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Optimization of an oxy-fuel CFB plant with oxygen production by electrolytic membranes

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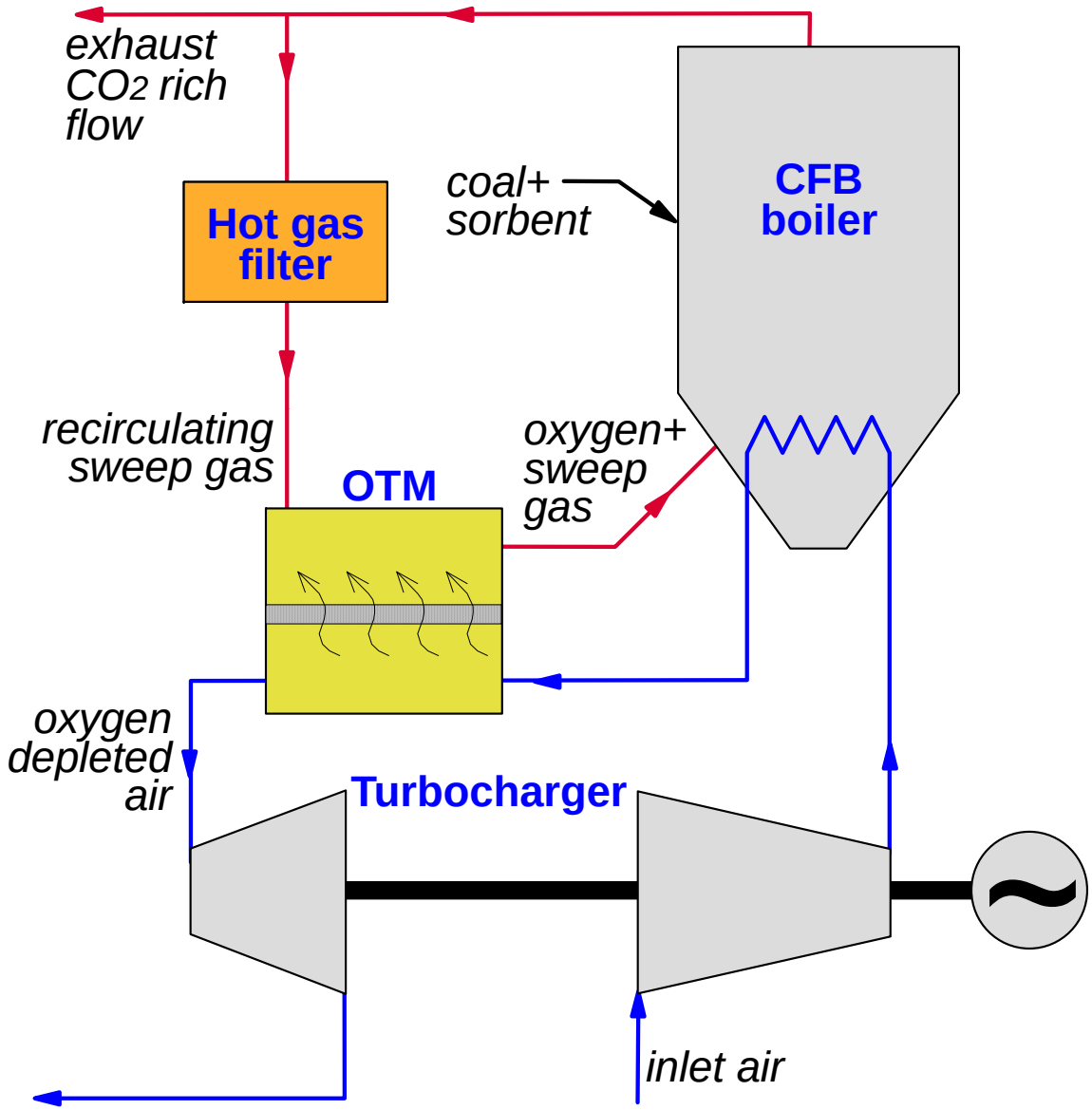
Motivation of the study

The use of oxygen membrane (OTM) can reduce the consumption for O_2 production with respect to cryogenic ASU → higher efficiency if properly integrated in power plants (oxyfuel plants and IGCC) and hydrogen plants.

A number of new process variables results from the integration of OTM in oxyfuel steam plants, to be optimized on a techno-economic basis as function of membrane properties and cost.

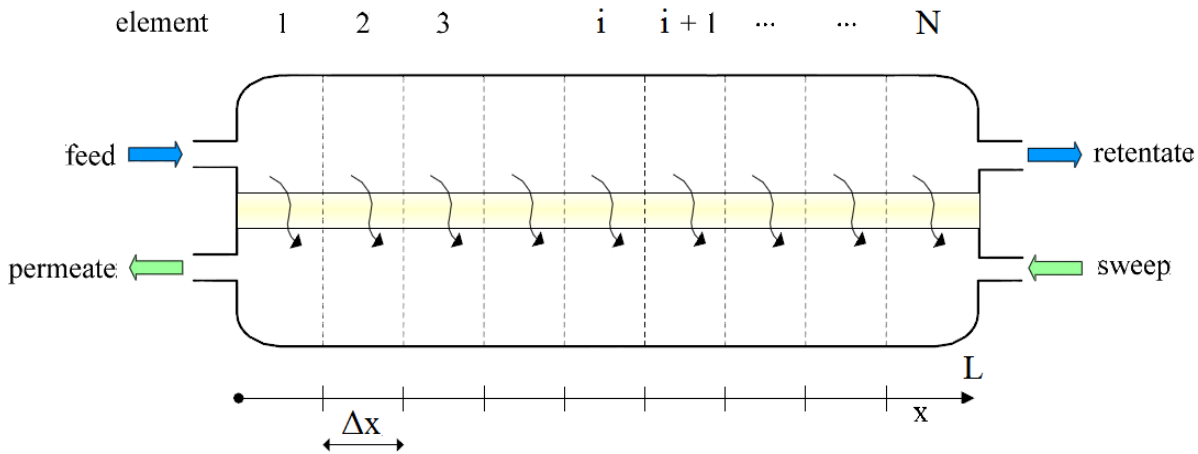
This work is part of the FP7 Demoys project, aiming at developing OTM with the “Plasma Spraying Thin Films” innovative deposition method.

Simplified power plant

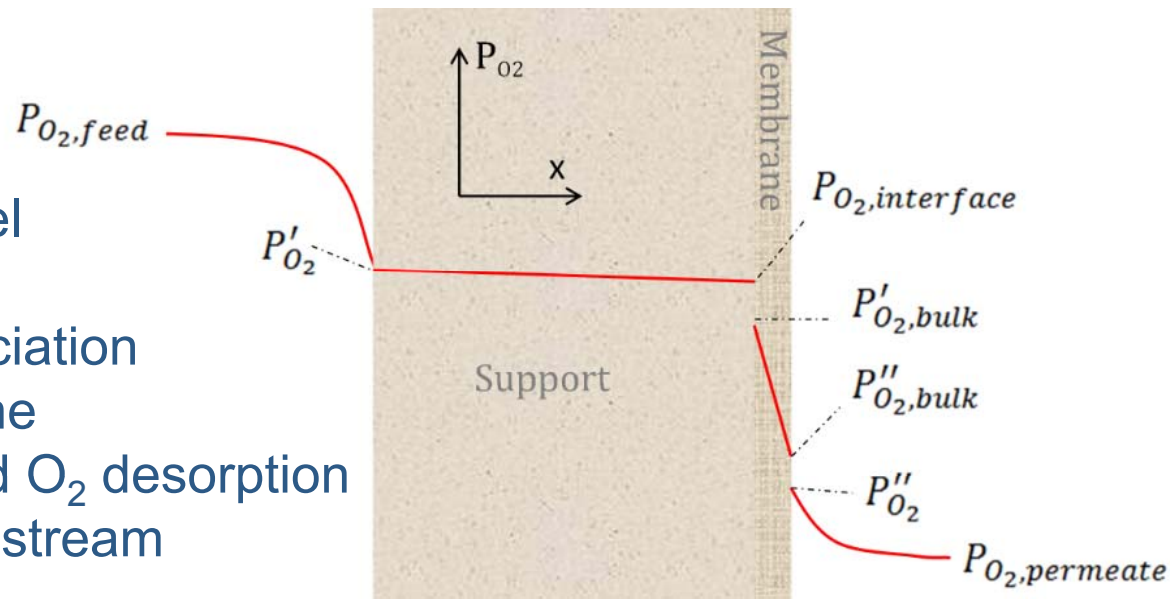


Oxygen membrane model

- Planar counter- or co-flow membrane
- 1D model solved with a finite difference Matlab code
- Both mass and heat transfer are modelled



- <u>Oxygen separation steps</u>:
  - O_2 diffusion in air channel
  - O_2 diffusion in support
  - O_2 adsorption and dissociation
  - $O_2^=$ diffusion in membrane
  - $O_2^= + 2e^-$ association and O_2 desorption
  - O_2 diffusion in permeate stream



Membrane model

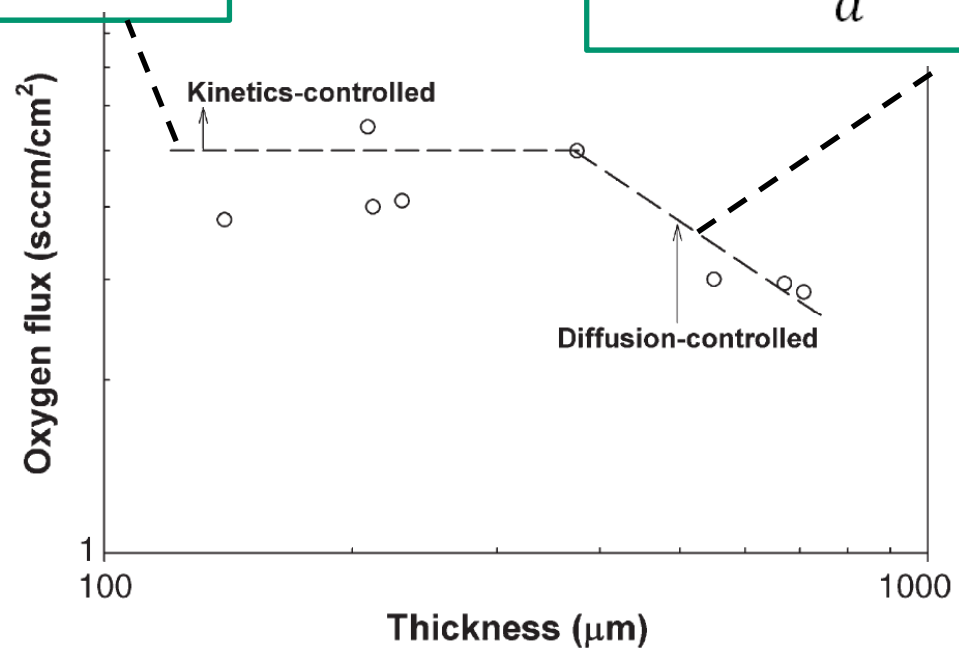
The three mass transfer steps on the membrane (O_2 adsorption and dissociation, bulk diffusion, O_2 association and desorption) can be modelled considering the limiting step, depending on membrane thickness.

Thin membrane: Kovalevsky equation

$$J_{O2} = \alpha k_r \frac{P_{O2}'^{0.5} - P_{O2}''^{0.5}}{P_{O2}'^{0.5} + P_{O2}''^{0.5}}$$

Thick membrane: Wagner equation

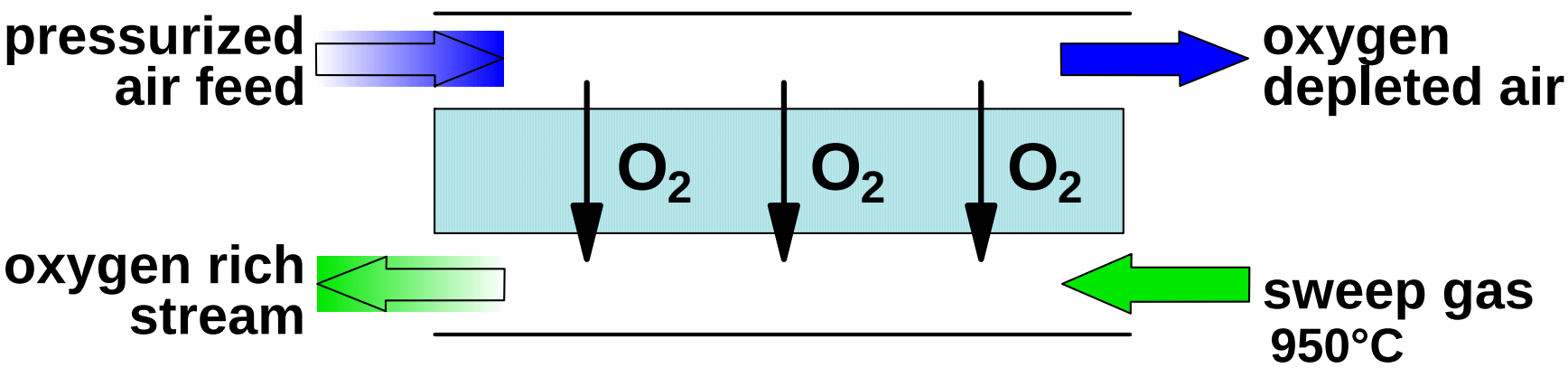
$$J_{O2} = \frac{C_w T}{d} e^{-\frac{K_w}{T}} ln\left(\frac{P_{O2}'}{P_{O2}''}\right)$$



Membrane model output

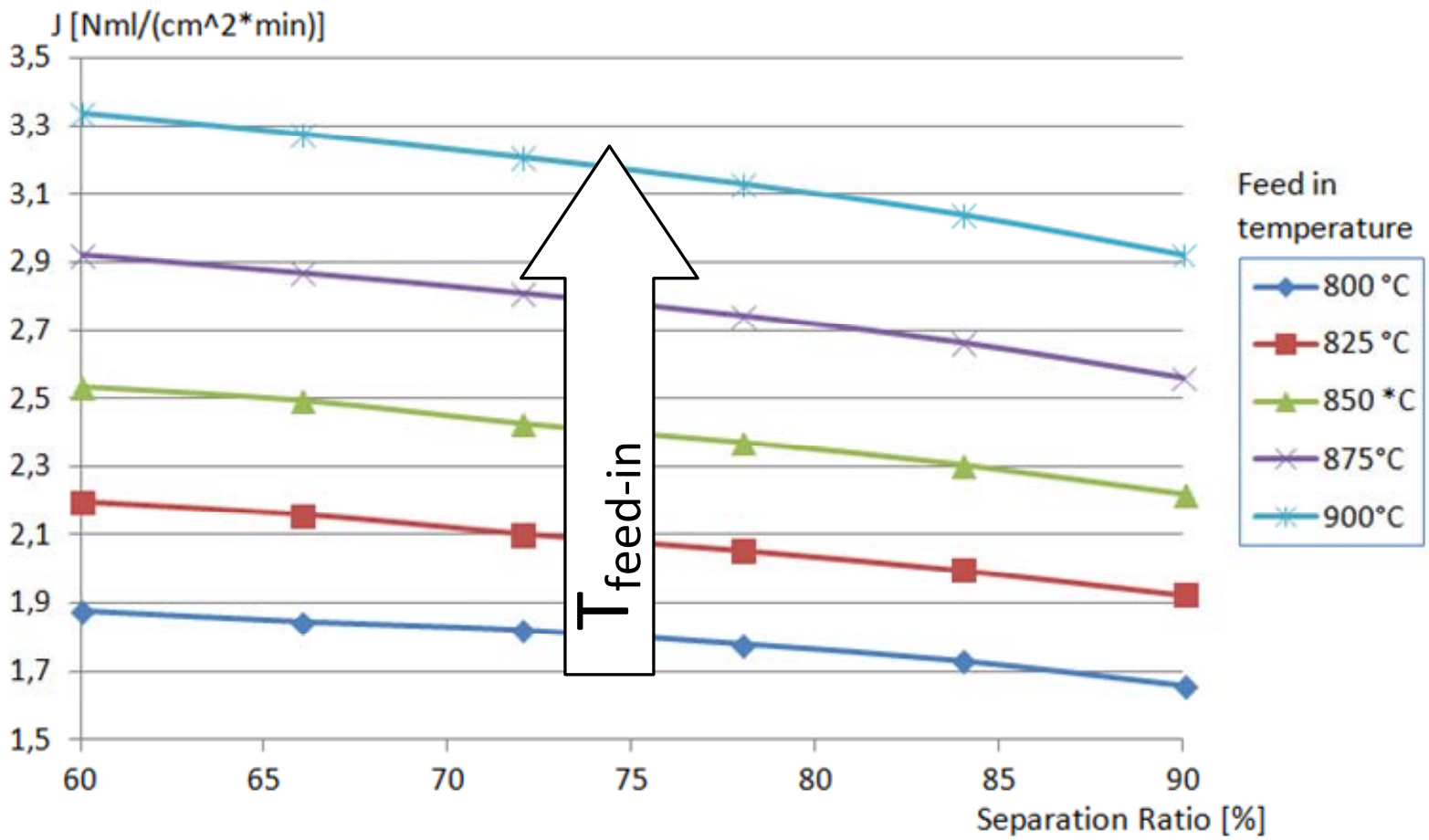
Main OTM operating variables:

- O_2 separation ratio "SR": % of O_2 in the feed air separated by the membrane (which determines the air flow rate on the feed side for a given flow rate of permeated oxygen)
- Temperature of air feed: "$T_{feed\text{-}in}$"
- Pressure of air feed (i.e. air compressor pressure ratio): "β"
- O_2 concentration at permeate flow outlet (i.e. sweep gas flow rate): "$x_{O2,perm\text{-}out}$"
- Temperature and pressure of sweep gas at membrane inlet (fixed by CFB in this case)



Membrane model output – effect of SR and $T_{feed\text{-}in}$

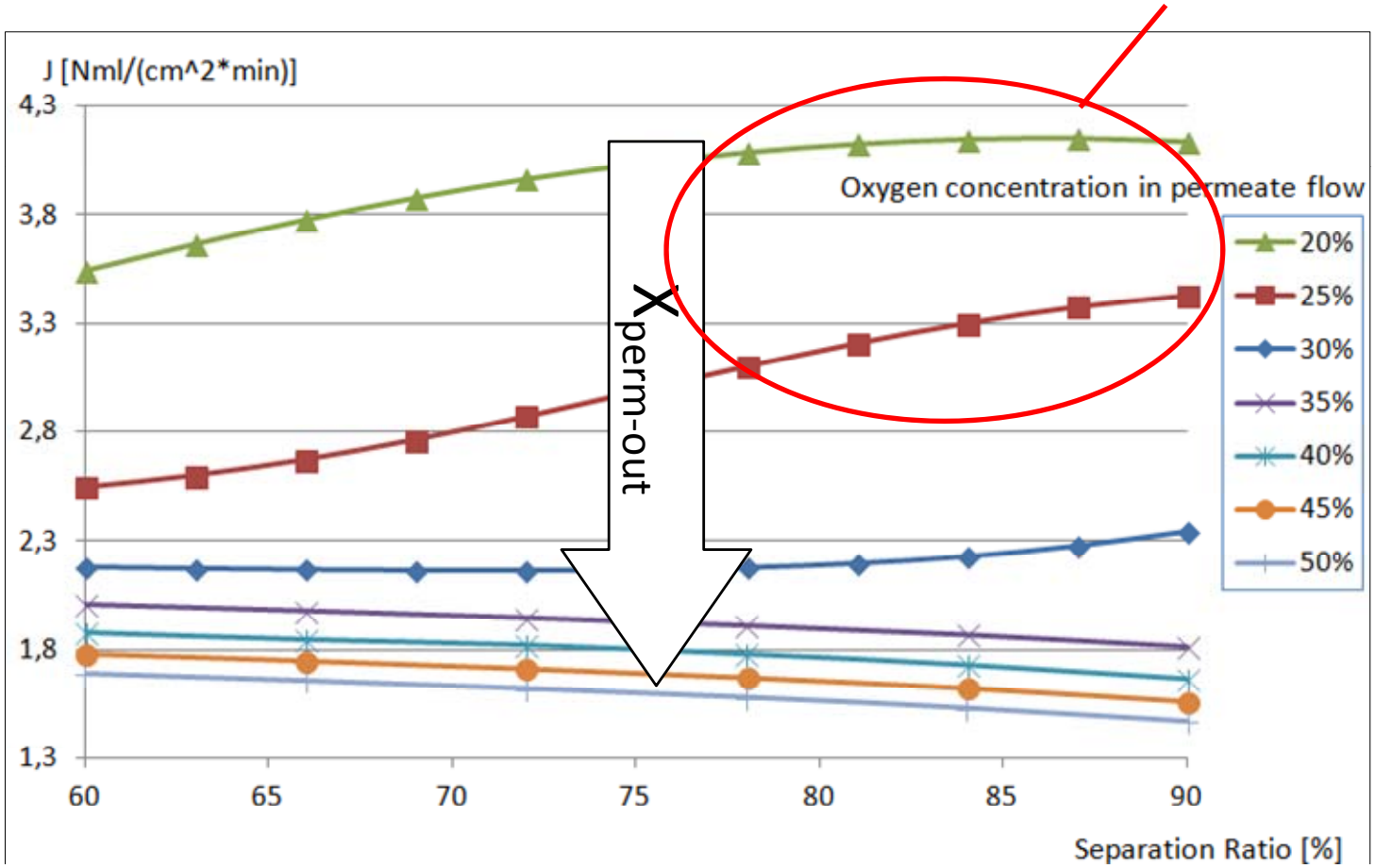
curves at constant permeated O_2 flow rate
β = 20, $x_{O2,PERM\text{-}OUT}$ = 40%, $T_{SWEEP,IN}$=950°C



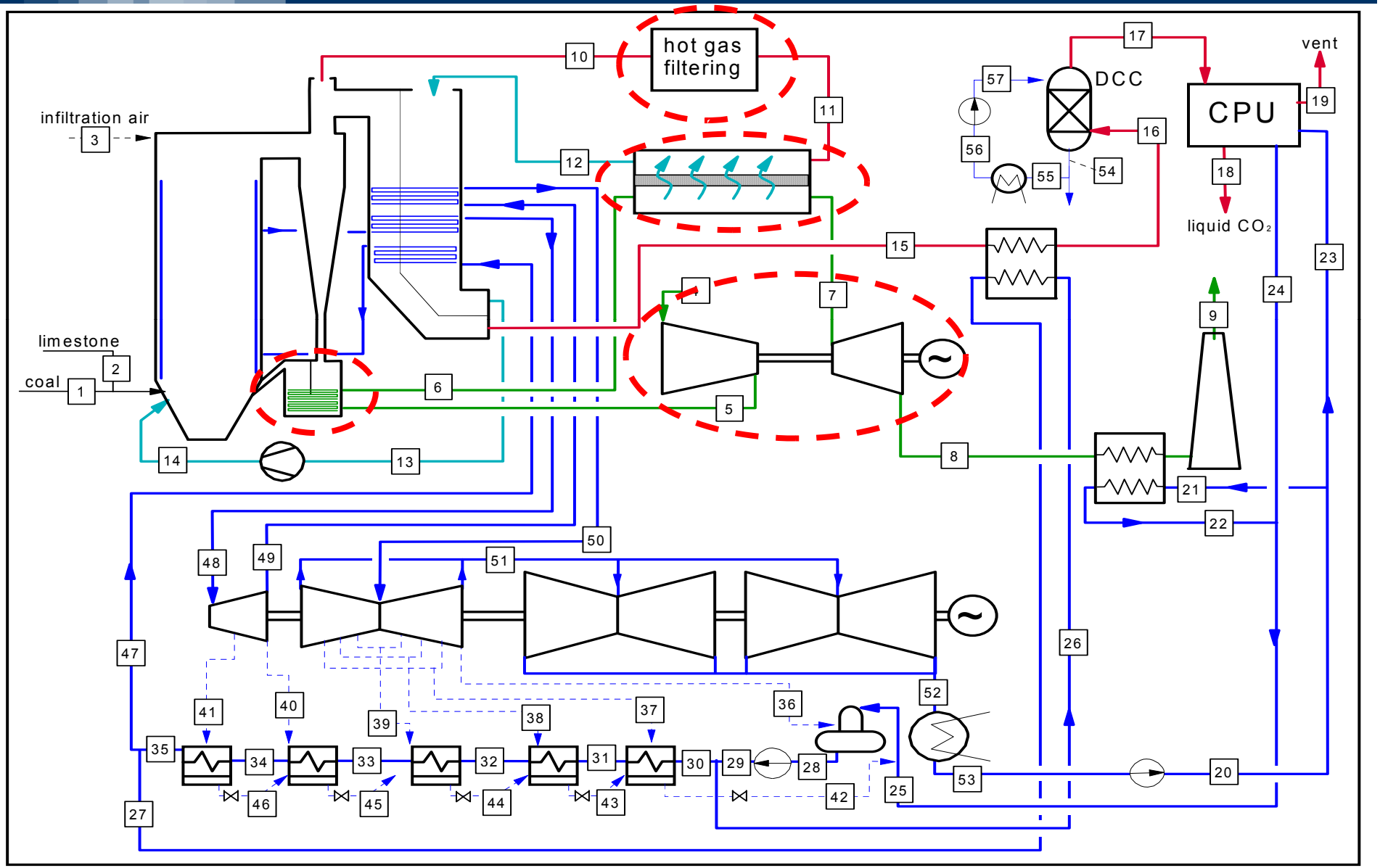
Membrane model output – Effect of SR and $x_{O2,perm-out}$

curves at constant permeated O_2 flow rate
β = 20, $T_{FEED,IN}$ = 800°C, $T_{SWEEP,IN}$=950°C

High sweep/air flow ratio → high average membrane temperature



Complete power plant layout



Simulation tools

GS code (*www.gecos.polimi.it/software/gs.php*):

- Modular structure: very complex schemes can be reproduced by assembling basic modules
- Efficiency of turbomachineries evaluated by built-in correlations accounting for operating conditions and the machine size
- Stage-by-stage calculation of steam and gas turbines
- Calculation of chemical equilibrium based on Gibbs free energy
- Thermodynamic properties of gases → NASA polynomials
- Thermodynamic properties of water/steam → IAPWS-IF97

Aspen Plus:

- CO_2 compression and purification

Matlab:

- Membrane model
- Economic optimization routine

Sensitivity analysis

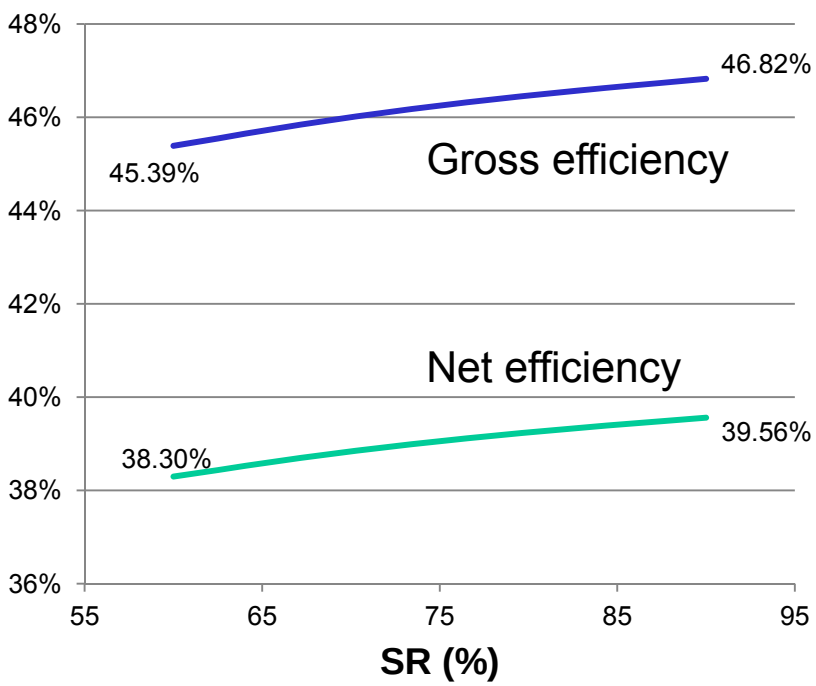
Example of sensitivity analysis on O_2 separation ratio:

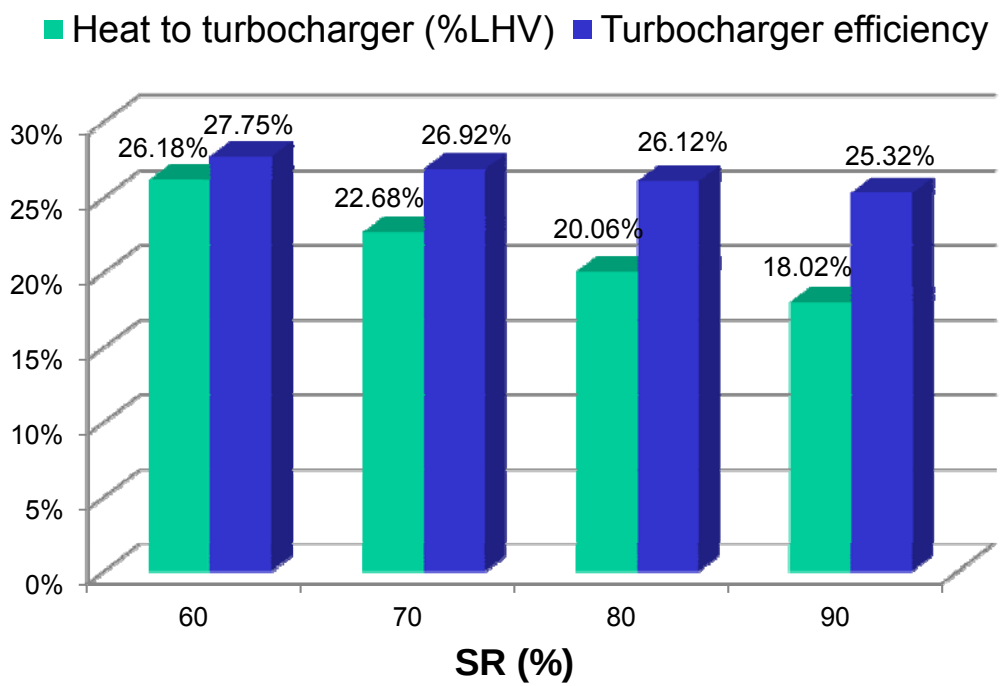
Higher SR → lower air compressed for a given O_2 production

→ Lower heat in the air heat exchanger

→ Lower heat input in the gas cycle (which has a lower efficiency than the steam cycle)

→ Higher net plant efficiency





Base case assumptions

Base case defined on the basis of “reasonable” OTM operating variables:

- O_2 separation ratio SR = 80%
- Temperature of air feed: $T_{feed\text{-}in}$ = 800°C
- Air compressor pressure ratio: β = 20
- O_2 concentration at permeate flow outlet: $x_{O2,perm\text{-}out}$ = 30%

Reference case performance

	air-CFB	ASU oxy-CFB	OTM oxy-CFB
Electric power balance, MW			
Steam turbine	814.1	717.4	693.1
ASU/Turbocharger	-	-85.61	37.03
CO_2 compression	-	-55.07	-60.18
Fans	-17.79	-11.94	-22.90
Other auxiliaries	-36.68	-33.18	-31.20
Net electric plant output, MW	759.64	531.62	615.88
Coal thermal input, MWLHV	1707.8	1436.3	1574.5
Net electric efficiency, %LHV	44.48	**37.01**	**39.12**
Carbon capture ratio, %	-	**91.60**	**96.21**
CO_2 specific emission, g/kWh	788.88	79.36	33.89
CO_2 avoided, %	-	89.94	95.70
SPECCA, MJ_{LHV}/kg_{CO2}	-	**2.30**	**1.47**

SPECCA index: specific primary energy consumption for CO_2 avoided

$$\text{SPECCA } [\text{MJ}_{\text{LHV}}/\text{kg}_{\text{CO2}}] = \frac{3600 \cdot ((1/\eta) - (1/\eta_{\text{ref}}))}{E_{\text{CO2,ref}} - E_{\text{CO2}}}$$

Cost analysis of reference cases

- a comprehensive economic model has been implemented
- the economic model includes equipment cost estimation for non conventional components (i.e. the membrane modules, high temperature heat exchanger and ceramic filters, turbocharger)
- cost of membrane module assumed at 1000 €/m^2

	air-CFB	ASU oxy-CFB	OTM oxy-CFB
Net electric plant output, MW	760	532	616
Net electric efficiency (LHV), %	44.5	37.0	39.1
Carbon capture ratio, %	----	91.6	96.2
CO_2 specific emission, g/kWh	788.9	79.6	34.0
CO_2 avoided, %	----	89.9	95.7
Total plant cost, M€	1142	1323	1681
Plant specific cost, €/kW	1503	**2489**	**2730**
Level. cost of electricity, €/MWh			
Investment	46.4	**76.8**	**84.3**
Fuel	22.7	27.3	25.9
O&M	10.6	**20.9**	**36.5**
Total cost of electricity	79.8	**125.0**	**146.6**
Cost of avoided CO_2, €/tonn	----	**63.7**	**88.5**

Economic model

Need of a comprehensive optimization procedure: operating variables have various effects and influence one each other. For example:

- If OTM feed air temperature ↑:
  - → cost of high temperature heat exchanger ↑ (-)
  - → cost of OTM ↓ (+)
- If O_2 separation ratio ↑ → air flow rate ↓:
  - → plant efficiency ↑ (less heat to the gas cycle) (+)
  - → size and cost of turbomachines and high T heat exchanger ↑ (-)
  - → OTM area ↑↓ (depends on $x_{O2,perm\text{-}out}$) (+/-)
- If $x_{O2,perm\text{-}out}$ ↑ → sweep gas flow ↑ → CO_2 recycle flow ↑
  - → OTM area ↓ (+)
  - → High temperature filtering surface ↑ (-)
  - → CFB boiler cross section ↑ (-)
  - → recycle fan power ↑ (-)

Economic model

Economic optimization procedure:

- Relatively simple functions (polynomials, exponentials, etc…) have been defined to have a fast calculation of the performance of the plant and of the main values for costing as function of the optimizing variables

→ Lose of accuracy

→ Gain in computational time (no iterations)

- Use of a Matlab optimization routine to minimize the cost of electricity.

Result of optimization

	"Tentative" base case	Optimized case
Optimization variables		
Oxygen separation ratio (SR), %	80	88.6
Temperature $T_{FEED,IN}$, °C	800	870
Compressor pressure ratio β	20	17.9
O_2 concentration $x_{O2,PERM-OUT}$, %	30	21
Achieved performance		
Average oxygen flux, Nml/cm^2-min	1.65	4.01
Net electric plant output, MW	616	639
Net electric efficiency (LHV), %	39.1	39.1
Carbon capture ratio, %	96.2	95.3
CO_2 specific emission, g/kWh	34.0	42.3
CO_2 avoided, %	96.2	94.6

Economic improvement

	"Tentative" base case	Optimized case	difference
Total plant direct cost, M€	1681	1374	
Plant specific cost, €/kW	2730	2149	-21%
Level. cost of electricity, €/MWh			
Investment	84.3	66.3	
Fuel	25.9	25.9	
O&M	36.5	30.1	
Total cost of electricity	146.6	122.4	-17%
Cost of avoided CO_2, €/tonn	83.0	57.0	-36%

Conclusions

- Membrane module represents a significant fraction (15-30%) of the total plant cost and of the O&M cost
- Specification of membrane design parameters and operating conditions involves economic optimization of the whole plant
- A change in the membrane characteristics eventually moves the optimal conditions and requires different design specs of the membrane module
- The number of parameters to be considered makes a "tentative" selection of the membrane module design specs hard
- In the specific case considered, multi-variable economic optimization led to plant configuration featuring:
  - air stream temperature at the feed side inlet $T_{feed\text{-}in}$ 860-880°C
  - membrane separation ratio SR = 80-90%
  - high sweep gas flow rate (i.e. low O_2 concentration)
- The optimized OTM case shows a cost of avoided CO_2 of 57 €/tonn. It is about 10% less than the cost of the corresponding plant based on cryogenic air separation unit

THANK YOU

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