Carbon Dioxide Capture and Sequestration in Saline Aquifers: Fundamental Studies of Multi-Phase Flow of CO$_2$ and Brine

Sally M. Benson, Jean-Christophe Perrin, Ljuba Miljkovic, Ethan Chabora, Michael Krause, and Chia-Wei Kuo
Energy Resources Engineering Department
Executive Director, Global Climate and Energy Project
Stanford University
Topics

• Motivation and importance of CCS
• Sequestration options
• Rationale for a focus on saline aquifers
• Key questions for saline aquifer storage
• Multi-phase flow investigations for CO₂ and brine
Large Point Sources are Create the Majority of CO$_2$ Emissions

- 60% of global fossil fuel emissions come from large stationary sources
- 40.5% from coal, mostly for power generation
- Fraction could be much greater if we adopt electric cars with fossil fuel based electricity production
Carbon Dioxide Capture and Geologic Sequestration is a Way to Reduce Emissions

Capture → Compression → Pipeline Transport → Underground Injection
Options for CO$_2$ Sequestration

Overview of Geological Storage Options

1. Depleted oil and gas reservoirs
2. Use of CO$_2$ in enhanced oil and gas recovery
3. Deep saline formations - (a) offshore (b) onshore
4. Use of CO$_2$ in enhanced coal bed methane recovery
Why Saline Aquifers?
Widespread Global Distribution

Saline aquifers in sedimentary basins are widely distributed and co-located with many CO$_2$ sources.

IPCC, 2005
Why Saline Aquifers?  
Largest Capacity

<table>
<thead>
<tr>
<th>Reservoir Type</th>
<th>Lower Estimate of Global Storage Capacity (GtCO₂)</th>
<th>Upper Estimate of Global Storage Capacity (GtCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil and gas fields</td>
<td>675&lt;sup&gt;a&lt;/sup&gt;</td>
<td>900&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Coal seams (ECBM)</td>
<td>3–15</td>
<td>200</td>
</tr>
<tr>
<td>Saline aquifers</td>
<td>1000</td>
<td>~10,000</td>
</tr>
</tbody>
</table>

<sup>a</sup> Estimates would be 25% larger if undiscovered reserves were included.  
IPCC, 2005

920 to 3,380 Gt CO₂  
Current U.S. Saline Aquifer Capacity Estimates (U.S. DOE)
Some Key Questions for Saline Aquifer Storage

- What fraction of the pore space can be used for storage?
- How far will the CO$_2$ move from the injection site?
- What is the long term fate of CO$_2$?
- Where does the displaced brine go?
- What is the risk of CO$_2$ leakage?

X-ray image of CO$_2$ in a saline aquifer
Questions Are Usually Answered Using Numerical Simulation

Geological Model

Depositional Setting
- B: Barrier bar
- D: Distributary channel
- BF: Interdistributary bay fill

Facies
- Barrier core
- Channel
- Splay-3
- Washover
- Splay-1
- Shelf

Simulation Results

Rock Parameters

- Permeability, $k$
- Porosity, $\phi$
- Relative permeability, $k_r$
- Capillary pressure, $P_c$

1 yr, 2 yrs, 5 yrs, 10 yrs, 20 yrs, 21 yrs, 25 yrs, 30 yrs, 50 yrs
Relative Permeability and Capillary Pressure Curves

Relative Permeability Curves for Multiphase Flow of CO$_2$ and Brine
Relative Permeability Curves

- CO₂
- Brine
Early Experimental Results: Small-Scale CO₂ Saturation Variations

Sub-corescale saturation variations generally overlooked in relative permeability measurements.

CO₂ Saturation:

- 0%
- 25%
- 50%
- 75%
- 100%
Simulated CO$_2$ Saturations

Variable $P_c$ Produces Small-scale CO$_2$ Saturation Variations

<table>
<thead>
<tr>
<th></th>
<th>Lab Data</th>
<th>Variable $\Phi$, $k$ Simulations</th>
<th>Variable $P_c$ Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% CO$_2$</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>90% CO$_2$</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>100% CO$_2$</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

CO$_2$ Saturation: 0% - 70%
Develop the ability to predict the spatial and temporal distribution of CO₂ saturation and trapping through an improved understanding of the pore and core scale physics over the life cycle of a sequestration project.
Schematic of Multi-Phase Flow Apparatus

- **CO₂ tank**
- **CO₂**
- **Brine**
- **T°= 5°C**
- **T°res**
- **T°room**
- **CO₂ Brine**
- **T° room**
- **back pressure Ppore**
- **confining pressure Pres**

**Key Components:**
- **Pressure transducer**
- **Relief valve**
- **Manual on/off valve**
- **Electric on/off valve**
- **Filter**
- **Check valve**
- **3-way valve**

**Flow Paths:**
- CO₂ tank to core holder
- CO₂ to separator
- Brine to core holder
- CO₂ and Brine to T°room
- T°room to back pressure

**Temperature:**
- T° = 5°C
Multi-Phase Flow Laboratory

Replicate *in situ* conditions
- Pressure
- Temperature
- Brine composition
Influence of Rock Heterogeneity

\[ f_{\text{CO}_2} = 50\% \]

\[ S_{\text{CO}_2} = 23.50\% \]

\[ S_{\text{CO}_2} = 41.40\% \]

Waare C Sandstone
Berea sandstone – “Homogeneous”
Porosity and permeability have important spatial variations due to the pore-scale structure of the rock sample.

- Slice-averaged values are relatively constant along the core.
Injection of 100% CO$_2$ @ 2mL/min

<table>
<thead>
<tr>
<th># pore volumes</th>
<th>0.88</th>
<th>2.06</th>
<th>3.38</th>
<th>5.29</th>
</tr>
</thead>
</table>

- The steady state is reached after ~ 5 pore volumes
- To be sure to always reach steady state $\Delta P$ and $S_{CO_2}$ are measured after having injected 8-10 pore volumes of fluid.
Effect of Flow Rate

![Graph showing CO₂ saturation vs. flow rate with different flow rates: 2.6 ml/min, 1.2 ml/min, and 0.5 ml/min. The graphs illustrate the CO₂ saturation levels at each flow rate with corresponding flow rate markers (f_CO₂ = 1, f_CO₂ = 0.60, f_CO₂ = 0.34, f_CO₂ = 0.25).]
Flow Rate Dependent Relative Permeability Curves

- Flow rate = 2.6 mL/min -

- Flow rate = 1.2 mL/min -
Petrophysical Characterization

Porosity Map

Analysis of Pore Space

Thin Section

Model 1

Model 2
Simulation of Saturation Distributions

Model A

Model B

Model C

Model D

Model E

Model F
Next Steps

- History matching experiments
- Sensitivity analysis
- Simulation artifacts
- Implication for large scale processes

- Test other types of rocks
- Continue to investigate flow-rate dependence with more experiments on additional rocks
- Tests with vertical orientation

- Numerical simulations

- Core-scale multiphase flow experiments

- Multiphase flow theory
- Petrophysical characterization

- Theoretical foundation for observed multi-phase flows
- Parametric formulation for rate dependent relative permeability curves

- Reliable methods for permeability mapping
- Reliable methods for capillary pressure mapping
Acknowledgements

• Post Doc – Jean-Christophe Perrin
• Research Associate – Ljuba Miljkovic
• Graduate Students – Michael Krause, Chia-Wei Kuo, Ethan Chabora
• ERE Department
  – Tony Kovišek, Louis Castanier, Roland Horne
• GCEP sponsors
  – ExxonMobil, Schlumberger, Toyota, GE