Optimization of CO$_2$ Sequestered as a Residual Phase in Brine-Saturated Formations

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Abstract

Geologic sequestration of CO2 in brine-saturated formations has been proposed as a possible method to reduce emissions of this greenhouse gas to the atmosphere. To optimize this method the largest possible volume of CO2 should be sequestered over geologic time. Sequestration over geologic time can be thought of as permanent for the purposes of relieving climate-changing increases in atmospheric CO2 concentration. The least risky way to achieve permanent sequestration is to store the CO2 as a residual phase within a brine aquifer. This optimization goal can best be achieved by sequestering CO2 as a residual phase under the most advantageous geologic conditions. Geologic conditions that impact the volume of CO2 stored as a residual phase include petrophysics, burial effects, temperature and pressure gradients, and CO2 pressure-volume-temperature character. Analyzing and integrating all of these parameters result in an optimal CO2 sequestration depth for a given geologic subprovince. The integrated sequestration optimization model was constructed from petrophysical, geological, and CO2 characteristics. Sequestering CO2 as a residual nonwetting phase is the key to obtaining its residency in rock over geologic time. Thus residual saturation and porosity were pivotal modeling characteristics. Sediment burial depth affects porosity, temperature, and pressure; thus depth is a key input variable that integrates the other parameters. Finally, CO2 density as a function of temperature and pressure was accounted for, resulting in a model that combines all the salient properties that affect the amount of CO2 that can reside within buried rock. A model for predicting residual nonwetting-phase saturation and a sequestration optimization curve (SOC) was developed. Results indicate that a sandstone porosity of 0.23 is optimal for CO2 sequestration. The SOC for the Frio Formation, Upper Texas Gulf Coast, indicates that the largest volume of CO2 could be trapped as a residual phase at about 10,000 to 11,000 ft. The SOC of depth versus CO2 residual phase bulk volume is a concave-down parabolic shape with a broad maximum indicating the optimal sequestration depth. Additionally, greater depth decreases the risk of surface leakage and increases the pressure differential between hydrostatic and lithostatic, both characteristics having sequestration benefits.
Presentation Outline

• Introduction
• Approaches in determining residual nonwetting saturations
  – Pore-scale trapping mechanisms
  – Theoretical and experimental
  – Empirical measurement and correlation with other properties
• Optimization of CO$_2$ as a residual phase
• Summary
Hypothesis

• Greenhouse gas emissions can be reduced by permanently sequestering CO₂ in the subsurface

Sequester- To remove or set apart; segregate
Physical Mechanisms for CO$_2$ Sequestration in a Porous Rock

- Adsorption to coal
- Mobile phase trapped by seal
- Dissolution in water
- Precipitation as a mineral
- Immobile phase as residual, nonwetting saturation
Previously Suggested Approaches to Geologic Sequestration

- Structural trapping
- Mineral trapping
- Solution trapping
- Trapping associated with enhanced oil recovery
- Trapping associated with coalbed methane
New Sequestration Paradigm

• Sequester CO$_2$ in a porous media as residual-phase saturation by capillary forces
Flow & Saturation Definitions

- **Drainage**: wetting phase being replaced by nonwetting phase.
- **Imbibition**: wetting phase replacing nonwetting phase.
- **Hysteresis**: lagging of an effect behind its cause.

The graph illustrates the relationship between capillary pressure (psi) and wetting-phase “water” saturation (percent).
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Pore-Scale Gas Trapping

Pore Doublet

- Moore and Slobod, 1956
  - Pore doublet model

Capillary force holds nonwetting phase in larger pore
Pore-Scale Gas Trapping Snap-Off

- Oh and Slattery, 1976
  - Snap-off model

Aspect ratio = \( \frac{\text{Pore radius}}{\text{Pore-throat radius}} \)

Capillary force causes nonwetting phase to snap off into pore
Pore-Scale Gas Trapping
Dead End

• Buoyancy forces of nonwetting CO$_2$ can form a microtrap
Presentation Outline

• **Introduction**

• Approaches in determining residual nonwetting saturations
  – Pore-scale trapping mechanisms
  – Theoretical and experimental
    • Cubic sphere packing
    • Finney dense packing if spheres
  – Empirical measurement and correlation with other properties

• **Optimization of CO\textsubscript{2} as a residual phase**

• **Summary**
Porosity Reduction Model

Delaunay cell as unit bulk volume

Delaunay cell

- Tetrahedron in 3D
- Joins nearest neighbor grains at center

Cementation model

Grain radius = R
Cementation of Cubic Packing

\[ y = 1.1005x^{-0.5428} \]

\[ R^2 = 0.97 \]
Model Sedimentation

sandstone with interparticle porosity

Finney’s random, dense packing of spheres
Model Sediment: the Finney sphere pack

- Dense, random, spherical packing of precision ball bearings
- Finney measured spatial coordinates of ~8,000 grains
- Porosity 36.2%
- Use of central 3,367 grains here
  - 15,000 pores
  - 30,000 pore throats
Aspect Ratio Increases as Cement is Added to Finney Packing
Number of Closed Throats Increases as Cement is Added to Finney Packing

Porosity (fraction)

Number of closed throats

Dead-end model

Nonwetting phase trapped

Wetting phase

Bureau of Economic Geology
Effects of Porosity Reduction in Ideal Sediment

• In cubic packing aspect, ratio increases logarithmically with decreasing porosity
• In Finney dense packing, both aspect ratio and number of closed pore throats increase logarithmically with decreasing porosity
Simulated Imbibition in Model Sandstones

(from Gladkikh, 2005)
Experimental Investigations

- Wardlaw, 1982
  - Applied glass-tube micromodel
  - Demonstrated snap-off
  - Concluded that snap-off caused residual saturation and was strongly affected by pore body/pore throat aspect ratio

- Chatzis et al., 1983
  - In consolidated sandstone cores, 80% of trapped, nonwetting phase was caused by snap-off
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  - Empirical measurement and correlation with other properties
  - Experimental
- **Optimization of CO₂ as a residual phase**
- **Summary**
Empirical Measurement and Correlation with Other Properties

• Properties having poor or no correlation with Sgr
  – Imbibition mechanism, rate, and nonwetting fluid type (Cromwell et al., 1952; Geffen et al., 1952; Kyte et al., 1956; Jerauld, 1996)
  – Temperature and pressure (Geffen et al., 1952; McKay, 1956; Delclaud, 1991)
  – Permeability (Keelan, 1976)

• Properties correlating with Sgr
  – Rock and pore type, grain size, and sorting
  – Wetting strength
  – Porosity
Geologic Effects on Residual Gas Saturation

Residual nonwetting saturation (fraction)

Initial gas saturation (fraction)

1 to 1 line
Cemented sandstone
Average Berea sandstone
Uniform unconsolidated sandstone

Increasing sorting and decreasing cementation and shale
Bead-pack measurements are on trend with rock measurements showing that the empirical model could represent interparticle pore geometry.

\[ y = -0.3106 \ln(x) - 0.1265 \]

\[ R^2 = 0.8532 \]

**Graph:**
- Red: Bead pack (Chatzis et al., 1983)
- Blue: Gas residual saturation to water (fraction), (From literature)
- Blue line: Log (gas residual saturation to water [fraction])

\( N = 143 \)
Swirr as a Function of Porosity and Permeability

Irreducible water saturation (fraction)

Log(k)/porosity (md)

y = 5.1593 x ^ -1.5594

R^2 = 0.9933
Nonwetting Phase Initial-Residual Curves

\[ S_{gr} = \frac{1}{\left( \frac{1}{S_{grm}} - 1 \right) + \left( \frac{1 - Swirr}{S_g} \right)} \]

with \( S_{grm} \) as a function of porosity.
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- **Optimization of CO$_2$ as a residual phase**
  - Development of a CO$_2$ sequestration optimization curve (SOC)
    - *Example from the Upper Gulf Coast Frio Sandstones, Texas*
- **Summary**
Frio Sandstones act petrophysically like interparticle pore dominated rock.

\[ y = -0.3136 \ln(x) - 0.1334 \]

\[ R^2 = 0.8536 \]

Nonwetting phase residual saturation (fraction) vs. Porosity (fraction) graph with data points and line of best fit. The graph shows a significant trend with a correlation coefficient of 0.8536.
Residual Phase Sequestration Optimization Curve

- Residual gas saturation
- Bulk volume residual

0.23 Maximum

Residual saturation

Bulk volume residual
Property Changes with Depth, Porosity, and CO₂ Density

Modified from Loucks and others, 1984
CO$_2$ Sequestration Optimization Curve

Bulk volume stored as a function of density, temperature, pressure, porosity, residual gas saturation, and burial depth

- Maximum storage capacity

Depth (ft)

CO$_2$ bulk volume residual ($\text{kgm/m}^3$)
Optimization of CO$_2$ Sequestration in the Upper Gulf Coast, Frio Formation

- A depth of 10,000–12,000 feet is the optimal sequestration depth
- At this increased depth, the additional influence of secondary porosity aids in optimization by increasing aspect ratio
- Deep depths reduce the risk of any mobile CO$_2$ migrating to the surface
Conclusions

• Decrease in aspect ratio with porosity in intergranular porosity is a likely control on residual phase saturation
• Snap-off can be inferred as an important mechanism for developing residual nonwetting phase saturation
• A logarithmic empirical correlation facilitates the prediction of residual nonwetting phase saturation
• Greatest bulk volume storage of a nonwetting phase in interparticle pore dominated sandstones occurs at a porosity of 0.23
Conclusions

• CO₂ sequestration optimization is a function of temperature, pressure, CO₂ density, burial depth, porosity, and residual gas saturation
• Optimal depth for sequestering CO₂ in the Gulf Coast Frio Formation is between 10,000 and 12,000 ft
• CO₂ optimization curves are a useful tool when determining regional sequestration potential
• For sequestering CO₂ over geologic time, the most promising mechanism is trapping it as a nonwetting residual phase
Effect of Porosity on Sgrm–Swi Relationship

Pay cutoff
\( \phi = 0.18 \)
\( k = 4.9 \text{ md} \)

Initial gas saturation (fraction)

Residual gas saturation (fraction)

1 to 1 line

\( \phi = 0.19 \)

0.21, 0.23, 0.25, 0.33, 0.43