Effect of Flow Rate, Gravity, and Sub-Core Scale Heterogeneities on CO₂/Brine Relative Permeability Measurements in Horizontal Core Floods

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Motivation
This paper presents an assessment of the conditions under which accurate core-scale relative permeability measurements of CO₂/Brine at reservoir conditions can be obtained. The results are based on the high resolution of 3D simulation results of relative permeability measurements over a range of relevant conditions. The combined effect of flow rate, capillary pressure, gravity, and sub-core heterogeneity on steady-state multiphase flow experiments have been simulated at different fractional flows of CO₂ to gain a more quantitative assessment of the influence of these parameters on relative permeability measurements and to allow defining operational regimes under which reliable measurements can be attempted. A systematic parametric study of the flow mechanism is important to solve the issues we have in the steady-state multiphase flow system.

Simulation Input: Capillary Pressure Curves
- Homogeneous cores: one uniform capillary pressure curve for each grid element based on mean porosity and mean permeability values
- Heterogeneous cores: each grid element has a unique pair of porosity and permeability values; hence a unique capillary pressure curve

To replicate the spatial variations in CO₂ saturation observed in the experiments, the capillary pressure characteristic curve must be different in each grid element.

Simulation Results: Average CO₂ Saturation/Relative Permeability Calculations
- The minimum flowrate required eliminating the saturation gradient along the length of the core is defined as the "critical flowrate (q_c)."
- The combined effect of viscous, gravity, and capillary forces leads to the observed saturation gradient.
- Core heterogeneity will enhance the flow rate dependency, decrease the average saturation, and increase the saturation gradient.

Simulation Input: Porosity and Permeability
- The homogeneous core study uses mean porosity and permeability values
- The heterogeneous core study uses measured porosity values and generates the corresponding permeability values based on porosity-permeability equation

Simulation Input: Relative Permeability Curves
The relative permeability curves used in the simulations are power-law functions. These three parameters in the relative permeability functions were chosen to fit the relative permeability data calculated from experimental measurements conducted by Perrin and Benson (2010).

Simulation Input: Total Injection Flow Rates
The last important input parameter is the total injection flow rate. Flowrates range from 10 ml/min to 0.1 ml/min, which is practical for relative permeability experiments. For a given flow rate, simulations of co-injection of CO₂ and brine are run until the pressure drop and core-averaged saturation reach steady-state. All of our simulations have been confirmed to run long enough (more than 10 pore volume injected) to reach steady-state.

Simulation Output: Saturation and Pressure Gradient
Example: CO₂ saturation distribution at steady-state for 95% fractional flow of CO₂ at a total injection flow rate 1.2 ml/min

Drainage relative permeability has been calculated based on the main simulation outputs such as gas pressure, capillary pressure and the saturation:

- Above the critical flowrate (viscous-dominated regime), saturation is constant and flowrate independent, and the calculated relative permeability is also independent of flowrate.
- Below the critical point, decreasing flowrate will result in saturation gradients along the core and hence result in large deviation of relative permeability to water.
- The accurate whole-core drainage relative permeability can be obtained even with the highly heterogeneous core once the flow rate is above the critical value.

General Rule: The accurate whole-core relative permeability measurements can be achieved when

\[ N_r \cdot \frac{\Delta P_o}{A} \cdot \frac{P_{inj}}{P_{sat}} \leq 10 \]

which assures that the flowrate is in the viscous-dominated regime. \( N_r \) is the capillary number, the ratio of capillary to viscous force.

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