



Research on Nuclear Magnetic Resonance Logging Inversion Method and Application

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Abstract. Nuclear magnetic resonance logging is an effective means of reservoir evaluation and has been widely used in oil and gas resources exploration and development. The traditional nuclear magnetic resonance logging application requires the inversion of the echo data first to get the inversion spectrum, from which then the required formation information is extracted. The evaluation of reservoir parameters, the prediction of capillary pressure curve and the micro-distribution of reservoir constraints and dynamic fluid are the three important aspects of nuclear magnetic resonance logging application. The existing application of nuclear magnetic resonance logging faces serious problems. In this paper, three methods of time-domain analysis are proposed, and the echo data is not required to be inverted to get the horizontal relaxation time (t_2) spectrum. The influence of inversion on the evaluation of the water saturation and permeability evaluation is avoided. Method 1 is the reservoir irreducible water saturation and permeability evaluation method based on echo data calibration. Method 2 is the reservoir of water saturation and permeability evaluation method based on the index hyperbola sinusoidal transformation. Method 3 is the reservoir permeability evaluation method based on the variable time domain characteristics parameter. Based on the prediction of the capillary pressure curve, this paper puts forward the prediction method of the capillary pressure curve based on the integral transformation-quantum genetic-neural network. The results of core rock experiment and nuclear magnetic resonance logging data showed that compared with the traditional nonlinear regression method, integral transformation, the traditional nonlinear regression method and the integral transformation, the integral transformation-the quantum genetic neural network method was the best method to predict the optimal effect of the capillary pressure curve.

Keywords: Nuclear magnetic resonance logging; Reservoir parameter evaluation; Capillary pressure curve prediction; Inversion; Microdistribution of fluids.

1 Introduction

1.1 Research Purpose and Significance

Nuclear magnetic resonance logging (NMR) has become one of the key techniques for reservoir logging evaluation to measure fluid signals directly in rock pores. With the deepening of exploration and development of unconventional oil and gas resources, nuclear magnetic resonance logging plays an increasingly important role, as well as facing many challenges. The research on the application basis of nuclear magnetic resonance logging and inversion methods has attracted much attention from scholars at home and abroad^[1]

Traditional NMR logging applications need to invert the echo data to obtain the inversion spectrum first, and then extract the required formation information from the inversion spectrum. However, the inversion of NMR echo data based on the first Fredholm integral equation is a serious pathological problem, the inversion results are not unique, and the measurement noise is very sensitive, especially in unconventional reservoirs, the uncertainty of NMR inversion spectrum is large, which leads to inaccurate reservoir evaluation. Reservoir parameter evaluation, transverse relaxation time (T₂) spectral conversion of capillary pressure curve, and characterization of the microscopic distribution of irreducible fluids are three important aspects in the application of NMR logging. The existing application of nuclear magnetic resonance logging faces the following problems: the impact of the nuclear magnetic resonance logging application is influenced by the uncertainty of the echo data inversion; The nuclear magnetic resonance logging interpretation model needs to be further optimized to adapt to the needs of the non-standard reservoir evaluation. For low signal-to-noise ratio echo data, the existing inversion method is large. The continuous quantitative representation of the microdistribution of formation and dynamic fluid is not achieved.

For reservoir parameter evaluation and capillary pressure curve prediction, most of the existing research methods are based on nuclear magnetic resonance inversion spectrum, which cannot eliminate the influence of uncertainty in the inversion of low-SNR echo data, while the time-domain analysis method is expected to directly extract reservoir information from the original echo data, and then establish a new reservoir parameter evaluation and capillary pressure curve prediction model to avoid the influence of uncertainty of echo data inversion. Therefore, this paper attempts to break through the traditional research ideas of NMR logging application methods, and develop reservoir parameter evaluation and capillary pressure curve prediction methods based on time domain analysis.^[2]

At present, the applications of NMR logging, such as reservoir fluid identification and microscopic distribution characterization, still rely on NMR inversion spectrum. The time domain analysis method is expected to extract the prior information from the original echo data to constrain the NMR inversion process, so as to improve the inversion accuracy. Therefore, it is necessary to explore the inversion method of NMR echo data based on prior information constraints.

The characterization of the microscopic distribution of reservoir bound and movable fluid is of great significance to reservoir evaluation and productivity prediction. Most of the existing studies are limited to the core rock scale in the laboratory, which cannot achieve continuous quantitative characterization of reservoir confinement and movable fluid microscopic distribution. Therefore, it is of great significance to study the characterization methods of reservoir bound and movable fluid microscopic distribution.

In summary, it is necessary to conduct further research on the application basis and inversion methods of NMR logging to promote the technical progress of NMR logging in reservoir oil and gas exploration.

1.2 Research Status at Home and Abroad

Research of NMR Reservoir Parameter Evaluation Methods.

Irreducible water saturation and permeability are important reservoir parameters, and the accurate determination of the irreducible water saturation permeability is of great significance for reservoir evaluation and productivity prediction.

(1) Irreducible water saturation Evaluation

At present, the evaluation methods of reservoir irreducible water saturation based on nuclear magnetic resonance mainly include T2 cutoff value method and non-cutoff value method.

The T2 cutoff value method can be divided into the single cutoff value method based on bimodal model and the gradual cutoff value method based on thin film model according to the different calculation models of irreducible water saturation. The non-cutoff value method does not need to determine the T2 cutoff value, but directly calculates the irreducible water saturation by statistical method^[3].

(2) Permeability Evaluation

Permeability is a key parameter of the ability of reactive fluid to flow through porous rock. Since the T2 spectrum measured by NMR can characterize the pore diameter distribution of porous rocks, relevant parameters can be extracted from the T2 spectrum to establish an empirical model for permeability evaluation.

In summary, irreducible water saturation and permeability evaluation methods based on time-domain analysis of NMR echo data can avoid the influence of T2 spectral inversion uncertainty, which shows a good application prospect. It is necessary to carry out further research on this kind of time-domain analysis methods.^[4]

Research of Capillary Pressure Curve Prediction Methods in NMR

Capillary pressure curve is one of the important means to investigate the petrophysical properties and pore structure characteristics of porous rocks. Previous studies had shown that there was a good correlation between the NMR T2 spectrum and the pore throat diameter distribution obtained from the capillary pressure curve, and the curve obtained by summing the normalized T2 spectrum from the long relaxation direction to the short relaxation direction (the cumulative amplitude was horizontal coordinate, and $1/T_2$ was longitudinal coordinate) was similar to the capillary pressure curve. The direct prediction method converted the reverse cumulative T2 spectrum into capillary pressure curve according to the scale conversion model of mercury

injection in core test results. The direct prediction method adopted simple linear scale model at the earliest, and had achieved good application effect in conventional reservoirs with relatively simple pore structure. The direct prediction method converted the reverse cumulative T2 spectrum into capillary pressure curve according to the scale conversion model of mercury injection in core test results. The indirect prediction method established the prediction model based on the multivariate statistical relationship between the characteristic parameters of NMR T2 spectrum and the capillary pressure curve. In recent years, Artificial intelligence algorithms represented by Artificial Neural Network (ANN) have provided an effective way to solve complex geophysical problems^[5].

2 Reservoir Parameter Evaluation Method Based on NMR Time-domain Analysis

Core samples of tight sandstone reservoir in 7 sections of Ordos Basin were selected for conventional helium porosity and permeability tests and nuclear magnetic resonance experiments. The PC-12B oil rock sample analysis centrifuge was used to centrifuge the sample for 1 hour at a speed of 9000r/min, so that it reached the irreducible water state. The core NMR was measured by the MARAN-DRX/2 NMR core analyzer produced by the Nuclear Magnetic Resonance Instrument Company of the United Kingdom. The test temperature was 35°C and the working frequency was 2MHz. The test parameters were as follows: echo interval was 0.3ms, waiting time was 8s, echo number was 4096, scan times were 128.

The rock core experimental measurement results were shown in Table 1 and Figure 1. Among them, the distribution range of porosity measurement was 4.71%~12.04%. The permeability measurements ranged from 0.0026 to 0.382mD. The measurement results of irreducible water saturation ranged from 52.51% to 86.11%. FIG. 2 showed the T2 spectrum obtained by inversion. According to Figures 1 and 2, the porosity and permeability of the study area were low, the irreducible water content was high, and T2 distribution was dominated by bimodal distribution with short relaxation components, which was a typical characteristic of tight sandstone reservoirs.

Table 1. Experimental Results of Tight Sandstone Samples

Core No.	Porosity (%)	Permeability (mD)	T_2 cut-off (ms)	S_{wb} (%)
1	8.63	0.0026	5.77	77.97
2	9.20	0.0167	22.98	74.28
3	9.27	0.0195	13.73	75.87
4	9.10	0.0028	9.10	75.39
15	10.26	0.0632	18.07	61.83
16	9.98	0.0547	19.09	70.26
17	10.71	0.1465	25.69	65.87
18	10.98	0.0887	13.79	56.68
19	12.04	0.1294	17.64	58.09
20	11.73	0.3817	23.00	54.61
21	9.42	0.0073	17.70	72.64
22	4.71	0.0028	6.48	76.26

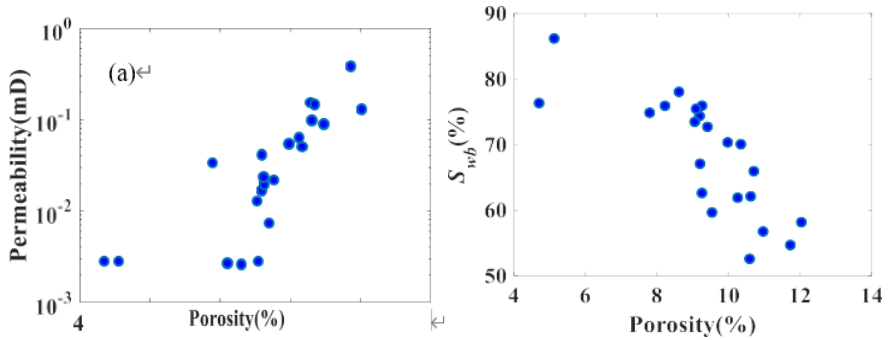


Fig. 1. The experimental results of samples. (a) Porosity vs. permeability; (b) Porosity vs. S_{wb}

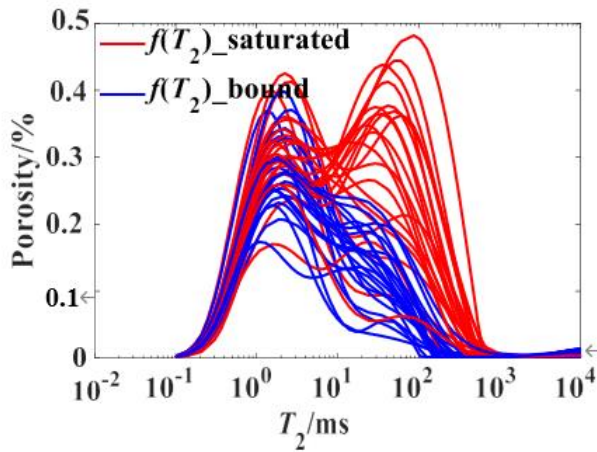


Fig. 2. The T_2 distributions of samples under fully brine-saturated condition and bound water condition

The T_2 cutoff values in Table 1 were obtained by comparing the cumulative T_2 distribution in saturated and irreducible water states. Figure 2 was the determination process of T_2 cutoff value of sample No. 19. The T_2 distributions in saturated water (red solid line) and irreducible water (blue solid line) states were added in the direction of T_2 from small to large, and the cumulative T_2 distributions in saturated water (red dashed line) and irreducible water (blue dashed line) states were obtained. Taking the maximum T_2 distribution of irreducible water accumulation as the starting point, a line parallel to the T_2 axis was drawn, and the T_2 value corresponding to the intersection of the line and the T_2 distribution of saturated water accumulation was the T_2 cut-off value corresponding to the core sample.^[6]

3 Capillary Pressure Curve Prediction Method Based on NMR Time-domain Analysis

3.1 Capillary Pressure Curve Prediction Method Based on Integral Transformation and Traditional Multiple Regression

The shape of capillary pressure curve is affected by many factors. Previous studies had shown that there was a correlation between non-wetting phase saturation (S_{nw}) and T2 distribution characteristic parameters when capillary pressure was given. At each pressure point, multiple regression method could be used to determine the functional relationship between S_{nw} and T2 distribution feature parameters, as shown in the following equation:

$$S_{nw,i} = F_i (P)$$

Where, i was the i th capillary pressure point and P was the characteristic parameter of T2 distribution. In traditional NMR petrophysical applications, the T2 distribution characteristic parameters used to characterize the properties of porous media were limited, and T2 arithmetic mean (T2am), geometric mean (T2lm) and cumulative porosity in different intervals were commonly used. However, capillary pressure curves were affected by many factors. In order to better characterize rock properties, seven sets of integral transform function pairs were constructed to extract rock information directly from echo data.^[7]

3.2 Logging Data Processing

The capillary pressure curve prediction method based on NMR time-domain analysis proposed in this chapter was applied to actual well data processing, and the processing results were shown in FIG. 3.15. The well section was a tight sandstone reservoir and the first line was a depth curve (DEPTH); The second was SP, CAL and gamma ray curves (GR); The third channel was density porosity curve (DEN), acoustic porosity curve (AC) and neutron porosity curve (CNL). The fourth track was T2 spectrum obtained by inversion (T2_DIST). The fifth and sixth methods were traditional multiple regression method (MICP_NEW1) based on integral transform-and capillary pressure curve predicted by integral transform-quantum genetic-neural network method (MICP_NEW2) respectively.^[8]

The seventh and eighth channels were based on two time-domain analysis methods (PD_NEW1, PD_NEW2) and displacement pressure (PD_CORE) obtained by core experiment, respectively. The ninth and tenth channels were based on two time-domain analysis methods (PC50_NEW1, PC50_NEW2) and the median saturation pressure (PC50_CORE) obtained from core experiments, respectively. By comparison, it could be seen that the displacement pressure and saturation median pressure calculated by the capillary pressure curve predicted by the integral transformation-quantum genetic-neural network method were more consistent with the measured results of the core experiment than those predicted by the integral transformation-

traditional multiple regression method. It was indicated that the method was superior to the integral transformation-traditional multiple regression method. This conclusion was consistent with the results of core experimental data processing.

4 Conclusions and Suggestions

In this paper, the inversion method of NMR data based on general prior information constraints was introduced. Firstly, one-dimensional and multidimensional response equations of NMR logging were introduced. Then, the time-domain extraction formulas of the prior information of NMR spectral inversion of one-dimensional, two-dimensional and three-dimensional spectra were derived respectively. Based on the objective function of L2 inversion method, a new inverse objective function was constructed with the prior information as the constraint conditions. Next, six sets of Laplace transform function pairs were constructed to extract six kinds of prior information from the echo data, and the six kinds of prior information were combined with numerical simulation for optimal combination, and the constraint effect of the optimized prior information on one-dimensional, two-dimensional and three-dimensional NMR inversion was explored. Numerical simulation and logging data processing results had showed that the NMR inversion method based on general prior information constraints was superior to the traditional L2 regularization inversion method, especially for the inversion of low SNR echo data.

The constructional extraction and optimal combination of prior information were two key steps in NMR inversion methods based on general prior information constraints. The results of the derivation of the extraction methods of the prior information of one-dimensional, two-dimensional and three-dimensional NMR spectral inversion showed that although the extraction methods of the prior information required for spectral inversion of different dimensions were different in the T2 domain, D-T2 domain, T1-T2 domain and D-T1-T2 domain, the extraction methods were the same in the time domain. The reason for this analysis was mainly because the functional forms of the constructed Laplace transform function pairs for extracting prior information were different in the T2 domain, D-T2 domain, T1-T2 domain and D-T1-T2 domain, while the functional forms in the time domain were exactly the same. All of them were univariate functions about time. The optimal combination process of prior information showed that different prior information had different noise resistance and different constraint effects on inversion. In this chapter, two optimization schemes of prior information were proposed. The purpose of the first optimization was to determine the values of unknown parameters in the constructed prior information according to the noise resistance of the prior information, and to preliminarily optimize the types of prior information. The purpose of quadratic optimization was to determine the prior information that could be used for constraint inversion according to the inversion constraint effect. After two prior information optimization, it was determined that the second and fourth of the six kinds of prior information extracted in this paper had stronger noise resistance and more obvious improvement on inversion results. Numerical simulation and actual well data processing results showed that

the L2+ method was superior to the L2 method, with higher spectral peak resolution and stronger fluid identification ability. Moreover, the method based on the two prior information constraints after optimization combined the advantages of the two prior information when constrained alone, and the inversion effect is optimal.

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