Journal of Petroleum Science and Engineering (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Research and application of the relationship between transverse relaxation time and resistivity index in tight sandstone reservoir

Guo Yu-hang*, Pan Bao-zhi, Zhang Li-hua, Fang Chuan-hui

College of Geo-exploration Science and Technology, Jilin University, Changchun 130046, China

ARTICLE INFO

Keywords:
Capillary pressure curve
Resistivity index
NMR T_2 spectrum
Fractal theory
Water saturation
Tight sandstone reservoir

ABSTRACT

This paper discusses the relationship among capillary pressure (P_C), nuclear magnetic transverse relaxation time (T_2) and resistivity index (I). The three parameters are related to the geometry of pore structure. We use the fractal concept to describe the relationship between T_2 and I.In addition, a new T_2-I model is established. 8 Cores from tight sandstone reservoir in China are selected to do experiments. The results reveal that the cores have continuous fractal dimension characteristics. Additionally, the fractal dimensions appear great differences in the different pore radius scales. Therefore, a piece-wise fitting method is adopted. We divided the pores into macropore, mesopore and micropore. Through the verification, our T_2-I model and piece-wise fitting method are feasible. An application example is also provided in this paper. Based on our researches, we adopt NMR logging data to obtain dynamic parameters of Archie's formula *b* and *n* for calculating water saturation in Tight Sandstone Reservoir. The comparison between our method and normal method demonstrated that our model is much better at matching the core water saturation.

1. Introduction

Capillary pressure curve, resistivity index and nuclear magnetic resonance measurement are very important experimental methods for researching the rock pore structure and electrical conductivity. The research of the relationship of the three rock physics parameters has been taken seriously in recent years. Both core nuclear magnetic resonance experiment and capillary pressure measurement experiment can evaluate the pore structure. In NMR experiment, when rock saturated with water, the transverse relaxation time (T_2) is proportional to the pore size (Chen et al., 2008). Capillary pressure (P_C) measured in experiment is two miscibility fluid pressure differences in the pore which has good corresponding relation to the pore radius. There are many studies of the transformation relationship between PC and T2, Coates et al. (2007) proposed that T2 and rock pore throat size distribution obtained by mercury injection experiment have a good correlation, through the appropriate conversion factor can be mutual conversion. A linear transformation method was applied to get pseudo capillary pressure curve by N. Li et al. (2013), Yakov and Wim L (1999) and Liu et al. (2003). He et al. (2005a, 2005b) and concluded that the relationship between T2 and the pore throat radius is a power function. Zhang and Weller (2014) used a fractal concept to describe the geometric structure and compare the fractal behavior of pore volume distribution investigated by capillary pressure curves and NMR.

Based on the notion that both the capillary pressure and resistivity are functions of saturation, a relationship between P_C and I can be established. Szabo (1974) assumed that the exponent of the relationship between capillary pressure and water saturation is equal to the exponent of the relationship between resistivity and water saturation, he propose a linear relationship between the resistivity index and capillary pressure. Li (2006) established a power law function between capillary pressure and resistivity index which has been widely used at present.

The current research on the relationship between T_2 and resistivity index (I) is scanty. Zhang et al. (2012) concluded that there is a power function relationship between T2 and I at the specific wetting phase saturation. Ge et al. (2012) proposed that T2 and I obey the scaling law when the saturation is greater than the irreducible water saturation. Bai et al. (2014) proposed a relationship between the two and calculated the corresponding coefficient. However, the existing research lacks the discussion and the application method of the influencing parameters.

In this paper, we want to establish a new T2-I model based on the relationship among T2, capillary pressure and resistivity index. We take low permeability cores from tight sandstone reservoir in China. The experimental results show that the relationship between Pc and I can't fit a straight line to the log-log plot. No uniform fractal dimension can be derived which is different from the phenomena showed in Li's

* Corresponding author.
E-mail address: 124563749@qq.com (G. Yu-hang).

http://dx.doi.org/10.1016/j.petrol.2017.01.034
Received 15 June 2016; Received in revised form 8 October 2016; Accepted 17 January 2017

paper (2006). Therefore, we adopt segmentation method to fit. Therefore, we set the pore radius which is greater than 1 μm as the macropore, the mesopore ranged from 1 μm and 0.03 μm, and the micropore is set as the pore radius below 0.03 μm. According to the classification of pore, the parameters of the new model need to be discussed. Through combining our new model with the Archie's formulas (the relationship between the resistivity index and water saturation), we can use NMR to obtain the parameters of Archie's formulas and water saturation. We show an application of our method and model. According to the theory above, it is possible to obtain the dynamic changes of resistivity index and parameters of Archie's formula by NMR logging in reservoir evaluation. We evaluate the tight sandstone reservoir of well M (located in the northwest of China, the Sulige area in the Ordos Basin), the dynamic saturation parameters are calculated by our method, and the result of the saturation is consistent with core data.

2. Theoretical background

2.1. Relationship between the capillary pressure (P_c) and the resistivity index (I)

In the Archie's formula put forward by Archie (1942), the relationship between the resistivity index and water saturation is shown as follows:

$$I = \frac{b}{S_w^n} = \frac{R_t}{R_0} \tag{1}$$

I is the resistivity index; b is the constant of the Archie's formula; n is the saturation index; R_t is the sample resistivity; R_O is the rock resistivity in the case of 100% water bearing; and S_w is the water saturation. In this study, the I - S_w curves are a single fractal dimension, and b and n are the fixed values throughout the saturation distribution.

The capillary pressure can be expressed as follows:

$$P_c = P_{nw} - P_w = \frac{2\sigma\cos\theta}{r} \tag{2}$$

Where P_{nw} and P_w are the pressures of the non-wetting phase and wetting phase fluids, respectively; P_c is the capillary pressure; r is the capillary radius; σ is the tension of the two-phase fluid boundary surface; and θ is the wetting angle. It is clear that the capillary pressure is inversely proportional to the capillary radius. The relationship between the capillary pressure and the saturation can be established through a mercury injection experiment.

Toledo et al. (1994) proposed that P_c is a function of saturation based on the fractal theory:

$$S_W \propto (P_c)^{-(3-D_f)} \tag{3}$$

Where D_f is the fractal dimension. Based on the fractal model of the porous media, the relationship between the capillary pressure and the resistivity index was given by Li (2006).

$$P_{cD} = I^{\beta} = \frac{P_c}{P_e} \tag{4}$$

β is the index related to the water-film thickness, which is the function of the fractal function D_f; P_{cD} is the dimensionless capillary pressure; and Pe is the threshold pressure.

2.2. Relationship between the capillary pressure (P_c) and the nuclear magnetic transverse relaxation time (T_2)

Researches on the relationship between P_c and T_2 are relatively abundant. The methods of using the T_2 distribution for transforming the pseudo capillary pressure curve mainly include linear method and power function method.

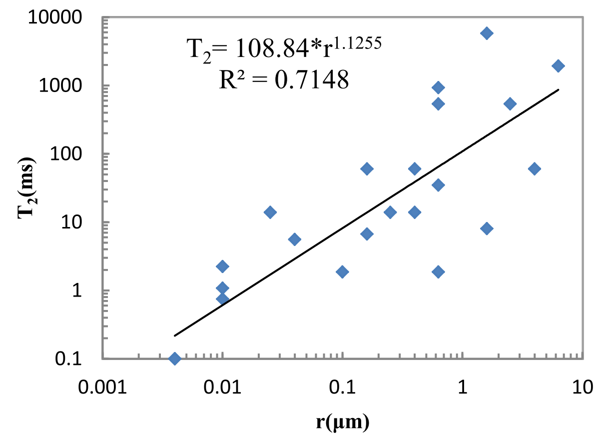

Fig. 1. The relationship between T_2 and the pore radius of cores in the study area.

In the linear method (Kleinberg et al., 1996; Yakov et al., 1999; Slijkerman et al., 2001; He et al., 2005a, 2005b), it is assumed that a linear relationship exists between P_C and the reciprocal of T_2 as detailed below:

$$P_c = \frac{2\sigma\cos\theta}{r} = \frac{C_l}{T_2} \tag{5}$$

In the equation, C_l is the linear transformation coefficient, and can be obtained by the core data analysis. The power function method is more frequently applied, and the relationship between T_2 and the corresponding capillary radius has been given by He et al. (2005a), and which was mentioned indirectly by Ge et al. (2012) as follows:

$$T_2 = m_t r^{n_t} \tag{6}$$

Where m_t and n_t are the empirical coefficients, obtained by the core data analysis. Fig. 1 displays the relationship between T_2 and the pore radius in our research area. It is obvious that the power function method is suitable for Tight Sandstone Reservoir. Therefore, the power function method has been used in this paper.

2.3. The new T_2-I model

Although the relationships between the T_2 and P_c, as well as between P_c and I, have been extensively studied, research on the relationship between the T_2 and I must be established and requires further development. By combining the previous research on the relationship between the capillary pressure and the resistivity index, the relationship between the T_2 and I was studied incorporating the fractal theory (Zhang et al., 2014). The pore volume distribution expression of the known space is shown as follows:

$$V \propto r^{3-D_f} \tag{7}$$

In the equation, V is the volume of the pores with the radius of r among rock samples; and this equation is used to derive r.

$$\frac{dV}{dr} \propto r^{2-D_f} \tag{8}$$

In accordance with the principle of fractal geometry, the integral was carried out on the above equation in order to obtain the expression of the cumulative pore volume V_r with a pore size less than r (Qin and Li, 2006; Zhang et al., 2007).

$$V_r = \int_{r_{min}}^{r} a_v r^{2-D_f} dr = b_v (r^{3-D_f} - r_{min}^{3-D_f}) \tag{9}$$

In the equation, r_{min} is the minimum pore radius of the reservoir rocks; and a_v is the proportionality constant $b_v = a_v/(3\text{-}D_f)$. The total pore volume V of the reservoir is as follows:

$$V = b_v (r_{max}^{3-D_f} - r_{min}^{3-D_f}) \tag{10}$$