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A New Method for Obtaining Irreductive Water Saturation and Other Parameters

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Abstract: The results show that the resistivity and water saturation data from a core obtained by core electrical experiments are power functions, which can reflect the conductivity characteristics of pore water in rock. Further research shows that when the resistivity data of power function shows a gentle change trend, it shows that the change of movable water pores affects the resistivity data, and when the resistivity data shows a drastic change trend, it shows that the irreducible water conductivity plays a leading role. Therefore, parameters such as irreducible water saturation and movable oil saturation can be determined from the morphological changes of the curve, just as the porosity lower limit of rocks can be determined. Compared with the irreducible water saturation data obtained by mercury injection and other data, a new method is proposed to determine the irreducible water saturation of a core by the cutoff value of slope of power function curve, and the movable oil saturation can be determined by the maximum curvature value of power function curve, which can further obtain the residual oil saturation. The preliminary application shows that the absolute error of irreducible water saturation and other parameters is within 5% and can be used in practice.

Keywords: Core Electricity Experiment Data, Data Analysis, Power Function, Irreducible Water Saturation, Movable Oil Saturation

1. Introduction

Irreducible water saturation and movable oil saturation are important parameters of oil and gas field development, which play key roles in evaluating oil field original reserves and recoverable reserves, identifying low resistivity reservoirs and calculating reservoir permeability [1-4]. Currently, reliable irreducible water saturation and movable oil saturation data are obtained mainly through core experiments and NMR logging [5-8]. However, the cost of NMR logging is high, so it is difficult to popularize it. There are many methods to determine irreducible water saturation in core experiments, such as mercury injection, high pressure semi permeable plate, etc., but it is impossible to do experiments in every layer and every block, and insufficient data often occur in actual use. At the same time, conventional logging data can be used to evaluate irreducible water saturation and movable oil saturation, but the accuracy is worse than that obtained by laboratory analysis and nuclear magnetic logging [9-11]. Therefore, it is very important to explore the method of determining irreducible water saturation with limited data.

Through the analysis of single core electricity experiment data, the relationship between core resistivity and water saturation data is power function. This relationship can be verified by archie's formula [12], which holds that the resistivity when the reservoir contains oil and gas is proportional to the resistivity when the reservoir is full of water, and its proportional coefficient is called resistivity index, denoted by I. Can be expressed as:

$$I = \frac{Rt}{Ro} = \frac{b}{Sw^n} \tag{1}$$

For a single rock sample, Ro is a constant, and it can be concluded that:

$$Rt = \frac{Ro*b}{Sw^n} = \frac{c}{Sw^n} \quad (2)$$

Where: Rt is the resistivity when the reservoir contains oil, Ro is the resistivity when the reservoir is full of water, b, c and n are constants.

It can be seen that the relationship between resistivity and water saturation of a single rock sample is a power function. The method of determining irreducible water saturation and movable oil saturation by using this relation is proposed. The practical application shows that the accuracy of irreducible water saturation and movable oil saturation calculated is high, and the absolute error is within 5% compared with core mercury injection data and NMR logging data, which can meet the application requirements.

2. Method Principle

Logging core electricity experiment is a core measurement conducted to provide calculation parameters for archie formula. The process is as follows:

Firstly, the rock samples after oil washing are soaked in aqueous solution configured according to formation water salinity, and then the water-bearing pore volume of the rock samples is reduced by high pressure gas displacement. The resistivity changes and water-bearing saturation changes are recorded by measuring each rock sample for 4-8 times. After the measurement of all rock samples of the same lithology and different pores in a block or a well is completed, regression of all measured data is carried out in the log-log coordinates to obtain the rock-electric parameters a, b, m and n.

For a rock sample, the regression relationship between measured resistivity and water saturation shows that these data are power functions. The Figure 1 shows the regression relationship between the measured resistivity and water saturation data of a single rock sample in different blocks. It can be seen that, no matter whether the porosity is high or low, or whether the lithology is the same, all the best relations are in the form of power function, and the correlation coefficient is above 0.99. There is no doubt that the core resistivity measured during the experiment has a power function relationship with the water saturation data.

Since the pore movable water was displaced by high-pressure gas during the measurement, these measurements can reflect the structural characteristics of the pores in the rock. As a complete power function curve (Figure 2), it can be seen that, with the process of gas-water displacement, when the water saturation gradually decreases from 100%, the resistivity curve shows a gentle change trend. When water saturation decreases to a certain extent, the trend of resistivity curve changes significantly. At the back of the curve, the resistivity curve changes dramatically. According to the analysis, in the initial stage of displacement, the pore water of movable oil which is easy to be displaced influences the change of resistivity. In the subsequent stage of displacement, it is difficult for the residual oil pore water to be displaced to affect the change of resistivity and continue the displacement process until the pore water is bound. Therefore, in the initial stage of displacement, the change of movable water pores affects the resistivity curve, leading to a flat change in the resistivity curve. In the subsequent stage of displacement, residual oil pore water and bound pore water play a leading role, leading to a drastic change in the resistivity curve.

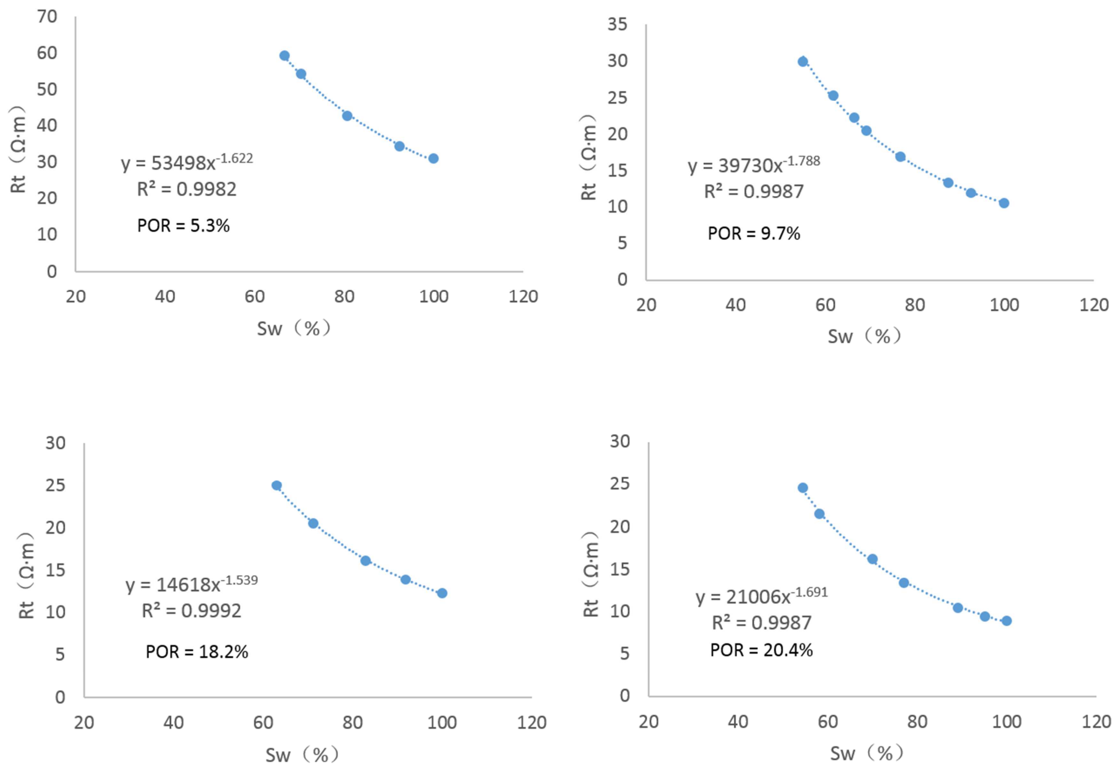

Figure 1. *Relationship between measured resistivity and water saturation in cores with different porosity.*

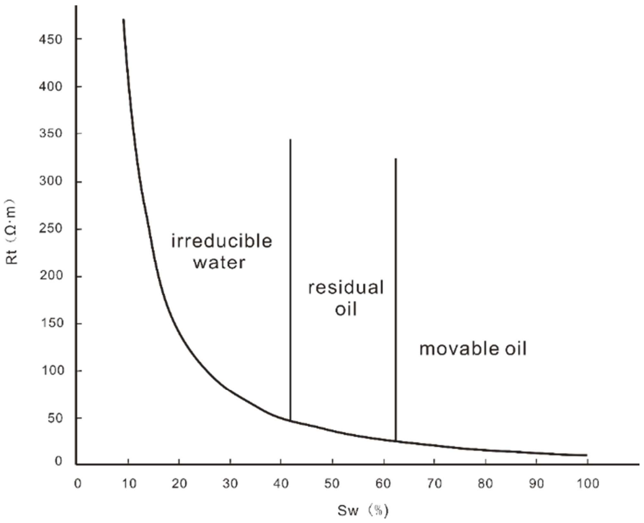

Figure 2. *Schematic diagram of irreducible water saturation and movable oil saturation determined by power function curve.*

Therefore, parameters such as irreducible water saturation and movable oil saturation can be determined from the morphological changes of the curve, just as the porosity lower limit of rocks can be determined. Based on the above analysis, a method is proposed to determine irreducible water saturation, movable oil saturation and residual oil saturation according to the power function curve of resistivity and water saturation. The schematic diagram of this method is shown in Figure 2.

3. Determination of Irreducible Water Saturation

The measured data of a single core shows that the relationship between resistivity and water saturation is a power function, and the function expression is:

$$y = cx^d \tag{3}$$

Where: x represents core water saturation, y represents core resistivity with water saturation change, and c and d are constants. Here, c is a positive number greater than 0, and d is a negative number less than 0. You can see that this curve has no inflection point, but the slope of the curve changes point by point. The calculation results of the actual data show that the slope is all negative. By comparing the irreducible water saturation with mercury injection data and nuclear magnetic logging data, it can be determined that the power function curve with a slope of -1.55 in a certain block is the irreducible water saturation of the core. Therefore, the irreducible water saturation of rock samples is calculated as follows:

Let's take the first derivative of the power function, then:

$$y' = cdx^{(d-1)} = -1.55 \tag{4}$$

$$x = 10^{\frac{\log_{10}\frac{-1.55}{cd}}{d-1}} \tag{5}$$

The calculation result of the above equation is the irreducible water saturation Swi of the core.

Determination of movable oil saturation and residual oil saturation

Although there is no inflection point, the curve of the relationship between resistivity and water saturation has a maximum point of curvature. The water saturation of this point can be determined as movable oil saturation by comparing with movable oil saturation determined by NMR logging data. The recoverable reserves of the reservoir correspond to movable oil, and the calculated movable oil saturation is about 80% of the oil saturation, which has been confirmed by a lot of data [13, 14].

According to the curvature calculation formula, the method to determine the movable oil saturation is as follows:

$$k = \frac{|y''|}{(1+y'^2)^{3/2}} \tag{6}$$

Here, k is the curvature of the power function curve, y′is the first derivative of the power function curve, y” is the second derivative of the power function curve. The curvature expression of the power function curve is:

$$k = \frac{|cd(d-1)x^{(d-2)}|}{\left(1+c^2d^2x^{(2d-2)}\right)^{3/2}} \tag{7}$$

Where, c and d are constants. When the first derivative of above equation is zero, the curvature has the maximum value, and it can be concluded that:

$$x^{(2d-2)} = \frac{d-2}{(2d-1)c^2d^2} \tag{8}$$

$$x = 10^{\frac{\log_{10}\frac{d-2}{(2d-1)c^2d^2}}{2d-2}} \tag{9}$$

Here, x is the water saturation corresponding to the movable oil saturation, so the movable oil saturation Som is:

$$s_{om} = 100 - x \tag{10}$$

Where Som is movable oil saturation and x is water saturation corresponds to movable oil saturation.

The region between movable oil saturation and irreducible water saturation is the residual oil region. The residual oil saturation can be calculated as follows:

$$s_{or} = 100 - S_{\mathrm{om}} - S_{wi} \tag{11}$$

Where Sor is residual oil saturation in % and Swi is irreducible water saturation in %.

4. Examples of Application

Using the above methods, the core data of Jizhong depression in north China were applied and analyzed. A total of 16 Wells were drilled in one block, 126 samples of core electricity experiment data, 5 rock samples of mercury injection data, and a nuclear magnetic logging data. Select 5 core samples with relevant data to calculate their irreducible water saturation and movable oil saturation. Figure 3 is an example of two core samples with porosity of 17.5% and 7.3%, the irreducible water saturation and movable oil saturation calculated results of one sample with porosity 17.5% are 46.4% and 43.5%, another are 57.2% and 30.6%. Compared with mercury injection and nuclear magnetic logging data, the absolute errors are all less than 5%. The comparative analysis of the calculation results of five samples is shown in table 1. It can be seen that it can meet the practical requirements.

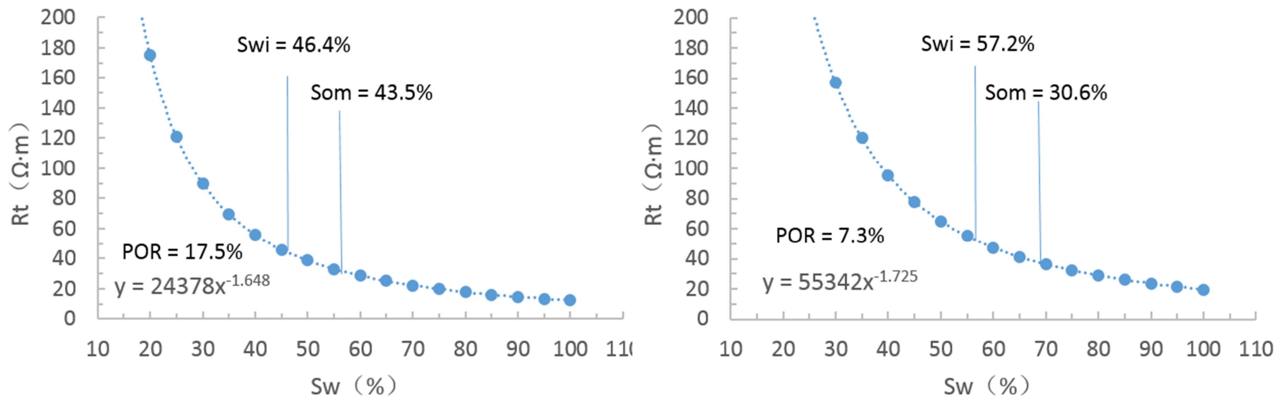

Figure 3. *Examples of irreducible water saturation and mobile oil saturation are determined using core electricity experiment data.*

Table 1. *The error analysis of Swi determinated by core electricity experiment data and mercury injection data.*

depth	core por	core k	Coefficient		Swi by mercury injection	Swi and Som by core electricity experiment data		absolute errors of Swi
m	%	mD	c	d	%	Swi (%)	Som (%)	%
2436.2	20.5	23.8	17536	-1.518	44.0	48.1	41.2	4.1
2439.7	17.5	31.5	24378	-1.648	45.8	46.4	43.5	0.6
2516.5	16.8	4.79	26695	-1.615	48.9	50.1	39.0	1.2
2522.8	9.5	1.37	33652	-1.666	53.9	51.3	37.7	-2.6
2537.1	7.3	0.976	55342	-1.725	59.6	57.2	30.6	-2.4

Rock electricity experiment data due to submit reserves, every oilfields or blocks has a large number of data, This method provides a new source for the determination of irreducible water saturation and movable oil saturation, and provides a new basis for the calculation of irreducible water saturation and movable oil saturation. It is helpful to improve the accuracy of reservoir permeability calculation, provide reliable irreducible water saturation data for identifying low resistivity reservoirs, and provide effective parameters for the preparation of oilfield development plan and improvement of oilfield development effect.

5. Conclusions

The resistivity of a single rock sample measured by rock electrical experiment has a power function relationship with water saturation. The flat variation trend reflects the conductive characteristics of pore water of movable oil. The slightly drastic variation trend reflects the conductivity characteristics of pore water of residual oil. The drastic variation trend reflects the conductive characteristics of bound pore water.

There is a certain theoretical basis for determining irreducible water saturation and movable oil saturation by using the power function relation of the core electricity experiment data of a single rock sample.

However, this method only relies on a small amount of sandstone data from oil fields, and the determined parameters are not necessarily universal. In the application of other oilfields, the parameters should be recalibrated according to the data of their own oilfields. In addition, for different lithology, such as limestone, data analysis and verification should be carried out again to ensure the reliability of calculation results.

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