Novel CO$_2$-Selective Membranes for CO$_2$ Capture from <1% CO$_2$ Sources

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Project Objective

• Develop a novel cost-effective membrane and design of membrane modules that capture CO₂ from <1% CO₂ sources
  • 90% CO₂ Capture
  • 95% CO₂ Purity
3-Budget Period Project

• BP1: 03/01/2016 – 02/28/2017
  – Conduct laboratory-scale membrane synthesis, characterization and transport performance studies
  – Carry out high-level preliminary techno-economic analysis

• BP2: 03/01/2017 – 02/28/2018
  – Continue laboratory-scale membrane synthesis, characterization and transport performance studies
  – Fabricate larger size membrane (~ 14” by > 20’)
  – Fabricate, evaluate and down-select from plate-and-frame and spiral-wound membrane modules
  – Update techno-economic analysis performed in BP 1

• BP3: 03/01/2018 – 02/28/2019
  – Fabricate 3 pilot membrane modules
  – Test modules with <1% CO₂ simulated gas mixture
  – Update techno-economic analysis

• Integrated program with fundamental studies, applied research, synthesis, characterization and transport studies, and high-level techno-economic analysis
Funding and Performance Dates

• Total Budget: 03/01/2016 – 02/28/2019
  DOE: $1,248,278; OSU: $372,864 (23% cost share)

• BP1: 03/01/2016 – 02/28/2017
  DOE: $407,616; OSU: $121,756

• BP2: 03/01/2017 – 02/28/2018
  DOE: $419,628; OSU: $125,344

• BP3: 03/01/2018 – 02/28/2019
  DOE: $421,034; OSU: $125,764
Process Proposed for CO₂ Capture from <1% CO₂ Sources

- Proposed membrane process does not require cryogenic distillation (compared to competition)

Diagram:

- <1% CO₂ Feed Gas
- Membrane Module 1 (0.2 atm)
- Treated Gas <0.1% CO₂
- Membrane Module 2 (0.2 atm)
- ~20% CO₂
- Vacuum Pump 1
- Vacuum Pump 2
- Compressor
- >95% CO₂ 152 bar
Location of Proposed Technology in Coal-fired Power Plant

- Pulverized Coal Boiler
- Primary Air Fans
- Secondary Air Fans
- Coal Feed
- Feed Water
- Bottom Ash
- Steam to Turbine
- Induced Draft Fans
- Baghouse
- FGD
- Primary CO₂ Capture System
- <1% CO₂ Feed Gas
- <0.1% CO₂ Treated Gas
- Membrane Module 1
- Membrane Module 2
- Vacuum Pump 1
- Vacuum Pump 2
- Compressor
- 152 bar
- >95% CO₂
- <0.1% CO₂
Selective Amine Polymer Layer on Polymer Support

Simplicity of Membrane for Low Cost

Selective amine polymer layer
(170 nm, dense layer)

Polymer support
(~30 μm, Ø ~40 nm)

Nonwoven fabric backing
(~120 μm)
Selective Amine Polymer Layer on Polymer Support

- Selective Amine Polymer Layer
  - Facilitated transport of CO₂ via reaction with amine
    \[
    \text{CO}_2 + \text{R-NH}_2 + \text{H}_2\text{O} \rightleftharpoons \text{R-NH}_3^+ + \text{HCO}_3^-
    \]
  - Facilitated transport = flux augmentation via reaction
  - High CO₂ permeance and CO₂/N₂ selectivity
BP1 Accomplishments

• Improved 14”-wide PES Polymer Support Fabricated with Continuous Machine
  – 13900 GPU CO₂ permeance obtained

• Composite Membrane Synthesized in Lab
  – Elucidated carrier saturation phenomenon
  – 980 GPU with 170 CO₂/N₂ selectivity obtained at 57°C from lab test using 1% CO₂ concentration feed gas
  + 780 GPU with 150 CO₂/N₂ selectivity obtained using 20% CO₂ feed

• High-Level Techno-economic Analysis Showed Capture Cost of ~$305/tonne CO₂ (in 2011 $)
  – ~22% increase in COE

• 2 PCT (Patent Cooperation Treaty) Applications Filed for New Membrane Composition and Process
BP2 Accomplishments

• Improved 14”-wide PES Support Fabricated with Continuous Machine (22500 GPU)

• Pilot Composite Membranes Synthesized
  – Membrane scaled up to 14” by roll-to-roll successfully

• Plate-and-Frame and Spiral-Wound (SW) Modules Fabricated
  – Both showed ~1500 GPU with ~220 selectivity at 57°C
    + Similar results to scale-up flat-sheet membrane
  – Both gave similar and acceptable pressure drop results
  – Down-selected to SW module for ease of manufacture

• Good Module Stability (3 ppm SO₂ & 7% O₂) – 1700 h

• High-Level Techno-economic Analysis Showed Capture Cost of $268/tonne CO₂ (in 2011 $)
  – ~19% increase in COE

• 8 Patent Applications Filed (New compositions & processes)
• Optimized Composite Membranes Synthesized
  – Membrane scaled up to 14” by roll-to-roll successfully
  – ~1930 GPU with 220 CO\textsubscript{2}/N\textsubscript{2} selectivity obtained at 67°C using 1% CO\textsubscript{2} conc. feed gas – similar to lab-scale results
  – ~1450 GPU & 180 Selectivity for 20% CO\textsubscript{2} conc. feed gas

• 8 Spiral-Wound (SW) Modules Fabricated
  – All showed ~1930 GPU with ~220 selectivity at 67°C using 1% CO\textsubscript{2} conc. simulated residual flue gas
    + ~1450 GPU & 180 Selectivity for 20% CO\textsubscript{2} conc. feed gas
    + Similar results to scale-up flat-sheet membrane
    + 1900-h good module stability obtained (3 ppm SO\textsubscript{2} & 7% O\textsubscript{2})
  – All gave similar and acceptable pressure drop results

• SW Module Test at NCCC (Related effort conducted under a separate ODSA-funded project)
  – Module showed ~1450 GPU with ~180 selectivity at 67°C
    + Similar results to scale-up flat-sheet membrane and modules using simulated flue gas
  – 500-hour good module stability obtained
  – Similar and acceptable pressure drop results obtained
Scale-up of PES Support and Composite Membrane

Continuous Membrane Fabrication Machine at OSU
Successful Continuous Fabrication of Affordable PES Support

SEM Analysis of 14-inch PES Support

Ave. pore size = 32.5 nm, Porosity = 12.5%

- Optimal pore size identified to reduce penetration during coating
- Hydrophilic additives improved adhesion & open porous morphology
Composite Membrane Synthesized
Selective Amine Polymer Layer on PES Support

Selective layer = 165 nm
Significant Membrane Performance Improvement Achieved

CO₂/N₂ selectivity vs CO₂ permeance (GPU)

- BP1-Q1
- BP1-Q2
- BP1-Q3
- BP1-Q4
- BP2-Q1
- BP2-Q2
- BP2-Q3
- BP2-Q4
- BP3-Q1
- BP3-Q2

Conditions:
- 57°C
- 1 atm feed
- Argon sweep
- 57°C
- 4 atm feed
- 0.2 atm vacuum
- 67°C
- 4 atm feed
- 0.3 atm vacuum

Continued performance improvement
Spiral-Wound Membrane Module Fabricated

Element Rolling Machine

Spiral-Wound Membrane Element

Membrane Module

Vacuum Permeate

Feed Outlet

Feed Inlet
Good SW Module Stability Obtained

Simulated Flue Gas
17.1% CO₂
68.5% N₂
7.4% H₂O
7% O₂
3 ppm SO₂

Simulated Residual Flue Gas
1% CO₂
84.6% N₂
7.4% H₂O
7% O₂
3 ppm SO₂

67°C
4 atm Feed

14,000 cm² Membrane Area

CO₂/N₂ selectivity

CO₂ permeance (GPU)

Time (hour)

17.1% CO₂
68.5% N₂
7.4% H₂O
7% O₂
3 ppm SO₂

67°C
4 atm Feed

Simulated Flue Gas
17.1% CO₂
68.5% N₂
7.4% H₂O
7% O₂
3 ppm SO₂

67°C
4 atm Feed

Simulated Residual Flue Gas
1% CO₂
84.6% N₂
7.4% H₂O
7% O₂
3 ppm SO₂

67°C
4 atm Feed

14,000 cm² Membrane Area
Good SW Module Stability at NCCC

Related effort conducted under a separate ODSA-funded project

14,000 cm² Membrane Area
High-Level Techno-Economic Calculations

• Basis: Membrane Results at 67°C
  • 1930 GPU & 220 Selectivity for 1% CO₂ concentration feed gas
  • 1450 GPU & 180 Selectivity for 20% CO₂ conc. feed gas
  • Include Membrane Module Installation Cost and 20% Process Contingency
  • In 2011 dollar: NETL Case 12 of Updated Costs (June 2011 Basis) for Selected Bituminous Baseline Cases

• Calculated Cost Results
  • 32.0 tonne/h of CO₂ captured from 1% CO₂ source
  • $91 million bare equipment cost
    ➢ Membrane 22%, blowers and vacuum pumps 73%, others 5%
  • 1.56 ¢/kWh (1.12 ¢/kWh capital cost, 0.21 ¢/kWh fixed cost, 0.20 ¢/kWh variable cost, and 0.03 ¢/kWh T&S cost)
    ➢ COE = 8.09 ¢/kWh for 550 MW supercritical pulverized coal power plant
  • $266/tonne capture cost ($15.6/MWh × 550 MW/(32.0 tonne/h))
  • 19.1% Increase in COE (1.56/8.09 = 19.1%)
Plans for Future Testing/Development

• Remaining BP3
  – Test new modules with <1% CO₂ simulated gas mixture
  – Update techno-economic analysis

• Will also complete testing of 3 pilot membrane modules at NCCC under related ODSA-funded project
  – One module for 500-hour testing
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– Also serving as cost share to ODSA project

ODSA (Ohio Development Services Agency)
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– AEP cost sharing
– NCCC membrane module testing