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Fast imaging of laboratory core floods using 3D compressed sensing RARE MRI

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ABSTRACT

Three-dimensional (3D) imaging of the fluid distributions within the rock is essential to enable the unambiguous interpretation of core flooding data. Magnetic resonance imaging (MRI) has been widely used to image fluid saturation in rock cores; however, conventional acquisition strategies are typically too slow to capture the dynamic nature of the displacement processes that are of interest. Using Compressed Sensing (CS), it is possible to reconstruct a near-perfect image from significantly fewer measurements than was previously thought necessary, and this can result in a significant reduction in the image acquisition times. In the present study, a method using the Rapid Acquisition with Relaxation Enhancement (RARE) pulse sequence with CS to provide 3D images of the fluid saturation in rock core samples during laboratory core floods is demonstrated. An objective method using image quality metrics for the determination of the most suitable regularisation functional to be used in the CS reconstructions is reported. It is shown that for the present application, Total Variation outperforms the Haar and Daubechies3 wavelet families in terms of the agreement of their respective CS reconstructions with a fully-sampled reference image. Using the CS-RARE approach, 3D images of the fluid saturation in the rock core have been acquired in 16 min. The CS-RARE technique has been applied to image the residual water saturation in the rock during a water-water displacement core flood. With a flow rate corresponding to an interstitial velocity of $v_i = 1.89 \pm 0.03$ ft day^{-1}, 0.1 pore volumes were injected over the course of each image acquisition, a four-fold reduction when compared to a fully-sampled RARE acquisition. Finally, the 3D CS-RARE technique has been used to image the drainage of dodecane into the water-saturated rock in which the dynamics of the coalescence of discrete clusters of the non-wetting phase are clearly observed. The enhancement in the temporal resolution that has been achieved using the CS-RARE approach enables dynamic transport processes pertinent to laboratory core floods to be investigated in 3D on a time-scale and with a spatial resolution that, until now, has not been possible.

1. Introduction

Laboratory-scale displacements in rock core-plug samples (core floods) are widely used to develop understanding of oil recovery mechanisms [1–5], for validating interpretations of field-pilot well logging data [2] and for oilfield evaluation [3,4]. Traditionally, dynamic monitoring of core-plug internal fluid distributions has not been possible. This limitation necessitates that the system is treated as a 'black-box', whereby only the volumes and compositions of recovered fluids can be determined [5]. In reality, accurate recoveries cannot be determined from such volumetric averages, due to capillary end effects, oil bank formations, and both structural and surface wettability heterogeneities [2,4,6–9]. To this end, acquiring spatially-resolved information on the fluid distributions occurring throughout the time-course of core-floods is of considerable interest.

Currently, magnetic resonance imaging (MRI) [1,2,4–6,10–23] and X-ray computed tomography (CT) [24–29] are the most widely used techniques for imaging *in situ* core flood fluid distributions; both of which can non-destructively image multiphase fluid systems in porous media. As is well known the origin of image contrast associated with the two methodologies is quite different [30]. Whilst X-ray CT produces images at higher spatial resolution than MRI, albeit typically on smaller samples, the range of non-invasive contrast mechanisms associated with MRI methods, combined with its existing applications in special core analysis

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(porosity, permeability [31–33], surface interaction and wettability [34] measurements) make using magnetic resonance for imaging laboratory core floods a natural choice [35].

In systems that exhibit an heterogeneous fluid distribution within the rock during the core flood, for instance due to the capillary end effect [9], formation of Saffman-Taylor instabilities [12,36] or so-called 'worm holes' in reactive flow [37], 3D images are required to fully characterise core-flood behaviour. In conventional MRI acquisitions, **k**-space data are uniformly sampled at the Nyquist rate at increments of $\Delta\mathbf{k}$, which is determined by the desired field-of-view (FOV) and image resolution [38,39]. Consequently, when multi-dimensional and high spatial resolution images are sought, this can result in long acquisition times. For example, when using the spin-warp pulse sequence [40] for a matrix size of $256 \times 128 \times 128$ (read $\times$ phase $\times$ phase) with a recycle time of 2 s and 4 scans for signal averaging, the acquisition time will be approximately 36 h. At an interstitial velocity of 1 ft day^{-1}, which is representative of that found in the reservoir, in a 1.5″ diameter by 3″ length cylindrical plug with a porosity of 20%, approximately seven pore volumes (P.V.) of the displacing fluid will have been injected over the course of the 36 h acquisition. From this it is evident that the acquisition times for conventional 3D MRI sequences are such that the dynamic nature of core flood displacements cannot be effectively monitored.

Image acquisition times can be reduced using fast imaging sequences such as Rapid Acquisition with Relaxation Enhancement (RARE) [41] and Echo Planar Imaging (EPI) [42]. The principle behind both RARE and EPI is that multiple lines of **k**-space are acquired from an individual excitation. The practical limit on the number of lines of data that can be acquired from each excitation, and correspondingly the reduction in acquisition time, is determined by the relaxation times of the sample under investigation. The transverse relaxation times for the fluid-saturated rock core samples, which are the subject of the present study, are expected to be in the range of tens to hundreds of milliseconds. Considering a RARE acquisition of a water-saturated rock core characterised by T_2 = 150 ms, with an echo time T_E = 4 ms, it is reasonable to suggest that 32 lines of **k**-space can be acquired from each excitation. Therefore, for a matrix size of $256 \times 128 \times 128$ (read $\times$ phase $\times$ phase) with a recycle time of 2 s and 4 scans for signal averaging, the acquisition time is approximately 68 min. For the same conditions of the hypothetical core-flood discussed previously, approximately 0.2 P.V. of the displacing fluid will have been injected during the course of the acquisition. Whilst this is a significant improvement relative to the spin-warp acquisition, it is desirable to reduce the amount of blurring over the image acquisition still further to ensure that 'snap-shots' of the fluid distribution can be acquired at specific time points during the core flood.

It has been demonstrated that by using compressed sensing (CS), a signal with a sparse representation, such as an image, can be recovered from a number of measurements sampled below the Nyquist rate [43,44]. It therefore follows that by combining CS with ultra-fast MRI acquisitions, further reductions in acquisition time can be achieved, thus enabling dynamic processes, such as the laboratory core flood, to be studied. A second advantage of the enhancement in temporal resolution using CS is that a higher signal-to-noise ratio (SNR) can be achieved through more signal averaging per unit acquisition time. Again, this is desirable to the petrophysics community as low-field magnets, with inherently low sensitivity, are commonly used in a core analysis laboratory.

In application to porous materials, CS has previously been combined with pure phase-encoding techniques. Due to their robustness in the presence of paramagnetic impurities and magnetic susceptibility gradients, the pure phase encode methods have proven to be suitable for providing quantitative measurements of the fluid content in particularly challenging systems, such as rock cores. Single point imaging (SPI) with CS has been employed to quantitatively 3D-image dynamic moisture absorption processes within cereal-based wafer material [45]. Under-sampling the acquisition (at 33% of **k**-space) reduced the acquisition time from 39 to 13 min. More recently, spin echo SPI (SESPI) was used to image a water-saturated Berea sandstone core-plug: under-sampling in both phase-encoding directions, in which 20% of a 64×32 **k**-space matrix was acquired, resulted in an acquisition time of 2 h, which represented a 5-fold enhancement in the temporal resolution relative to a fully-sampled acquisition [46].

CS has also been compared with restricted **k**-space 'keyhole' imaging to provide spatially-resolved, 2D T_2 distributions [47]. While it was determined that the keyhole approach was more robust than CS in obtaining T_2 distributions from the image, both methods were found to be able to produce spin density maps in close-agreement with the fully-sampled reference image. However, there is an inherent limitation of the keyhole method when it cannot be assumed that the high spatial frequency regions of **k**-space, that are not sampled, do not change significantly over the time-course of experiments. The idea of restricted **k**-space sampling, as a means of decreasing acquisition times, has since been extended to obtain 2D Hybrid-SESPI, as well as 2D and 3D SPRITE images [48]. Xiao and Balcom [49] have presented a method using SESPI to acquire 1D water-saturation profiles during the dynamic flooding of a sandstone rock core. It has been shown that correlations in the spatial and temporal dimensions can be exploited to enable under-sampling of **k**-*t*-space, thus resulting in significant reductions in the acquisition time.

However, even with **k**-space under-sampling, the pure phase encoding techniques are too slow for studying dynamic displacement processes with 3D MRI. Depending on the system under investigation and the information sought, the choice of MRI pulse sequence is a trade-off between how quantitative the resulting image is and the achievable temporal resolution. In the application to imaging of rock cores, the most commonly used fast imaging techniques are π-EPI (PEPI) [50] and RARE [41]. The latter has certain advantages over the former, in that it is both T_1 and T_2-weighted as opposed to solely T_2-weighted, which, in theory, means that the signal lifetime is longer and more echoes may be acquired from a single excitation for a given echo time [35]. Additionally, due to non-ideal radio frequency (r.f.) pulses and imperfect gradients, PEPI is a notoriously difficult pulse sequence to implement. However, it has been shown by Xiao and Balcom [51] that by using composite broadband refocusing r.f. pulses and gradient pre-equalization, 3D PEPI can be successfully implemented to image water saturation in rock core plugs. This method has recently been applied to measure the oil distribution within a rock during a dynamic core flood [52]. As will be discussed in detail in Section 3, the RARE pulse sequence is particularly well-suited to CS acquisitions. This is due to the fact that the magnetisation is returned to the same position in **k**-space following the acquisition of each echo thus allowing much greater freedom in the design of the **k**-space sampling patterns. Considering the relative merits of these two ultra-fast MRI sequences, the RARE pulse sequence will be used as the basis for the CS acquisitions in the present study.

In this work, a 3D RARE with CS technique is demonstrated for imaging the fluid saturation during a laboratory core flood. The optimal **k**-space under-sampling strategy and image reconstruction protocols are described. The 3D CS-RARE technique is then applied to monitoring the forced displacement of water from a Bentheimer sandstone and subsequently the injection of dodecane into the water-saturated rock.