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Solute mixing during immiscible displacements in porous media

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Understanding the nature of solute transport in the subsurface is important for applications such as CO₂ storage in deep saline aquifers and the extraction of oil and gas from deep sandstone or carbonate formations. However, limited knowledge exists in this area due to the extent of heterogeneity in geological formations and the additional complexity coming from presence of multiple fluid phases. Heterogeneity plays a key role in these natural environments; the latter is manifested through the spatial variability of petrophysical properties, which in turns creates preferential flow paths and results in significant lateral spreading of the solute plume. The main focus of this study is to understand the effect of permeability heterogeneity on solute mixing and spreading in the presence of a second immiscible fluid phase. To this aim, single- and multi-phase pulse-tracer experiments were conducted on both unconsolidated systems (beadpack) and reservoir cores (Bentheimer Sandstone) using the N₂/water system, and breakthrough curves were measured. X-Ray Computed tomography (CT) and Positron Emission Tomography (PET) were used to obtain 3D distribution of fluid phase saturations and to simultaneously image the dynamic displacement of a radiotracer within the sample, respectively. In addition to the conventional transmission-mode tracer test, the “echo” technique is applied to decouple spreading introduced by (relative) permeability heterogeneity and Fickian mixing. The postulate tested here is whether the trapped non-wetting phase introduces a similar spreading mechanism, as would be expected from varying grain sizes in a single-phase scenario, and if this additional advective distortion is reversible in “echo” mode pulse-tracer tests. This is of paramount importance for investigating the extent of mixing caused by heterogeneity in multi-phase flow systems and to identify a correlation between dispersivity and fluid saturation in various reservoir cores.

In this study, we have validated the ability of the “echo” technique to describe heterogeneous systems with conventional advection dispersion equation (ADE) for both single- and multi-phase cases. This in turns provides a simple reliable approach to obtain intrinsic dispersivity of a heterogeneous porous system over a wide range of nonwetting saturation levels (~0-0.5). We observe (i) that dispersivity does depend on the saturation level of the non-wetting phase and (ii) that this dependency is stronger in the beadpack system as compared to Bentheimer Sandstone. We contend that this is due an inherently different microscopic configuration of the trapped ganglia in the pore space of unconsolidated and consolidated systems, as supported through images acquired at higher resolution on an X-ray microCT scanner.

References

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