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Research progress on reservoir permeability calculation model of NMR logging

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Abstract

Permeability is an important reference standard of reservoir micro-seepage characteristics, which not only reflects the difficulty of oil and gas recovery, but also is an important parameter to determine the productivity. Therefore, in the process of oil and gas field development, it is very important to accurately calculate permeability. Reservoir permeability is not only related to macroscopic porosity, but also has a very important relationship with microscopic pore structure of reservoir. Nuclear magnetic resonance logging technology can reflect the characteristics of pore proportion and pore structure of reservoirs with different pore diameters. In order to give full play to the application of nuclear magnetic resonance logging in permeability evaluation of complex reservoirs. Through combing and summarizing, the permeability methods of NMR logging technology are divided into four categories: calculation method based on T2 spectrum shape, permeability based on pore size components, permeability calculation method based on pore structure, and composite method, and the advantages and limitations of these methods are analyzed, so as to provide ideas for permeability evaluation of complex reservoirs.

Keywords

Nuclear magnetic resonance logging, permeability, calculation method.

1. Introduction

Permeability is an important reference index of reservoir micro-seepage characteristics, which can provide effective reservoir evaluation information. It not only reflects the difficulty of oil and gas recovery, but also is an important factor to determine the productivity. Compared with conventional logging methods, nuclear magnetic resonance logging has incomparable advantages in porosity calculation, fluid identification and oil-gas bearing property, and has become a very important method for reservoir evaluation. In the evaluation of permeability, the permeability explained by NMR logging not only reflects the pore structure information of rocks, but also overcomes the shortcoming that the conventional logging method can not calculate the permeability accurately because it only considers the pore size and ignores the influence of different rock particle sizes [1]. With the improvement of nuclear magnetic resonance technology, it provides a new way for fine evaluation of reservoirs. Permeability is an important reference index of reservoir micro-seepage characteristics, which can provide effective reservoir evaluation information. It not only reflects the difficulty of oil and gas recovery, but also is an important factor to determine the productivity. Compared with conventional logging methods, nuclear magnetic resonance logging has incomparable advantages in porosity calculation, fluid identification and oil-gas bearing property, and has become a very important method for reservoir evaluation. In the evaluation of permeability, the permeability explained by NMR logging not only reflects the pore structure information of rocks, but also overcomes the shortcoming that the conventional logging method can not calculate the permeability accurately because it only considers the pore size and ignores the influence of different rock particle sizes [1]. With the improvement of nuclear magnetic resonance technology, it provides a new way for fine evaluation of reservoirs.

Nuclear magnetic resonance (NMR) technology constructs T2 spectrum based on the resonance signal of formation hydrogen nuclei, and the components of T2 spectrum can describe the size of pore size, and then obtain the volume of fluid in the formation, thus determining the permeability of the formation.

The calculation formula of permeability parameters is generally based on Kozeny-Carmen[2-3] formula. This formula combines the parameters of effective porosity, tortuosity and specific surface area with Darcy's law to calculate permeability:

$$K = \frac{\varphi_{eff}}{8\tau^2} r^2 \tag{1}$$

Formula, K is permeability. φ_{eff} effective porosity. τ is tortuosity. r is the capillary radius.

Kozeny-Carmen formula is developed on the concept of average radius of pore throat. Some scholars have found that [4-6] performs well in isotropic homogeneous porous rocks, but it is not effective for complex anisotropic porous rocks and is greatly influenced by experience.

Nuclear magnetic resonance logging data contains a lot of valuable information, mainly including total porosity, effective porosity, bound water volume of clay, free water volume, pore size distribution, oil and gas content and other information. Compared with conventional logging methods, NMR logging can reflect formation permeability on a microscopic basis, and the calculation accuracy is higher. At present, the methods of calculating permeability by NMR logging are very diverse. This paper systematically sorts out the calculation methods of NMR permeability, which provides strong support for accurately calculating reservoir permeability.

2. Calculation of permeability based on T2 spectral morphology

Based on the characteristic information of nuclear magnetic resonance in T_2 spectrum dimension, the quantitative relationship between permeability and T_2 geometric mean of nuclear magnetic resonance is established through a large number of NMR petrophysical experiments. Among them, there are two classical models for calculating permeability by nuclear magnetic resonance, namely Schlumberger laboratory model SDR[7] model which depends on pore size and Coates[8] model which depends on fluid saturation.

$$K = C_1 \times \phi^{\text{m1}} \times T_{2gm}^{n_1} \tag{2}$$

$$K = \left(\frac{\phi}{C_2}\right)^{m_1} \times \left(\frac{FFI}{BVI}\right)^{n_2} \tag{3}$$

Formula, ϕ is the total porosity of rock. T_{2gm} is the geometric average of T_2. FFI is the free fluid volume index. BVI is the volume of bound fluid (usually bound water) m_1, n_1, C_1, m_2, n_2, C_2 is a model parameter whose value is obtained from core sample data.

These two models can both show good results in conventional sandstone reservoir interpretation [9-11], so they are also commonly used models for calculating reservoir permeability by T_2 spectrum of nuclear magnetic resonance at present. Although the commonly used SDR and Timur/Coates models are more accurate, with the further development of oil and gas fields, the complexity of reservoirs has gradually increased, and the calculation based on single SDR and Timur/Coates models can no longer meet the actual production requirements.

In addition, Garcia and Heidari[12] used a fluid substitution method to convert the nuclear magnetic resonance T_2 spectrum of partially saturated water into the corresponding nuclear magnetic resonance T_2 spectrum distribution of fully saturated water rocks,and introduced shrinkage factors according to resistivity and dielectric constant, and established a new permeability calculation model, which improved the accuracy of nuclear magnetic resonance T_2 spectrum in evaluating permeability in hydrocarbon-bearing reservoirs.

The above-mentioned permeability calculation method is mainly based on the form of T_2, which is relatively simple. However, with the development of oil and gas exploration, how to simply distinguish different pore size components and obtain pore connectivity has become a major challenge for this method.

3. Calculation of permeability based on pore size components

The traditional view is that the higher the porosity, the better the permeability. However, with the appearance of low porosity and low permeability reservoirs, this view is contrary. In order to better adapt to the reservoirs with complex pore structures, researchers have focused on the nuclear magnetic resonance logging technology, and nuclear magnetic resonance logging has achieved good results in the evaluation of low porosity and low permeability reservoirs with complex pore structures.

Liu and Zhou et al. [13-14] put forward the "three porosity component percentage method" to evaluate reservoir porosity. Percentage of total porosity components in a certain range by pore size. Xu Feng et al. [15] based on the study of reservoir pore structure, used NMR logging data to provide a new idea for evaluating reservoir pore structure: three parameters S_1, S_2 and S_3 were extracted from T_2 spectrum, representing the percentages of three porosity components with T_2 relaxation time in the range of 1 ~ 10ms, 10 ~ 100ms and 100 ~ 10～100ms respectively, and based on this, a new permeability calculation method was proposed.

$$K = C_{new}\phi^{a_{new}}\left[S_3^{\beta new} + e^{AS_1} + e^{BS_2}\right] \tag{6}$$

Formula: C_{new}, α_{new}, β_{new},A,B are model parameters.S_1、S_2、S_3 is the proportion of small pore, medium pore and large pore components in the total porosity.

The key to the method of calculating permeability based on pore size components is to use the proportion of pore size, which breaks the limitation of traditional NMR logging permeability calculation models that their characterization accuracy of pore structure reflected by T_2 distribution in complex reservoirs is not enough. A more detailed description of pore structure is proposed to represent the contribution of different pore size distributions to permeability, thus improving the calculation accuracy of permeability.

4. Calculation of permeability based on pore structure

Because of the close relationship between reservoir pore structure and permeability, the relationship model between pore structure and permeability can be established. Both capillary pressure and nuclear magnetic resonance can reflect pore structure, so the relationship model between permeability and mercury injection parameters can be established by using mercury injection data, and then the relationship model between T_2 geometric mean of nuclear magnetic resonance and mercury injection parameters can be used to calculate reservoir permeability.

Li et al. [16] put forward the pore structure parameters combined by porosity, pore throat radius and sorting coefficient, established the statistical model of permeability and the pore structure parameters, and then calculated the reservoir permeability.

Cheng Zhigang et al. [17] compared a large number of core samples, which were tested by mercury intrusion and nuclear magnetic resonance logging, and pseudo capillary pressure curves. The displacement pressure is calculated by cubic spline difference function, the quantitative parameters representing pore structure are obtained, and the model for quantitative calculation of permeability is constructed according to the regional experience parameters. The model has good effect in tight sandstone reservoir.

$$\delta=\frac{\phi\times R_z}{p_d} \tag{7}$$

Formula: δ is a permeability interpretation model. R_z Is the throat radius of the mainstream hole. ϕ is porosity. P_d is the displacement pressure.

Xiao et al. [18-19] studied tight sandstone reservoirs and compared the traditional SDR model, Timur-Coates model, Swanson parameter [20] method and other methods, and found that Swanson parameter method performed well in tight sandstone reservoirs, but for reservoirs with low porosity and low permeability heterogeneity, it was not effective to calculate permeability by using conventional logging curves. At this time, the T_2 spectrum of nuclear magnetic resonance and capillary pressure conversion method can be used to continuously measure and curve capillary pressure in the whole interval, reflecting the advantages of pore throat structure and making a breakthrough in permeability calculation. After years of development, this method has become a more mature permeability calculation method.

5. Composite method for calculating permeability

In addition to the above three methods for calculating permeability based on nuclear magnetic resonance, domestic researchers have proposed a multi-disciplinary fusion method combined with experimental data to obtain more accurate permeability.

5.1. Permeability evaluation method based on spatial physical field distribution model

In order to analyze the permeability of ultra-low permeability sandstone reservoirs more accurately, Li Chaoliu et al. [21-22] combined the spatial physical field distribution model in meteorological research with nuclear magnetic resonance technology, introduced the pore spatial centralized distribution model C value, evaluated the low porosity and low permeability reservoirs, and proposed a new permeability calculation method. In the application of this method, attention should be paid to the influence of shale content and its distribution in pore space, and comprehensive research should be carried out with various data to improve the accuracy.

$$K_C=\beta C^{\alpha}\times\phi^2/S_{wirr}^{0.5} \tag{8}$$

Formula: K_C is the permeability calculated by the pore space centralized distribution model. α , β is the model parameter, S_{wirr} is the irreducible water saturation.

5.2. Permeability evaluation method based on artificial intelligence

In recent years, artificial intelligence technology [23-26] has been widely used in calculating reservoir permeability by nuclear magnetic resonance. Neural network and other algorithms are used to establish the relationship between the results of nuclear magnetic resonance data processing and permeability. It is mainly divided into the following three categories: the first category, based on neural network, uses genetic algorithm to select the nearest parameters and initial values for neural network, thus calculating the nuclear magnetic permeability. In the second category, a positive integration regularization improved neural network algorithm is used to evaluate reservoir permeability, which is combined with Adaboost integration algorithm, adaptive rainforest algorithm and improved BP(Back Propagation) neural network.

Thirdly, a new double neural network system composed of Bayesian neural network and artificial neural network can be used to calculate rock permeability. The above three methods have achieved remarkable results in the actual production process. Although the artificial intelligence model has higher calculation accuracy than the traditional Coates model, it also has limitations and requires a large number of training samples, which leads to an increase in experimental costs.

6. Conclusion and understanding

Permeability, as an important parameter to guide reservoir development, greatly affects reservoir productivity. Compared with other logging methods, the measurement results of NMR logging are basically unaffected by the rock skeleton, so it has unique advantages in interpreting reservoir parameters such as permeability. Through the integration and application of various models, the calculation method of nuclear magnetic resonance permeability has been gradually developed, which can be applied not only to conventional strata, but also to the evaluation of complex reservoirs. The wide application of these methods proves their effectiveness and provides a new idea for the evaluation of complex reservoirs.

In recent years, the method of calculating permeability by NMR is developing towards the direction of double cut-off value and D-T_2 two-dimensional NMR. Each method has its own advantages and limitations, and its application effect is different under different reservoir conditions. Therefore, the future research still needs to continue to explore the calculation method of nuclear magnetic permeability and its application effect under special reservoir conditions.

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