Development and Bench-Scale Testing of a Novel Biphasic Solvent-Enabled Absorption Process for Post-Combustion Carbon Capture

primary project goal

The University of Illinois at Urbana-Champaign (UIUC) advances the development of a novel biphasic carbon dioxide (CO_2) absorption process (BiCAP) and validates its technical advantages by testing an integrated system at a 40-kilowatt-electric (kWe) bench scale with actual coal-derived flue gas. The novel water-lean biphasic solvents have previously demonstrated (FE0026434) the desired vapor-liquid equilibrium (VLE) behavior, rapid absorption kinetics, and high stability in lab-scale characterization experiments, and individual major process steps have been tested on the lab-scale equipment or assessed by modeling studies. This project moves the technology development forward via fully integrated bench-scale testing in a relevant flue gas environment.

technical goals

- Develop process simulations using an Aspen Plus model to determine the optimal process configuration and operating conditions.
- Investigate biphasic solvent losses, emission control, and reclamation of the degradation products.
- Design, fabricate, and test a 40-kWe integrated bench-scale biphasic solvent-based capture unit with simulated flue gas. A subsequent test will use a flue gas slipstream from a coal-fired power plant.
- Assess the techno-economic performance of the technology integrated into a net 650-megawatt-electric (MWe) coal-fired power plant.
- Analyze technology gaps and potential environmental, health, and safety (EH&S) risks to advance the technology toward further scale-up and commercialization.

technical content

The BiCAP utilizes biphasic solvents, which are water-lean solvent blends, that can form and develop dual liquid phases, with the absorbed CO_2 highly enriched in one of the phases and lean solvent in the other. The phase transition behavior of a biphasic solvent is illustrated in Figure 1. The process features multiple stages of liquid-liquid phase separation (LLPS) during CO_2 absorption to maximize the CO_2 absorption kinetics and minimize the increase in solvent viscosity.

program area:
Point Source Carbon Capture

ending scale:
Bench Scale

application:
Post-Combustion Power Generation PSC

key technology:
Solvents

project focus:
Biphasic Solvents for Post-Combustion CO_2 Absorption in Coal Flue Gas

participant:
University of Illinois at Urbana-Champaign

project number:
FE0031600

predecessor project:
FE0026434

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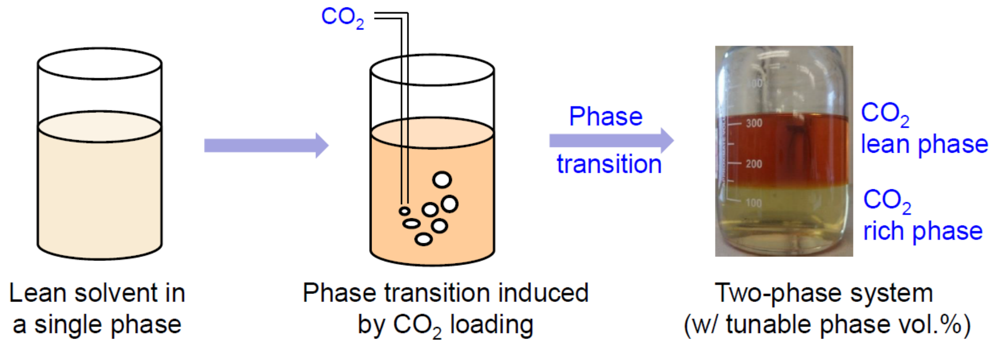

Figure 1: Phase transition behavior of a biphasic solvent.

A schematic diagram of the BiCAP is shown in Figure 2. The flue gas, after the cooling and sulfur dioxide (SO_2) polishing stages, enters the absorption column, which contains multiple stages of packed beds, and the CO_2 is absorbed into a biphasic solvent. At each stage, upon CO_2 loading, the biphasic solvent undergoes a phase transition and forms dual liquid phases. The heavy, CO_2-enriched phase is separated and pumped to a rich solvent tank. The CO_2-lean phase then flows via gravity to a heat exchanger to reduce the solvent temperature before entering the next stage of the packed bed. At the last stage, the solvent exiting the absorber is sent to an LLPS tank, in which the CO_2-enriched phase is pumped into the rich solvent tank. Both the hot and cold rich solvents are fed to a flash/stripper to remove CO_2, while the CO_2-lean phase is mixed with the regenerated solvent from the CO_2 stripper before recycling to the absorber. The CO_2 product streams from both the flash and stripper are cooled and compressed.

TABLE 1: SOLVENT PROCESS PARAMETERS

Pure Solvent	Units	Current R&D Value	Target R&D Value
Molecular Weight	mol^{-1}	60-240	<230
Normal Boiling Point	°C	140-300	>140
Normal Freezing Point	°C	-30 to 110	<20
Vapor Pressure @ 20 °C	bar	1×10^{-5} to 4×10^{-3}	$<1.0 \times 10^{-3}$
Manufacturing Cost for Solvent	$/kg	3-10	<15
Working Solution			
Concentration	kg/kg	0.6-0.8	>0.5
Specific Gravity (15 °C/15 °C)	-	~1.0	0.9–1.4
Specific Heat Capacity @ STP	kJ/kg-K	2.5–3.5	<3.5
Viscosity @ STP	cP	2-15	<20
Absorption			
Pressure*	bar	0.05 (equilibrium P_{CO2} at absorber bottom)	<0.07
Temperature	°C	40	30–50
Equilibrium CO_2 Loading	mol/mol	0.375-0.625 (0.7-1.0 in CO_2-enriched phase)	>0.375
Heat of Absorption	kJ/mol CO_2	65-85	~75
Solution Viscosity	cP	5–10/30–50 (upper/lower phases)	<50 (CO_2-enriched phase)
Desorption			
Flash			
Pressure**	bar	4-9 (5-11 in total)	≥7 (10 in total)
Temperature	°C	100-140	<140

Equilibrium CO_2 Loading	mol/mol	0.4-0.7	
Stripping (lean solution)			
Pressure***	bar	2-5 (3-7 in total)	≥3 (≥4 in total)
Temperature	°C	120-150	<150
Equilibrium CO_2 Loading	mol/mol	0.05-0.35	<0.35
Heat of Desorption (flash + stripping)	kJ/mol CO_2	65-85	~75
Proposed Module Design		*(for equipment developers)*	
Flue Gas Flowrate	kg/hr	not available	
CO_2 Recovery, Purity, and Pressure	%/%/bar	90% / >99% / >4	
Absorber Pressure Drop	Bar	0.14	
Estimated Absorber/Stripper Cost of Manufacturing and Installation	$\frac{\$}{kg/hr}$	not available	

*CO_2 partial pressure in the flue gas; **CO_2 partial pressure exiting flash; ***CO_2 partial pressure exiting stripper.

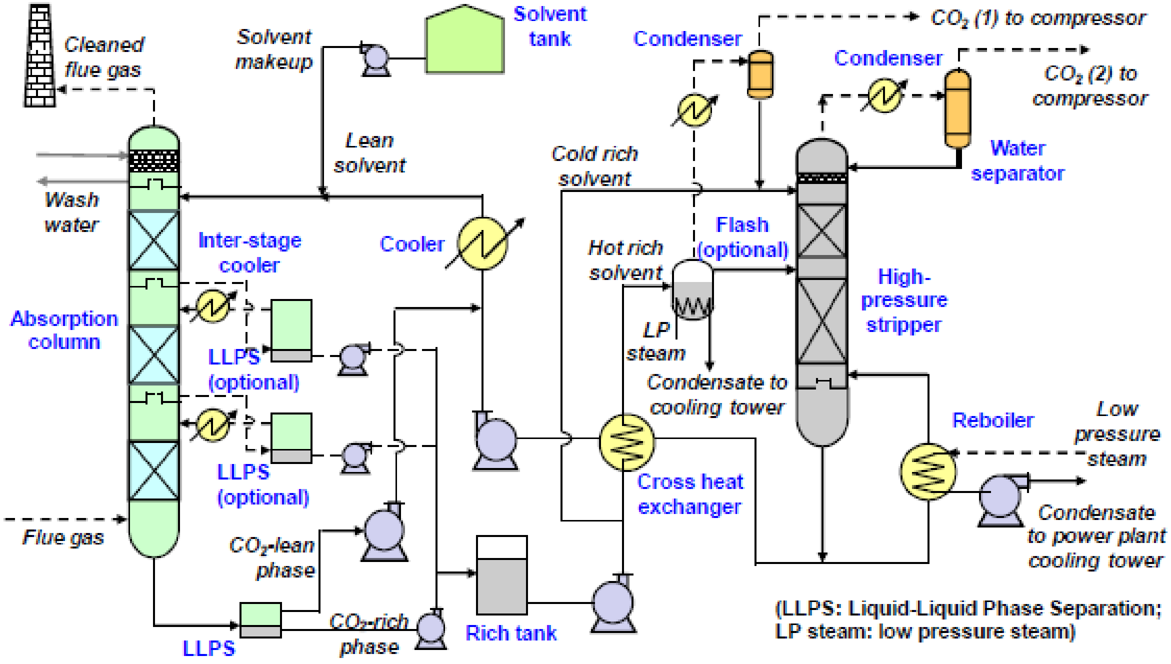

Figure 2: Schematic diagram of the BiCAP with multiple stages of LLPS.

Key features of the BiCAP include: (1) a unique process configuration of multi-stage CO_2 absorption and phase transition allows continual separation and removal of the CO_2-enriched liquid phase, maintaining rapid kinetics and low solvent viscosity throughout CO_2 absorption; (2) only the CO_2-enriched liquid phase is used for CO_2 desorption, thus lowering the mass flow of solvent required for regeneration; (3) a combination of flash and CO_2 stripping operations allows the high pressure of CO_2 desorption to further improve the energy efficiency; and (4) a portion of cold feed stream enters the stripping column, bypassing the cross heat exchanger, further reducing the stripping heat requirement.

In a previous U.S. Department of Energy (DOE)-funded project (FE0026434), the BiCAP was tested at laboratory scale (10 kWe) and exhibited a 34% reduction in parasitic power requirements and twice the CO_2 working capacity for desorption when compared with a process using the amine-based solvent, monoethanolamine (MEA). After determining the optimal process configuration and operating conditions, the team has designed and fabricated the 40-kWe integrated bench-scale capture unit. Parametric testing for two of the best-performing biphasic solvents identified from previous research (FE0026434) has been conducted with simulated flue gas at UIUC's Abbott power plant. One selected biphasic solvent is being further evaluated with a slipstream of coal-derived flue gas at the power plant. The team will use the test results to prepare a techno-economic analysis (TEA), as well as an analysis of the technology gaps and potential EH&S

risks, to advance the technology for further scale-up and commercialization. The system-wide results of this analysis are shown in Table 2.

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	40.4	30.0
Cost of Carbon Avoided	\$/tonne CO_2	50.7	37.7
Capital Expenditures	\$/MWhr	60.4	51.9
Operating Expenditures	\$/MWhr	56.1	55.5
Cost of Electricity	\$/MWhr	116.5	107.4

*Estimated based on DOE/NETL baseline Cases 11 and 12, Revision 2a, September 2013, DOE/NETL-2010/1397 and Updated Costs (June 2011 Basis), August 2012, DOE/NETL-341/082312.

Definitions:

Cost of Carbon Captured – Projected cost of capture per mass of CO_2 captured under expected operating conditions.

Cost of Carbon Avoided – Projected cost of capture per mass of CO_2 avoided under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per unit of energy produced.

Operating Expenditures – Projected operating expenditures in dollars per unit of energy produced.

Cost of Electricity – Projected cost of electricity per unit of energy produced under expected operating conditions.

STP – Standard temperature and pressure (15°C, 1 atmosphere [atm]).

Pure Solvent – Chemical agent(s), working alone or as a component of a working solution, responsible for enhanced CO_2 absorption (e.g., MEA in an aqueous solution).

Manufacturing Cost for Solvent – “Current” is market price of chemical, if applicable; “Target” is estimated manufacturing cost for new solvents, or the estimated cost of bulk manufacturing for existing solvents.

Working Solution – The solute-free (i.e., CO_2-free) liquid solution used as the working solvent in the absorption/desorption process (e.g., the liquid mixture of MEA and water).

Absorption – The conditions of interest for absorption are those that prevail at maximum solvent loading, which typically occurs at the bottom of the absorption column. These may be assumed to be 1 atm total flue gas pressure (corresponding to a CO_2 partial pressure of 0.13 bar) and 40°C; however, measured data at other conditions are preferable to estimated data.

Desorption – The conditions of interest for desorption are those that prevail at minimum solvent loading, which typically occurs at the bottom of the desorption column. Operating pressure and temperature for the desorber/stripper are process-dependent (e.g., an MEA-based absorption system has a typical CO_2 partial pressure of 1.8 bar and a reboiler temperature of 120°C). Measured data at other conditions are preferable to estimated data.

Pressure – The pressure of CO_2 in equilibrium with the solution. If the vapor phase is pure CO_2, this is the total pressure; if it is a mixture of gases, this is the partial pressure of CO_2. Note that for a typical pulverized coal power plant, the total pressure of the flue gas is about 1 atm and the concentration of CO_2 is about 13.2%. Therefore, the partial pressure of CO_2 is roughly 0.132 atm or 0.130 bar.

Concentration – Mass fraction of pure solvent in working solution.

Loading – The basis for CO_2 loadings is moles of pure solvent.

Estimated Cost – Basis is kg/hr of CO_2 in CO_2-rich product gas; assuming targets are met.

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

		Composition						
Pressure	**Temperature**	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:

Chemical/Physical Solvent Mechanism – The developed solvent belongs to a new class of biphasic solvents. The solvent is a blend of amines or the like and is a water-lean system containing less than 30 wt% water. The solvent absorbs CO_2 through chemical reactions between amines and CO_2. The solvent undergoes a phase transition to form dual liquid phases based on the difference of hydrophobicity between different species.

Solvent Contaminant Resistance – The developed biphasic solvent is highly resistant to oxygen and heat. Experiments revealed that the oxidative degradation of the biphasic solvent was eight times slower than the benchmark MEA under similar absorption conditions and its thermal stability at 150°C was comparable to the benchmark MEA at 120°C.

Solvent Foaming Tendency – No foaming issue was observed for the biphasic solvent, either in a gas bubbler tested continually for two weeks or in a laboratory absorption column operated intermittently for several months.

Flue Gas Pretreatment Requirements – The flue gas leaving the FGD needs be further polished to reduce the content of SO_2 below 10 parts per million volume (ppmv).

Solvent Makeup Requirements – Laboratory solvent stability experiments indicate that the makeup requirement of the biphasic solvent is lower than the benchmark MEA (i.e., less than 2 kg/ton CO_2 captured).

Waste Streams Generated – Waste streams from the BiCAP are similar to those from amine-based processes, including flue gas condensate, water wash blowdown, cooling water blowdown, heat stable salts, spent solvent wastes, and spent solvent reclamation materials (e.g., activated carbon).

Process Design Concept – See Figure 2.

technology advantages

- BiCAP maintains rapid kinetics throughout the CO_2 absorption process and thus can reduce the footprint and cost of absorption equipment compared with either MEA or other biphasic solvent-based processes.
- BiCAP can maintain the solvent at a lower viscosity and thus retain rapid mass transfer in the absorber, potentially increasing the CO_2 working capacity of the solvent and reducing the footprint and capital cost of the absorber.
- The combination of flash and stripping operations achieves high-pressure CO_2 desorption and thus lowers the energy use for CO_2 separation and compression.
- BiCAP desorption configuration with a cold rich solvent stream directly fed to the top of the stripper, in addition to the main rich solvent feed, results in reduced water vapor in the CO_2 stream and thus further reduces the stripping heat duty.
- The energy efficiency advantages of the BiCAP coupled with reduced equipment sizes when scaled-up for commercial systems leads to reductions in both capital and operating expenses compared to the benchmark MEA process.

R&D challenges

- Developing methods for controlling solvent losses caused by volatility of the selected biphasic solvents.
- Identifying the optimal process design and operating conditions for the proposed BiCAP.
- Developing methods for solvent reclamation with high efficiency and low environmental impact.
- Demonstrating reliable operation and stable performance of the bench-scale unit in an actual power plant environment.

status

Parametric testing for BiCAP1 and BiCAP2 biphasic solvents and the benchmark MEA using synthetic flue gas have been completed. Slipstream testing with real flue gas from the Abbott power plant started in late January 2022 and is currently underway.

available reports/technical papers/presentations

Lu, Y., 2021, “Development and Bench-Scale Testing of a Novel Biphasic Solvent-Enabled Absorption Process for Post-Combustion Carbon Capture.” Presented at the 2021 NETL/DOE Carbon Management and Natural Gas & Oil Research Project Review Meeting. Pittsburgh, PA. *https://netl.doe.gov/sites/default/files/netl-file/21CMOG_PSC_Lu.pdf*.

Nielsen, P. et al., 2021, "Modeling, Design, and Testing of a Novel Biphasic Solvent-Enabled Absorption System for Post-Combustion Carbon Capture," In the Proceedings of the 15th Greenhouse Gas Control Technologies Conference, Virtual. *https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3812737.*

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Lu, Y., 2018, “Development and Bench-Scale Testing of a Novel Biphasic Solvent-Enabled Absorption Process for Post-Combustion Carbon Capture.” kickoff meeting presentation. *https://netl.doe.gov/projects/plp-download.aspx?id=10472&filename=Development+and+Bench-Scale+Testing+of+a+Novel+Biphasic+Solvent-Enabled+Absorption+Process+for+Post-Combustion+Carbon+Capture.pdf*.

Du, Y. et al., 2018, “A Novel Water-Lean Biphasic Solvent System for CO_2 Capture,” presented at the 4th University of Texas Conference on Carbon Capture and Storage, Austin, TX.

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Du, Y. et al., 2017“A Novel Biphasic Solvent for Post-Combustion CO_2 Capture,” presented at the 4th Post-Combustion Capture Conference, Birmingham, AL.

Lu, Y., 2017, “Development of a Novel Biphasic CO_2 Absorption Process with Multiple Stages of Liquid-Liquid Phase Separation for Post-Combustion Carbon Capture,” presented at the 2017 NETL CO_2 Capture Technology Project Review Meeting, Pittsburgh, PA.

Lu, H. et al., 2017, “Bench-Scale Testing of CO_2 Absorption with a Biphasic Solvent in an Absorption Column with Staged Phase Separations,” presented at the 2017 Carbon Capture, Utilization & Storage Conference, Chicago, IL.

Lu, Y., 2017, “Development of a Novel Biphasic CO_2 Absorption Process with Multiple Stages of Liquid-Liquid Phase Separation for Post-Combustion Carbon Capture,” Budget Period 1 Project Review Meeting presentation, Pittsburgh, PA.

Lu, Y., 2016, “Development of a Novel Biphasic CO_2 Absorption Process with Multiple Stages of Liquid-Liquid Phase Separation for Post-Combustion Carbon Capture,” presented at the 2016 NETL CO_2 Capture Technology Meeting, Pittsburgh, PA. *https://www.netl.doe.gov/sites/default/files/event-proceedings/2016/c02%20cap%20review/4-Thursday/Y-Lu-ISGS-Biphasic-CO2-Absorption-Process.pdf*.

Ye, Q. et al., 2015, “Screening and Evaluation of Novel Biphasic Solvents for Energy-Efficient Post-Combustion CO_2 Capture,” International Journal of Greenhouse Gas Control, Volume 39, pp. 205-214.