Effect of capillary induced flow on CO$_2$ residual trapping

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Abstract

Residual trapping as a result of capillary forces at the pore-scale is one of the main mechanisms to immobilize CO$_2$ during geological carbon sequestration. It is often assumed that in the capillary dominated regime, capillary equilibrium within the system is reached instantaneously. This approximation is valid for homogeneous systems where the largest scale of heterogeneity is at the pore scale. However, for heterogeneous systems, there is, next to the capillary potential at the pore scale, a capillary potential at the scale of the heterogeneity which will result in capillary induced flow. A good understanding of the capillary forces is important, not just to verify if the system has truly reached local capillary equilibrium, but more importantly because capillary induced flow can potentially have a big impact on the residual trapping capacity of a reservoir.

![Permeability fields (mD) for each of the cores used in the simulations. A. High-low permeability. B. Low-high permeability. C. Vertically layered permeability. D. Permeability field of vertically layered Berea (Liver) sandstone. E. Two-layered permeability. F. Horizontally layered permeability. G. Permeability field of horizontally layered Berea (Liver) sandstone. H. Permeability field of Berea sandstone core of Pini et al. 2013.](image)

We investigate the impact of rock structure heterogeneity on capillary induced flow in multiphase flow systems and its implications for residual trapping of CO$_2$ by performing numerical core-flood tests. The Stanford University general purpose research simulator (GPRS) is used to model drainage experiments where a mixture of CO$_2$ and water is injected into an initially water-saturated core. Several cores (~10cm long and ~5cm diameter) containing simple heterogeneity structures in the
permeability field are used for the simulations (Figure 1 A, B, C, E, F) together with cores containing realistic sub-core scale permeability fields of a range of sandstones (including the Fontainebleau, Berea (Figure 1 D, G, H), Bentheimer, and Dundee). The realistic permeability fields are constructed from experimentally obtained drainage saturation data. For each of the cores, multiple fractional flows are simulated for several flow velocities.

Our core-flood tests confirm that for relatively homogeneous rocks capillary equilibration occurs almost instantly. For systems with a larger scale of heterogeneity, capillary disequilibrium can exist locally within a core even in the capillary dominated regime.

Figure 2. Capillary pressure versus water saturation graphs after injecting 10 PV for three fractional flows (f_{50,50}, f_{10,90} and f_{1,99}) and two injection rates, 2ml/min (left) and 25ml/min (right), for the Pini core (Figure 1H).

Figure 2 shows the capillary pressure versus water saturation graphs for each of the voxels in the model for two different flow velocities within the capillary dominated regime for the Berea sandstone (Figure 1 H). The different colors indicate the distance from the inlet, with blue being close to the inlet and red being close to the outlet. Capillary equilibrium is reflected by the presence of a line of points with a constant capillary pressure but variable saturation. Capillary equilibrium within a slice perpendicular to the flow directions is reached for all fractional flows for the low injection rate. This is not the case for the higher injection rate where a wide range of capillary pressures is observed within a slice. This suggests that one cannot determine whether a heterogeneous system has reached capillary equilibrium by just calculating the traditional capillary number.

To quantify the impact of capillary forces relative to viscous forces at the voxel scale, a capillary strength number is calculated. For the horizontally layered cores (Figure 3 (A, B, C)) the capillary forces at the voxel scale are relatively strong at the inlet (low capillary strength numbers) but decrease with distance when the phases redistribute over the different layers (low permeability layers retain the water while CO\textsubscript{2} is drawn into the high permeability layers) and the system becomes closer to equilibrium. The capillary strength numbers are lower for the vertically layered cores because the system is pushed out of equilibrium near each interface (Figure 3D and Figure 4). The cross-flow forces are stronger for the low-high permeability core compared to the high-low permeability core. This shows that the direction of flow has an impact on the capillary pressure and saturation distribution.

For the horizontally layered Berea, most of the trapping takes place in the low permeability zones where the initial CO\textsubscript{2} saturation is high. However, in the vertically layered core, trapping also happens in low permeability regions with initially low CO\textsubscript{2} saturation but with high capillary strength (Figure 5). The redistribution of phases as a result of capillary induced flow can potentially control residual trapping. In horizontally layered systems it can lead to by-pass of CO\textsubscript{2} in horizontal low permeability lenses. In vertical layered systems, the high capillary strength near the interfaces could play an important role in snap-off.
Figure 3. Slice average capillary strength number for the synthetic horizontally layered core (A), the synthetic two-layered core (B), the horizontally layered Berea (C), and the vertically layered Berea (D). Flow direction is from left to right.

Figure 4. Capillary induced flow number versus slice number (solid lines) and water (dashed line) and CO₂ saturation (dotted line) versus slice number plotted on top of the permeability field for \( f_{1.05} \). The blue arrows indicate the preferred layer for the water phase. The green arrows indicate the preferred layer for the CO₂ phase. Red indicates the low flow velocity (2ml/min). Black indicates the high flow velocity (25ml/min). The capillary induced flow number gives the ratio of the viscous force to capillary induced flow forces.
Figure 5. CO₂ saturation after drainage, CO₂ saturation after imbibition, permeability field, and capillary strength number for a slice of the core perpendicular to the flow direction. Left: horizontally layered Berea. Right: vertically layered Berea.