Direct Air Capture of Energy for Carbon Capture, Utilization, and Storage Partnership (DAC RECO$_2$UP)

primary project goal

Southern States Energy Board (SSEB) is leading efforts together with AirCapture LLC to advance a solid amine sorbent-based technology for direct air capture (DAC) through field testing in a commercially relevant environment. The primary goal of the DAC RECO$_2$UP project is to decrease the cost of DAC through the testing of existing DAC materials in integrated field units that produce a concentrated carbon dioxide (CO_2) stream of at least 95% purity. This project is focused on engineering design of an integrated DAC system utilizing energy recovery and support services at the National Carbon Capture Center (NCCC).

technical goals

- Conduct applied research and development (R&D) to decrease the cost of DAC from atmospheric air and mixtures of air and simulated industrial gases available in a test bay at the NCCC.
- Develop and scale-up an integrated system utilizing energy recovery at the NCCC.
- Increase the integrated system's fidelity by validating and demonstrating operations in a simulated commercial environment by maximizing capital efficiency and energy efficiency.
- Identify and address key technical barriers, within a representative operating environment, in support of DAC technology commercialization.
- Perform a pre-screening TEA and LCA to determine the environmental sustainability (amount of carbon negativity) and economic viability (cost impacts) of the integrated DAC system.

technical content

The technology, previously developed by Global Thermostat, employs a solid-amine CO_2 adsorption-desorption cycle using a honeycomb-type monolithic contactor impregnated with a solid polyethylenimine polymer that forms agglomerations of polymeric amine capture sites within the mesopores of the contactor. A fan draws air or mixtures of air and CO_2-rich gas streams through the contactor in a laminar flow regime wherein CO_2 is adsorbed by the contactor via diffusion into the contactor walls perpendicular to the airflow. The ultra-low pressure drop monoliths maximize the efficiency of air flow, increasing mass transfer of CO_2 for adsorption. Once the sites bind sufficient quantities of CO_2, the monoliths are then exposed to vacuum and steam heat to desorb the CO_2 from the solid sorbent. The latent heat and hydration from the steam liberates the CO_2 from the amine capture sites and acts as a sweep gas pushing the CO_2 out of the contactor towards a condenser, which condenses the steam back into water for recycle, leaving greater than 98.5% CO_2 gas. The CO_2 is collected and the contactor is cooled via thermal recovery and evaporative heat loss and cycled back to adsorption mode, repeating the cycle.

program area:
Carbon Dioxide Removal

ending scale:
Bench Scale

application:
Direct Air Capture

key technology:
Sorbents

project focus:
Monolith Contactor with Amine-Based Sorbent for DAC

participant:
Southern States Energy Board (SSEB)

project number:
FE0031961

predecessor projects:
N/A

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start date:
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The technology employs a desorption mechanism that leverages a combination of vacuum and low-temperature steam, which together provide a rapid and efficient mechanism of CO_2 desorption while reducing the primary deactivation mechanism of amine oxidation at regeneration temperatures. Laboratory testing has demonstrated the technology's highest efficiency of CO_2 adsorption-desorption mass transfer ratio 10:1 with 900:90 second adsorption-desorption for air concentrations of CO_2. Increasing the technology fidelity in a system capable of continuously cycling 10 contactor assemblies, wherein nine positions are in CO_2 capture mode with one position in regeneration mode, with integrated system architecture and robust operations is required to advance the design. Engineering principles of airflow dynamics, movement of contactors through a cyclically sealed regeneration system, and efficient thermal transfer of low-temperature steam are all well understood.

Detailed laboratory-scale research has been conducted with pre-prototypical configurations using integrated unit operations achieving Technology Readiness Level (TRL) 4. Figure 1 shows a laboratory-scale system used to test and validate monolith adsorption performance, desorption performance, and cycle times. Various tests were carried out on air concentrations of CO_2, along with higher feed concentrations of CO_2, both within co-fed air streams and simulated air streams.

Figure 1: GT's laboratory-scale system used to test and validate monolith adsorption performance, desorption performance, and cycle times.

The laboratory system used the following primary process steps and time/control targets: airflow (5–20 minutes); drain (drain water, 5 seconds); pump down (remove air/O_2 from chamber to prevent oxidation and increase pressure, 10 seconds, 0.2 bar); pressurize (increase pressure in chamber, 10 seconds, 0.6–1.5 bar); regen/CO_2 collection (regenerate monolith, collect CO_2, 30–240 s); and cool (reduce pressure, flash off steam, 0.3–0.6 bar). The heat demand of the system was 4.7 British thermal units (Btu)/g-CO_2 with a pressure drop of 150 pa and sorbent working capacity of 0.1 kg-CO_2/kg.

Figure 2: CO_2 compression, storage, and upgrading skid.

This project invoves a three-phased testing campaign being conducted in an integrated system environment at the NCCC. A DAC skid capable of adsorbing/desorbing CO_2 using GT's solid-amine sorbent monolithic contactors and an energy recovery integration skid that uses process control and heat exchangers to produce the required steam for the DAC process are being constructed and installed at the NCCC. AirCapture is also providing an existing third skid capable of compressing, liquifying, and purifying the CO_2 (Figure 2).

TABLE 1: DAC SORBENT PROCESS PARAMETERS

Sorbent	Units	Current R&D Value	Target R&D Value
True Density @ STP	kg/m^3	2,300	2,300
Bulk Density	kg/m^3	500	500
Average Particle Diameter	mm	0.23	0.23
Particle Void Fraction	m^3/m^3	0.78	0.78
Packing Density	m^2/m^3	1,800	1,800
Solid Heat Capacity @ STP	kJ/kg-K	0.81	0.81
Crush Strength	kg_f	4	4
Thermal Conductivity	W/(m-K)	0.4	0.4
Adsorption			
Pressure	bar	1.0	1.0
Temperature	°C	25	25
Equilibrium Loading	g mol CO_2/kg	2.5	2.5
Heat of Adsorption	kJ/mol CO_2	85-95	85-95
CO_2 Adsorption Kinetics	gmol/kg-min	0.043	0.043
Desorption			
Pressure	bar	1.0	1.0
Temperature	°C	80-100	80-100
Equilibrium CO_2 Loading	g mol CO_2/kg	<0.05	<0.05
Heat of Desorption	kJ/mol CO_2	85-95	85-95
CO_2 Desorption Kinetics	gmol/kg-min	0.3	0.3

Proposed Module Design		(for equipment developers)		
Flow Arrangement/Operation	—		Honeycomb Monolith	
Air Feed Approach Velocity	m/sec		5	
Space Velocity	hr^{-1}		120	
Volumetric Productivity	$gmol_{CO2}/(hr\ kg_{sorbent})$		—	
CO_2 Recovery, Purity, and Pressure	% / % / bar	>50	>95	1.0
Adsorber Pressure Drop	bar		0.002	
Degradation	% capacity fade/yr		5%	

Definitions:

STP – Standard Temperature and Pressure (15°C, 1 atm).

Sorbent – Adsorbate-free (i.e., CO_2-free) and dry material as used in adsorption/desorption cycle.

Manufacturing Cost for Sorbent – "Current" is market price of material, if applicable; "Target" is estimated manufacturing cost for new materials, or the estimated cost of bulk manufacturing for existing materials.

Adsorption – The conditions of interest for adsorption are those that prevail at maximum sorbent loading. Measured data are preferable to estimated data.

Desorption – The conditions of interest for desorption are those that prevail at minimum sorbent loading. Operating pressure and temperature for the desorber/stripper are process-dependent. Measured data are preferable to estimated data.

Pressure – The pressure of CO_2 in equilibrium with the sorbent. 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.

Packing Density – Ratio of the active sorbent area to the bulk sorbent volume.

Loading – The basis for CO_2 loadings is mass of dry, adsorbate-free sorbent.

Kinetics – A characterization of the CO_2 adsorption/desorption trend with respect to time, as complete in the range of time as possible.

Flow Arrangement/Operation – Gas-solid module designs include fixed, fluidized, and moving bed, which result in either *continuous*, *cyclic*, or *semi-regenerative* operation.

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

Atmospheric Air Feed-Gas Assumptions – Update values below to describe the air feed-gas pressure, temperature, and composition entering the capture system:

		Composition						
		vol%					ppmv	
Pressure	Temperature	CO_2	H_2O	N_2	O_2	Ar	SO_x	NO_x
14.7 psia	Ambient	0.04	variable	78.09	20.95	0.93	trace	trace

Chemical/Physical Sorbent Mechanism – Solid-sorbent system.

Sorbent Contaminant Resistance – Airborne contamination mitigated with filters.

Sorbent Attrition and Thermal/Hydrothermal Stability – Targeted sorbent lifetime: approximately three years.

Flue Gas Pretreatment Requirements – N/A.

Sorbent Make-Up Requirements – Replacement as needed, drop-in.

Waste Streams Generated – Mostly water.

Proposed Module Design – 100 tonne/year DAC modular design together with heat integration skid module and scale-matched CO_2 upgrading/liquefaction module.

technology advantages

- Monolithic contactor provides low pressure drop, low thermal mass, high geometric surface area, and compatibility with various construction methods.
- Adsorption cycle capable capturing greater than 6.5L CO_2 in 900 seconds.
- Desorption cycle releases CO_2 via saturated steam in less than 90 seconds.
- Modular system design enables commercial application in a wide variety of applications.
- Integrated system design for production of high-grade CO_2 from DAC increases overall system exergy.

R&D challenges

- Construction and testing of integrated high-fidelity system in an operational test environment.

status

CFD modelling provided insight in system design and architecture and validated preliminary design concepts. Iterative design based on CFD analysis supported design to maximize overall system energy efficiency and performance. Research efforts are continuing to finalize the design of the desorption chamber sealing mechanism, the construction of a prototype sealing chamber test rig with two different sealing mechanisms, the testing of each mechanism, and the selection of the mechanism to be used when building the DAC system in Budget Period 2. Development of the system design and process model to validate the system timing and anticipated electrical and thermal performance is also ongoing. Construction of the DAC and heat integration skids has commenced.

available reports/technical papers/presentations

Matt Atwood, Bran Raskovic, "Direct Air Capture of Energy for Carbon Capture, Utilization, and Storage (CCUS) Partnership (DAC RECO$_2$UP)," Project kickoff meeting presentation, Pittsburgh, PA, April 2021. *http://www.netl.doe.gov/projects/plp-download.aspx?id=11080&filename=Direct+Air+Capture+of+Energy+for+Carbon+Capture%2c+Utilization%2c+and+Storage+(CCUS)+Partnership+(DAC+RECO2UP).pdf*.

Patricia Berry, Matt Atwood, "Direct Air Capture of Energy for Carbon Capture, Utilization, and Storage (CCUS) Partnership (DAC RECO$_2$UP)," Budget Period 1 Review Meeting Presentation, Pittsburgh, PA, October 2021. *http://www.netl.doe.gov/projects/plp-download.aspx?id=11078&filename=Direct+Air+Capture+of+Energy+for+Carbon+Capture%2c+Utilization%2c+and+Storage+(CCUS)+Partnership+(DAC+RECO2UP).pptx*.