Fog- and Froth-Based Post-Combustion CO_2 Capture in Fossil Fuel Power Plants

primary project goal

The University of Kentucky Center for Applied Energy Research (UKy-CAER) is developing a transformational compact carbon dioxide (CO_2) absorber with internal fog and froth formation, for use in a solvent-based post-combustion CO_2 capture process, to surmount the limitations of packed-bed CO_2 absorption columns and to lower the capital cost of carbon capture.

technical goals

- Design and fabricate a compact absorber with internal fog and froth sections.
- Develop and finalize the atomizing nozzle and froth-generating screens and operation conditions for fog and froth formation and destruction.
- Evaluate the fog and froth sections performance in a cold test unit.
- Complete a bench-scale parametric testing campaign followed by a long-term campaign to assess performance and investigate the effects of solvent degradation on fog and froth formation.
- Prepare a techno-economic analysis (TEA) and environmental, health, and safety (EH&S) assessment.

technical content

UKy-CAER is developing an open-tower compact absorber with internal fog and froth for enhanced solvent-based CO_2 capture, as shown in Figure 1. In the process, the flue gas enters the bottom of the absorber and contacts the solvent in a counter-current flow through a section containing structured packing, capturing approximately 30% of the total CO_2 before passing through a riser to the top of the fog/froth capture section. In this section, the gas first contacts a lean amine mist in a co-current flow in a temperature-controlled environment, with up to five times the liquid/gas contact area. Both the gas and liquid exiting from the fog section are forced through froth-generating and -propagating screens in the froth section. Here, also a temperature-controlled environment, the mass transfer is increased because a thin (target of ~10 μm) liquid film virtually eliminates the CO_2-amine diffusion resistance that typically impedes mass transfer in the conventional capture technologies. By greatly increasing the liquid/gas contact area and minimizing the diffusion resistance, the absorber column size can be reduced by up to 70% compared to a standard absorber design. Combining this fog/froth process with other UKy-CAER CO_2 capture technologies could potentially reduce the CO_2 capture capital cost by 57%.

program area:
Point Source Carbon Capture

ending scale:
Bench Scale

application:
Post-Combustion Power Generation PSC

key technology:
Solvents

project focus:
High Contact Compact Absorber

participant:
University of Kentucky Center for Applied Energy Research

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FE0031733

predecessor projects:
N/A

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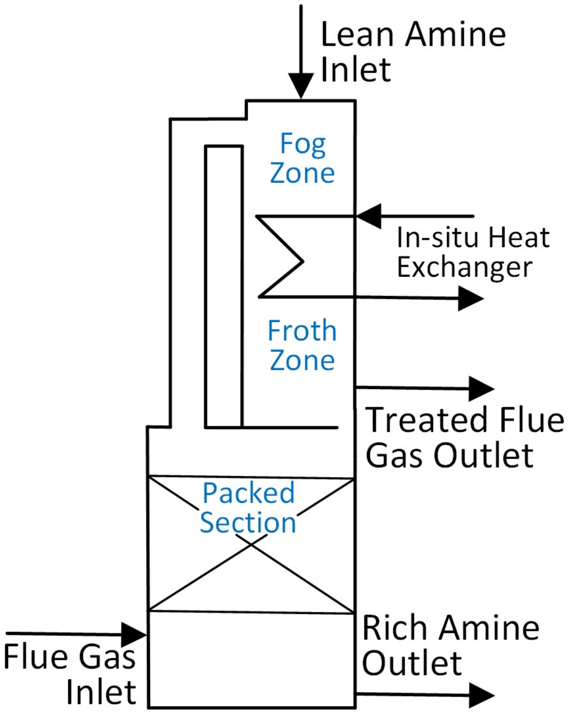

Figure 1: Schematic of University of Kentucky's compact absorber.

The project is designing and fabricating the complete compact absorber, including the atomizing nozzle, froth-generating and -propagating screens, and in situ heat removal. The frothing screens, as shown in Figure 2, are optimized for froth generation and propagation. They are designed and supplied by Industrial Climate Solutions. Fog generation includes spray nozzle selection and optimization of the nozzle arrangement, as well as mist size distribution in the column, via liquid supply parameters and solvent properties. Individual testing of the fog section and froth section will be followed by parametric and long-term testing of the compact absorber integrated in UKy-CAER bench-scale post-combustion capture facilities using simulated and actual flue gas. Data from testing supports development of a TEA and EH&S assessment for the process.

Figure 2: Froth-generating and -propagating screens.

The solvent and process parameters are provided in Table 1.

TABLE 1: SOLVENT PROCESS PARAMETERS

Pure Solvent	Units	Current R&D Value	Target R&D Value
Molecular Weight	g/mol	Amine	Amine
Normal Boiling Point	°C	155-170	155-170
Normal Freezing Point	°C	-2	-2
Vapor Pressure @ 20°C	bar	0.0007	0.0007
Manufacturing Cost for Solvent	\$/kg (pure chemical, small batch)	14.74	14.74
Working Solution			
Concentration	kg/kg	0.35 to 0.45	0.35 to 0.45
Specific Gravity (15°C/15°C)	-	~1.0	~1.0
Specific Heat Capacity @ 40°C	kJ/kg-K	2.7-3.3	2.7-3.3
Viscosity @ STP	cP	5-7	5-7
Absorption			
Pressure	bar	1.01	1.01
Temperature	°C	40	40
Equilibrium CO_2 Loading	mol/mol	0.5	0.45
Heat of Absorption	kJ/mol CO_2	~-65	~-70
Solution Viscosity	cP	3-5	3-5
Desorption			
Pressure	bara	3-5	3-5
Temperature	°C	110-130	110-130
Equilibrium CO_2 Loading	mol/mol	0.20	0.20
Heat of Desorption	kJ/mol CO_2	~85	~85
Proposed Module Design		*(for equipment developers)*	
Flue Gas Flowrate	kg/hr	24	
CO_2 Recovery, Purity, and Pressure	% / % / bara	90	>95% 1.65
Absorber Pressure Drop	bar	<20"WC	
Estimated Absorber/Stripper Cost of Manufacturing and Installation	\$	\$36K	

Definitions:

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., monoethanolamine [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 processdependent (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

Chemical/Physical Solvent Mechanism – The solvent is an aqueous solution of a hindered primary amine. A carbamate species is formed upon CO_2 absorption. In a CO_2 capture absorber, the absorption rate, **R**, as a function of temperature, **T**, and carbon loading, **C/N**, can be expressed as: $\mathbf{R(T, C/N) = k_G \cdot a \cdot (P_{CO2} - P^*_{CO2})}$ where $\mathbf{k_G}$ is mass transfer coefficient, **a** is effective wetted surface area, and $\mathbf{(P_{CO2} - P^*_{CO2})}$ is the driving force, the difference in the concentration of CO_2 in liquid from the gas. Significant increase in **R**, via $\mathbf{k_G}$ and **a**, and corresponding reduction of capital cost comes from the mass transfer enhancement of the aqueous system compared to any 2nd-generation technology because there is an order of magnitude greater effective wetted surface area in the top of the absorber.

Solvent Contaminant Resistance – UKy-CAER analysis show the solvent is more resistant to degradation, 40–50% improvement than 30 wt% MEA. Accumulation of metals within the solvent is expected to be equivalent to that within 30 wt% MEA.

Solvent Foaming Tendency – Unstable froth formation (not persistent foaming) is a key aspect to the compact absorber. Surfactant is added to reduce the surface tension and therefore control the frothing behavior. Initial CO_2 capture experiments on solvent physical properties were performed in a packed column (2-inch internal diameter [ID] mini-scrubber). Adding surfactant to change the solvent surface tension led to a CO_2 capture efficiency increase of 15–20% throughout the carbon loading range. The key reason for this enhancement is the presence of fine froth (bubbles) that increase surface area with the addition of surfactant. It was also found that as carbon loading increases, the tendency to form bubbles decreases due to increased viscosity and surface tension. For an unstable froth, the dispersion rate is also important. A surfactant was chosen with the faster dispersion rate compared to others considered.

Flue Gas Pretreatment Requirements – The flue gas pretreatment requirement is sulfur dioxide (SO_2) removal to less than 5 parts per million (ppm) to minimize heat stable salt formation. This can be done with a standard counter-current pretreatment column with a circulating solution of either of soda ash (Na_2CO_3) or sodium hydroxide (NaOH). The solvent used is a hindered primary amine and does not form stable nitrosamine species, therefore no additional nitrogen oxide (NO_X) removal is required. No additional moisture removal required, as it is for ionic liquids.

Solvent Makeup Requirements – Two factors contributing to solvent makeup rate are degradation and emission. UKy-CAER analysis show the solvent has degradation rates less than 30 wt% MEA and when the UKy-CAER developed solvent recovery technology is applied, the solvent emission will be about 0.5 ppm. The anticipated solvent makeup rate is less than 0.5 kg/tonne CO_2 captured.

Waste Streams Generated – The waste streams of the post-combustion CO_2 capture process using the compact absorber are the same as any other post-combustion CO_2 capture process. There will be a blowdown stream from the SO_2 pretreatment column and a reclaimer waste stream from the solvent loop.

Process Design Concept – The design concept is shown in Figure 3. A 3-inch column is used for the fogging and frothing section where the flue gas and solvent flow in a co-current fashion. The bottom section contains typical structured packing with the flue gas and solvent moving in a counter-current fashion.

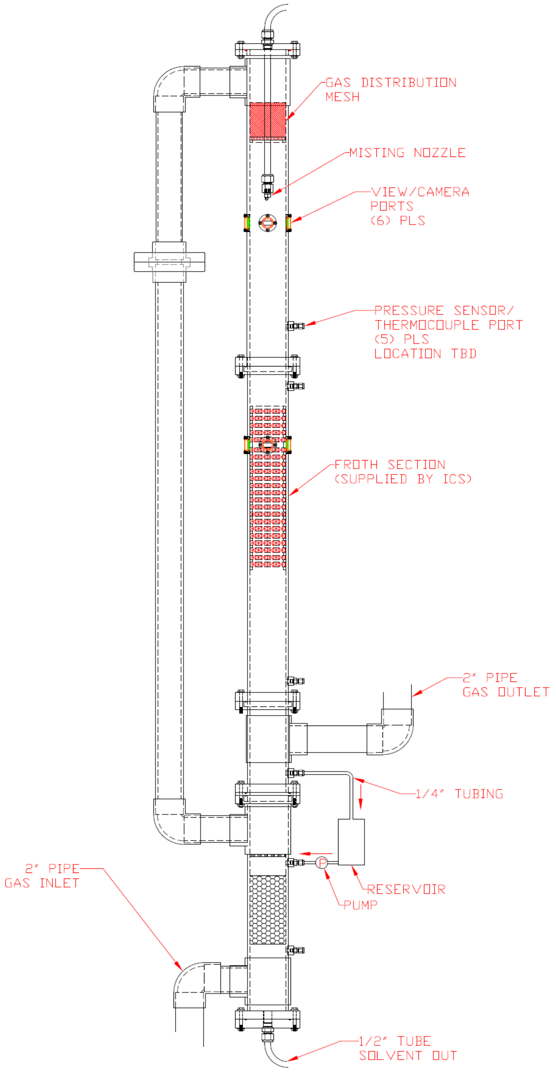

Figure 3: Compact absorber design concept.

Proposed Module Design – The absorber is modular with a natural divide between the bottom packed section and the top fog and froth section.

TABLE 2: POWER PLANT CARBON CAPTURE ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured (excluding TS&M)	2011\$/tonne CO_2	31.95	—
Cost of Carbon Avoided (excluding TS&M)	2011\$/tonne CO_2	37.00	—
Capital Expenditures	2011\$/MWhr	52.98	—
Operating Expenditures	2011\$/MWhr	11.36	—
Cost of Electricity (excluding TS&M)	2011\$/MWhr	106.17	—

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.

Calculations Basis – The numbers provided in the table are based on the reference plant provided by the National Energy Technology Laboratory (NETL) for TEA, found in the "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity" report Revision 2a, $2011.

Scale of Validation of Technology Used in TEA – 0.1 megawatt-thermal (MWth) bench.

technology advantages

- Up to five times increase in liquid/gas contact area over structured packing.
- Up to four times increase in mass transfer over conventional columns due to a thin (target of ~10 μm) liquid film, eliminating the CO_2-amine diffusion resistance that can impede the overall mass transfer of a capture technology.
- Up to 70% reduction in absorber height.
- Up to 50% reduced pump power requirement.
- Maintain carbon loading as close as achieved with conventional column containing structured packing.
- Potential, when combined with other University of Kentucky CO_2 capture features, for a 57% reduction in capital cost for carbon capture.

R&D challenges

- Demonstration at the bench scale due to wall effects in the small column.
- Controlling the froth size.

status

The University of Kentucky has compared and selected options for the atomizing nozzle and frothing screens for their system. Fogging and frothing sections were designed, constructed, and connected with the existing 0.1-MWth facility. Both batch and continuous operations were conducted. The parametric campaign was completed after 827 hours of testing with bottled gas. More than 60% CO_2 capture and 0.45 mol C/mol N rich loading was demonstrated with a 3-foot fog and froth and 2-foot structured packing. This is on par with traditional absorber performance having greater than twice the amount of structured packing. The long-term campaign was conducted with approximately 1,000 hours of testing with fossil fuel-derived flue gas. The State Point Data Table was completed for the UKy-CAER hindered amine blend solvent. Work on the TEA is underway. The EH&S assessment will be conducted.

available reports/technical papers/presentations

Nikolic, H. "Fog+Froth-based Post-Combustion CO_2 Capture in Fossil-Fuel Power Plants," Presented at the 2021 NETL Carbon Management Research Project Review Meeting, Pittsburgh, PA, August 2021. *https://netl.doe.gov/sites/default/files/netl-file/21CMOG_PSC_Nikolic.pdf*.

Nikolic, H. "Fog+Froth-based Post-Combustion CO_2 Capture in Fossil-Fuel Power Plants," Presented at the CO_2 Capture BP1 Review Meeting, Pittsburgh, PA, August 2021. *https://netl.doe.gov/projects/plp-download.aspx?id=10750&filename=Fog+and+Froth+Based+Post+Combustion+CO2+Capture+in+Fossil+Fuel+Power+Plants.pptx*.

Nikolic, H. "Fog+Froth-based Post-Combustion CO_2 Capture in Fossil-Fuel Power Plants," Presented at 2019 NETL CO_2 Capture Technology Meeting, Pittsburgh, PA, August 2019. *https://netl.doe.gov/sites/default/files/netl-file/H-Nikolic-UKY-CAER-Fog-Froth-Capture.pdf*.

Nikolic, H. "Fog+Froth-based Post-Combustion CO_2 Capture in Fossil-Fuel Power Plants," Presented at the Project Kickoff Meeting, Pittsburgh, PA, May 2018. *https://netl.doe.gov/projects/plp-download.aspx?id=10752&filename=Fog+and+Froth+Based+Post+Combustion+CO2+Capture+in+Fossil+Fuel+Power+Plants.pdf*.