Development of Permeability Relationships for use in Simulations of Core Flooding Experiments

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RESEARCH GOALS

General Research Objective

The research groups stated goal is to develop the ability to spatially and temporally predict the distribution of CO_2 in a sequestration environment. Study is conducted through carefully designed experiments which measure the CO_2 distribution in a rock core, through numerical simulations which use the fundamental physics of multiphase flow to explain observed phenomena, and through geological characterization of the rock core in the experiment.

Objectives of This Work

Numerical simulation requires several parameters and rock properties to be used as input, some of these properties can be measured directly, others must be extrapolated from a known set of data. This research focuses on testing and developing methods for representing permeability at the sub-core scale for use in numerical simulation studies.

NUMERICAL SIMULATIONS

Purpose of Simulations

To study CO_2-brine systems, CO_2 is injected into a brine-saturated rock core and a CT scanner measured the saturation of CO_2 within the rock core at the sub-mm scale. Numerical simulations of the experiment are then conducted using the same thermophysical conditions, with the goal of reproducing the sub-mm CO_2 saturation distribution within the rock core.

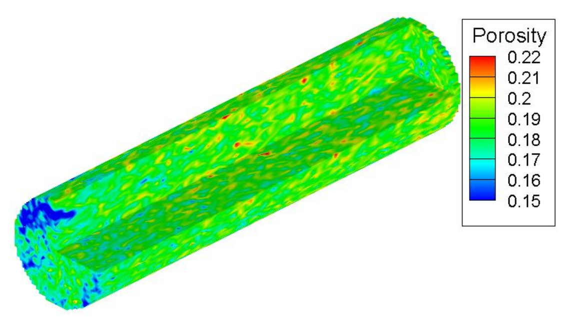
Required Simulation Input

Experimental measurements are taken at two scales, the core-scale and the sub-core scale. Measurements are typically made at one scale and then extrapolated to the other as required using averaging and scaling laws.

- Porosity – Measured at sub-core scale using a medical CT scanner
- Absolute Permeability – Measured at core scale using relative permeability experiment
- Relative Permeability – Measured at core scale using relative permeability experiment
- Capillary Pressure – Measured at core scale using mercury intrusion technique

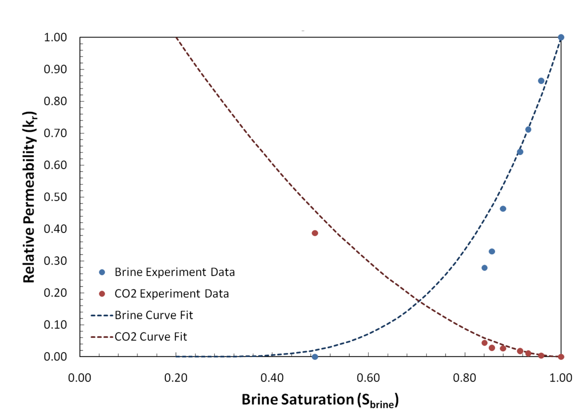
Porosity Input

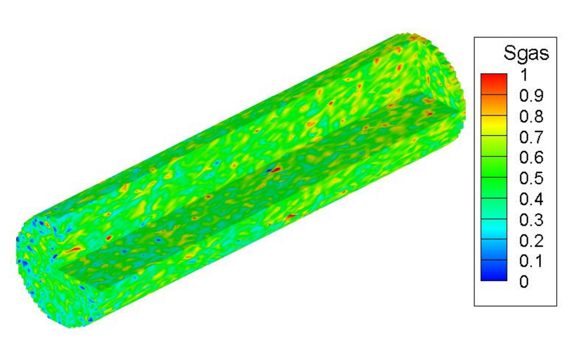
Porosity can be directly measured at the sub-core scale using the CT scanner. Core scale porosity is easily calculated by averaging the sub-core scale values across the whole core. The porosity image of the core is shown at right, the grid element size is 1.27 mm x 1.27 mm x 3 mm



Relative Permeability Input

Relative permeability is measured as a core-average property using a steady-state relative permeability experiment. Relative permeability is represented numerically as a power law function of saturation, shown at right. Saturation can be measured in the same way as porosity using the CT scanner, where the core average saturation corresponding to each core average relative permeability data point is calculated by averaging together all of the sub-core scale measurements. Sub-core scale saturation is shown at lower right, the grid element scale is the same as porosity.





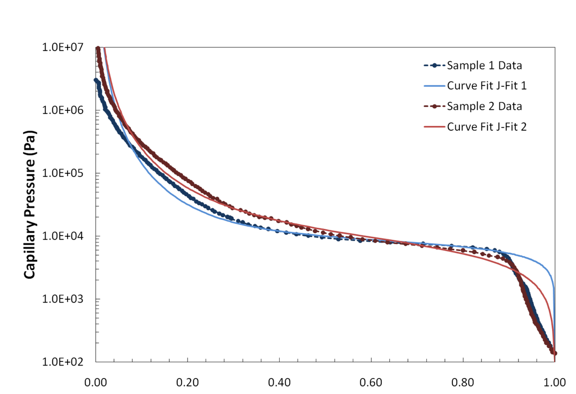
Capillary Pressure Input

Capillary pressure is measured on a representative piece of core using a standard mercury intrusion device. The single measured curve is then used to create unique sub-core scale curves for each grid element using Leverett's scaling relationship and an empirical J-Function fit to the single measured data set, shown in Eqs. 1 and 2 respectively.

$$P_{c,i} = \sigma_{CO_2-brine}\cos(\theta_{CO_2-brine})\sqrt{\frac{\phi_i}{k_i}}J(S_w) \quad \text{Eq. 1}$$

$$J(S_w) = A\left(\frac{1}{S_*^{\lambda_1}}-1\right)+B\left(1-S_*^{\lambda_2}\right)^{1/\lambda_2} \quad \text{Eq. 2}$$

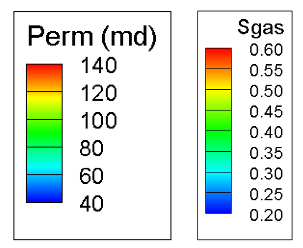
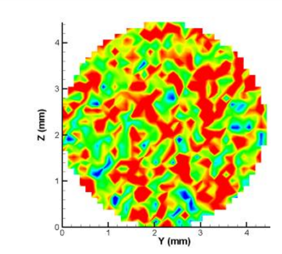
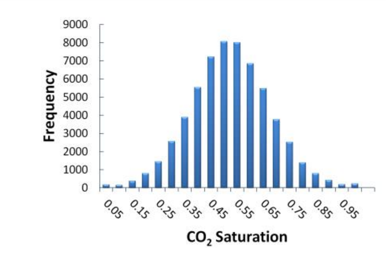
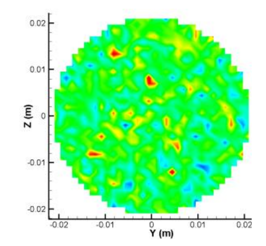
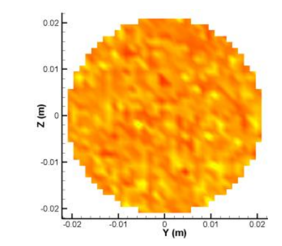
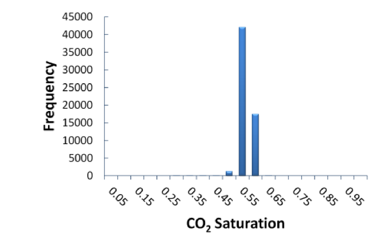
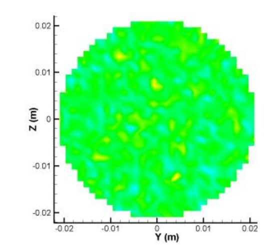
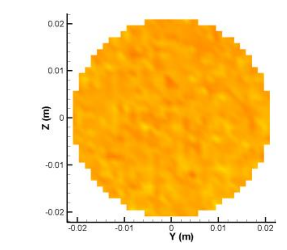
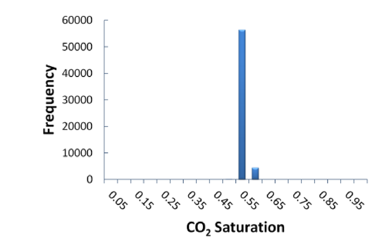
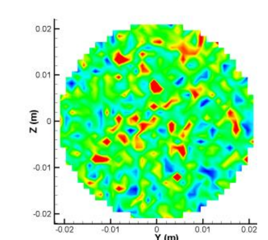
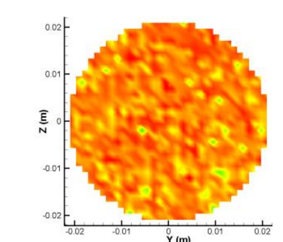
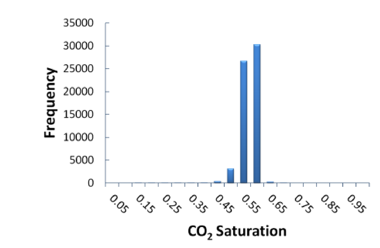
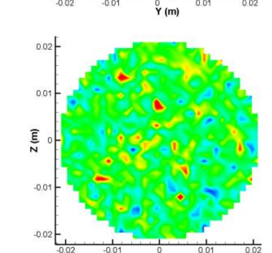
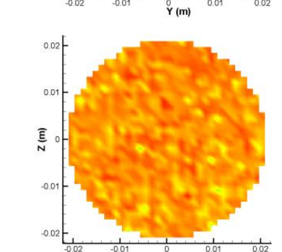
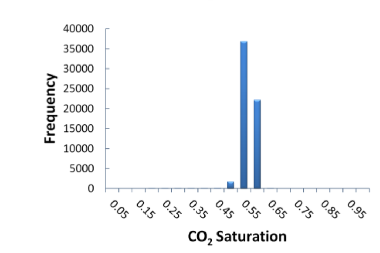
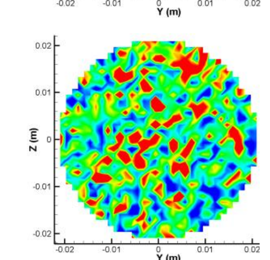
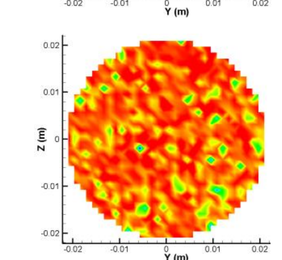
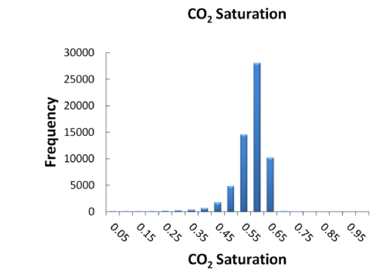
$$S_* = \frac{S_{brine}-S_{lr}}{1-S_{lr}} \quad \text{Eq. 3}$$



POROSITY-BASED PERMEABILITY PREDICTION

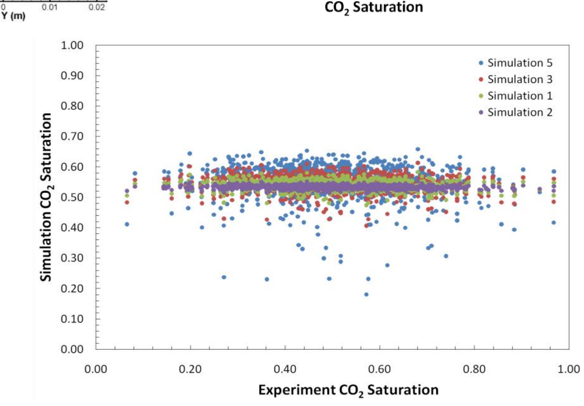
Permeability Calculation

- Permeability can be measured at the core scale. Many equations for calculating permeability using porosity measurements exist, but none have been thoroughly tested for use at the sub-core scale.
- Since porosity is measured at the sub-core scale, porosity-based methods lend themselves easily to this problem. Several different porosity-based methods have been selected with simulation results shown compared to the experimental measurement for a single slice below

Description	Slice Permeability	Slice CO_2 Saturation	Core Saturation Histogram
Experimentally Measured Data CO_2 Saturation Std. Dev. 0.1572			
Simulation 1[1] CO_2 Saturation Std. Dev. 0.0171 $k_i = S\frac{\phi_i^3}{(1-\phi_i)^2}$			
Simulation 2[2] CO_2 Saturation Std. Dev. 0.0103 $k_i = S\frac{\phi_i^{1.42}}{(1-\phi_i)^2}$			
Simulation 3[3] CO_2 Saturation Std. Dev. 0.0288 $k_i = S\frac{\phi_i^5}{(1-\phi_i)^2}$			
Simulation 4[3] CO_2 Saturation Std. Dev. 0.0198 $k_i = S\frac{(\phi_i-\phi_c)^3}{(1-\phi_i+\phi_c)^2}$			
Simulation 5[4] CO_2 Saturation Std. Dev. 0.0594 $k_i = S\cdot\left(6.2\phi_i+1493\phi_i^2+58(10\phi_i)^{10}\right)$			

Discussion of Results

- The saturation images in the table show that none of the simulation results has a visual match to the experiment.
- The histograms show that the distribution of saturation in the simulations is not close to the experiment.
- The cross plot at right of simulated saturation values vs. the experimental measurements for the slice shown in the table shows that there is no spatial correlation.



CONCLUSIONS AND FUTURE WORK

1. Using porosity-only based methods to predict permeability produces saturation results which do not match the degree of contrast in the saturation distribution.
2. Using porosity-only based methods results in spatial saturation distributions which are not correlated to the measured values.
3. Using the capillary pressure-based method to predict permeability much more accurately replicates the degree of contrast in the measured CO_2 saturation distribution.
4. Using capillary pressure-based methods results in spatial CO_2 saturation distributions which are uniquely correlated to the measured CO_2 saturation value.

CAPILLARY PRESSURE-BASED PERMEABILITY PREDICTION

Theoretical Development

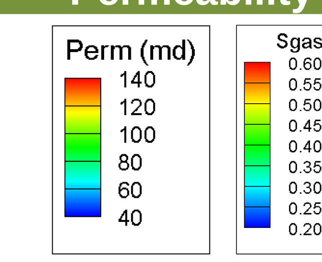
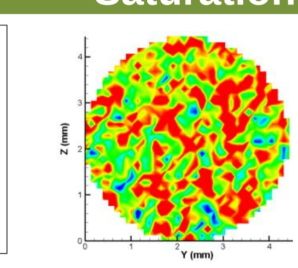
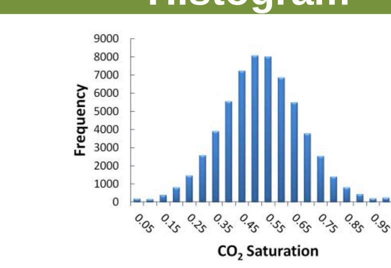
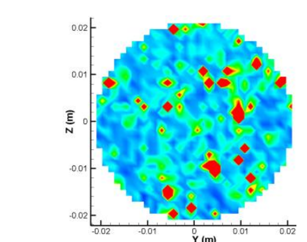
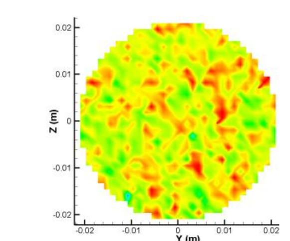
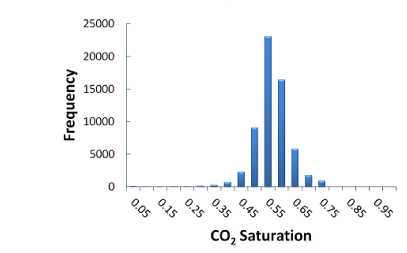
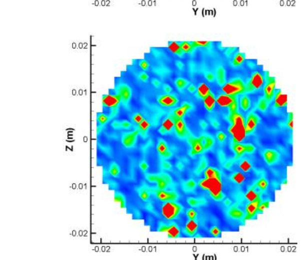
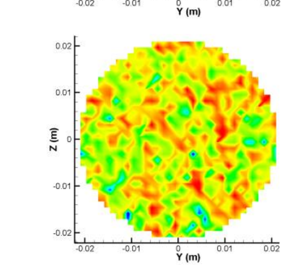
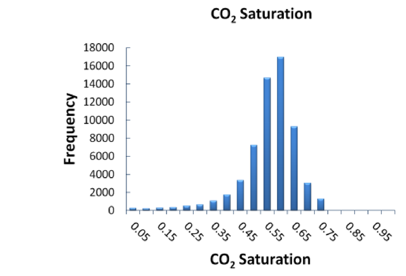
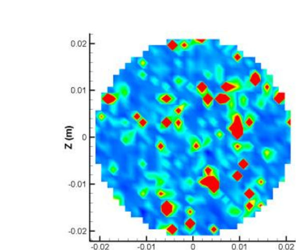
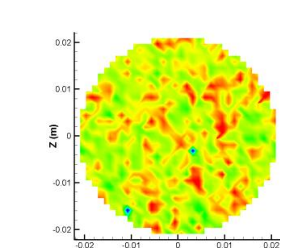
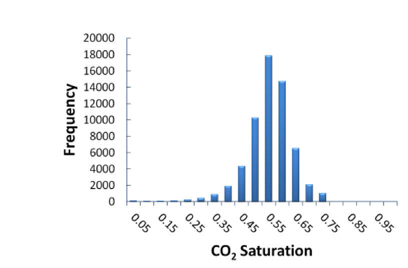
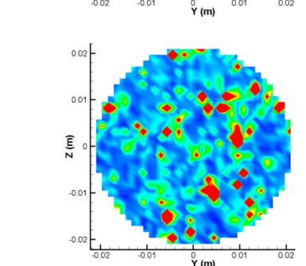
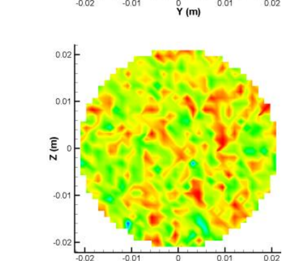
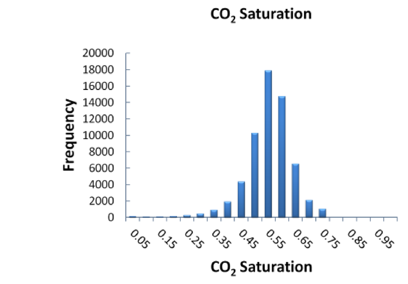
- Capillary pressure can be used to calculate permeability in the core by using Eq. 1.

$$k_i = \frac{1}{p_c^2}\phi_i[J(S_w)]^2(\sigma\cos\theta)^2 \quad \text{Eq. 4}$$

- The J-Function, J(Sw) is evaluated for each grid element using the measured saturation value from the experiment and using the fitting parameters in Eq. 2 for each curve.
- Capillary pressure , P_c, is evaluated at the core average saturation value and using the measured capillary pressure data.
- The resulting equation for permeability is shown in Eq. 5, where A, B, λ_1, and λ_2 are empirical fitting parameters selected to best fit the two measured capillary pressure curves (J-Fit 1 & 2).

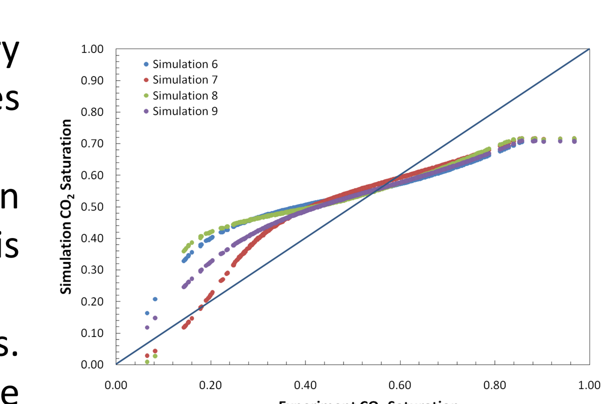
$$k_i = S\cdot\phi_i\left[A\left(\frac{1}{S_{*,i}^{\lambda_1}}-1\right)+B\left(1-S_{*,i}^{\lambda_2}\right)^{1/\lambda_2}\right]^2\left(\frac{\sigma\cos\theta}{\overline{P_c}}\right)^2 \quad \text{Eq. 5}$$

- Two different sets of fitting parameters are used in the J-Function in both the simulation and for calculating permeability for testing sensitivity to small changes in the Pc curve

Description	Slice Permeability	Slice CO_2 Saturation	Core Saturation Histogram
Experimentally Measured Data CO_2 Saturation Std. Dev. 0.1572			
Simulation 6 Perm $J(S_w)$ – J-Fit 1 Sim $J(S_w)$ – J-Fit 1 Std. Dev. 0.06898			
Simulation 7 Perm $J(S_w)$ – J-Fit 2 Sim $J(S_w)$ – J-Fit 1 Std. Dev. 0.1037			
Simulation 8 Perm $J(S_w)$ – Discrete Data Sim P_c – J-Fit 1 Std. Dev. 0.0765			
Simulation 9 Perm $J(S_w)$ – J-Fit 2 Sim P_c – J-Fit 2 Std. Dev. 0.0859			

Discussion of Results

- The saturation images in the table show that the capillary pressure-based method yields much closer visual matches to the experimental measurement.
- The histograms show that the distribution of saturation in the simulations still does not match the experiment, but is much improved over the porosity-based method results.
- The cross plot at right of simulated saturation values vs. the experimental measurements for the slice shown in the table above shows that there is an exact although not perfect correlation between the numerically predicted saturation and the experimental measurement.



5th Annual GCEP Research Symposium
Thursday October 1st, 2009, Stanford, CA

The Authors would like to gratefully acknowledge the financial support of the Global Climate and Energy Project

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