Advanced fluid-typing methods for NMR logging

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Abstract: In recent years, nuclear magnetic resonance (NMR) has been increasingly used for fluid-typing in well-logging because of the improved generations of NMR logging tools. This paper first discusses the applicable conditions of two one-dimensional NMR methods: the dual TW method and dual TE method. Then, the two-dimensional (T_2 , D) and (T_2 , T_1) NMR methods are introduced. These different typing methods for hydrocarbon are compared and analyzed by numerical simulation. The results show that the dual TW method is not suitable for identifying a macroporous water layer. The dual TE method is not suitable for typing gas and irreducible water. (T_2 , T_1) method is more effective in typing a gas layer. In an oil-bearing layer of movable water containing big pores, (T_2 , T_1) method can solve the misinterpretation problem in the dual TW method between a water layer with big pores and an oil layer. The (T_2 , T_1) method can distinguish irreducible water from oil of a medium viscosity, and the viscosity range of oil becomes wide in contrast with that of the dual TW method. The (T_2 , D) method is more effective in typing oil and water layers. In a gas layer, when the SNR is higher than a threshold, the (T_2 , D) method can resolve the overlapping T_2 signals of irreducible water and gas that occurs due to the use of the dual TE method. Two-dimensional NMR for fluid-typing is an important development of well logging technology.

Key words: NMR logging, one-dimensional NMR, two-dimensional NMR, reservoir evaluation, fluid-typing

1 Introduction

Nuclear magnetic resonance (NMR) technology, which has been widely used in well-logging and in petrophysics for core analysis, is crucial for oil and gas exploration and development. NMR logging can provide much information on porosity, capillary bound water, clay bound water, the volume of movable fluid, permeability, and pore size distribution (Coates et al, 1999; Dunn et al, 2002; Xie et al, 2006; Xie et al, 2008; Lu et al, 2007; He et al, 2005), all of which are important in well-logging for evaluating reservoirs, estimating water saturation, and understanding the fluid flow in pore networks, especially for prospecting and developing areas with a complex lithology. Akkurt and Prammer showed that NMR logging not only could provide porosity, bulk volume irreducible water, free fluids, permeability but also allow the identification and quantification of fluids in a reservoir. They suggested a dual TW method based on the T_1 contrast between water and hydrocarbon and a dual TE method based on the diffusion coefficient contrast between fluids (Akkurt et al, 1995; Prammer et al, 1995). These two NMR methods, which have been widely used for typing fluids in well-logging

service companies of China, have generated some successful as well as unsuccessful examples (Tan et al, 2006; Yun and Tan, 2006). The latter sometimes even have results opposite to the prediction of oil and water zone interpretation (Xiao, 2007). In 2002, Sun and Dunn of Chevron Texaco Energy Technology Company, Hurlimann, Venkataramanan and Song et al of Schlumberger-Doll Research proposed independently a new concept of two-dimensional (2D) NMR (Sun and Dunn, 2002; Hurlimann et al, 2002; Song et al, 2002; Sun et al, 2004). This technical development gives rise to the expectation of better typing and evaluating reservoir fluids based on two-dimensional NMR logging. The basic problem with the theory and application of 2D NMR logging has been explored recently (Xie et al, 2005; Xie et al, 2009a; Xie and Xiao, 2009). This paper presents the applicable condition of typing fluids (oil, gas and water) with one-dimensional (1D) NMR methods, introduces the (T_2 , D) and (T_2 , T_1) 2D NMR methods, and discusses the advantage and limitation of different methods by numerical simulation.

2 Theoretical basis of NMR logging typing fluids

The differences in T_1 , T_2 and D among the main fluids in well-logging (oil, gas and water) in a reservoir condition form a theoretical basis for NMR fluid-typing, since the NMR

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properties of different reservoir fluids are quite different from one another. Table 1 is an example of T_1 , T_2 and D of reservoir fluids in a field gradient of 17 Gauss/cm with a TE of 1.2ms for a typical sandstone reservoir (Dunn et al, 2002). The properties of these fluids are quite different. For example, T_1 for oil and gas is much longer than T_1 for water in the rock, which is the scientific basis for the dual TW method. Diffusion coefficients are also quite different among oil, gas and water, which form the basis of the dual TE measurements. When multiple pore fluids, such as oil, gas and water, are present, it can become difficult to differentiate them, especially when their T_2 signals overlap due to a change of NMR properties of reservoir fluids, various crude oils components, wide viscosity ranges (Xie et al, 2007) and complex rock pore structures (He et al, 2005). Consequently, the prediction of oil and water zone interpretation can be inconsistent with the results from 1D NMR fluid- typing (Xiao, 2007). By comparison, the extra dimension acquired from the use of 2D NMR logging methods enables the construction of a 2D map of the proton distribution function of (T_2, D) or (T_2, T_1) , which is capable of handling complex reservoir fluid typing and evaluation.

Table 1 NMR properties of fluids for a typical sandstone reservoir ($G=17$ Gauss/cm, $TE=1.2$ ms) (Dunn et al, 2002)

Fluid	T_1 ms	T_2 ms	D $\times 10^{-5} \text{cm}^2/\text{s}$	$\frac{1}{12} \gamma^2 G^2 D (TE)^2$ s^{-1}
Brine	1-500	0.67-200	7.7	1.9
Oil	1000	670	2	0.5
Gas	4000	40	100	24.8

3 One-dimensional NMR logging typing fluid methods

3.1 Dual TW method

Oil and gas are usually nonwetting phases. Their T_1 s are much longer than the T_1 of water in the rock. Dual TW uses different waiting time for full polarization of oil, gas and water. Two sets of echo trains are acquired in a long or short waiting time independently. Short waiting time (TW_s) is shorter than $T_{1,\text{gas}}$ for gas, or $T_{1,\text{oil}}$ for oil, but longer than three times the longest T_{1w} of the water contained in rock and ensures full recovery for water, and long waiting time (TW_L) is long enough for recovering all gas and oil signals in the following (Dunn et al, 2002):

$$3T_{1w,\text{max}} < TW_s < T_{1,\text{gas}} (\text{and/or } T_{1,\text{oil}}) < TW_L \quad (1)$$

NMR T_2 relaxation signals measured with long and short periods of waiting time are shown independently in the following forms:

$$\phi_{TW_L} = \phi_w + \phi_{\text{gas}} (1 - e^{-TW_L/T_{1,\text{gas}}}) + \phi_{\text{oil}} (1 - e^{-TW_L/T_{1,\text{oil}}}) \quad (2)$$

$$\phi_{TW_s} = \phi_w + \phi_{\text{gas}} (1 - e^{-TW_s/T_{1,\text{gas}}}) + \phi_{\text{oil}} (1 - e^{-TW_s/T_{1,\text{oil}}}) \quad (3)$$

Eq. (3) is subtracted with Eq. (2)

$$\begin{aligned} \phi_{TW_L} - \phi_{TW_s} &= \phi_{\text{gas}} (e^{-TW_s/T_{1,\text{gas}}} - e^{-TW_L/T_{1,\text{gas}}}) \\ &+ \phi_{\text{oil}} (e^{-TW_s/T_{1,\text{oil}}} - e^{-TW_L/T_{1,\text{oil}}}) \end{aligned} \quad (4)$$

where ϕ_{TW_L} and ϕ_{TW_s} represent the T_2 signals for long and short periods of waiting time, respectively, and ϕ_w for water signal, ϕ_{gas} for gas signal, and ϕ_{oil} for oil signal. The factors, $e^{-TW_L/T_{1,\text{gas}}}$ and $e^{-TW_L/T_{1,\text{oil}}}$, are very small and can be omitted. Eq.(4) becomes (Dunn et al, 2002):

$$\phi_{TW_L} - \phi_{TW_s} = \phi_{\text{gas}} e^{-TW_s/T_{1,\text{gas}}} + \phi_{\text{oil}} e^{-TW_s/T_{1,\text{oil}}} \quad (5)$$

From Eq. (5), oil and gas saturations can be obtained. The success of the application of this method depends on NMR relaxation contrast between water and light hydrocarbons, physical properties of reservoir rock, and NMR logging acquisition parameter. Dual TW has favourable results of typing gas and light oil (viscosity within 1-5 mPa.S) (Coates et al, 1999). When water zones with macropores are present in a reservoir, the presence of water signals in the differential spectrum could result in erroneous interpretation. Fig.1 is an example of NMR Dual TW logging from an oilfield. TW_L is 13s, and TW_s is 1s. The differential spectrum signals appeared in every zone in the figure (the eighth channel), but production test results (the ninth channel) indicate that they were water zones. The macropore throats are quite open, leading to a large T_1 for water. The short waiting time of 1s was not sufficient for the water to fully recover, which resulted in the appearance of water signals in Eq. (5).

3.2 Dual TE method

The dual TE method is based on different diffusion coefficients among oil, gas and water in a constant field gradient. The shift of T_2 amplitude distributions to shorter relaxation time is different for different fluids when long and short echo spacings are applied. For water wet rock in a constant field gradient, the T_2 relaxation rate of water $1/T_{2,w}$ is given as follows:

$$\frac{1}{T_{2,w}} = \frac{1}{T_{2B,w}} + \frac{1}{T_{2S,w}} + \frac{1}{12} \gamma^2 G^2 D_w (TE)^2 \quad (6)$$

where $T_{2B,w}$ is the T_2 of bulk water, $T_{2S,w}$ the T_2 of surface relaxation, G the constant field gradient, D_w the self diffusion coefficient of water, TE the spacing (or time) between echoes, γ the proton gyromagnetic ratio. By increasing TE , the T_2 amplitude distributions shift to a shorter relaxation time. Since the increase of the relaxation rate (the third term in Eq. (6)) is a constant, the shift of T_2 because of this diffusion term will become larger at long relaxation time but quite small at short relaxation time (Dunn et al, 2002).

Because oil is usually a nonwetting phase, its $1/T_{2,0}$ depends on the bulk $T_{2B,0}$, diffusion coefficients D_0 , the echo spacing TE , and the gradient strength G , i.e.:

$$\frac{1}{T_{2,0}} = \frac{1}{T_{2B,0}} + \frac{1}{12} \gamma^2 G^2 D_0 (TE)^2 \quad (7)$$

Fig. 1 An example for differential spectrum signals in water zones with Dual TW measurements

Notes: In this figure, the first channel includes gamma ray log, GR (red solid line), spontaneous potential log, SP (blue long dashed line), caliper log (black dotted line) and T_2 binary digit from long TW ; The second channel includes the permeability curve, PERM (green dot dashed line), deep lateral resistivity log, LLD (red solid line), shallow lateral resistivity log, LLS (blue long dashed line) and microresistivity log, MSFL (black dotted line). The third channel includes sonic log, AC (green solid line), density log, DEN (red dotted line) and neutron log, CNL (blue long dashed line). The fourth channel includes T_2 cutoff (red solid line) and standard T_2 spectrum. The fifth includes total porosity, MSIG (red solid line), effective porosity, MPH (green solid line) and capillary bound water porosity, MBVI (black solid line). The sixth channel is the long TW T_2 spectrum. The seventh channel represent the short TW T_2 spectrum. The eighth channel is the differential spectrum. The ninth channel is the production test result.

The diffusion coefficient of water, D_w is usually an order of magnitude higher than that of oil. Thus the diffusion term in the relaxation rate equation Eqs. (6) and (7) for water is much larger than that for oil. If the signals for water and oil overlap initially, a larger TE can often produce sufficient relative shift in T_2 and hence can help identify both oil and water signals. The diffusion coefficient of gas is often two orders of magnitude larger than that of water. The T_2 for gas is in the neighborhood of 40ms as shown in Table 1. Further increase in TE would shift the gas signal to the region of irreducible water. Besides, it is very hard to detect the effect of varying TE because the gas signal is very weak (Dunn et al, 2002). Hence, Dual TE is often used for typing oil and water, while dual TW can be used for oil, gas and water.

4 Two-dimensional NMR logging typing fluid methods

4.1 (T_2 , D) method

The new generation of NMR logging tools can acquire spin echo trains of multiple TE s. The echo amplitude $b(t, TE)$ can be shown as follows (Depavia et al, 2003; Chen et al, 2003; Xie, 2008):

$$b(t, TE) = \iint f(T_2, D) e^{-t/T_2} e^{-\frac{1}{12} \gamma^2 G^2 (TE)^2 D t} dD dT_2 + \varepsilon \quad (8)$$

where $b(t, TE)$ is the echo amplitude, $f(T_2, D)$ the two dimensional function, γ the gyromagnetic ratio. G the con-

stant magnetic field gradient, D the diffusion coefficient, TE the time between echoes and ε is the noise.

In the discrete form, Eq.(8) can be written as:

$$b_{ik} = \sum_{j=1}^m \sum_{l=1}^p f_{jl} e^{-t_l/T_{2j}} e^{-\frac{1}{12} \gamma^2 G^2 (TE_k)^2 D_l t_l} + \varepsilon_{ik} \quad (9)$$

where b_{ik} is the amplitude of i -th echo using TE_k , f_{jl} the number of hydrogen nuclei with diffusion coefficient D_l and at relaxation time T_{2j} , ε_{ik} the noise, m the number of relaxation times T_{2j} , and p the number of diffusion coefficients D_l , all equally spaced on their respective logarithmic scales. By inverting Eq.(9), we can obtain the 2D distribution function f_{jl} (Xie et al, 2009b).

4.2 (T_2 , T_1) method

The echo amplitude $b(t, TW)$ acquired with multiple periods of waiting time (TW) in a single logging pass can be shown as follows (Xie et al, 2009a; Xie, 2008; Xie et al, 2009b):

$$b(t, TW) = \iint f(T_2, T_1) e^{-t/T_2} (1 - e^{-TW/T_1}) dT_2 dT_1 + \varepsilon \quad (10)$$

where $b(t, TW)$ is the echo amplitude, $f(T_2, T_1)$ a 2D function, TW the waiting time between successive CPMG excitations, and ε is the noise.

In the discrete form, Eq.(10) can be written as:

$$b_{ik} = \sum_{j=1}^m \sum_{r=1}^n f_{jr} e^{-t_l/T_{2j}} (1 - e^{-TW_k/T_{1r}}) + \varepsilon_{ik} \quad (11)$$

where b_{ik} is the amplitude of i -th echo using TW_k , f_{jr} the number of hydrogen nuclei at transverse relaxation time T_{2j} and longitudinal relaxation time T_{1r} , and ε_{ik} the noise. m is the

preset number of T_{2j} relaxation time, n also the preset number of T_{1r} relaxation time assumed by the model, both equally spaced on their respective logarithmic scales. By inverting Eq.(11), we can obtain the 2D distribution function f_{jr} (Xie et al, 2009b).

4.3 Numerical simulation and result analysis

2D NMR logging can provide more information on multiple periods of waiting time or echo spacing time than 1D NMR logging in a single logging pass, both of which have been shown to greatly improve the capability of hydrocarbon typing (Xie et al, 2009a; Xie and Xiao, 2009). In this work, two kinds of reservoir are taken into consideration: gas-bearing water layer with movable water in big pores and oil-bearing water layer with movable water in big pores. These two different situations are simulated respectively in order to study the capability of 2D NMR logging fluid typing methods concerning the complex effect of both macroporous structures and different reservoir fluids.

Suppose the gas-bearing water layer is composed of irreducible water and gas and movable water in big pores, the distribution of each component in the (T_2 , D) chart assumes a Gaussian shape. We set the T_2 relaxation of irreducible water to be 10 ms and T_1 to be 30 ms with a saturation of 40%; the T_2 of movable water in big pores to be 1000 ms and T_1 to be 2000 ms with a saturation of 30%, the diffusion coefficient D to be $2.5 \times 10^{-5} \text{ cm}^2/\text{s}$ for both irreducible water and movable water; and the T_2 of gas to be 40 ms, T_1 to be 3000 ms and D to be $1 \times 10^{-3} \text{ cm}^2/\text{s}$ with a gas saturation of 30%. The field gradient G used in the simulation is 0.35 T/m. Fifteen sets of echo trains are generated with the time of echo spacings being respectively 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.6, 2.0, 2.4, 4.8 and 9.6 ms. Fig. 2 illustrates the (T_2 ,

Fig. 2 (T_2 , D) two-dimensional inversion results of a gas-bearing water layer with movable water in big pores at different SNRs

D) inversion results for the gas-bearing water layer with movable water in big pores at different SNRs with fixed G 0.35 T/m. It shows that the (T_2, D) method for fluid typing becomes much easier with the increase of SNR. Even though the SNR is less than 20, the movable water in big pores can be clearly distinguished. When SNR is less than 50, the (T_2, D) method cannot separate the irreducible water from gas. With the increase of SNR, the effectiveness of the (T_2, D) method for typing irreducible water and gas can be further improved, which can differentiate the overlapping T_2 signals of irreducible water and gas encountered in the use of the

dual TE method in 1D NMR.

Fifteen sets of echo trains are generated with the length of waiting time being 10, 30, 50, 70, 100, 300, 500, 700, 1000, 2000, 4000, 8000, 10000, 12000 and 15000 ms. Fig. 3 shows the (T_2, T_1) inversion results for this gas-bearing water layer with movable water in big pores at different SNRs. It shows that the (T_2, T_1) method can clearly distinguish gas, irreducible water and movable water in big pores, even though the SNR is less than 20. When Fig. 3 is compared with Fig. 2, the (T_2, T_1) method has more advantages in typing irreducible water and gas than the (T_2, D) method.

Fig. 3 (T_2, T_1) two-dimensional inversion results of a gas-bearing water layer with movable water in big pores at different SNRs

In a different situation, instead of gas we use medium viscosity oil with T_2 being 200 ms and keep the T_2, T_1 and D of irreducible water and movable water unchanged in big pores in the above model. The estimated viscosity of oil is about 14.7 mPa·s at 35 °C using the equation established by Lo et al (2000). Suppose the oil bearing water layer is composed of irreducible water, big pore movable water and oil. Assuming that the T_1 of oil is 400 ms, D being 2×10^{-6} cm²/s with oil saturation of 30%, fifteen sets of echo trains are generated with the time of echo spacings being 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.6, 2.0, 2.4, 4.8 and 9.6 ms with the simulated field gradient G being 0.35 T/m. Fig. 4 illustrates the (T_2, D) inversion results for the layer at different SNRs. It shows that the (T_2, D) method can distinguish irreducible water, movable water in big pores and medium viscosity oil, even though the SNR is less than 20. The effectiveness of the (T_2, D) method for typing fluids becomes better with an

increase of SNR. Comparing Fig. 4 with Fig. 2, the (T_2, D) method has more advantages in typing an oil-bearing water layer than a gas-bearing water layer when the SNR of data is low.

Fifteen sets of echo trains are generated with waiting times of 10, 30, 50, 70, 100, 300, 500, 700, 1000, 2000, 4000, 8000, 10000, 12000 and 15000 ms. Fig. 5 shows the (T_2, T_1) inversion results for this oil-bearing water layer with movable water in big pores at different SNRs. The results indicate that the (T_2, T_1) method can distinguish irreducible water, movable water and oil as long as the difference of T_2 between the movable water and oil is sufficiently large. Thus, the (T_2, T_1) method can resolve this particular situation where the dual TW method often mistakes water in big pores for oil. The (T_2, T_1) method can distinguish irreducible water and medium viscosity oil with a wider viscosity range than can be resolved by the dual TW method.

Fig. 4 (T_2 , D) two-dimensional inversion results of an oil-bearing water layer with movable water in big pores at different SNRs

Fig. 5 (T_2 , T_1) two-dimensional inversion results of an oil-bearing water layer with movable water in big pores at different SNRs

5 Conclusions

1) The dual TW method is effective in typing gas and light oil (viscosity from 1 mPa·s to 5 mPa·s). When water zones with big pores are present in a reservoir, the water signal will appear in differential spectra in the water zone due to the insufficiency of the short waiting time, resulting in an incorrect interpretation of a water layer as an oil layer.

2) The dual TE method is not suitable for typing gas and irreducible water because of the T_2 signals of irreducible water significantly overlapping that of the gas in the 1D T_2 distribution.

3) The (T_2, T_1) method is effective in typing gas layers. In an oil-bearing water layer with movable water in big pores, the (T_2, T_1) method can distinguish movable water, oil and irreducible water when their T_2 distributions are separate, which can solve the problem arising from an incorrect interpretation of a water layer in big pores as an oil layer due to the use of the dual TW method. The (T_2, T_1) method can distinguish irreducible water from medium viscosity oil and as a result, the viscosity range of oil which can be identified becomes wide in contrast with that of the dual TW method.

4) The (T_2, D) method is more effective than (T_2, T_1) in typing an oil and water layer. In a gas layer, when the SNR is higher than a threshold, the (T_2, D) method can resolve the problem of the overlapping T_2 signals of irreducible water and gas for the dual TE method which is encountered in 1D NMR.

5) Both the (T_2, D) and (T_2, T_1) methods use the contrasts in relaxation time and diffusion coefficients between water and hydrocarbon. They significantly improve the capability of fluids typing. This is the future direction of NMR logging for typing complex reservoir fluids.

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