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CBM & ECBM
Reservoir Simulation

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Acknowledgements

- Presentation Created by
  - Peter Sammon (CMG, Ltd.) – Technical Coordinator of GEM development team
  - Mohamed Hassam (CMG, Ltd.) – member of GEM development team

- Work performed with assistance from
  - David H.-S. Law (Alberta Research Council) – Head of CBM Consortium
  - Bill Gunter (Alberta Research Council) -

- Multi-component extension to Palmer-Mansoori Theory
  - Matt Mavor (Tesseract) - Consultant
Structure of Coal

- Primary Porosity
  - Coal Matrix
- Secondary Porosity
  - Cleats (Fractures)
Flow in Coal

- Primary CBM recovery
- CO₂ enhanced recovery (CO₂-ECBM)
- N₂ enhanced recovery (N₂-ECBM)
- Flue gas enhanced recovery
Primary CBM Recovery Mechanisms

- Reduce cleat pressure by producing water
- Methane desorbs from matrix, diffuses to cleats
- Methane and water flow to wellbore
- Cleat permeability affected by matrix responses
ECBM Processes

• Enhanced Coalbed Methane (ECBM) Recovery
• Green House Gas (GHG) Sequestration
Modelling Issues: Properties of Coal

- **Primary porosity system (coal matrix)**
  - Microporosity (< 2 nm)
  - Mesoporosity (2 – 50 nm)
  - Very low flow capacity: perms in microDarcy range

- **Secondary porosity system (coal cleats)**
  - Macroporosity (> 50 nm)
  - Natural fractures
  - Much greater flow capacity: perms in milliDarcy range
Issues for CBM Modelling

- Multiple porosity model required
  - Allows standard Darcy flow in fracture (Cleat) system

- Diffusion process for gas from matrix to fracture
  - No Darcy flow required here

- Adsorption/desorption of gas in the matrix
  - Pressure-dependent isotherms

- Coal shrinkage due to gas desorption and swelling due to cleat depressurization
  - Alters fracture permeability

- Water Blockage Issues
  - Water in cleats can interfere with gas flow from/to matrix
Issues for ECBM Modelling

☐ All the above for CBM but add

- Multi-component gas (CH$_4$, CO$_2$, N$_2$, …)
  - Need to calculate accurate gas properties
- Multi-component adsorption/desorption isotherms
- Multi-component diffusion modelling
  - Can have bi-lateral diffusion
- Coal mechanics become more complicated
  - Additional coal swelling due to CO$_2$ adsorption competing with other effects
- Could take place in an non-isothermal environment
How GEM addresses these issues

- Start with a multi-component, multi-phase reservoir simulator: GEM (CMG’s EOS Reservoir Simulator)

- GEM uses an Equation of State (EOS) formulation
  - Accurate fluid properties
  - Can use library components
  - Can tune to lab data
  - For instance, could tune to viscosities for CO$_2$ mixtures measured near the critical point of CO$_2$
GEM: Adsorption Definition

☐ GEM has different adsorption models

- **Extended Langmuir model**

\[
\omega_i = \omega_{i,\text{max}} \left( \frac{(y_{ig} \ p/p_{Li})}{1 + \sum_j (y_{jg} \ p/p_{Lj})} \right)
\]

- Based on Langmuir isotherm for single components
- Provides a multi-component extension

- **Tabular input for binary systems**
- Allows direct input of measured lab data
GEM: Adsorption Definition

- GEM uses different adsorption models
  - General tabular input
  - For more complicated systems

![Graphs showing adsorption isotherms](image-url)
Adsorption isotherms (Langmuir type)
GEM: Diffusion Modelling

- **Input of coal diffusion “times”**
  - Use measured coal desorption times (days) directly
    - Can be component dependent
  - Internally calculates diffusive flow

- **Direct input of gas phase diffusion “rates”**
  - Enter diffusion constants (cm²/sec)
  - Enter estimated coal cleat (fracture) spacings
    - Leads to an effective inverse area: Shape Factor
  - Flow based on product of the two terms
Direct input of gas phase diffusion “rates”

- Specify \{\text{DiffCoeff}_i\} for each component
- Specify fracture spacings: \text{DFrac}_i, \text{DFrac}_j, \text{DFrac}_k
- These imply the following shape factor:

\[
\text{Shape} = 4 \sum_i \frac{1}{(\text{DFrac}_i)^2}
\]

- Used to find diffusional flow from bulk coal ↔ cleats

- Diffusion Constant = Shape \times \text{DiffCoeff}_i
GEM: Matrix Swelling and Shrinkage

- When gas/water is produced initially
  - Pressure in cleats decreases, alters effective stresses
  - Cleats close, lowering permeability

- But desorbing methane
  - Causes matrix shrinkage, opening cleats, increasing k
  - Reduces water saturation

- Injecting other gases
  - Causes matrix swelling

- Offsetting effects requires simulation to resolve
GEM: Matrix Swelling and Shrinkage

GEM has capabilities for shrinkage/swelling

- Input for a “compaction/dilation” option
  - Porosity/permeability multipliers
  - Functions of pressure
  - Uses tabular input
GEM: Matrix Swelling and Shrinkage

- Compaction/dilation scanning curves

Tables of $\phi$ and/or $k$ multipliers as functions of pressure
GEM also has Palmer/Mansoori models

- Basic model uses relevant rock mechanics
  - Initial pressure \( (p_{\text{init}}) \) and porosity \( (\phi_{\text{init}}) \)
  - Young’s modulus \( (E) \) and Poisson’s Ratio \( (\nu) \)
  - Max strain at inf pres \( (\varepsilon_L) \) and half-strain pressure \( (p_\varepsilon) \)
    (amounting to a Langmuir-type model for strain)

\[
\frac{\phi}{\phi_{\text{init}}} = 1 + c_f (p - p_{\text{init}}) + \frac{\varepsilon_L}{\phi_{\text{init}}} \left(1 - \frac{K}{M}\right) \left(\frac{p_{\text{init}}}{p_\varepsilon + p_{\text{init}}} - \frac{p}{p_\varepsilon + p}\right)
\]

Function of \( \nu \) and \( 1/(E\phi_{\text{init}}) \)
Function of \( \nu \)
- Typical cleat permeability plot for methane
  - Using \( \frac{k}{k_{init}} = \left( \frac{\phi}{\phi_{init}} \right)^{pwr} \)
Multi-component Palmer/Mansoori models

- Problem: CO₂ injection causes coal matrix to swell
  - Swelling much greater than shrinkage due to CH₄ desorption
  - Expect that wells might seriously lose injectivity

- Need compositionally-dependent P&M parameters
  - Improvement over the user needing to input one “average” set of parameters
  - Specifying composition-dependent εₗ and pₑ
GEM: Matrix Swelling and Shrinkage

- Multi-component Palmer/Mansoori models
  - Max strain at inf pres ($\varepsilon_L$) and half-strain pressure ($p_\varepsilon$) have been made component dependent, Based on work by Mavor & ARC
  - Law and Mavor used to match FBV field tests
  - Law using to match CUCBM pilot test

$$\frac{\phi}{\phi_{\text{init}}} = 1 + c_f (p - p_{\text{init}}) + \frac{1}{\phi_{\text{init}}} \left( 1 - \frac{K}{M} \right) \left( \sum_{j=1}^{n_c} \frac{p_{\text{init}} \varepsilon_{L_j} (y_{\text{init},j} / p_{\varepsilon,j})}{1 + p_{\text{init}} \sum_{k=1}^{n_c} (y_{\text{init},k} / p_{\varepsilon,k})} - \sum_{j=1}^{n_c} \frac{p_{\varepsilon_{L_j}} (y_j / p_{\varepsilon,j})}{1 + p \sum_{k=1}^{n_c} (y_k / p_{\varepsilon,k})} \right)$$
Other GEM features

Many other possibilities available with GEM

- Can model gas solubility in water, water vapourization
- Non-isothermal problems
- Non-Darcy flow models available
  - Forchheimer modifications, in reservoir and at wells
- Diffusion/Velocity-Dependent Dispersion modelling
  - In cleat system
- Numerical dispersion reduction (TVD schemes)

Geochemical reactions being tested for CO₂ sequestration in saline aquifers

- Application to ECBM (e.g. carbonic acid dissolving minerals in coal)?
Other GEM features

- Typical full-field simulator features
  - Can specify spatially dependent properties, including those for adsorption, rock mechanics, …
  - Various initializations, including saturated and under-saturated coals

- Full Windows-based input processing and graphics
Example

- GEM for CBM has been used for both
  - Investigative modelling
  - Field studies

- Look at results from a 5-spot investigative model
  - Production with & without CO₂ or N₂ injection
2D X-section – Dewatering Cleats
Results from a 5-spot injection model
5-Spot Injection Study

- Results from a 5-spot injection model

- Primary (No Gas Injection)
  - 100% N₂
- 100% CO₂
- Flue Gas (50% CO₂ & 50% N₂)
5-Spot Injection Study

Injection profiles

<table>
<thead>
<tr>
<th>T₁</th>
<th>T₂</th>
<th>CO₂ Injection</th>
<th>N₂ Injection</th>
<th>50% CO₂ &amp; 50% N₂ Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>N₂</td>
<td>CO₂</td>
<td>N₂</td>
<td>CO₂/N₂</td>
</tr>
</tbody>
</table>

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5-Spot Injection Study

Effects of varying desorption times

- Desorption Time Constant = 0.004 days
- Desorption Time Constant = 77.2 days
- Desorption Time Constant = 192.9 days
- Desorption Time Constant = 385.8 days

Graph showing CO₂ injection with different desorption time constants.
Effects of shrinkage/swelling (P&M model)
5-Spot Injection Study

Effects of shrinkage/swelling

No effect modelled

\[ E = 3.068 \times 10^6 \text{ kPa} \]

\[ E = 1.999 \times 10^6 \text{ kPa} \]
Conclusions (1)

- A multi-purpose compositional model (GEM) has been upgraded to include the physics for modelling CBM/ECBM recovery processes
  1. Multi-component, pressure and composition-dependent gas adsorption, desorption, and re-adsorption in the coal matrix using an extended Langmuir isotherm technique, or tables
  2. Dual porosity (i.e., coal matrix and cleat) system behavior
  3. Diffusional flow of gas between the coal matrix and the cleats
  4. Cleat permeability and porosity can be modelled as functions of effective stress (Palmer and Mansoori model)
A multi-purpose compositional model (GEM) has been upgraded to include the physics for modelling CBM/ECBM recovery processes

5. Coal swelling and shrinkage can be modelled as a function of gas (e.g. CO2) adsorption or gas (e.g. methane) desorption, respectively

6. General distributions of porosity and (anisotropic) permeabilities can be assigned in both the coal matrix and the cleat systems

7. Multi-phase Darcy and Non-Darcy (i.e. Klinkenberg for low pressure conditions and turbulent for high velocity conditions) flow of gas and water through the cleat system to the wells

8. Mixing of injected and in-place gases via multi-component molecular diffusion and velocity-dependent, longitudinal and transverse convective dispersion

9. Dissolution of injected and in-place gases into the aqueous (water) phase
Consultants/Universities/Labs using GEM for CBM/ECBM/CO2 Sequestration

- Tesseract (Park City) – Matt Mavor
- Mansoori & Assoc (Denver) – John Mansoori
- Sproule (Denver) – John Seidle
- Raven Ridge Resources (Grand Junction) – Ron Collings
- SI International (Denver) – George Lane
- Malkewicz Hueni Associates (Denver) – Tim Hower & Dan Simpson
- Epic Consulting (Calgary) - Richard Baker
- Ticora Geosciences (Denver) – Simon Testa
- NIOSH (Pittsburgh) - Ozgen Karacan
- KGS (Lawrence) – Tim Carr
- ARC (Edmonton) – David Law
- Penn State (State College) – Turgay Ertekin
- WVU (Morgantown) – Shahab D. Mohaghegh
- Oklahoma U (Norman) – Richard Hughes
- U of Texas (Austin) – Gary Pope
- Texas A&M (College Station) – David S. Schechter
E&P Companies using GEM for CBM/ECBM/CO2 Sequestration

- ConocoPhilips (Calgary) - Kevin Ratterman
- ChevronTexaco (Houston) – Kirk McIvor
- Shell (Houston) – Jeff Bain
- EOG Resources (Houston) – Charles Smith
- Encana (Denver) – Robert Downey & John Mansoori
- Burlington Resources (Calgary) – Chris Clarkson
- Devon (Calgary) - ?
- Talisman (Calgary) - ?
- PetroChina (China) - ?
- CUCBM (China) - ?
- Gazonor (Russia) - ?