Use of a Novel Process for Revolutionizing CO_2 Capture

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Senior Personnel:	Qinghua Lai
NTEL Collaboration Leader:	Janice A. Steckel

Project team

- University of Wyoming
  - PI: Maohong Fan – Professor
  - Co-PI: Associate Professor Gang Tan
  - Co-PI: Professor Khaled A. M. Gasem
  - Assistant Research Scientist Qinghua Lai
- Penn State University
  - Co-PI: Associate Research Professor Xiaoxing Wang
  - Co-PI: Professor Randy Lee vander Wal
- NETL

Collaboration Leader: Dr. Janice A. Steckel

Statement of Problems

- Low CO_2 sorption and desorption kinetics
  - $-NH_2 + CO_2 + H_2O \xleftrightarrow{k_{R1},\ k_{-R1}} (-NH_3^+)(HCO_3^-)$ R1 and -R1

    where k_{R1} and k_{-R1} are determined by their corresponding activation energies (E_{R1} and E_{-R1}) are the apparent rate constants of the CO_2 sorption and desorption steps, respectively

  - $CO_2 + OH^- \xleftrightarrow{k_{R2},\ k_{-R2}} HCO_3^-$ R2 and -R2

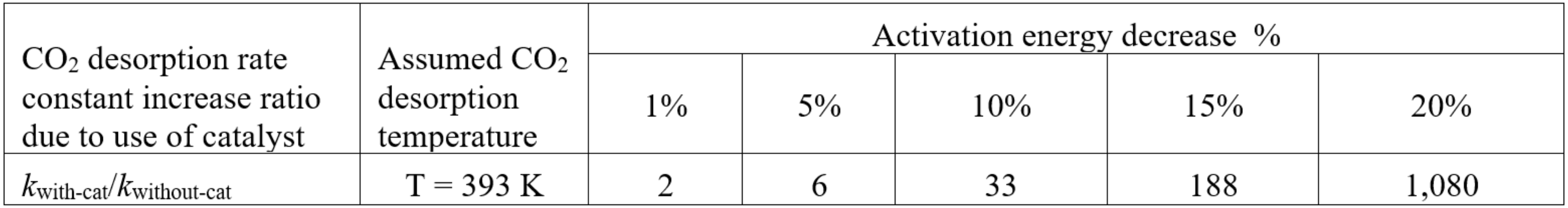
    where k_{R2} and k_{-R2} determined by their corresponding activation energies (E_{R2} and E_{-R2}) are the apparent rate constants of CO_2 sorption and desorption steps, respectively.
- High energy consumption

Hypothesis

How can we accelerate both CO_2 sorption and desorption? Firstly, let us how catalysis can help CO_2 desorption. Based on the reported E_a of CO_2 desorption in amine sorption system, 114.25 kJ/mol, the increase ratios of the reaction rate constant (k) in Arrhenius equation of CO_2 desorption at 80 ^{o}C due to the use of a catalyst is estimated according to:

$$\frac{k_{with-catalyst}}{k_{without-catalyst}} = \frac{A}{A} e^{-\frac{E_{with-catalyst} - E_{without-catalyst}}{RT}} = e^{\frac{m * E_{without-catalyst}}{RT}} \qquad \text{(E1)}$$

where m is the activation energy reduction percentage due to the use of a catalyst and presented below.



CO_2 desorption rate constant increase ratio due to use of catalyst	Assumed CO_2 desorption temperature	Activation energy decrease %				
		1%	5%	10%	15%	20%
$k_{\text{with-cat}}/k_{\text{without-cat}}$	T = 393 K	2	6	33	188	1,080

Hypothesis (continued)

Obviously, the catalytic potential for CO_2 desorption is significant. Also, reducing the activation energy of the CO_2 desorption reaction can lead to a decrease in the activation energy of the CO_2 sorption according to the relation

$$\Delta H = E_{a,desorption} - E_{sorption} \qquad \text{(E2)}$$

where ΔH is the heat of reaction, $E_{a,\ desorption}$ is the activation energy of the CO_2 desorption, and $E_{a,-adsorption}$ is the activation energy of CO_2 adsorption because ΔH is constant for a given temperature according to thermodynamic theories, a reduction in $E_{a,\ desorption}$ due to use of the catalyst means that $E_{a,-adsorption}$ is also decreased. Thus, a catalyst can accelerate both CO_2 sorption and desorption.

Potential significance of the results of the work

- Economic significance – Overcoming the challenges
  - Lower CO_2 capture cost and make CO_2 capture acceptable in more industries
  - Generate high-quality CO_2 via relatively low temperature CO_2 capture via avoidance of amine oxidation
  - Increase employments through the commercialization of both CO_2 capture and utilization technologies
  - Reduce the cost of CO_2 utilization and thus improve CO_2 utilization-based economy

Potential significance of the results of the work

- Environmental benefits:
  - Capturing CO_2 is beneficial to environment. The additional benefits of this technology include
    - Lowering CO_2 emission resulting from CO_2 capture itself due to the lower energy demand of the new CO_2 capture technology
      - ¤ lower energy consumption means lower CO_2 emission
  - Liquid waste discharge is reduced due to a higher CO_2 capture efficiency of the new technology (or higher amine utilization efficiency) and thus less demands for the solvent and water for capturing the same amount of CO_2
  - Secondary air pollution is reduced because
    - Any amines used for CO_2 captures could generate secondary pollution, resulting from the oxidation of amines
    - A higher CO_2 capture efficiency means less demand for amine

Relevancy to fossil energy

- The new CO_2 capture technology can help DOE
  - Meet its mission – ensuring America's access to and use of safe, secure, reliable, and affordable fossil energy resources and strategic reserves
  - Realize its vision – improving the living standards of the American people with clean, efficient, and reliable energy
  - Achieve its goal –
    - Develop secure and affordable fossil energy technologies
    - Enhance U.S. economic and energy security
    - Develop and maintain world-class organizational excellence

Statement of project objectives (SOPO)

- **Objectives**
  - Develop an innovative catalytic CO_2 capture technology (never reported in literature)
    - Dramatically increasing CO_2 sorption and desorption rates at <100 ^oC (especially CO_2 desorption rate)
      - So that the waste heat in industry can be well used
    - Avoiding the need for state-of-the-art spent solvent regeneration at >100 ^oC
    - Lowing CO_2 capture cost to <\$30/tonne-CO_2
    - Generating >95%-purity CO_2

Statement of project objectives (SOPO)

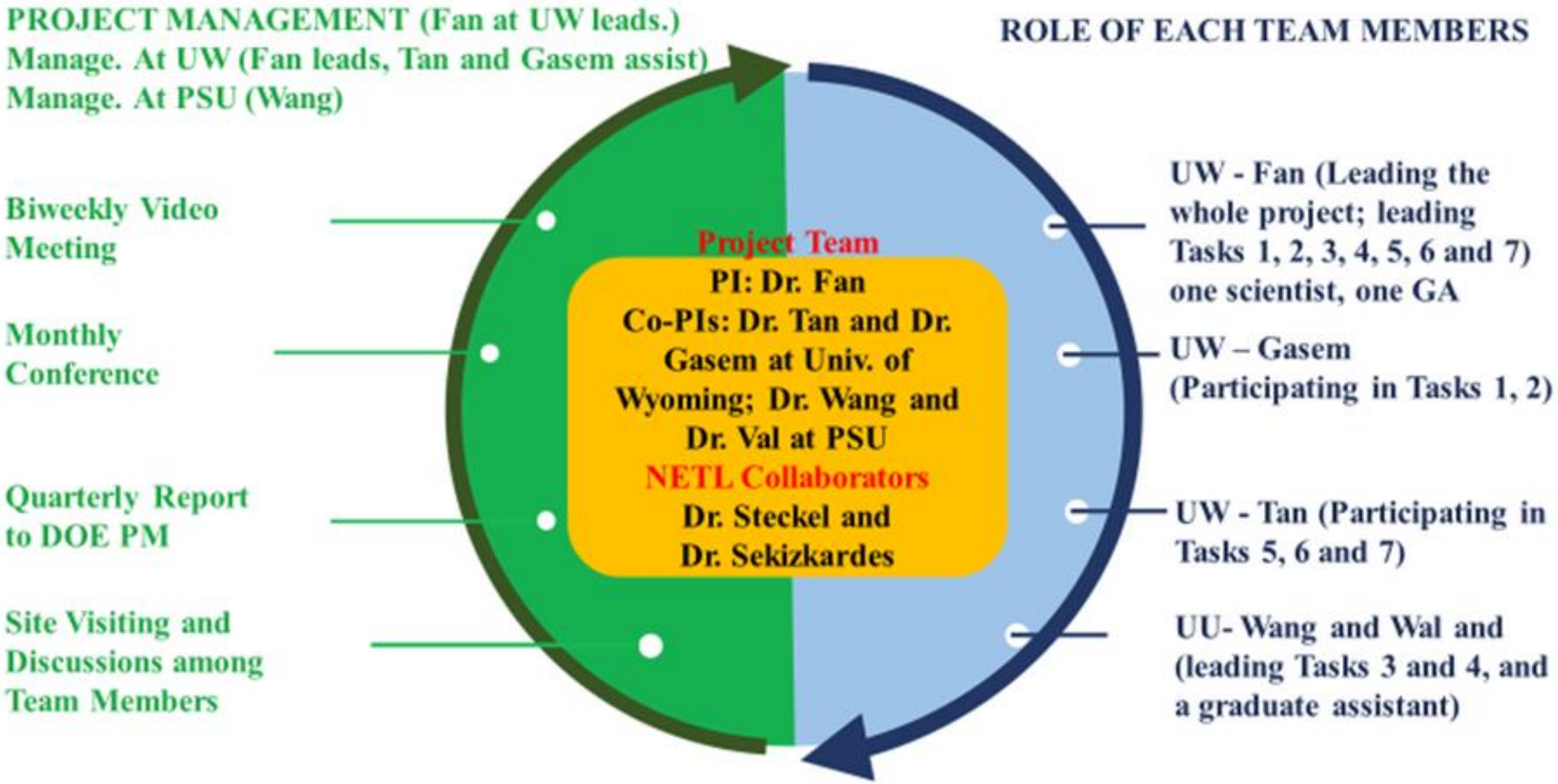
- **Scope of work**
  - Preparation and characterization of catalyst
    - ChCl-$C_3H_3AlO_6$ (choline chloride-aluminum formate) or CCAF
  - Evaluation of the CO_2 capture performance of the catalytic solvent
  - Study on the thermodynamics, reaction kinetics, mass and heat transfer, reaction mechanism
  - Techno-economic analysis

Collaborative work with NETL

- Work with NETL's Materials Engineering & Manufacturing Directorate (MEM) on
  - Task 1 - Catalyst preparation and characterization
  - Task 2 - Evaluation of the new CO_2 capture technology
  - Task 3 - Study on thermodynamics and reaction kinetics
  - Task 5 - Investigation of mass and heat transfer
  - Task 7 – Techno-economic analysis
- Work with System Engineering and Analysis (SEA) to quantify the potential advantages associated with the proposed novel CO capture technology via the performance of Task 7

Other relevant aspects of the project management plan (PMP)

- *Project organization and structure*



PROJECT MANAGEMENT (Fan at UW leads.)
Manage. At UW (Fan leads, Tan and Gasem assist)
Manage. At PSU (Wang)

Biweekly Video Meeting

Monthly Conference

Quarterly Report to DOE PM

Site Visiting and Discussions among Team Members

Project Team
PI: Dr. Fan
Co-PIs: Dr. Tan and Dr. Gasem at Univ. of Wyoming; Dr. Wang and Dr. Val at PSU
NETL Collaborators
Dr. Steckel and Dr. Sekizkardes

ROLE OF EACH TEAM MEMBERS

UW - Fan (Leading the whole project; leading Tasks 1, 2, 3, 4, 5, 6 and 7) one scientist, one GA

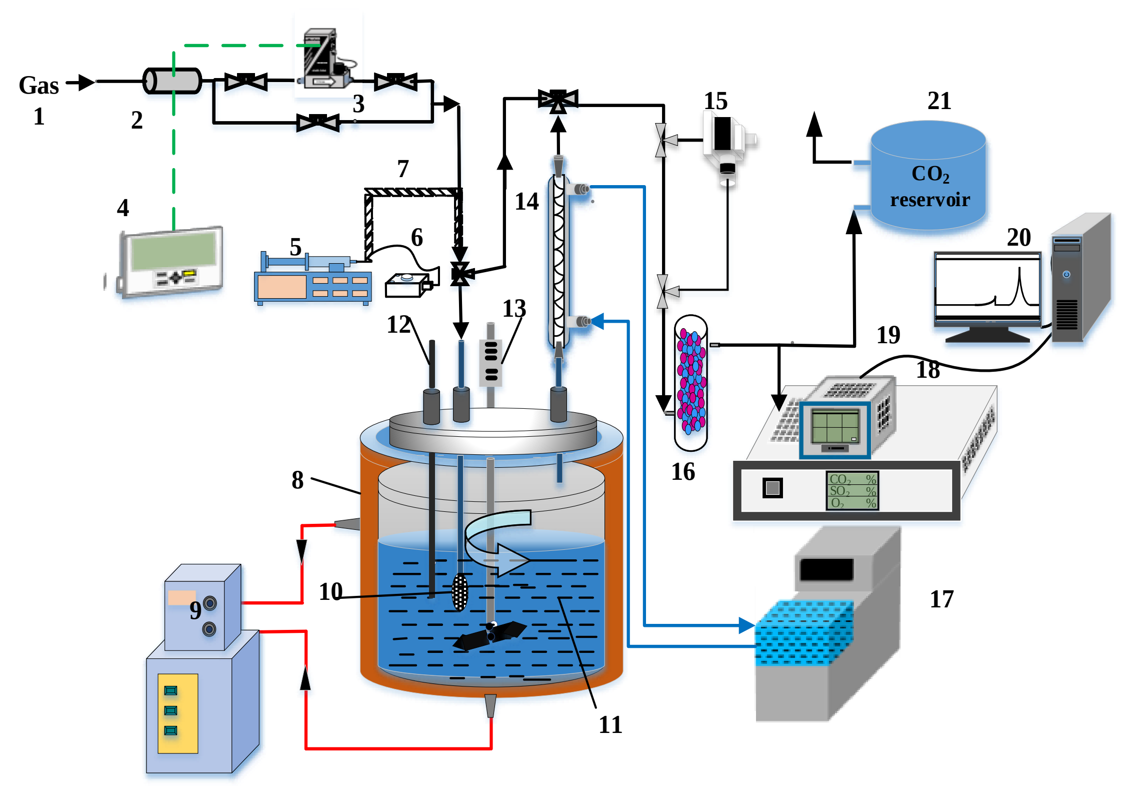
UW – Gasem (Participating in Tasks 1, 2)

UW - Tan (Participating in Tasks 5, 6 and 7)

UU- Wang and Wal and (leading Tasks 3 and 4, and a graduate assistant)

Project Status

- CO_2 capture setup



1, Air; 2: filter; 3: mass flow controller; 4: mass flow controller control module; 5: syringe pump 5: temperature controller for heating tap; 7: heating tap; 8: furnace; 9: thermostatic water bath; 10: catalytic sorbent or CCAF-P; 11: muffler for inlet gas; 12: thermocouple; 13: mechanical stirrer; 14: condenser; 15: vacuum pump; 16: moisture remover; 17: cooling unit; 18: gas analyzer; 19: data recorder; 20: computer; 21: CO_2 reservoir.

Project Status

- Pitures of CO_2 capture setup

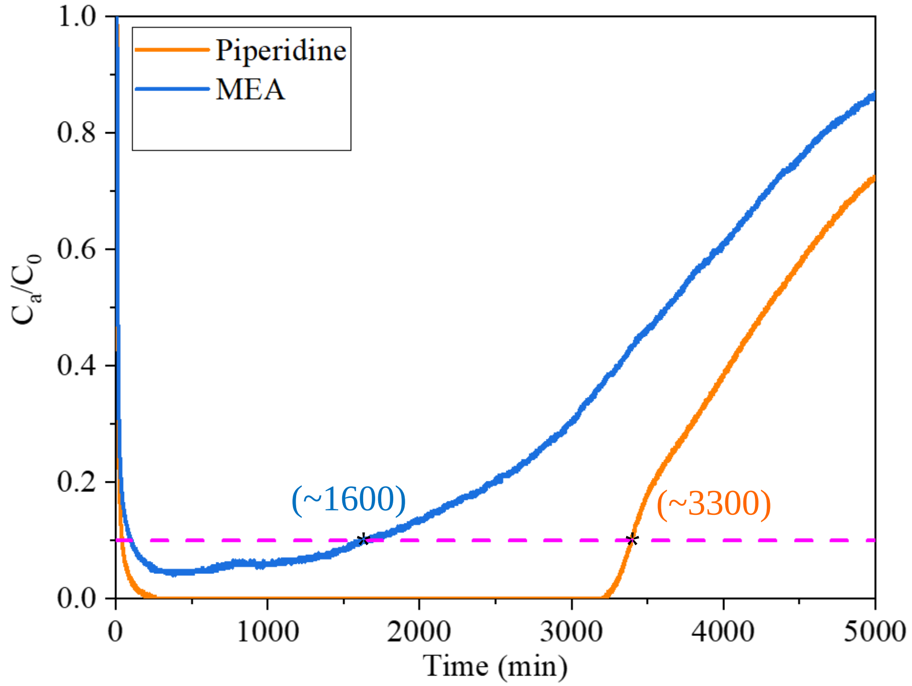
CO_2 capture experiment

- **Absorption**: Piperidine solutions are prepared by mixing piperidine with deionized water. Predetermined amount of catalysts (ChCl-$C_3H_3AlO_6$) are added into the reactor. The mass flow controller is used to control flow rate of the simulated flue gas. H_2O is introduced into the inlet gas stream by a syringe pump The simulated flue gas is bubbled into piperidine solution via a corrosion-resistant muffler (<100 microns). The CO_2 concentration of the outlet gas of the reactor is measured with an inline gas analyzer, and the measured concentration-time profile is recorded by a data recording unit.

- **Desorption**: CO_2 desorption is realized by heating the spent sorbent obtained from CO_2 sorption step to a desired desorption temperature. A vacuum pump can be added to promoted the desorption. The desorbed CO_2 goes through a check valve and mixed with carrier gas (N_2) with a flow rate of 500 mL/min. The CO_2 concentration of the gas mixture is measured by an in-line gas analyzer. The quantity of CO_2 desorbed can be calculated by integrating the recorded CO_2 sorption profiles.

Project status

Capture of 400 ppm CO_2

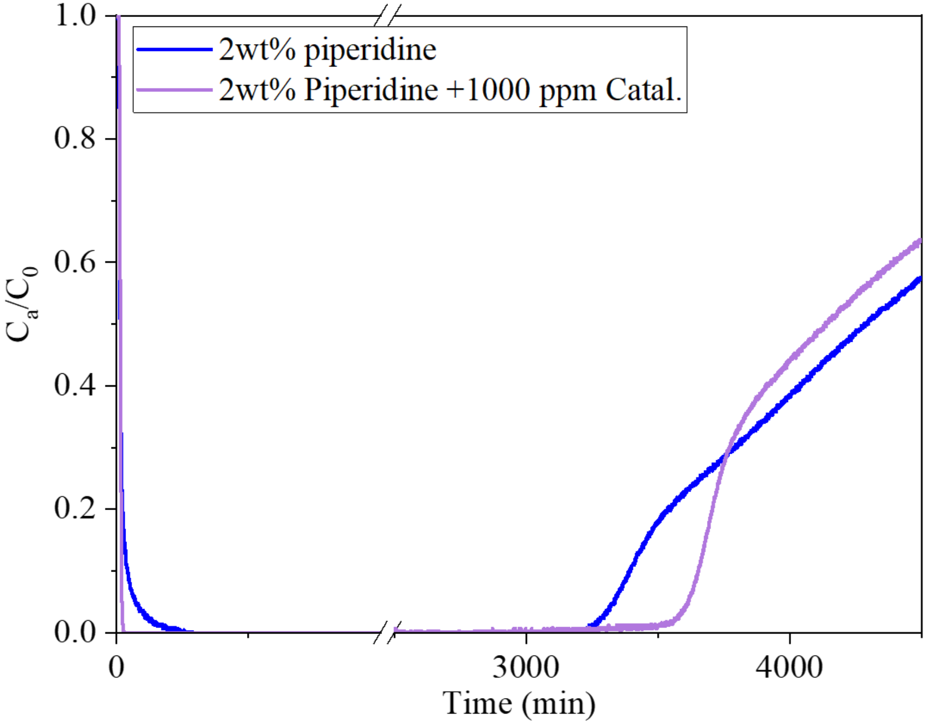


[Absorption conditions: Solution: 100 g; Piperidine/MEA concentration: 0.235mmol/g; 400 ppm CO_2; Flow rate of gas: 1,000 mL/min; Absorption temperature: 25 ^oC]

- Piperidine-based sorbent showed better CO_2 absorption performance than MEA-based sorbent, especially, the effective time for achieving 90% or 100% CO_2 absorption efficiency.
- Piperidine-based sorbent can keep achieving 100% CO_2 for 3200 min under tested conditions. MEA-based sorbent can not achieve 100% time.
- Piperidine-based sorbent can achieve >90% CO_2 absorption for 3300 min under tested conditions. MEA-based sorbent can achieve >90% CO_2 absorption 1600 min.

Project status

Capture of 400ppm CO_2

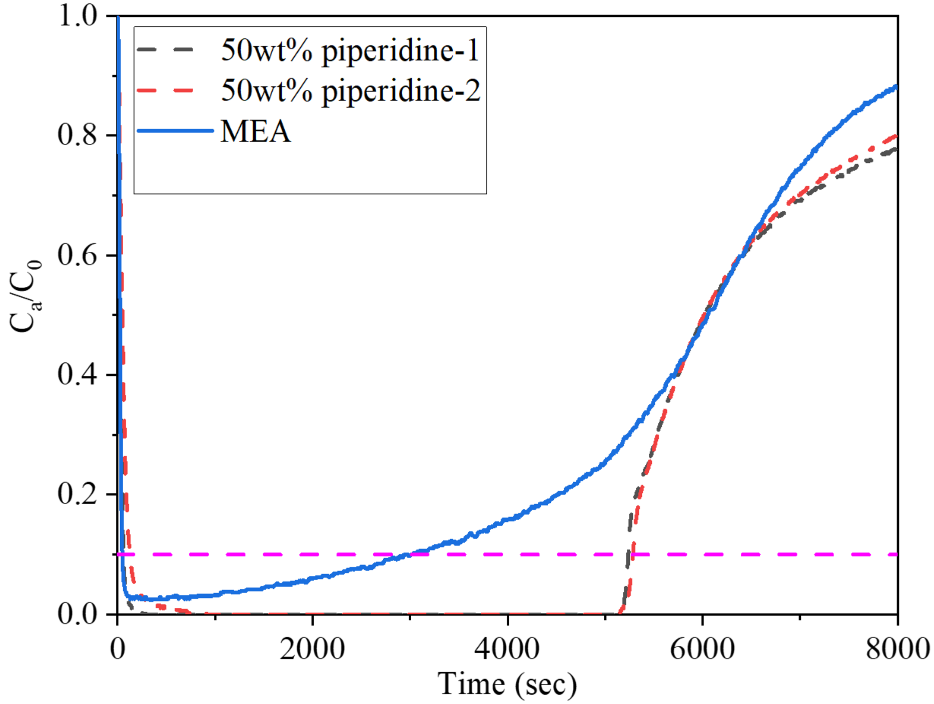


[Absorption conditions: Solution: 100 g; Piperidine/MEA concentration: 0.235mmol/g; 400 ppm CO_2; Flow rate of gas: 1,000 mL/min; Absorption temperature: 25 °C]

- 1000 ppm is the optimal catalyst loading for 2 wt% piperidine-based sorbent.

Project status

Capture of 10% CO_2

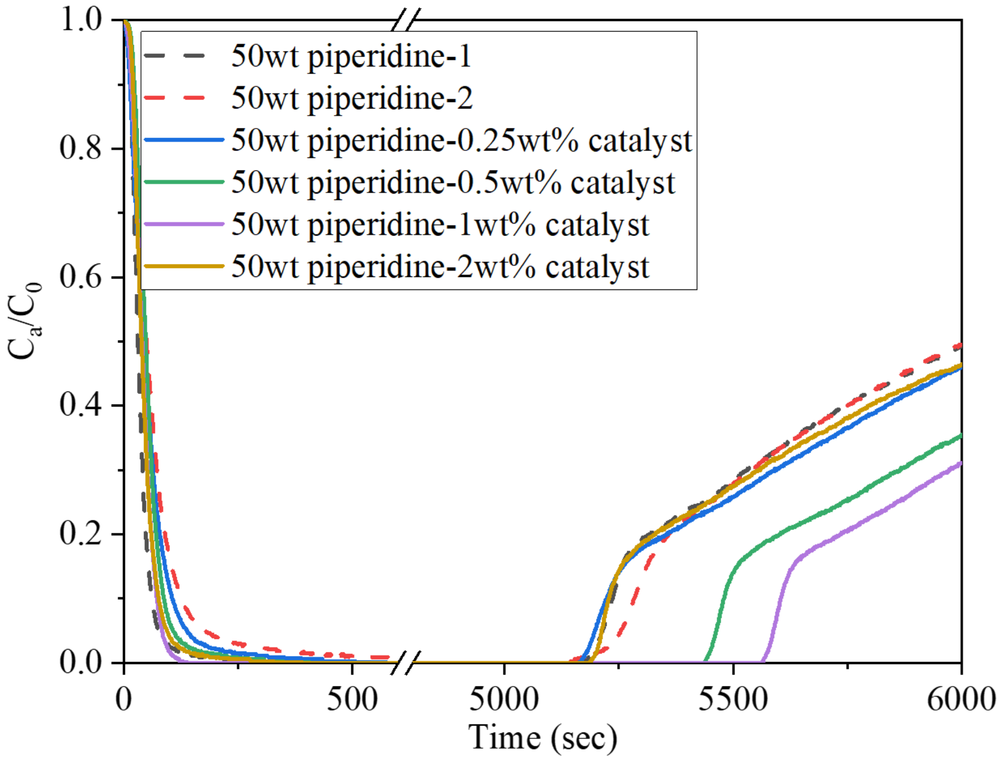


[Absorption conditions: Solution: 100 g; Piperidine/MEA concentration: 5.87mmol/g; 10% CO_2; Flow rate of gas: 1,000 mL/min; Absorption temperature: 25 ^oC]

- Piperidine-based sorbent showed better CO_2 absorption performance than MEA-based sorbent, especially, the effective time for achieving 90% or 100% CO_2 absorption efficiency.
- Piperidine-based sorbent can keep achieving 100% CO_2 for 5150 sec under tested conditions. MEA-based sorbent can not achieve 100% time.
- Piperidine-based sorbent can achieve >90% CO_2 absorption for 5200 sec under tested conditions. MEA-based sorbent can achieve >90% CO_2 absorption 3000 sec.

Project status

Capture of 10% CO_2

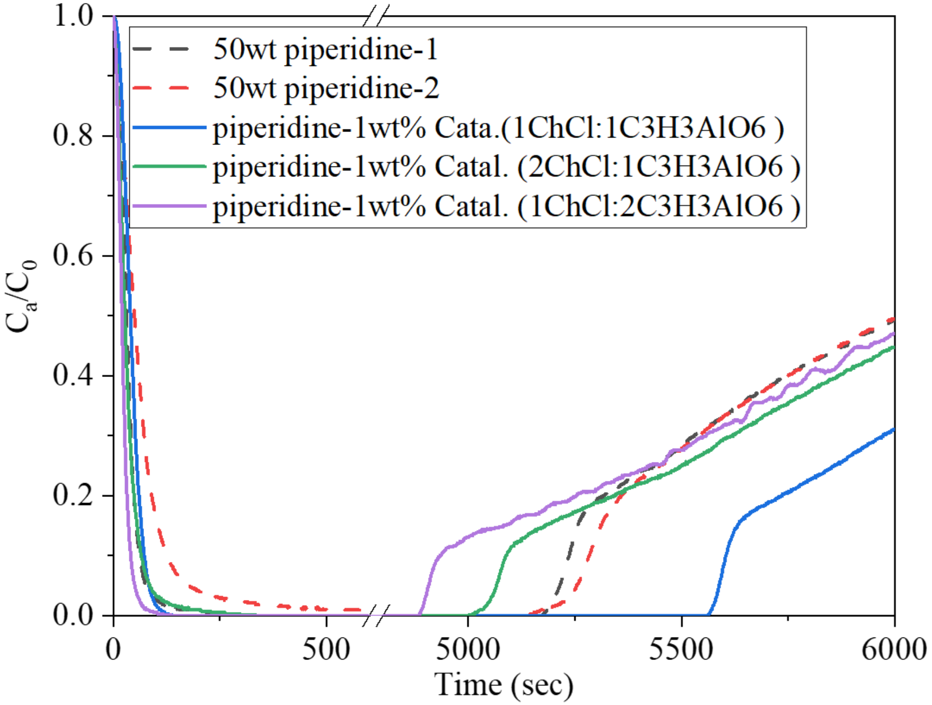


- 1wt% is the optimized catalyst loading for 50 wt% piperidine-based sorbent.

[Absorption conditions: Solution: 100 g; Piperidine concentration: 50 wt%; 10% CO_2; Catalyst with $1ChCl:1C_3H_3AlO_6$; Flow rate of gas: 1,000 mL/min; Absorption temperature: 25 ^oC]

Project status

Capture of 10% CO_2

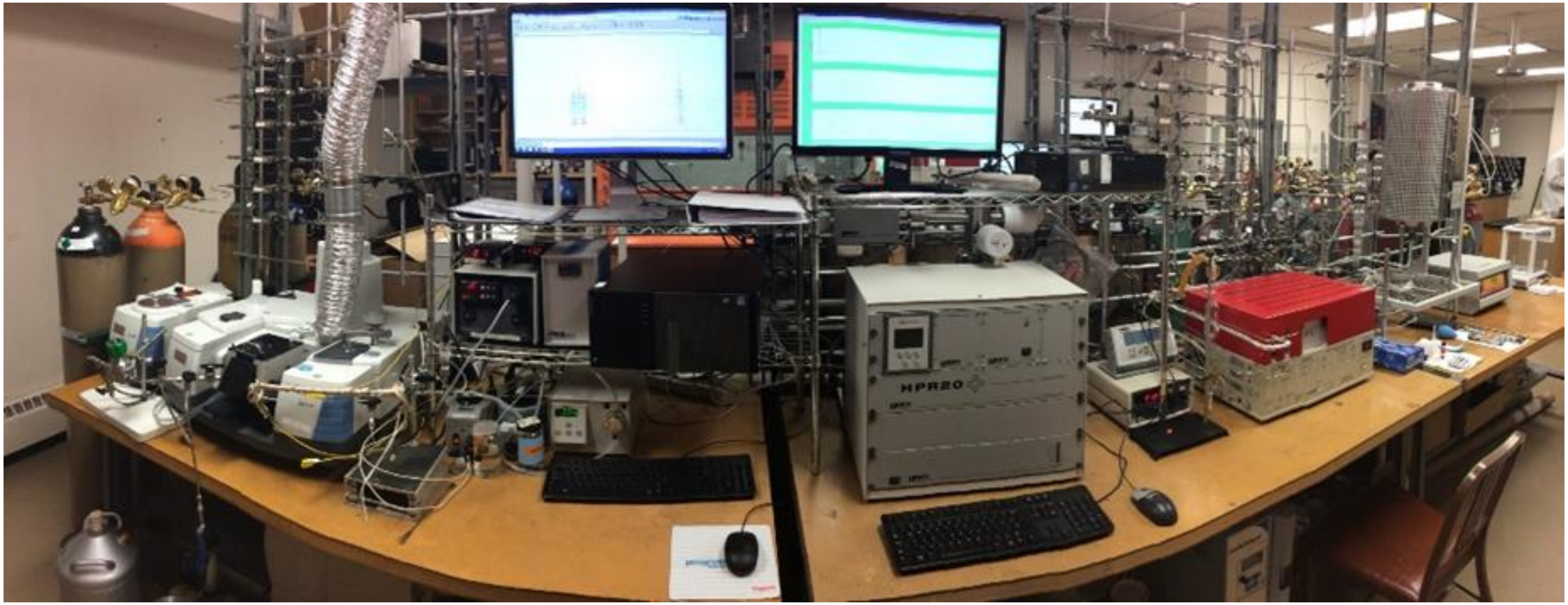


- 1ChCl:1$C_3H_3AlO_6$ is the best ratio for Piperidine-based sorbent.

[Absorption conditions: Solution: 100 g; Piperidine concentration: 50 wt%; 10% CO_2; Flow rate of gas: 1,000 mL/min; Absorption temperature: 25 ^{o}C]

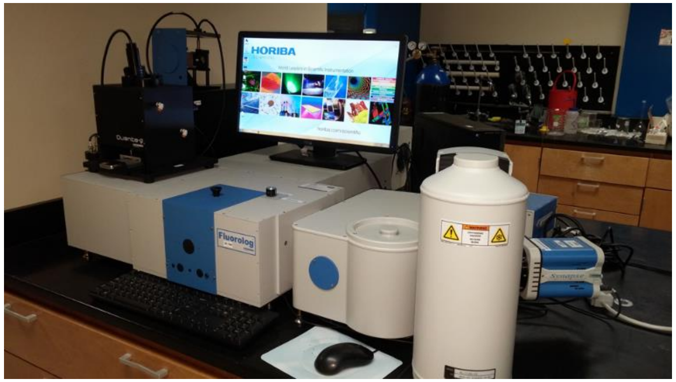
Project Status

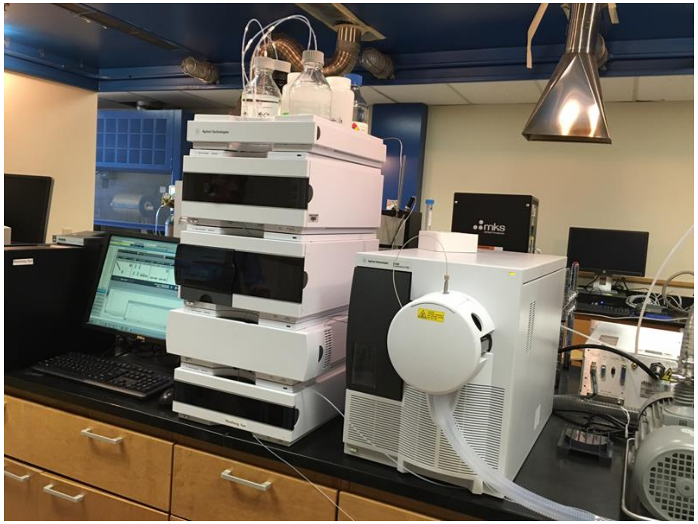
- FTIR based reaction mechanim study setup is ready

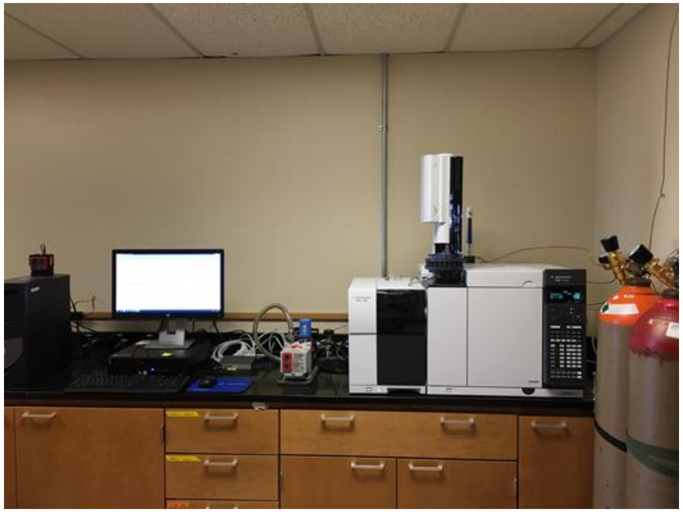


Project Status

- Other frequently used instruments for the project are ready







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- Carbon Capture Project Manager Dr Carl Laird at NETL
- Dr. Janice A. Steckel at all the people at NETL

for their guidance!

Questions? Please.