Characterising drainage, imbibition and trapping in heterogeneous porous media from the mm to m scale

S.J. Jackson and S. Krevor
Department of Earth Science & Engineering
Imperial College London, London, United Kingdom.

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Abstract

Recent experimental and numerical work has shown how mm scale capillary pressure heterogeneities in porous media can significantly impact the flow and trapping of migrating fluid under a low flow potential [1, 2]. In fluid migration far from an injection site, the low flow potential plume can be effectively trapped by small scale capillary barriers, creating localised accumulations of the non-wetting phase [3, 4].

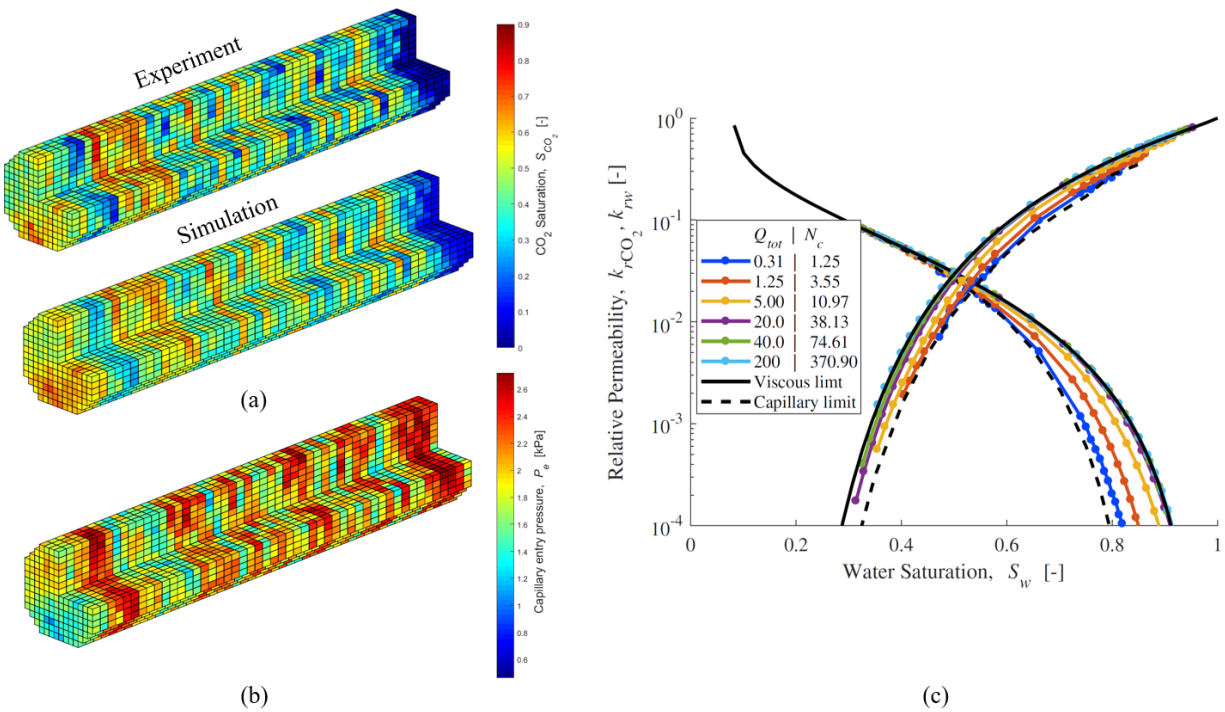

Figure 1: (a) Voxel (1.875 x 1.875 x 3 mm^3) saturation maps of a drainage steady-state CO_2-brine core flood in a Bunter sandstone core, $f(CO_2) = 0.975$. (b) Characterised 3D capillary entry pressure. CO_2 builds up behind high capillary entry pressure regions, which create localised barriers to flow. (c) Resulting drainage equivalent permeabilities incorporating capillary heterogeneity at different flow rates and capillary numbers N_c. Capillary limit relative permeability derived from steady-state numerical upscaling.

Through characterisation of the mm scale capillary pressure heterogeneity and the viscous limit relative permeability, experimental saturation heterogeneities and the build-up of the non-wetting phase behind capillary barriers can be accurately predicted with numerical simulations in 3D, see Figure 1(a)-(b). Although it is possible to explicitly model these heterogeneities in mm-m scale 3D simulations [5], it is computationally infeasible to do so for field scale modelling over kilometres.

To incorporate capillary pressure heterogeneity at the field scale therefore requires upscaling, whereby the fine scale flow physics are captured by upscaled functions deifned on large grid blocks (order of cm-m). When upscaling is performed on drainage multiphase flow, equivalent relative permeabilities are produced, which are both heterogeneity and flow rate dependent, e.g. dependent on the capillary number [6], see Figure 1(c). Through the use of appropirate upscaled equivalent relative permeabilities and average capillary pressure curves, plume migration can be accurately captured using cm-m scale grid blocks [5].

To analyse imbibition multiphase flow and the effects that sub-metre scale heterogeneities have on residual and capillary trapping, hysteresis needs to also be incorporated into the upscaled equivalent relative permeability functions. Recently, [7] show how the modelling of capillary pressure heterogeneity can be extended to incorporate hysteresis using a similar universal scaling law as the drainage process. In the current work, we extend these ideas by deriving upscaled equivalent relative permeabilities incorporating hysteresis, which are suitable for field scale modelling of flow and trapping.

We make use of a rich experimental core flood dataset obtained on CO_2-brine systems across multiple fractional flows, total flow rates and drainage-imbibition cycles. The experiments are performed on three distinct sandstone rock cores from UK North Sea reservoirs suitable for CO_2 storage. Through characterisation of the intrinsic multiphase flow functions incorporating hysteresis, we create a parametrised 'digital core'. The digital core is validated by numerically simulating core flood experiments across a wide range of flow conditions, showing that mm-m scale experimental saturations, equivalent relative permeabilities and trapping characteristics can be accurately predicted for both drainage and imbibition cycles.

The digital cores are then used to derive equivalent relative permeabilities across a wide range of flow regimes, incorporating mm scale capillary pressure heterogeneities and saturation hysteresis. We show how trapping characteristics vary from the mm to m scale, in which small scale capillary heterogeneities impact the initial-residual saturation relationship. Significant deviation from core-scale trapping models can be found at the mm scale, implying that localised trapping may have a significant effect on field scale flow.

References

[1] C.A. Reynolds and S.C. Krevor. Characterizing flow behaviour for gas injection: Relative permeability of CO_2-brine and N_2-water in heterogeneous rocks. *Water Resources Research*, 51(12):9464–9489, 2015.

[2] L. Trevisan, R. Pini, A. Cihan nd J.T. Birkholzer, Q. Zhou, A. González-Nicolás, and T.H. Illangasekare. Imaging and quantification of spreading and trapping of carbon dioxide in saline aquifers using meter-scale laboratory experiments. *Water Resources Research*, 53(1):485–502, 2017.

[3] S.C.M. Krevor, R. Pini, B. Li, and S.M. Benson. Capillary heterogeneity trapping of CO_2 in a sandstone rock at reservoir conditions. *Geophysical Research Letters*, 38:L15401, 2011.

[4] Y. Debbabi, M.D. Jackson, G.J. Hampson, and P. Salinas. Capillary heterogeneity trapping and crossflow in layered porous media. *Transport in Porous Media*, 2017.

[5] B. Li and S.M. Benson. Influence of small-scale heterogeneity on upward CO_2 plume migration in storage aquifers. *Advances in Water Resources*, 83:389–404, 2015.

[6] A. Rabinovich, K. Itthisawatpan, and L.J. Durlofsky. Upscaling of CO_2 injection into brine with capillary heterogeneity effects. *Journal of Petroleum Science and Engineering*, 134:60–75, 2015.

[7] R. Pini and S.M. Benson. Capillary pressure heterogeneity and hysteresis for the supercritical CO_2/water system in a sandstone. *Advances in Water Resources*, 108:277–292, 2017.