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The Effects of Membrane-based CO_2 Capture System on Pulverized Coal Power Plant Performance and Cost

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Abstract

Membrane systems are under development for cost-effective carbon dioxide (CO_2) capture. This study is to investigate the effects of adding CO_2-selective polymeric membrane systems to coal-fired power plants using newly developed performance and cost models. Sensitivity analysis is further carried out to explore the influences of key parameters and factors on the power plant and the membrane-based capture system. The results show that adding a two-stage membrane system for 90% CO_2 capture to a coal-fired power plant nearly doubles the plant cost of electricity and incurs a high energy penalty up to about 30% of the gross electrical output; using both compressors and vacuum pumps to produce driving force for membrane gas separation is effective with reducing the capture cost; and recycling a portion of CO_2 via a multi-stage/step membrane configuration with air sweep would significantly reduce the overall system energy penalty and the cost of CO_2 avoided by roughly one-third in comparison with the two-stage membrane system, which exhibits that membrane capture systems could be a viable alternative to current amine-based processes.

Keywords: CO_2 capture and storage; membrane system; coal-fired power plants

1. Introduction and Objectives

Coal-fired power plants are the largest sources of U.S. power generation and national emissions of carbon dioxide (CO_2). To address global climate change, post-combustion carbon capture and storage (CCS) has been regarded widely as a key technology for deeply cutting CO_2 emissions from coal-fired

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electric utilities. Some studies have demonstrated the feasibility of membrane systems for CO_2 capture at pulverized coal (PC) power plants (Van der Sluijs *et al*, 1992, Ho *et al*, 2008, Merkel *et al*, 2010, Zhao *et al*, 2010). However, a more complete picture of performance and cost estimates for membrane-based CCS, especially on a coherent costing basis, is critically important to assessing the technology's viability.

The objective of this study is to evaluate the performance and cost impacts of adding polymeric membrane-based CCS systems that simultaneously achieve 90% CO_2 removal efficiency and 95% product purity at PC power plants. We further conduct a series of sensitivity analyses to investigate the influences of key parameters and factors and explore paths for facilitating the viability of membrane technology.

Nomenclature

x	CO_2 concentrations of in the feed stream (vol %)
y	CO_2 concentrations of in the permeate stream (vol %)
q	gas flow rate (cm^3/s)
A	membrane area (cm^2)
J	volumetric flux ($cm^3/(cm^2.s)$)
P_f	pressure in the feed side (cmHg)
P_p	pressure in the permeate side (cmHg)
P^*	gas permeability of either CO_2 or N_2 ($cm^3.cm/(s.cm^2.cmHg)$)
α	membrane selectivity for CO_2 versus N_2 gases (ratio)
ϕ	pressure ratio for feed versus permeate sides (ratio)
δ	membrane thickness (cm)

2. Analytical Method and Tool

Gas separation by polymeric membranes replies on the gas permeability. The driving force for membrane gas separation is the partial pressure difference of a gas component across membranes. Gas streams may operate for different flow patterns such as complete mixing, cross-flow, and countercurrent flow. Theoretical models for membrane gas separation vary with flow patterns to some extent. However, constant permeability of each gas component, isothermal conditions and negligible pressure drop in both feed and permeate streams are generally assumed in the development of theoretical models for different types of operation (Geankoplis, 1993). For the widely-adopted cross-flow pattern, the local permeation rate of a gas component in a binary (CO_2 and N_2) membrane system over a differential membrane area is (Geankoplis, 1993):

$$-ydq = J_{CO2}dA = \frac{P^*_{CO2}}{\delta}\ xP_f - yP_p\ dA \quad (1)$$

$$-\ 1 - y\ dq = J_{N2}dA\ = \frac{P^*_{N2}}{\delta}\ (1-x)P_f - (1-y)P_p\ dA \quad (2)$$

Diving two equations above leads to:

$$\frac{y}{1-y} = \frac{\alpha\ 1-y\ \phi}{1-x\ -\ 1-y\ /\phi} \quad (3)$$

The resultant equation relates the concentrations of CO_2 in both feed and permeate streams at a point along the pathway. Mathematical transformations are applied to obtain an analytical solution to the above three governing equations (Geankoplis, 1993).

Power plant flue gases typically have 10% to 15% CO_2 by volume, which results in a low CO_2 partial pressure. The sufficient partial pressure difference of CO_2 across membranes can be generated by three strategies including feed-side compression, permeate-side vacuum pumping, and a combination of both the previous methods. When a compressor is used in the feed side, the compression energy can be partly recovered from the residue gas stream by an expander.

A wide range of process scenarios are designed to explore the potential operational space of a two-stage membrane-based capture process (further illustrated later) and characterize key input-output response relations. The reduced-order response models are then embedded in the Integrated Environmental Control Model (IECM), a computer-modeling program developed by Carnegie Mellon for the U.S. Department of Energy's National Energy Technology Laboratory (IECM, 2012). In the IECM, the process performance models are linked to engineering-economic models, in which the costing method and nomenclature are based on the Electric Power Research Institute's (EPRI) Technical Assessment Guide (TAG) (EPRI, 1993). In this study, we apply the IECM to evaluate how the addition of membrane-based capture systems would affect the performance and cost of coal-fired power plants.

3. Base Case Results

The IECM v 7.0-beta was used to conduct base case studies for illustrative supercritical PC power plants with and without membrane-based CCS. The base plants comply with federal New Source Performance Standards for air and water pollutants. Table 1 summarizes major technical and economic assumptions for the base plants with a net power output of 550 MW. Figure 1 presents schematic of a two-stage membrane CCS system for postcombustion CO_2 capture.

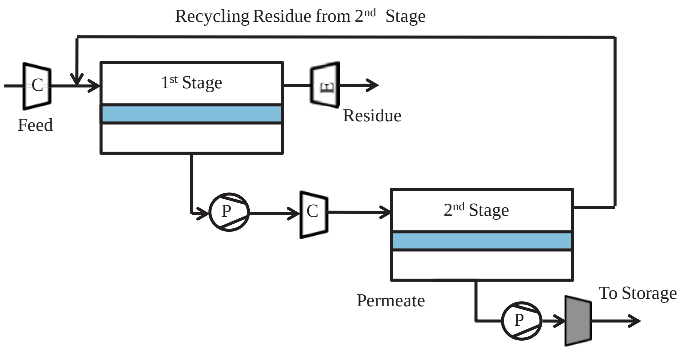

Figure 1. Schematic of a two-stage membrane system for postcombustion CO_2 capture

The membrane system employed in the base capture case is configured with two stages operated for the cross-flow pattern. As shown in Figure 1, the residue stream out of the first stage is vented out to atmosphere. The residue stream out of the second membrane is recycled to the entrance of the capture system, and has the same CO_2 concentration as the inlet flue gas. The CO_2-rich permeate stream out of the second stage is further compressed via a multi-stage compressor before it is transported to a storage site. In this system the combination design of feed-side compression and permeate-side vacuum pumping is adopted to generate the driving force for CO_2/N_2 separation. Nominal values of major technical and cost metrics defining the membrane-based capture system are also presented in Table 1. The two stages of the capture system have identical material properties and pressure designs.

Table 1. Major technical and economic assumptions for base power plant and membrane system

Category	Variable	Value
Power plant	Plant type	Supercritical
	Coal type	Illinois #6
	Environmental controls	SCR + ESP + FGD[a]
	Cooling system	Wet tower
	Capacity factor (%)	75
	Net electrical output (MW)	550
	CO_2 molar concentration in flue gas (%)	11.8
	Fixed charge factor	0.113
	Dollar year/type	2010/constant
Membrane system	CO_2 permeance (S.T.P. gpu)[c]	1000
	CO_2/N_2 selectivity (S.T.P.)	50
	CO_2 product compression (kWh/mt CO_2)	93
	Membrane module price ($\$/m^2$)	50
	Gas compressor installed cost ($/hp)	500
	Gas vacuum pump installed cost ($/hp)	1000
	Gas expander unit cost ($/kW)	500
	Heat exchanger capital cost ($\$/m^2$)	300
	Product compression installed cost ($/kW)	900
	General facilities capital (% of PFC)	10
	Engineering & home office fees (% of PFC)	7
	Project contingency cost (% of PFC)	15
	Process contingency cost (% of PFC)	5
	Royalty fees (% of PFC)	0.5
	CO_2 transport and storage costs ($/mt)	5.0
	Material replacement rate (%)	20
	Material replacement cost ($\$/m^2$)	10
	Labor rate ($/hr)	34.65

[a] SCR = selective catalytic reduction; ESP =electrostatic precipitator device; and FGD = flue gas desulfurization; [b] The S.T.P. indicates the standard temperature and pressure conditions (0^oC and 1 atmospheric pressure); [c] 1 gas permeation unit (gpu) = 10^{-6} cm^3 (S.T.P.)/(cm^2·s·cmHg).

Table 2. Performance and cost results of coal-fired power plant with and without two-stage membrane system for 90% CO_2 capture

Parameter	Carbon capture and storage (CCS)	
	Without (reference plant)	With
Gross electrical output (MW)	589.7	883.2
Net electrical output (MW)	550.0	550.0
Net plant efficiency(%, HHV)	38.4	25.7
CO_2 emission rate (kg/kWh)	0.816	0.122
Two-stage membrane CCS system		
Pressure ratio for permeate versus feed sides	n/a	20.5
Feed-side pressure (bars)	n/a	4.1
System power use (% of MWg)	n/a	31.1
Plant cost of electricity (COE) ($/MWh)	59.4	117.0
Added COE for CCS ($/MWh)		57.6
Cost of CO_2 avoided ($/mt)		83

To achieve 90% CO_2 removal efficiency and 95% product purity, the pressure ratio for feed versus permeate sides is required to be about 20 for the membrane properties given in Table 1. To reach this pressure ratio, the feed stream is compressed to be 4.1 bars and the permeate stream is vacuumed to be 0.2 bar. The results presented in Table 2 show that with the addition of CCS, the net plant efficiency (HHV) decreases from 38.4% to 25.7% mainly because the power use of the capture system accounts for 31% of the gross power output. Meanwhile, the plant levelized cost of electricity (COE) increases by 97%, which is larger than the added cost for adding current amine-based CCS systems to PC power plants (Rubin *et al*, 2007). The resulting cost of CO_2 avoided for the PC power plants with and without capture is $83 per metric tonne of CO_2. Because a number of factors affect the capture system performance and cost, we next undertake a series of parametric analyses to examine the effects of various parameters and designs on the plant performance and the cost of CO_2 avoided by membrane systems.

4. Sensitivity Analysis

Parametric analyses also were conducted to investigate the effects of feed-side pressure, membrane properties and price. Furthermore, this study looked into a new configuration recycling a portion of CO_2 to evaluate the effects of increasing the CO_2 partial pressure of feed flue gas on the power plant and the capture system. In each case, other parameters were kept at their base case values, unless otherwise noted.

4.1 Feed-side Pressure

We first examine how different feed-side pressure designs affect the plant performance and the cost of CO_2 avoided by the two-stage membrane system. The feed-side pressure is varied from 2.0 bars to 10.0 bars, whereas the pressure ratio for feed versus permeate sides is maintained constantly at twenty. Elevation in the feed-side pressure significantly increases the system power requirements, although it reduces the required membrane area. Figure 2 shows that as a result of increasing the feed-side pressure by compressors, the net plane efficiency (HHV) decreases from 27.8% to 20.1%, and the cost of CO_2 avoided for the PC plants with and without capture increases from $73 to $141 per metric tonne of CO_2. These results imply that using compressors alone would make the capture system's overall energy penalty far too large to be affordable, even if an expander is used to recover part of the energy.

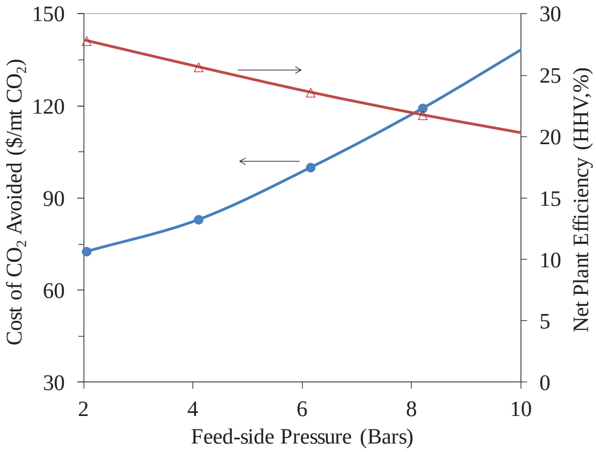

Figure 2. Effects of membrane feed-side pressure on net plant efficiency and cost of CO_2 avoided by two-stage membrane capture and storage

4.2 Membrane Properties and Price

We conduct additional sensitivity analyses to evaluate the effects of membrane CO_2/N_2 selectivity and CO_2 permeance on the cost of CO_2 avoided by the two-stage membrane system. Here the CO_2/N_2 selectivity is changed from 40 to 70, while the CO_2 permeance is evaluated at 1000, 2000 and 3000 gpu. In this analysis, the permeate-side pressure is held at 0.20 bar for all cases. The required pressure ratio decreases from 29.3 to 14.3 and the net plant efficiency (HHV) increases from 23.4% to 27.5%, when the selectivity increases within the selected range. Figure 3 shows the cost of CO_2 avoided as a function of the membrane selectivity. For a given permeance, the cost decreases up to a selectivity of 60, then remains roughly constant. For a given selectivity, increasing the CO_2 permeance reduces the cost of CO_2 avoided by decreasing the required membrane area. These results clearly indicate the cost of CO_2 avoided is highly affected by membrane properties.

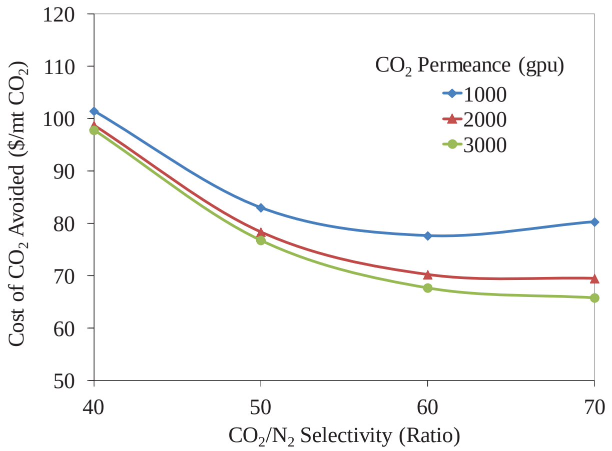

Figure 3. Effect of membrane properties on cost of CO_2 avoided by two-stage membrane capture and storage

The assumption of membrane module price directly affects cost estimates. Figure 4 shows that effect of membrane price for three CO_2 permeances. To reduce the cost of producing membrane modules decreases the cost of CO_2 avoided by the capture system. For example, for a permeance of 1000 gpu the cost of CO_2 avoided decreases from \$98.4/mt to \$76.9/mt as the unit price falls from \$150 to \$10 per square meter. When the membrane module price approaches to the smallest value, the cost of CO_2 avoided is still high up to more than \$70/mt CO_2, which is mainly accounted for by the costs of compressors, vacuum pumps and an expander as well as the CO_2 product compression and storage.

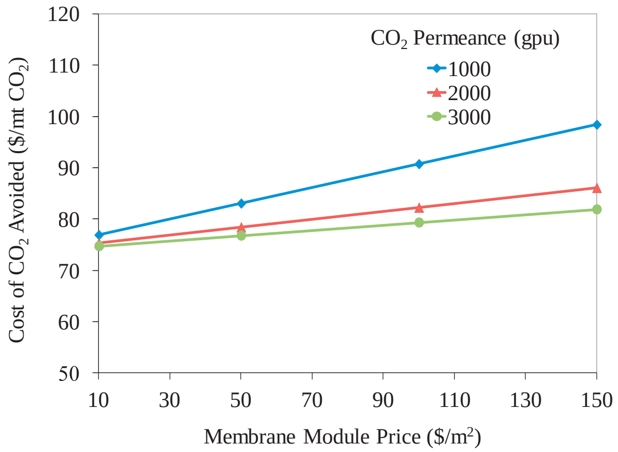

Figure 4. Effect of membrane module price on cost of CO_2 avoided by two-stage membrane capture and storage

4.3 CO_2 Recycling

To generate driving force for gas separation, a sweep gas can be used in a countercurrent module to increase the partial pressure of a gas in the permeate side (Pan and Habgood, 1974). A recent study presented a novel process design that uses boiler combustion air as a sweep gas to produce driving force and boost the inlet CO_2 concentration of flue gas into a membrane system (Merkel *et al*, 2010). Here, we investigate a two-stage, two-step configuration (TSTS) with gas sweep. As shown in Figure 5, combustion air is used as the sweep gas to carry a portion of CO_2 back to the boiler. A mathematical framework established by Pan and Habgood (1974) was applied to model the sweep-based gas separation.

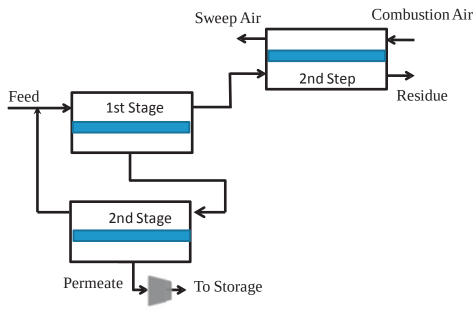

Figure 5. A two-stage, two-step membrane system with air sweep

The TSTS system adopts the hybrid driving force design: the feed-side pressure of the first two stages is designed at 2.0 bars, whereas the permeate-side pressure is 0.20 bar at the 1^{st} and 2^{nd} stages and 1.0 bar at the 2^{nd} step module. The inlet CO_2 concentration of feed flue gas increases from the original 11.8% to 17.1%. This, in turn, decreases the energy required by the capture system to generate the driving force for CO_2/N_2 separation. We then compare the two configurations with and without recycling CO_2. Table 3 summarizes the comparative results. The energy use of the sweep-based TSTS configuration accounts for 19% of the gross electrical output, compared to 31% for the two-stage system. Adding the sweep-based capture system with CO_2 recycling increases the plant COE by 62%, which is much lower than that of the two-stage configuration. Furthermore, this higher inlet concentration of CO_2 reduces the cost of CO_2 avoided from $83/mt (of the two-stage system) to $52 per metric ton of CO_2.

Table 3. Comparisons of performance and cost between two membrane systems for 90% CO_2 capture

Variable	Two-stage configuration	Two-stage, two-step configuration with air sweep
Inlet CO_2 concentration of system (%)	11.8	17.1
Feed-side pressure (bars)	4.1	2.0
Permeate-side pressure @1st and 2nd stages (bar)	0.2	0.2
CO_2 product purity (%)	95	95+
Membrane area (10^6 m^2)	1.5	2.2
System energy penalty (% of MWg)	31	19
Net plant efficiency (HHV, %)	25.7	30.6
Cost of power plant with CCS ($/MWh)	117.0	96.3
Added cost for CCS ($/MWh)	57.6	36.9

5. Conclusions

The system analyses demonstrate that to achieve 90% capture and 95% product purity for CO_2, adding a two-stage membrane system to a PC plant nearly doubles the plant COE and incurs a high energy penalty. The driving force design of using both compressors and vacuum pumps to lower the feed-side compression pressures is helpful to reduce the capture system's energy penalty and cost of CO_2 avoided; improvement of membrane properties effectively reduces the capture cost. Using boiler combustion air as a sweep gas in the two-stage, two-step membrane system would reduce the cost of CO_2 avoided by roughly one-third compared to the two-stage membrane system without recycling CO_2, which indicates membrane capture systems could be a viable alternative to current amine-based processes.

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References

[1] *Electric Power Resear*ch Institute (EPRI). *TAG^{TM} –Technical Assessment Guide Vol.1: Electricity Supply, Rev.7*; ReportNo.TR-102276-VIR7; Electric Power Research Institute, Palo Alto, CA, June 1993.
[2] Geankoplis, C. J. *Transport Processes and Unit Operations*, 3rd Edition. Prentice Hall, **1993**.
[3] Ho, M. T.; Allinson, G. W.; Wiley, D. E. Reducing the cost of CO_2 capture from flue gases using membrane technology. *Ind. Eng. Chem. Res.* **2008**, 47, 1562–1568.
[4] *Carnegie Mellon University's Integrated Environmental Control Model (IECM) Website*. http://www.cmu.edu/epp/iecm/index.html (accessed May 2012).
[5] Merkel, T. C.; Lin, H.; Wei, X.; Baker, R. Power plant post-combustion carbon dioxide capture: an opportunity for membranes. *J. Membr. Sci.***2010**, 359(1-2), 126–139.
[6] Pan, C. Y.; Habgood, H. W. An analysis of the single-stage gaseous permeation process, *Ind. Eng. Chem. Fundam.* **1974**, 13, 323–331.
[7] Rubin E. S.; Chen, C.; Rao, A. B. Cost and performance of fossil fuel power plants with CO_2 capture and storage. *Energy Policy* **2007**, 35, 4444–4454.
[8] Van Der Sluijs, J. P.; Hendriks, C. A.; Blok, K. Feasibility of polymer membranes for carbon dioxide recovery from flue gases. *Energy Convers. Manage.* **1992**, 33(5-8), 429–436.
[9] Zhao, L.; Riensche, E.; Blum, L.; Stolten, D. Multi-stage gas separation membrane processes used in post-combustion capture: energetic and economic analyses. *J. Membr. Sci.* **2010**, 359(1-2), 160–172.