaction temperature cannot be controlled by an excess of air flow rate
- Since a large amount of reduced metal is available in the reactor, the reaction proceeds until all the metal is oxidized. More air is fed into the reactor, more heat is released
- Heat released in the reaction is stored inside the bed by increasing the temperature of the bed material

Oxidation phase

Temperature profile inside the bed



Temperature of the outlet stream



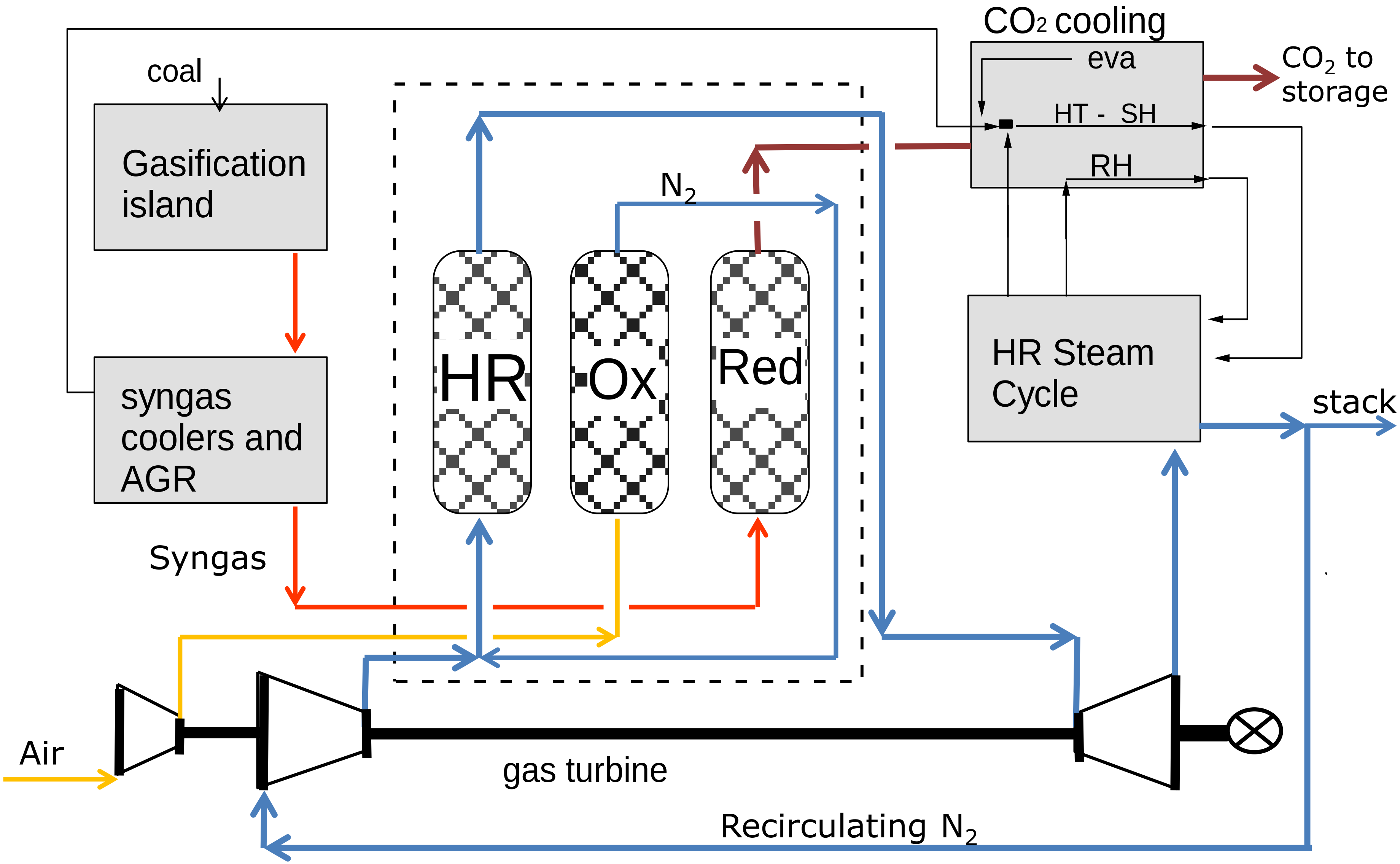
- **Oxidation proceeds faster than heat removal from the bed.**
- **The reaction front (red dotted line) moves to the right faster than the heat front (blue dotted line).**
- **Sensible heat stored in the bed can be collected between time t3 and t4 for power generation**
- **PROBLEM**
  The temperature profile of solids during the reduction phase influences the kinetics

Spallina V., Gallucci F., Romano M.C., Chiesa P., Lozza G., van Sint Annaland M.: **"Investigation of heat management for CLC of syngas in packed bed reactors"**, Chemical Engineering Journal, Volume 225, , Pages 174-191, June 2013,
DOI: 10.1016/j.cej.2013.03.054

Phase sequence

- Ilmenite is used as oxygen carrier because it is cheap and non-toxic
- If CO (included in syngas from coal gasification) is sent over an oxidized ilmenite at low temperature (< 900°C), metal reduction is extremely slow
- No matters with oxidation, which occurs fast at any temperature > 350°C
- To cope with this issue, an alternative phase sequence has been devised:
  1) After oxidation the bed material is at high temperature
  2) Reduction is performed just after oxidation, when the bed is extremely hot.
     Metal reduction is a strongly endothermic reaction. It is thermally balanced by simultaneous fuel oxidation, which is exothermic. Bed temperature profile is scarcely affected by this process
  3) Heat removal is finally carried out over the reduced bed. An inert stream (composed of N_2) is required to avoid oxidation of the material

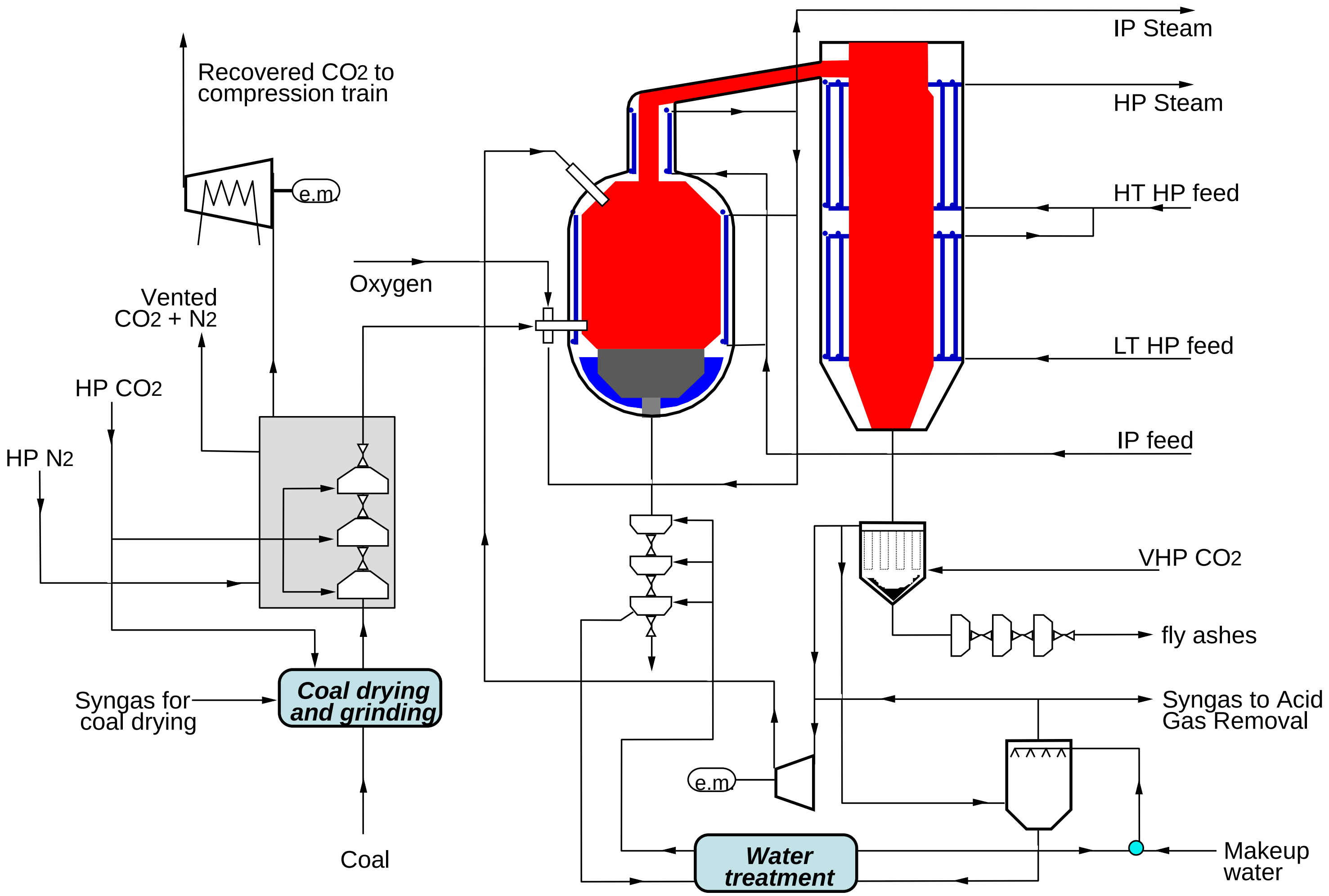
Integration of PBR-CLC in coal-based power plant



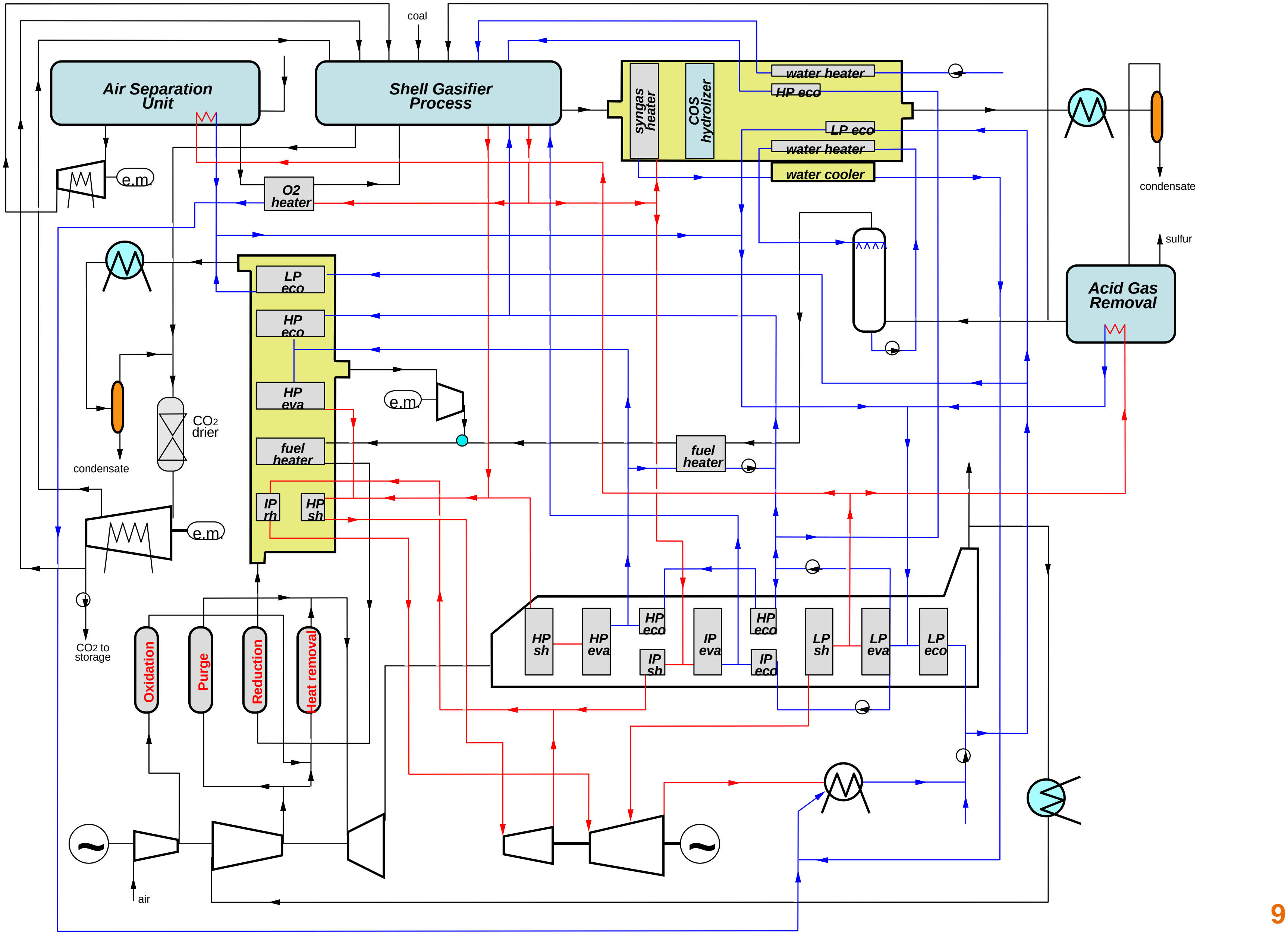
Gasification section

Shell-type technology:

- Entrained flow reactor
- Dry feed
- Oxygen blown
- Gas quench + convective syngas cooling for steam generation



Full plant flow diagram



Plant performance

Coal input [t/h]	122.9
Coal thermal input [MW_{LHV}]	853.9
Gas Turbine Electric Power Output [MW]	175.2
Steam Turbine Electric Power Output [MW]	240.6
Auxiliary Power Demand [MW]	67.0
Net Electric Plant Output [MW]	348.8
Electric Efficiency [$\%_{LHV}$]	40.8
CO_2 mass flow rate release to ambient [t/h]	11.7
Specific Emission of CO_2 [g/kWh]	33.5
Carbon Capture Ratio [%]	96.1

~ reference IGCC cycle

Including 75 MW air compressor

34 MW for Air Separation Unit

~ 1/20 of a conventional coal plant

Spallina V., Romano M.C., Chiesa P., Gallucci F., van Sint Annaland M., Lozza G.: **"Integration of coal gasification and packed bed CLC for high efficiency and near-zero emission power generation"**, International Journal of Greenhouse Gas Control, Volume 27, Pages 28–41, August 2014
DOI: 10.1016/j.ijggc.2014.04.029

Reactor cluster

- A cluster of reactors is required to operate the plant on a continuous duty (oxidation, reduction, heat removal occurring simultaneously in different reactors)
- Temperature of the streams exiting the reactors may vary during time → phases of the single reactor have to be synchronized in order to originate streams at a temperature as constant as possible because rapid changes in temperature can damage the components
- An adequate phase duration is preferable to avoid overstressing the switching system (consisting of piping and valves) and to reduce CO_2 leakages occurring during the phase changes → large amount of metal oxides in the beds
- Low pressure drops on air and N_2 streams to increase the gas turbine performance

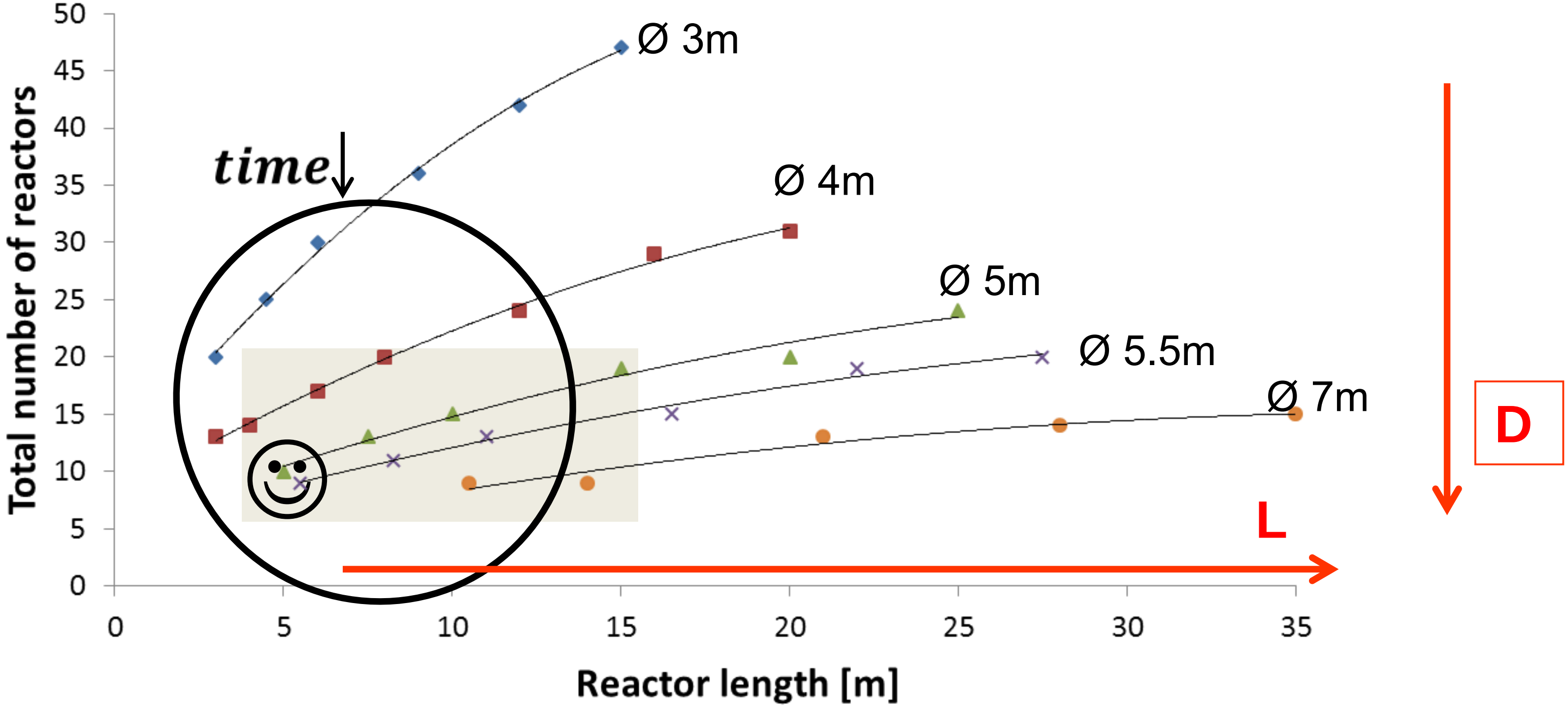
Assumptions:

- **Active material fraction in oxidation: 0.306 kg_{active}/kg_{solid} set to exceed 1200°C in the oxidation phase**
- **Reactor void fraction (ε) : 40%;**
- **Diameter of the spherical particles (d_p): 5 mm**
- **Solid porosity (α) : 40%;**
- **Pressure drops by Ergun equation:**

$$\frac{\Delta P}{L} = 150 \cdot \mu \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot \frac{U}{dp^2} + 1.75 \cdot \frac{(1-\varepsilon)}{\varepsilon^3} \cdot \frac{\rho \cdot U^2}{dp}$$

- **Minimum duration of oxidation/reduction phase: 15 min.**
- **Geometric constraints:**
  max. internal diameter = 5.5 m   max. reactor length = 20 m
  min. lenght to diameter ratio = 1.5

Choice of the number of reactors



- Reducing diameter (D):
  - velocity increases (fluidization starts in the bed) and the number of reactors has to be increased (the total mass flow rate is the same);
- Increasing Length (L):
  - time cycle increases (more material in the bed to be converted)
  - pressure drops increase and the number of reactors has to be increased (less mass flow rate have to be used to contain pressure drops)

Design of the reactors cluster

Sizing of the reactors cluster for oxidation in co-current mode:

- **Number of reactors: 14**
- **Internal diameter of the reactor: 5.5 m**
- **Length of the reactor bed: 11 m**

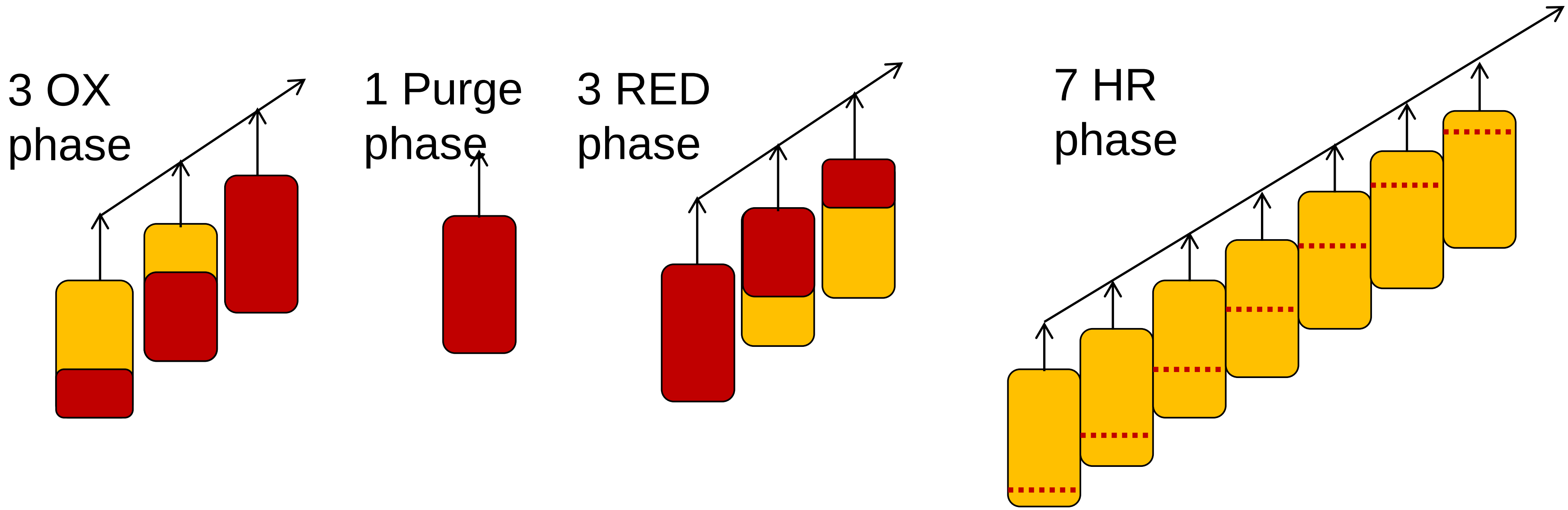
Phase	$N_{reactors}$	$\dot{m}\left[\frac{kg}{s}\right]$	τ [s]	$\Delta P/P_{in}$ [%]
Oxidation	3	59.3	1028	4.77
Purge *	1	30.5	343	1.48
Reduction	3	49.3	1028	3.90
Heat Removal	7	75.7	2380	7.51

*** Purge phase required is required to flush oxygen from the reactor before reduction to prevent explosions**

Spallina V. Chiesa P., Martelli E., Gallucci F., Romano M.C., Lozza G., van Sint Annaland M.: **"Reactor design and operation strategies for a large-scale packed-bed CLC power plant with coal syngas"**, International Journal of Greenhouse Gas Control, vol. 36, p. 34-50, May 2015
DOI: 10.1016/j.ijggc.2015.01.025

- **Lower number of reactors by increasing the particle diameter (d_p)**
- **Similar results are obtained for counter-current oxidation feed**

Operation of the reactors cluster



D 5.5	L 11	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
	τ/3	OXI	HR	HR	HR	HR	HR	HR	HR	RED	RED	RED	PURGE	OXI	OXI
τ	τ/3	OXI	OXI	HR	HR	HR	HR	HR	HR	HR	RED	RED	RED	PURGE	OXI
	τ/3	OXI	OXI	OXI	HR	HR	HR	HR	HR	HR	HR	RED	RED	RED	PURGE
	τ/3	PURGE	OXI	OXI	OXI	HR	HR	HR	HR	HR	HR	HR	RED	RED	RED
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	τ/3	RED	RED	RED	PURGE	OXI	OXI	OXI	HR	HR	HR	HR	HR	HR	HR
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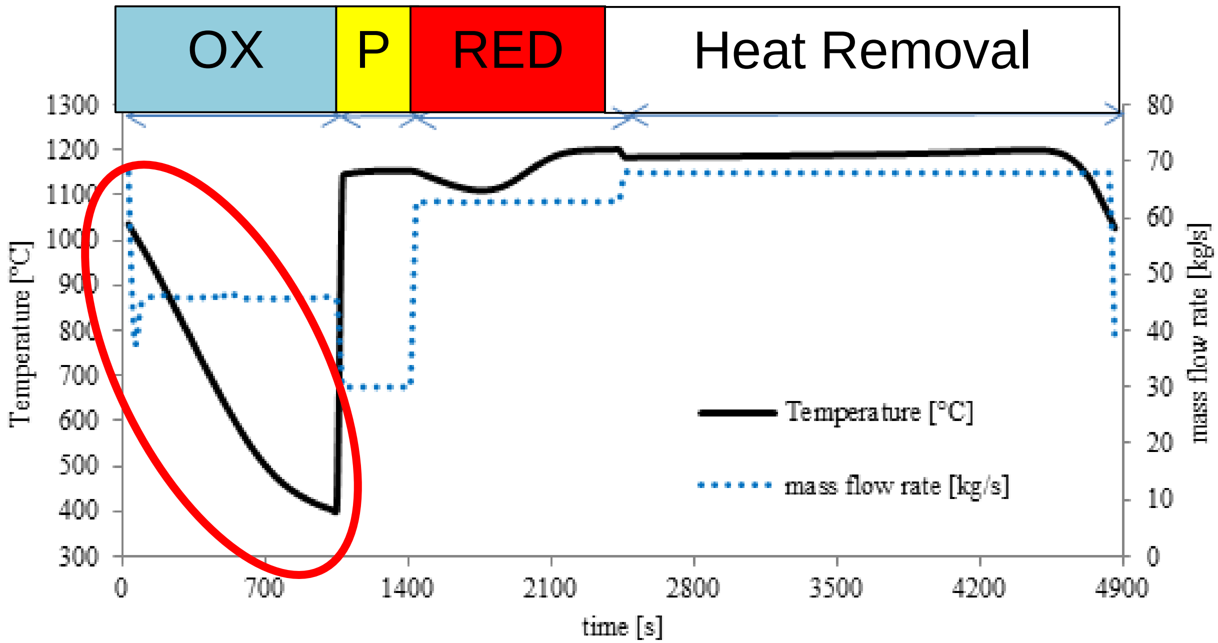
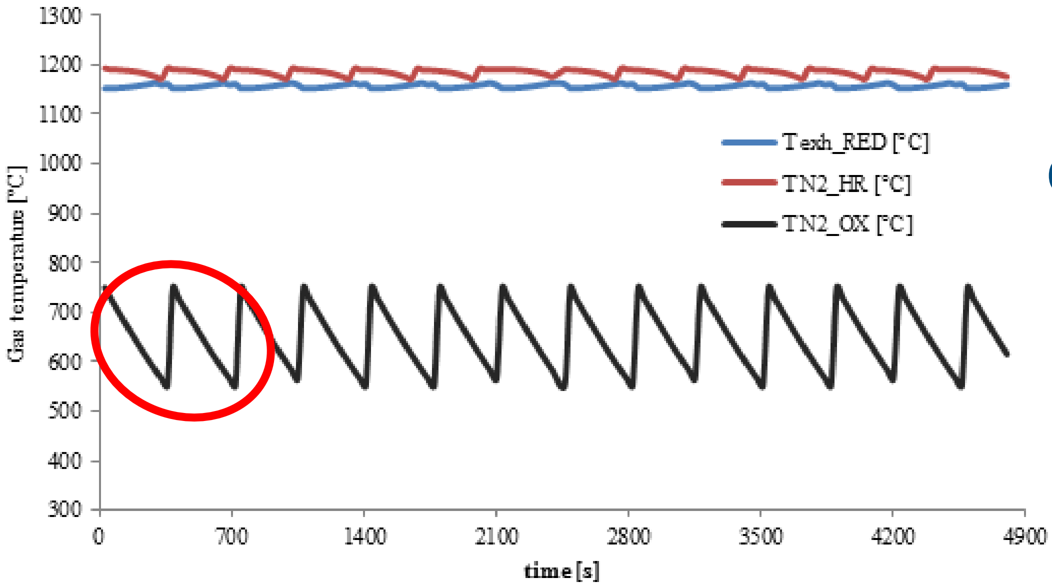
	τ/3	HR	HR	HR	HR	HR	HR	HR	RED	RED	RED	PURGE	OXI	OXI	OXI

Evolution of temperature

Single reactor



Cluster of reactors



Conclusions

- **Chemical Looping Combustion in Packed Bed Reactor is a promising technology for high efficiency coal power plant with near-zero CO_2 emissions**

- **The main advantages of pressurized CLC is the low energy consumption for CO_2 separation and compression**

- **Choice of ilmenite as oxygen carrier is convenient for low cost and non-toxicity**

- **The slow kinetics of ilmenite in the reduction phase imposes a proper heat management of the reactors cluster to match the requirements of a power cycle**

Thank You!

Questions?