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Calculation of water-flooded layers oil saturation based on modified Archie model

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ABSTRACT

Archie model is the basis of calculating oil saturation, but there are some limitations when using this model to calculate oil saturation in water-flooded layer. The main reason is that the main parameters, such as rock resistivity and formation water resistivity, are constantly changing dynamic parameters in the underground with the influence of injected water. Considering that water-flooded layers changes with injection waters, influence factors of rock resistivity and formation water resistivity of primary parameters are analyzed. Considering the dynamic data of water cut is the most reactive underground fluid characteristics of real information, combined with dynamic and static, and the "double ratio" model of later development by the same sedimentary layer is established, which realizes the inversion of rock resistivity and formation water resistivity, then modified Archie model relating to water-flooded layers of the same sedimentary explaining formation. The explanation of actual data indicates that the "double ratio" model well considers the dynamic variation of production data, which makes the inversion of the flooded rock resistivity relatively accurate, besides, the modified Archie model can accurately calculate the oil saturation of water-flooded layers with a reasonable result, which offers scientific basis for the predicting of remaining oil distribution rules.

Keywords: Modified Archie model; Water-flooded layers; Oil saturation; "Double ratio" model; the same sedimentary layer

1. Introduction

In the field of geophysical exploration technology, water-flooding is one of the main ways to recharge formation energy [1-2]. From the initial stage to the middle stage, then to the later stage, with the increase of injected water, the oil saturation of oil reservoir changes, and the reservoir is gradually flooded. The change of oil saturation in water-flooded reservoir will have a great impact on the development measures of remaining oil [3-7]. The calculation of oil saturation in water-flooded layers has always been a difficult problem for geologists. In reason is that the interpretation process relies too much on empirical formula and ignores the influence of reservoir lithology, physical property, oil-bearing property and electrical property changes on the original model in the process of water injection development [8-11]. To improve the logging interpretation accuracy of water-flooded layers, according to the variation law of resistivity and spontaneous potential curve, Yin-Jun Gao et al., [12] used fuzzy comprehensive evaluation method and fractal dimension method to qualitatively identify water-flooded layers, and achieved certain static effect. Xiong-Yan Li et al., [13] introduced data mining technology to establish an efficient model for predicting reservoir water-flooded layers degree from the perspective of domain drive, according to the changes of rock properties after water flooding and the logging response characteristics of water-flooded layers. Jing-Long Lin et al., [14] used image processing technology and fuzzy neural network to identify and describe water-flooded layers. At present, the prediction of remaining oil distribution is only on the static level. There are still many technical difficulties in how to realize the real integrated comprehensive research between interpretation model and processing to improve the interpretation accuracy.

Calculation of oil saturation of water-flooded layers is a dynamic process, and the water cut of production material is the real information that can reflect the dynamic state of underground fluid in water-flooding oilfield at present [15-18]. How to use water cut to calculate oil saturation of water-flooded layers provides a breakthrough point for people to solve the problem. Based on the analysis of water cut data, an appropriate formation model can be established to calculate the oil saturation of water-flooded layers with dynamic distribution. By analyzing the dynamic changes of main parameters of Archie model, the dynamic calculation method of rock resistivity and formation water resistivity is proposed. Based on Archie model, the Archie model is modified, and the oil saturation of water-flooded layers is accurately calculated, which provides scientific basis for predicting the distribution law of remaining oil. The aim of stabilizing oil production and controlling water and improving oil recovery in water-flooding oilfield is achieved.

2. The limitation of Archie model

Archie model, which is widely used at present, is the basic model for calculating oil saturation. This model is suitable for the static conditions of oil and gas migration and accumulation, that is, oil saturation can only be calculated accurately in the state of displacement of water with oil [19]. However, the water-flooded layers is always in the dynamic environment of water driving oil, so the calculation of oil saturation of water-flooded layers by Archie model is bound to cause certain limitations [20].

Compared with the original oil-gas reservoir, the water-flooded layers is different in three aspects: 1) the interpretation of water-flooded layers has strong timeliness, and its oil saturation is a dynamic process of constant change. 2) the lithology, physical property and electrical property of water-flooded layers are also constantly changing, which will also cause the change of oil saturation calculation. 3) there is a fluid in the water-flooded layers that has never existed in the original state, Moreover, the fluid itself varies with various factors (fresh water, sewage, mixed water, etc.).

When Archie model is used to calculate oil saturation, it is found that the calculated value of oil saturation varies greatly with the degree of water flooding and the property of injected water. It is mainly manifested as [21-24]: ① In the case of fresh water injection, the resistivity of water-flooded layers generally changes in "U" shape; in the case of sewage injection, the resistivity changes mainly in "L" shape; the relationship between rock resistivity and oil saturation is that one rock resistivity value corresponds to two oil saturation values, but the real oil saturation is still unknown. ② The salinity of injected water and formation water is different, As a result, the formation water resistivity changes with the increase of injected water. At this time, the formation water resistivity should be the resistivity of mixed filtrate, and it is also a variable parameter. ③ Under the action of injected water, the lithology and physical properties of the reservoir are changed, resulting in the change of porosity, which affects the calculation of oil saturation, and the change of porosity generally presents the phenomenon of polarization, that is, the reservoir with better physical property will increase the porosity, while the reservoir with poor physical property will have a better physical property, the porosity is basically unchanged or decreased.

Archie's classic model:

$$Sw = \sqrt[n]{\frac{a \cdot b \cdot Rw}{Rt \cdot \varphi^m}} \tag{1}$$

$$So = 1 - Sw \tag{2}$$

Where: R_w is the resistivity of formation water; R_t is the resistivity of rock; Φ is the porosity, %; m is the cementation index; n is the saturation index; a, b, m, n are the rock electrical coefficients, which are controlled by the pore geometry including pore type, shape and connectivity.

Archie model considers that the oil saturation is controlled by formation water resistivity R_w, rock resistivity R_t, porosity Φ and rock electrical coefficient, among which the rock electrical coefficient is only related to lithology, and the data can be accurately obtained through core sampling and rock electrical experiment.

Then, the oil saturation is determined by rock resistivity, formation water resistivity and porosity, Expressed as a mathematical function:

$$So = f(Rt, Rw, \varphi) \tag{3}$$

From formula (3), it can be considered that the calculation of oil saturation of water-flooded layers can be attributed to the inversion of rock resistivity, formation water resistivity and porosity. Because the change of porosity is small, this paper does not discuss the change of porosity, and the porosity value is calculated by acoustic transit time logging.

3. Establishment of modified Archie model

3.1. Determination of rock resistivity

3.1.1. Influencing factors of rock resistivity

There are three main factors affecting rock resistivity [25-26]: 1) the tortuosity of current conduction path, mainly including coordination number, pore radius, throat radius and other parameters; 2) characteristics of conductive phase in rock, including formation water resistivity, water film thickness and equilibrium ion concentration in the electric double layer; 3) distribution characteristics of conductive phase in rock pore, i.e. interface characteristics between conductive phase and rock pore wall, It reflects the continuity of irreducible water film on rock surface.

The conduction of ions in pore solution is the main method in real sandstone reservoir,

The conductivity of porous media is controlled by pore structure, pore volume and relative volume content of conductive liquid, Archie summed it up as

$$F = \frac{Ro}{Rw} = \frac{a}{\varphi^m} \tag{4}$$

$$I = \frac{Rt}{Ro} = \frac{b}{S_w{}^n} \tag{5}$$

Where, F is the formation factor and I is the resistivity increase rate.

The factors affecting the electrical properties of rocks can be reflected in the length of the conduction path of current in porous media and the flow process of current in different pore channels. Generally, the ratio of the actual length of the channel to the geometric length L of the porous medium is defined as the tortuosity τ. In fact, the tortuosity τ is the concentrated reflection of the conductivity of the porous medium per unit length[18]. Therefore, formula (4) can be converted into the following formula:

$$F = \frac{\tau^2}{\varphi} \tag{6}$$

Then combined with formula (1), rock resistivity RT can be expressed as follows:

$$Rt = \frac{Rw \cdot \tau^2}{\varphi \cdot Sw^n} \tag{7}$$

At present, the water cut of production data is the real information that can best reflect the dynamic state of underground fluid in oil field. Generally, water cut is obtained by relative permeability of oil and water, Its equation expression is:

$$Fw = \frac{1}{1+\frac{Kro \cdot Uw}{Krw \cdot Uo}} \tag{8}$$

Where Kro is the relative permeability of oil; Krw is the relative permeability of water; Uo and Uw are the viscosity of oil and water under underground conditions.

Oil water relative permeability is generally calculated by water saturation, residual oil saturation and irreducible water saturation, Its equation expression is:

$$Kro = a \cdot (1 - Sw - Sor)^2 - b \cdot (1 - Sw - Sor) + c \tag{9}$$

$$Krw = m \cdot (\frac{Sw - Swi}{1 - Swi - Sor})^n \tag{10}$$

Where: Sor is residual oil saturation; S_{wi} is irreducible water saturation; a, B, C, m, n are constants.

The residual oil saturation is generally calculated by irreducible water saturation, which shows a linear relationship. The irreducible water saturation is exponentially related to porosity:

$$Sor = a \cdot Swi + b \tag{11}$$

$$Swi = m \cdot e^{n \cdot \varphi} \tag{12}$$

In conclusion, water saturation S_w and porosity Φ determine water cut F_w according to formula (8 ~ 12), Its relationship is expressed as a mathematical function:

$$Fw = f(Sw, \varphi) \tag{13}$$

Combined with formula (7), then:

$$Rt = f(Fw, Rw, \tau, \varphi) \tag{14}$$

If the elastic change of fluid and rock skeleton is not considered, there is a direct relationship between rock resistivity and water cut.

3.1.2. "Double rate ratio" model

According to the different sedimentary types of sand bodies in the study area, the logging information of different periods drilled on the same sedimentary type sand body is counted, and the relationship between them is analyzed, and the accurate evaluation is carried out. In the process of actual data processing, it is found that for the same sedimentary facies interpretation layer, the initial resistivity value R_0 of different sand bodies is different. In order to eliminate the influence of too large or too small initial value R_0 and enhance the effect of resistivity, the method of resistivity ratio is used to simulate the water cut with appropriate

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mathematical method, The method of facies control constraint is put forward to establish the "water cut resistivity ratio" model of the same sedimentary type.

The specific methods are as follows:

In Figure 1, A, B, C and D represents sand bodies of different sedimentary types. For the same type of sedimentary sand body, the resistivity of the first drilled sand body is recorded as R_0, and the initial resistivity and initial water cut of wells drilled in other periods are recorded as Rt and F_w, Then the sequence according to the drilling time is as follows:

A1(R_{t1},F_{w1})、A2(R_{t2},F_{w2})、…、Ai(R_{ti},F_{wi}) i=1,…,n

To eliminate the influence of original resistivity, then:

$$Rt' = \frac{R_0 - Rt}{R_0} \tag{15}$$

(R_t', F_w) regression analysis was carried out to establish the relationship between them, then:

$$Rt = R_0 - R_0 \cdot f(Fw) = R_0[1 - f(Fw)] \tag{16}$$

Through the current water cut data of the study area, the current resistivity of the rock can be calculated.

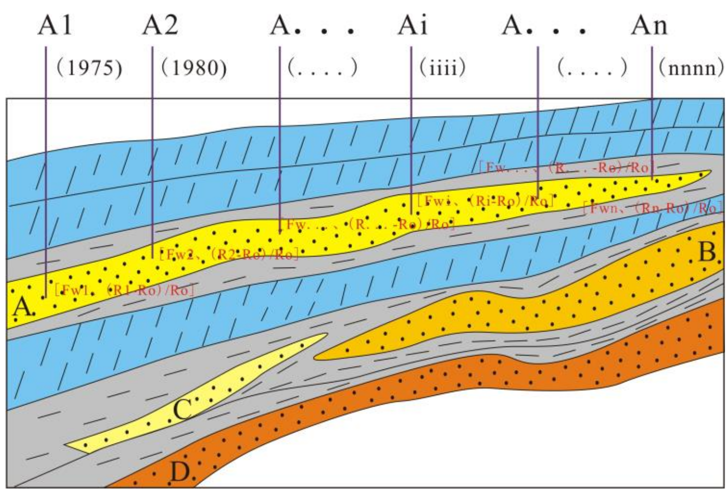

Figure 1. Geological basis of "double rate ratio" model

3.2. Calculation of formation water resistivity

The formation water resistivity of water-flooded layers should be the combination of original formation water resistivity and injected water resistivity, which is the resistivity of mixed filtrate. If the elastic changes of fluid and rock skeleton are not considered, it can be considered that the main factor affecting formation water resistivity is the salinity of formation water [25,27-30]. That is to say, the formation produced fluid is only caused by the formation injected water, and it is assumed that the injected water and the original formation water are fully ion exchanged and mixed in the process of water injection. Therefore, for water-flooded reservoirs, the correct calculation of formation mixture resistivity mainly depends on the salinity of injected water, original formation water salinity, injected water volume and liquid production, etc. then the formula for calculating the salinity of the mixed liquid is as follows:

$$Pz = \frac{k(Sw - Swi)pj + Swi \cdot pi}{k(Sw - Swi) + Swi} \tag{17}$$

Among them:

$$k = \frac{Qin}{Qout} \tag{18}$$

Where: S_w is the current water saturation; S_{wi} is the irreducible water saturation; P_j is the salinity of injected water; P_i is the salinity of original formation water; k is the injection water coefficient; Q_{in} is the total injected water volume and Q_{out} is the total liquid production.

According to P_z, the resistivity of formation mixture R_{wz} is calculated by using the iterative method of mineralization degree:

$$Rwz = \frac{0.55965 + \frac{165968.07}{Pz^{0.995}}}{t + 21.5} \tag{19}$$

Where t is the temperature, ℃ is related to the depth.

4. Oil saturation calculation

The above analysis shows that the key to the calculation of oil saturation in water-flooded layers is the calculation of formation mixed fluid resistivity (R_{wz}) and reservoir rock resistivity (R_t).

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Taking braided channel sand body of ×× oilfield as an example, water injection was started in 1978 for sewage reinjection. As of March 2021, the daily oil production level was 300.4t/d, the daily water yield was 2986.5t/d, and the comprehensive water cut was 90.9%. It entered the stage of high to ultra-high water cut. At present, the oilfield has been flooded seriously. Because the oilfield is mainly sewage reinjection, the rock resistivity changes mainly in the "L" shape. Eight wells drilled in different periods of this sand body are selected. The first well is 1 well drilled in 1987, and its initial resistivity R_0 is 29.303 Ω· m. the initial resistivity, initial water cut and current water cut of each well are calculated (Table 1).

Table 1. Statistics of well parameters of braided channel facies sand body in ×× Oilfield

Well name	Horizon	Sedimentary type	time	Initial resistivity (Rt)	Resistivity ratio (Rt')	Original water cut (F_w)	Current water cut (F_w)
Well 1	$E_2s_1^{6-2}$	Braided channel	1987	29.303	-	-	-
Well 2	$E_2s_1^{6-2}$	Braided channel	1987	22.89	0.219	0.084	0.915
Well 3	$E_2s_1^{6-2}$	Braided channel	1990	17	0.42	0.493	0.939
Well 4	$E_2s_1^{6-2}$	Braided channel	1991	14.18	0.516	0.612	0.709
Well 5	$E_2s_1^{6-2}$	Braided channel	1994	13.56	0.537	0.726	0.941
Well 6	$E_2s_1^{6-2}$	Braided channel	1996	3.76	0.872	0.759	0.951
Well 7	$E_2s_1^{6-2}$	Braided channel	2005	5.84	0.801	0.983	0.98
Well 8	$E_2s_1^{6-2}$	Braided channel	2018	8.67	0.704	0.597	0.933

Based on the above data, the relationship between resistivity ratio and original water cut is established (Figure 2).

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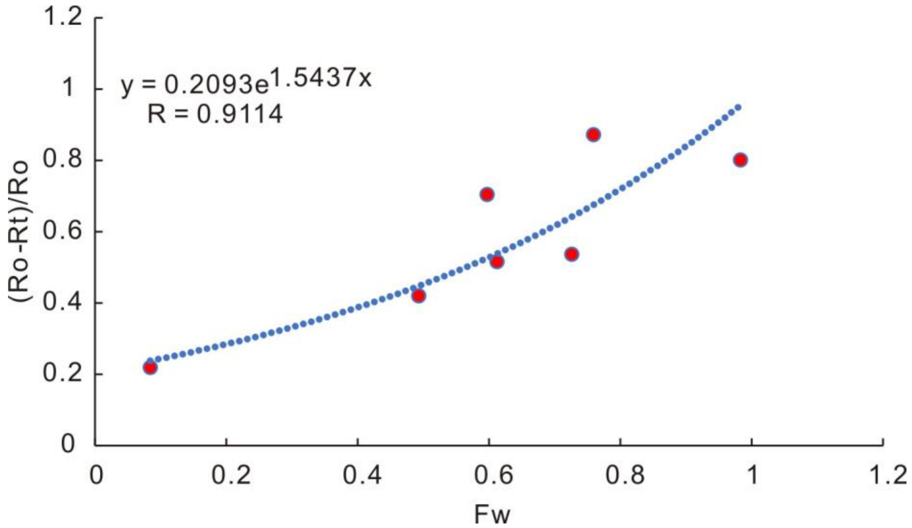

Figure 2. intersection of resistivity ratio and original water cut of braided channel sand body in ×× Oilfield

The braided channel sand bodies are as follows:

$$\frac{R_0-Rt}{R_0}=0.2093e^{1.5437Fw} \qquad R=0.9114 \qquad (20)$$

From the transformation of the above formula, it can be obtained that:

$$Rt=R_0-0.2093e^{1.5437Fw}\cdot R_0 \qquad R=0.9114 \qquad (21)$$

According to formula (21), the current resistivity of the old well can be inversely calculated through the statistics of current water cut.

Then, the resistivity of formation mixture (Rwz) is calculated and combined with Archie formula

$$Sw=\sqrt[n]{\frac{a\cdot b\cdot Rw}{\varphi^m\cdot Rt}} \qquad (22)$$

The modified Archie model for oil saturation calculation of braided channel facies water-flooded layers is as follows:

$$Sw=\sqrt[n]{\frac{a\cdot b\cdot \left(0.55965+\frac{165968.07}{Pz^{0.995}}\right)\Big/(t+21.5)}{\varphi^m\cdot(R_0-0.2093e^{1.5437Fw}\cdot R_0)}} \qquad (23\text{-}1)$$

$$So=1-Sw \qquad (23\text{-}2)$$

In formula (23-1), the rock electrical parameters m, n, a and b are obtained by establishing the relationship between F - Φ and I-S_w through rock electrical experiment; Pi is the original formation water salinity, which is obtained by counting the formation water salinity at the initial stage of water injection development; P_j is the injected water salinity, which is obtained by statistics of the injected water salinity; k is the injection water coefficient, which is the ratio of total water injection to total liquid production; f_i is the irreducible water saturation, It is obtained by establishing the relationship between irreducible water saturation and porosity through relative permeability data. Through the modified Archie model, the current water cut is known, and the rock resistivity can be calculated, thus the oil saturation of braided channel facies water-flooded layers can be accurately calculated. The calculation results are shown in Table 2.

Table 2. Comparison of oil saturation calculation results between modified Archie model and Archie model

Well No	R_w(Ω·m)	Por(%)	Current F_w%	modified Archie model		Archie model	
				Rt(Ω·m)	So(%)	Rt(Ω·m)	So(%)
Well 2	0.2011	24	91.5	2.69	13.77	22.89	80.02
Well 3	0.1975	22	93.9	1.64	0.00	17	70.41
Well 4	0.2016	23	70.9	10.23	60.55	14.18	67.69
Well 5	0.1975	22.66	94.1	1.55	0.00	13.56	66.82
Well 6	0.1975	27	95.1	1.09	0.00	3.76	36.83
Well 7	0.1954	22.5	98.0	0.26	0.00	5.84	44.46
Well 8	0.1975	26.5	93.3	1.9	2.61	8.67	61.55

It can be seen from the table that at present, the resistivity of underground rocks has been reduced to varying degrees, and the reduction range is related to the current water cut of oil wells. The higher the water cut is, the greater the reduction of resistivity is, and vice versa. For example, the current water cut of well 4 is 70.9%, and its resistivity is reduced by 3.95 Ω· m; while that of well 5 is 94.1%, and its resistivity is only 1.55 Ω· m, which is nearly 12 Ω· m lower than the original resistivity. Compared with the oil saturation calculated by modified Archie model and Archie model, the interpretation result of Archie model can only represent the original stage oil saturation, while the interpretation result of modified Archie model is the current underground oil saturation. It can be found that the oil saturation calculated by modified Archie model is more reasonable from the perspective of timeliness, it provides a scientific basis for predicting the distribution of remaining oil.

5. Verification of calculation results

Well 9 is an inspection well recently completed in ×× oilfield. Systematic closed coring has been carried out in this well. However, core saturation has been measured, which can reflect the latest underground situation more realistically and objectively. A total of 157 rock samples were measured for oil saturation in well 9. Considering the difference between logging depth and core depth, single layer was used for statistical analysis in this study. A total of 7 single layers (157 points) were counted and compared with logging interpretation (Table 3).

The oil saturation calculated by the modified Archie model is compared with the oil saturation measured by closed coring core analysis. It is found that the calculated oil saturation value is low whether the oil saturation is interpreted by logging or analyzed by core analysis. The main reason is that the oil saturation value is too small due to the serious water flooding in the later stage of water injection development. The calculated results are generally slightly higher than the measured results, but the variation trend of oil saturation in log interpretation is consistent with that in core analysis, with an average absolute error of 5.46%. The calculated oil saturation error is generally within the required error range (Table 3). The research conclusion is reasonable, which can provide scientific basis for the subsequent adjustment and development, stable oil and water control, and enhanced oil recovery in ×× oilfield.

Table 3. Well 9 logging interpretation with core analysis and original logging interpretation

Top depth (m)	Bottom depth (m)	So interpretation%	So core (%)	Absolute error (%)	F_w(%)
1862.6	1871.1	29.59	-	-	84.49
1885.8	1893.8	40.48	31.56	8.92	82.89
1898.4	1904.8	32.82	28.86	3.96	83.29
1911.3	1916.5	52.18	-		76.84
1932.1	1944.5	33.88	36.23	-2.35	83.81

1945.6	1952.0	61.07	53.35	7.72	65.82
1954.0	1968.4	41.61	35.34	6.27	79.79
1991.9	1995.5	39.54	31.94	7.6	79.91
1996.3	2002.3	38.57	32.42	6.15	81.33
2018.3	2023.0	60.98	-	-	56.65
2026.3	2028.1	42.64	-	-	82.08
		average		5.46	

6. Conclusion

There are some limitations in using Archie model to calculate the oil saturation of water-flooded layers. The main reason is that in the process of water injection, the dynamic change of oil saturation will be caused by the different degree of water flooding and the property of injected water. Based on Archie model, the analysis of oil saturation in water-flooded layers can be attributed to the inversion of rock resistivity and formation water resistivity. The "double rate ratio" model can consider the dynamic change process of rock resistivity, and the current resistivity of rock after water injection can be inversely calculated by water cut; the formation water resistivity mainly considers the change of salinity after the mixing of injected water and original formation water, and the resistivity of formation mixed fluid is calculated by salinity iteration method, which lays a foundation for oil saturation calculation of water-flooded layers. The modified Archie model algorithm based on phase control constraints is stable and reliable, and the oil saturation calculated by the modified Archie model is more reasonable, which provides a scientific basis for predicting the distribution of remaining oil. However, when resistivity does not change regularly or water cut data is insufficient, modified Archie model needs further discussion and improvement.

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