Integrated Experimental and Modeling Studies of CO₂ Sequestration in Coal

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Sequestration in Coalbeds

- $\text{CO}_2$ is sequestered as an adsorbed phase.
- $\text{CO}_2$ injection can result in enhanced coalbed methane (ECBM) recovery, off-setting costs for sequestration.
- Potential to store large volumes of $\text{CO}_2$ (U.S./Canada/China/India/Russia)
- Critically important in rapidly growing economies of China and India

Transport Modeling of CO₂ Storage and ECBM
Carolyn Seto, Kristian Jessen and Lynn Orr

Sorption and Transport in Coalbeds: A Laboratory and Simulation Investigation

Seismic Monitoring of CO₂ Storage in Coal Beds
Chuntang Xu, Jolene Robin-McCaskill, Youli Quan and Jerry Harris

Simulation Studies of CO₂ Sequestration and ECBM in Coalbeds of the Powder River Basin
Hannah Ross, Paul Hagin and Mark Zoback

Using CO₂ Injection to Quench Coal Bed Fires – Lynn Orr
Motivating Questions

1. Is it feasible to sequester CO$_2$ in unmineable coalbeds? Are there potential show-stoppers such as a severe reduction of perm with CO$_2$ saturation or the plasticization of coal in the presence of CO$_2$?

2. If so, what volumes of CO$_2$ can be sequestered? Are we accurately simulating injection into a heterogeneous, dual-porosity medium in which transport is controlled by complex physical and chemical processes?

3. To what degree could CO$_2$ injection result in significant improvements in CH$_4$ recovery (ECBM)? Can we accurately simulate cost recovery in commercial applications?

4. How do we effectively monitor CO$_2$ storage in coal? Can we distinguish among gases present in situ (CO$_2$, CH$_4$, N$_2$, etc.)?
Transport In Coal

- Adsorption on internal coal surfaces
- Diffusion through matrix and micropores
- Bulk flow in the fracture network

If diffusion times are small, matrix is in equilibrium with fracture system.
Asorption/Desorption During Transport

Kovscek and Tang, 2004
5-spot, 80-acre well spacing using the simulator GEM.

1. Primary production 5 years:
   - 4 production wells

2. Base case:
   - One injector and 4 producers – Years 6-11.
   - Injector BHP constraint of 4 MPa (~600 psi).

3. Hydraulic fracture case:
   - Hydraulic fracture placed at base of injection well
     • 60m in radius, permeability of 1000 md, and porosity of 30%.
Currently ~15,000 active CBM wells.

~50,000 more to be drilled in next decade.
History-Matching to Constrain Model Parameters

### Geostatistics

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum and Maximum Value</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal face cleat permeability</td>
<td>100-500 mD</td>
<td>300 mD</td>
</tr>
<tr>
<td>Horizontal butt cleat permeability</td>
<td>10-160 mD</td>
<td>100 mD</td>
</tr>
<tr>
<td>Vertical face cleat permeability</td>
<td>10-160 mD</td>
<td>100 mD</td>
</tr>
<tr>
<td>Matrix permeability</td>
<td>0.04-0.7 mD</td>
<td>0.5 mD</td>
</tr>
<tr>
<td>Matrix porosity</td>
<td>0.011-0.1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### History-matching water production

<table>
<thead>
<tr>
<th>Production Wells</th>
<th>Average Water Production per Month (bbl/month) (WOGCC, 2006)</th>
<th>History-matched Average Water Production per Month (bbl/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 1</td>
<td>1768</td>
<td>1762</td>
</tr>
<tr>
<td>Well 2</td>
<td>2844</td>
<td>2854</td>
</tr>
<tr>
<td>Well 3</td>
<td>1696</td>
<td>1695</td>
</tr>
<tr>
<td>Well 4</td>
<td>3153</td>
<td>3151</td>
</tr>
<tr>
<td>Well 5</td>
<td>937</td>
<td>930</td>
</tr>
</tbody>
</table>
3D Model and Cleat Permeabilities

Depth to the top: 315-361 m (1030-1180 ft)
Pressure grad: 7.25 kPa/m (0.315 psi/ft)

a) Horizontal face cleat permeability
b) Horizontal butt cleat permeability
c) Vertical permeability
CO₂ and CH₄ Adsorption/Desorption
After 11 Years

CO₂ Adsorption

CH₄ Desorption
Volumes of CO$_2$ Injected and CH$_4$ Produced after 6 Years of Injection

- One injection well can inject ~23 kt of CO$_2$ per year.
- Sequester ~95% of total CO$_2$ injected.
- With ECBM, CH$_4$ production increased by ~7 fold.
- To first order, need ~2,300 injection wells to sequester the annual CO$_2$ emissions for the state of Wyoming.
- Hydraulic fracture increased injection by ~30%.
Importance of CH$_4$ Adsorption

![Bar graph showing total volume of CH$_4$ produced with different methods: CBM only, Injection with S&S, high adsorption, and Injection with S&S, lower adsorption. The injection with S&S, high adsorption method produces the highest volume.]
CO$_2$, CH$_4$, N$_2$ Adsorption/Desorption

• Pure components are well fit by Langmuir isotherms
• CO$_2$ adsorbs preferentially to CH$_4$ and N$_2$
• Adsorption hysteresis for all gases (small for N$_2$)
Adsorption/desorption Isotherms for Dry Coal

Adsorption Isotherms for Moist Coal

Kovscek and Tang, 2004
Total Volumes of CO₂ Injected and CH₄ Produced after 6 Years of Injection

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Coal Matrix Shrinkage and Swelling

- Shrinkage of coal matrix
  - Increase in permeability with CH$_4$ desorption.

- Swelling of coal matrix
  - Decrease in permeability with CO$_2$ adsorption

- Stress dependent permeability
  - Decrease in permeability with decrease in pore pressure.
Apparatus for sorption/k-reduction/displacement

- Pore pressure: 60~1100 psi
- Gas mixtures made in the lab by weight
Permeability Reduction with CO₂ Adsorption
Crushed Coal Pack

Severe decrease in permeability due to CO₂ adsorption (matrix swelling).

How do changes in porosity and permeability with adsorption or desorption affect flow processes?
Net Permeability Reduction
Pure and Mixed Gases (Crushed Coal Pack)

- Small fraction of N₂ prevents severe perm reduction
- Overall perm reduction may be smaller at elevated temperature
- Overall perm reduction may be smaller in whole cores
Simulation of CO$_2$ Selectivity During Flow

Coal & CH$_4$

$\text{CO}_2 / \text{N}_2$

$p = 600$ psi
$S_w = 0$

CH$_4$ + CO$_2$ + N$_2$

Gas analyzer

Flue Gas

24/76 CO$_2$ / N$_2$

Data

Simulation

Post Separation

85/15 CO$_2$ / N$_2$
Sensitivity to Hysteresis

54% $\text{N}_2$ + 46% $\text{CO}_2$

$\text{CH}_4 + \text{N}_2 + \text{CO}_2$

- Case 1: Base case
- Case 2: Ignoring hysteresis of $\text{N}_2$ adsorp/desorp
Advanced Modeling Questions

Analytical Solutions for Simple Flow Paths
• Can multiphase, multicomponent flow in coal be described with analytical 1D solutions?

Streamlines for Computational Efficiency
• Can 1D analytical solutions be used for rapid and efficient streamline calculations or are numerical solutions along streamlines required?
Analytical Solutions by the Method of Characteristics (and Finite Differences)

- Compositional mechanisms are revealed by the analytical theory.
- Numerical solutions will likely be required for streamline simulations with gravity.
- 1D solutions will be useful for evaluation of adsorption models and comparison with experiments.
Extension of Analytic Solutions to 4 Component/2 Phase Flow

Relatively diffuse displacement front
Streamlines for 3D Coal Bed Simulation?

- Streamlines can capture flow in heterogeneous systems.
- If they evolve slowly, then 1D solutions along streamlines can be used to model the combination of compositional effects and flow.
- Streamline computations are fast and affected less by numerical dispersion.
- Compare with conventional coal bed simulation approaches.
Gas injection: streamlines for transport

Adaptive pressure solve

Move compositions
MOC (analytic) or
HO (numerical) upwind

Improved mapping to streamlines

Or, Improved mapping to pressure grid

Stop

Accurate streamline tracing
Seismic Monitoring of CO₂ Storage in Coal Beds

• Acoustic measurements of saturated coals
  - Differential Acoustical Resonance Spectroscopy
  - Changes in compressibility and attenuation with saturation

• Seismic monitoring of CO₂ Storage
  - Time-lapse simulation of seismic attributes
  - Integration of active and passive monitoring strategies

**DARS**
Acoustical Spectroscopy

-Time Lapse:
  - Acoustical Properties vs.
  - Saturation: CH₄, CO₂, H₂O

3-D Seismic Simulation

- Active/Passive Seismic
  - Seismic attributes
  - Dynamic aperture geometry
  - Time regularized inversion
DARS: Differential Acoustical Resonance Spectroscopy
Resonance Profile

\[ Q = \frac{f}{W} \]

Acoustic Resonance Spectroscopy

Energy Density

Frequency (Hz)

Position

Acoustic Velocity

Boise SS

Acoustic pressure

Velocity
DARS Calibration with Gas Permeability

Dynamic Diffusion

\[ \kappa_e = \kappa_\infty + \frac{2\phi\kappa_f}{l_0} \sqrt{\frac{D}{i\omega}} \left[ 1 - \exp\left( -\sqrt{i\omega / D} \frac{l_0}{2} \right) \right] \]

\[ D = \frac{k}{\phi \eta (\kappa_f + \kappa_p)} \quad l_0 = \text{sample length} \]
DARS Measurements of Coal Samples

<table>
<thead>
<tr>
<th>Coal Samples</th>
<th>Measured Volume (cc)</th>
<th>Measured Porosity (%)</th>
<th>Estimated Permeability (md)</th>
<th>DARS Bulk Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Sample 1</td>
<td>19 +/- 0.5</td>
<td>1.9</td>
<td>0.05 – 0.1</td>
<td>2.73 +/- 0.15</td>
</tr>
<tr>
<td>Coal Sample 2</td>
<td>18 +/- 0.5</td>
<td>7.14</td>
<td>218*</td>
<td>2.62 +/- 0.15</td>
</tr>
<tr>
<td>Coal Sample 3</td>
<td>15 +/- 0.5</td>
<td>13.9</td>
<td>325*</td>
<td>2.51 +/- 0.2</td>
</tr>
<tr>
<td>Coal Sample 4</td>
<td>11 +/- 0.5</td>
<td>12.1</td>
<td>770*</td>
<td>2.31 +/- 0.2</td>
</tr>
<tr>
<td>Coal Sample 5</td>
<td>7 +/- 0.5</td>
<td>8</td>
<td>240*</td>
<td>2.42 +/- 0.3</td>
</tr>
</tbody>
</table>

* Dynamic diffusion estimates of permeability
High Interest: Attenuation

<table>
<thead>
<tr>
<th></th>
<th>Berea-1</th>
<th>Berea-2</th>
<th>Boise</th>
<th>Chalk</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>2.1</td>
<td>2.1</td>
<td>2.3</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>22.0</td>
<td>19.2</td>
<td>12.0</td>
<td>34.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Permeability (mD)</td>
<td>367.7</td>
<td>127.1</td>
<td>0.9</td>
<td>2.1</td>
<td>0.1</td>
</tr>
<tr>
<td>V dry (km/s)</td>
<td>2.5</td>
<td>2.8</td>
<td>2.6</td>
<td>3.0</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Acoustic Resonance Spectroscopy

\[ Q = \frac{f}{\text{Linewidth}} \]

\[ E = |W| \]

Linewidth (Hz) vs. Frequency (Hz)
DARS: Flow-induced Attenuation
(Drained vs Undrained Sample)

Sample position

Q_{sys}

-50 -40 -30 -20 -10 0 10 20 30 40 50

Berea Sandstone

Open

Closed
Seismic Monitoring of CO₂ Storage in Coal Beds

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### Diagram:

- **DARS Acoustical Spectroscopy**
  - Low Frequency
    - Compressibility
    - Attenuation
- **Time Lapse:**
  - Acoustical Properties vs.
  - Saturation: CH₄, CO₂, H₂O
- **3-D Seismic Simulation**
  - Active/Passive Seismic
    - Seismic attributes
    - Dynamic aperture geometry
    - Time regularized inversion
Triaxial Deformation Experiments

- Permeability as a function of effective stress, differential stress, CO₂ saturation and temperature
- Static and dynamic elastic moduli
- Coal plasticization

Conventional Triaxial Press
Max. Confining Pressure = 100 MPa
Modification of Triaxial Testing System for Coal
Core Holder Assembly

- Pore Pressure Inlet
- Axial and Radial Strain Gauges
- Axial Load Cell
- Ultrasonic P/S2 Transducers
- Pore Pressure Outlet
Permeability and Effective Stress

Field Measurements (San Juan Basin)

Laboratory Samples (Appalachian Basin)

McKee et al., 1988
Effect of CO$_2$ on Coal Plasticity

Plasticization Temperature of Bituminous Coal, °C

Effective Stress (MPa)

CO$_2$

He

Khan and Jenkins (1985)
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For more information, see 5 posters this afternoon
Permeability Reduction Due to Surface Coverage?

Pure Gases

Coverage = 1.2882\log\left(\frac{K_i}{K}\right) + 0.7095

\begin{align*}
\text{Coverage Ratio} & \quad \text{Permeability Reduction Factor, } \frac{K_i}{K} \\
0 & \quad 0 \\
1 & \quad 10 \\
2 & \quad 20 \\
3 & \quad 30 \\
4 & \quad 40 \\
5 & \quad 50 \\
6 & \quad 60 \\
7 & \quad 70 \\
8 & \quad 80 \\
\end{align*}

100% CH₄

100% CO₂

100% N₂

Log. (pure gases)

Crushed Coal Pack
Sensitivity Analyses