Scaling of Viscous-Unstable CO_2-Brine Displacement

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Operational safety and long-term secure CO_2 storage requires proper characterization of the storage site and a careful engineering of the operation. While many aspects, such as the various trapping mechanisms, have already been researched in great detail, comparably little attention has been given to unstable displacement in the subsurface, which could have a significant impact on CO_2 plume migration. Since CO_2 has a significantly lower viscosity than the displaced brine, viscous instability becomes an obvious aspect of the process. Viscous fingering is a hydrodynamic instability that can occur when a more mobile fluid phase displaces a less mobile one, causing it to propagate much farther than predicted with volumetric injection.
There are two key questions: (a) is the displacement stable or unstable, and (b) if the displacement is unstable, i.e., subject to viscous fingering, what is the relevant fingering wavelength λ? The magnitude of λ relative to the length scales of geologic structures can be important. Unstable displacements can amplify the effect of geological heterogeneities and gravity, which can lead to uncontrolled migration of the CO_2 plume, increasing the risk of leakage.
To assess the potential impact of viscous fingers on CO_2 sequestration, it is difficult to understand which of the different formulations of the problem are applicable. In the presented study, we perform numerical simulations on the Darcy scale to evaluate the relevant CO_2 finger wavelength. Our simulations indicate that the wavelength of the fingers scales linearly with the interfacial tension and permeability, which is consistent with the long-wavelength instability studied by linear stability analysis [2], which is rarely used due to its impractical formulation; under CCS-relevant conditions, we predict finger wavelengths of tens to hundreds of meters [3, 4], rather than the centimeter scale or less predicted by the more commonly applied short-wavelength solution [1]. The findings may have implications for the implementation of CCS projects at the field scale where numerical modeling is used as a primary tool for design and uncertainty assessment. Long-wavelength instability combined with gravity may provide an explanation for the discrepancy between plume migration modeling predictions and actual field-scale observations, such as alignment with the top seal structures. The consistency with capillary-controlled migration modeling, even at tens of meters, is in line with laboratory-scale CCS experiments where the heterogeneity scale was smaller than the finger wavelength, emphasizing the importance of the finger wavelength. Explicitly capturing the effects of viscous instability requires a grid resolution finer than the finger wavelength. The quantitative estimate provided in this work can serve as a practical starting point.

References:

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