DISCRIMINATION OF BOUND WATER IN SMALL PORES AND THIN FILMS IN POROUS MEDIA BY NMR METHOD

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ABSTRACT

According to conventional practice of down-hole NMR log interpretation, the NMR signal from bound water (BFV) in the porous media can be distinguished from free water by means of transverse relaxation time threshold value ($T_{2cutoff}$). The currently accepted interpretation practice assumes that in water-saturated rocks the signals characterized by relaxation times greater than $T_{2cutoff}$ only represent free water defined by free fluid index, FFI. This assumption implies that once the moveable water is displaced from a rock under a certain pressure, no water remains in the emptied pores. Obviously, this is only an approximation.

A new theoretical approach to determining the actual value of FFI and BFV taking into account intra-pore surface-bound water is presented. An extensive experimental program was performed to prove this approach. Both artificial and native state samples (clean sandstone and carbonates) were investigated at different irreducible water conditions. With the presented approach the intra-pore-surface-bound water is taken into account properly. Thus we believe that reservoir evaluation is improved, particularly in the case of clean well-sorted sand and carbonates.

PROPOSED METHOD

According to conventional practice of down-hole NMR log interpretation, the assumption that in water-saturated rocks the signal characterized by relaxation times greater than $T_{2cutoff}$ only represent free water defined by FFI. Correspondingly, pores containing only bound water are represented by T_2 values less than $T_{2cutoff}$.

It was shown theoretically (Brownstein and Tarr, 1977) and experimentally (Straley *et al.*, 1995), that in the fast diffusion regime, the longitudinal and transverse relaxation processes of a water-saturated pore containing no clay-bound water are expressed by corresponding single decay exponents (T_1 and T_2). This was concluded despite the fact that the pore may contain both the free and surface-bound water. In other words, the surface bound water influences the measured relaxation time of a water-saturated pore but cannot be directly revealed from NMR measurements. Certain approaches to determining the surface-bound water were suggested in the literature (Kleinberg and Body, 1997; Coates *et al*., 1997). The present work presents an approach for the determination distribution of the surface-bound water volumes over the full range of T_2 spectra.

The observed rate of transverse (as well as of longitudinal) relaxation R_2 of a pore containing both surface-bound and free water may be represented by a mean-weighted value:

$$R_2 = S_f R_{2blk} + S_{sb} R_{2sb} \tag{1}$$

Where R_{2blk} and R_{2sb} are relaxation rates of free water measured in a free volume, i.e. separately from the porous medium and surface-bound water correspondingly. By definition:

$$R_2 = 1/T_2,\ R_{2blk} = 1/T_{2blk},\ R_{2sb} = 1/T_{2sb} \tag{2}$$

S_f and S_{sb} are the relative free and surface-bound water-saturation values. Therefore:

$$S_f = W_f/\phi,\ \ S_{sb} = W_{sb}/\phi \tag{3}$$

Where ϕ is porosity derived from the T_2 distribution curve segment related to $T_2 > T_{2cutoff}$, while $W_f = FFI$ and W_{sb} are water volumes in porosity units. Combining equations (1) – (3), the following equation may be derived:

$$\frac{FFI}{\phi} = \frac{(1/T_{2sb} - 1/T_2)}{(1/T_{2sb} - 1/T_{2blk})} \tag{4}$$

Once the T_{2blk} and T_2 values are measured and T_{2sb} is defined through laboratory measurements of core samples after free water displacement, the FFI-to-porosity ratio, $\alpha_f = FFI/\phi_f$ can be calculated from the equation (4). If in the interval $T_2 > T_{2sb}$ the T_2 distribution is divided into several (n) segments, or bins, (see Figure 1a) and each bin's porosity ϕ_i ($i = 1,2,\ ,n$) and arithmetic mean T_{2i} are determined, the ratio FFI_i/ϕ_i for each i^th bin, α_{fi}, may be calculated from an equation similar to (4).

$$\alpha_{fi} = \frac{FFI_i}{\phi_i} = \frac{(1/T_{2sb} - 1/T_{2i})}{(1/T_{2sb} - 1/T_{2blk})} \tag{5}$$

The free and the surface-bound water volumes of the i^{th} bin should then be calculated as follows:

$$W_{fi} = \alpha_{fi}\ \phi_i \tag{6}$$

$$W_{sbi} = f_i - W_{fi} \quad (7)$$

The surface-bound water T_{2sb} value can be estimated as the highest value of bound water of a core after the whole free water volume is displaced from the sample under a certain pressure. In other words, $T_{2sb} = T_{2cutoff}$ is the T_2 value related to the right edge of the T_2 distribution curve (Figure 1b).

EXPERIMENTAL

To check the feasibility of the suggested approach a series of laboratory measurements was performed on rock and artificial porous samples. The T_2 distribution curves for each sample were obtained in two conditions: full water saturation and irreducible saturation after free water displacement in a centrifuge under 6000 RPM. T_2 distributions related to the irreducible water saturation were used to estimate the relaxation time values of the surface-bound water T_{2sb} (the second column in Table 1). Evaluation of the surface-bound water volumes was performed by processing T_2 distributions of fully water-saturated samples. The data obtained are represented in Table 1. Here, S_{sbi} (i=1-5) are the values of relative bound-water saturation that correspond to various bins. Obviously, according to (3) the total surface-bound water saturation W_{sb} is equal to the sum of partial W_{sbi} values ($W_{sb} = S\, W_{sbi} = S\, S_{sbi} / f_{bi}$).

Table 1: Summary of experimental results

Sample	T_{2sb} ms	Porosity f, %	W_f, %	W_{sb}, %	Bin 1 S_{sb1}	Bin 2 S_{sb2}	Bin 3 S_{sb3}	Bin 4 S_{sb4}	Bin 5 S_{sb5}
239 Carbonate	100	10.81	9.96	0.84	0.19	0.07	0.03	0.1	0
215 Carbonate	100	13.52	11.7	1.82	0.22	0.24	0.025	0.03	-
85B Carbonate	100	4.51	3.48	1.03	0.57	0.18	0.03	0.003	-
4_5,Shally sandstone	31	2.96	1.57	1.38	0.69	0.29	0.1	0.05	-
P-8, Shally sandstone	31	6.73	3.38	3.35	0.74	0.37	0.1	0.05	-
P_9, Shally sandstone	31	2.83	1.56	1.27	0.73	0.54	0.1	0	-
1_1, Berea sandstone	31	12.12	9.58	2.54	0.64	0.2	0.1	0.05	-
2_2, Berea sandstone	31	18.27	15.64	2.63	0.58	0.24	0.09	0.04	-
1a, Artificial medium	80	34.7	34.4	0.3	0.09	-	-	-	-
1c, Artificial medium	80	33.54	32.8	0.74	0.02	-	-	-	-

The results presented show that there is always a certain amount of surface-bound water in the pore system characterized by transverse relaxation time greater than the $T_{2cutoff}$ value. Relative bound water-saturation S_{sb} is not evenly distributed through bins with different T_2 values, that is, through different pore sizes. As it can be seen from Table 1 and Figure 2, the surface-bound water saturation S_{sb} gradually decreases with the rise of the bin's relaxation time, which is equivalent to increase of the pore size. The surface bound water is observed not only in shaly sandstones (Figure 2a) but as well in carbonates (Figure 2b). In both cases, the relative surface-bound water saturation decreases with the relaxation time. This is illustrated by the bar-diagram superimposed on the T_2 distribution (Figure 2a,b). The artificial porous samples are likely to predominately contain pores of similar size, so only one bin containing both free and surface bound water can be delineated from the T_2 distribution curve.

REFERENCES

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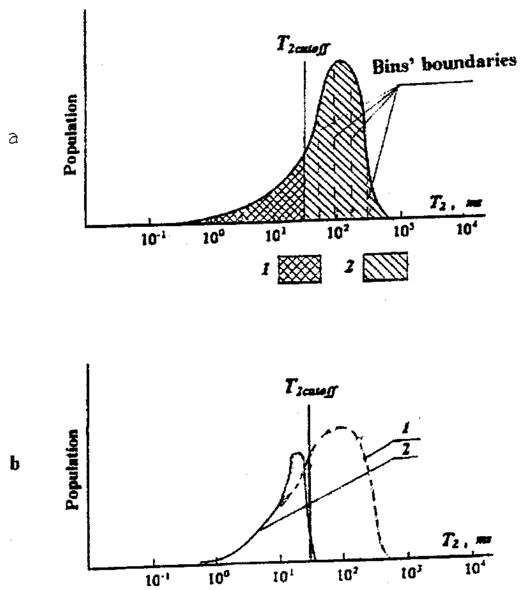
NOMENCLATURE

FFI/ϕ	free fluid indEx-to-porosity ratio
$T_{2\,am}$	arithmetic mean of the T_2
$T_{2\,lm}$	logarithmic mean of the T_2
$T_{2cutoff}$	the maximum value of the bound water T_2 defined from the T_2 distribution after water displacement at 6000 RPM
W_{frb}	free water volume of a bin
W_{sb}	surface-bound water volume of a bin
W_{tb}	total water volume of a bin (equal to porosity of a corresponding fully saturated pore group)
W_{irr}	irreducible water volume (after free water displacement under 6000 RPM)
W_b	bound water related to a whole T_2 distribution
W_{fr}	free water related to the whole T_2 distribution
W_t	total water volume (porosity) related to the whole T_2 distribution
W_{bn}	bound water related to the non-permeable segment of the T_2 distribution ($T_2 < T_{2cutoff}$)
W_{frn}	free water related to the non-permeable segment of the T_2 distribution
W_{tn}	total water volume (porosity) related to a non-permeable segment of the T_2 distribution
W_{bp}	bound water related to the permeable segment of the T_2 distribution ($T_2 > T_{2cutoff}$)
W_{frp}	free water related to the a permeable segment of the T_2 distribution
W_{tp}	total water volume (porosity) related to a permeable segment the whole T_2 distribution



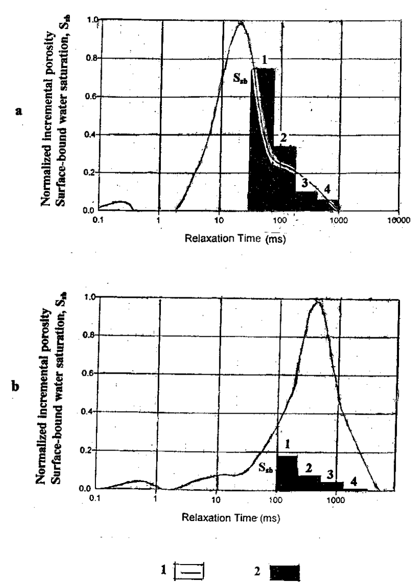


Figure 1: Schematic T_2 distribution curves of a water saturated reservoir rock
(a) – T_2 distribution of a fully saturated water-wet rock: (1) part of the pore system only containing irreducible (pore-bound) water; (2) part of the pore system containing both irreducible (surface-bound) and free water.
(b) T_2 distribution of the bound-water-saturated rock: (1) T_2 distribution prior to free water displacement; (2) T_2 distribution after the free water displacement.

Figure 2: Surface-bound water saturation, S_{sb}, in the part of a rock pore system containing free water
(a) shally sandstone, sample P-8,
(b) carbonate sample 239 (1) distribution curve (normalized incremental porosity, (2) surface-bound water saturation.