Cascaded Membrane Processes for Post-Combustion CO_2 Capture

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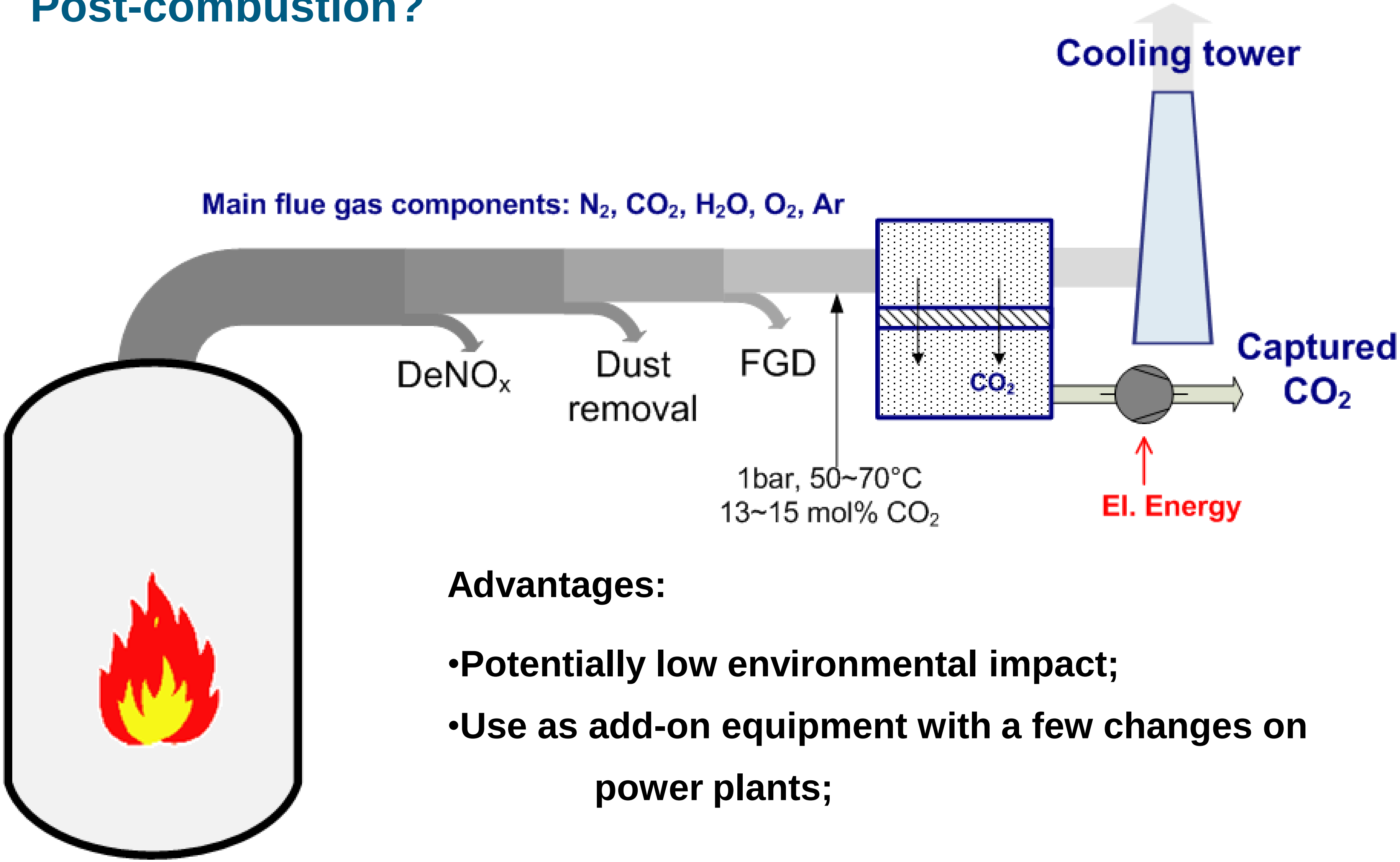
Outline

1. Why CO_2/N_2 gas separation membrane for post-combustion ?
2. Why not a single-stage membrane?
3. Membrane cascade concepts
4. Water removal
5. Pressure losses in membrane modules
6. Concluding remarks

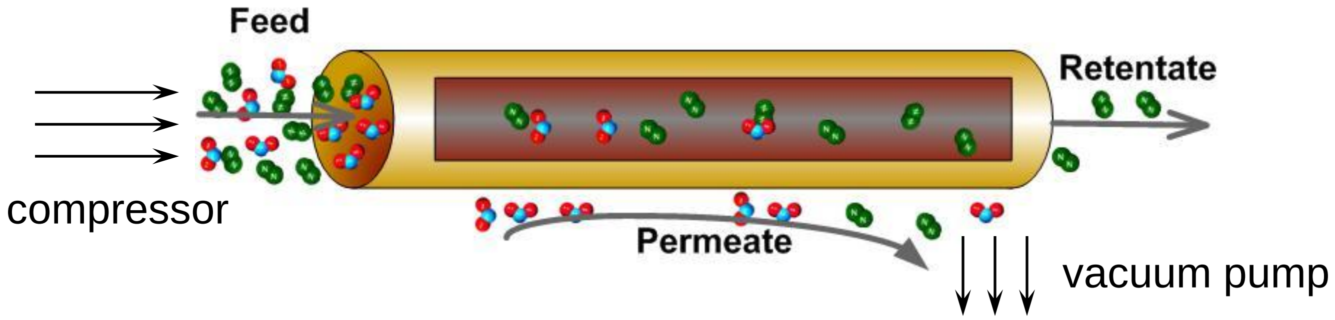
Why CO_2/N_2 Gas Separation Membrane for Post-combustion?

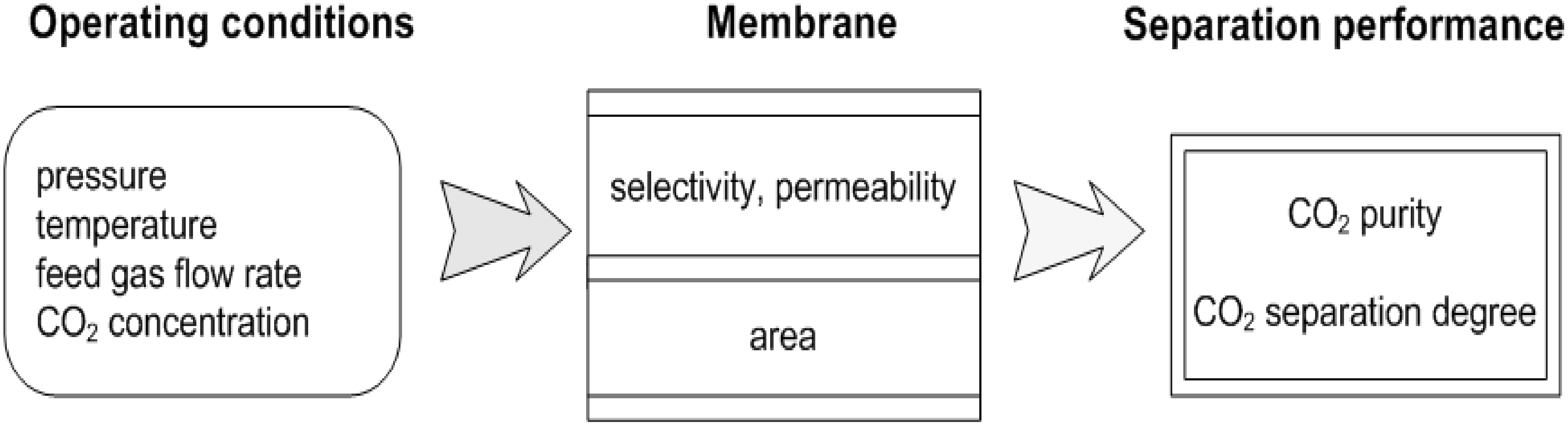


Advantages:

- **Potentially low environmental impact;**
- **Use as add-on equipment with a few changes on power plants;**

How a Single-stage Membrane Works?





Operating conditions

pressure
temperature
feed gas flow rate
CO_2 concentration

Membrane

selectivity, permeability

area

Separation performance

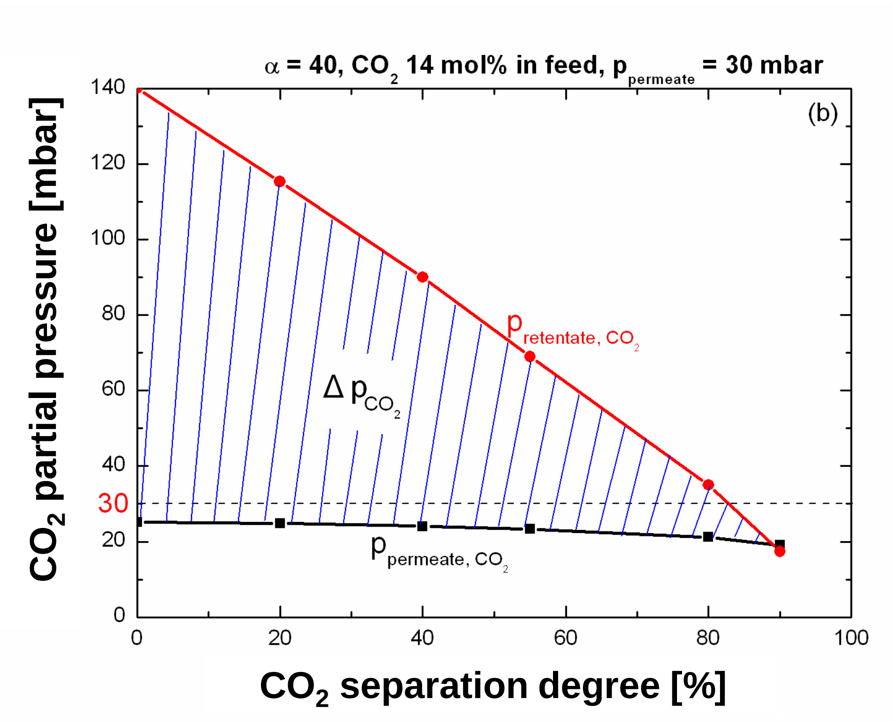
CO_2 purity

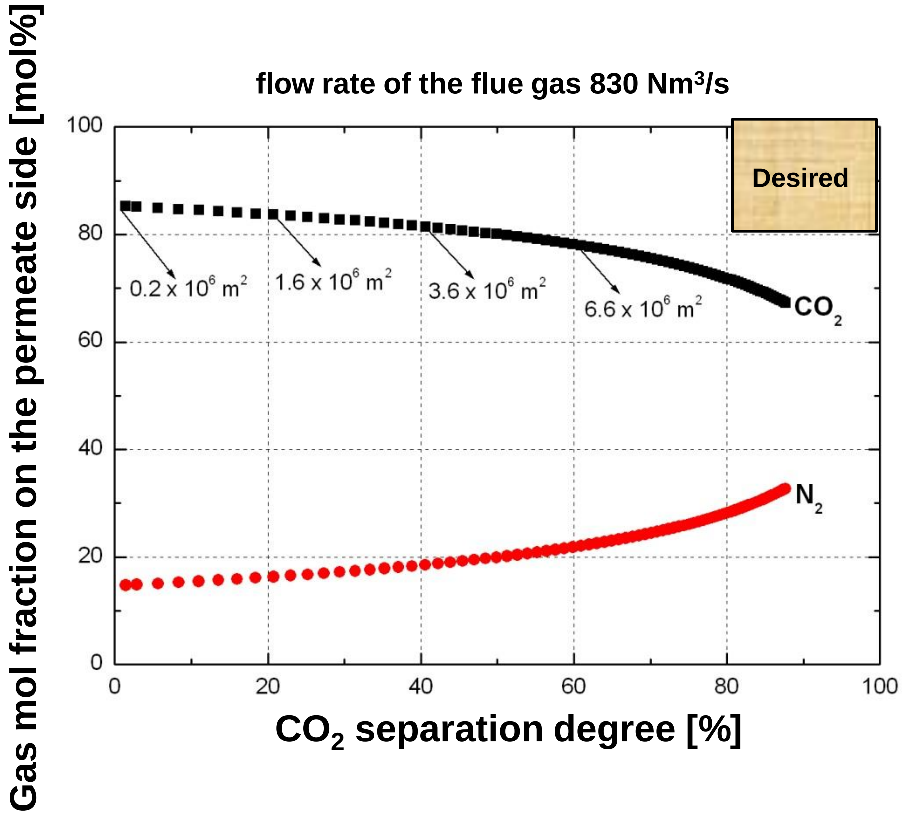
CO_2 separation degree

Driving Force

CO_2 partial pressure difference

$$\Delta p_{CO_2} = p_{feed} \cdot x_{f,\ CO_2} - p_{permeate} \cdot y_{p,\ CO_2}$$





Membrane area ↑ Degree of CO_2 separation ↑ CO_2 purity ↓

Why not a Single-stage Membrane?

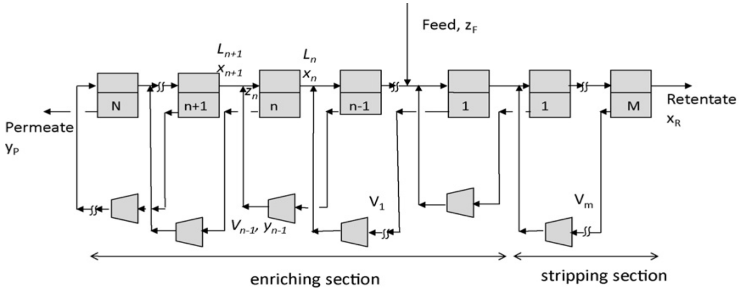
600 MW North Rhine-Westphalia (NRW) reference power plant of 45.9% net efficiency

Ideal flue gas: 14 mol% CO_2, 86 mol% N_2

Membrane CO_2 permance: 3 Nm^3/m^2hbar

Permeate vacuum [mbar]	Degree of CO_2 separation [%]	CO_2 purity [mol%]	CO_2/N_2 permselectivity	Δη [%-Ponints]
30	50	95	200	-3,4
100	50	95	3750	-2,8
100	70	95	No solution	-
	90	95	No solution	-

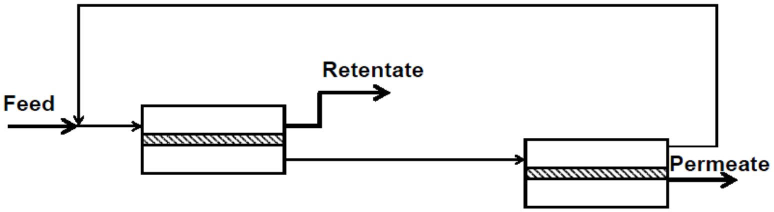
Optimization of a Membrane Cascade



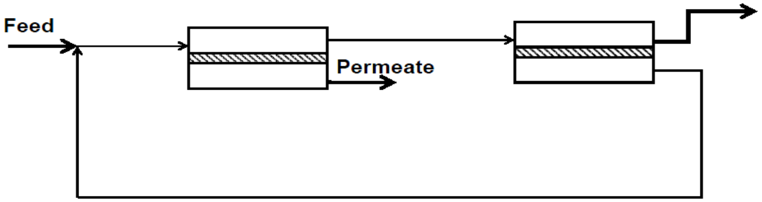
R. Pathare, R. Agrawal, J. Membr. Sci. 364 (2010) 263–277

2-stage

2 e_2s_0

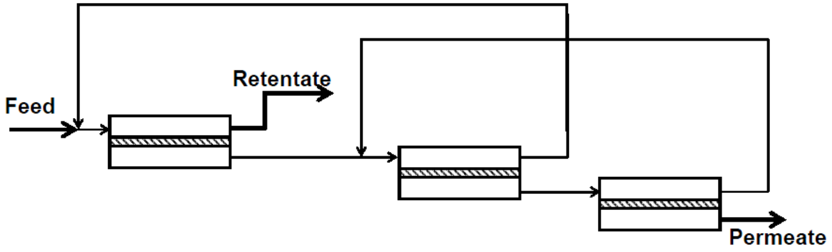


2 e_1s_1

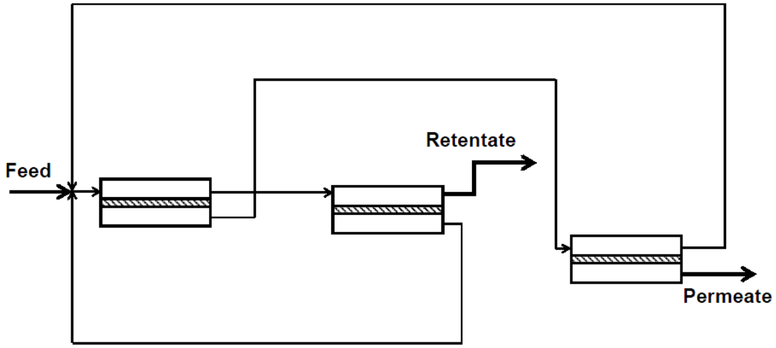


3-stage

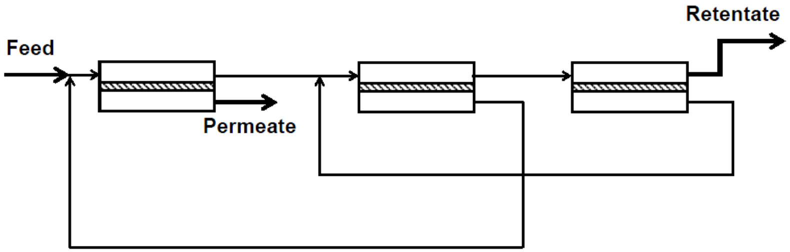
3 e_3s_0



3 e_2s_1

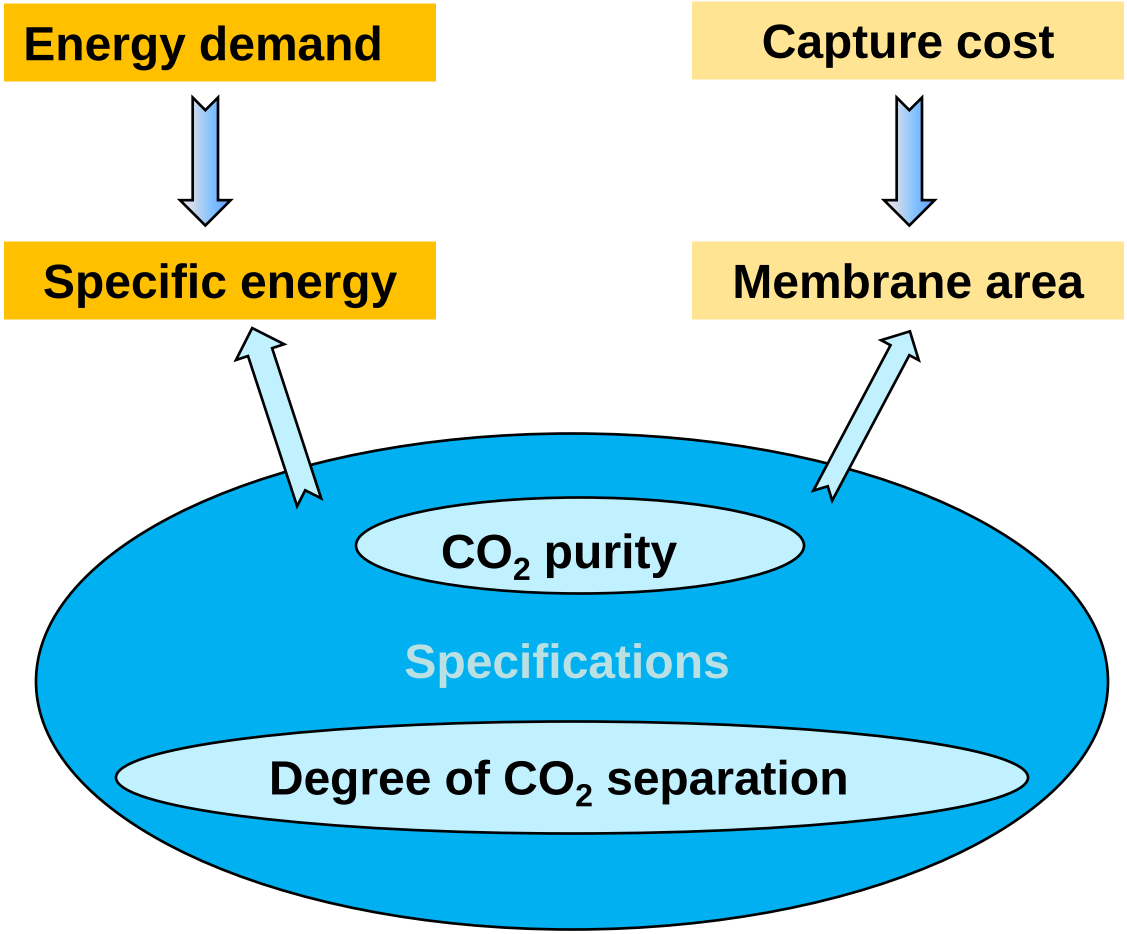


3 e_1s_2



4 variants for each cascade
Using compressor or vacuum pump for each membrane

Criteria for the Evaluation



Energy demand

Capture cost

Specific energy

Membrane area

CO_2 purity

Specifications

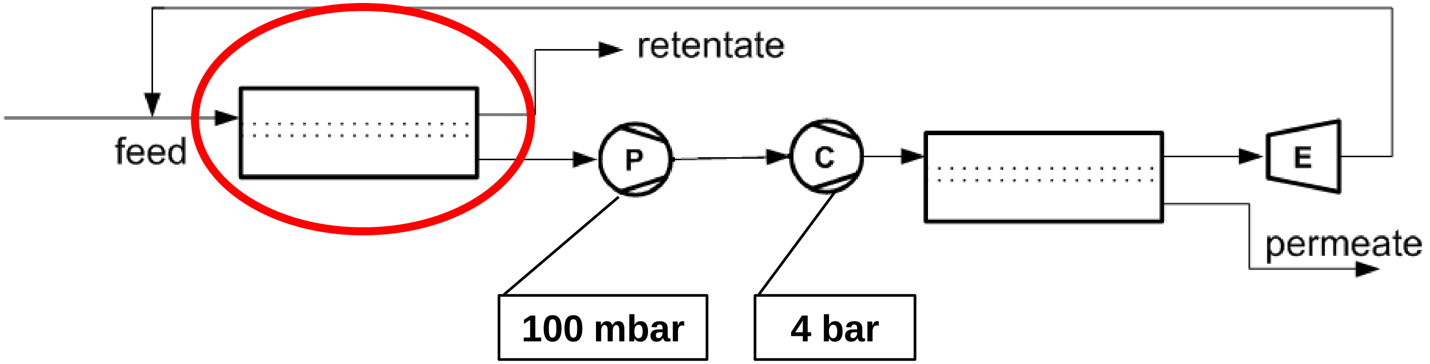
Degree of CO_2 separation

Cascade Concepts

Cascade A

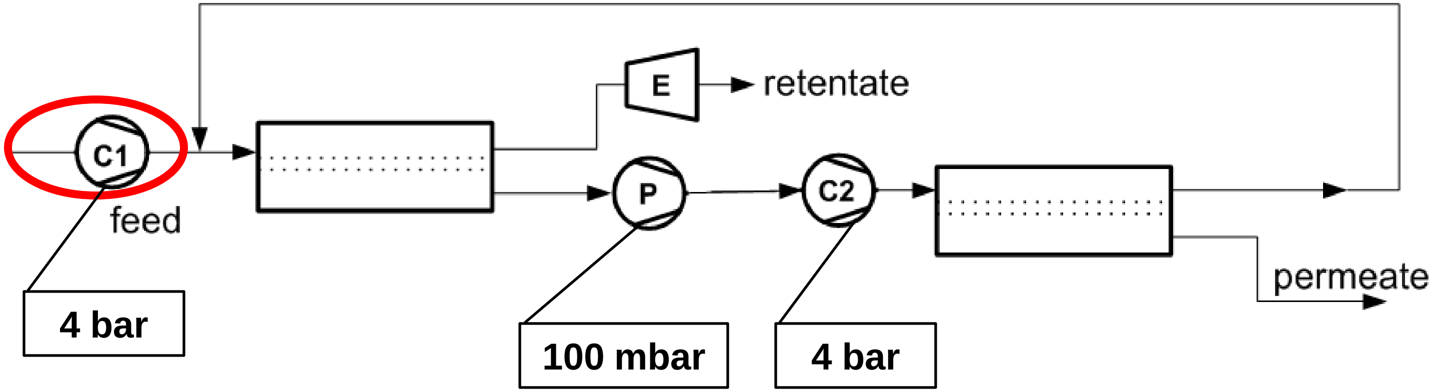
Lowest energy consumption

(70% degree of CO_2 separation)



Cascade B

A higher energy demand, distinctly decreased membrane area



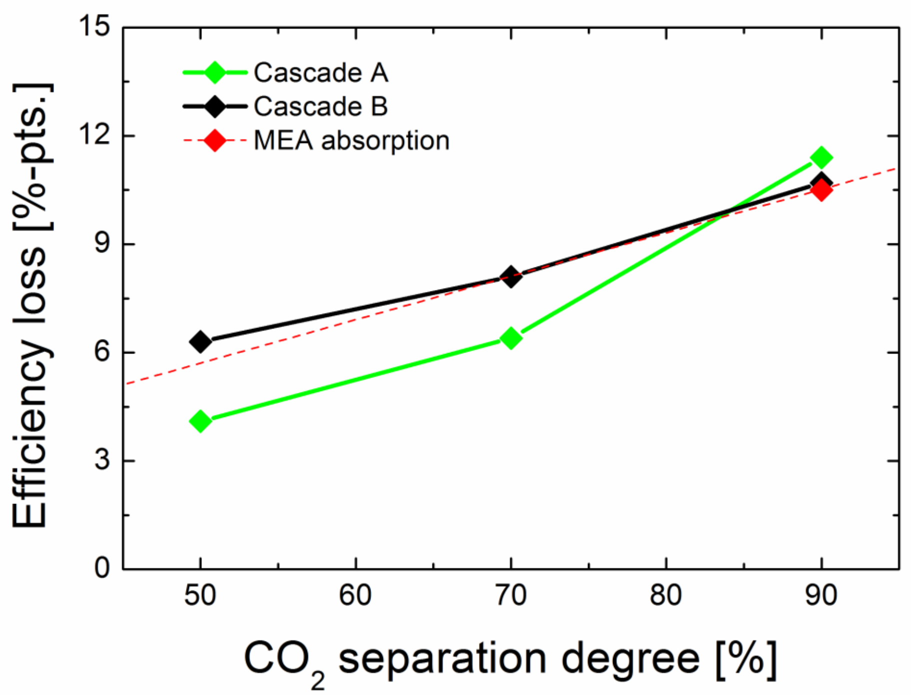
Membrane CO_2 permeance: 3 Nm^3/m^2hbar; CO_2/N_2 selectivity: 50 (HZG)

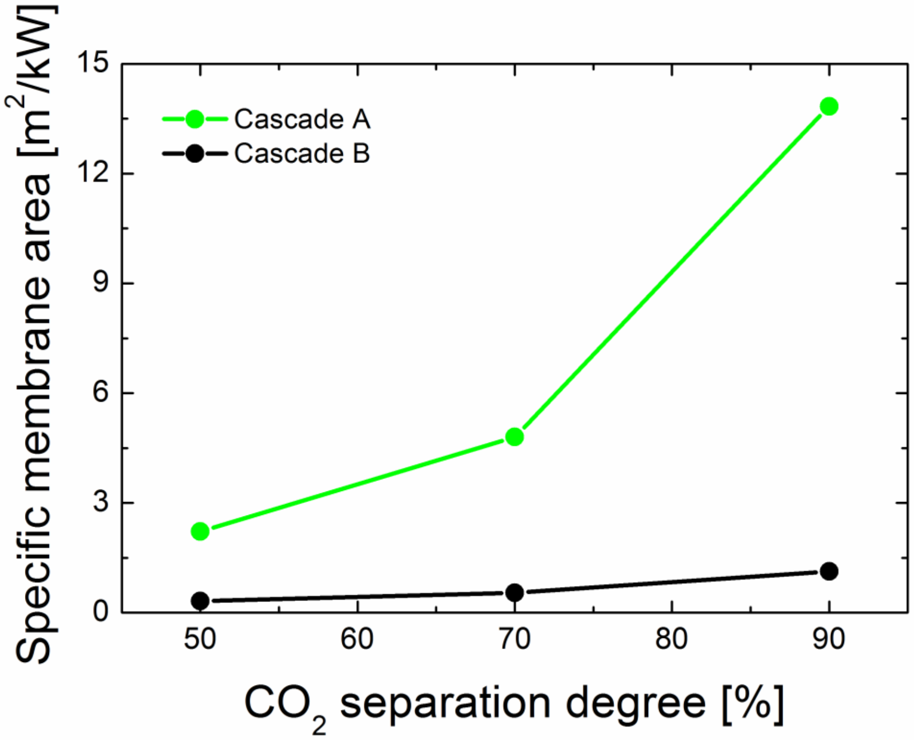
Simulation Results

600 MW North Rhine-Westphalia (NRW) reference power plant of 45.9% net efficiency

Ideal flue gas: 14 mol% CO_2, 86 mol% N_2

Membrane CO_2 permance: 3 Nm^3/m^2hbar , CO_2/N_2 selectivity: 50 (HZG, Germany)





Short Summary for ideal flue gas

- **For 50% and 70% degree of CO_2 separation**
  cascade A (w/o feed flue gas compression) has energetic advantage against MEA absorption**;**
- **For 90% degree of CO_2 separation**
  cascade A has a slight energetic disadvantage, while **cascade B** (feed flue gas compression) is on the MEA absorption level.
- **For all separation degrees**
  cascade A needs much more membrane area than **cascade B**.

Water Removal

Ideal flue gas

CO_2	14 mol%
N_2	86 mol%

Real flue gas *

CO_2	13.5 mol%
N_2	70.1 mol%
O_2	3.7 mol%
H_2O	11.9 mol%
Ar	0.8 mol%
SO_x	200 mg/Nm^3
NO_x	200 mg/Nm^3

* Hard coal combustion,
50°C after FGD

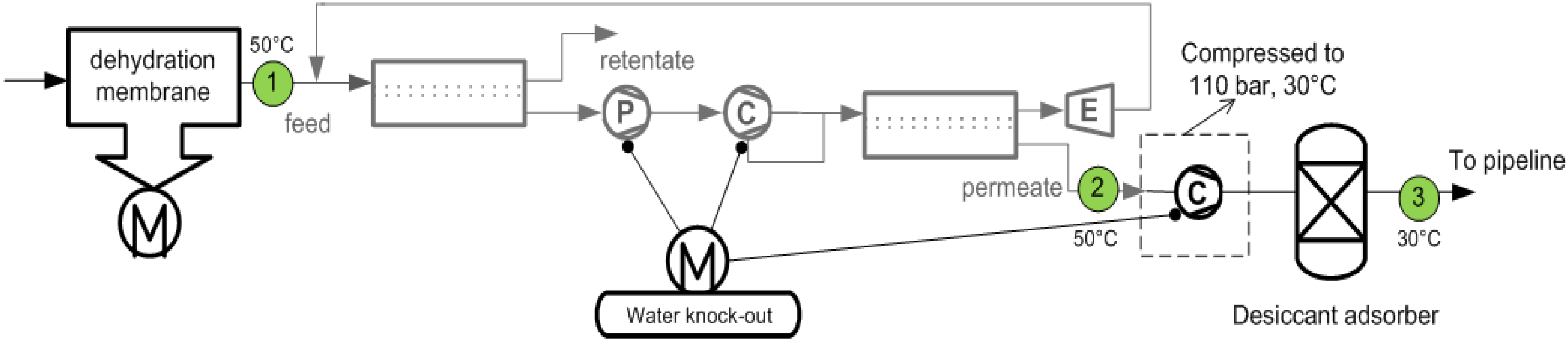
Purity requirements for pipeline

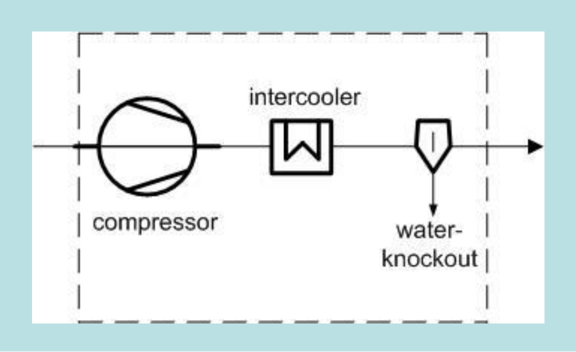
- CO_2 > 95 mol%
- No free water, < 500 ppm
- Limited non-condensable gas (N_2, Ar, H_2, NO_x and CH_4), < 4 mol%
- Limited contaminants (SO_2, H_2S, O_2)

[Hagdoorn 2007]

For post-combustion using membrane capture method, water removal is the other important topic in addition to CO_2 separation.

Measures for Dewatering (Cascade A)

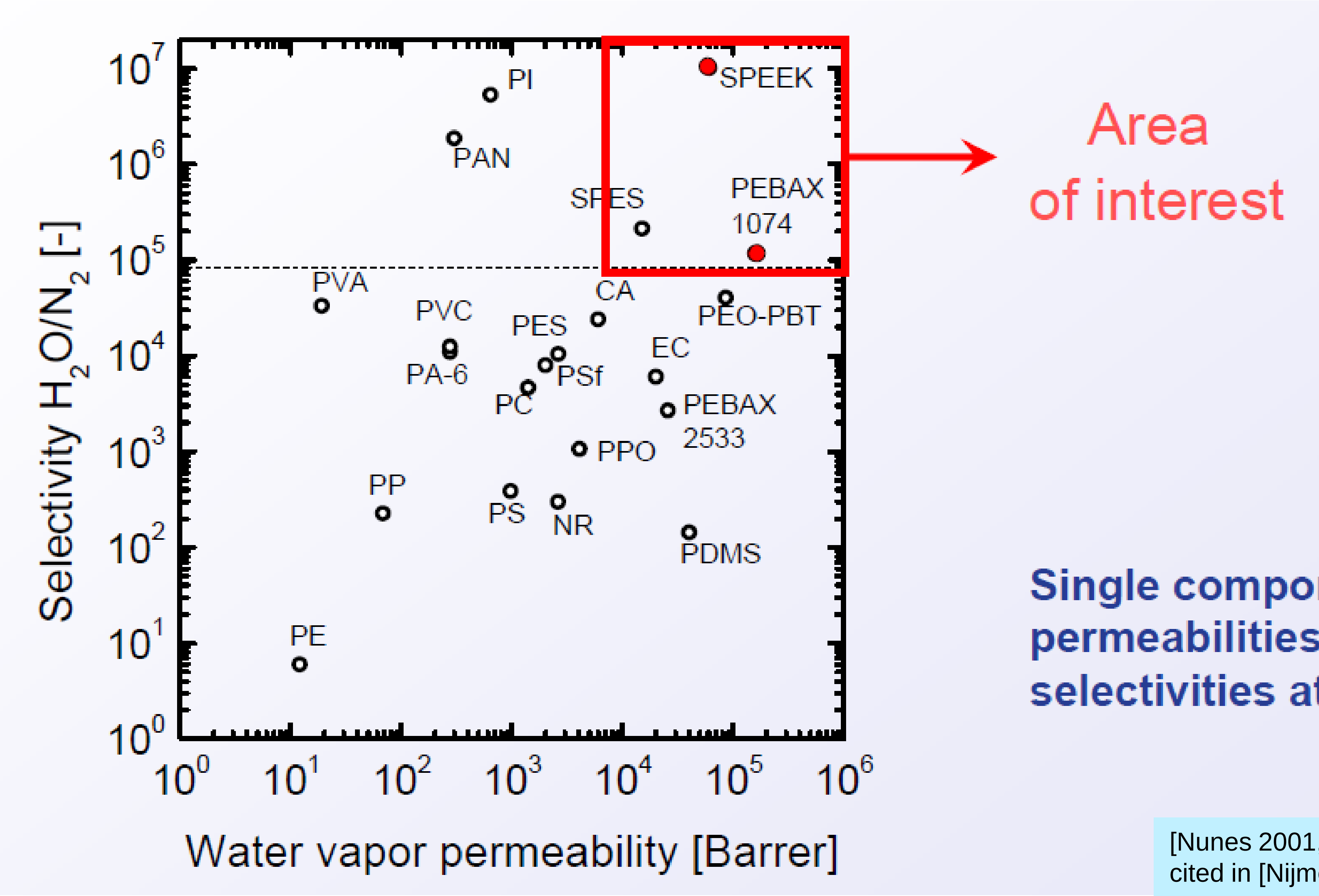




Dewatering procedures:

- **Using dehydration membrane prior to CO_2 separation**
- **Combing with inter- and aftercooling for each compression stage**
- **Remaining water removed by desiccant**

Dehydration Membranes

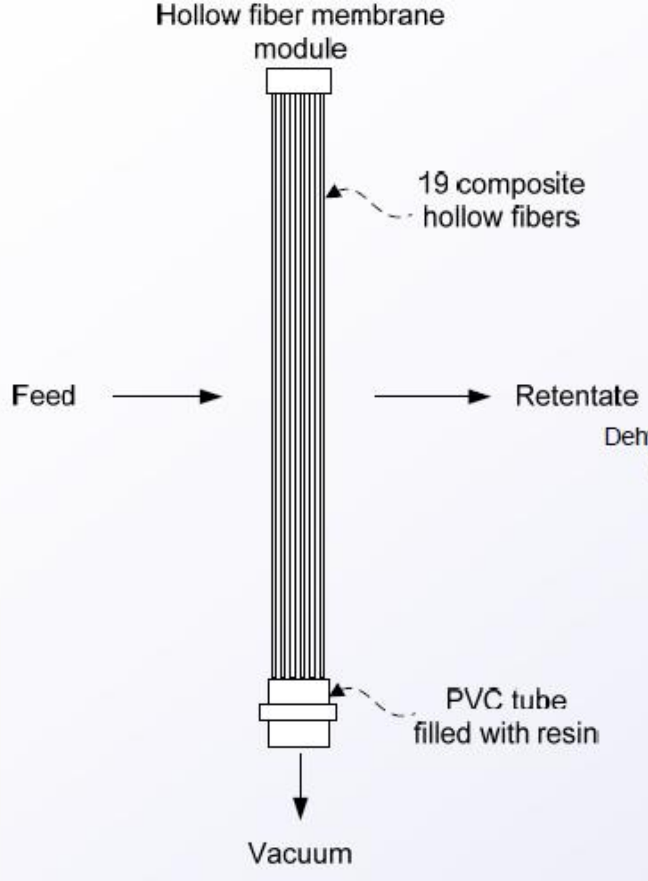


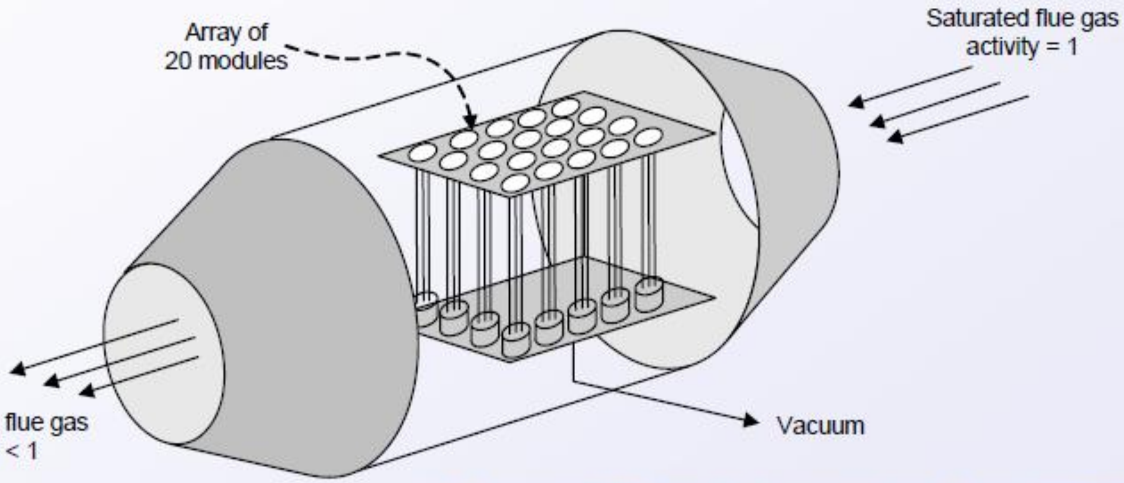
Single component permeabilities and selectivities at 25°C

[Nunes 2001, Metz 2005] cited in [Nijmeijer 2007].

Schematic illustration

K. Nijmeijer, 10th Jülicher Werkstoffsyposium, 2007





Case Studies

600 MW North Rhine-Westphalia (NRW) reference power plant of 45.9% net efficiency

The energy consumption for driving the water pump and for the regeneration of the desiccant medium are neglected.

Membrane CO_2 permance: 3 Nm^3/m^2hbar

Quasi real flue gas *

CO_2	13.5 mol%
N_2	70.1 mol%
O_2	3.7 mol%
H_2O	11.9 mol%
Ar	0.8 mol%

* Hard coal combustion,
50°C after FGD

Selectivity

CO_2/N_2	50
N_2/N_2	1
O_2/N_2	2
H_2O/N_2	10^5
Ar/N_2	2

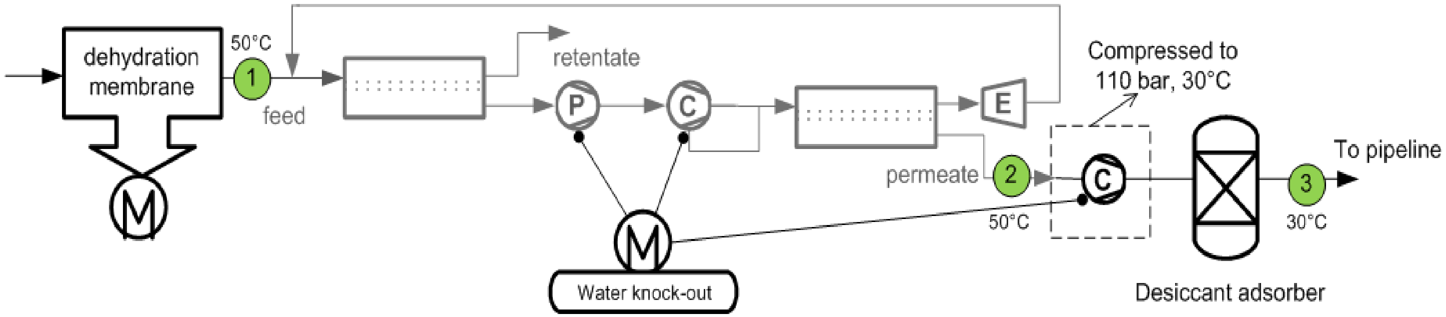
Simulation Results

Cascade A, 70% degree of CO_2 separation

Water removal prior to CO_2 separation	Separation degree	Membrane area [10^6 m^2]		Specific energy for capture [kWh_e/t_{CO2}]	Specific energy for compression [kWh_e/t_{CO2}]	Efficiency loss [%-pts]
		1st	2nd			
1/3	**78**	2.39	0.06	**198**	110	**8.4**
2/3	**78**	2.39	0.06	**181**	110	**7.9**
ideal flue gas	**70**	2.39	0.06	**151**	105	**6.4**

More water in flue gas, more energy consumption for CO_2 separtion.

Gas compositions



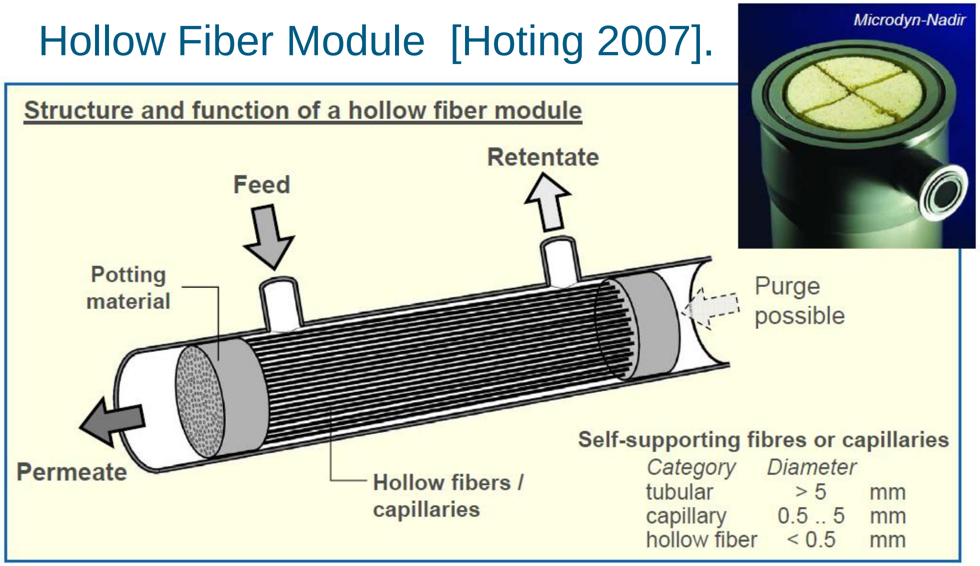
Position	Cases of CO_2 removal	p [bar]	Flow rate of total stream [kmol/h]	CO_2 [mol%]	N_2 [mol%]	O_2 [mol%]	Ar [mol%]	H_2O [mol%]
Flue gas		1.05	70499	13.5	70.1	3.7	0.8	11.9
1	1/3	1.05	68147	14.0	72.70	3.83	0.82	8.64
	2/3	1.05	65624	14.54	75.49	3.98	0.86	5.13
2	1/3	1	8364	90.06	3.57	0.71	0.04	5.63
	2/3	1	8293	89.99	3.61	0.72	0.04	5.64
3	1/3	110	7897	95.38	3.78	0.75	0.04	500 ppm
	2/3	110	7830	95.32	3.82	0.76	0.04	500 ppm

Short Summary for quasi real flue gas

- **Water removal** is an important procedure of membrane separation process for post-combustion capture.
- **Water in flue gas increases energy demand** for post-combustion CO_2 capture using gas separation membranes**.**
- **Water content** in the flue gas shows a **positive sweep gas effect for CO_2 separation membrane**.

Pressure Losses in Membrane Modules

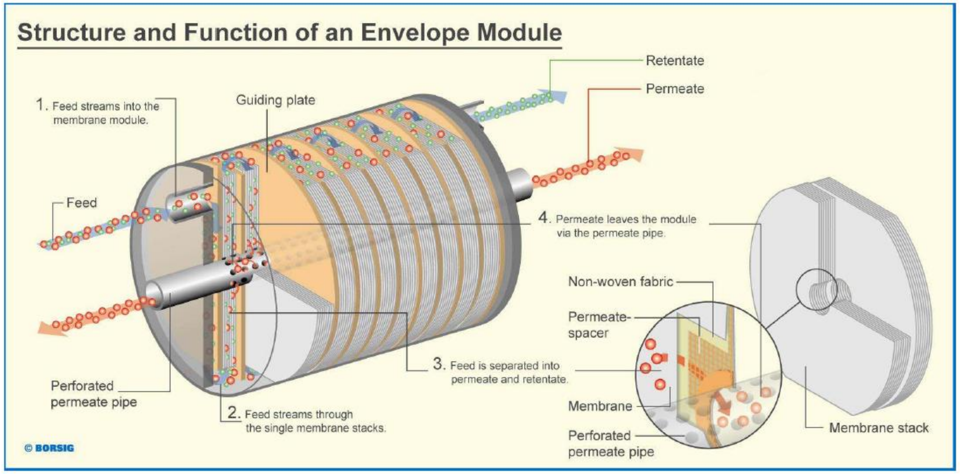
Hollow Fiber Module [Hoting 2007].


Structure and function of a hollow fiber module

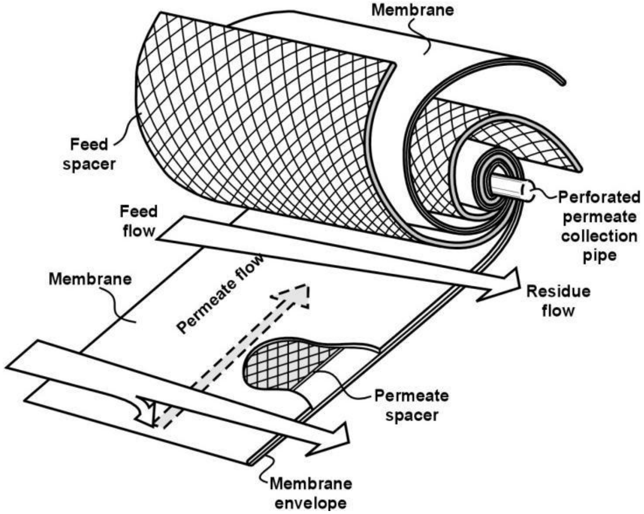
Self-supporting fibres or capillaries

Category	*Diameter*	
tubular	> 5	mm
capillary	0.5 .. 5	mm
hollow fiber	< 0.5	mm

Envelope Module [Beeskow 2007].


Structure and Function of an Envelope Module

Spiral-Wound Module [NETL-2]



Source: http://www.netl.doe.gov/publications/proceedings/10/co2capture/presentations/thursday/Tim%20Merkel%20-%20Membrane%20Technology%20and%20Research%20Inc.pdf

Influence on the Energy Demand

	Δp Feed	Δp Permeate	Compensation of Δp	Spec. energy demand $kWh_e/t_{CO2\text{-}sep}$	Δη %-points
Case 1	50 mbar	---	Blower 1.05-1.10 bar	10.5	-0.26
Case 2	---	50 mbar	Vacuum pump 50-100 mbar	31.5	-0.79

The extra energy demand shows how it is important to avoid pressure loss in membrane module design.

Concluding remarks

- For **ideal flue gas**
  - For **50% and 70%** degree of CO_2 separation the **cascade without feed flue gas compression** has energetic energy advantage against MEA absorption;
  - For **90%** degree of CO_2 separation the **cascade with feed flue compression** is on the MEA absorption level of the specific energy.
  - For all separation degrees the cascade without feed flue gas compression needs much **more membrane area**.

- **Water in flue gas increases the energy demand**, but sweep effect allows to reach a higher degree of CO_2-separation. Detailed investigations are needed.

- **Pressure losses** on the feed side as well as on the permeate side must be taken into account for **membrane module design**.

Thank you for your attention!