Optimization of Geological Storage of CO₂ and Enhanced Oil Recovery

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Outline

- Research Objectives and Methodology
- General Background
- Model Validation and Small-scale Simulation Studies
- Experimental Design and Method of Response Surfaces
- Field-Scale Water-Alternating-Gas (WAG) Simulations
- Summary and Conclusions
Research Objectives and Methodology

Objective
- Investigate effect of hysteresis and Water-Alternating-Gas process (WAG) parameters to optimize oil recovery and amount of CO$_2$ sequestered in compositional simulation of 3D heterogeneous fields

Methodology
- Sensitivity analysis is preformed to investigate the effect of uncertainties in the considered parameters

- Apply statistical analysis such as Design of Experiment (DOE) and Method of Response Surfaces (MRS) to achieve efficient studies
Coupled CO₂ Sequestration and EOR

- **Enhanced Oil Recovery Goals**
  - Maximize Oil Recovery
  - Minimize Amount of CO₂ Injected
  - Maximize Profit

- **Geological CO₂ Sequestration Goals**
  - Maximize Amount of CO₂ Sequestered
  - Store for Thousands of Years without Leakage
  - Minimize Costs

- **Co-optimization Is Needed to Meet Both Goals**
Simulator Description

- Compositional Equation of State Model (PR-EOS)
- Multidimensional, Multicomponent, Multiphase
- Hysteresis in Relative Permeability
- Solubility of CO$_2$ in Brine
- Geochemistry Models (GEM-GHG)
  - Precipitation reactions & Dissolution
- Explicit, Fully Implicit, and Adaptive Implicit Formulations
- Handling Complex Reservoirs
  - ✓ Corner Point Grid Blocks
  - ✓ Local and Hybrid Grid Refinement
Hysteresis Model

- **Modified Land’s Equation:**

\[
\frac{1}{S_{gr}^{\text{max}}} - \frac{1}{S_g^{\text{max}}} = \frac{1}{S_{grh}} - \frac{1}{S_{gh}}
\]

- Correlation between maximum residual gas saturation, \(S_{gr}^{\text{max}}\), and porosity

![Graph showing the correlation between maximum residual gas saturation and porosity](image)

- Jerauld's experiment
- Simulated values

- Text:
  - Modified land's equation
  - Fontainebleau Holtz (2002)
Hysteresis in Gas Relative Permeability

Jerauld's (1996) Gas Relative Permeability Model

\[ k_{rg} = \frac{(1 + C_{g2}) \left( \frac{S_g(\text{shifted}) - S_{gr}}{1 - S_{gr}} \right)^{C_{g1}}}{1 + C_{g2} \left( \frac{S_g(\text{shifted}) - S_{gr}}{1 - S_{gr}} \right)^{C_{g1}(1+1/C_{g2})}} \]

\[ S_g(\text{shifted}) = S_{gr} + \frac{(S_g - S_{grh})(S_{gh} - S_{gr})}{(S_{gh} - S_{grh})} \]
Convergence of 2D Simulations

2-D Cross section of permeability field in oil reservoir

Oil Production Well

CO2 Injection Well

Oil Recovery, % OOIP

Waterflooding
WAG With Hystres.

1/Nx

0.004 0.008 0.012 0.016 0.02

0 10 20 30 40 50 60

Waterflooding
WAG With Hystres.

1/Nz

0 0.02 0.04 0.06 0.08 0.1

0 10 20 30 40 50 60
2-D Cross-sectional Simulations of CO2 Injection with a WAG Ratio of 1 with a max GOR=30 MCF

- **Sensitivity of Oil Recovery to Hysteresis**
- **Sensitivity of Ave. CO2 Saturation to Hysteresis**

![Graphs showing the comparison between Average CO2 Saturation and Cumulative Oil SC with and without hysteresis.](image-url)
Gas Saturation Distribution

- Production Well
- Injection Well
- Gas (CO₂) Saturation (Historical maximum)
- Trapped Gas (CO₂) Saturation
Field-Scale Simulations

- Quantifying the effect of WAG parameters (e.g. WAG ratio and CO₂ slug size) and hysteresis as well as reservoir heterogeneity in the WAG injection processes for coupled CO₂-EOR and sequestration studies.

- Experimental design and method of response surfaces to optimize the flood with range of uncertainties for each parameter and interaction among different parameters:
  - Six different parameters with their range of uncertainty
  - Two level fractional factorial design
  - Three objective functions (Responses)

- Stochastic permeability fields with the same reservoir fluid, relative permeability, and hysteresis data used in the 2-D cases.
Experimental Design

Experimental Design → Reservoir Model → High Performance Computing

Optimization → Response Surface Modeling → Sensitive Parameters Defined → Statistic Map File
Sensitivity Parameters and Simulation Cases

<table>
<thead>
<tr>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAG Ratio</td>
<td>Slug Size</td>
<td>$V_{dp}$</td>
<td>Hysteresis</td>
<td>$\lambda_{Dx,y}$</td>
<td>$\lambda_{Dz}$</td>
</tr>
<tr>
<td>(0.25-3.0)</td>
<td>(0.5-8.0)</td>
<td>(0.6-0.9)</td>
<td>(D1-D2)</td>
<td>(0.2-2.0)</td>
<td>(0.3-0.4)</td>
</tr>
</tbody>
</table>

- Initially two objective functions defined:
  - Oil Recovery, %OOIP
  - CO₂ Saturation, frac. P.V.

Vdp=0.6
$\lambda_{Dx,y}=2.0$
$\lambda_{Dz}=0.2$

Vdp=0.9
$\lambda_{Dx,y}=0.3$
$\lambda_{Dz}=0.2$

D1: Hysteresis applied
D2: Hysteresis not applied
### Simulation Results

<table>
<thead>
<tr>
<th>Run #</th>
<th>Duration Of WAG Flood, yrs</th>
<th>Response 1: Oil Rec., %OOIP</th>
<th>Response 2: CO2 Sat., frac.</th>
<th>Response 3: $ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td>$/MCF Stored $/STB Prod.</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>23.3</td>
<td>0.26</td>
<td>0.88 $8.7</td>
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<tr>
<td>2</td>
<td>4.8</td>
<td>16.9</td>
<td>0.16</td>
<td>1.04 $8.2</td>
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<tr>
<td>3</td>
<td>4.6</td>
<td>20.5</td>
<td>0.21</td>
<td>0.97 $8.4</td>
</tr>
<tr>
<td>4</td>
<td>8.8</td>
<td>21.3</td>
<td>0.18</td>
<td>1.3 $9.5</td>
</tr>
<tr>
<td>5</td>
<td>41</td>
<td>22.7</td>
<td>0.12</td>
<td>0.41 $9.9</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>25.9</td>
<td>0.25</td>
<td>1.06 $6.7</td>
</tr>
<tr>
<td>7</td>
<td>44</td>
<td>21.3</td>
<td>0.08</td>
<td>0.45 $6.1</td>
</tr>
<tr>
<td>8</td>
<td>21</td>
<td>14.7</td>
<td>0.07</td>
<td>0.21 $3.6</td>
</tr>
<tr>
<td>9</td>
<td>52</td>
<td>19.6</td>
<td>0.07</td>
<td>2.58 $8.7</td>
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<tr>
<td>10</td>
<td>2.1</td>
<td>19.8</td>
<td>0.21</td>
<td>1.02 $8.6</td>
</tr>
<tr>
<td>11</td>
<td>18</td>
<td>20.3</td>
<td>0.06</td>
<td>0.43 $5.8</td>
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<tr>
<td>12</td>
<td>54</td>
<td>20.0</td>
<td>0.09</td>
<td>2.18 $5.4</td>
</tr>
<tr>
<td>13</td>
<td>4.7</td>
<td>15.9</td>
<td>0.16</td>
<td>1.00 $8.3</td>
</tr>
<tr>
<td>14</td>
<td>18</td>
<td>14.9</td>
<td>0.04</td>
<td>0.21 $3.6</td>
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<td>19.4</td>
<td>0.10</td>
<td>0.41 $6.0</td>
</tr>
<tr>
<td>16</td>
<td>38</td>
<td>25.8</td>
<td>0.26</td>
<td>1.03 $6.4</td>
</tr>
</tbody>
</table>

**Parameters for Discounted Cash Flow Analysis**

- **Oil Price**: $35 /bo
- **Oil Price Increase**: 10 %
- **Royalty**: 12.5 %
- **CO₂ Price**: $0.85 /mcf
- **Op. Cost Inflation**: 1.5 %
- **Recycle Cost**: $0.35 /mcf
- **Lift Cost**: $0.2 /bbl
- **Discount Rate**: 12 %
- **Fed. Tax Rate**: 32 %
- **EOR Tax Credit**: 20 %
Sensitive Parameters

A: WAG
B: Slug
C: Vdp
D: Hysteresis
E: Lambda Dxy
F: Lambda Dz

Positive Effects
Negative Effects
Response Surfaces

C: \( V_{dp} = 0.9 \)
D: Hysteresis = D1
E: \( \lambda_{D_{x,y}} = 0.3 \)
F: \( \lambda_{D_{z}} = 0.2 \)
## Optimization - Suggested Runs

<table>
<thead>
<tr>
<th><strong>Objectives</strong></th>
<th>Maximizing Oil Recovery</th>
<th>Maximizing CO₂ Storage</th>
<th>Maximizing Profit</th>
<th>Equal weight for oil recovery and CO₂ storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A: WAG Ratio</td>
<td>0.26</td>
<td>0.29</td>
<td>3</td>
<td>0.25</td>
</tr>
<tr>
<td>Factor 2</td>
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<tr>
<td>B: % Slug Size</td>
<td>0.63</td>
<td>1.51</td>
<td>8</td>
<td>0.57</td>
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<tr>
<td>Factor 3</td>
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<tr>
<td>C: V&lt;sub&gt;dp&lt;/sub&gt;</td>
<td>0.9</td>
<td>0.88</td>
<td>0.6</td>
<td>0.9</td>
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<tr>
<td>Factor 4</td>
<td></td>
<td>D2 (Not Applied)</td>
<td>D1(Applied)</td>
<td>D1(Applied)</td>
</tr>
<tr>
<td>D: Hysteresis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Factor 5</td>
<td>E: λ&lt;sub&gt;Dx,y&lt;/sub&gt;</td>
<td>0.3</td>
<td>1.33</td>
<td>0.3</td>
</tr>
<tr>
<td>Factor 6</td>
<td>F: λ&lt;sub&gt;Dz&lt;/sub&gt;</td>
<td>0.2</td>
<td>0.23</td>
<td>0.4</td>
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<tr>
<td>Oil Recovery,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% OOIP</td>
<td>25.9</td>
<td>24.3</td>
<td>18.6</td>
<td>25.2</td>
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<tr>
<td>CO₂ Saturation,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>frac. P.V.</td>
<td>25.5</td>
<td>28.0</td>
<td>6.2</td>
<td>26.6</td>
</tr>
<tr>
<td>$/MCF</td>
<td>1.1</td>
<td>1.4</td>
<td>0.42</td>
<td>0.95</td>
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<tr>
<td>$/STB Prod.</td>
<td>6.9</td>
<td>6.2</td>
<td>8.7</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Summary

- The optimized values for all objective functions predicted by Design of Experiment and Response Surface Method are close to the values obtained by an exhaustive simulation study but with a very efficient computational time.

- Compositional reservoir simulation in conjunction with experimental design can be used to efficiently optimize both CO2 storage and oil recovery.
Conclusions

- Hysteresis has a very large impact on the behavior of CO2 in terms of both oil recovery and storage in heterogeneous oil reservoirs.

- CO2 storage is greater for:
  - Oil reservoirs with low heterogeneity
  - Low WAG ratio
  - Small CO2 slug sizes

- Profit from CO2 EOR is greater for:
  - Oil reservoirs with low heterogeneity
  - High WAG ratio
  - Large CO2 slug sizes