Modelling for Geological Carbon Sequestration

IEAGHG Summer School, Tsinghua University, Beijing
12-17 August 2011

Lingli Wei
Shell China Innovation R&D Centre, Beijing
Previous Lecturers on modelling

2010 Summer School

- Svalbard (Norway), 22-28 August 2010
- Philip Ringrose (Statoil)

2011 Summer School

- Champaign, Illinois (USA), 18-22 July 2011
- Edward Mehnert (Illinois State Geological Survey; University of Illinois)
Modelling: Outline

1) Introduction
   - What is modelling
   - Types of modelling

2) Why & what to model for geological carbon storage

3) Reservoir / aquifer models
   - Computer modelling (simulation) approaches
   - Available computer modelling tools
   - Examples

4) Well models (wellbore, single well, abandoned wells)

5) Summary – Take home messages
1) Intro: What is modelling

- Via modelling, scientists / engineers seek to represent empirical objects, phenomena and physical (and chemical) processes in a logical and objective way.

- All models are simplified reflections of reality, but, despite their inherent falsity, they are nevertheless extremely useful.

- Building and disputing models is fundamental to the scientific process.

Source: Ed Menhert (2011 Summer School) based on info from Wikipedia
1) Intro: Types of modelling

- Physical models
- Analytical models
- Numerical models (computer models)
### 2) Why & what to model for CO₂ storage

<table>
<thead>
<tr>
<th>Work streams</th>
<th>Processes to be modelled / Roles of modelling</th>
<th>Relevant temporal scale / spatial scale</th>
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<tr>
<td>Site Selection</td>
<td>e.g. Hydrodynamics, 1000s yrs, regional/basin scale</td>
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<td>Capacity</td>
<td>e.g. Trapping mechanisms</td>
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## 2) Why & what to model for CO2 storage

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# 2) Why & what to model for CO₂ storage

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3) Reservoir / Aquifer Models (a)

a) Hydrodynamic invasion percolation models
   - Geometrical consideration
   - Capillary and gravity dominated flow
   - Fast, high resolution, large scale models
   - Ideal for identifying potential leakage pathways at regional scales
   - Also used for capacity estimation at regional scales

   - Tool: Permedia CO₂ Toolkit

b) Vertical equilibrium (vertically integrated) models

c) “Full physics” flow models

d) Coupled models: Reactive transport models with and without geomechanics
3a) Invasion percolation model example – In Salah

Topography | Faults | Fractures | Fractured and Faulted

104 million cells; 17.5km x 25km; resolution 20x20x2 m

Andrew Cavanagh and Phillip Ringrose, AAPG Convention, New Orleans, Louisiana, April 11-14, 2010
3a) Invasion percolation model example -

**Weyburn**

Assessing migration pathways at regional scale (50km x 40km)

PTRC & Permedia 2010-2012
3) Reservoir / Aquifer Models (b)

a) Hydrodynamic invasion percolation models

b) Vertical equilibrium (vertically integrated) models
   - Mathematically transform 3D problem into 2D (areal)
   - Accounts for all horizontal flow parameters: Topography, (Relative) Permeability, capillary pressure, heterogeneity, hysteresis...
   - Accounts for first-order physics: Multi-phase flow, gravity, capillarity, dissolution, transport, upscaled convective mixing
   - Order-of-magnitude faster than “traditional 3D simulation”
     - Tools: MatMoRA Project (Jan Nordbotten, Univ of Bergen); VESA (Princeton Univ)

c) “Full physics” flow models

d) Coupled models: Reactive transport models with and without geomechanics
Reproducing seismic data using VE-simulator

Seismic data (2006) / 3D simulation (tough2)  VE simulation


Source: MatMoRA, H. K. Dahle, J. M. Nordbotten, University of Bergen
3) Reservoir / Aquifer Models (c)

a) Hydrodynamic invasion percolation models

b) Vertical equilibrium (vertically integrated) models

c) “Full physics” flow models (conventional simulators)
   - Accounts for all flow parameters: Topography, (Relative) Permeability, capillary pressure, heterogeneity, hysteresis...
   - Accounts for **full** physics: Multi-phase flow, gravity, capillarity, dissolution, transport, convective mixing, EOS
   - Tools: Numerous (e.g., MODFLOW, Eclipse, CMG-GEM, Landmark VIP, TOUGH2, IFP-COORES, oil company in-house simulators, university R&D codes)

d) Coupled models: Reactive transport models with and without geomechanics
3c) Example – Johansen Formation

Modelling objective: Storage capacity estimations
3c) Johansen Formation - Benchmarking

Holger Class et al (2009) Computational Geosciences
3c) Johansen Formation – With or without hysteresis

**Case (1) no hysteresis**

- **Total Injected CO2**
- **Dissolved CO2 + Leakage**
- **Leaked out of model**

**Case (2) with hysteresis - Basecase**

- **Total Injected CO2**
- **Trapped gas + Dissolved + Leaked**
- **Dissolved + Leaked**
- **Leaked out of model**
3c) Johansen Formation – With or without LGR
3c) Johansen Formation – With different relperms

1. Krg drainage Corey = 1.5
2. Krg drainage Corey = 1.75
3. Krg drainage Corey = 3.0
4. Krg drainage Corey = 3.0; Krg=0.5
3c) Johansen Formation – With different relperms

- Total injected CO₂
- Base case (Figure 5)
- Krg Corey = 1.5
- Krg Corey = 1.75
- Krg Corey = 3.0
- Krg Corey = 3.0; Krg=0.5

CO₂ distribution (% of injected)

Time (years)

Residual gas + Dissolved + Leakage

Dissolved + Leakage

Leakage
3c) Johansen Formation – With hydrodynamics

(a) Basecase - static aquifer

(b) West to East ~1m/year

(c) South to North ~1m/year

CO2 leakage outside the modelling region for different aquifer hydrodynamics
3) Reservoir / Aquifer Models (d)

a) Hydrodynamic invasion percolation models
b) Vertical equilibrium (vertically integrated) models
c) “Full physics” flow models (conventional simulators)
d) Coupled models: Reactive transport models with and without geomechanics
   o Incorporate geochemistry into the “full physics” flow models
   o Coupling with geomechanics to consider fracture / fault reactivation (containment integrity) and formation deformation (storage capacity)

   o Tools: Numerous (e.g., MT3D, Eclipse 300, CMG-GEM/STARS, TOUGHREACT, NUFT, STOMP, oil company in-house simulators, university R&D codes)
3d) Reactive transport

CO$_2$ solubility is a chemical process but modelled as a physical process in a “conventional simulator” (3c)

Dissolved CO$_2$ changes the chemistry of the formation brine, consequently trigger further reactions. This process may increase or decrease the amount of CO$_2$ dissolved.

In carbonates, the effect is likely to be less than sandstones.

(a) Dissolved CO$_2$ at 50 years, Without chemical reaction, single Pc curve

(b) Dissolved CO$_2$ at 50 years, With chemical reactions, single Pc curve
3d) Tilt aquifer – CO$_2$ plume may not migrate forever

- $3^\circ$ slope; 100mD permeability, 2000m length, 100m thickness

Low salinity (25,000ppm TDS)

High salinity (170,000ppm TDS)
3d) Coupled with geomechanics – In Salah

Modelling using:
Abacus (Statoil)
NUFT (Livermoor)
Tough2-FLAC (LBNL)
(among many others)

Krechba satellite time series (InSAR):
- August 2009
- MDA/Pinnacle dataset
4) Well models
**Injector wellbore (flow and thermal) models**

- Predicting bottomhole pressure and temperature
  - Joule-Thomson effects
  - Risk assessment for hydrate forming in depleted gas reservoirs

- Modelling approaches
  - 1D wellbore plus correlations for radial heat exchange (e.g. OLGA)
  - Full numerical (e.g. FLUENT)

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Binglu Ruan, Ruina Xu, Peixue Jiang, Tsinghua University
Injector well model for injectivity/integrity assessment

- More complex physics & chemistry than reservoir / aquifer models
- Coupled H-T-M-C models (assessing potential leakage risk behind casing)
- Higher resolutions than reservoir / aquifer models

- Dry-out zone modelling
  - Salt precipitation
  - Require geochemical (Pitzer) model
  - Thermal model (temperature impacting activity coefficients)

Ref: H. Ott, K. de Kloe, F. Marcelis, A. Makurat (GHGT-10)
Leakage assessment of abandoned wells

- Semi-analytical models
- Celia, Noordbotten, Bachu et al (Princeton University, University of Bergen)

Solution provides a method to compute the position of the CO₂ plume and the mass distribution of CO₂ in the various aquifers as a function of time.
5) Summary – Take home messages

- No single model that could fulfill all modelling objectives for CO₂ geological storage (consider wide ranges of temporal and spatial scales)

- “Fit-for-purpose” modelling: Models are used to answer a question(s) to support a business (technical / economical / commercial) decision(s)

- Data is “king”: Garbage in, garbage out. Only quality data as model inputs could generate quality results to support quality decision-making

- There are still many modelling challenges – active research areas