Maps for the Evaluation of Membrane Performances in CO_2 Post-Combustion Capture

A. Brunetti, G. Chiappetta, A. Pudia,
E. Drioli, G. Barbieri

Institute for Membrane Technology, ITM–CNR 87036 Rende CS, Italy

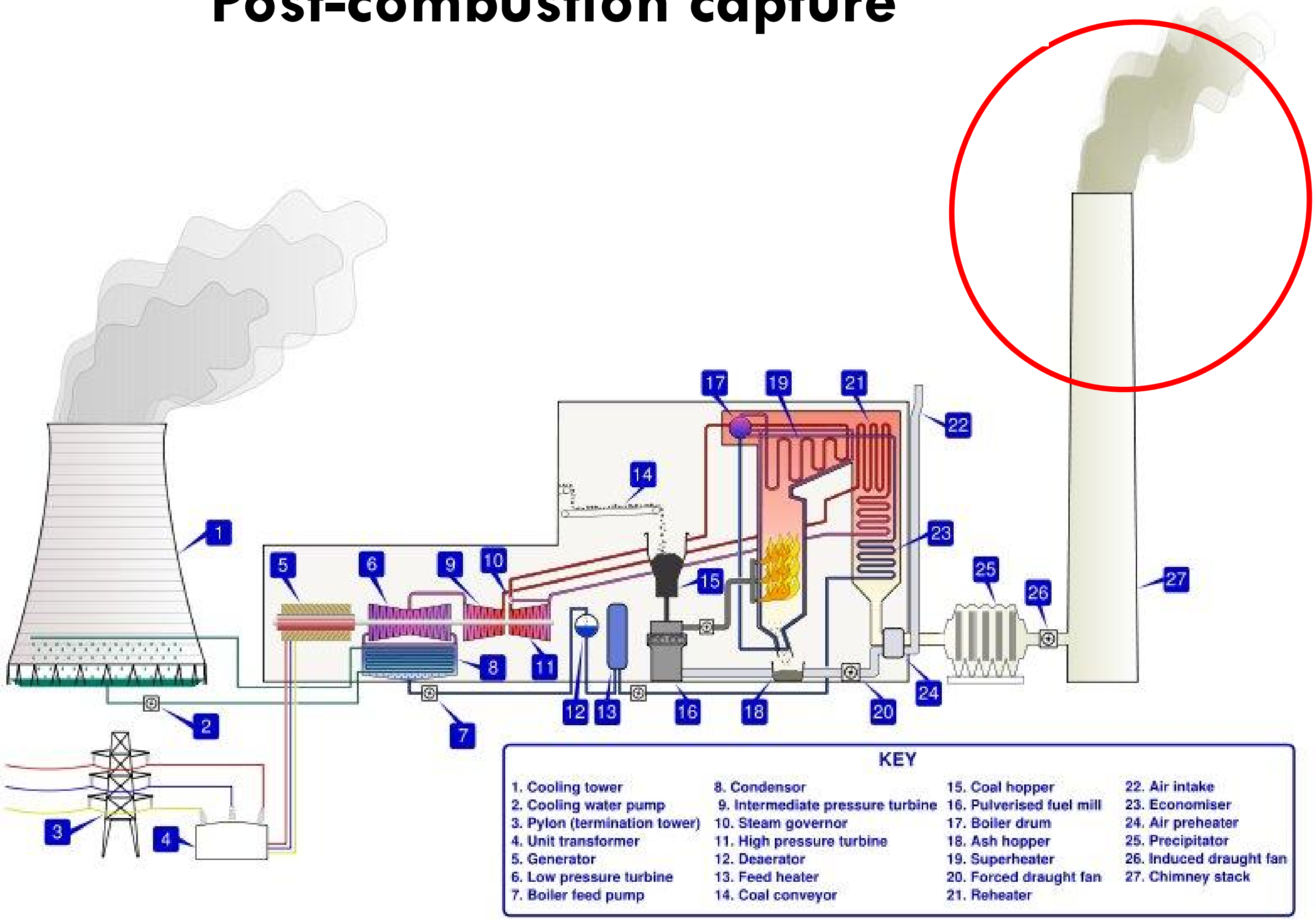
Department of Chemical Engineering and Materials, The University of Calabria 87036 Rende CS, Italy

Trondheim CCS Conference – CO_2 Capture, Transport and Storage
Trondheim, June14 -16, 2011

Summary

- ☐ Introduction
- ☐ Elaboration of Global Maps by 1-D theoretical model and comparison with literature data
- ☐ Conclusions

Post-combustion capture



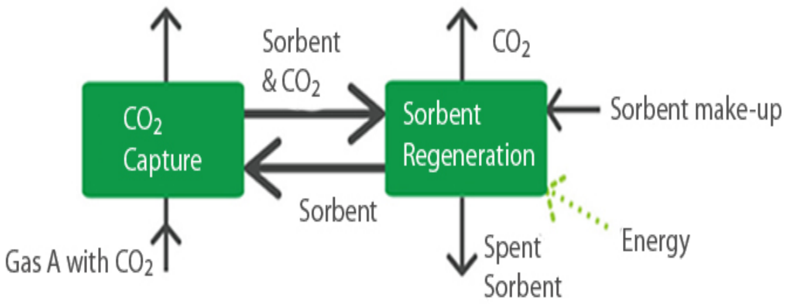
CO_2 *(concentration of ca. 5–25%)* has to be separated, at relatively low temperature and atmospheric pressure, from the flue gas emitted after the combustion of fossil fuels.

This possibility shows the essential advantage of being compatible to a retrofit strategy (i.e. an already existing installation can be, in principle, subject to this type of adaptation).

Favre E., *Journal of Membrane Science*, 294 (2007) 645

Traditional operations for CO_2 Separation

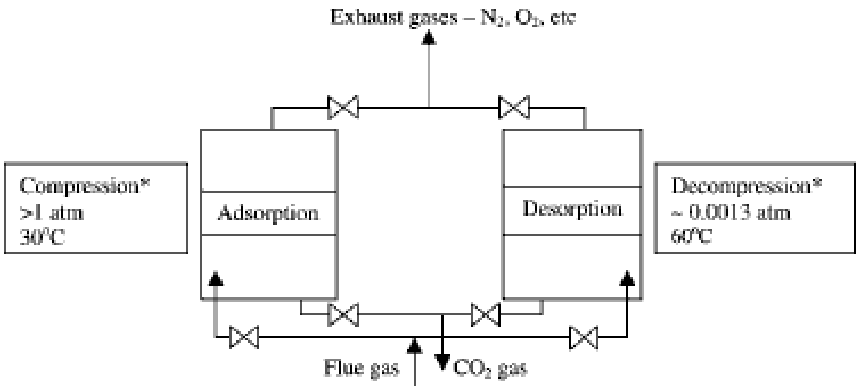
ABSORPTION



Use monoethanolammine (MEA) to dissolve CO_2. The CO_2-rich solution (i.e >90%) is pumped to a regeneration column, where the CO_2 is stripped from the solution and the solvent recycled.

High amount of energy is consumed for the regeneration of solvent. Solvent is degraded in oxidising environment of flue gas

ADSORPTION



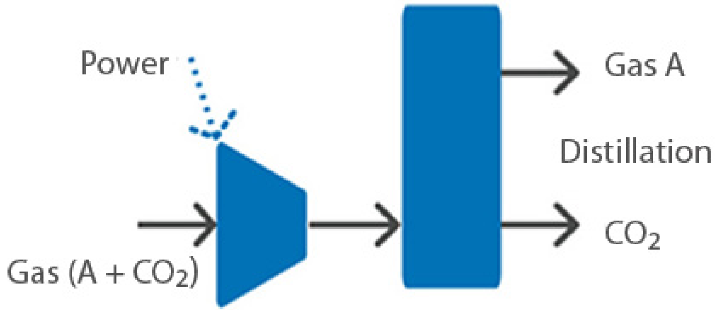
CO_2 is adsorbed onto the sorbent particles. In PSA, the gas mixture flows through a packed bed until the desired gas concentration approaches equilibrium. A vacuum can then be applied to liberate the CO_2 from the sorbent.

High pressure is required.

CRYOGENIC

After the removal of all of the other gases and particulates a mixture of CO_2 (i.e. at high concentration) and N_2 is fed into a cryogenic chamber where liquid CO_2 can be separated by cooling and condensation whereas N_2 remains as a gas.

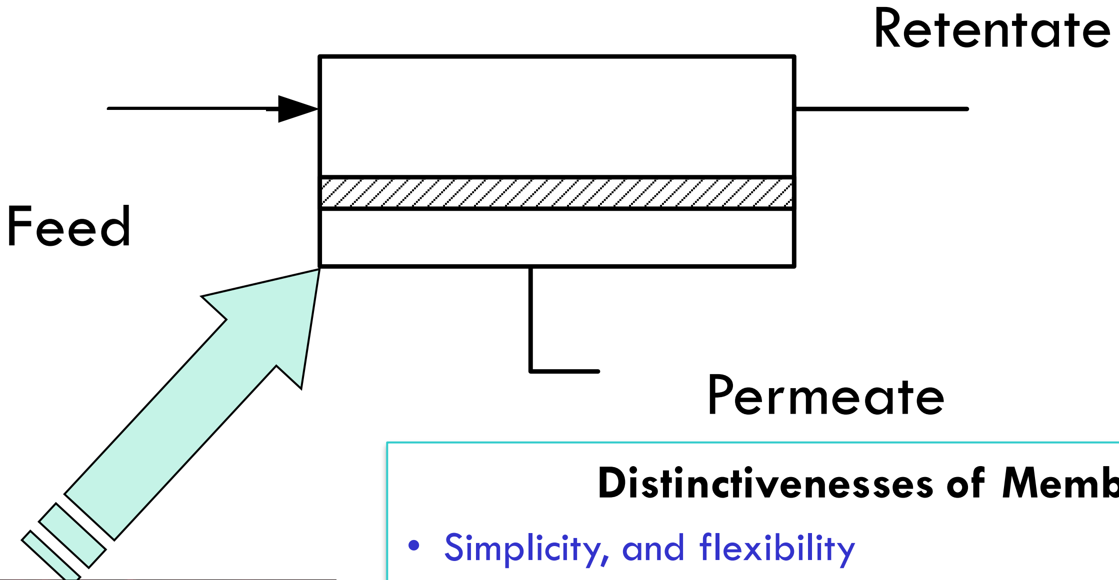
High amount of energy is consumed in refrigeration process. Pre - treatment stages for the water removal are necessary to avoid blockages in the system



Aaron D., Tsouris C., *Separation Science & Technology*, 40, (2005), 321

Consiglio Nazionale delle Ricerche

Membrane Gas Separation



Distinctivenesses of Membranes

- Simplicity, and flexibility
- Modularity, and ease of scale-up
- Reduced Equipment Size
- Low Investment Costs
- Ease of installation and incorporation of new membrane developments
- A flue gas compression much smaller than that for PSA is required.
- No extreme temperature (*i.e.* as in cryogenic separation)

C. E. Powell, G. G. Qiao, *Journal of Membrane Science*, 279 (2006) 1

Comparison among the different separation technologies

ABSORPTION		ADSORPTION		CRYOGENIC		MEMBRANE GS	
Advantages	**Drawbacks**	**Advantages**	**Drawbacks**	**Advantages**	**Drawbacks**	**Advantages**	**Drawbacks**
Recycling of the sorbent	Corrosion of carbon steel facilities due to oxygen	Recycling of the sorbent	Not able to handle large concentrations of CO_2	No requirement of chemical absorbents	Several costly steps required to remove all water traces	**No moving parts and modularity**	**Current low selectivity of membrane materials**
Non-dependence on human operators	Degradation of the solvent due to SO_x and NO_x	High operating flexibility	Adsorption also of gases smaller than CO_2	Atmospheric pressures	Increasing layer of solid CO_2 onto heat exchanger surfaces	**Istantaneous response to variations**	**Limitation on the suitable operating temperature for polymeric membranes**
Consolidated know how of the technology	Energetic load for solvent recovery		Slow process		Complex control systems	**Easy of expansion**	

A Simple Tool for a preliminary analysis in one-stage membrane system

Feed/Retentate side

$$\frac{d\varphi_{CO_2}^{Retentate}}{d\zeta} = -\Theta_{CO_2}\left(\phi\, x_{CO_2}^{Retentate} - x_{CO_2}^{Permeate}\right)$$

$$\frac{d\varphi_{N_2}^{Retentate}}{d\zeta} = -\frac{x_{CO_2}^{Feed}}{x_{N_2}^{Feed}}\frac{1}{\alpha_{CO_2/N_2}}\Theta_{CO_2}\left(\phi\, x_{N_2}^{Retentate} - x_{N_2}^{Permeate}\right)$$

Permeate side

$$\varphi_{CO_2}^{Permeate}(\zeta) = \varphi_{CO_2}^{Feed} - \varphi_{CO_2}^{Retentate}(\zeta)$$

$$\varphi_{N_2}^{Permeate}(\zeta) = \varphi_{N_2}^{Feed} - \varphi_{N_2}^{Retentate}(\zeta)$$

- 1-D model
  - steady-state permeation
  - no sweep mode
  - co-current configuration
  - Flue gas stream containing **13% of CO_2**

Parameters used in simulation tests	
Flue gas **composition**	**13% CO_2**; 87% N_2
Flue gas **feed pressure**	1 bar
Membrane Selectivity	30-300
Pressures ratio	5-50
Number of stages	1

Brunetti A., Scura F., Barbieri G., Drioli E., *Journal of Membrane Science*, 359 (2010) 115

dimensionless molar flow rate

(*i*.e. for CO_2 and N_2)

$$\varphi_i = \frac{Q_i}{Q_i^{Feed}}$$

dimensionless module length

$$\zeta = \frac{z}{L}$$

Pressures Ratio

$$\Phi = \frac{P^{Feed}}{P^{Permeate}}$$

Permeation number

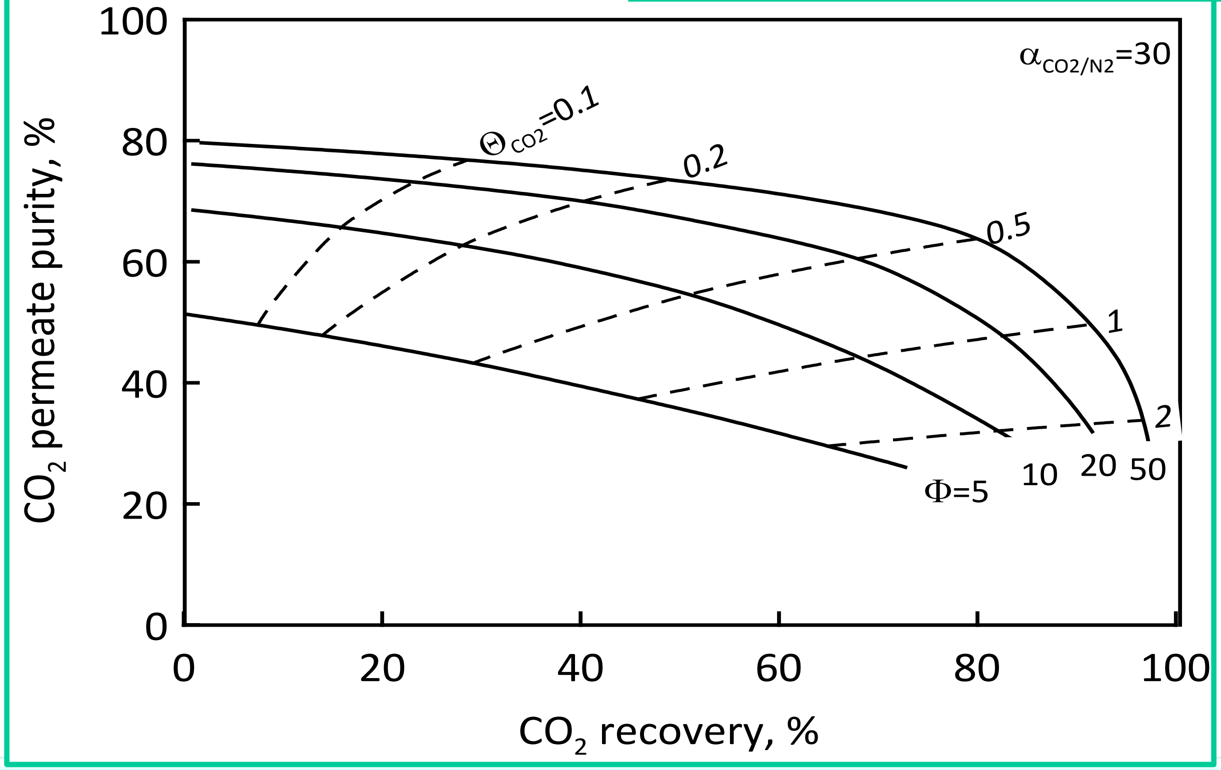
$$\Theta_{CO_2} = \frac{Permeance_{CO_2} \; A^{Membrane} \; P^{Feed}}{x_{CO_2}^{Feed} \; Q^{Feed} \; \Phi}$$

Θ_i compares two main mass transport mechanisms involved. It affects the performance of a one-stage membrane system as well as ϕ_i. A high Θ_i corresponds to a high residence time for the stream and, then, to a high permeation rate through the membrane with the respect to the convective flux along the module.

Global Maps: Modelling Results

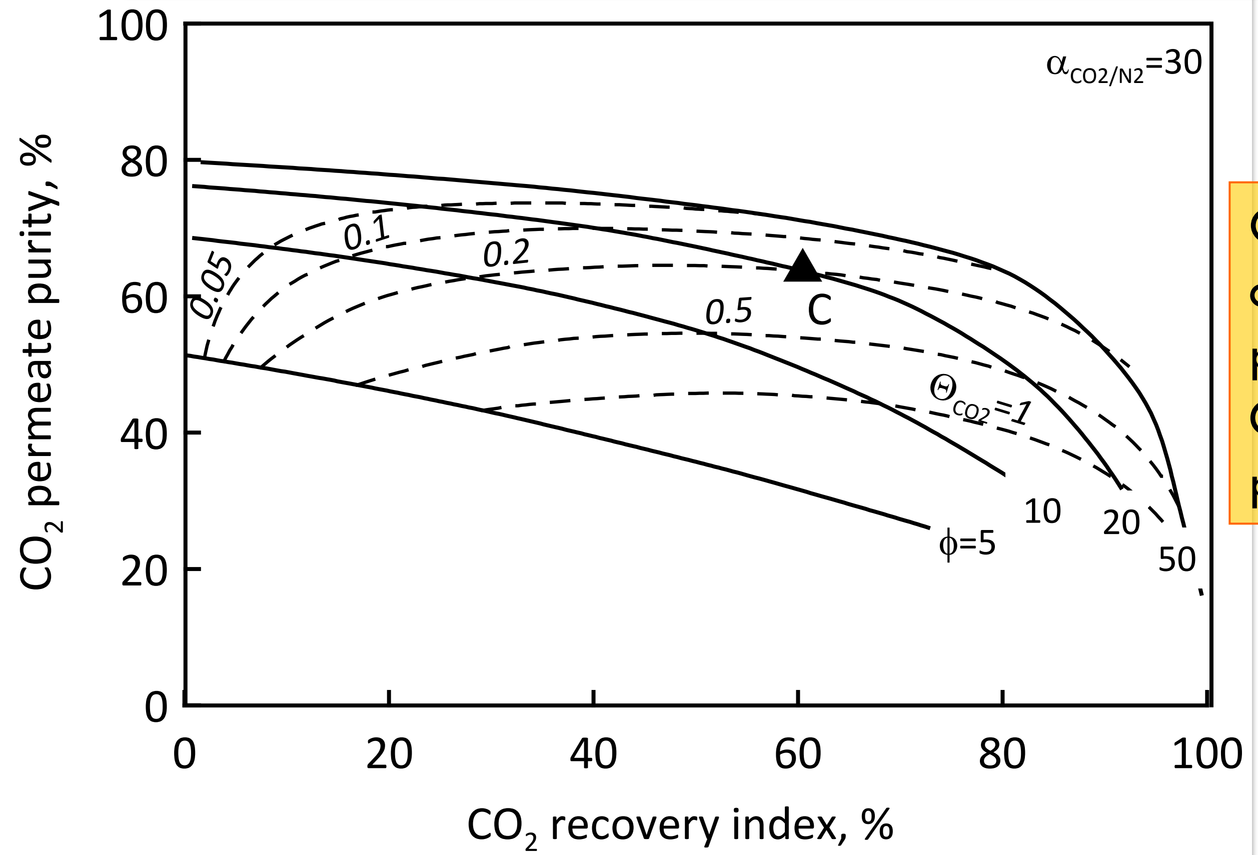
$$Stage\ Cut = \frac{\text{Permeate flow rate}}{\text{Feed flow rate}}$$

$$\text{CO}_2\ \text{recovery index} = \frac{\text{CO}_2\ \text{Permeate flow rate}}{\text{CO}_2\ \text{Feed flow rate}}$$



At a given permeation number (dashed lines), CO_2 purity increases with the recovery. A high permeation number leads to a higher recovery but lower purity: the main part of the feed flow rate permeates, preferentially in the first part of the module, through the membrane and N_2 dilutes the CO_2 permeated.

Use of Global Maps



Global maps could be considered a starting point in the *Carbon Capture* and *storage* process design

For a given membrane geometry and properties Θ_{CO2} and Φ are obtained by infinite couples of operating conditions

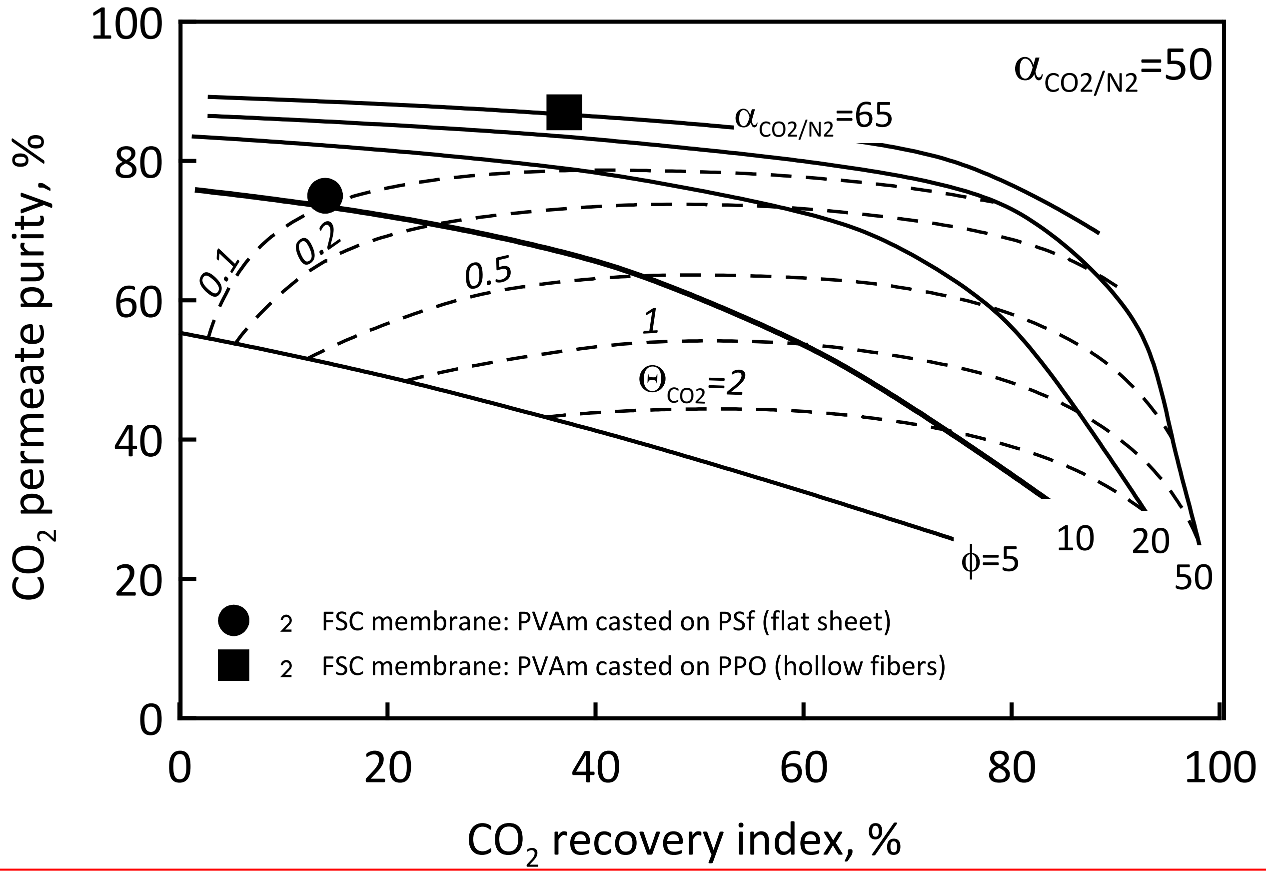
For instance, 64% CO2 purity and 61% recovery corresponds to a system having a Φ of 20 and a Θ_{CO2} of 0.2.

Brunetti A., Scura F., Barbieri G., Drioli E., *Journal of Membrane Science*, 359 (2010) 115

Use of Global Maps

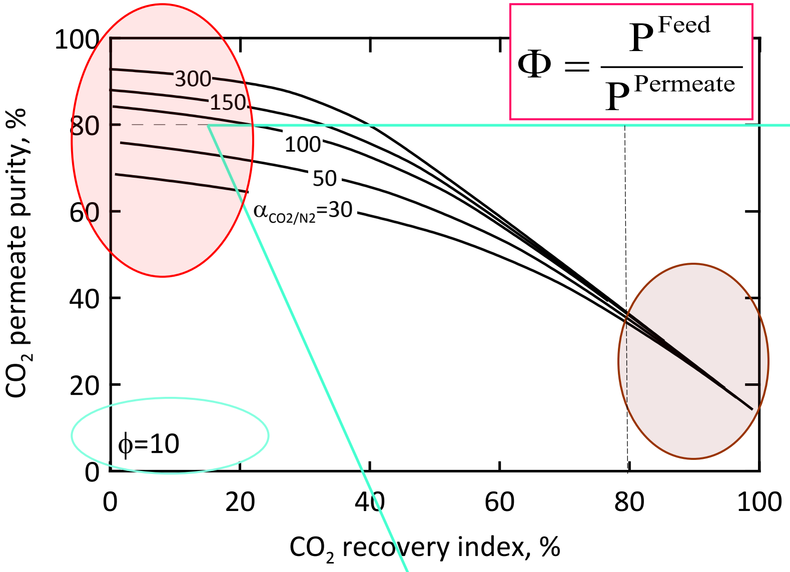
[1] Brunetti A., Scura F., Barbieri G., Drioli E., *Journal of Membrane Science*, 359 (2010) 115

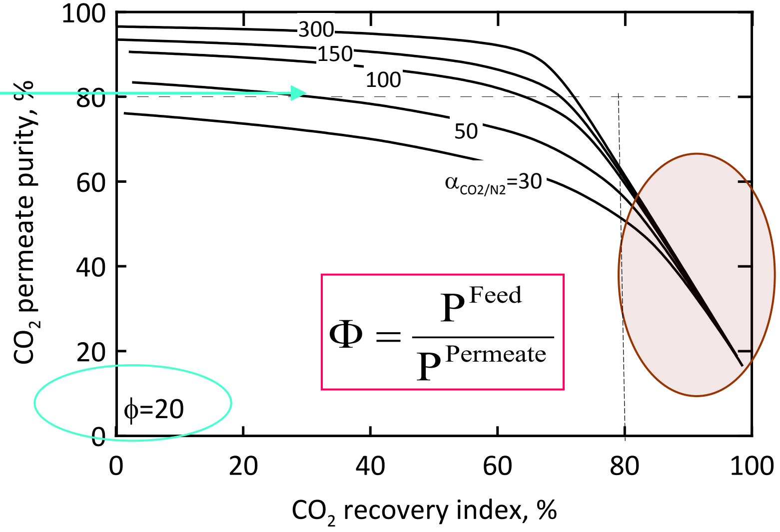
[2] M.Sandru, *PhD Thesis*, Dep. of Chem. Eng. Faculty of Natural Sci. and Tech., Norwegian University of Science and Technology

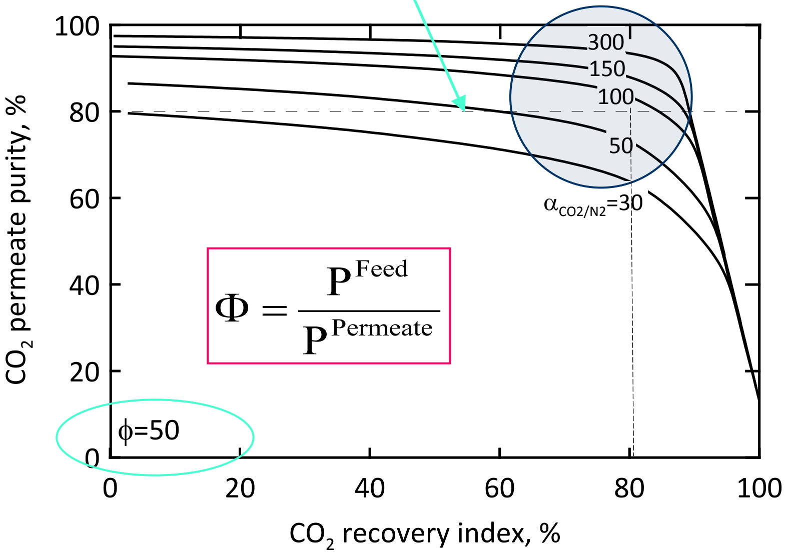


For a pressure ratio of 10, the simulation provides a maximum achievable purity of CO_2 in permeate stream of around 76% at low recovery (i.e. close to zero). The purity decreases monotonically down to 39% when recovery is, instead, 76%.

Effect of ideal selectivity and pressure ratio on the membrane module performance







A value of **80%** is the **minimum purity** (corresponding to a recovery of 80%) **admitted for the storage** by the International Energy Agency[1] (i.e. dashed line in figures)

[1] Bounaceur R., Lape D., Roizard D., Vallieres C., Favre E., *Energy*, 31 (2006) 2556

[2] Brunetti A., Scura F., Barbieri G., Drioli E., *Journal of Membrane Science*, 359 (2010) 115

CONCLUSIONS

Some general guidelines to drive the application of Membrane Gas Separation Technology in an one-stage has been given for CO_2 – Post Combustion Capture.

For currently available membranes ($\alpha_{CO2/N2}=50$) it is not possible to get, simultaneously, an interesting CO_2 recovery and purity (i.e. 80% CO_2 in permeate stream). **Two membrane stages will give the required separation but higher costs will be obtained for compression intermediate stages .**

When high recoveries have to be approached pressure ratio (Φ) has a role much more determining than selectivity. In fact, for a selectivity of 100, **an increase of the pressure ratio from 10 to 50 shifts CO_2 recovery from 22% to 80%.**

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Thank you for your attention

Institute on Membrane Technology-
National Research Council
(Headquarter)
c/o University of Calabria,
Via Pietro BUCCI, 17/C, I-87030 Rende CS,
Italy
Tel. +39 0984-492039-492050;
Fax. +39 0984-402103
www.itm.cnr.it