● *Contributed Paper*

# DETERMINATION OF SURFACE RELAXIVITY FROM NMR DIFFUSION MEASUREMENTS

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Nuclear magnetic resonance (NMR) $T_2$-decay measurements are usually interpreted in terms of pore-size distributions. The $T_2$ relaxation time of a water-wet pore is proportional to the size of the pore via surface relaxivity. Quantitative knowledge of the surface relaxivity is important when $T_2$ spectra are to be used for further use such as NMR derived capillary curves.

In this study, we demonstrate that surface relaxivity can be directly determined from NMR measurements. Diffusion of hydrogen spins is restricted by the pore size and this effect is independent of surface relaxivity. Hence, surface relaxivity can be determined by combining restricted diffusion and $T_2$-relaxation. The latter two effects are measured simultaneously in a NMR $T_2$ decay measurement performed in a static magnetic field gradient. This method generalises existing ones for uniform pore systems to full pore-size distributions of realistic rocks.

We have performed laboratory NMR diffusion measurements on a number of sandstone core plugs. The surface relaxivities found from these data are compared to those obtained from other methods.

This method of measuring surface relaxivity can in principle be applied to NMR data obtained in boreholes which leads to a new application of NMR logging in the characterisation of oil and gas reservoirs.   © 1998 Elsevier Science Inc.

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## INTRODUCTION

The relationship that exists between $T_2$ decay time and pore size in a water-wet pore system ($T_2 \propto$ volume-to-surface ratio ($V/S$)) is at the heart of many of the applications of nuclear magnetic resonance (NMR) in well logging. The discrimination between bound and movable fluids contained in the porous reservoir rock and the estimation of permeability are possible because of this correspondence. The proportionality constant between $T_2$ decay time and pore size is called surface relaxivity. The mentioned applications are often used without knowing the exact value of surface relaxivity for the rock under study. This paper deals with the determination of surface relaxivity from NMR diffusion measurements. Knowledge of the surface relaxivity may lead to more accurate answers in the above mentioned applications.

Also, novel applications like NMR derived capillary pressure curves come within reach.

## METHOD

$T_2$ decay measurements performed in a fixed gradient field for various inter-echo times allow the extraction of surface relaxivity by modelling the effect of restricted diffusion. Given a fully water-saturated pore with a certain $S/V$. The water in that pore will decay with a $T_2$ equal to:

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} = \frac{1}{T_{2B}} + \frac{\rho S}{V} \tag{1}$$

When that decay is measured in a gradient field an additional decay will be seen that is due to diffusion in

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the gradient field. The combined effect of diffusion decay and surface relaxation decay is a faster decay given by:

$$\frac{1}{T_{2D}} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} + \frac{D\gamma^2 G^2 T_e^2}{12}, \qquad (2)$$

in which $D$ is the diffusion constant of the fluid, $\gamma$ the gyromagnetic ratio, $G$ is the sensed field gradient and $T_e$ is the inter-echo time.

Diffusion may be restricted when the fluids are confined in a small pore. The models for restricted diffusion show that the reduction in diffusion coefficient as a function of the $S/V$ of the pore and for small $T_e$ is given by:

$$\frac{D_{eff}(T_e)}{D_0} = 1 - \alpha \, \frac{S}{V} \, \sqrt{D_0 T_e}, \qquad (3)$$

in which $S/V$ is surface-to-volume ratio of the pore and $D_0$ is bulk diffusion coefficient and $\alpha$ is a constant equal to 0.2223.[1] At large $T_e$ the reduction in diffusion coefficient levels off:

$$\frac{D_{eff}(T_e)}{D_0} = \frac{1}{F\phi}. \qquad (4)$$

With $F$ the formation factor and $\phi$ the porosity. Equation (3) and (4) are usually glued together in a Padé approximation.[2] By performing measurements for a few (two or more) $T_e$ the reduction in diffusion constant may be probed and effectively the $S/V$ of the pore may be determined. As $T_2$ of the pore is also measured the surface relaxivity is found by applying Eq. (1). More explicitly, combining Eq. (1) with Eq. (3) to eliminate $S/V$ and ignoring $T_{2B}$ results in:

$$\frac{1}{T_{2D}} = \frac{1}{T_{2S}} + \frac{D_0\left(1 - \alpha \dfrac{1}{\rho T_{2S}} \sqrt{D_0 T_e}\right)\gamma^2 G^2 T_e^2}{12}. \qquad (5)$$

The equation shows that for known $D_0$, $T_e$ and $G$, $T_{2S}$ and $\rho$ are the only remaining unknowns and the measurement of $T_{2D}$ at two different $T_e$ in principle suffices to determine the two unknowns. In case measurements at more than two $T_e$ are acquired then $T_{2S}$ and $\rho$ are found by error minimisation. Equation (5) applies for a single pore with a single valued $S/V$. In a core plug the measured signal will contain responses from all the pores. To extract surface relaxivity in that case a more comprehensive version of Eq. (5) (including the Padé approximation for restricted diffusion) which takes into account that a
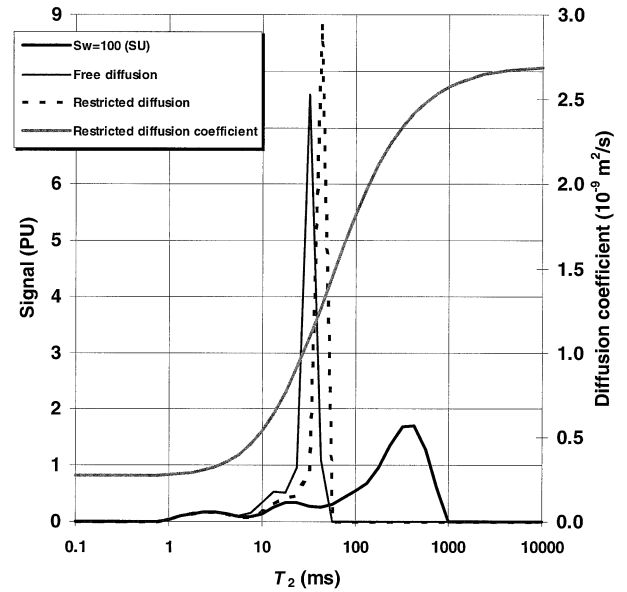
realistic core sample displays a pore-size distribution (and hence an $T_{2S}$ distribution) needs to be inverted for surface relaxivity and $T_{2S}$ distribution.

Figure 1 shows a $T_2$ spectrum measured in a homogeneous field for a fully water saturated sample. With the aid of Eq. (5) $T_2$ spectra were simulated with respectively free and restricted diffusion as if acquired in a gradient field. The figure shows discernible differences. The corresponding echo decays are plotted in Fig. 2. Differences of up to 0.6 pu are seen which can be easily resolved with a laboratory NMR-spectrometer.

The water-diffusion coefficient is determined in a separate NMR diffusion experiment and is not a free parameter. NMR decay measurements in a (known) gradient field on a container filled with bulk water were done with various inter-echo times. The measured $T_2$ was plotted as a function of $T_e$ according to Eq. (2). Water diffusion coefficient was determined to be $2.76 \times 10^{-9}$ m$^2$/s. The bulk water $T_2$ was found to be 3 s.



Fig. 1. Simulated $T_2$ spectra as acquired in a gradient field with free and restricted diffusion. The $T_2$ spectrum extending to 1000 ms is measured in a homogeneous field.

## ASSUMPTIONS

The following assumptions are made when applying the described method to a realistic core plug:

1) Every grain has the same surface relaxivity and hence, every pore experiences the same surface relaxivity.

2) Internal gradients are assumed negligible.

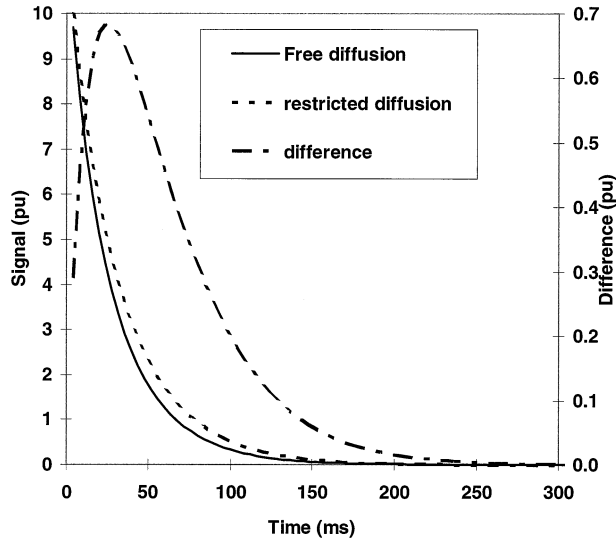3) The restricted diffusion model is quantitatively correct.

Fig. 2. Simulated-echo decays for the $T_2$ spectra in Fig. 1, i.e., with free and restricted diffusion. The difference between the two decays is also plotted.



Fig. 3. $T_2$ spectra for the four samples as measured in a homogeneous field.

## RESULTS

Measurements were performed on four core samples obtained from a sandstone reservoir. $T_2$ decay measurements in a gradient of 33.9 G/cm were made at inter-echo times of 0.5, 2, 4 and 6 ms at 1 MHz. The surface relaxivities were determined as described above. Table 1 lists the best fit surface relaxivities. Figure 3 shows the $T_2$ spectra measured in a homogeneous field and Fig. 4 shows the pore-size distributions obtained using the measured surface relaxivities. It is somewhat coincidental that the pore-size distributions appear very similar in contrast to the $T_2$ spectra that peak at distinct $T_2$.

## ACCURACY

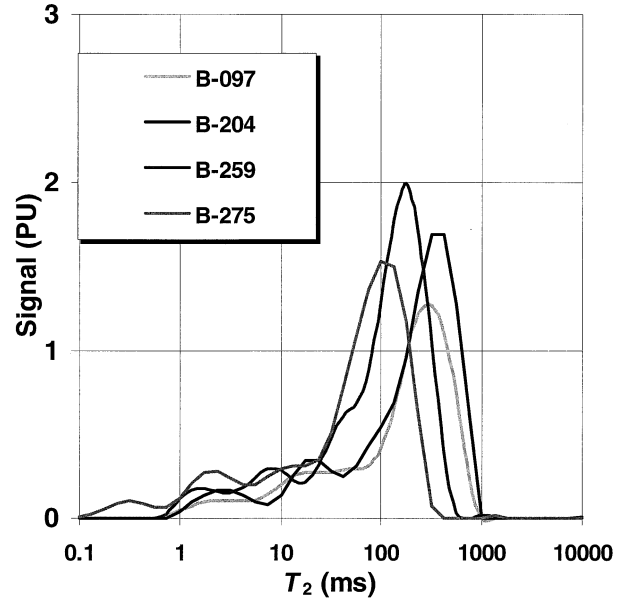The values of surface relaxivities that were found can be compared to results from other techniques that are either sensitive to $S/V$ or surface relaxivity of the pore system. Comparisons can be made with scanning electron microscopy (SEM) image analysis (IA) results. The difficulty in the comparison is that SEM/IA measures in two dimensions and has a lower dynamic range then the NMR measurements. Alternatively, one can compare with surface relaxivity determinations from capillary pressure curves.[3] In that comparison the assumption is made that the pore-size distribution of a core sample is the same as a pore-neck distribution which is certainly not justified in all cases. Table 1 lists the $S/V$ ratios obtained from SEM/IA and the surface relaxivities obtained from comparison of $T_2$ spectra and capillary pressure curves. The table shows that the values are consistent showing that the surface relaxivities obtained with the described method yield sensible results. Calibration

Table 1

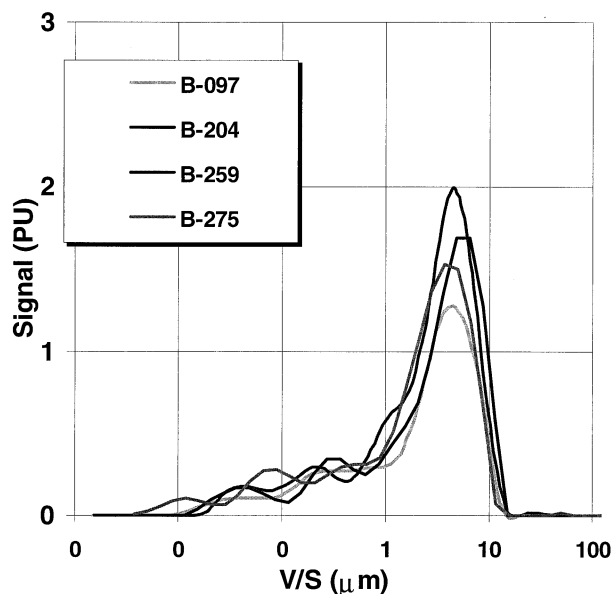| | This work | | Comparisons | |
| | | | | |
| Sample | $\rho$ ($\mu$m/s) | Mean $S/V$ (1/$\mu m$) | $S/V$ from SEM IA (1/$\mu$m) | $\rho$ from capillary pressure ($\mu$m/s) |
| --- | --- | --- | --- | --- |
| B-097 | 14.3 | 0.30 | 0.19 | 6.8 |
| B-204 | 15.8 | 0.24 | 0.19 | 6.8 |
| B-259 | 29.3 | 0.28 | 0.22 | |
| B-275 | 51.2 | 0.33 | 0.25 | |

Fig. 4. Pore-size (*V/S*) distributions as derived from the $T_2$ spectra in Fig. 3 and the measured surface relaxivities.

of the new method may be achieved by performing random walk simulations.[4]

## APPLICATION ENVELOPE

As effectively the restricted diffusion effect is exploited to determine $S/V$ of the pore system various boundary conditions have to be fulfilled to make the described method yield reliable results:

Average pore size should not be too large because otherwise diffusion is not restricted and no surface relaxivity determination is possible. Increasing $T_e$ in order to be in the region (Eq. (3)) where diffusion is restricted does not provide a solution. With the increasing $T_e$ also $T_{2D}$ decreases (Eq. (2)) to values where either no measurable difference between restricted or unrestricted diffusion is seen or is not measured at all because of too crude an inter-echo spacing.

Mean $T_2$ in a homogeneous field should not be too low. Diffusion in a gradient field causes $T_2$ to become lower (Eq. (2)). In case the $T_2$ in a homogeneous field is already rather low the difference between free and restricted diffusion effects become too small to be detected. A not too low $T_2$ in a homogeneous field implies that surface relaxivity should not be too large.

The application envelope can be quantitatively established by performing a sensitivity analysis starting from Eq. (5).

## DISCUSSION AND CONCLUSIONS

We have described a method for determination of surface relaxation based on NMR diffusion measurements. Results are obtained that compare favourably with results obtained from SEM/IA and values derived from capillary pressure curves. Application of the method is limited to pore systems that have not too large pore sizes and not too high surface relaxivities. The method can in principle be applied to log data provided noise levels are sufficiently low.

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