APPLICATION OF COMPRESSED SENSING MRI TO LABORATORY CORE-FLOODS

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ABSTRACT

Imaging of fluid distributions is essential to enable the unambiguous interpretation of core flooding data. In the present study, a rapid and robust magnetic resonance imaging (MRI) approach to provide 3D images of the fluid saturation in rock core samples during laboratory core floods has been demonstrated. MRI has been widely used to image fluid saturation in rock cores; however, the 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 significant reductions in the image acquisition times. Using a CS-MRI approach, 3D images of the fluid saturation in the rock core have been acquired in minutes as opposed to hours, as is the case with the conventional methods.

As a proof-of-principle, the CS-MRI technique has been applied to image the residual water saturation in the rock during a water-water displacement core flood. The enhancement in the temporal resolution that has been achieved using the CS-MRI approach will enable dynamic transport processes pertinent to laboratory core floods to be investigated on a time-scale that, until now, has not been possible.

INTRODUCTION

Laboratory-scale displacements in rock core-plugs (core floods) are widely used to develop the understanding of oil recovery mechanisms [1,2]. Magnetic resonance imaging (MRI) and X-ray tomography (CT) are the most widely used techniques for imaging *in situ* core flood fluid distributions – of which both can non-destructively image multiphase fluid systems in porous media [3-6]. CT images bulk densities and effective atomic numbers, distinguishing multicomponent systems based on atomic density differences. While this enables detection of both the rock matrix and imbibed fluids, this presents a challenge in providing contrast between fluids within the pore space, *i.e.* oil and brine, which, without the addition of dopants, the difference in atomic densities is small. In contrast, MRI has the advantage that there are numerous contrast mechanisms that can be implemented to provide contrast between different chemical species, namely: chemical selectivity of NMR-active nuclei detected (e.g. ^{1}H, ^{23}Na), spectroscopic chemical shift, relaxation time (T_1 and T_2) weighting, diffusivity contrast and use of lower gyromagnetic species, such as D_2O water [7].

However, conventional 3D MRI suffers low temporal resolution and hence, the dynamic nature of core flood displacements cannot be effectively monitored. In conventional MRI, data are uniformly sampled at the Nyquist rate (at a rate of at least twice the frequency of the highest frequency components present in the signal of interest). This is determined by the desired field of view (FOV) and image resolution. Therefore, when multi-dimensional and high spatial resolution images are sought, this can result in long acquisition times. It has been shown that using Compressed Sensing (CS), a near-perfect reconstruction can be obtained from a number of measurements sampled below the Nyquist rate. Therefore, by applying CS to MRI, reducing the number of data points sampled would lead to a reduction in the image acquisition time [8].

CS has previously been applied to pure phase-encoding techniques for the study of porous materials [9,10]. 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. However, even with under sampling, these techniques are too slow for studying dynamic displacement processes, particularly when 3D images are required. Depending on the system under investigation and the information sought, the choice of MRI pulse sequence is a trade-off between how quantitative it is and its achievable temporal resolution. In this work, Rapid Acquisition with Relaxation Enhancement (RARE) [11] with CS has been used to image the residual fluid saturation during a laboratory core flood.

PROCEDURE

In the present study, a Bentheimer sandstone plug, 38 mm in diameter and 68 mm in length has been used. The pore volume of the rock was determined to be 18 ml corresponding to a porosity of ~24 %. The rock was initially saturated with deionised water, which was displaced by a gadolinium chloride ($GdCl_3$) doped-water solution during the core flood. The concentration of the $GdCl_3$ (aq) solution (~8 mM) was chosen to ensure that the transverse relaxation time (T_2) was sufficiently short that it could not be detected in the images. The sample was held in-place by an Aflas sleeve within a PEEK rock core holder (ErgoTech, Conwy, UK). A constant confining pressure was applied to the outside of the Aflas sleeve by per-fluorinated oil (Fluorinert FC-43) using a Gilson 307 (Gilson Inc., USA) HPLC pump maintained at 250±25 psig by a back pressure regulator (Idex Health and Science, USA). The injectant was pumped through the rock at a flow rate of 0.025 ml min^{-1} using a Quizix QX1500 (Chandler Engineering, USA) dual-syringe pump. The corresponding interstitial pore velocity was ~0.4 ft day^{-1}.

The MRI experiments were carried out on a 2 T (85 MHz for ^1H) horizontal bore magnet controlled by a Bruker AV spectrometer. Prior to the start of the core flood, a fully-sampled 3D image was acquired as a reference and has been used for CS simulations.

During the core flood, under-sampled 3D images were acquired. For the acquisition of both fully and under-sampled 3D images, the RARE pulse sequence has been used. The field of view (FOV) was 80 mm × 50 mm × 50 mm in the *z*, *x* and *y* directions respectively. Correspondingly, for a data matrix size of 256 × 128 × 128 pixels in the read (*z*) direction and first (*x*) and second (*y*) phase encoding directions, the image resolution is 0.31 × 0.39 × 0.39 mm pixel^{-1}. For the fully-sampled 3D RARE images, the acquisition time was 2 hours and 9 minutes whereas for the 3D CS-RARE images, with 25 % sampling the acquisition time was approximately 16 minutes.

RESULTS AND DISCUSSION

Three-dimensional Compressed Sensing Simulations

In order to demonstrate the performance of CS, a qualitative comparison has been made between an image reconstructed from the fully-sampled data set and that from a CS reconstruction. For details on the CS reconstruction method used herein, the reader is directed to [12]. A more detailed description of the CS acquisitions and reconstructions employed in the present study will be reported in a future publication. Figure 1 a) shows a 2D *xz* slice taken from the reconstruction of the fully-sampled 3D reference image. For the CS simulation, a 30 % sampled data set was created by replacing 70 % of the data points, from the fully-sampled data, with zeros. Figure 1 b) and c) show 2D *xz* slices taken from the 3D images obtained from the zero-filled Fourier transform and CS reconstructions of the simulated under-sampled data, respectively.

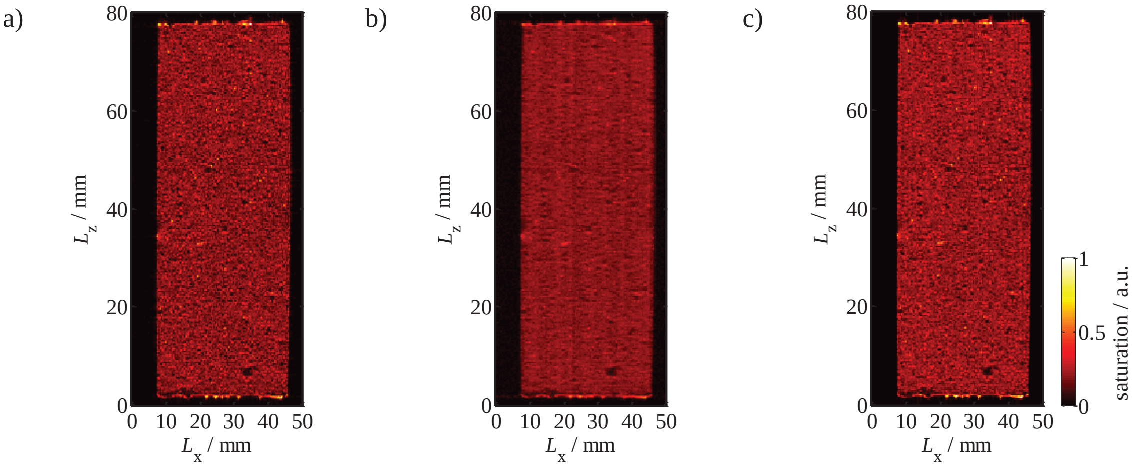


Figure 1. 2D *xz* slices taken from the centre of 3D images of the water-saturated Bentheimer rock prior to the core flood obtained by a) Fourier transform of the fully-sampled data, b) Fourier transform of the 30 % sampled data and c) CS reconstruction of the 30 % sampled data.

It can be seen that, due to the aliasing artefacts that arise from under-sampling, the contrast in the image the reconstruction from the zero-filled Fourier transform (Figure 1 b)) is somewhat reduced with respect to the fully-sampled case (Figure 1 a)). However, due to the bias towards a 'sparse' solution in the CS reconstruction (Figure 1 c)), an image with greater contrast than the zero-filled Fourier transform is obtained and is, visually, much closer to the fully-sampled image. A quantitative assessment of the CS methodology that has been implemented in the present study will be discussed in detail in a future publication. However, the qualitative comparison shown in Figure 1 has demonstrated that a near-perfect image has been recovered from data sampled significantly below the Nyquist rate, and would therefore allow for significant improvements in the temporal resolution for the acquisition of 3D images.

Application of 3D CS-MRI Imaging to a Water-Water displacement core flood

The fully and under-sampled 3D images of the initially water-saturated rock cores, prior to the start of the core flood, are shown in Figure 2 a) and b), respectively.

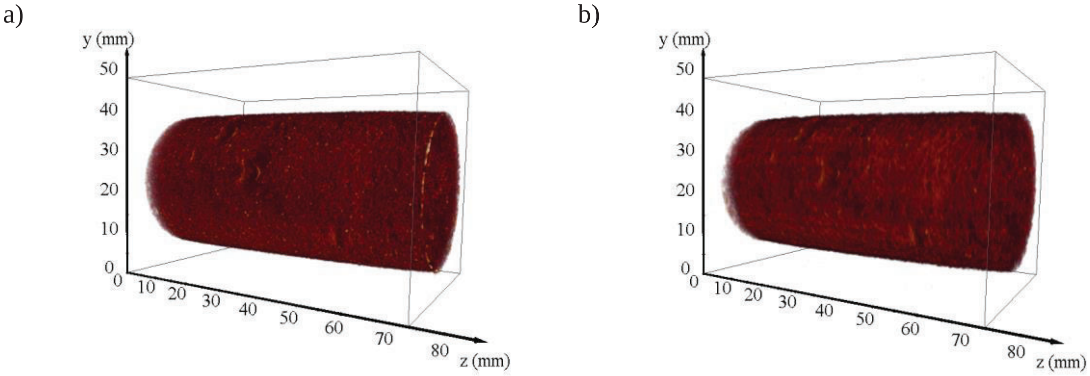
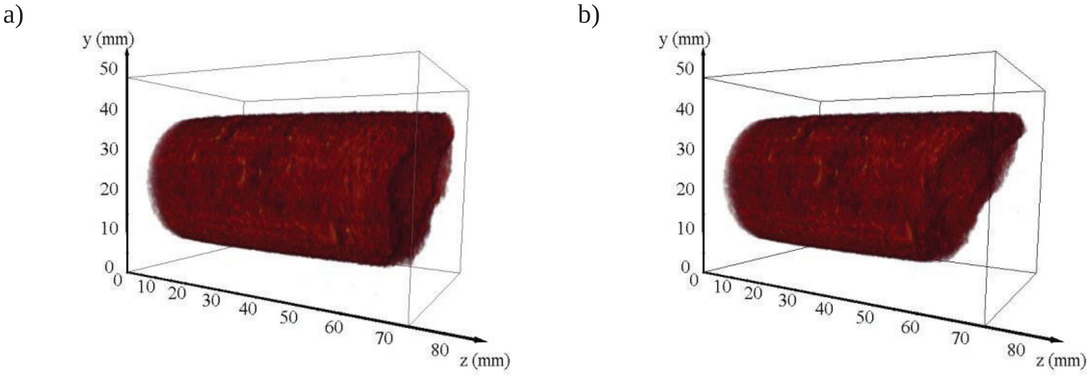


Figure 2. 3D images of the initially water-saturated Bentheimer rock from a) fully-sampled and b) 25 % sampled data set for which the acquisition times were 2 hours 9 minutes and 16 minutes, respectively.

By using CS combined with RARE, an enhancement in the temporal resolution by a factor of 8 has been achieved. It should be noted that the reduction in acquisition times relative to a standard spin-echo sequence or purely phase-encoded would be significantly greater. For instance, a 3D image of the same resolution as those presented herein acquired with a standard spin-echo sequence would take around 60 hours to acquire.

Figure 3 shows the 3D CS images of the residual saturation of the water that was *initially* present in the rock at various times following injection of the injectant solution. The flow of the injectant is from right-to-left, *i.e.* in the –z direction.



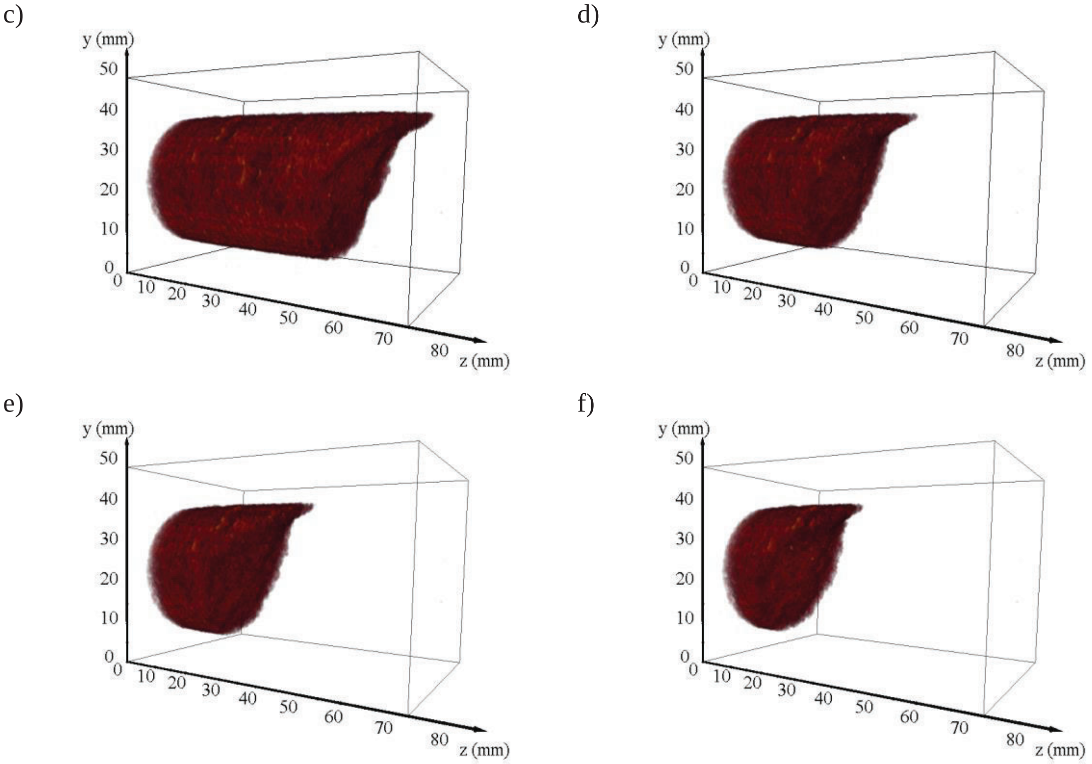


Figure 3. 3D CS images of the residual water in the Bentheimer rock core after a) 82, b) 180, c) 279, d) 377, e) 476 and f) 574 minutes of flowing a ~8 mM $GdCl_3$ (aq) solution at 0.025 ml min^{-1}. The flow of the injectant is from right-to-left, in the $-z$ direction. The concentration of the $GdCl_3$ (aq) solution was chosen as such to ensure that the transverse relaxation time (T_2) was sufficiently short thus it was 'invisible' in the images. From the series of images, the invasion front throughout the core flood is evident.

From the series of images presented in Figure 3, the progress of the displacement front through the rock during the core flood can be clearly observed.

CONCLUSIONS

In this paper, a CS MRI method for 3D imaging of the fluid saturation in rocks during a laboratory core flood has been demonstrated. Firstly, it has been shown that, visually, a near-perfect image can be reconstructed from data sampled in violation of the Nyquist criteria, thus allowing for significant reductions in the acquisition times. Using CS with RARE, an eight-fold improvement in the temporal resolution has been achieved, relative to the fully-sampled RARE acquisition. However greater time savings are possible over more standard pulse sequences. Secondly, the CS-RARE technique has been applied to image the residual water saturation during a water-water displacement core flood.

The enhancement in the temporal resolution obtained with CS will unlock the potential to observe phenomena during a core flood on a time scale that would not be possible using conventional MRI protocols. It is therefore the aim of future work that this method will be applied to investigate pertinent issues such as ganglion dynamics [6] and the influence of capillary end effects [13] during an oil recovery core flood.

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