Fundamental Reservoir Properties for High Priority Depositional Environments Targeted for CO$_2$ Storage

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Program Overview

• 2016 - 2020
  – Development of fundamental understanding of how scCO\textsubscript{2} moves through, and is trapped in, storage environments.
    • scCO\textsubscript{2}/brine relative permeability database published
    • scCO\textsubscript{2}/brine trapping mechanisms described
    • core characterized and reports published
    • 3D printed fracture flow models developed
Program Overview

• TEAM: Angela Goodman, Johnathan Moore, Foad Haeri, Laura Dalton, Deepak Tapriyal, Sean Sanguinito, Cheng Chen, Scott Workman, Karl Jarvis, Terry McKisic, Bryan Tennant, Seth King, Jeong Choi, Fan Shi, John Baltrus, Lauren Burrows, Bret Howard, Christopher Matranga, and many more (full listing in the appendix!)

• OBJECTIVE: Understand and describe how real rocks from active and potential carbon storage locations interact with scCO$_2$ under real sequestration conditions
Technology Section

Real rocks, tested under carbon sequestration conditions in controlled systems.

Detailed understanding of trapping and flow, with quantified measurements.
Technical Approach/Project Scope

High level milestones for this project

1. Measure relative permeability of scCO₂/brine through various rock types and publish data and results.
2. Measure contact angles of scCO₂/brine in various rock types and publish results and methods.
3. Obtain core from relevant carbon storage formations, non-destructively characterize and publish technical reports on results.
4. Create 3D printed fractures from computed tomography data and show potential to directly measure flow through these systems.
Progress and Current Status of Project

1. Relative permeability of scCO$_2$/brine in various depositional environments
   a. Relative permeability ($k_r$) defines the movement of multiple fluids in a porous medium. $k_r$ is an imperfect descriptor for capturing the complexity of this behavior, but this is the nail that reservoir simulation hammers can hit.
   b. While there are multiple papers out in the public domain, there is a paucity of detailed data that enables researchers to review/confirm the accuracy of the $k_r$ measurement process.

2. Starting in 2017, we started a series of measurements using a combination of computed tomography scanning and controlled flow systems to measure the saturation of scCO$_2$ displacing brine in various rock cores.
   a. Various flow rates were examined to determine change in flow properties due to mass flux. Not typically captured or described, but we have seen an impact.
   b. Twelve different core types, with multiple flow rates for most, tested. Results for 34 individual tests fully characterized.
   c. Core properties (XRF, baseline permeability, porosity, etc) captured.
   d. Process for calculation of $k_r$ from raw data laid out.
Experimental system flow through system inside of medical computed tomography scanner.

Core Scan Results in volume transformed into slices; similar to loaf of bread.

Each slice has a thickness, known as Z in this instance and 0.5 mm.

Slices are comprised of voxels with a defined X & Y dimension in addition to the Z. The X/Y are 0.43 x 0.43 mm.
Progress and Current Status of Project

Data analysis process. Modified from Toth et al. (1998, 2002)
Progress and Current Status of Project

https://edx.netl.doe.gov/hosting/co2bra/

Data fully available on the CO₂ Brine Relative Permeability Accessible Database
Progress and Current Status of Project

Data fully available on the CO₂ Brine Relative Permeability Accessible Database

Baseline core characterization including elemental XRF, porosity, permeability and test conditions.


Dynamic CT derived scCO₂ saturation in the core.

https://edx.netl.doe.gov/hosting/co2bra/
Progress and Current Status of Project

- For the scCO\textsubscript{2}/brine a peer-reviewed publication describing the methodology and results has been submitted:

- Data is being mined for internal and external projects and publications derived from this work expected to continue for years.

- Side project, we’ve been able to measure $k_r$ as reactive flow changes the porosity of a carbonate system, which is very cool, informative, and not published elsewhere.
Measurement of scCO$_2$/brine contact angles under in situ conditions, both inside of pores and using traditional techniques, and coupling with pore scale simulations.
Progress and Current Status of Project

- Micro-CT scanner used to capture scCO$_2$ droplets under residual saturation conditions
  - Trapping shown to be influenced by pore structure.
  - Virtual reality used to measure angles with similar accuracy to standard methods, and faster.
  - Large variation in contact angles in situ; range of wettability types observed.
  - Additional water cycling shown to increase trapped scCO$_2$ volumes.
Progress and Current Status of Project

- More than 1100 sessile drop measurements of gas, liquid, and scCO₂
  - Samples are primarily water-wet with mean contact angle of 22°.
  - scCO₂ is more wetting than liquid or gas.
  - Surface roughness and localized heterogeneity play a role in contact angle variation, particularly for small bubbles.
Progress and Current Status of Project

- Porting digital core data to simulations has enabled impact of contact angle to $k_r$ examined.
  - Virginia Tech
  - Impact of localized low wettability clays shown to significantly decrease ability for scCO$_2$ migration

https://doi.org/10.1029/2020GL088545
Progress and Current Status of Project

Non-destructive core characterization and public reporting of results. Reports can be found at: [https://edx.netl.doe.gov/group/core-characterization](https://edx.netl.doe.gov/group/core-characterization)
Summary Slide

- Project ended in March 2020.
  Couple of reports and publications still working through the system.
- Full listing of publications in the presentation appendix.
  Average impact factor of journals where papers published is 3.2

Published Peer Reviewed Papers – 9
Conference Publications – 23
Published Technical Reports – 3
https://edx.netl.doe.gov/group/core-characterization

Online database of scCO$_2$/brine relative permeability data
https://edx.netl.doe.gov/hosting/co2bra/
scCO$_2$/brine relative permeability ($k_r$) curves developed for 12 different rocks.
  - Data made publicly available, [https://edx.netl.doe.gov/hosting/co2bra/](https://edx.netl.doe.gov/hosting/co2bra/)
  - Flow rate shown to influence $k_r$, generally higher flow rates result in more scCO$_2$ saturation and mobility.
  - Method for calculating $k_r$ during carbonate core dissolution developed and described.

scCO$_2$ contact angles in brine measured in cores and using sessile drop technique.
  - Pore structure and water cycling shown to influence trapped scCO$_2$ droplets.
  - Virtual reality measurement technique developed and proven.
  - Surface roughness shown to influence scCO$_2$ contact angles in sessile drops.
  - Coupling with simulations have shown influence of wettability alteration in constricting throats on $k_r$.

Non-destructive core characterization of relevant carbon storage formations completed and reported on.
  - Data publicly available, [https://edx.netl.doe.gov/group/core-characterization](https://edx.netl.doe.gov/group/core-characterization)
Appendix

– These slides will not be discussed during the presentation, **but** are mandatory.
Technical Transfer - 1

Peer Reviewed Publications

- 2017

- 2018

- 2019

- 2020

- Submitted and Under Review
  - Moore, J., Holcomb, P., Crandall, D., Choi, J., and Brown, S. (*submitted*) Rapid determination of relative permeability curves for brine and supercritical CO$_2$ systems using CT and unsteady state flow methods, *Fluids*
• Conferences (1)
  – 2016
  – 2017
    • Dalton, L.E., Crandall, D., Goodman, A. (March 2017) In situ contact angle measurements of supercritical CO2, brine, and sandstone cores using micro-CT imaging, 3rd Annual review meeting of the Energy Frontier Research Consortium GSCO2, March 29-30, Champaign IL
    • Dalton, L., Crandall, D., Goodman, A. (August 2017) In situ contact angle measurements of supercritical CO2, brine, and sandstone cores using micro-CT imaging, Microscopy and Microanalysis 2017, August 6-10, St. Louis, MO
• Conferences (2)
  – 2018
  – 2019
Published Technical Reports


Draft Reports

- CarbonSAFE Wabash core has been scanned
- Wellington 1-32 and 2-32 wells scanned and draft reports being generated
  - CO₂ site run by Kansas Geological Survey in the queue
Organization Chart

- Dustin Crandall, Angela Goodman, Christopher Matranga, Bret Howard, John Baltrus, Yee Soong – US DOE NETL
- Johnathan Moore, Foad Haeri, Laura Dalton, Deepak Tapriyal, Sean Sanguinito, Karl Jarvis, Tom Paronish, Sarah Brown, Terry McKisic, Seth King, Jeong Choi, Fan Shi, Lauren Burrows – LRST NETL
- Rhiannon Schmitt, Paige Mackey, John Tudek, William Harbert – ORISE NETL
- Jamie Vornlocher, Charity Betters – MLEF NETL
- Scott Workman, Bryan Tennant – SOS NETL
- Samantha Fuchs – ORISE NETL/UT Austin
- Cheng Chen, Ruichang Guo, Ming Fan, James McClure – UCFER NETL/Virginia Tech
Gantt Chart

<table>
<thead>
<tr>
<th>Research Activities</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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<tbody>
<tr>
<td></td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
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<tr>
<td>Subtask 17.1.1 – Relative Permeability Data Generation</td>
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<td>Subtask 17.1.2 – Micro-scale displacement efficiency</td>
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<td>Subtask 17.1.3 – Contact angle measurement</td>
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<td>Subtask 17.1.4 – Core acquisition and tool development</td>
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<td>Subtask 17.1.5 – Fracture Flow</td>
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Milestones

1. Perform final full relative permeability tests of depositional environments at scCO2 conditions. (April ‘19)
2. Complete lattice Boltzmann simulations of scCO2/brine flow through umCT geometry at conditions of experiment. (December ‘18)
3. Development of relative permeability curves from lattice Boltzmann simulations that illustrate the influence of contact angle variation. (July ‘19)
4. Submission of peer reviewed manuscript that describes the influence of contact angle variation on trapping efficiencies in reservoirs. (April ‘20)
5. Complete shakedown of reactor cell and perform 6 in situ contact angle measurements on a synthetic mineral substrate. (December ‘18)
6. Completed contact angle measurements of scCO2/brine on reservoir rocks (June ‘19)
7. A written report and slide deck of how this approach can be used to correlate surface chemistry, surface composition, and surface roughness with wettability and relative permeability. (December ‘19)
9. Final relative permeability values incorporated into tool. (March ’19)
10. Calculation of relative permeability curve in 3D printed fracture from experimental data. (April ’19)
11. Experiments in 3D printed fracture completed with 3 different pairs of immiscible fluid. (September ’19)
12. Submission of manuscript describing the influence of fracture properties on multiphase flow transport. (April ’20)

Go / No-Go

Full descriptions in subtask details.
17.1.2 – Dec ’18 No-Go if simulated results do not match experimental results.
17.1.3 – March ’19 No-Go if experimental results do not provide insight into surface chemistry, roughness, and composition.
17.1.5 – March ’19 No-Go if k, curves in 3D printed fracture not obtained

Impact

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<th>Accomplishments</th>
<th>Value Delivered</th>
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<td>Fundamental measurements of CO2/brine/reservoir rock to understand how trapping and flow occurs at real conditions</td>
<td>Functional, open, and comprehensive database of flow parameters needed for accurate reservoir simulation</td>
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Key Accomplishments/Deliverables

- Over the past year five different depositional environments have been successfully tested using the techniques developed at NETL.
- Fundamental measurements of scCO2 contact angles were obtained inside pores and with traditional methods:
- 3D printed model of a CT scanned rock fracture was developed and used to test flow properties.
- The product of this work is to deliver a database with measurements of relative permeability, residual saturation, and wettability for high priority depositional environments targeted for CO2 storage and accessible tools for reservoir modelers to access this data and reduce uncertainty in their estimates.