

Estimating saturation exponent from NMR logging

Dan Huang · Liqiang Sima · Feng Wu · Liang Wang · Qing Li

Received: 16 July 2014 / Accepted: 19 December 2014 / Published online: 6 January 2015
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Abstract A new interpretation of the relationship between the saturation exponent (n) and the water saturation (S_w) of a reservoir rock is presented. Based on the capillary theory and Purcell equation, the relationship between resistivity index (I) and the permeability (k), water-phase permeability (k_w) has been obtained. By combining SDR model, such relationship can be transferred into a novel model of probing the saturation exponent under variable saturation conditions. Based on the theoretical derivation, NMR experimental measurements of core examples were implemented to testify the reliability brought by this development. Laboratory measurements of transverse relaxation were carried out on core samples from a formation in the Middle East. NMR experimental measurements were made with 50 samples fully water saturated. Measurements at various air/water saturation (i.e., at residual water saturation) were made on 16 samples among them obtained by different centrifuging speeds. The experimental results show that the calculated saturation exponent values and water saturations follow a power law relationship which is in accordance with researches have been published about that n is not a constant but a variable parameter dependent on water saturation, quantitatively. This study has inferred the quantitative relationship between n and S_w through NMR information firstly.

Keywords NMR · Saturation exponent · Capillary theory · Purcell equation

Introduction

The relationship of resistivity index and water saturation is not linear correlation in log-log coordinate which is called as non-Archie phenomenon and exists not only in carbonates, but also in sandstones (Diederix 1982; Swanson 1985; Brown 1988; Worthington et al. 1989; Herrick and Kennedy 1993). This behavior may be the results of conductive mineral, residual water in micro-pore space, roughness of the rock surface and the conductive path, etc., and it turns prediction of water and hydrocarbon saturation of formations into a challenge (Khelil 1971; Herrick 1988; Salem 1994). In order to obtain accurate saturation exponent, the influence factors such as components of rocks, pore structure, and fluid distribution coupled with wettability of rocks have been studied (Donaldson and Siddiqui 1989; Dunlap et al. 1991; Suman and Knight 1997; Küntz et al. 2000).

There have been some attempts to express the relation between n and S_w . Wang and Sharma (1988) and Suman and Knight (1997) used a three dimensional pore network model to simulate the effects of wettability, pore structure, and the saturation history on the electrical conductivity of rocks. Their results showed that n was a variable parameter which the wettability was seen to have the most significant effect on the electrical conductivity, hence on n . Yue (2003) and Tao et al. (2004) have studied the electrical transport behavior of porous media and the physical meaning of the Archie's parameters by 2D lattice gas automata. Their results showed that there existed a power function relationship between n and S_w with the exponent related to the porosity. Kumar et al. (2011) coupled 3D imaging, high-resolution SEM analysis, and in situ observations of fluid saturation with numerical simulations to probe the saturation exponent under variable saturation conditions. They found that non-Archie phenomenon mainly occurred at lower S_w , and concentration of water film at or on the perimeter of grain contacts and microporosity

D. Huang (✉) · L. Sima · F. Wu · L. Wang · Q. Li
Institute of Geoscience and Technology, Southwest Petroleum University, Chengdu 610500, China
e-mail: xiaoxiaohuang1987@163.com

accounted for most of this phenomenon for the clean water-wet sandstone and carbonate, respectively.

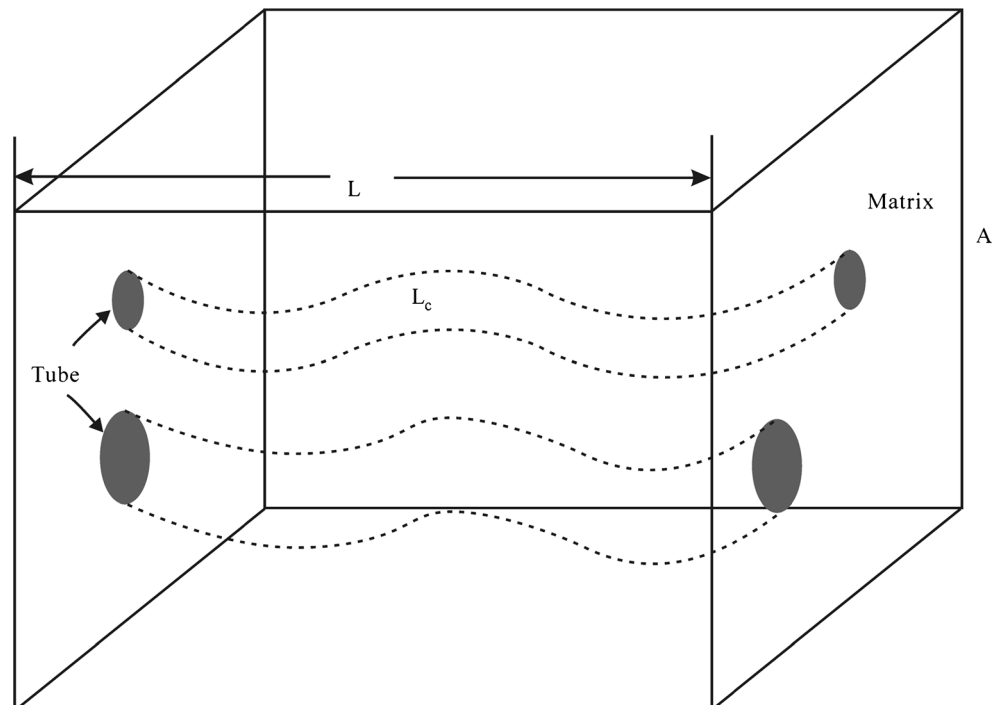
However, due to the technical limitation of pore scale, it is hard to quantify the influence factors of n . Most studies carried out on reservoirs with complex petrophysical properties were based on pore network model or 3D imaging with complicated procedure and high technical requirements, as well as high costs. Most of the results were still qualitative rather than quantitative. The relationship between saturation exponent and water saturation is still unclear. To contribute to the solution of this concern, this paper details an attempt to investigate the saturation exponent by combining the classic capillary theory and Purcell equation with NMR logging and core plugs experiments. This is an attractive alternative to complicated methods for estimating this relationship and provides a better insight into their initial relationship which has a certain theoretical basis.

Derivation of resistivity index from capillary theory and Purcell equation

Formation factor of fully water saturated rock

Capillary theory is widely used in the estimation of formation property (Kozeny 1927; Carman 1937, 1948, 1956; Pape et al. 1999). It describes the pore space of porous rock with cross-section area A and length L by a bundle of parallel fluid saturated bent cylindrical capillary tubes of equal length but random diameters (Fig. 1). The resistance of the rock is

Fig. 1 The capillary tube model of porous rock which is made up of a number of bent parallel capillary tubes with equal length but random radius (Liu et al. 2007)



equivalent to the parallel connection of resistance of the bundle of capillary tubes (Fig. 2). In terms of Ohm's law, the resistance of a given water saturated capillary tube can be expressed as

$$r_i = R_w \frac{L_c}{\pi r_{ci}^2} \quad (1)$$

where r_i is the resistance of the i th water saturated capillary tube in ohm, R_w is the resistivity of saturated water in ohmm, L_c is the length of the capillary tube in meter, and r_{ci} is i th capillary tube radius in meter.

Purcell (1949) proposed the theoretical equation which related to the permeability of a system of parallel cylindrical capillaries of equal length, but various radii, to the porosity of the system and to the capillary pressures and volumes of its component parts

$$k = \frac{(\sigma \cos \theta)^2}{2} \phi \sum_{i=1}^N S_i \left(\frac{1}{P_{ci}} \right)^2 \quad (2)$$

where k is the permeability in millidarcy, σ is the interfacial tension in millinewton per meter, θ is the contact angle in degree, ϕ is the porosity in percent, P_{ci} is the i th capillary pressure in megapascal, and S_i is the percentage of the cross-section area of capillary tube with r_{ci} radius in cross-section areas of all the capillary tubes.

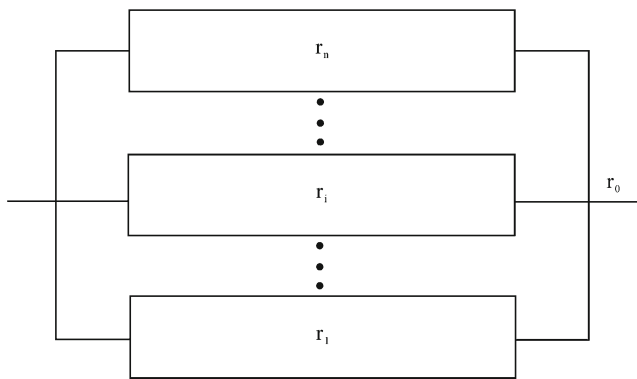


Fig. 2 The parallel connection of resistance of the bundle of capillary tubes (Wang et al. 2014)

Based on the capillary theory and Purcell equation, Wang et al. (2014) have deduced the formation factor equation of fully water saturated rock as

$$F = \frac{R_0}{R_w} = \frac{1}{\phi^m} = \frac{e' \tau A'_N \phi}{8\pi k} \tag{3}$$

where F is the formation factor, R_0 is the resistivity of fully water saturated rocks in ohmm, m is the cementation factor, τ ($\tau=L_c/L$) is the tortuosity of capillary tubes, A'_N ($A'_N = A/\sum_{i=1}^N D'_i$, D'_i is the number of capillary tube with the i th resistance) is apparent average cross-section area in meter squared and e' is a constant exponent.

Resistivity index of partially water saturated rock

While hydrocarbon charging occurs, water in larger pores will be displaced first. At the end of this proceeding, the larger pores are filled by hydrocarbon and water film, and the remaining are still filled with water. Hydrocarbon and the matrix are seen to be none conductive. The conductivity of hydrocarbon-bearing rock is still contributed by saturated water. According to the parallel connection of resistance of tube bundle model, the resistance of partially water saturated rock can be obtained as

$$\frac{1}{r_t} = D_1 \frac{1}{r_1} + D_i \frac{1}{r_i} + \dots + D_N \frac{1}{r_N} = \sum_{i=1}^N D_i \frac{1}{r_i} \tag{4}$$

where r_i is the resistance of partially water saturated rock in ohm. Substituting Eq. (1) into Eq. (4), this relationship becomes

$$\frac{1}{r_t} = \sum_{i=1}^N D_i \frac{1}{R_w \frac{L_c}{\pi r_{ci}^2}} \tag{5}$$

Carrying out some algebraic transformations, and it becomes

$$r_t = \frac{R_w}{\pi} L_c \left(\sum_{i=1}^N D_i r_{ci}^2 \right)^{-1} \tag{6}$$

The form of Ohm’s law for partially water saturated rock is

$$r_t = R_t \frac{L}{A} \tag{7}$$

where R_t is the resistivity of partially water saturated rocks in ohmm.

Combine Eqs. (7) and (6) and then

$$R_t = \frac{R_w}{\pi} \tau A_N \left(\sum_{i=1}^N d_i r_{ci}^2 \right)^{-1} \tag{8}$$

where A_N is the apparent average cross-section area in partially water saturated rocks in meter squared and is expressed as

$$A_N = A / \sum_{i=1}^N D_i \tag{9}$$

and d_i is the percentage of the number of capillary tubes with the r_{ci} radius in all the capillary tubes, and is expressed as

$$d_i = D_i / \sum_{i=1}^N D_i \tag{10}$$

P_{ci} in Pucrcell equation (Eq. (2)) can be obtained by

$$P_{ci} = \frac{2\sigma \cos\theta}{r_{ci}} \tag{11}$$

Thus, Pucrcell equation for fully water saturated rock can be expressed as

$$k = \frac{\phi}{8} \sum_{i=1}^N S_i' r_{ci}^2 \tag{12}$$

From the percolation theory, when two phases (water and oil/gas) coexist in pore space, each phase has its own flow

path with a stable interface when this two phase flow steadily (Helba et al. 1992). That means when one phase flows, the other phase can be seen as matrix which has no contribution to the flow. As the same form in Eq. (12), water-phase permeability can be regarded as

$$k_w = \frac{\phi_w}{8} \sum_{i=1}^N S_i r_{ci}^2 \quad (13)$$

where k_w is the permeability of water-phase in millidarcy and ϕ_w is the porosity of water in percent.

Introducing a constant exponent e to account for the difference between $\sum_{i=1}^N S_i r_{ci}^2$ and $\sum_{i=1}^N d_i r_{ci}^2$, then yield

$$\sum_{i=1}^N S_i r_{ci}^2 = e \sum_{i=1}^N d_i r_{ci}^2 \quad (14)$$

Combine Eqs. (8), (13), (14) and then

$$\frac{R_t}{R_w} = \frac{\tau A_N}{\pi} \left(\sum_{i=1}^N d_i r_{ci}^2 \right)^{-1} = \frac{e \tau A_N \phi_w}{8 \pi k_w} \quad (15)$$

Eq. (15) divided by Eq. (3) and then

$$\begin{aligned} I &= \frac{R_t}{R_0} = \left(\frac{e \tau A_N \phi_w}{8 \pi k_w} \right) / \left(\frac{e' \tau A_N \phi}{8 \pi k} \right) \\ &= \frac{e \phi_w}{e' \phi} \frac{k}{k_w} \cong \frac{\phi_w}{\phi} \frac{k}{k_w} = S_w \frac{k}{k_w} \end{aligned} \quad (16)$$

where I is the resistivity index.

Saturation exponent model from NMR

One of the widely used two permeability models in NMR log evaluation is SDR model which proposed by Schlumberger Doll Research Center (Kenyon et al. 1988; Kenyon 1997) is

$$k = C_1 \times \phi^{m_1} \times T_{2gm}^{n_1} \quad (17)$$

where T_{2gm} is the geometric mean of the NMR T_2 spectrum of fully water saturated rock in ms, C_1 , m_1 and n_1 are the statistical model parameters which can be acquired from core

sample experimental results, while without enough core samples, these three parameters can be assigned to empirical values of 10, 4, and 2, respectively.

When the rock is partially water saturated in laboratory, the water-phase permeability can be gained by

$$k_w = C_1 \times \phi_w^{m_1} \times T_{2wgm}^{n_1} \quad (18)$$

where T_{2wgm} is the geometric mean of the NMR T_2 spectrum of partially water saturated rock in ms.

Eq. (17) divided by Eq. (18) and then

$$\begin{aligned} \frac{k}{k_w} &= \frac{C_1 \times \phi^{m_1} \times T_{2gm}^{n_1}}{C_1 \times \phi_w^{m_1} \times T_{2wgm}^{n_1}} = \left(\frac{\phi}{\phi_w} \right)^{m_1} \left(\frac{T_{2gm}}{T_{2wgm}} \right)^{n_1} \\ &= \left(\frac{1}{S_w} \right)^{m_1} \left(\frac{T_{2gm}}{T_{2wgm}} \right)^{n_1} \end{aligned} \quad (19)$$

Combine Eqs. (19) and (16), then

$$I = S_w \frac{k}{k_w} = S_w \left(\frac{1}{S_w} \right)^{m_1} \left(\frac{T_{2gm}}{T_{2wgm}} \right)^{n_1} = S_w^{-n} \quad (20)$$

That means

$$\left(\frac{1}{S_w} \right)^{m_1-1} \left(\frac{T_{2gm}}{T_{2wgm}} \right)^{n_1} = S_w^{-n} \quad (21)$$

Thus, the relation between n and S_w was developed, which is expressed in terms of NMR information by

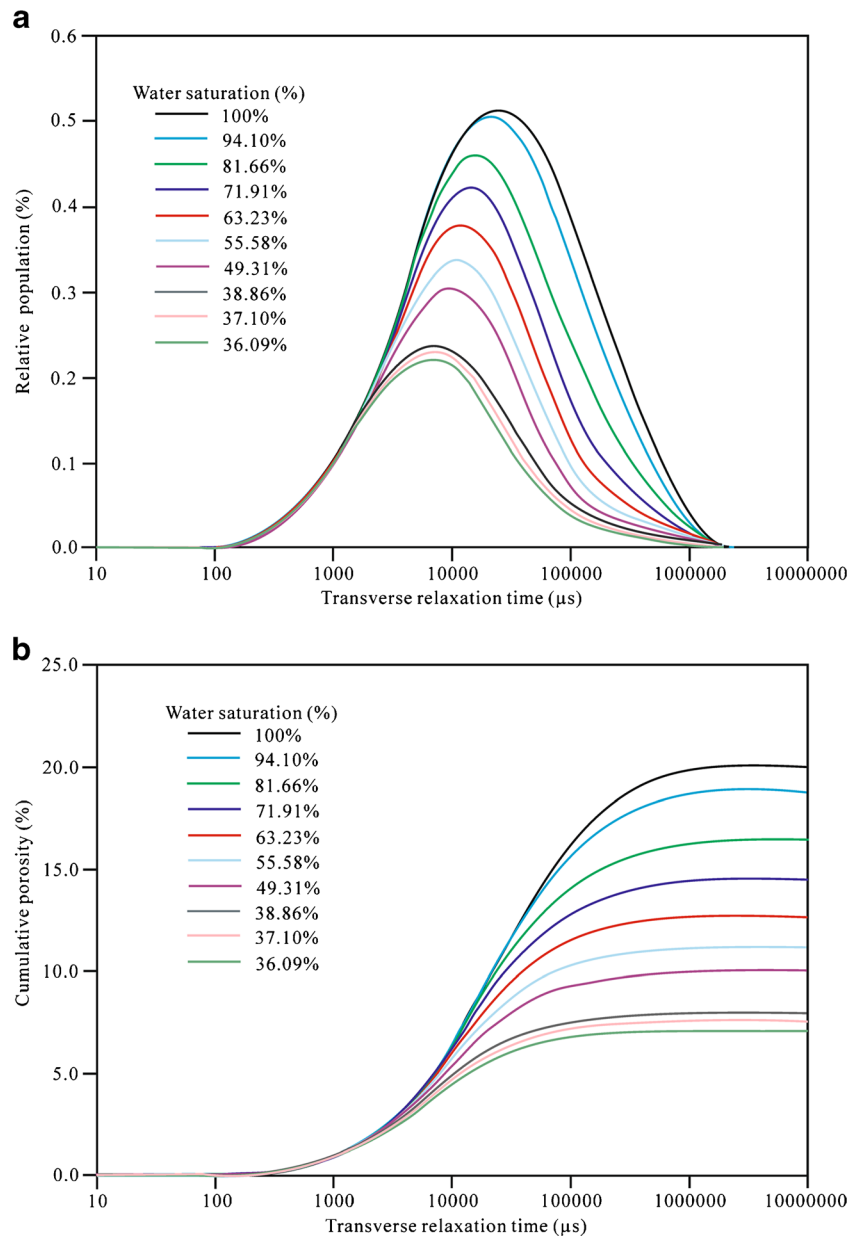
$$n = m_1 - 1 - n_1 \frac{\ln \left(\frac{T_{2gm}}{T_{2wgm}} \right)}{\ln S_w} \quad (22)$$

T_2 spectrum of water

It is widely accepted that T_2 spectrum varies with lithology as seen in complex sandstones, as well as in carbonates where rock properties vary significantly. In addition, there are other parameters that affect the T_2 distribution, such as the pore body diameter to pore throat diameter (aspect ratio). Currently, all the variables that influence the T_2 distribution are not fully understood or identified.

The laboratory NMR measurements carried out on partially water saturated rocks have shown that as air replaces water in pores, the long T_2 components

Fig. 3 T_2 spectrum at variable water saturations of sample B8



disappear first, corresponding to the draining of the largest pores first, as shown in (Fig. 3). Disappearance of the long T_2 components at each increment of centrifuge speed corresponds directly to the loss of water from the largest pores. The air that replaces the water generates no NMR signal since it contains no hydrogen (Straley et al. 1991). Combining percolation theory, the water phase (water/air) T_2 spectrum can be obtained by centrifuging (Helba et al. 1992).

For the given formation, especially the given core samples, the influence factors of NMR T_2 spectrum are almost the same except the fluid property. The geometric mean of the T_2 spectrum of partially water saturated samples to that of fully water saturated samples

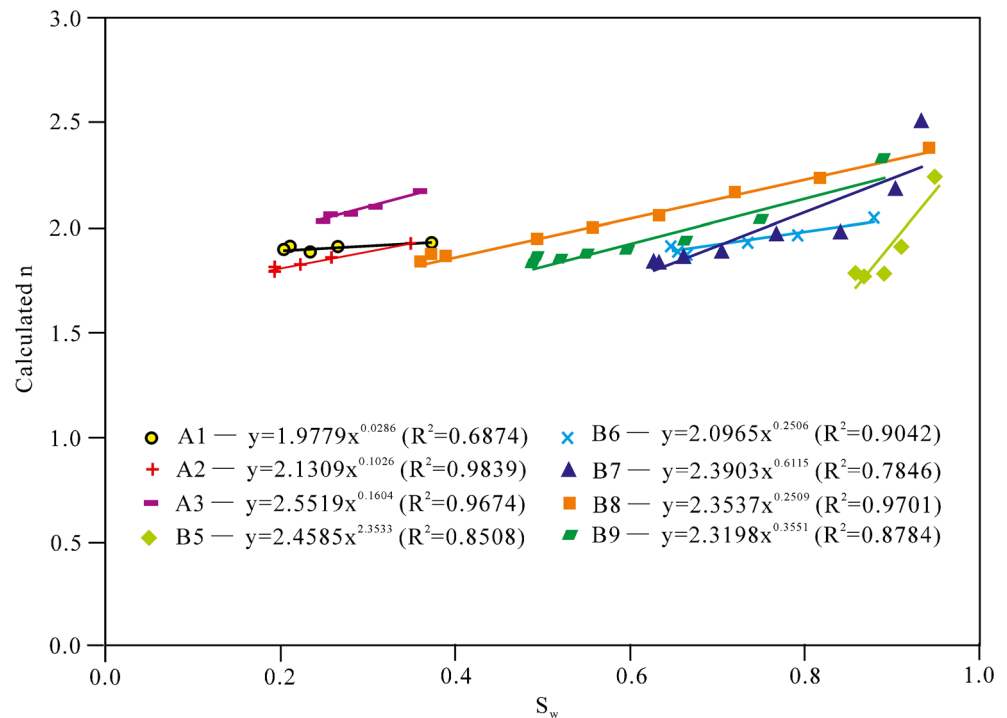
Table 1 k , ϕ , and T_{2gm} of some core samples used to regress m_1 and n_1

Sample no.	k (mD)	ϕ (%)	T_{2gm} (ms)
A1	8.39	26.90	117.97
A2	23.00	23.60	183.87
A3	58.10	21.50	227.40
B1	18.00	36.80	39.66
B2	3.92	33.00	83.33
B3	8.60	33.80	24.37
B4	1.06	23.00	10.75
B6	11.90	24.40	12.09
B7	14.70	27.50	7.99
B8	0.89	20.30	24.36

Table 2 Calculated and experimental values of n

Sample no.	S_w (%)	T_{2gm} (T_{2wgm}) (ms)	Calculated n	Measured n	Sample no.	S_w (%)	T_{2gm} (T_{2wgm}) (ms)	Calculated n	Measured n
A2	100.00	183.87	/	1.800	B5	100.00	6.060	/	2.467
	34.87	46.337	1.916			94.71	5.503	2.242	
	25.87	35.536	1.851			90.98	5.359	1.910	
	22.27	31.539	1.822			89.01	5.323	1.780	
	19.50	27.682	1.811			86.71	5.185	1.765	
	19.31	28.258	1.797			85.78	5.106	1.782	
A3	100.00	227.40	/	1.970	B7	100.00	7.992	/	1.747
	35.56	53.050	1.985			93.24	6.864	2.522	
	30.42	46.893	1.929			90.28	6.711	2.196	
	27.52	44.702	1.883			84.01	6.251	1.987	
	25.18	47.209	1.798			76.61	5.518	1.973	
	24.34	42.166	2.033			70.41	5.114	1.891	
B8	100.00	24.375	/	1.84	B9	100.00	15.991	/	2.911
	94.11	21.631	2.377			88.78	12.757	2.329	
	81.66	17.060	2.233			74.93	10.440	2.034	
	71.91	14.082	2.165			66.19	9.223	1.934	
	63.23	12.161	2.062			59.60	8.280	1.890	
	55.58	10.573	1.995			55.00	7.629	1.867	
	49.31	9.435	1.940			51.95	7.272	1.842	
	38.86	7.643	1.859			49.33	6.791	1.848	
	37.10	7.113	1.869			48.79	6.819	1.831	
	36.09	7.175	1.840						

Fig. 4 The relationship between S_w and n through application of the new model in the Middle East reservoir core samples



may offset many influence factors which hard to be expressed quantitatively.

Case studies

To verify the reliability of the saturation exponent model proposed in Eq. (22), NMR measurements on both fully water saturated and partially water saturated (i.e., under different centrifuge forces) 16 core samples drilled from a reservoir in the Middle East were conducted. To calculate n , five parameters (constant parameters m_I and n_I , geometric mean of the NMR T_2 spectrum of fully water saturated rocks and partially water saturated rocks T_{2gm} and T_{2wgm} , water saturation and S_w) are required.

Calculation of m_I and n_I

The values of m_I and n_I in SDR model can be obtained through combining porosity and permeability measured from core samples in laboratory and NMR T_2 spectrum. Fifty core samples were used to calculate them and some of them are shown in Table 1. The values of m_I and n_I are 2.00 and 0.69 by regression, respectively, as shown in Table 1.

Calculation of n

Sixteen samples have been tested under different centrifuge speeds and the values of T_{2gm} and T_{2wgm} can be obtained both. The values of n of all these samples under different water saturations have been calculated through the model which have been inferred by Eq. (22), and only the samples which both NMR and resistivity measurement have been conducted are shown in Table 2. Calculated and experimental values of n are shown in Table 2 and Fig. 4.

Saturation exponent values acquired from resistivity experimental measurements and predicted from NMR log information show that:

1. Saturation exponent values decrease as water saturation decreasing, and they obey the law of power function which is in accord with the result of network simulation from Tao et al. (2004)

$$n = aS_w^b \quad (23)$$

and this can also be a good proof of the reliability of this new model.

2. The calculated saturation exponent values range from 1.782 to 2.522 while the measured values are ranging from 1.747 to 2.911.

Besides, in reservoir with consecutive NMR logs, once the T_2 spectrum distribution of water and gas or oil can be distinguished, water saturation can be calculate without the application of Archie equation, hence n and m which are difficult to determine. The S_w estimation equation can be gained from Eq. (20) as

$$S_w = \left(\left(\frac{T_{2gm}}{T_{2wgm}} \right)^{n_I} \frac{R_0}{R_t} \right)^{\frac{1}{m_I-1}} \quad (24)$$

This will be valuable for the calculation of hydrocarbon and water saturation in complex reservoirs, such as carbonates, so as sandstones.

Conclusions

A new method for probing the saturation exponent under variable water saturations by combining the NMR with capillary theory and Purcell equation has been developed. In the process of derivation of the formula, a key hypothesis which is accepted in percolation theory has been introduced. That is when two phases (water and oil/gas) coexist in pore space, each phase has its own flow path with a stable interface when this two phase flow steadily (i.e., when one phase flow, the other phase can be seen as matrix which has no contribution to the flow). Based on these theories, the proposed new saturation exponent estimator quantitatively reveals that the saturation exponent is not a constant but a variable parameter depends on water saturation and pore structure. NMR measurements on partially water saturated core samples were used to calculate n through this new model. Result shows that n and S_w followed a power law which is in accordance with that gained by network model simulation that has been published. And it is also accord with the power law in percolation theory that has been widely proved in transport property of porous media. Water saturation equation is also gained from the T_2 spectrum and well logging resistivity without the application of Archie equation, hence n and m which are difficult to determine.

Notice that for the given formation, especially the given core samples, the influence factors of NMR T_2 spectrum are almost the same except the fluid property. T_{2gm}/T_{2wgm} may offset many influence factors of T_2 spectrum which hard to be expressed quantitatively, and the same case for water saturation equation. But, this saturation exponent model and water saturation equation is based on that T_2 spectrum distribution of water and gas or oil

can be distinguished. For example, T_2 spectrum of high viscosity oil in water-base mud well is often overlapping that of salinity water. Then, this method will be invalid.

Anyhow, the results have a certain practical significance in the evaluation of water saturation, while further study is still required.

Acknowledgments This study was supported by the National Science and Technology Major Project of China (Grant No. 2011ZX05031) (Key Technology of Exploration and Development of Large Projects of Oil & Gas Rich Fields in the Middle East and Central Asia). The authors also would like to thank the reviewers and editors for their attention and valuable comments to improve the manuscript quality.

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