Mapping pore-scale flow heterogeneity in rock with 3D spatially-resolved propagators acquired using compressed-sensing APGSTE-RARE MRI

D.W. de Kort[a], *K. Karlsons*[a], *M. Appel*[b], *M.D. Mantle*[a], *A.J. Sederman*[a], *L.F. Gladden*[a]
[a]Magnetic Resonance Research Centre, University of Cambridge, UK, [b]Shell Technology Centre Amsterdam, The Netherlands

Introduction: This work demonstrates the acquisition of spatially-resolved flow propagators in porous carbonate rocks at pore-scale spatial resolution (100 μm), and the way in which they can be used to look at flow and dispersion processes at a pore scale. Measurement of flow propagators is one of the most powerful and comprehensive tools for characterising these phenomena, as they contain information about self-diffusion, flow, and dispersion [1]. Carbonate rocks are typically structurally heterogeneous across a wide range of length scales, ranging from the micrometre (pore) scale through the centimetre (rock core plug) scale to the field scale. Understanding flow and dispersion processes in such rocks is critical for the improvement of enhanced oil recovery and carbon sequestration technology.

Methods: A novel under-sampling APGSTE-RARE MRI experiment for 3D spatial resolution of flow propagators was implemented. [2,3] We have previously demonstrated that, from ~10% sampled data, spatially-resolved propagators can be recovered artefact-free [3–4] through a compressed sensing [5] approach that imposes sparsity in the reconstruction. In this work, the method was used to acquire propagators of creeping flow through 4-mm diameter rock plugs at an isotropic voxel resolution of 100 μm (acquisition time 2 days). 192,000 local propagators were obtained within each rock sample. The experiments were carried out on Ketton and Estaillades, both of which are carbonates, but with very different microstructures. The observation time (Δ) and flow rate were varied in order study local fluid mixing processes.

Results and discussion: At a spatial resolution of 100 μm, pore-scale features could be seen in the spatially-resolved propagator. This made it possible to co-align the data with X-ray μCT images of the same rocks, which visualise the pore and grain space at a much higher spatial resolution (~5 μm), thereby aiding in the interpretation of the MRI data in terms of the microstructural features of the pore space. The spatially-resolved propagators (Δ=150 ms) were then used to segment the pore space into stagnant and flow-carrying components. It could be seen that localised flow channels formed within the rocks, whilst the largest amount fluid was not associated with a significant flow rate. To observe mixing between the flowing and stagnant fluid components, additional spatially-resolved propagators were acquired at a longer observation time of 900 ms. By looking at individual propagators at the per-voxel level, the effect of mixing between the different components could be seen.

Conclusion: It was shown that 3D spatially-resolved propagators reveal significant heterogeneity of the flow field in carbonate rocks. At 100 μm spatial resolution, pore-scale features could be discerned in the spatially-resolved propagators, allowing co-registration of the MRI data with X-ray μCT images of the same rocks. A segmentation of the pore space then revealed which of the pores carry flow and in which pores the fluid is stagnant. An analysis of individual individual, per-voxel propagators revealed local mixing processes as a function of observation time Δ.

References: [1] Manz, AIChE J. (1999). [2] Scheenen, J. Magn. Reson. (2001). [3] de Kort, J. Magn. Reson. (2018). [4] Ramskill, Transp. Porous Med. (2018). [5] Lustig, Magn. Reson. Med. (2006).