

SURFACE RELAXIVITY ESTIMATION AND NMR-MICP MATCHING IN DIFFUSIONALLY COUPLED ROCKS

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ABSTRACT

The surface relaxivity, ρ , is one of the most important parameters in NMR petrophysics, since it scales NMR relaxation time measurements of fluid saturated rocks to their pore size distributions. NMR-MICP matching techniques can be used to obtain an estimation of ρ , but in general they are very dependent on an optimal correlation between these two measurements, thus are not appropriate in cases where the NMR measurements are heavily affected by diffusional coupling between micro and macro pores. Simulations of the NMR T_2 relaxation time phenomena were conducted using a coupled dual porosity model calibrated to match real T_2 distributions of three carbonate samples. Once calibrated, the simulations were then repeated with the same parameters, but without allowing diffusional coupling between the micro and macro pores of the model. The results of the decoupled simulations showed better correlation with MICP data for these carbonates, and were used to improve the estimation of ρ using NMR-MICP matching techniques. Furthermore, a diffusional coupling parameter was calculated based on the model parameters, to evaluate the strength of diffusional coupling of these carbonates.

INTRODUCTION

In Nuclear Magnetic Resonance (NMR) petrophysics, transversal relaxation time (T_2) measurements of 100% brine saturated rocks are commonly used to estimate their pore size distribution, which then can provide reasonable estimations for the permeability (k), irreducible water saturation (S_{wi}) and other petrophysical properties. This approach is valid when four main assumptions are applicable: fluid's relaxation within pores occurs in the fast diffusion regime; diffusion and bulk relaxations are negligible; the diffusion coupling effect is negligible; and surface relaxivity is homogeneous throughout the pore walls [1]. By considering these assumptions, the pore size distribution of the pore system is related to T_2 as follows:

$$\frac{1}{T_2} = \rho_2 \left(\frac{S}{V} \right)_{pore} \quad (1)$$

where $\left(\frac{S}{V} \right)_{pore}$ is the surface-to-volume ratio of the pores and ρ_2 is the transverse surface relaxivity. While $(S/V)_{pore}$ is representative of the pore size, the surface relaxivity

parameter is related to the strength of the fluid's magnetic interaction with the pore walls, which causes the relaxation phenomena [2].

Equation 1 shows the importance of ρ_2 for NMR petrophysics, since it scales T_2 measurements with pore size. For simple lithologies, ρ_2 is commonly considered to be homogeneous for each formation and several NMR predictions, such as the classical SDR permeability equation (k_{SDR}) and Swi, can be reasonably estimated without knowing the actual value for ρ_2 . However, in heterogeneous rocks with complex lithologies, like carbonates, variations of ρ_2 may occur in small scales within a formation and the lack of information of this parameter may result in poor accuracy of the NMR predictions.

One of the first methods developed for estimating ρ_2 from rock cores consists in correlating in a common dimension T_2 distributions measurements with pore throat distributions obtained from the Mercury Injection Capillary Pressure technique (MICP). In this case, it is assumed that the pore geometry in the pore system is predominantly cylindrical, thus T_2 and throat radius (R_t) can be correlated through equation 1 by [3]:

$$\left(\frac{S}{V}\right)_{cylinder} = \frac{2\pi R_t l}{\pi R_t^2 l} = 2^*/R_t \rightarrow R_{t_{cylinder}} = 2\rho_s T_2 \quad (2)$$

where ρ_s is an effective surface relaxivity and l is the length of the cylinder. The value of 2^* is the number that converts the $(S/V)_{pore}$ term from equation 1 into the pore radius, called pore shape factor. The effective relaxivity ρ_s is then adjusted as the value that maximizes the cross-correlation (CC) between the T_2 and R_t distributions, using:

$$CC(\rho_2) = \sum_i A_{Hg}(r_i) \cdot A_{NMR}(r_i = 2\rho_s T_2) \quad (3)$$

where A_{Hg} is the amplitude of the R_t distribution, and A_{NMR} is the amplitude of the T_2 distribution scaled by $2\rho_s$. Although the NMR-MICP matching provides a reasonable estimation of ρ , it relies on the optimal correlation between these two techniques. So, it is dependent on the ability each technique has to reflect the actual pore size and pore throat distributions of the rock. Considering this, directly matching T_2 and R_t may not be the best approach in cases where the pore's saturating fluid dynamics is under a strong diffusional coupling between micro and macro pores, a situation that enhances the diffusional coupling effect. In these cases, diffusional coupling mixes the NMR magnetic response of coupled pores with different sizes, causing it to lose its correspondence to the actual pore size. Because of this, one must consider the strength of the diffusional coupling effect before applying the NMR-MICP matching and calculating ρ_s .

NMR SIMULATIONS IN DUAL POROSITY SYSTEMS

In order to understand the diffusional coupling effect in complex porous systems, simulations of the NMR T_2 relaxation time, developed by Ramakrishnan et al [6], were applied in porous media models with porosity mixed between interconnected micro- and macro-pores. These simulations use random walk techniques to mimic the saturating fluid's diffusion, in which each particle (called "walker") represents a group of fluid

molecules moving randomly inside pores. The simulation starts with the walkers being placed randomly in the model's porous space, with an initial energy that represents the magnetic moment. The random walking is then performed in a stepwise fashion, where the distance traveled by each step takes an amount of time related to the self-diffusion coefficient of the fluid. When a walker meets a pore wall, this energy can be decreased by a factor or annihilated by chance, where both approaches depend on the value of ρ [6,7].

The dual porosity model used in this work is the Micro-Grain Consolidation Model (μ GC) [6,7], which is a cubic packing of overlapping spherical small grains with radius R_{small} , that composes bigger spherical grains centered at each corner of the cube, with radius R_{big} . This emulates the rock matrix as a network of bigger grains with intra-granular micro porosity, while the macro porosity consists in the inter-granular space of the bigger grains. Micro- and macro- porosity fractions are controlled by R_{small} and R_{big} , while the sizes of the micro- and macro- grids control the interconnectivity of the pores. An advantage of using this model is that we can introduce an artificial 'barrier' that prevents walkers from entering or exiting the micro or macro pores. This makes it possible to simulate the NMR experiment with or without diffusional coupling between the two domains. This approach is useful to infer how the MICP and NMR relaxation times correlate with each other when the diffusional coupling phenomenon is turned off.

DIFFUSIONAL COUPLING STRENGTH

Diffusional coupling between micro and macro pores has been modeled by Anand et al [4], in which the fluid's molecules relaxes at the surface of flake-like micro-pores while diffusing between micro and macro pores. The model's coupled pore geometry is defined by its half-length and half-width, named $L1$ and $L2$ respectively, and the micro-porosity fraction β . In the work, the authors introduced a coupling parameter α , described by:

$$\alpha = \beta\eta\mu \quad (4)$$

where η is $L2/L1$ and μ is the Brownstein Number [5]. μ can be estimated by calculating $L2\rho/D$, where D is the self-diffusion coefficient of the fluid ($2.5 \times 10^{-9} \mu\text{m}^2/\text{s}$ for water at 25°C). The study also related this diffusional coupling model to the μ GC by having $L1 = R_{small}$ and $L2 = R_{big}$, in order to apply the model for carbonates. Furthermore, α is described as being inversely proportional to diffusional coupling strength.

RESULTS

To evaluate the described methodology, three carbonate rock cores were chosen, MICP measured, NMR T_2 measured (as described in [2]) and simulated using the μ GC model described above. The random walk simulations were written in Fortran™ language and the micro and macro grains radius R_{small} and R_{big} were determined by matching the micro- and macro-porosity fractions from the μ GC model with the ones observed in the MICP distributions. These values are shown in Table 1. Other parameters of the simulation, such as micro- and macro-grid sizes, were adjusted so that the simulation results best match with the experimental T_2 distributions. Figures 1, 2 and 3 show the distributions of

measured and simulated T_2 and MICP from the selected carbonate samples, named respectively as H11, H23 and Silurian Dolomite. All samples showed (in the left side of the figures) excellent agreement between experimental (full blue curves) and simulated (called “coupled”, the green dashed curves) distributions. As described above, the random walk algorithm was executed again using the same parameters, but restricting the diffusive process of the walker: now, it is not allowed to leave the pore that they are randomly probing. The results of the decoupled simulations are shown on the figures as the black dashed curves called “uncoupled”. The difference between decoupled and real T_2 distributions suggests that when coupled, the T_2 distribution’s modes of micro- and macro-porosities (small and long T_2 ’s, respectively) are averaged in a degree that indicates diffusional coupling. Through this approach and comparing it with the shape of the MICP distributions (right side of the figures), it is clear that samples H11 and H23 have higher diffusional coupling strength, while the Silurian Dolomite have lower effect.

In order to estimate ρ_e , both decoupled and real T_2 distributions were matched with MICP distributions using the method described in equation 3. The matched distributions are shown together in the right side of the figures, while the values of ρ_e obtained from this matching are presented in Table 1. The results show that the decoupled distributions have much better correlation with MICP than the experimental T_2 distributions, suggesting that matching decoupled T_2 distributions with MICP R_t distributions provides a more robust and accurate ρ_e values. Both the H23 and Silurian Dolomite samples showed excellent correlations between decoupled T_2 and R_t , while the micro- and macro-modes from the decoupled simulation of the sample H11 did not match exactly with the ones from MICP. This fact can be explained if both porosities did not match for a unique choice of ρ_e and pore shape factor, or the pore system have a variable pore body-to-throat ratio (BTR). On the other hand, the excellent correlations in the Silurian Dolomite and H23 samples suggest that ρ_e and the pore shape factor are constants throughout the cores (not being a function of pore size). These are interesting cases where the analysis of decoupled T_2 distributions can provide significant insight about the properties of the porous system.

After matching the distributions, the α parameter was calculated using the R_{small} and R_{big} from the simulations, the micro porosity fraction observed in the MICP distribution and the Brownstein number estimated with ρ_e from the matching of the decoupled distributions (with equation 3). The results showed that the initial supposition regarding the comparison between strengths of diffusional coupling on the samples were correct, as H11 and H13 shows more coupling effect (α equals to 1.38 and 2.37 respectively), while the Silurian Dolomite shows much less effect ($\alpha = 12.99$).

CONCLUSION

The presented study showed that simulated decoupled T_2 distributions produces better matching with R_t distributions obtained from MICP curves, thus providing a more reliable estimation for surface relaxivity for carbonates. In cases where this approach

does not generate an exact correlation between decoupled T_2 and MICP, it was inferred that different pore size families on complex samples may present different pore shapes, BTR or surface relaxivities between them. This subject is important to the study of pore systems. The diffusional coupling parameter was calculated successfully using sample's parameters, showing indeed an inverse relation with the strength of the diffusional coupling effect on T_2 distributions. This shows that the α parameter can be used to estimate the coupling strength and that it helps to validate the T_2 distribution as a reliable estimation of pore size.

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Table 1: Characteristic parameters used to, and extracted from, the experimental analysis and simulations performed.

Sample Name	H11	H23	Silurian Dolomite
Porosity (p.u.)	28.8	28.1	18.3
MICP micro-porosity fraction (%)	40.0	45.0	41.8
R_{small} (μm)	1.29	1.27	1.34
R_{big} (μm)	122.68	124.46	129.75
NMR-MICP matched ρ_e (coupled) ($\mu\text{m/s}$)	1.72	1.76	9.78
NMR-MICP matched ρ_e (decoupled) ($\mu\text{m/s}$)	0.74	1.08	6.17
Estimated Brownstein number	0.036	0.054	0.320
α	1.38	2.37	12.99

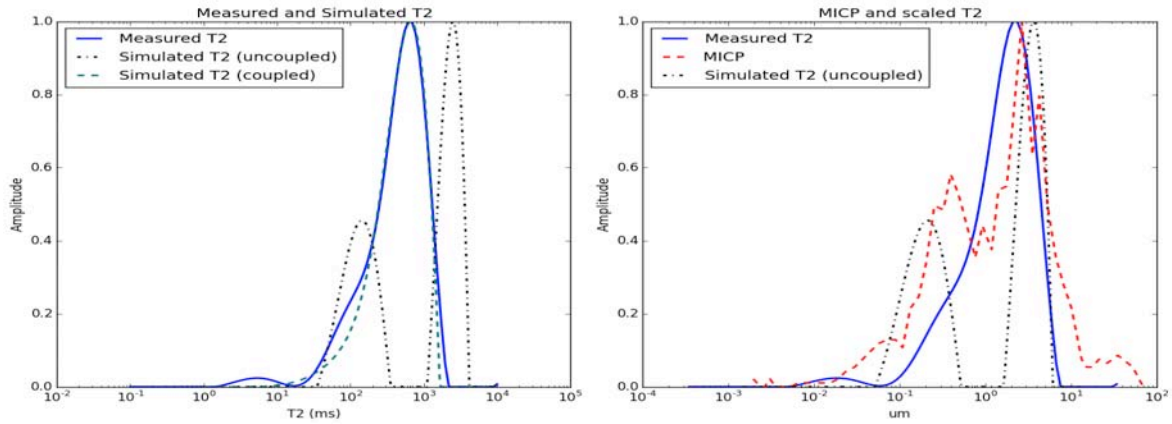


Figure 1: Data from the sample “H11”. Left: measured and simulated T₂ distributions and right: MICP distribution with T₂ measured and simulated, scaled by their optimal ρ_E .

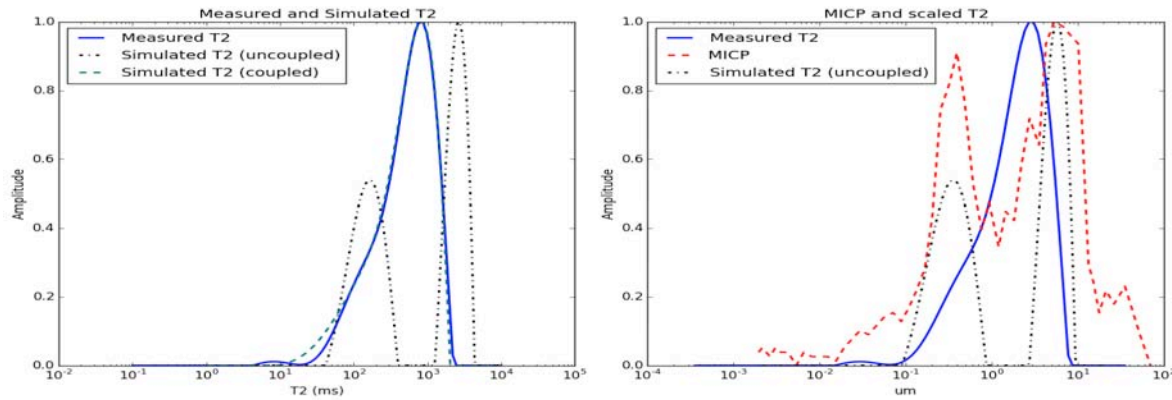


Figure 2: Data from the sample “H23”. Left: measured and simulated T₂ distributions and right: MICP distribution with T₂ measured and simulated, scaled by their optimal ρ_E .

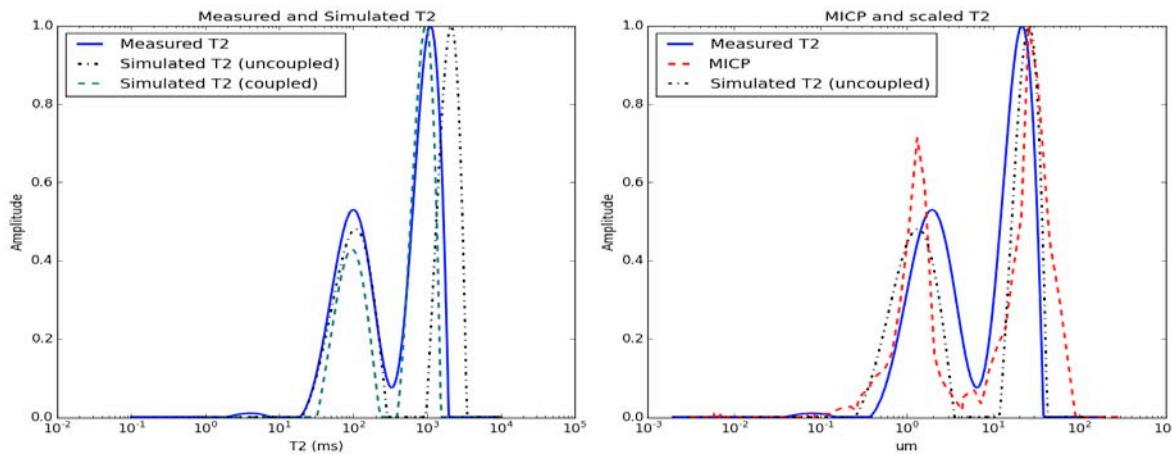


Figure 3: Data from the sample “Silurian Dolomite”. Left: measured and simulated T₂ distributions and right: MICP distribution with T₂ measured and simulated, scaled by their optimal ρ_E .