Energy penalty of a single stage gas permeation process for CO₂ capture in postcombustion: a rigorous parametric analysis of temperature, humidity and membrane performances

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Abstract

Over the last decade membrane separation processes have attracted a considerable research attention, due to its potential to lower the costs of post-combustion CO₂ capture [1], compared to more established technologies based on chemical solvents whose main factor of energy penalty is due to solvent regeneration. It is well known that membrane-based CO₂ capture are intrinsically less selective than chemical systems; but this technology has the potential to decrease a lot the footprint of CCS by solving the drawbacks of conventional chemical absorption, such as the requirement of high energy for solvent regeneration, and concerns related to the chemical handling and final disposal and the environmental pollutions caused by amines [2]. However, the performances of membrane system can vary a lot and are related to several factors, including the flue gas composition, the membrane material, the system design and the operating conditions. Among operating parameters, membrane working temperature [3], inlet pressure and gas humidity are interplay factors having several implications on CO₂ separation process. Surprisingly, the interplay as key operating variable has not been investigated in detail. Indeed, it influences not only the intrinsic membrane properties and the feed composition, but it indirectly affects the energy behavior of the whole capture system. Hence, the resulting outcomes cannot be intuitively deduced.

This work reports the study of the effect of membrane operating temperature on a CO₂ capture process operated by means of a single stage unit with feed compression and permeate vacuum pumping. Considering the flue gas from a coal-fired power plant, variation of separation performances and energy expenses are evaluated with respect to two types of polymeric membranes (P1 and P2), having different gas separation properties with opposite separation properties was evaluated (permeability, selectivity): P1: P=150 Barrer α=53 and P2: P=3700 Barrer α=23 at 30°C. The representative study case is from a coal-fired power plant with a design rated capacity of 550 MW and specific CO₂ emissions of approximately 856 kg/MWh [3]. Based on a flue gas flow rate of 635.5 kg/s, the CO₂ and water vapor molar fractions, at $T_{\text{exh}} = 57^\circ \text{C}$, are 13.5% and 15.2% respectively. Figure 1 below shows the studied layout of a single stage membrane system, which is based on feed side compression and vacuum pumping on the permeate side. We consider the use of tub expander to allow the use of pressure ratio up to 30 which are compulsory to reach good capture performances; indeed the expander allows to recover enough compression energy of the retentate to make the process viable.

Combining feed compression and vacuum pumping, the pressure ratio across the membrane states at 30. Membrane gas separation has been simulated using the proprietary software tool M3PRO®, properly integrated into Aspen Plus environment, to carry out the energy analysis of the whole system.
Figure 1: CO₂ capture system: four mains blocks can be identified, i.e., the feed compression and cooling system, the energy recovery system, the membrane separation unit and the permeate vacuum pumping system

The transport of flue gas across a single stage membrane module was simulated using a mono-dimensional hollow fiber model, assuming the following main assumptions:

- steady-state operation in adiabatic and countercurrent mode;
- flue gas mimicked by a multicomponent gas mixture;
- cross-plug flow conditions, that assume plug flow on the upstream feed side of the membrane and free flow on the downstream permeate side;
- CO₂ diffusion through the membrane described by Fick’s first law;
- constant gases permeabilities along the module length, with no coupling effects and negligible pressure drop on both membrane sides.

The simulation results provide realistic energy requirements needed to capture and concentrate CO₂ up to 70% without the use of any volatile chemical solvents. The study also confirms that it is impossible to simultaneously achieve a 90% CO₂ purity and a 90% capture ratio through a single stage membrane module whatever the operating conditions used.

The study reveals that the increase of membrane operating temperature negatively affects CO₂ permeate purity and power consumption to drive the separation process, while the influence on area requirement is strictly related to the type of membrane material. The following highlights can be drawn:

i) Water content in inlet flue gas decreases surface area and increases energy requirement
ii) Flue gas compression affects inlet water content which can act as an internal sweep from CO₂ in the permeate side
iii) A lower inlet temperature decreases energy requirement
iv) Simultaneously a 70% CO₂ purity and a 90% capture ratio can be achieved
v) A minimal energy requirement of 2.4 GJ/ton is achievable

References