Understanding of Multiphase Flow for Improved Injectivity and Trapping

Dustin Crandall, URS
PI: Grant Bromhal, NETL ORD
Morgantown, West Virginia
Presentation Outline

- Benefit to the program
- Project overview
- Breakdown of FY12 project tasks
- Facilities and personnel
- Task progress to date
- Planned task successes
- Tech transfer and summary
Benefit to the Program

• Program goal being addressed
  – Develop technologies that will support industries’ ability to predict CO$_2$ storage capacity in geologic formations to within ±30%.

• Project benefits statement
  – This research project is an examination of pore scale multiphase flow behavior, in the lab and with micro-scale simulations, to inform key processes of reservoir-scale simulations (e.g. capacity & injectivity prediction, sweep efficiency, storage permanence). This insight contributes to the Carbon Storage Program’s effort of ability to predict CO$_2$ storage capacity in geologic formations to within ±30%.
Project Overview: Goals and Objectives

• Numerical modeling, laboratory measurements, and field samples to focus on the key processes that will allow more accurate prediction of CO$_2$ capacity, injectivity, sweep efficiency and storage permanence.

• Objectives for FY12:
  – Make measurements of key parameters for injectivity, sweep efficiency, and trapping
  – Perform simulations to investigate the effects of parameter variability
  – Develop a framework for understanding “atypical” CO$_2$ migration
Project Tasks for FY12

- Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores
- Task 2.5.2 - Immiscible flow scaling relationship
- Task 2.5.3 - Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping
- Task 2.5.4 - Estimation of CO$_2$ losses along leakage pathways between the reservoir and the near-surface
- Task 2.5.5 - CO$_2$ trapping mechanisms in clay materials
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• Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores

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• Task 2.5.4 - Estimation of CO₂ losses along leakage pathways between the reservoir and the near-surface

• Task 2.5.5 - CO₂ trapping mechanisms in clay materials
Collaboration Is Key

• Team Members/Collaborators:
  – Grant Bromhal – NETL-ORD
  – Dustin McIntyre – NETL-ORD
  – Martin Ferer – ORISE
  – Dustin Crandall - URS
  – W. Neal Sams – URS
  – Shahab Mohaghegh – WVU
  – Donald Gray – WVU
  – Egemen Ogretim – WVU
  – Jeong Choi – ORISE
  – Eugene Myshakin – ORISE
  – Vinod Kumar – UTEP

  – Ale Hakala – NETL-ORD
  – Christina Lopano – NETL-ORD
  – Robert Warzinski – NETL-ORD
  – Kathy Bruner – URS
  – Corinne Disenhof – URS
  – Igor Haljasmaa – URS
  – Magdalena Gill – URS
  – Yongkoo Seol – NETL-ORD
  – Ken Jordan – Pitt
  – Dan Mareno - WVU
  – Paul Delgado – UTEP
Multi-Scale CT Scanning

Measuring flow at in situ P, T, stress, and geochemical conditions

Simulating flow through pore and fracture networks

CT/well log comparison

Medical CT Scanner
-10^{-4} to 10^{-2} m
- Core scale
- Pressure, temperature, and flow controls

Industrial CT Scanner
-10^{-6} to 10^{-3} m
- Pore & core scale
- Pressure & flow controls

Micro CT Scanner
- Resolution 10^{-6} to 10^{-5} m
- Pore scale

Current Collaborations

MSCL for geophysical logging
Pore Geometry Measurement

• Isolation and measurement of pores within various pertinent formations within the industrial and micro CT scanners has been performed

• Example: CO$_2$ reacted Wallua Gap basalts

Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores
Residual Saturation: Core Scale

- Ordos Basin core samples procured from Chinese Academy of Sciences (CAS)
- Core sub-sampled for multiple scales of analysis: micro to core-scales

Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores
Residual Saturation: Core Scale

- Dynamic flow in medical scanner
  - $k_{\text{int}} \approx 6.4 \text{mD}$ & $\phi_{\text{int}} \approx 7\%$
  - $Q = 0.02 \text{ ml/min}$
  - $P_{\text{conf}} = 2450 \text{ psi}$
  - $P_{\text{inj}} = 2200 \text{ psi}$
  - $\text{CO}_2$ displacing 5wt% KI brine
    - Angled bedding planes!

Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores
Residual Saturation Micro-Scale

- Arkosic arenite Q/F/RF = 51/32/17
- Calcite ~16%; main cementing agent
- Porosity of ~10%
- Permeability in the range of 50mD

Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores
Immiscible flow relationship

• Pore-scale simulation of two-phase flow for the purpose of being able to generate relative permeability “data” without needing large numbers of experiments
  • Multiple techniques have been used for multiphase flow simulations in pore scale
    • Lattice Boltzmann
    • Navier-Stokes with Volume-of-Fluid
    • Pore-Network modeling
Pore Geometry Extraction

• Generation of irregular pore network from CT images
• Initial network has been generated

Task 2.5.2 - Immiscible flow scaling relationship
Small NS-VOF Models Run

- Mt Simon sandstone pores
  - 1 x 1 x 3.5 mm domain. CO₂ & brine properties at a depth approximate of 5800 ft
  - Ran a series of variations to complement flow through tests in the medical scanner performed
  - Increased saturation of CO₂ with increased CO₂ viscosity
Molecular Modeling of CO$_2$/Clay

- Using molecular modeling to understand CO$_2$ trapping in clays:
  - Amount of CO$_2$ trapped
  - Clay volume changes
  - Clay transport property changes

Task 2.5.5 - CO$_2$ trapping mechanisms in clay materials
Molecular Modeling Results

3D plot and 2D map of basal spacing dependence on initial water content and amount of intercalated carbon dioxide.

Task 2.5.5 - CO$_2$ trapping mechanisms in clay materials
Sodium ions are migrating over the internal montmorillonite surfaces, the small blue balls are sodium ions, the big cyan ones are Ca2+. CO2 and H2O are represented by sticks.

Task 2.5.5 - CO₂ trapping mechanisms in clay materials
Reservoir Modeling

- At the small scale we can determine relationships applicable to flow at the field-scale results. Relative permeability is chief among these.
- Reservoir modeling with appropriate $k_r$

SPE 99326 Bennion D., Bachu S. “Drainage and imbibition relative permeability relationship for supercritical CO$_2$/brine systems in intergranular sandstones, carbonate, shale and Anhydrite rocks”

Task 2.5.3 Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping
Reservoir Modeling of Citronelle

SPE 99326 Bennion D., Bachu S. “Drainage and imbibition relative permeability relationship for supercritical CO₂/brine systems in intergranular sandstones, carbonate, shale and Anhydrite rocks”

Task 2.5.3 Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping
Modeling with Hysteresis

Considering Hysteresis plays a very important role regarding residual gas trapping, leading to an immobile and spread out distribution of CO₂, rather than to a structural trap of mobile CO₂.

Example: Viking Sandstone

Task 2.5.3: Impact of relative permeability and residual saturations on injectivity and capillary trapping
Task 2.5.1 – Future Plans

- Relative permeability and residual saturation values are keys to sweep efficiency and trapping
- Use regional partnership cores that have been collected
- Generate additional $k_r$ relationships (FY13)
- Compare to pore-scale simulation results (FY14 with Task 2.5.2)

Combining measurements with CT images will provide significant enhancement to understanding of these fundamental phenomena

Task 2.5.1 - Measurement of pore geometries and residual saturation/relative permeability in cores
Task 2.5.3 – Future Plans

- Started in June
- Reservoir simulation model will be generated in CMG (by 10/12)
  - Modify solubility in brine
  - Use variety of relative permeability relationships
- Simulations will be performed for sensitivity analysis (FY13)
- Results will be compared for sweep efficiency (FY13)
- Longer simulations will be performed to study trapping mechanisms (FY14)

Task 2.5.3 - Reservoir scale impacts of relative permeabilities and residual saturations on injectivity and capillary trapping.
Task 2.5.4 – Future Plans

• Started March 1
• Begun work to develop framework for predicting non-continuous flow outside of reservoir
  – Literature survey, focused on oil and gas field experience
• Assessment of bubble flow rates (summer)
• Incorporate background aquifer flow (thru Q1 FY13)
Task 2.5.5 – Future Plans

• Refocus work on clays in caprock and volume changes that could effect seal integrity
  – Develop estimates of volumes of clays in caprock layers
  – Assess the stable states of clays in the presence of CO$_2$ and identify corresponding volume changes
  – Determine if volume changes will have an impact on seal integrity
Accomplishments to Date

✓ Milestone Q1: CT imaged flood of CO$_2$ into brine-saturated permeable rock core from potential sequestration field site.
✓ Milestone Q2: Completed simulations of CO$_2$ injection into brine-filled sample based on actual pore geometry.
✓ Milestone Q3: Complete modeling of CO$_2$ intercalation in smectite clay minerals in presence of brine to elucidate the trapping mechanism and the chemical environment favorable for permanent retention of carbon dioxide in the interlayer space.
• Milestone Q4: Completed reservoir model of synthetic site.
• Milestone Q4: Calculation of percentage of CO$_2$ that reaches the surface through a permeable wellbore as a function of bottomhole pressure.
Published Accomplishments

• Peer Reviewed Publications

• Conference Presentations
  – Bromhal, G. et al. (May 2012) CAS-NETL-PNNL collaboration to evaluate CO\textsubscript{2} storage potential in the Ordos basin. 11\textsuperscript{th} Annual Conference on Carbon Capture Utilization & Sequestration. Pittsburgh PA.

• Conference Poster
Summary

– Key Findings
• We are able to view experimental multiphase flows on multiple scales to isolate pertinent relationships
• Simulations at the small-scale are in good agreement with the experiments to date
• Shale swelling is likely to have little effect on reservoir behavior for reservoirs with small volumes of clay, but it may have an effect on seals

– Lessons Learned
• Involving simulation in experimental planning and vice-versa at the earliest possible times improves efficiency and effectiveness
Thank you
Visualization of Liquid CO$_2$ Flow

CO$_2$ displacing brine within sandstone

These tests performed in April as part of our Pitt/RUA collaboration