Novel Transformational Membranes and Process for CO_2 Capture from Flue Gas

primary project goals

The Ohio State University (OSU), along with its partners Gas Technology Institute, the National Carbon Capture Center (NCCC), and American Electric Power, is developing a cost-effective design and fabrication process for a novel transformational membrane and its membrane modules that capture carbon dioxide (CO_2) from flue gas. The project goal is to achieve 60 to 90% capture of CO_2 with greater than 95% CO_2 purity ready for compression to 152 bar (2,200 pounds per square inch [psi]) for storage or enhanced oil recovery and for less than $30/tonne CO_2 captured.

technical goals

- Optimize and characterize the transformational membrane (including morphology, transport properties, and stability).
- Synthesize an improved polymer support with a CO_2 permeance greater than 23,000 gas permeation units (GPU) for the membrane.
- Develop a polymeric composite membrane with CO_2 permeance greater than 3,300 GPU and CO_2/nitrogen (N_2) selectivity more than 140 at 77°C.
- Design and construct an integrated bench-scale testing system to be tested at OSU and NCCC.
- Complete a techno-economic analysis (TEA) of the project.

technical content

OSU and its partners are developing a cost-effective design and fabrication process for a novel transformational membrane and its membrane modules that capture CO_2 from flue gas. Based on density functional theory (DFT) calculations indicating a new carrier with high reactivity with CO_2, OSU will synthesize novel transformational polymer membranes with the new carrier, showing a very high CO_2 permeance of about 3,300 GPU (1 GPU = 10^{-6} cm^3(STP [Standard Temperature and Pressure])/(cm^2/s/cm mercury [Hg]) and a very high CO_2/N_2 selectivity of greater than 140. Optimization of the novel transformational membrane, scale-up of the membrane to a prototype size of about 21 inches wide in continuous roll-to-roll fabrication, and construction and testing of a bench skid for the integrated membrane process will be performed.

For the design of this membrane, OSU is using a cost-effective polyethersulfone (PES) support and coating a thin top layer of the membrane (Figure 1). This membrane design offers a low cost for the membrane element in commercial spiral-wound configuration (less than $2.00/$ft^2$ or $21/$m^2$). Operating parameters and various properties of the membrane are detailed in Table 1. The prototype membrane is used to fabricate at least six pilot-size membrane modules (each about 20-inch length and 35-m^2 membrane area) for testing with simulated flue gas at OSU and subsequently with actual flue gas at NCCC (Wilsonville, Alabama), using the skid to capture the CO_2 (at 60 to 90%) with at least 95% CO_2 purity (Figure 2). The prototype membrane modules will be in commercial spiral-wound configuration with a minimal pressure drop (less than 0.103 bar/meter or 1.5 psi/meter).

program area:
Point Source Carbon Capture

ending scale:
Bench Scale

application:
Post-Combustion Power Generation PSC

key technology:
Membranes

project focus:
Polymeric Composite Membranes

participant:
The Ohio State University

project number:
FE00031731

predecessor project:
FE0026919

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partners:
Gas Technology Institute; National Carbon Capture Center; American Electric Power

start date:
07.01.2019

percent complete:
70%

After the skid testing, OSU will determine the identity and concentration of any possible contaminates on the membrane via laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS), Fourier transform infrared spectroscopy (FTIR), X-ray photoemission spectrometry (XPS), and nuclear magnetic resonance spectroscopy (NMR). Economic data is shown in Table 2.

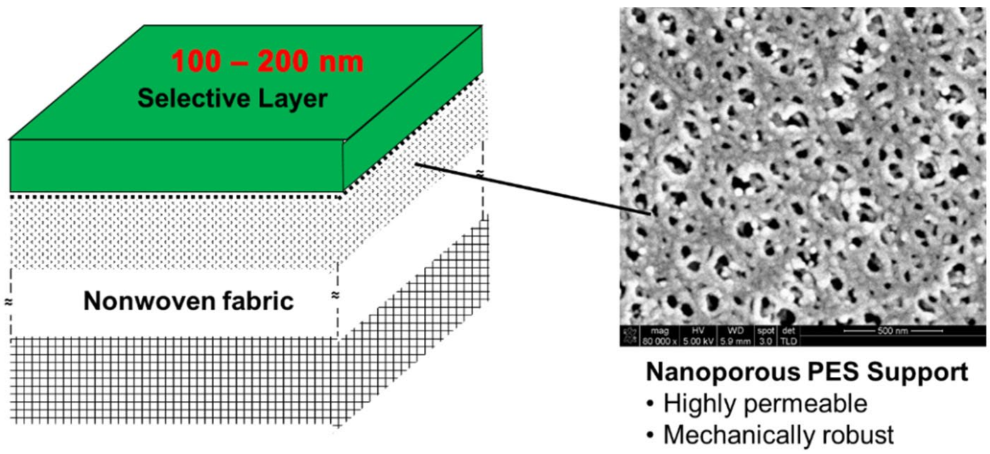

Figure 1: Schematic of thin-film composite membrane consisting of an amine-containing cover layer on a nanoporous PES support.

TABLE 1: MEMBRANE PROCESS PARAMETERS

Materials Properties	Units	Current R&D Value	Target R&D Value
Materials of Fabrication for Selective Layer	—	amine-containing polymer	
Materials of Fabrication for Support Layer	—	polyethersulfone on non-woven fabric	
Nominal Thickness of Selective Layer	nm	170	150–250
Membrane Geometry	—	flat sheet	flat sheet
Max Trans-Membrane Pressure	bar	4	4
Hours Tested without Significant Degradation	—	2,500 hours	500 hours
Manufacturing Cost for Membrane Material	$/m^2	20	20
Membrane Performance			
Temperature	°C	57–77°C	57–77°C
CO_2 Pressure Normalized Flux	GPU	3,670 GPU	>3,300 GPU
CO_2/H_2O Selectivity	—	1	1
CO_2/N_2 Selectivity	—	155	>140
Proposed Module Design		*(for equipment developers)*	
Flow Arrangement	—	spiral-wound	
Packing Density	m^2/m^3	about 2,000	
Permeate-Side Fluid	—	vacuum or retentate recycle	
Flue Gas Flowrate	ft^3/min	10.3	
CO_2 Recovery, Purity, and Pressure	%/%/bar	>60%–90%, >95%, 1 bar	
Pressure Drops Feed/Permeate Side	psi/m	1.5/1.5	
Estimated Module Cost of Manufacturing and Installation	$\frac{\$}{m^2}$	32.3	

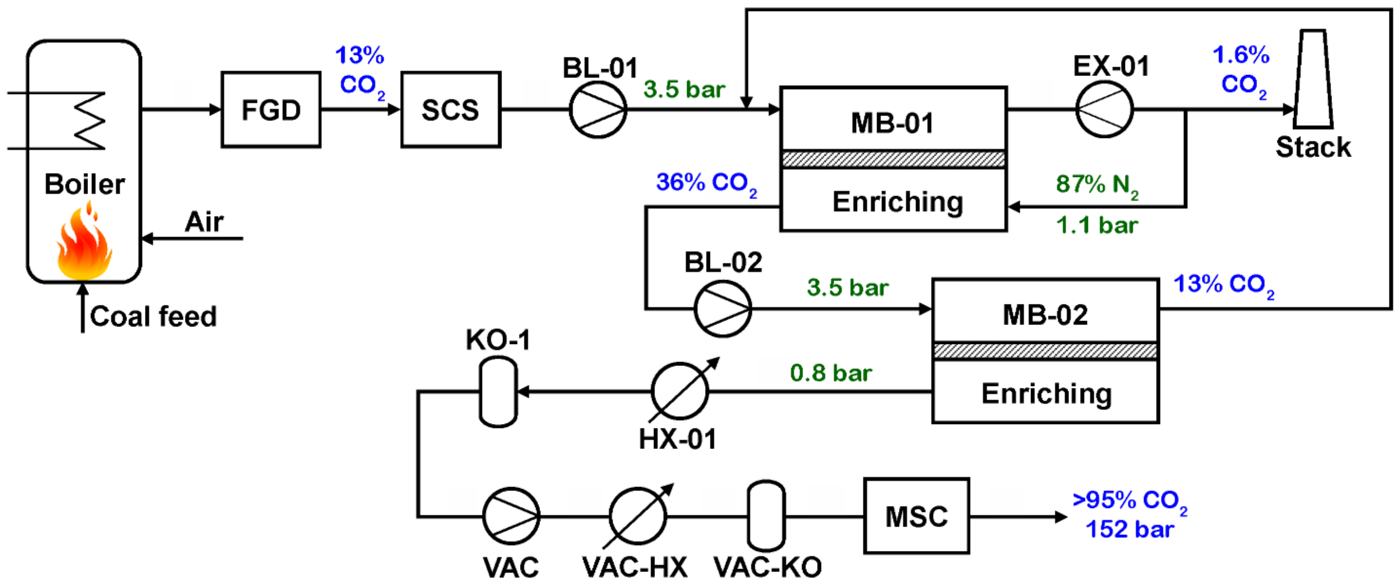

Figure 2: Process concept for two-stage membrane system. Initialisms: FGD = flue gas desulfurization; SCS = SO_2 caustic scrubber; BL = blower; MB = membrane; EX = turbo expander; HX = heat exchanger; KO = knockout; VAC = vacuum pump; MSC = multi-stage compressor.

TABLE 2: POWER PLANT CARBON CAPTURE ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured	\$/tonne CO_2	39.3	40.0
Cost of Carbon Avoided	\$/tonne CO_2	53.9	55.2
Capital Expenditures	\$/MWhr	21.4	22.0
Operating Expenditures	\$/MWhr	11.4	12.0
Levelized Cost of Electricity	\$/MWhr	100.5	101.0

Definitions:

Membrane Geometry – Flat discs or sheets, hollow fibers, tubes, etc.

Pressure Normalized Flux – For materials that display a linear dependence of flux on partial pressure differential, this is equivalent to the membrane's permeance.

GPU – Gas permeation unit, which is equivalent to 10^{-6} cm^3 (1 atmosphere [atm], 0°C)/cm^2/s/cm Hg). For non-linear materials, the dimensional units reported should be based on flux measured in cm^3 (1 atm, 0°C)/cm^2/s with pressures measured in cm Hg. Note: 1 GPU = 3.3464 × 10^{-10} kg mol/m^2-s-kPa (SI units).

Type of Measurement – Either mixed or pure gas measurements; target permeance and selectivities should be for mixture of gases found in desulfurized flue gas.

Flow Arrangement – Typical gas-separation module designs include spiral-wound sheets, hollow-fiber bundles, shell-and-tube, and plate-and-frame, which result in either cocurrent, countercurrent, crossflow arrangements, or some complex combination of these.

Packing Density – Ratio of the active surface area of the membrane to the volume of the module.

Permeate-Side Fluid – Either vacuum or a sweep gas.

Estimated Cost – Basis is m^2 membrane area.

Flue Gas Assumptions – Unless noted, flue gas pressure, temperature, and composition leaving the flue gas desulfurization (FGD) unit (wet basis) should be assumed as:

Pressure	Temperature	Composition						
		vol%					ppmv	
psia	°F	CO_2	H_2O	N_2	O_2	Ar	SO_X	NO_X
14.7	135	13.17	17.25	66.44	2.34	0.80	42	74

Other Parameter Descriptions:

Membrane Permeation Mechanism – Facilitated transport for amine-containing selective layer.

Contaminant Resistance – Resist up to 3 parts per million volume (ppmv) sulfur dioxide (SO_2).

Flue Gas Pretreatment Requirements – Removal of particulates and SO_2 polishing to 3 ppmv.

Membrane Replacement Requirements – Estimated approximately four years.

Waste Streams Generated – Nitrogen with water (H_2O), about 1% CO_2, and minor impurities.

Process Design Concept – See Figure 2.

technology advantages

This membrane consists of a thin selective polymer layer on a polymer support so that it can be made efficiently in continuous roll-to-roll manufacturing. The membrane offers high CO_2/N_2 selectivity at greater than 57°C, which does not require flue gas cooling or cryogenic distillation. The simplicity of this membrane design offers a low cost for the membrane element in commercial spiral-wound configurations. If successful, the process can achieve less than $30/tonne CO_2 for 70% recovery.

R&D challenges

- Membrane stability in the presence of high-level contaminants, such as SO_2 and nitrogen oxide (NO_X).
- Design and fabrication of prototype spiral-wound membrane module with 8-inch diameter.
- Requires two membrane stages.

status

A highly permeable PES support with bicontinuous morphology was developed. The polymer support exhibited a CO_2 permeance of 310,000 GPU, 13 times more permeable than the project target. A thin-film composite membrane containing a novel CO_2 carrier was synthesized and scaled up to 21-inch width. The prototype membrane demonstrated a CO_2 permeance of 3,670 GPU and a CO_2/N_2 selectivity of 155 with simulated flue gas. The scaled-up membrane was successfully rolled into a prototype spiral-wound (SW) membrane module with 8-inch diameter and 35-m^2 membrane area. The SW module demonstrated a CO_2/N_2 separation performance on par with the flat-sheet membrane.

available reports/technical papers/presentations

Ho, W.; Han, Y.; Lin, L-C., "Novel Transformational Membranes and Process for CO_2 Capture from Flue Gas." National Energy Technology Laboratory. Carbon Management and Natural Gas & Oil Research Project Review Meeting. Pittsburgh, PA. August 2021. *https://netl.doe.gov/sites/default/files/netl-file/21CMOG_PSC_Ho_0.pdf*.

R. Pang, K. K. Chen, Y. Han, and W. S. W. Ho, "Highly Permeable Polyethersulfone Substrates with Bicontinuous Structure for Composite Membranes in CO_2/N_2 Separation", Journal of Membrane Science, 612, 118443 (2020).

Ho, W., Han, Y., "Novel Transformational Membranes and Process for CO_2 Capture from Flue Gas," poster presented at the 2019 NETL CO_2 Capture Technology Meeting, Pittsburgh, PA, August 2019.

Ho, W., Han, Y., "Novel Transformational Membranes and Process for CO_2 Capture from Flue Gas," presented at the 2019 NETL CO_2 Capture Technology Meeting, Pittsburgh, PA, August 2019. *https://netl.doe.gov/sites/default/files/netl-file/Y-Han-OSU-Transformational-Membrane.pdf*.