Reducing Uncertainties in Model Predictions via History Matching of CO$_2$ Plume Migration at the Sleipner Project, Norwegian North Sea

Project Number (DE-FE0004381)

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Presentation Outline

- Benefits to the program
- Project overall objectives
- Technical status
- Project summary
- Conclusions and future plans
Benefit to the Program

- Develop technologies that will support industries’ ability to predict CO$_2$ storage capacity in geologic formations to within ±30 percent.
- Develop technologies to demonstrate that 99 percent of injected CO$_2$ remains in the injection zones.
- This research project applies two multi-phase compositional simulators to the Sleipner Benchmark model for simulating CO$_2$ plume migration in the uppermost layer (Layer 9) in the Utsira Sand. The Sleipner project in the Norwegian North Sea is the world’s first commercial scale geological carbon storage project. 4D seismic data have delineated the CO$_2$ plume migration history. The relatively long history and high fidelity data make Sleipner one of the best places in the world to conduct multi-phase flow and reactive mass transport modeling of CO$_2$ migration. This work contributes to the Program’s efforts of demonstrating 99% of injected CO$_2$ remaining in the injected zone and ability to predict storage capacity within ±30%.
Project Overview Objectives

To assess and reduce uncertainties of model predictions of CO$_2$ plume migration, trapping mechanisms, and storage capacity estimates through history matching, sensitivity analysis, and long-term fate modeling of CO$_2$ through implementing rigorous chemical kinetics and through a number of bounding calculations and sensitivity analyses.
Norwegian Sleipner Project

Sleipner CO₂ injection:
- World’s first industrial-scale geological carbon storage project
- In operation since 1996
- 1 million ton CO₂/year
- Storage: Utsira Formation. A saline reservoir 800-1000 meters (2600-3300ft) below the sea floor
Time-lapse seismic images of the CO$_2$ plume at Sleipner

Upper row: N-S seismic section through the plume.
Lower row: plan views of the plume showing total integrated reflection amplitude (Chadwick et al., 2010)
Statoil-IEA Benchmark Geological Model

- An area ~ 3 x 6 km
- Grid dimensions: x = 65, y = 119, z = 43; total 332,605 blocks
- The basic grid resolution is 50 m x 50 m.

Layer 9 = “Sand Wedge”

5 m mudstone underneath
Previous modeling work

Seismic Response

Invasion percolation migration

CO$_2$ Black Oil Simulator using up-scaled relative permeability curves

CO$_2$ Black Oil Simulator using the Vertical Equilibrium option

Singh et al. (2010) using Eclipse 100/300

Haukaas et al. (2013)
Results of this study: Two calibrated models

Seismic response (Boait et al., 2012) = calibration targets

Calibrated Model 1: 1 Feeder, $T=35^\circ C$, $\text{CH}_4=1.8\%$ mol, Anisotropic permeability

Calibrated Model 2: 2 Feeders, Anisotropic permeability

Calibrated Model 2: TOUGH2

Approximate history match can be achieved with widely available multi-phase compositional simulators and parameters reported in the literature
Sensitivity analysis for aerial extent of CO$_2$ plume

(a)-(d): The black outlines represents CWC observed from 4D seismic (Boait et al., 2012); Red lines represent the Base Case; Blue lines in (a)-(d) represent simulated results of test cases

Base Case: Calibrated model 2 (2Feeders, Anisotropic permeability, with 33.2 °C and 8.3 MPa)
CO$_2$ velocity along N-S for test cases

Velocity at the position shown by the circle
First—Applying Permeability Anisotropy

*N-S higher permeability supported by geology*

Observed extents

**Topography of the Layer 9.**

**GEM simulation**

*Cannot achieve the match by adjusting permeability anisotropy alone*

**Tough 2 simulations** (Chadwick and Noy, 2010)
Calibrated Model 1: A combination of temperature and CH$_4$

- CO$_2$ streams contain 1.5-2.5% methane and also butenes, toluenes, and xylenes (BTX) (Arts et al., 2008; Chadwick and Noy, 2010b; Zweigel et al., 2004; Zweigel and Heill, 2003).
- No direct measurements of reservoir $T$ in Layer 9. $T$ 31.5 – 35 °C in literature

(a) Combinations of $T$ and CH$_4$ along the line can produce similar good match as “Test Case-1Feeder, $T$=35 °C, CH$_4$=1.8%” (b) calibrated model 2: 1Feeder, $T$=34 °C, CH$_4$=2.7%, Anisotropic permeability
Calibrated Model 2: Additional Feeder together with Permeability Anisotropy

CO₂ plume thicknesses derived from reflection amplitudes (Chadwick and Noy, 2010). A thick area of CO₂ plume (red circle) is clearly shown in 2004 and 2006 map. Propose to add a second feeder to that area after year 2001.
Calibrated Model 2: -Additional Feeder with Permeability Anisotropy

Accepted results with the second feeder.

Observed extents 2006

100% CO₂ volume into main feeder

85% CO₂ volume injected into the main feeder and 15% into the second feeder (the triangle) starting from 2002.

Estimated total mass into L9 by Statoil

- Main Feeder: 100% mass 1999-2001; 85% mass 2002-2031
- Secondary feeder: 0% mass 1999-2001; 15% mass 2002-2031
Topography uncertainty effect: Vertical profile of the CO$_2$ plume in 2006

(a) Profile along J=51
- Red lines: simulated bottom of the CO$_2$ plume
- Black lines: the topography of the caprock bottom
- Vertical black dash lines: the boundary of CO$_2$ plume

(b) Profile along J=62
- Red lines: simulated bottom of the CO$_2$ plume
- Black lines: the topography of the caprock bottom
- Vertical black dash lines: the boundary of CO$_2$ plume

Locations of profiles
Sensitivity analysis for CO₂ fate

(a) Green color denotes parameter values higher than those in the Base Case and blue color lower than those for the Base Case.

(b) Green color denotes parameter values higher than those in the Base Case and blue color lower than those for the Base Case.

(a), (b): Green color denotes parameter values higher than those in the Base Case and blue color lower than those for the Base Case.

Structural trapping

Solubility trapping
Geochemical process in model structure: Geochemical results

Concentration (molality) of $\text{HCO}_3^-$  

Percentage of calcite dissolution

Porosity change

(a) The concentration at the section crossing $l=33$ (b) distribution at the top sub-layer of Layer 9 in 3D in 2006 (c) distribution at the top sub-layer of Layer 9 in 2006; negative value represents the increase of the porosity due to mineral dissolution.
## Model Predictions

<table>
<thead>
<tr>
<th>Year</th>
<th>Calibrated Model 1</th>
<th>Calibrated Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td><img src="image1" alt="2010 Model 1" /></td>
<td><img src="image2" alt="2010 Model 2" /></td>
</tr>
<tr>
<td>2012</td>
<td><img src="image3" alt="2012 Model 1" /></td>
<td><img src="image4" alt="2012 Model 2" /></td>
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<tr>
<td>2016</td>
<td><img src="image7" alt="2016 Model 1" /></td>
<td><img src="image8" alt="2016 Model 2" /></td>
</tr>
<tr>
<td>2018</td>
<td><img src="image9" alt="2018 Model 1" /></td>
<td><img src="image10" alt="2018 Model 2" /></td>
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</tbody>
</table>
Water-alternating Gas (WAG) injection– axisymmetric Utsira model

Optimal WAG pattern, and CO$_2$ migration for CGI and WAG injection, axisymmetric Utsira formation

<table>
<thead>
<tr>
<th></th>
<th>$I_{CO2}$ (kg/s)</th>
<th>$I_{water}$ (kg/s)</th>
<th>WAG</th>
<th>Fitness (m/k ton of water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Value</td>
<td>95.75</td>
<td>75.32</td>
<td>0.64</td>
<td>0.0251</td>
</tr>
</tbody>
</table>

Optimal WAG injection pattern, 2D Utsira formation

<table>
<thead>
<tr>
<th></th>
<th>CGI</th>
<th>WAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ Radial Migration</td>
<td>Dissolution</td>
<td>CO$_2$ Radial Reduction</td>
</tr>
<tr>
<td>946.7 m</td>
<td>16.89 %</td>
<td>65.2 m</td>
</tr>
</tbody>
</table>

Summary of the best benefits for adopting WAG injection scheme, axisymmetric Utsira formation
WAG injection pattern design – WAG for axisymmetric Utsira formation

In situ CO₂ migration for CGI operation, year 1~5

In situ CO₂ migration for optimal WAG operation, year 1~5

Collaboration with Ramesh Agarwal and Zheming Zhang, Washington University in St. Louis
Conclusions from Modeling Study

• Approximate match between simulations based on Sleipner benchmark model and seismic delineated CO₂ plume history can be achieved with two widely available multi-phase compositional simulators
• History match is labor and computational intensive, our approximate match resulted from hundreds of simulations on supercomputers
• Introducing permeability anistropy is necessary and justifiable based on geology
• A combination of reservoir temperature and CH₄ % within the ranges in literature can result in approximate match
• Adding second feeder help achieve match with observed plume development
• Model-predicted plume thickness, CO₂ saturation, CO₂ solubility, none of them used as calibration targets, are comparable with those based on seismic data interpretations (including mass of CO2 spilled into Layer 9);
• Even with a range of uncertain modeling parameters, the predicted fate of CO₂ is within a narrow band, ~93±2% structural/hydrodynamic trapping and ~7±2% solubility trapping
• Modeling results provide feedback to monitoring and characterization needs
Accomplishments to Date

1. Acquired datasets for the Sleipner project, one of the best field dataset for U.S. scientists, engineers, and students working on CCUS. Fulfilling the international/global collaboration program need;

2. Simulated multiphase reactive flow in Layer 9 and calibrated two models against 4D plume migration data;

3. Conducting parameter sensitivity analysis;

4. Submitted a manuscript to a peer-referred journal and gave conference presentations;

5. Continuing coupled reactive transport model to evaluate long-term effects on reservoir prosperities by water-rock interactions.
Summary - Key Findings & Lessons Learned

– Can we predict CO₂ plumes at proposed sites (size, directions)?
  • Yes, we can. Accurate enough for AoR?

– What takes to match the CO₂ plume history at Sleipner?
  • We matched it without using out of ordinary parameters or assumptions, and with two widely available reservoir simulators.

– Do we understand CO₂-H₂O multi-phase flow in geological systems?
  • Reasonably well, (a) we approximately matched the plume migration history; (b) model-predicted CO₂ solubility, CO₂ saturation (?), plume thickness match with geophysical interpretations; (c) plume aerial extent and thickness match with estimated CO₂ spill into Layer 9.
– Future Plans:

1) Develop coupled reactive transport model to simulate long-term CO$_2$ fate
   a) Complete conceptual model and axisymmetric TOUGHReact modeling of Utsira Sand
   b) Calcite dissolution with reservoir geometry

Hypothesis: Models have over-predicted mineral dissolution – precipitation reactions. Using realistic rate laws would see much less reactions
Appendix

– These slides will not be discussed during the presentation, but are mandatory
Organization Chart

• **PRINCIPAL INVESTIGATOR**
  • Professor Chen Zhu
  • Indiana University

• **Co-Principal Investigator**
  • Professor Per Aaggard
  • University of Oslo
Gantt Chart

**Task 1.0 - Project Management, Planning and Reporting**

**Task 2.0 - Data Acquisition and Interpretation**

**Task 3.0 - History Matching of CO\textsubscript{2} Plume Migration with a Reservoir Model**
Gantt Chart

- **TASK 1.0** - PROJECT MANAGEMENT, PLANNING AND REPORTING
- **TASK 2.0** – DATA ACQUISITION AND INTERPRETATION
- **TASK 3.0** – HISTORY MATCHING OF CO₂ PLUME MIGRATION WITH A RESERVOIR MODEL
- **TASK 4.0** – MODELING LONG-TERM CO₂ FATE
TASK 3.0 – HISTORY MATCHING OF CO$_2$ PLUME MIGRATION WITH A RESERVOIR MODEL

TASK 4.0 – MODELING LONG-TERM CO2 FATE
Bibliography

• Peer-reviewed journal articles:
Conference proceeding papers and abstracts:


• Conference proceeding papers and abstracts (continued):

Book chapter: