Engineering-Scale Testing of Transformational Non-Aqueous Solvent-Based Carbon Dioxide Capture Process at Technology Centre Mongstad

primary project goal

Research Triangle Institute (RTI) is developing and testing, at large pilot scale, a non-aqueous solvent (NAS; i.e., water-lean solvent) carbon dioxide (CO₂) capture process to confirm the potential to reduce the parasitic energy penalty associated with the capture of CO₂ from flue gas; demonstrate the long-term process operational reliability at static and dynamic conditions; and verify the solvent degradation rate, emissions, solvent loss, and corrosion characteristics of the solvent at engineering scale.

technical goals

- Evaluate water-lean solvent degradation and material compatibility.
- Measure water-lean solvent performance over static and dynamic operating conditions.
- Design/procure water-lean solvent-specific components for implementation in the host site facility.
- Confirm a reduction in parasitic energy penalty to less than 2.6 gigajoules (GJ)/tonne CO₂ captured.
- Complete a techno-economic analysis (TEA) to confirm RTI's NAS process can reduce CO₂ capture costs.

technical content

RTI is advancing the development of a water-lean solvent-based CO₂ capture process that was previously developed and tested at lab- and bench-scale (~10 kilowatts [kW]) with simulated flue gas under the U.S. Department of Energy (DOE)-funded project FE0013865. Water-lean solvents have the potential to significantly reduce the cost of CO₂ capture from coal-fired flue gas when compared to aqueous amine-based solvent processes by reducing the energy required for solvent regeneration. RTI's water-lean solvent is a hydrophobic, sterically hindered, carbamate-forming amine with low-water solubility solubilized in a diluent having low vapor pressure and low viscosity. It is characterized by low heats of absorption and generation of high CO₂ partial pressures at low temperatures and has the potential to reduce the regeneration energy to less than 2.1 GJ/tonne CO₂. The overall reboiler heat duty, or thermal regeneration energy, is made up of the sensible heat, heat of vaporization of water, and heat of absorption. The heat of vaporization, due to the lack of water, is significantly less for water-lean solvents than for aqueous amine-based processes. Also, waterlean solvents overcome the foaming issues that are often associated with aqueous

program area:

Point Source Carbon Capture

ending scale: Large Pilot

application:

Post-Combustion Power Generation PSC

key technology:

Solvents

project focus:

Water-Lean Solvent for Coal-Fired Flue Gas

participant: Research Triangle Institute

project number: FE0031590

predecessor projects:

FE0026466 FE0013865

NETL project manager:

Mariah Richardson mariah.richardson@netl.doe.gov

principal investigator:

Marty Lail Research Triangle Institute mlail@rti.org

partners:

Technology Centre Mongstad (TCM); Electric Power Research Institute Inc.

start date:

08.08.2018

percent complete: 82% solvents, as shown in Figure 1. RTI's CO2-rich water-lean solvent has a viscosity of less than 30 cP and is non-foaming.



Figure 1: Comparison of foaming in aqueous and RTI's water-lean solvents.

The NAS CO₂ capture process includes a solvent regenerator design specifically for water-lean solvents that combines heat delivery and gas release in a single-step process unit to maintain lower regeneration temperatures. The process, as shown in Figure 2, is like conventional solvent scrubbing systems with key novel design features:

- NAS solvent recovery and wash section—similar to water washing, but water-lean solvents have low water-solubility.
- Solvent regenerator—lack of low-boiling component (conventional reboilers are not applicable).



Figure 2: NAS CO₂ capture process diagram.

Under DOE-funded project DE-FE0026466, RTI used the bench-scale test unit (up to 60 kW) at SINTEF's Tiller plant to experimentally show that the water-lean solvent can achieve 90% CO₂ capture and generating a high-purity CO₂ product (greater than 95% CO₂), as well as to evaluate the effectiveness of the developed NAS recovery/wash section and solvent regenerator design. Bench-scale testing at SINTEF's Tiller plant was first performed using the monoethanolamine (MEA) control and the water-lean solvent in an unmodified configuration of the test unit. Baseline testing of the water-lean solvent

using propane and coal-fired flue gas was performed over a period of approximately four months, showing a CO₂ capture rate of approximately 90%. Heat stable salts (HSS) and metals analyses were used to determine the solvent stability and corrosion. The HSS level was relatively constant and low during the test campaign. The results also indicate that the corrosion rate of NAS is quite low and stable, confirming previous test results that showed much lower corrosion rate for NAS as compared with MEA.

As the CO₂ capture system at Tiller was designed specifically to achieve the optimum performance for an aqueous-based solvent, it is not an ideal setup to realize the energy reduction benefit by using the water-lean solvent. Based on the knowledge acquired throughout the testing in RTI's gas absorption system (BsGAS) with various process configurations, the following modifications (Figure 3) to the existing absorption system at the Tiller plant were made:

- Addition of two interstage coolers between existing sections of packing in the absorber.
- Replacement of three existing packing sections in the regenerator column with three new sections consisting of an electric/steam heating portion located at the top-half of the section and a high surface area packing portion located at the bottom-half of the section.
- Expansion of lean-rich heat exchanger by adding a second crossover plate-and-frame heat exchanger in series.
- Addition of coal-fired burner.
- Rich solvent preheater installed at regenerator inlet.
- Addition of an acid wash/water wash section.



- Interstage heaters: 2.19 (all) to 2.86 (none) GJ/tonne-CO₂
- Interstage coolers: 2.19 (all) to 3.23 (none) GJ/tonne-CO₂
- The use of preheater (HX-305) lowers the SRD



Figure 3: Design improvements for NAS-based process.

The solvent formulation was also refined to increase CO₂ loading and working capacity and to reduce the reboiler heat duty required for solvent regeneration. The improved formulation (NAS-5) results in an increase in CO₂ working capacity from ~0.45 mol_{CO2}/mol_{amine} to ~0.48 mol_{CO2}/mol_{amine}, a decrease in heat of absorption from ~82 kilojoules (kJ)/mol_{CO2} to ~75 kJ/mol_{CO2}, and is expected to reduce the reboiler heat duty by decreasing the liquid/gas (L/G) ratios and the heat of absorption at higher temperatures. Through testing in RTI's bench-scale BsGAS, it was found to be advantageous to use two interstage coolers in the absorber column (with one at the bottom and one at the top) to achieve a heat duty near 2 MJ/kg-CO₂. The coolers play an essential role in lowering the temperature in the absorber column to maintain a high CO₂ loading in the solvent. A wash column was added to RTI's BsGAS to allow for testing different conditions to reduce amine losses for the technology, demonstrating that the wash section could effectively remove 92–93% of the amine emissions from the absorber. The process parameters of the solvent are shown in Table 1.

| Pure Solvent | Units | Current R&D Value | Target R&D Value | |
|-------------------------------------|-----------------------|-------------------|------------------|--|
| Molecular Weight | mol ⁻¹ | 95–115** | 99 | |
| Normal Boiling Point | °C | 185–243** | 200 | |
| Normal Freezing Point | °C | (-6 to -24)** | -9.15 | |
| Vapor Pressure @ 15°C | bar | 4.47e-4** | 4.47e-4 | |
| Manufacturing Cost for Solvent | \$/kg | 14 | 5 | |
| Working Solution | | | | |
| Concentration | kg/kg | 0.5–0.6* | 0.55 | |
| Specific Gravity (15°C/15°C) | - | 0.9-1.035* | 1.035 | |
| Specific Heat Capacity @ STP | kJ/kg-K | 2.78* | 2.78 | |
| Viscosity @ STP | cP | 4.38-4.7* | 4.7 | |
| Absorption | | | | |
| Pressure | bar | 0.133* | 0.133 | |
| Temperature | °C | 35–45* | 38 | |
| Equilibrium CO ₂ Loading | mol/mol | 2.04-2.22* | 2.04 | |
| Heat of Absorption | kJ/kg CO ₂ | 1,700–2,000* | 1,931 | |
| Solution Viscosity | cP | 4–30* | 28 | |
| Desorption | | | | |
| Pressure | bar | 2-7.8* | 2 | |
| Temperature | °C | 90-110* | 105 | |
| Equilibrium CO ₂ Loading | mol/mol | 0.45-1.13* | 0.45 | |
| Heat of Desorption | kJ/kg CO ₂ | 2,100* | 2,045 | |

TABLE 1: SOLVENT PROCESS PARAMETERS

* Experimentally measured data.

** Calculated data for different concentrations and conditions using standard mixing rules from pure components data.

Following the installation of the NAS-specific components into the Tiller plant, including a new particulate filter, updated coal-burner control software, additional absorber intercoolers, additional water wash section, regenerative "inter-heaters," and one additional crossflow heat exchanger, parametric testing was performed with NAS-5 to allow optimal operating conditions to be identified and long-term testing to be completed. Test results showed an average CO_2 capture rate of 90% and the lowest reboiler heat duty obtained was 2.3 GJ/tonne CO_2 when the rich solvent pre-heater was used.

Additional baseline testing of the new water-lean solvent formulation was performed at the National Carbon Capture Center (NCCC) to investigate solvent degradation, corrosion, and emissions using the Slipstream Solvent Test Unit (SSTU) with long-term exposure to coal-derived flue gas from the Gaston Power Plant in Wilsonville, Alabama. The NCCC system was operated for 580 hours with flue gas with intermittent delays. The effects of flue gas velocity, CO_2 capture efficiency, and aerosols on amine emissions were studied during the test campaign. Preliminary testing has indicated that the water-lean solvent displays minimal corrosion; therefore, the materials of construction for some of the equipment could be replaced with lower cost options. A TEA and environmental, health, and safety (EH&S) assessment of the NAS process based on test data obtained from SINTEF's Tiller plant and from the SSTU at NCCC show that the NAS technology has the potential to meet DOE's \$40/tonne CO_2 capture target when it is fully developed and poses little EH&S risk.

In RTI's current DOE-funded project, engineering-scale tests are being performed using the existing large pilot infrastructure at the Technology Centre Mongstad (TCM) in Norway. The test campaign includes baseline testing with the water-lean solvent in TCM's 12-megawatt-electric (MWe) pilot plant in the configuration designed for aqueous-amine solvents, a hardware revamp of the plant to implement NAS-specific components, and follow-on NAS testing under optimized conditions. Based on the findings realized during the evaluation of RTI's BsGAS and SINTEF's Tiller plant under various process configurations, the following modifications to the existing system at TCM are being made:

- Addition of one interstage cooler between existing sections of packing in the absorber.
- Higher capacity pump in the thermosyphon reboiler for efficient regeneration.

• Adjustment of water wash flue gas inlet to maintain volume during operation.

In addition, strategies for reducing the amine emissions to less than 1 part per million (ppm) are being implemented to meet TCM's emissions requirements, including modifying the existing water wash section of the TCM unit, lowering the gas flow rate, and adding an intercooler to the absorber. Large pilot-scale test results will be used to demonstrate the applicability of the water-lean solvent as a drop-in replacement solvent in conventional capture systems and the process scalability and commercial potential of RTI's transformational NAS CO₂ capture process for pulverized coal power plants.

Included in this study is a TEA. The economic data for the current integrated power plant with CO₂ capture is 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 CO2 | 43.3 | 43.3 | |
| Cost of Carbon Avoided | \$/tonne CO2 | 59.2 | 59.2 | |
| Capital Expenditures | \$/MWhr | 62.4 | 62.4 | |
| Operating Expenditures | \$/MWhr | 25.7 | 25.7 | |
| Cost of Electricity | \$/MWhr | 80.95 | 80.95 | |

Definitions:

Cost of Carbon Captured – Projected cost of capture per mass of CO₂ captured under expected operating conditions.

Cost of Carbon Avoided – Projected cost of capture per mass of CO₂ 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 CO₂ 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., CO₂-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 CO₂ 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 CO₂ loadings is moles of pure solvent.

Estimated Cost – Basis is kg/hr of CO₂ in CO₂-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 ₂ O | N ₂ | O ₂ | Ar | SOx | NOx | |
| 14.7 | 135 | 13.17 | 17.25 | 66.44 | 2.34 | 0.80 | 42 | 74 | |

Other Parameter Descriptions:

Chemical/Physical Solvent Mechanism - Chemical.

Solvent Contaminant Resistance – More resistant than MEA to sulfur oxides (SO_X) and nitrogen oxides (NO_X).

Solvent Foaming Tendency - Less foaming than aqueous amine solvent.

Flue Gas Pretreatment Requirements – Temperature adjustment and SO_X control.

Solvent Makeup Requirements – 0.2–0.5 kg/tonne CO₂.

Waste Streams Generated - None.

Process Design Concept – See Figure 2.

technology advantages

- · Low water solubility.
- Reduced regeneration energy.
- High solvent regeneration pressure at low regeneration temperatures, such that desorbed CO₂ can go directly to second stage of compression.
- Favorable thermodynamics.
 - o Low heat of absorption.
 - o High working capacity based on vapor-liquid equilibrium (VLE).
- Excellent thermal and oxidative stability; no formation of HSS.
- Low vapor pressure (less than 0.3 kPa [40°C], less than 10 ppm emissions in treated flue gas).
- Low conductivity; low corrosion rates.
- Low oxygen solubility.

R&D challenges

- Implementation of NAS-specific components into host site facility.
- Effective control of water content in both the rich and lean water-lean solvent solution to minimize regeneration energy required.
- Minimizing the rise in absorber temperature.
- Operating TCM plant within emissions requirements.
- Obtaining sufficient heat exchange for optimal performance.
- Improving the working capacity of the solvent.
- Solvent emissions control.

status

RTI has tested multiple water-lean solvent formulations and identified an improved formulation (NAS-5). Experimental testing of NAS-5 in RTI's BsGAS showed that the lowest regeneration of 2.15 MJ/kg CO_2 was achieved when the system

operated at L/G of 4.2. The team performed 405 hours of NAS baseline testing at the SINTEF Tiller plant in an unmodified configuration, revealing that the energy required for solvent regeneration is 15% lower for NAS than that for MEA, even though NAS was run under less-than-optimal conditions. Parametric testing and a cumulative 1,200 hours of long-term testing of NAS-5 in the Tiller plant were conducted following installation of NAS-specific components to determine optimal operating parameters and validate reduced reboiler duty. The lowest specific reboiler heat duty of 2.3 GJ/tonne CO₂, water balance, and operational stability were maintained during about 1,600 hours of testing using the NAS-5 formulation. Additional water-lean solvent baseline testing using coal-fired flue gas at NCCC showed that 90% CO₂ capture is consistently observed under varying test conditions. In preparation for large pilot-scale testing, RTI initiated design and engineering of TCM facility modifications, as well as a front-end engineering design (FEED) study to determine the cost of modifications. In addition, solvent qualification testing was completed at SINTEF to demonstrate performance of the manufactured solvent. RTI has received and installed the key components for the facility modifications (interstage cooler, recirculation pump, etc.) to begin commissioning as of February 2022.

available reports/technical papers/presentations

Lail, M., 2021, "Engineering Scale Testing of Transformational Non-Aqueous Solvent-Based CO₂ Capture Process at Technology Center Mongstad." Presented at the 2021 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_Lail.pdf*.

Lail, M., 2019, "Engineering Scale Testing of Transformational Non-Aqueous Solvent-Based CO₂ Capture Process at Technology Centre Mongstad," presented at the 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting, Pittsburgh, PA, August 2019. *https://netl.doe.gov/sites/default/files/netl-file/M-Lail-RTI-Testing%20at%20TC%20Mongstad.pdf*.

Zhou, S. James, et.al., 2018, "Pilot Testing of a Non-Aqueous Solvent (NAS) CO₂ Capture Process," 14th International Conference on Greenhouse Gas Control Technologies, GHGT-14, 21st -25th October 2018, Melbourne, Australia.

Zhou, S. James et al., 2018, "Engineering Scale Testing of Transformational Non-Aqueous Solvent-Based CO₂ Capture Process at Technology Centre Mongstad," Project Kickoff Meeting, October 2018. *https://netl.doe.gov/projects/plp-download.aspx?id=10417&filename=Engineering+Scale+Testing+of+Transformational+Non-Aqueous+Solvent-Based+CO2+Capture+Process+at+Technology+Centre+Mongstad.pdf*.

Zhou, S. James et al., 2018, "Engineering Scale Testing of Transformational Non-Aqueous Solvent-Based CO₂ Capture Process at Technology Centre Mongstad," presented at the 2018 NETL CO₂ Capture Technology Project Review Meeting, Pittsburgh, PA, August 2018. *https://netl.doe.gov/sites/default/files/netl-file/SJ-Zhou-RTI-Solvent-Based-Capture-at-Centre-Mongstad.pdf*.

Tanthana, J., 2018, "Large Bench-Scale Development of a Non-Aqueous Solvent CO₂ Capture Process for Coal-Fired Power Plants," presented at the 2018 NETL CO₂ Capture Technology Project Review Meeting, Pittsburgh, PA, August 2018. https://netl.doe.gov/sites/default/files/netl-file/J-Tanthana-RTI-Non-Aqueous-Solvent-Capture-Process.pdf.

Zhou, S., 2017, "Large Bench-Scale Development of a Non-Aqueous Solvent CO₂ Capture Process for Coal-Fired Power Plants Utilizing Real Coal Derived Flue Gas," presented at the 2017 NETL CO₂ Capture Technology Project Review Meeting, Pittsburgh, PA, August 2017.

https://www.netl.doe.gov/File%20Library/Events/2017/co2%20capture/2-Tuesday/S-J-Zhou-RTI-Non-Aqueous-Solvent-CO2-Capture.pdf.

Zhou, S. James, et. al., 2017, "Large Bench-scale Development of a Non-Aqueous Solvent CO₂ Capture Process for Coal-fired Power Plants," 9th Trondheim Conference on CO₂ Capture, Transport and Storage, Trondheim, Norway, June 12 - 14, 2017.

Zhou, S., 2017, "Large Bench-Scale Development of a Non-Aqueous Solvent CO₂ Capture Process for Coal-Fired Power Plants Utilizing Real Coal Derived Flue Gas," Budget Period 1 Project Review Meeting, Pittsburgh, PA, April 2017.

Lail, M., 2016, "Bench-Scale Development of a Non-Aqueous Solvent CO₂ Capture Process for Coal-Fired Power Plants," Final Scientific/Technical Report, December 2016. *https://www.osti.gov/servlets/purl/1389565*.

Zhou, S. James, et. al., 2016, "Non-Aqueous Solvent CO₂ Capture Process," *Proceedings of the 13th Annual International Conference on Greenhouse Gas Control Technologies*. Lausanne, Switzerland. November 14 - 18

Lail, M., 2016, "Bench-Scale Development of a Non-Aqueous Solvent CO₂ Capture Process for Coal-Fired Power Plants," 2016 NETL CO₂ Capture Technology Meeting, Pittsburgh, PA, August 2016. http://netl.doe.gov/File%20Library/Events/2016/c02%20cap%20review/4-Thursday/M-Lail-RTI-Non-Aqueous-Solvent-CO2-Capture.pdf.

Lail, M., 2015, "Bench-Scale Development of a Non-Aqueous Solvent CO₂ Capture Process for Coal-Fired Power Plants," 2015 NETL CO₂ Capture Technology Meeting, Pittsburgh, PA, June 2015.

Coleman, L., 2014, "Bench-Scale Development of a Non-Aqueous Solvent CO₂ Capture Process for Coal-Fired Power Plants," 2014 NETL CO₂ Capture Technology Meeting, Pittsburgh, PA, July 2014.