Effect of Small Scale Heterogeneity on Multiphase Flow of CO_2 and Brine

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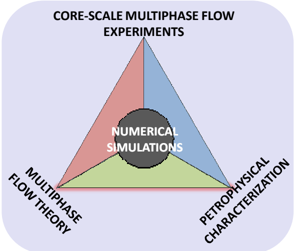
Motivation



THE SEQUESTRATION LAB

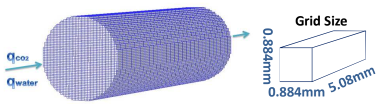
The goal of the Sequestration Lab is to develop ability to predict spatial and temporal distribution of CO_2 saturation and trapping through an improved understanding of the pore and core scale physics over the life cycle of a sequestration project

Focus of this work

Model behavior of brine displacement by injected CO_2 in a series of core-scale laboratory experiments

Gain better understanding of the influence of sub-core scale heterogeneity on CO_2 storage

Numerical Simulation: Core Description

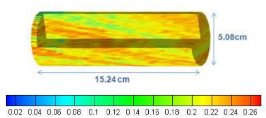


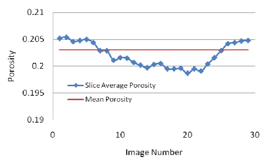
X: 31 grid
Y: 53 grid (159 pixel)
Z: 53 grid (159 pixel)
Total Grid = 64,635 Rectangular Elements

Tough2 MP with ECO2N module

- Used for numerical simulation
- Designed for large-scale simulations
- Robust treatment of thermodynamic and thermophysical properties of CO_2, H_2O and NaCl

Rock Properties: Porosity Map

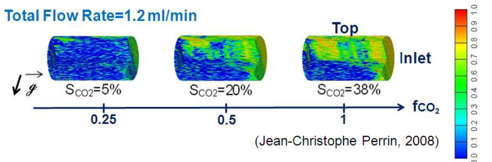




Berea Sandstone
29 lateral images data
Mean Φ=0.203/ Mean k=430 mD

Slice averaged porosity nearly constant
Sub-core scale heterogeneities
Bedding at a high dip angle

Experimental Results: Saturation Maps



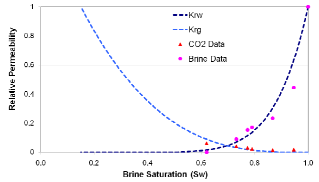
- Large part of the core poorly filled with CO_2 even at injection of 100% CO_2
- Want to explain bypass of bottom part of the core near the outlet

Simulation Input : Relative Permeability Curves

The relative permeability relation used in the simulation was the following:

$$k_{r,CO_2} = \left(\frac{1-S_w-S_{CO_2,r}}{1-S_{wrn}}\right)^{n_{CO2}}$$

$$k_{r,w} = \left(\frac{S_w-S_{wr}}{1-S_{wr}}\right)^{n_w}$$



These power-laws functions are used to fit the measured relative permeability data for brine and CO_2 and are used as inputs to the TOUGH2 model. The four free parameters (Swr, Swrn, nco2, and nw) are determined by the optimization.

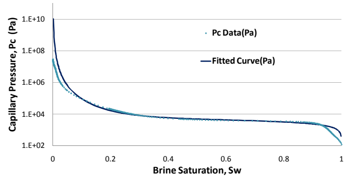
Simulation Input : Capillary Pressure Curves

- Measured capillary curve adjusted based on porosity and permeability values
- Each grid element has a unique pair of porosity and permeability values; hence a unique capillary pressure curve

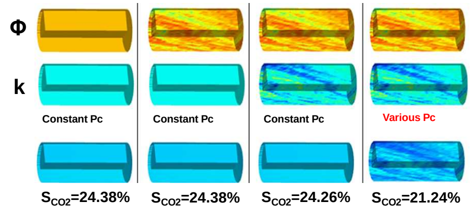
$$P_{c,i}(S) = \sigma\sqrt{\frac{\Phi_i}{k_i}}J(S)$$

$$J(S) = A\left(\frac{1}{S_*^{\lambda_1}}-1\right)+B\left(1-S_*^{\lambda_2}\right)^{1/\lambda_2}$$

$$S_* = \frac{S-S_P}{1-S_P}$$

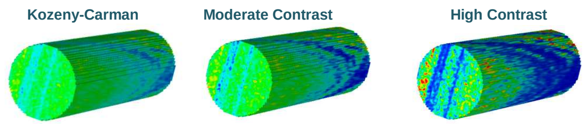


To replicate the spatial variations in CO_2 saturation observed in the experiments, the capillary pressure characteristic curve must be different in each grid element. The following figure shows various capillary pressure curves play an important roll for the saturation distribution.

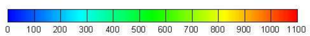


Simulation Input : Permeability-Porosity Models

A number of different porosity-permeability correlation models were tested in order to match the spatial distribution of CO_2 in the experiments. Three models are used to compare the experiments.

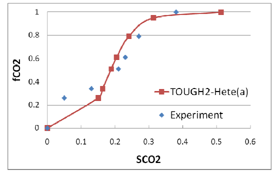


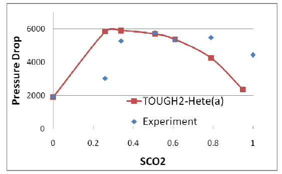
Permeability Map of Three Different Permeability-Porosity Relations



Simulation Results and Discussion

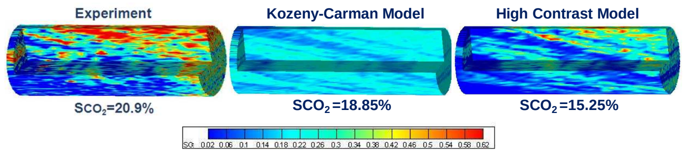
Compare Experiment and Simulation at 1.2ml/min





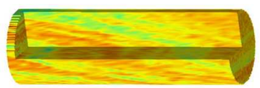
- The average saturation and the pressure drop can be replicated
- The matches of high and low fractional flow are not very good

Experiment for 51% CO_2 at 1.2ml/min



- Larger contrasts in permeability results in larger saturation contrasts
- Average CO_2 saturation decreased because of a higher degree of sub-core scale heterogeneity
- Measured CO_2 saturation patterns can be qualitatively replicated using simulation models
- Can reproduce absence of CO_2 in lower portion of outlet end of the core

Compare Porosity Map to CO_2 Saturation Map



Porosity Map

- Similar structural features
- Strong correlation close to the inlet end
- High porosity regions → high CO_2 saturations
- Low porosity layers act as capillary barriers, resulting in bypass of portions of the core

Conclusion

- Spatially varying porosity, permeability and capillary pressure curves are used in the simulations, and CO_2 distribution is controlled by varied capillary pressure curves
- Match CO_2 saturation magnitude and pressure drop quite good
- Measured CO_2 saturation patterns can be qualitatively replicated
- Low Φ→ low k→ high capillary entry pressure→ low CO_2 saturation
- Higher degree contrast in rock properties→ greater contrast in saturation
- Higher degree heterogeneity in the core→ lower average saturation

Future Work

1. Improve simulations to replicate experiment qualitatively and quantitatively
2. Investigate all the possible factors that may affect CO_2 saturation, such as flow rate effect, gravity effect and length effect
3. Identify and minimize numerical artifacts by different grid size and time step size

Acknowledgement

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