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Local diffusion and diffusion-T_2 distribution measurements in porous media

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ABSTRACT

Slice-selective pulsed field gradient (PFG) and PFG-T_2 measurements are developed to measure spatially-resolved molecular diffusion and diffusion-T_2 distributions. A spatially selective adiabatic inversion pulse was employed for slice-selection. The slice-selective pulse is able to select a coarse slice, on the order of 1 cm, at an arbitrary position in the sample.

The new method can be employed to characterize oil-water mixtures in porous media. The new technique has an inherent sensitivity advantage over phase encoding imaging based methods due to signal being localized from a thick slice. The method will be advantageous for magnetic resonance of porous media at low field where sensitivity is problematic.

Experimental CPMG data, following PFG diffusion measurement, were compromised by a transient $\Delta B_0(t)$ field offset. The off resonance effects of $\Delta B_0(t)$ were examined by simulation. The ΔB_0 offset artifact in D-T_2 distribution measurements may be avoided by employing real data, instead of magnitude data.

1. Introduction

Magnetic resonance (MR) is an important method for characterization of the petrophysical properties of reservoir core plugs. MR analysis of fluids in reservoir cores and core plugs is well-established in petroleum reservoir core analysis. MR measurements of water or brine-saturated porous media are commonly undertaken to determine the geometry and surface properties of the pore system. The simple T_2 distribution may be correlated, in advantageous systems, to a distribution of pore sizes [1–3].

In partially saturated rocks the individual brine and oil T_2 distributions frequently overlap. The T_2 distribution may not in such cases permit one to distinguish oil from brine. However, the molecular diffusion coefficients of oil and brine often differ significantly and this difference can be employed to discriminate the MR signals for the two fluids [4].

Spin-echo pulsed magnetic field gradient (SE-PFG) measurement has been utilized to measure translational diffusion coefficients, D, of molecules in homogeneous liquids and porous solids [5]. In microporous systems where T_2 is less than the longitudinal relaxation time (T_1), stimulated echo pulsed magnetic field gradient measurements (STE-PFG) may be beneficial [6,7].

The SE-PFG and STE-PFG experiments have been combined with CPMG measurement to measure bulk diffusion-T_2 relaxation (D-T_2) distributions [8–12]. The measurement of a bulk D-T_2 distribution function enhances our ability to discriminate signals of the two fluid phases. D-T_2 distribution measurement methods may be applied to identify the wetting phase and to yield information on the distribution of phases within the pore space [12,13].

Bulk D-T_2 measurements generate information from the whole sample. In many cases spatially-resolved D-T_2 measurement of the sample is desirable. One example is water flooding experiments in reservoir rocks, where the efficiency of flooding is examined by spatial monitoring of the water and oil displacement within the sample. MRI has been combined with D-T_2 measurement to achieve spatial resolution of fluid behaviour within specific regions of a sample. Spatially-resolved D-T_2 measurements was proposed by Li and Petrov in one dimension [14]. Zhang and Blümich investigated spatial resolution of the D-T_2 distribution in two dimensions [15,16].

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The challenge of imaging based D-T_2 methods is to undertake the measurement with a low B_0 field (0.2 T) in reasonable time. The low B_0 field is often required in porous media MR measurements to limit micro and macro scale susceptibility driven field distortion [17–22]. Low field translates to low SNR; hence, it is advantageous to develop spatially-resolved D-T_2 measurements that are more sensitive.

In this study, a spatially-selective adiabatic inversion [23] is combined with SE-PFG and SE-PFG-T_2 measurements to measure D and D-T_2 data for slices of interest within the sample. The inversion pulse is able to select a coarse slice, on the order of 1 cm, at an arbitrary position. Data are thus acquired with low spatial resolution. This work builds on previous slice-selective adiabatic inversion T_2 distribution measurements [24–26]. The slice-selective D-T_2 method does not employ conventional selective excitation, but rather employs a subtraction with measurements acquired with and without an adiabatic inversion slice-selection.

Although slice-selective D-T_2 has lower resolution, in comparison with imaging based spatially-resolved measurements [14,15], the method is simple (no imaging gradients) and this is one of its principle advantages. Slice-selective D-T_2 measurement employing adiabatic inversion pulses provides an alternative to spatially-resolved imaging based D-T_2 techniques, when D-T_2 needs to be measured at only a few positions within a sample during flooding measurements and high spatial resolution is not necessary. In contrast to an imaging based spatially-resolved D-T_2 approach, the method can yield either contiguous or non-contiguous slices.

Switching of magnetic field gradients induces eddy currents in the conducting structures of the magnet. Eddy currents cause magnetic field variations that may persist for a prolonged time after the primary gradient has been switched off [27–30]. The effects of eddy currents in the magnet pole pieces may be described by a $\Delta B_0(t)$ which decays in time. The off resonance effects of $\Delta B_0(t)$ were examined by simulation. These results are described in Appendix A.

2. Methods

2.1. Slice-selective SE-PFG

The adiabatic inversion pulse was combined with a bulk PFG measurement as shown in Fig. 1a. The bulk PFG measurement was performed with a conventional SE-PFG (Fig. 1a without slice-selection). If $2\tau \ll T_2$ and $\Delta \ll T_2$, the attenuation of the spin echo is given by Eq. (1), where D is the diffusion coefficient, Δ is the diffusion time, δ is the duration of gradient pulses and $q = \gamma\, G\, \delta$. γ is the gyro-magnetic ratio and G is the amplitude of the gradient pulse [17].

$$\frac{S(q^2)}{S(0)} = \int dD\, f(D) \times \exp\{-q^2 D(\Delta - \delta/3)\} \tag{1}$$

S(0) is the echo amplitude at $q = 0$.

Slice-selective SE-PFG consists of two successive scans: during the first scan, the magnetization is inverted from z to $-z$ inside a desired frequency band, while during the second scan, all magnetization is maintained along z. Subtracting the signals leaves only the selected frequency band. Slice-selective magnetic field gradients were employed orthogonal to the PFG gradients to reduce the effect of residual magnetic field gradients.

2.2. Slice-selective SE-PFG-T_2

Slice-selective SE-PFG-T_2, Fig. 1b is conceptually similar to the slice-selective SE-PFG method. The adiabatic inversion pulse was combined with a bulk SE-PFG-T_2 to measure D-T_2 data. If $2\tau \ll T_2$ and $\Delta \ll T_2$, the attenuation of the first spin echo by diffusion is identical to the expression in Eq. (1). Given a short echo time $2\tau'$, signal attenuation by diffusion can be neglected during the detection of the CPMG echo train. Attenuation of the CPMG echo train depends on T_2 as described by the second exponential term in Eq. (2) with $t = n2\tau'$. The overall expression, Eq. (2), depends on the D-T_2 distribution $f(D, T_2)$.

$$\frac{S(q^2,t)}{S(0)} = \int dD\; d(T_2) f(D,T_2) \times \exp\{-q^2 D(\Delta - \delta/3)\} \times \exp\{-t/T_2\} \tag{2}$$

3. Experimental

3.1. Data processing

The WinDXP program (Oxford Instruments, Oxford, UK) was employed for T_2 distribution determination. WinDXP is a windows-based software toolbox, which allows distributed exponential fitting of data acquired using RINMR (Oxford Instruments, Oxford, UK) data acquisition software.

One-dimensional Fast Laplace Inversion (Laplace Inversion Software, Schlumberger-Doll Research) was utilized for diffusion distribution determination. Two-dimensional Fast Laplace Inversion (Laplace Inversion Software, Schlumberger-Doll Research) was employed for D-T_2 distribution determination.

3.2. Equipment

All MRI measurements were performed on a Maran DRX-HF (Oxford Instruments Ltd., Oxford, UK) 0.2 T permanent magnet which is 8.5 MHz for ^{1}H. The RF probe was a custom-built solenoid, 4.4 cm inner diameter, driven by a 1 kW 3445 RF amplifier (TOMCO Technologies, Sydney, Australia). The 90° RF pulses were 11.4 μs with an RF power of 300 W. A shielded three axis gradient coil driven by Techron (Elkhart, IN) 7782 gradient amplifiers, provided maximum magnetic field gradients of 25.7 G cm^{-1}, 24.7 G cm^{-1} and 33.7 G cm^{-1} in x, y (vertical), and z, respectively.

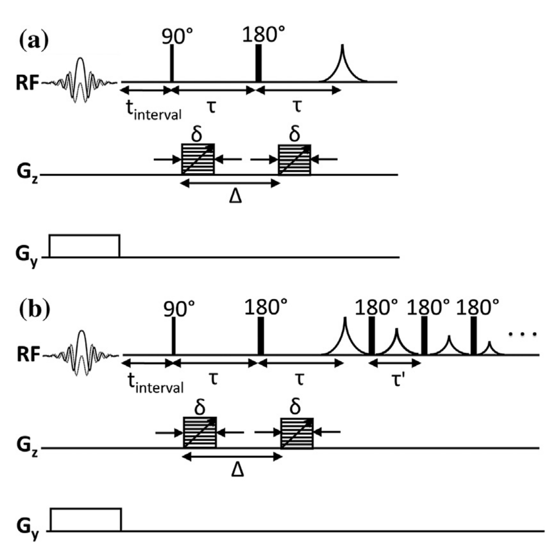

Fig. 1. (a) Adiabatic inversion SE-PFG method to measure diffusion coefficients for slices of interest. (b) Adiabatic inversion SE-PFG-T_2 for slice-selective D-T_2 measurements of regions of interest.