Relative Permeability and Capillary Pressure Controls on CO$_2$ Migration and Brine Displacement

Sally M. Benson$^1$
Ljuba Miljkovic$^2$, Liviu Tomutsa$^2$ and Christine Doughty$^2$

$^1$Energy Resources Engineering Dept., Stanford University
$^2$Earth Sciences Division, Lawrence Berkeley National Laboratory
Acknowledgements

- Funded by DOE Fossil Energy through the Zero Emissions Research and Technology Program (ZERT)
- Outstanding co-authors from Lawrence Berkeley National Laboratory
  - Ljuba Miljkovic
  - Liviu Tomutsa
  - Christine Doughty
Some Key Issues for CO$_2$ Storage in Deep Saline Aquifers

- What fraction of the pore space can be filled with CO$_2$?
- How big will the CO$_2$ plume be?
- How much CO$_2$ will be dissolved?
- How much will capillary trapping immobilize CO$_2$?
- Can accurate models be developed to predict CO$_2$ fate and transport?

Answering these questions depends on the complex interplay of viscous, capillary, buoyancy forces and heterogeneity and structure on CO$_2$ plume migration.
Core-flood Set-Up for Relative Permeability Measurements

- Brine composition: CO₂ saturated brine with 0.5 molar potassium iodide
- Overburden Pressure: 100 bars
- Differential Pressure Transducer
- Pressure Data Acquisition
- Room Temperature: 16.5° C
- Constant Pressure (65 bars)

\[ \frac{\mu_w}{\mu_{CO_2}} = 14.3 \]
Core-Scale Imaging of CO$_2$ Distributions

High Pressure Pumps

Core Holder In Scanner
CT Scans Measure Core Porosity

Core Length (cm)

Porosity

\[ \bar{\phi} = 0.22 \]
Calculation of Permeability

\[ k_i = \frac{\phi_i^3}{S(1 - \phi_i)^2} \]

Porosity

Kozeny-Carmen

Permeability
Laboratory Injections of Various CO$_2$-Brine Proportions

- **Experimental Setup:**
  - 5%, 10%, 20%, 50%, 80%, 90%, 100% CO$_2$ injections
  - 3mL/min constant flow-rate
  - 6.89MPa constant back-pressure
  - 16 ±2°C lab temperature
  - Brine contains dissolved CO$_2$
  - CO$_2$ contains dissolved water

- **Measure CO$_2$ Saturation with CT Scanner**
  - Digitally reconstruct image
Small-scale CO$_2$ Saturation Variations

Sub-corescale saturation variations generally overlooked in relative permeability measurements.
Simulated Injection of Various CO$_2$-Brine Proportions

• Simulation Cases
  ➢ 10%, 90%, 100% CO$_2$ injections
  ➢ 3mL/min constant flow-rate
  ➢ 6.89MPa constant back-pressure
  ➢ 16°C constant temperature
  ➢ Brine contains dissolved CO$_2$
  ➢ CO$_2$ contains dissolved water

• Core Characterization
  ➢ Porosity/permeability “map” coarsened
  ➢ Relative permeability/capillary pressure curves matched to experimental curves

• TOUGH2 (Pruess, LBNL)
Simulated CO₂ Saturations

Constant P_c Produces Homogeneous CO₂ Saturations

<table>
<thead>
<tr>
<th>10% CO₂</th>
<th>90% CO₂</th>
<th>100% CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Data</td>
<td>Homogeneous Simulations</td>
<td>Variable Φ, k Simulations</td>
</tr>
</tbody>
</table>

CO₂ Saturation: 0% - 70%
Fitting Capillary Pressure Curve

\[ P_{c,i} \propto \sqrt{\frac{\Phi_i}{k_i}} \]

\[ \bar{P}_{cap} = 4500 \text{Pa} \]

given 20% CO₂

*Silin et al. (submitted, 2007)*
Simulated CO₂ Saturations

Variable P_c Produces Small-scale CO₂ Saturation Variations

![Diagram showing CO₂ saturations for different percentages of CO₂ in simulations and lab data.](image-url)
Capillary Pressure Curve

Capillary Pressure Curve (P_cap) vs. Brine Saturation.

- **Avg. P_c**: Φ=.22 k=301 mD
- **P_c Envelope**

**CO₂ Saturation:**
- 0% to 70%
- 100% CO₂
- 90% CO₂
- 10% CO₂

Graph shows data points color-coded for CO₂ saturation and brine saturation ranges.
Why should we care?
Why Should We Care?

Average CO$_2$ saturation is:

- Decreased by sub-corescale heterogeneity
- Flow-rate dependent
- Affected by simulation grid resolution
Subcore-scale Heterogeneity Decreases CO₂ Saturation

Length Along Core (cm)

CO₂ Saturation

100% CO₂ Injection

90% CO₂ Injection

10% CO₂ Injection
Effects of Flow Rate on CO₂ Saturation
90% CO₂ Injection Simulation

- Relative Permeability vs. Brine Saturation
- Fractional Flow (CO₂) vs. CO₂ Saturation
- Injection Rate vs. Distance from Well (m)

Graphs show the relationship between flow rate and CO₂ saturation, with the injection rate decreasing significantly as the distance from the well increases. The plots also illustrate the impact of varying flow rates on the permeability and fractional flow, indicating a complex interplay between these factors and the overall efficiency of CO₂ injection.
Capillary Pressure Distribution at Different Flow Rates

Capillary Pressure Curves:
- Average: $\phi=0.22$ $k=206\text{mD}$
- Upper Bound: $\phi=0.12$ $k=35.7\text{mD}$
- Lower Bound: $\phi=0.25$ $k=444\text{mD}$

- 9 mL/min
- 3 mL/min
- 0.3 mL/min
- 0.065 mL/min
- 0.03 mL/min
- 0.01 mL/min
90% CO$_2$, 10% Brine Injection
Variable Simulation Resolutions

Grid Size: 0.6×0.6×3mm
Grid Count: 67,350

Grid Size: 1×1×3mm
Grid Count: 23,400

Grid Size: 2×2×3mm
Grid Count: 5,400
Finer Simulation Grids Decrease CO$_2$ Saturation

![Graph showing CO$_2$ Saturation vs. Length Along Core (cm)]
Conclusions

- Core-scale multi-phase flow experiments reveal strong influence of sub core-scale heterogeneity
- Spatial variations in capillary pressure behavior control CO$_2$ saturations
- CO$_2$ saturation:
  - Decreases due to bypass of low porosity regions
  - Decreases at lower flow rates
  - Predictions depend on grid size
- Similar phenomena are expected at all spatial scales
- Fundamental research needed to improve model predictions
  - Fundamental process understanding based on lab and field experiments
  - Up-scaling strategies that accurately include the effects of sub-grid scale heterogeneity
  - Calibration and validation of predictive models