DETERMINING THE SATURATION EXPONENT BASED ON NMR PORE STRUCTURE INFORMATION

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ABSTRACT

In the tight sandstone reservoir, the saturation exponent with Archie's relation varies greatly from the usual value n=2. This is usually attributed to complex porous structure. In this work, we involved a series of NMR T2 measurements and experimental RI measurements on core plugs in different brine saturations. Based on NMR, MICP porous structure characterizations and RI results, we found a close relationship between NMR porous structure information and the saturation exponent. The new approach enables deeper understand of the rock porous structure and how the porous structure controls the flow path of the core plug by NMR.

INTRODUCTION

In petroleum industry, the brine saturation is important in reservoir evaluation and production, and the electrical property is used to estimate the saturation exponent and the brine saturation. In experimental RI measurements, the fluid in core plugs of the tight sandstone reservoir is very hard to be drained, so the RI results cannot show the real transport property of core plugs, and saturation exponents vary greatly from the usual value n=2. In this paper, we attempt to present an experimental method to estimate the saturation exponent from NMR measurements. As a transport property, the electrical conductivity depends not only on porosity but is also strongly sensitive to the connectivity of the pore space and their micro-geometry (Cerepi et al., 2002). In a T2 measurement, the NMR signal, when extrapolated back to zero time, is proportional to the population of the hydrogen nuclei in the probed zone. When properly calibrated, the NMR measurement is an excellent way to measure lithology-independent total porosity. And NMR has matured over into a powerful petrophysical tool for permeability estimation, which is a transport property of the reservoir (Kenyon, 1997). So the NMR technology has potential as a new tool for describing transport properties and determining the saturation exponent. Coates,G.R. (1994) comprehensively dealt with the MRIL data and deep resistivity data, and built the MRIAN model for brine saturation evaluation. Emmanuel Toumelin (2006) introduced a geometrical framework to simulate electrical conductivity and NMR rock responses with diffusion random walks. Luo Shaocheng

(2014) used NMR T2 distribution to deliver porous structure parameters, and built the empirical formula by several important parameters. The results from these studies show that NMR is capable of delivering both porous structure parameters and saturation evaluation parameters.

In the present work, fully brine saturated core plugs were centrifuged in air with different capillary pressures in sequence. We did NMR T2 measurements and RI measurements on core plugs in fully brine saturated state and partially saturated state, and studied the relationship between the electrical property and the NMR information. In this way, we analyzed the connectivity of the pore space and their micro-geometry. We calculated ratios of the logarithmic mean T2 between the fully saturation and partially saturations, and these ratios were able to reveal effects on the flow path of core plugs. The saturation exponent can be found by analyzing the functional relationship between ratios and the corresponding saturations. During these experiments, partially saturated core plugs were always in high saturation range. In order to study their micro-geometry at low saturation range, we found a relationship between the logarithmic mean T2 and the T2 mean value. Based on this relationship, the logarithmic mean T2 in any saturation can be obtained, which laid a foundation for up-scaling to reservoir level. When core plugs were in low saturation, the saturation exponent can show the real connectivity of the pore space and their micro-geometry and would be helpful for reservoir evaluation and production.

EXPERIMENTAL

Core Samples and Measurements

For Chang7 reservoir characteristics, representative core plugs were used in this study. The porosity ranged from 6.2% to 12.2%, and the permeability ranged from 0.012mD to 0.262mD. Core plugs had length and diameter of about 3 cm and 2.5 cm, respectively (cf. Table1). They were dried and then evacuated for 12 hours before brine was introduced into the vacuum chamber. A method combined the NMR measurement, the electrical measurement and the centrifuge technique was carried out to measure these core plugs in fully brine saturation and partially brine saturation. NMR T2 measurements were performed by using a 2 MHz MARAN DRX spectrometer from Oxford Instruments. A CPMG pulse sequence was used to generate the T2 decay. Parameters used for NMR measurements were: 512 scans, 4096 echoes and an inter-echo time of 200 µs. The de-saturation experiments were carried by the URC-628 URLTRA-ROCK centrifuge and centrifugal forces were designed as 150 psi, 600 psi, 940 psi. Figure1 shows experimental procedures.

RESULTS AND DISCUSSIONS

Relation between Porous Structure and Saturation Exponent

Table 1 indicates petrophysical parameters and porous structure parameters. N94 and N19 were selected for detailed studies. Figure 2 shows the mercury injection capillary pressure curves of the previous cores. Figure 3 presents the incremental saturation plots of the same mercury injection tests showed in Figure 2. As can be seen in the two figures, the main pore throat radius range of N94 is in MESO size, while N19 is dominated by MICRO and NANO pore throats. A better understanding of the behavior of MICP is achieved when it is integrated with the information provided by NMR. The main part of N94's T2 distribution is over 10ms and its peak value is about 70ms, while the T2 distribution of N19 is concentrated below 10ms, and the peak value is about 3ms. In order to find the relationship between the porous structure and the saturation exponent, porous structure parameters from MICP, NMR and the saturation exponent were analyzed. It was found that a good fit was achieved between the mean value of throat radius and the logarithmic mean T2 (cf. Figure 4). Figure 5 is the crossplot between the saturation exponent and the mean value of throat radius. This points out that the saturation exponent of tight sandstones reservoir is to a large extent controlled by porous structure. The saturation exponent of the core plug with good pore structure quality, such as N94, ranges from 1.5 to 2. When the main pore throat radius that contributes to the flow property is the MICRO or NANO size, the saturation exponent is over 2 (cf. Figure 5). Basically, the worse of the porous structure, the larger of the saturation exponent.

Relation between Logarithmic Mean T2 and Electrical Property

As can be seen, the logarithmic mean T2 and the mean value of throat radius play an equally important role in describing the porous structure (cf. Figure 4). The logarithmic mean T2 is calculated by Equation1, which is a comprehensive parameter on the pore radius and the porosity in theory. Where, T2 is the relaxation time and Sa is the signal amplitude.

$$< T_{2LM} >= \exp\left(\frac{\sum_i Sa_i * \log T_{2i}}{\sum_i Sa_i}\right) \tag{1}$$

In order to validate that NMR technology could be a tool for describing the transport property, we need to analyze the evolution data of the core plug in drainage mode, and find the relationship between the logarithmic mean T2 and the electrical resistivity. During the centrifugation process (cf. Figure 6, 7), the meso-pores are drained progressively at low speed. At high speed, the partial brine in the micro-pores is drained out of the core plug. The brine in nano-pores is very hard to drain (Sw=75% of N19). In the process of de-saturation, micro-pores and nano-pores have a growing influence on the transport property. Specifically, with decreasing the brine saturation, the logarithmic mean T2 decreases and the electrical resistivity increases. Although their changes are different, they show the change of the transport property from different aspects. Figure 8 shows that there is a power function relationship between the logarithmic mean T2 and the electrical resistivity. There are differences in the porous structure of N94 and N19. So the power function varies with the porous structure in a way, which lays a foundation for calculating saturation exponent with NMR method.

New NMR Method for Saturation Exponent

New NMR method is concentrated on the logarithmic mean T2 and the corresponding brine saturation. At each saturation, we calculated the ratio of the logarithmic mean T2 between the fully saturation and the corresponding saturation. These ratios revealed the effect of porous structure on the flow path of the core plug. The new saturation exponent was calculated by Equation 2. New results and saturation exponents from traditional RI measurements are showed in Table1.

$$\frac{T_{2LM(Sw=100\%)}}{T_{2LM(Swi)}} = \frac{B}{S_w^N} \tag{2}$$

Where, $T_{2LM\,(Sw=100\%)}$ is the logarithmic mean T2 in fully brine saturated condition, $T_{2LM\,(Swi)}$ is the logarithmic mean T2 in different partially brine saturated condition,
N is the new saturation exponent, B is the coefficient.

In the new experimental procedure, on the one hand, we need to do several NMR measurements and centrifuge measurements, which were inconvenient for us to up-scale to the reservoir level. On the other hand, the irreducible brine saturation was in the high saturation range. In Figure 9, we found that there was a good fit between the logarithmic mean T2 and the T2 mean value (Equation 3). The T2 mean value in any saturation is easily to calculate from the T2 distribution in fully brine saturation, so the logarithmic mean T2 in any saturation can be obtained from Equation 3. Where, X is the T2 mean value.

$$\langle T_{2LM} \rangle = 1.0943X - 0.1237 \tag{3}$$

At low saturation range, the flow path is limited, and depends on the connectivity of the micro-porosity and the water film. In order to reduce the influence of the disconnection of the pore space, the minimal water saturation was selected as 30%, and the water saturation step was 10%.We recalculated the logarithmic mean T2 in different water saturations, and recalculated the saturation exponent using Equation 2. The results are also showed in Table 1. As more micro-porosity is included, results are slightly different from centrifuge ones.

CONCLUSION

We introduced a new method to calculate the saturation exponent in the tight sandstone reservoir. This method was focused on the porous structure, and solved some difficulties in calculating the saturation exponent with the traditional method. It was more helpful for the oil saturation determination and reservoir evaluation in the tight sandstone reservoir.

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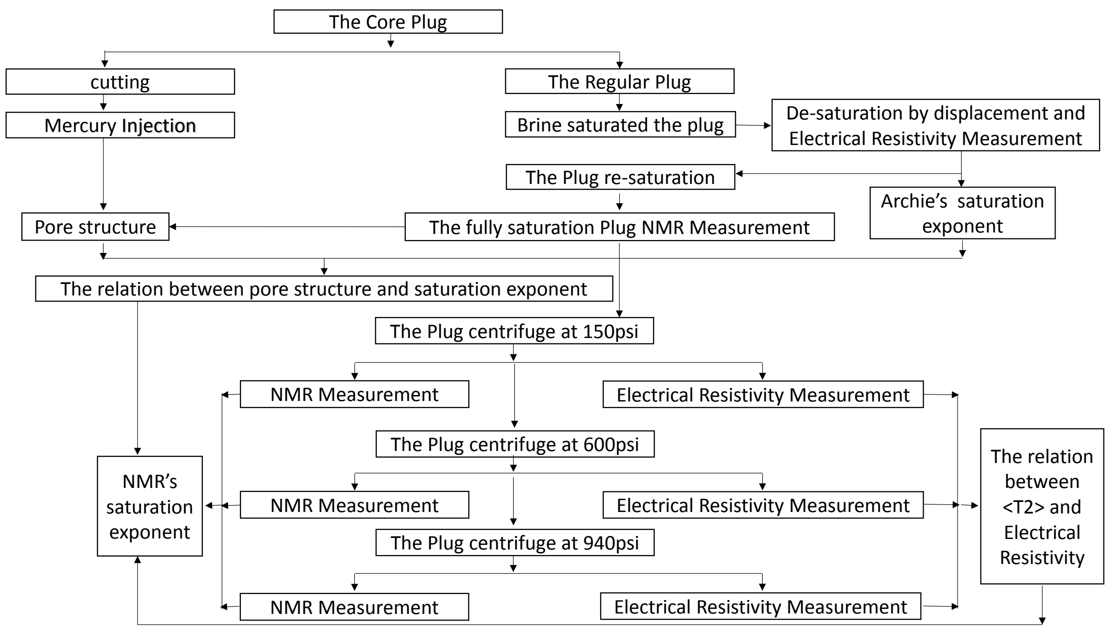

Figure1. Experimental Procedures

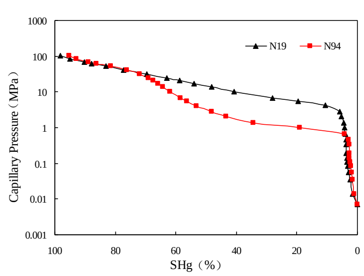

Figure 2. MICP profile

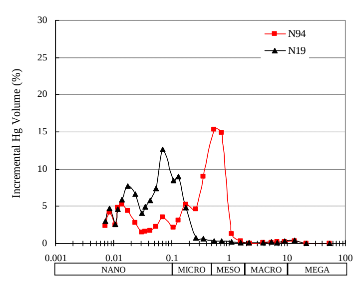

Figure 3 Incremental saturation plots

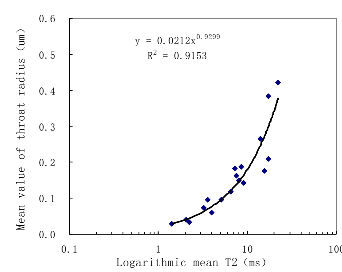

Figure 4 Corssplot of the logarithmic mean T2 and the mean value of throat radius

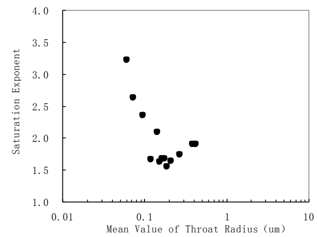

Figure 5. Crossplot of the saturation exponent and the mean value of throat radius

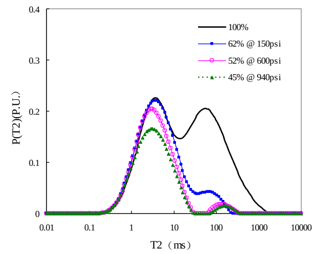

Figure 6 The T2 distribution evolution of N94 in drainage

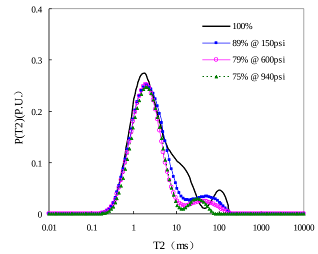

Figure 7 The T2 distribution evolution of N19 in drainage

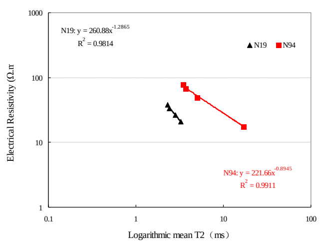

Figure 8. Crossplot of the logarithmic mean T2 and the electrical resistivity

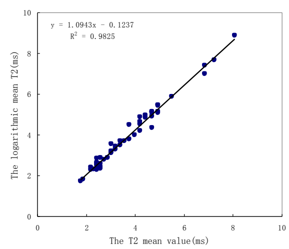

Figure 9. Crossplot of the logarithmic mean T2 and the T2 mean value

Table1.Petrophysical Parameters and Saturation Exponents

Sample ID	Helium Porosity(%)	Permeability (mD)	Mean Value of Throat Radius(um)	logarithmic mean T2(ms)	Saturation Exponent(Electrical Resistivity)	Saturation Exponent(NMR & centrifuge)	Saturation Exponent(NMR @ any saturation)
N15	11.2	0.105	0.151	8.0	1.624	1.642	1.352
N17	8.1	0.037	0.095	5.1	2.354	2.069	1.225
N19	7.1	0.028	0.073	3.2	2.635	1.651	1.127
N24	8.5	0.062	0.142	9.1	2.097	1.834	1.286
N45	11.5	0.217	0.187	8.5	1.548	1.756	1.376
N51	7.3	0.098	0.176	12.6	1.682	1.971	1.507
N53	11.0	0.115	0.163	7.8	1.684	1.659	1.347
N58	7.7	0.099	0.209	13.9	1.643	1.676	1.482
N64	9.7	0.012	0.061	4.0	3.221	2.138	1.225
N75	12.2	0.075	0.118	6.6	1.664	1.622	1.351
N90	6.2	0.103	0.266	13.9	1.736	1.577	1.398
N91	9.4	0.214	0.422	22.3	1.908	1.920	1.616
N94	10.0	0.262	0.384	17.6	1.910	2.158	1.709