Modeling Sub-Core Scale Permeability Distributions in Sandstone Cores

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Science and technology for a low GHG emission world.
Motivation

What are we doing?
- Conduct CO\textsubscript{2}-brine core flooding experiments at reservoir conditions
- Conduct simulations of CO\textsubscript{2}-brine core flooding experiments
- Study the effects of relative permeability, capillary pressure and heterogeneity on the distribution of CO\textsubscript{2} at the sub-core scale

Why are we doing it?
- Experimental results provides saturation distribution in actual rock cores
- Investigate sensitivity of saturation distributions to rock and fluid properties
- Enable development of methods to accurately predict CO\textsubscript{2} distribution
Recap - Experiments

Experiments
Simulation
Input
Permeability
Simulation
Results

Steady State Saturation at 100% CO$_2$
Injection

Inject Supercritical CO$_2$

Porosity

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Recap - Simulations

- Experiments
- Simulation Input
- Permeability
- Simulation Results

**Relative Permeability**

- Core-Average
- Porosity
- Unique Values

**Capillary Pressure**

- Unique Curves
- Simulation Grid
Recap - Permeability

Porosity Method

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

Equations Tested

1. \[ k_i = c_o \frac{\phi_i^{3}}{(1 - \phi_i)^2} \]
2. \[ k_i = c_o \frac{\phi_i^{1.42}}{(1 - \phi_i)^2} \]
3. \[ k_i = c_o \frac{\phi_i^{5}}{(1 - \phi_i)^2} \]
4. \[ k_i = c_o \frac{(\phi_i - \phi_c)^3}{(1 - \phi_i + \phi_c)^2} \]
5. \[ k_i = c_o \left(6.2\phi_i + 1493\phi_i^2 + 58(10\phi_i)^{10}\right) \]

*Krause, M.H., Perrin, J.-C., & Benson, S.M.  2009. Modeling Permeability Distributions in a Sandstone Core for History Matching Coreflood Experiments. SPE #126340*
Conclusions:
- No qualitative match between simulations and experiment
- No statistical correlation between simulations and experiment
- Core-average match is good, but porosity-based methods are not accurate at sub-core scale

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Sub-Core CO₂ Saturation $R^2$</th>
<th>Core ΔP Error (%)</th>
<th>Core $S_{CO₂}$ Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.004</td>
<td>-3.50</td>
<td>4.59</td>
</tr>
<tr>
<td>2</td>
<td>0.003</td>
<td>-1.77</td>
<td>3.61</td>
</tr>
<tr>
<td>3</td>
<td>-0.045</td>
<td>-5.91</td>
<td>5.62</td>
</tr>
<tr>
<td>4</td>
<td>-0.022</td>
<td>-4.28</td>
<td>4.89</td>
</tr>
<tr>
<td>5</td>
<td>-0.133</td>
<td>-10.21</td>
<td>7.10</td>
</tr>
</tbody>
</table>

*Simulation numbers correspond to equation numbers
Revisit - Permeability

**Porosity Method**

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

**Cap. Pressure Method**

\[ k_i = c_o \frac{1}{P_c^2} \phi_i \left[ J(S_{w,i})^2 \right] (\sigma \cos \theta)^2 \]
Calculate $J(S_w, i)$

Measure $S_{CO2,i}$

Measure $\phi_i$

Measure Capillary Pressure

$P_c = \sigma \cos \theta \sqrt{\frac{\phi}{k} J(S_w)}$

Calculate $J(S_w, i)$

$J(S_{w,i}) = A\left(\frac{1}{S_{*,i}^{1/\lambda_1}} - 1\right) + B\left(1 - S_{*,i}^{1/\lambda_2}\right)^{1/\lambda_2}$

Calculate $k_i$

$k_i = c_o \frac{1}{P_c^2} \phi_i \left[J(S_{w,i})^2\right] (\sigma \cos \theta)^2$
$\sigma = 0.1564$

Experiment

$\sigma = 0.0974$

$P_c$ Result (12)

$\sigma = 0.0441$

“Best” $\phi$-Based Result (5)
Conclusions:

- Clear correlation between experimental measurement and numerical prediction
- Statistically significant match of both core and sub-core scale experimental measurements

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Sub-Core CO₂ Saturation R²</th>
<th>Core ΔP Error (%)</th>
<th>Core S&lt;sub&gt;CO₂&lt;/sub&gt; Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.620</td>
<td>-8.87</td>
<td>6.03</td>
</tr>
<tr>
<td>7</td>
<td>0.744</td>
<td>-6.37</td>
<td>2.73</td>
</tr>
<tr>
<td>9</td>
<td>0.664</td>
<td>-8.47</td>
<td>5.27</td>
</tr>
<tr>
<td>10</td>
<td>0.731</td>
<td>-5.76</td>
<td>2.43</td>
</tr>
<tr>
<td>11</td>
<td>0.779</td>
<td>-7.08</td>
<td>2.68</td>
</tr>
<tr>
<td>12</td>
<td>0.805</td>
<td>0.03</td>
<td>-3.21</td>
</tr>
</tbody>
</table>

* Difference in simulations is just J-function fitting parameters A, B, λ₁, λ₂
How Important is Grid Size?

Grid Size Effect – do porosity-based and Pc-based methods produce similar sub-core scale results as the grid coarsens?

$P_c$-Method Permeability

$$k_i = c_o \frac{1}{P^2} \phi_i \left[ J(S_{w,i})^2 \right] (\sigma \cos \theta)^2$$

Porosity-Method Low Contrast Perm.

$$k_i = c_o \left( \frac{\phi_i^{1.42}}{(1- \phi_i)^2} \right)$$

Porosity-Method High Contrast Perm.

$$k_i = c_o \left( 6.2 \phi_i + 1493 \phi_i^2 + 58(10\phi_i)^{10} \right)$$
Comparison of Grid Size Results

- $P_c$-method results are most accurate at all grid resolutions.
- $P_c$-method results are most accurate at fine resolution.
- Low contrast porosity-method increases in accuracy at low grid resolution.
- High contrast porosity-method does not increase in accuracy at low grid resolution.

![Comparison of $R^2$ Values for Different Upscaling](image)

**Legend**
- Blue dots: Porosity Low Contrast
- Red dots: Porosity High Contrast
- Green dots: $P_c$ "Best" Fit

*Comparison of $R^2$ Values for Different Upscaling*
What About More Heterogeneity?

- Otway Basin Pilot Project core
- Very heterogeneous sandstone
- Test the limits of the method and core flooding simulations

Thin Section Images

1.27 mm

2.0 mm

3.0 mm

Porosity Image

Sat. at 100% CO₂ Injection

Simulation Grid

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What about Heterogeneity?

- Similar trend to homogeneous Berea
- Good qualitative and quantitative match

Simulation Experiment

Saturation Comparison in Slice 3

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Conclusions & Future Work

- $P_c$-based permeability methods are more accurate than simple porosity-based methods.
- $P_c$-based permeability distributions have high accuracy across a range of grid resolution.
- Porosity-based method results do not approach $P_c$-based method results as the grid coarsens.
- Method is still robust for highly heterogeneous cores.
- Improvement at high saturation is still required.
Future Work and Questions

● Future Work
  ● Introduce variable relative permeability curves
  ● Verify our solutions are correct for different flow scenarios
  ● Study integration of sub-core and core scale knowledge to reservoir-scale problems

● Acknowledgements
  ● Jean-Christophe Perrin for conducting the experiments
  ● GCEP for sponsoring the work
## Supplemental Data

<table>
<thead>
<tr>
<th>Property</th>
<th>Homogeneous Berea</th>
<th>Heterogeneous Otway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>12.41 MPa</td>
<td>12.41 MPa</td>
</tr>
<tr>
<td>Temperature</td>
<td>50C</td>
<td>63C</td>
</tr>
<tr>
<td>Salinity</td>
<td>6500 ppm NaCl</td>
<td>6500 ppm NaCl</td>
</tr>
<tr>
<td>Injection Rate</td>
<td>3 ml/min</td>
<td>3 ml/min</td>
</tr>
<tr>
<td>Grid Element Size</td>
<td>1.27mm x 1.27mm x 3mm</td>
<td>1mm x 1mm x 2mm</td>
</tr>
<tr>
<td>$\phi_{\text{core}}$</td>
<td>18.49%</td>
<td>18.04%</td>
</tr>
<tr>
<td>Core Average Permeability</td>
<td>85 md</td>
<td>62.3 md</td>
</tr>
<tr>
<td>Length</td>
<td>20.2 cm</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>5.08 cm</td>
<td>5.08 cm</td>
</tr>
</tbody>
</table>