Flow Modeling for CO_2 Sequestration: The Frio Brine Pilot

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Flow Modeling for CO_2 Sequestration: The Frio Brine Pilot

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Numerical modeling of the flow behavior of supercritical carbon dioxide (CO_2) injected into a brine-bearing sandstone was an integral part of the Frio brine pilot for CO_2 sequestration. Modeling was used to help design the pilot and to improve understanding of multi-phase and multi-component flow processes involved in geologic CO_2 sequestration. During the design phase, modeling was used to determine which of several layers to inject into, how far apart injection and observation wells should be (in particular showing that existing wells were too far apart, necessitating the drilling of a new injection well), how much CO_2 to inject, and at what rate. Modeling of pre-injection, site-characterization pump and tracer tests helped design these tests to optimize the information gained on formation flow properties, in situ phase conditions, and boundary conditions. As site-characterization proceeded, the model was modified to incorporate new information. CO_2 injection was simulated prior to the actual pilot, to assess the model's predictive ability. Further model improvements were added subsequently, based on detailed comparisons to the observed subsurface CO_2 distribution. Modeling illustrated the complex interplay between phase interference and buoyancy flow that occurs as CO_2 is injected into a high-permeability, steeply dipping sand layer. By running simulations with a range of parameters and comparing model results to field data we improved our understanding of these flow processes. Generally good agreement between observed and modeled CO_2 spatial distributions and travel times between injection and observation wells validated our ability to model CO_2 injection, while discrepancies pointed out areas where future research is needed. The iterative sequence of model development, application, and refinement proved useful for getting early results in a timely manner as well as incorporating more complexities at later stages. This work has demonstrated that we have an effective modeling capability for representing the physical processes occurring during CO_2 sequestration in brine-bearing sandstones, and moreover that the incorporation of modeling into geologic CO_2 sequestration activities is beneficial from the earliest design stages through the final interpretation of field data.

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ABSTRACT

Numerical modeling of the flow behavior of supercritical carbon dioxide (CO_2) injected into a brine-bearing sandstone was an integral part of the Frio brine pilot for CO_2 sequestration. Modeling was used to help design the pilot and to improve understanding of multi-phase and multi-component flow processes involved in geologic CO_2 sequestration. During the design phase, modeling was used to determine which of several layers to inject into, how far apart injection and observation wells should be (in particular showing that existing wells were too far apart, necessitating the drilling of a new injection well), how much CO2 to inject, and at what rate. Modeling of pre-injection, site-characterization pump and tracer tests helped design these tests to optimize the information gained on formation flow properties, in situ phase conditions, and boundary conditions. As site-characterization proceeded, the model was modified to incorporate new information. CO_2 injection was simulated prior to the actual pilot, to assess the model's predictive ability. Further model improvements were added subsequently, based on detailed comparisons to the observed subsurface CO_2 distribution.

OBJECTIVES

❖Pre-Test Modeling

- Design experiment
- Design site-characterization studies
- Predict CO_2 arrival at observation well
- Predict spatial distribution of CO_2 in subsurface

❖Post-Test Modeling

- Compare model results to field observations
- Assess state of knowledge

METHODS

❖Numerical simulator TOUGH2 (Pruess et al., 1999)

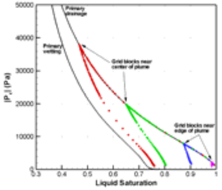
- Multi-phase, multi-component fluid flow through porous/fractured geologic media with heat flow
  - Multi-phase Darcy's law

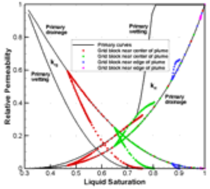
$$q_\beta = -\frac{k k_{r\beta} \rho_\beta}{\mu_\beta} (\nabla P_\beta - \rho_\beta g)$$

  - Hysteretic capillary pressure and relative permeability (Finsterle et al., 1998; Niemi and Bodvarsson, 1988)
  - Modified version of Land (1969) equation for residual gas saturation

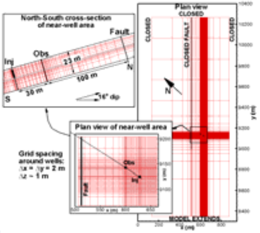
$$S_{gr}^{\Delta} = \frac{(1 - S_l^{\Delta})}{1 + [1/S_{gr\max} - 1/(1 - S_{lr})](1 - S_l^{\Delta})}$$

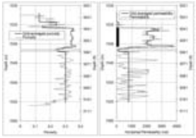
- Equation of State: ECO2 (Pruess and García, 2002)
  - Water (liquid, gas)
  - CO_2 (supercritical free phase, dissolved)
  - NaCl (dissolved, precipitate)
  - Supercritical CO_2 is much less dense and viscous than brine, strongly buoyant
- Integral-finite-difference method for spatial discretization
- Present simulations isothermal





❖Three-dimensional Model of Frio C Sand at South Liberty Site, Texas (Hovorka et al., 2004; Doughty and Pruess, 2004)





- Porosity and permeability profiles from wire line logs calibrated to core sample analysis
- Other properties (k_v/k_h, S_{lr}, S_{grmax}) from literature-based correlations

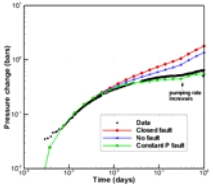
RESULTS

❖Experiment Design

- How much CO_2 to inject: budget versus monitorable constraints
- What rate to inject: pressure regulations versus field time
- What layer to inject into: compact, thick plume versus extensive, thin plume
- Well separation for timely/economical breakthrough: existing well spacing 150 m determined to be too large, new well drilled for 30 m separation

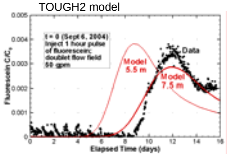
❖Site characterization

- Interference well-test
  - Pump from observation well at 50 gpm
  - Monitor pressure-transients at both wells
  - Well-test analysis
    - Confirms core permeabilities ~2400 md
    - Suggests small fault ~100 m from observation well is not closed
    - Pressure transients insensitive to outer fault block boundaries



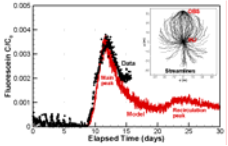
- Doublet tracer test: Single-phase breakthrough time constrains layer thickness

TOUGH2 model



Vary sand thickness to match tracer peak

Streamline model with random walk



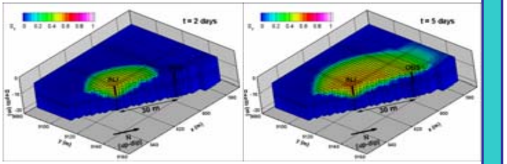
Estimate dispersivity $\alpha = 0.1$ m

❖Predictions

- CO_2 arrival at observation well – compare to tracer test

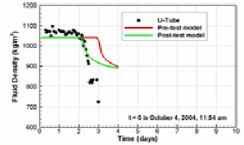
Feature	Tracer Test	CO2 Injection	Impact on CO2
Flow field	Doublet	Single well	3 times slower
Phase conditions	Single-phase	Two-phase	Faster
Density contrast	None	1.5	Faster
Viscosity contrast	None	12	Faster
Injection rate	50 gpm	40 gpm	20% slower
Density in situ	1060 kg/m^3	~700 kg/m^3	50% faster
Arrival at observation well	9 days (peak 12 days)	Predict 3 days	

- CO_2 spatial distributions



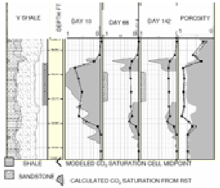
❖Comparison with Observations

- U-tube sampling – CO_2 arrival at observation well

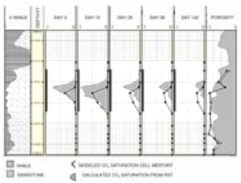


- RST – saturation profiles in wells

Injection well

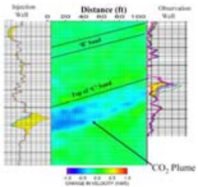


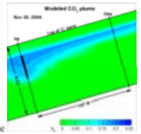
Observation well



- Crosswell seismic

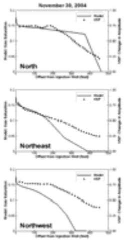
Saturation distribution between wells





- VSP

Saturation distribution beyond wells



CONCLUSIONS

- ❖Complex interplay between phase interference and buoyancy flow occurs as CO_2 is injected into a high-permeability, steeply dipping sand layer
- ❖Running simulations with a range of parameters and comparing model results to field data improves understanding of flow processes
- ❖Generally good agreement between observed and modeled CO_2 spatial distributions and travel times validates ability to model CO_2 injection, while discrepancies identify areas for future research
- ❖Iterative sequence of model development, application, and refinement is useful for getting early results in a timely manner and incorporating more complexities at later stages
- ❖Work has demonstrated
  - an effective modeling capability for representing physical processes occurring during CO_2 sequestration in brine-bearing sandstones
  - incorporation of modeling into geologic CO_2 sequestration activities is beneficial from the earliest design stages through the final interpretation of field data

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