Storing Carbon Dioxide in Coalbeds

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Overview

• Integration of enhanced coalbed methane (ECBM) and renewable energy
• Challenges for modeling ECBM processes with streamlines
• Conceptual/numerical model development
  – experimental program
    • permeability reduction
    • ECBM and CO₂ storage
• Looking forward
• Conclusions
Integration
Solar I Power Plant

1% of land area could provide U.S. energy needs

- 20% capture
- 164 W/m²

But what happens at night or on less than optimal days?

from A. DaRosa, Fundamentals of Energy Processes
Integration
Renewables, enhanced CBM, sequestration

1% of land area

Coal Resource

source: USGS
Such methods are useful to:
- predict where CO₂ is likely to flow
- interpret the volume and space contacted
- optimize injection and recovery operations

What is the process model for ECBM with CO₂ storage?
Experimental Objective

- Establish a feasible $\text{CO}_2/\text{CH}_4/\text{N}_2$ adsorption/desorption model and displacement mechanism that is implementable within a streamline framework so that CBM production and $\text{CO}_2$ storage on field scale is predicted.

- Probe:
  - adsorption/desorption behavior
  - permeability with respect to gas composition
  - recovery efficiency and $\text{CO}_2$ storage
## Relevant Coalpack Data
(Powder River Basin, WY)

### As received vs. After grinding

![Coalpack images]

### Table: Relevant Coalpack Data

<table>
<thead>
<tr>
<th>Coalpack</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of coal particles, meshes</td>
<td>&lt;60</td>
<td>&lt;60</td>
<td>&lt;60</td>
</tr>
<tr>
<td>Length of the coalpack, cm</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Diameter of the coalpack, cm</td>
<td>4.25</td>
<td>4.25</td>
<td>4.25</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>44</td>
<td>37</td>
<td>34</td>
</tr>
<tr>
<td>Permeability, md</td>
<td>144.0</td>
<td>43.0</td>
<td>26.3</td>
</tr>
<tr>
<td>Weight of coal, g</td>
<td>218.0</td>
<td>231.0</td>
<td>239.4</td>
</tr>
<tr>
<td>$S_{wi}$, %</td>
<td>0</td>
<td>0</td>
<td>8-10</td>
</tr>
</tbody>
</table>
Adsorption/Desorption Phenomena
Experimental Setup
Adsorption/Desorption CO$_2$/N$_2$/CH$_4$

- Vacuum pump
- Pressure gauge
- Reference cell
- Gas Cylinder
- Electronic balance
- Coreholder
Langmuir Adsorption Isotherm: Pure Gas

$V =$ gas adsorption

$P =$ pressure

$V_m =$ saturation adsorption constant

$b =$ constant
CO$_2$, CH$_4$, N$_2$

Adsorption/Desorption

- All adsorption data is well fit by Langmuir isotherm
- CO$_2$ adsorbs preferentially
- adsorption hysteresis for all gases
- scanning loops are evident

![Adsorption/Desorption Graph]

3 CO$_2$ : 1 CH$_4$
CH$_4$ Scanning Loops

Initial pressure influences desorption hysteresis
Why is there hysteresis?
Surface geometry heterogeneity—Seri-Levy and Avnir (1993)

- Monte Carlo simulation
- rough surfaces
- various hysteresis curves obtained by modifying surface geometry
Why is there hysteresis?

Surface geometry heterogeneity—Seri-Levy and Avnir (1993)

rough surface

\( p/p_0 = 0.13 \)

\( p/p_0 = 0.61 \)
Extended Langmuir Isotherm: Binary Gas

\[ V: \text{adsorption} \]
\[ P=\text{partial pressure} \]
\[ V_m=\text{saturation adsorption constant} \]
\[ b=\text{constant} \]
\[ y=\text{free gas mole fraction} \]
\[ \alpha=\text{selectivity ratio} \]
\[ x=\text{sorbed gas mole fraction} \]
\[ i, j=\text{gas components} \]

(cf, SPE 24363, Arri, et al, 1992)
Summary of Langmuir Constants

<table>
<thead>
<tr>
<th>Constants</th>
<th>$V_m$</th>
<th>$b$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>714.8</td>
<td>0.0029</td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1666.7</td>
<td>0.0062</td>
<td></td>
</tr>
<tr>
<td>N$_2$</td>
<td>263.2</td>
<td>0.0025</td>
<td></td>
</tr>
<tr>
<td>CH$_4$ + CO$_2$</td>
<td></td>
<td></td>
<td>0.2006</td>
</tr>
<tr>
<td>CH$_4$ + N$_2$</td>
<td></td>
<td></td>
<td>3.1503</td>
</tr>
<tr>
<td>CO$_2$ + N$_2$</td>
<td></td>
<td></td>
<td>15.705</td>
</tr>
</tbody>
</table>
CO$_2$+N$_2$ Mixture Adsorption
Extended Langmuir Appears to be Acceptable
Permeability Versus Gas Composition
(CH₄, N₂, CO₂)
Flow Through Apparatus

- Net overburden pressure = 400 psi, Pore pressure: 60~1100 psi
- Gas mixtures made in the lab by weight
Core Holder

coalpack: 1 inch diameter, 12 inches long
Steady State Permeability

\[ P_{\text{confining}} - P_{\text{pore}} = 400 \text{ psi} \]
Permeability Reduction Correlates With Surface Coverage

Coverage = 1.2882 \log(K_i/K) + 0.7095

Pure Gases
Coverage vs Permeability Reduction
Pure and Mixed Gases

![Graph showing the relationship between Coverage and Ki/K for different gas mixtures. The graph includes markers for 100% CH4, 100% N2, 25% CO2+75% N2, 50% CO2+50% N2, 75% CO2+25% N2, 85% CO2+15% N2, and 100% CO2.]
Permeability Reduction
Phase Behavior (CO$_2$/N$_2$)

\( T > T_c \)
no phase behavior
gas-solid interactions dominant

\( T < T_c \)
phase behavior
vapor-vapor interactions dominant

<table>
<thead>
<tr>
<th>Gas</th>
<th>( T_c ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>-147</td>
</tr>
<tr>
<td>N$_2$</td>
<td>-83</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>31</td>
</tr>
</tbody>
</table>
Coverage vs Permeability Reduction
Pure and Mixed Gases

$T > T_c$
no phase behavior
gas-solid interactions dominant

$T < T_c$
phase behavior
vapor-vapor interactions dominant
ECBM and CO\textsubscript{2} Storage
CO$_2$ Displacing CH$_4$

Piston like advance of CO$_2$

gas analyzer

CO$_2$ Displacing CH$_4$

CO$_2$ Produced, %

CO$_2$ Injected, PV

$X_d=0.2$

$X_d=0.4$

$X_d=0.6$

$X_d=0.8$

$X_d=1.0$

$q_m=0.9$ m/d

$T=22^\circ$C
Mixed Gas Injection Data

Temperature: 72°F
Pressure: 600 psia
Initial Water Saturation: 0
Gas Injection Rate: 0.5 cc/min

Injection-gas composition:

-100% CO₂, 0% N₂ (c100n0)
-85% CO₂, 15% N₂ (c85n15)
-46% CO₂, 54% N₂ (c46n54)
-24% CO₂, 76% N₂ (c24n76)
-0% CO₂, 100% N₂ (c0n100)
Mixed Gas (CO$_2$ and N$_2$)
Chromatographic Separation of CO$_2$ and N$_2$

CH$_4$ + CO$_2$ + N$_2$ → coal & CH$_4$ → CO$_2$ + N$_2$

Gas analyzer

p = 600 psi

CH$_4$ + CO$_2$ + N$_2$ → 0% CO$_2$ 24% CO$_2$ 76% N$_2$

p = 600 psia
Mixed Gas (CO$_2$ and N$_2$)
Chromatographic Separation of CO$_2$ and N$_2$

46% CO$_2$, 54% N$_2$

85% CO$_2$, 15% N$_2$

100% CO$_2$
Comparison:
76% N₂ + 24% CO₂

Experimental

Analytical model by Zhu et al
CH$_4$ Recovery

%OGIP Recovered > 92% All Cases

Experimental

Analytical model by Zhu et al
Looking Forward

- Permeability of coal to supercritical \( \text{CO}_2 \) \((T>T_c)\)
- \( \text{N}_2 \) permeability preservation wrt to geological setting \((T \text{ and } P)\)
- Effect of moisture
  - wettability as pH approaches 3.5
- Permeability versus gas composition under triaxial stress
- Verification of analytical and numerical models
  - dry coal: ternary systems
  - wet coal: quaternary systems
Conclusions

- Pure and mixture CH$_4$, CO$_2$, N$_2$ adsorption on Wyoming PBR coal is well described by the Langmuir Isotherm.
  - CO$_2$: CH$_4$ is about 3:1
  - CO$_2$: N$_2$ is about 8:1

- Significant hysteresis measured. It is a function of maximum adsorption pressure (scanning loops).

- Permeability decreases as pore space fills with immobile adsorbed gas
  - reduction in porosity available for flow
  - not necessarily swelling
  - some N$_2$ appears to preserve permeability

- CO$_2$ displacement displays piston-like behavior, but N$_2$ is more dispersed.
Acknowledgement

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