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Numerical simulation of rock pore-throat structure effects on NMR T_2 distribution

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Abstract: We built a three-dimensional irregular network model which can adequately describe reservoir rock pore-throat structures. We carried out numerical simulations to study the NMR T_2 distribution of water-saturated rocks. The results indicate that there is a good correlation between T_2 distribution and the pore radius frequency histogram. The total T_2 distribution can be partitioned into pore body and pore throat parts. The effect of parameters including throat radius, pore-throat ratio, and coordination number of the micro-pore structure on the T_2 distribution can be evaluated individually. The result indicates that: 1) with the increase of the pore throat radius, the T_2 distribution moves toward longer relaxation times and its peak intensity increases; 2) with the increase of the pore-throat ratio, the T_2 distribution moves towards longer T_2 with the peak intensity increasing and the overlap between pore body T_2 and pore throat T_2 decreasing; 3) With the increase of connectivity, the short T_2 component increases and peak signal intensity decreases slightly.
Key words: Network model; NMR; T_2 distribution; Pore structure; Microstructure modeling

Introduction

NMR logging, introduced in the early 1990s, has played an important role in the characterization of reservoir pore structure and the identification and quantification of oil and gas in the earth formation. NMR logging is continuous, fast, and non-destructive. It is certainly superior to Pc curves which can only be obtained from core plugs sampled sparingly. Up to now, most researches have been focused on the relationship between T_2 distribution and Pc curves (Morris et al., 1994; Yakov and Win, 2001; Lowden et al.1998; Yun et al., 2002). The major conclusion is that, if we ignore the bulk relaxation and diffusion effects, there is a simple relation between P_C and T_2 values, i.e., $P_C = C/T_2$, where C is a constant. This simple relation reflects that both the T_2 distribution and P_C curve are affected by pore structures but overlooks the differences between the two. The P_C curve is usually obtained in the laboratory by injecting mercury using a constant pressure. It reflects the pore space accessible by a certain pore throat size. Hence, the pore size distribution derived from the Pc curve is not the distribution of the total pore size but the distribution of the pore throat and the pore bodies controlled by that throat. On the other hand, the NMR T_2 distribution reflects the size distribution of all pores (pore throat and pore body) in the reservoir rock. We should realize the basic difference between the two. Liu et al. (2004) studied the inversion of NMR core measurements using a sphere-tube model where the pore space is divided into capillary tubes and spherical pores. Zhou et al. (2006) further developed the optimum restriction method of the sphere-tube model and applied it to reservoir pore structure evaluation. Their work considered the effects of the correlation between pore body and pore throat and has a significant meaning for NMR log data interpretation.

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The experimental result is a combined reflection of pores of all different sizes and shapes. It is impossible to measure the signal of a particular micro-pore and how it affects the NMR relaxation behavior. On the other hand, theoretical research can only model pores of simple geometries. It is difficult to study the effects of real microscopic pore structures of reservoir rocks using the characteristics of NMR relaxation signals. A pore network model that can truly reflect the pore structures of the reservoir and fluid properties can be used for numerical simulation to study its effect on T_2 distribution characteristics and avoid the difficulty of the signal inversion. There have been such kind of microstructure modeling studies on NMR properties of rocks, for example, the simulation work by Al-Mahrooqi et al. (2006) using the capillary model.

We built a three-dimensional irregular network model based on our previous work (Wang et al., 2007) to study the characteristics of T_2 distribution of water-saturated rocks. The study focuses on the correlation between T_2 distribution and pore-throat size distribution, throat radius, pore-throat ratio, connectivity, and etc. We believe that results of the numerical simulations should improve our understanding of how to use NMR measurements for formation evaluation.

Network model

The network model is made up of pore bodies connected by pore throats. The pore body represents relatively large void spaces and pore throats relatively narrow void spaces in rocks. The number of pore throats connected to a pore body is the coordination number Z. The average value of all pore bodies' coordination numbers is the mean coordination number of the network model which reflects the connectivity of the void space. The shape of pore bodies and pore throats is usually cylindrical but other complex shapes such as Delaunay triangles, rectangles, and triangles can be used in order to study the effects of wetting layers in corners. In the simulation, we have used circular and non-circular cross-sections. The irregularity of the void space is described by a shape factor, *G* defined as

$$G = \frac{A}{P^2}, \tag{1}$$

where *A* is the cross-sectional area (μm^2) and *P* is the length of the cross-section's perimeter (μm). The smaller the *G*, the rougher the pore surface. Because of capillary pressure effects, the water in the rough corners and micropores can't move freely but it can provide a path for electric flow.

The radius of pore bodies and pore throats in the network model is determined by a distribution function. Al-Futaisi found that the Weibull function can describe features of the reservoir pore structures better than the normal or log normal distributions. Therefore, we have adopted the Weibull function for our simulation study.

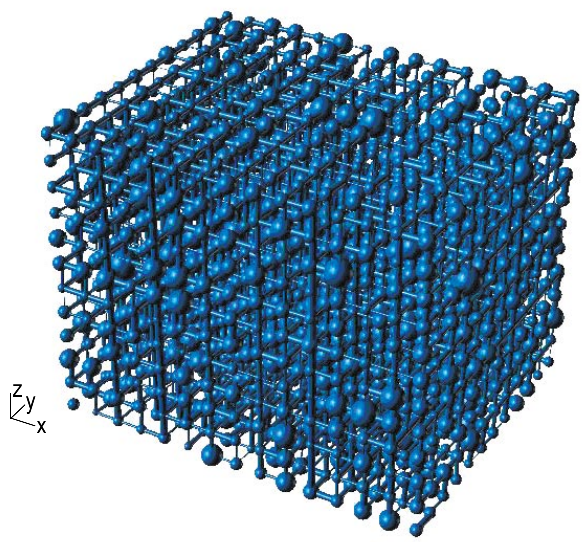

Fig. 1 Three-dimensional reservoir rock network model.

Figure 1 shows a three dimensional network model that represents the pore structure of a rock. For convenience, pore bodies and throats are represented as spheres and tubes, respectively. Their real shapes are determined by the shape factor G, which can have non-circular cross-sections. The size of the pore body and the throat depends on the pore radius. In the network model, pore bodies and pore throats are given certain geometric shapes and physical properties.

Simulation method

Based on NMR theory of fluid-saturated porous media, when a rock is saturated by a single phase fluid, the transverse relaxation rate $1/T_2$ is composed of three parts: bulk, surface, and enhanced diffusion relaxation rates (Richard, 1994; Yun, et al. 2002; Toumelin, et al. 2007):

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \rho_2 \frac{S}{V} + \frac{D\left(GT_E\gamma\right)^2}{12}, \tag{2}$$

where T_{2B} is the bulk relaxation time of the fluid, ρ_2 is the transverse surface relaxation strength, *D* is the diffusion coefficient, G is the magnetic field gradient, T_E is the echo spacing, γ is the gyromagnetic ratio, S is the pore surface area, and V is the pore volume.

In general, the bulk relaxation of the fluid is much slower than the surface relaxation (the value of T_{2B} for water is usually 2 – 3s), so the first term on the right hand side of (2) can be ignored. When the magnetic field is uniform or magnetic field gradient is very small, the diffusion term can also be ignored. Hence, (2) reduces to

$$\frac{1}{T_2} \approx \rho_2 \frac{S}{V}. \tag{3}$$

Assuming the cross-sectional area of some pore (or throat) is A_i and the shape factor is G_i, then the transverse relaxation time of the pore is given by

$$\frac{1}{T_{2i}} \approx \frac{\rho_2}{\sqrt{A_i G_i}}. \tag{4}$$

The cross-sectional area A_i is related to the radius (or equivalent radius for pores of non-circular cross section), so we can study the effect of the pore radius on relaxation properties. Because the diffusion effect is ignored, the total signal intensity $E(T_2)$, when the relaxation time is T_2 is the sum of that from the pore body $E_p(T_2)$ and that from the pore throat $E_t(T_2)$:

$$E(T_2) = E_p(T_2) + E_t(T_2). \tag{5}$$

The fractional signal intensity of a certain pore (or throat), E_i, is

$$E_i = \frac{A_i \cdot L_i}{\sum_{j=1}^{N} A_j \cdot L_j}, \tag{6}$$

where L is the length of the pore (or throat) and N is the total number of the pores and throats in the model.

We can obtain the T_2 distribution of the water-saturated rock by taking T_2 values of all pore bodies and throats as the X-axis and the signal intensity as the Y-axis. By changing the model parameters, the effects of the throat radius, pore-throat ratio, and coordination number on T_2 distribution can be studied.

Modeling results and discussion

Based on the model described above, the T_2 distribution characteristics of the water-saturated rock and the effects of the microstructure parameters on T_2 distribution have been studied using the three-dimensional network model. The important parameters used in the model are listed in Table 1.

Table 1 Basic model parameters

Parameter	Value	Parameter	Value
Throat radius μm	0.05 - 3.0	Porosity %	12.0
Pore-throat ratio	1.3 - 5.0	Permeability mD	16.8
Coordination Number	4.0	Surface relaxivity μm/s	20.0

Modeling result of T_2 distribution

Figure 2 shows the T_2 distributions from the pore bodies, throats, and combined total. From the modeling results, we find that: the radius of the pore bodies and the ratio of their surface area to volume are large, their T_2 values are large, lying to the right of the curve; the radius of the throats and the ratio of their surface area to volume are small, their T_2 values are small, lying to the left of the curve. In real reservoir rock, there is superposition between pore body size distribution and throat size distribution. Our modeling has delineated such characteristics.

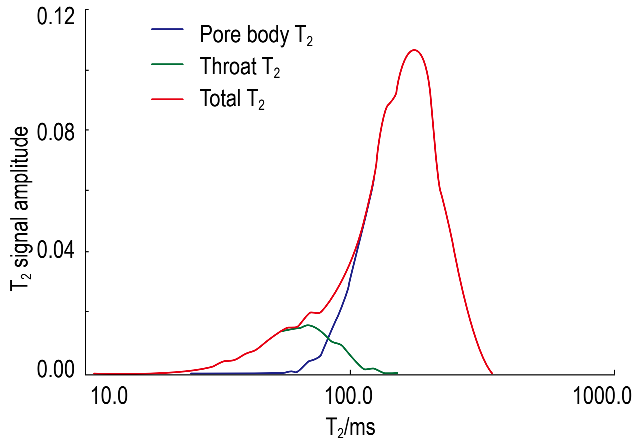

Fig. 2 Modeling results of the water-saturated T_2 distribution.

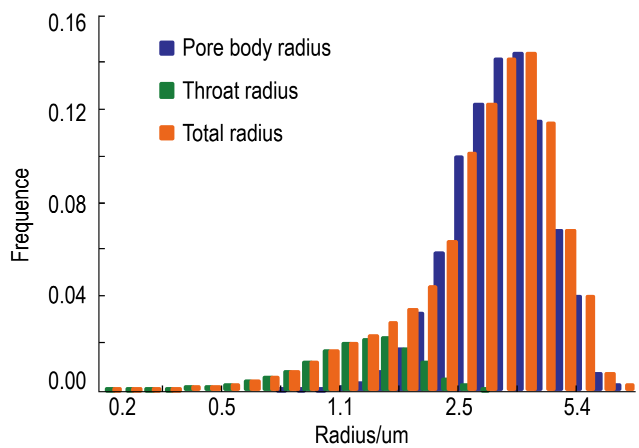

Fig. 3 Frequency histogram of the pore throat radius.

Because the T_2 distribution of water-saturated rocks reflects the transverse relaxation characteristics of all pores and throats, it is one of the important pieces of information for pore structure analysis. Figure 3 shows the histogram of the pore size distribution from pore bodies, throats, and the total. We find that the T_2 distributions in Figure 2 correspond quite well to the pore size distributions shown in Figure 3. Therefore, if we can divide the total T_2 curve to pore T_2 curves and throat T_2 curves, we can use NMR properties to evaluate the reservoir properties, such as pore-throat ratio, porosity, permeability and so on.

Effects of pore structure on T_2 distribution

Effects of throat radius on T_2 distribution

In order to study the effect of throat radius on T_2 distribution, the model parameters such as pore-throat ratios, coordination number, and so on are kept fixed while the radius is varied. The result is shown in Figure 4. We find that as the throat radius increases, the T_2 distribution as a whole moves towards longer relaxation times and the width of the T_2 distribution stays more or less the same, with the peak value gradually increasing and the contribution from throat gradually decreasing. Because the pore-throat ratio is fixed, increasing the throat radius is equivalent to increasing the pore radius and porosity. Therefore, what we observe in Figure 4 corresponds to the situation when both pore body and throat increase at the same scale, which is usually associated with compaction as a function of depth in the reservoir.

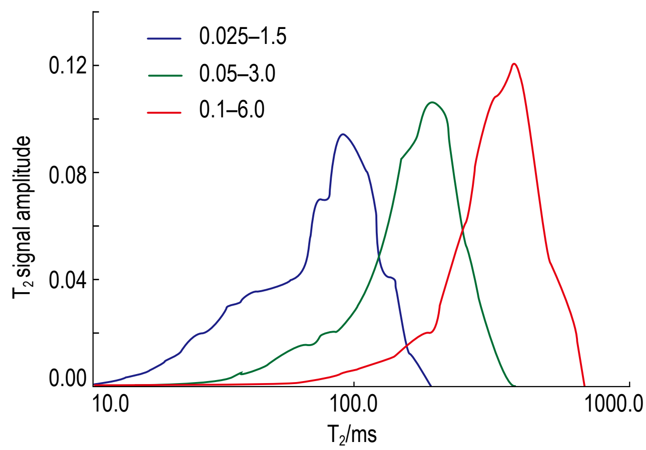

Fig.4 Effect of throat radius on T_2 curves.

Effect of pore-throat ratio on T_2 distribution

Pore-throat ratio is defined as the ratio of the radii for the pore body and throat. Its value is related to the sedimentary environment, compaction, and cementation. In Figure 5, the modeling results of three different models having different pore-throat ratios are shown. We find that when the pore-throat ratio increases, the width of the T_2 distribution expands, the T_2 value of the peak signal becomes larger, and the peak intensity increases. When the pore-throat ratio is small, there is more overlap between the T_2 distributions of pores and throats. When the pore-throat ratio is big, such overlap becomes less and a low amplitude bump of short T_2 emerges. In real rocks, such short T_2 bump is associated with the micropores.

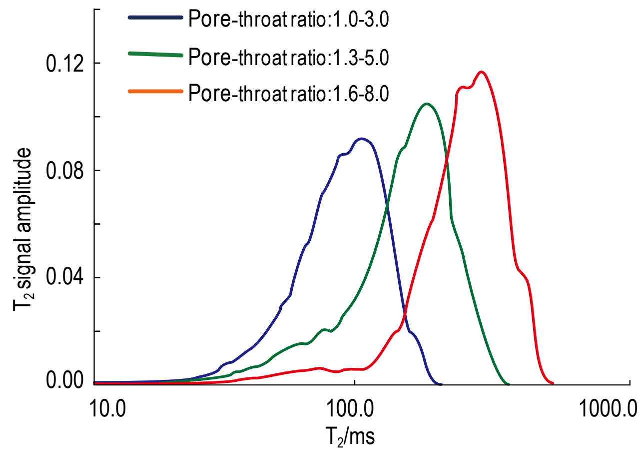

Fig. 5 Effect of the pore-throat ratio on T_2 curves.

Effect of pore connectivity on T_2 distribution

The pore connectivity is one of the important pore structure characteristics. Usually, the connectivity greatly influences reservoir rock permeability. If the pore throat sizes (including pore body radius and throat radius) of two reservoirs are similar, the reservoir with the larger connectivity has the higher permeability (Ling, 2004). In core analysis and microstructure modeling, the connectivity of the reservoir rocks is usually characterized by the coordination number, Z.

Figure 6 shows the modeling results of the T_2 distributions with three different coordination numbers ($Z = 2.5$, $Z = 4.0$, and $Z = 6.0$) where all other model parameters are kept the same. We find that when the connectivity increases, the width and location of the T_2 distribution remain the same, the peak intensity decreases, and the short T_2 bump increases. This is because increasing connectivity increases the number of throats leading to the increase of short T_2 components. The increase of connectivity also leads to a permeability increase. They are 3.7 mD, 16.8 mD, and 59.3 mD for $Z = 2.5$, $Z = 4.0$, and $Z = 6.0$, respectively.

The relations between T_2 distribution and permeability

T_2 distribution data is used, not only for evaluating the pore structures, but also for estimating the permeability. There are some permeability models such as Coates

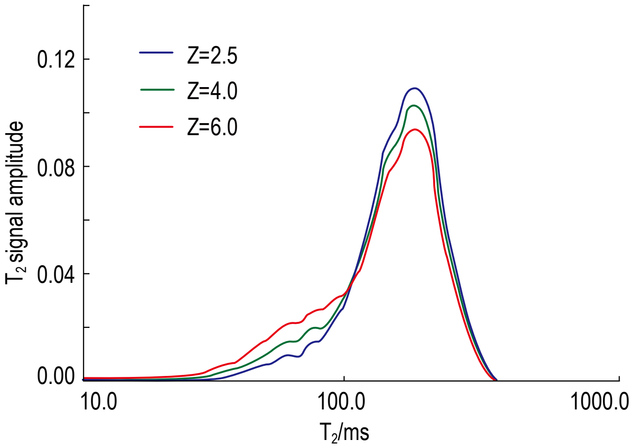

Fig. 6 Effect of the connectivity on T_2 curve

and SDR models (Coates, et al.,1997; Kenyon, 1992) used for formation evaluation. It is generally believed that the increase of the short T_2 components reduces the permeability. This is not always the case. Through modeling, we find that as the throat radius reduces, the permeability reduces and the short T_2 amplitudes increase. As the pore-throat ratio reduces, the short T_2 amplitudes increase and the permeability increases. As the connectivity increases, the short T_2 amplitudes increase and the permeability increases. Therefore, the increase of the short T_2 components does not always lead to a reduction in permeability. In order to correctly evaluate the impact of T_2 distribution to permeability, we should study the influencing factors carefully.

Conclusions

(1) Microstructure modeling of rocks is an important method for the study of NMR properties of rocks. Through numerical modeling, we can study the impact of each individual factor of the complex pore structures on the T_2 distribution.

(2) The T_2 value of the throat is small and the T_2 value of the pore body is large. Because there is an overlap between the distributions of pore body and throat radii, so are their corresponding T_2 distributions. The shape of the T_2 distribution curve is similar to the frequency histogram of the pore throat radius. By decomposing the total T_2 signal into T_2 signals for pore body and throat, T_2 data can be used to evaluate reservoir pore connectivity, pore throat radius, permeability, and so on.

(3) With the increase of throat radius, the T_2 distribution as a whole moves towards long relaxation times, the peak signal intensity increases, and the signal associated with throats decreases. With the increase of the pore-throat ratio, the width of the T_2 distribution expands, the peak moves to longer T_2 with its intensity increasing, and the overlap between pore T_2 and throat T_2 decreases.

(4) When the connectivity increases, the width and location of the T_2 distribution remain the same, with an increase in the short relaxation signal and a slight reduction in the peak signal intensity.

This paper mainly focused on the NMR properties of water-saturated rock and the effects of the pore structure on the T_2 distribution curve. Our next goal is to study the NMR characteristics of rocks at different saturations and different fluid distributions in the displacement process.

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