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Spatially resolved measurements of mean spin–spin relaxation time constants

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ABSTRACT

Magnetic Resonance measurements of the T_2 distribution have become very common and they are a powerful way to probe microporous fluid bearing solids. While the structure of the T_2 distribution, and changes in the structure, are often very informative, it is common to reduce the T_2 distribution to a mean numeric quantity in order to provide a quantitative interpretation of the distribution. Magnetic Resonance Imaging measurements of the T_2 distribution have recently been introduced, but they are time consuming, especially for 2 and 3 spatial dimensions.

In this paper we explore a direct MRI measurement of the arithmetic mean of $1/T_2$, characterizing the distribution by using the initial slope of the spatially resolved T_2 decay in a CPMG prepared Centric Scan SPRITE experiment. The methodology is explored with a test phantom sample and realistic petroleum reservoir core plug samples. The arithmetic mean of $1/T_2$ is related to the harmonic mean of T_2. The mean obtained from the early decay is explored through measurements of uniform saturated core plug samples and by comparison to other means determined from the complete T_2 distribution. Complementary data were obtained using SE-SPI T_2 distribution MRI measurements.

The utility of the arithmetic mean $1/T_2$ is explored through measurements of centrifuged core plug samples where the T_2 distribution varies spatially. The harmonic mean T_2 obtained from the early decay was employed to estimate the irreducible water saturation for core plug samples.

1. Introduction

T_2 distribution measurements have become very important and common in investigations of fluids in microporous samples. The structure of the T_2 distribution is often informative, but it is common to reduce the distribution to a mean numeric quantity, in order to provide a quantitative interpretation of the T_2 distribution.

T_2 distribution measurements are most frequently bulk measurements, but the distribution may be spatially resolved [1]. Spatially resolved MRI measurements of the T_2 distribution are relatively new [2,3]. Spatially resolved T_2 distribution measurements are time consuming measurements in 2 and 3 spatial dimensions.

The T_2 distribution is most commonly determined by inverse Laplace transform (ILT) of the T_2 decay. The ILT process is an ill-conditioned problem [4–9]. Noisy data hinders determination of the T_2 distribution, therefore a better representation of the relaxation time distribution may be possible using means independently obtained [10]. This paper presents a direct way to determine the spatially resolved T_2 relaxation time based on the arithmetic mean of the relaxation rate. The arithmetic mean obtained in this way is independent of the inverse Laplace transform process.

The arithmetic mean of the relaxation rate is obtained from the initial slope of the CPMG decay and is used to directly determine the harmonic mean T_2. The accuracy of this harmonic mean is tested by comparing it with different relaxation time means determined from the T_2 distribution. Spatially resolved measurements are undertaken with two pure phase encode MRI methods. Uniform phantoms and brine saturated porous rock core plugs are employed as test samples.

Direct measurement of the mean T_2 relaxation time may be advantageous for core analysis, or studies of different types of porous media. In this work the harmonic mean T_2 relaxation time is used to estimate the irreducible water saturation for centrifuged core plugs. The irreducible water saturation obtained based on the T_2 harmonic mean is compared with the irreducible water saturation obtained by the classic cutoff bulk volume of irreducible water (CBVI) method [11,12] and gravimetric measurements.

2. Mean T_2 parameters and MRI methods

The T_2 CPMG echo decay experiment [13,14] is often fit to a single or multiple exponential decay model, with Eq. (1):

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$$A(t) = f(t) = \sum_{i=1}^{n} A_i \cdot e^{-\frac{t}{T_{2i}}} \quad (1)$$

where $A(t)$ is the time dependent signal observed, A_i is the amplitude of the ith component of the signal, T_{2i} is the ith component of the relaxation time and t is the time.

If there is a distribution of the relaxation time it is common to use the ILT in order to determine the T_2 distribution. From the T_2 distribution it is possible to determine a variety of different mean T_2s.

2.1. Mean T_2s

The T_2 distribution may be characterized by different means, for example the arithmetic mean, harmonic mean and logarithmic mean. These means are outlined below.

The *arithmetic mean* (AM) [15,16] of the probability distribution of the relaxation times is given by Eq. (2):

$$T_{2AM} = \frac{\sum_{i=1}^{n} T_{2i} \cdot P_i(T_{2i})}{\sum_{i=1}^{n} P_i(T_{2i})} \quad (2)$$

where T_{2i} are the discrete values of the relaxation times and $P_i(T_{2i})$ are the corresponding probabilities. The arithmetic mean is known to be sensitive to large extremes of the discrete values of the distribution [10,15].

The *harmonic mean* (HM) is defined [15,16] in terms of the T_2 distribution by Eq. (3):

$$T_{2HM} = \sum_{i=1}^{n} P_i(T_{2i}) \cdot \left[\sum_{i=1}^{n} P_i(T_{2i}) \cdot \left(\frac{1}{T_{2i}} \right) \right]^{-1} \quad (3)$$

where T_{2i} are the discrete values of the relaxation times and $P_i(T_{2i}) \cdot \left(\frac{1}{T_{2i}}\right)$ are the corresponding probabilities of the relaxation rate. The harmonic mean is known to be sensitive to the small extremes of the discrete values of the distribution [10,15].

The *logarithmic mean* (LM) is defined in two ways [2,17], but in terms of the T_2 distribution the logarithmic mean is calculated by Eq. (4):

$$T_{2LM} = \exp\left\{ \frac{\sum_{i=1}^{n} [P_i \cdot \ln(T_{2i})]}{\sum_{i=1}^{n} P_i(T_{2i})} \right\} \quad (4)$$

The logarithmic mean computed using Eq. (4) is identical to the geometric mean. Both are relatively insensitive to the extremes of the discrete values of the distribution [10,15].

2.2. Arithmetic mean of the relaxation rate

In this work we explore direct measurement of a related mean, the mean of the relaxation rate. Differentiating Eq. (1) which describes the CPMG decay curve, with respect to time we obtain:

$$f'(t) = \sum_{i=1}^{n} A_i \left(-\frac{1}{T_{2i}} \right) \exp\left(-\frac{t}{T_{2i}} \right) \quad (5)$$

and for time $t = 0$ this (6) becomes:

$$f'(0) = \sum_{i=1}^{n} A_i \left(\frac{1}{T_{2i}} \right) \quad (6)$$

$f'(0)$represents the slope of the tangent line to the CPMG decay at maximum amplitude when $t = 0$. Eq. (6) can be rewritten:

$$f'(0) = \frac{\Delta f}{\Delta t} \quad (7)$$

Eq. (1) at $t = 0$ equals:

$$f(0) = \sum_{i=1}^{n} A_i = A_{\max} \quad (8)$$

Experimentally $f(0)$ represents the maximum signal amplitude of the CPMG decay. If this maximum amplitude cannot be directly acquired experimentally, it can be determined by extrapolation of the early decay.

Dividing Eq. (7) by Eq. (8), in accord with Eq. (2), the arithmetic mean of the relaxation rate will be obtained:

$$\left\langle \frac{1}{T_2} \right\rangle = \frac{f'(0)}{f(0)} = \frac{\frac{\Delta f}{\Delta t}}{f(0)} = \frac{\sum_{i=1}^{n} A_i \left(\frac{1}{T_{2i}}\right)}{\sum_{i=1}^{n} A_i} = \frac{Initial\,Slope}{A_{\max}} \quad (9)$$

Based on Eq. (9) the initial slope and the maximum amplitude can be used to obtain the arithmetic mean of the relaxation rate. The brackets $\langle\ \rangle$ in Eq. (9) indicate the arithmetic mean of the relaxation rate. As suggested by Eq. (3) the arithmetic mean of the relaxation rate is related to the harmonic mean of the relaxation time, as Eq. (10) describes:

$$T_{2HM} = \frac{\sum_{i=1}^{n} A_i}{\sum_{i=1}^{n} A_i \left(\frac{1}{T_{2i}}\right)} = \frac{A_{\max}}{Initial\,Slope} \quad (10)$$

The arithmetic mean of the relaxation rate can be used to determine the harmonic mean of the relaxation time, Eq. (11):

$$\left\langle \frac{1}{T_2} \right\rangle = \frac{1}{T_{2HM}} \quad (11)$$

The relationship of Eq. (11) has been verified through simulation of model data sets with a variety of T_2 distributions.

The early decay approach has been used successfully in MR measurements of motion [18]. It has recently been employed in MRI, for velocity imaging [19,20].

2.3. NMR and MRI pulse sequences

Experimental data were acquired using bulk CMPG and three MRI techniques: CPMG-prepared Centric Scan SPRITE (Single Point Ramped Imaging with T_1 Enhancement) [3], SPRITE [21] and SE-SPI (Spin-Echo Single Point Imaging) [2]. Both pure phase-encode MRI techniques were employed for one dimensional T_2 mapping experiments.

Fig. 1(a) presents the CPMG-prepared Centric Scan SPRITE pulse sequence and (b) presents the SE-SPI pulse sequence. The CPMG-prepared Centric Scan SPRITE pulse sequence commences with a CPMG preparation followed by a 90° RF pulse for Z-storage, and a spoiler gradient. The preparation process can have a variable numbers of echoes. The last part of the pulse sequence consists of a 1D Centric Scan SPRITE image for spatial encoding.

The pure phase encoding SE-SPI pulse sequence, Fig. 1(b), contains a phase encode gradient between the 90° and 180° RF pulses. The phase encoded magnetization is then read out through multiple refocusing. From each scan a single k-space point is acquired for all echoes. These k-space data sets are then Fourier transformed to generate a series of T_2-weighted profiles. Based on these profiles the local CPMG decay can be extracted.

The SE-SPI experiment has limitations on the duration of the first echo, therefore this experiment will not permit spatial resolution of shorter T_2 components. A full CPMG decay with the CPMG-prepared Centric Scan SPRITE technique is a time consuming experiment. Nevertheless the CPMG-prepared SPRITE technique [3] can be applied successfully, in a time efficient manner, if we reduce considerably the number of profiles which comprise the CPMG decay. In this case the harmonic mean T_2 is measured only from the initial slope, as suggested by Eqs. (9) and (10).