ARCHIE'S PARAMETERS DETERMINATION WITH SATURATION ANALYSIS DATA

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The first study on correlations between rock resistivity and lithology properties was carried out by G. E. Archie around 1942, which laid the foundation of integrated quantitative interpretation by geophysical logging data[1]. Based on the study, Archie summarized the models of water-wet rocks and oil-wet rocks both with intergranular pores to two basic relations called Archie's equation. Many efforts have been made in the study and application of Archie's equation, especially in the determination of parameters in Archie's equation and great progress has been made in recent years. For determination of Archie's parameters, the basic method is first to measure the formation factors and the corresponding porosity of a sample, and to measure the resistivity index at different water saturations in laboratory. Then Archie's parameters are determined by graphic or least-squares methods. Chen et al. used simplex methods and Fuzzy regression analysis[2] and El-khatib presented weighted regression analysis[3]. All the data used in the above methods must be characteristic values of lithology properties provided by laboratories, in other words, they depend on petrophysical parameter measurements. During the early exploration period, due to limited laboratory conditions or the nature of rock itself, petrophysical properties can not be measured directly, so the above methods can not be used. This paper presents a method to determine Archie's parameters by using saturation analysis data combined with the corresponding value of geophysical logging response. For short, we may call it saturation regression analysis.

PRINCIPLE

Archie equation is expressed as follows:

$$F = \frac{R_o}{R_w} = \frac{a}{\Phi^m} \quad , \qquad (1)$$

$$I = \frac{R_t}{R_o} = \frac{b}{S_w{}^n} \quad , \qquad (2)$$

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Symbol F is the formation resistivity factor, I is the resistivity index; Ro and Rw are the resistivities of the water-wet rock and the formation water respectively; R_t is the resistivity of the partly saturated sand; Φ is the porosity, S_w is the water saturation; a and b are lithology coefficients; m and n are the porous cementing exponent and the saturation exponent; a, b, m and n are all called Archie's parameters. Merging (1) and (2), we can get the water saturation formula:

$$S_w = \left(\frac{abR_w}{R_t \Phi^m}\right)^{\frac{1}{n}}, \qquad (3)$$

Take the logarithm of both sides of (3), then we get:

$$\log S_w = \frac{1}{n}\log abR_w - \frac{1}{n}\log R_t - \frac{m}{n}\log\Phi, \qquad (4)$$

If $Y = \log S_w$, $C_1 = \frac{1}{n}$, $X_1 = \log R_t$, $C_2 = \frac{m}{n}$, $X_2 = \log\Phi$,

$C_3 = \frac{1}{n}\log abR_w$, thus (4) is transformed to:

$$Y = -C_1X_1 - C_2X_2 + C_3 \quad , \qquad (5)$$

Thus, the problem of calculating values of *a, b, m* and *n* is transferred to the problem of calculating the coefficients of equation(5). Saturation data from sealed coring sample analysis are taken as dependent variables, R_t and Φ as independent variables. Based on calculations of C_1,C_2,C_3 with regression programs written in *FORTRAN* and transferring them to Archie's parameters, we can obtain a formula of logging response values and saturation of a certain layer and calculate the oil saturation of this layer.

CORRECTION OF SATURATION ANALYSIS VALUES

The key issue of determining Archie's parameters with saturation analysis data is the accuracy of the measured saturation which reflects the saturation distribution in the subsoil and guarantees the accuracy of Archie's parameters. In fact, degasification of cores and volatilization of light hydrocarbons occurred in the time between sealed coring operation and the saturation measurement may result in errors of measured values. Yang et al. believe the error could range from 5% to 35% and present a method for saturation correction[4]. In principle, if different intervals in a well are cored at almost the same pressure and temperature with the same coring process and it the saturation measurements are carried out with the same methods, the losses of oil and water in cores with the same lithology and physical properties should be similar. If the pores are filled only with oil and water without free gas, the sum of oil saturation and water saturation should be 100%[4]. On the basis of an investigation on reservoir saturation in Junggar Basin, we would be able to correct the data with the thought above and further gain the Archie's parameters.

Supposing that the remaining rate of oil is η_1 and that of water is η_2, then:

$$S_o * \eta_1 = S_{o'}, \quad S_w * \eta_2 = S_{w'} \qquad (6)$$

S_o and S_w are original saturation respectively. $S_{o'}$ and $S_{w'}$ are measured saturation. Therefore:

$$S_o + S_w = 1, \quad S_{o'}/\eta_1 + S_{w'}/\eta_2 = 1 \qquad (7)$$

We get a liner relationship:

$$S_{w'} = c_1 + c_2 * S_{o'} \qquad (8)$$

We further get η_2 equal to c_1 and η_1 equal to $-c_1/c_2$. c_1 and c_2 are the coefficients of equation(8) respectively. In figs 1-3, after getting η_1 and η_2, we could correct the measured saturations.

After correction, if the sum of water saturation and oil saturation is still not equal 100%, we should further process these data. The correction factor must be transformed into the percents of total loss of water and oil. The method is described as follows:

$$S_o = (1 - S_{o'} - S_{w'}) * C_o + S_{o'}, \quad S_w = (1 - S_{o'} - S_{w'}) * (1 - C_o) + S_{w'} \qquad (9)$$

C_o is the percent of oil in the total loss of saturations, and $(1-C_o)$ is that of water.

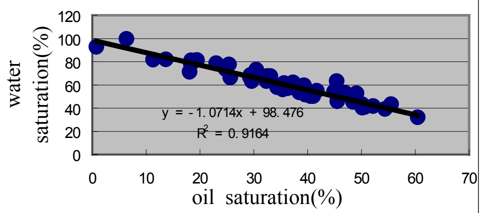

Fig.1 Relations between oil saturation and water saturation in Well S007

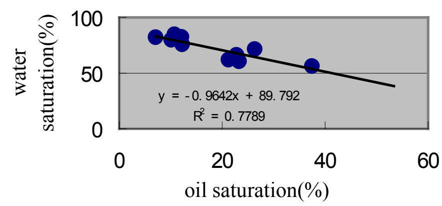

Fig.2 Relations between oil saturation and water saturation in Well S004

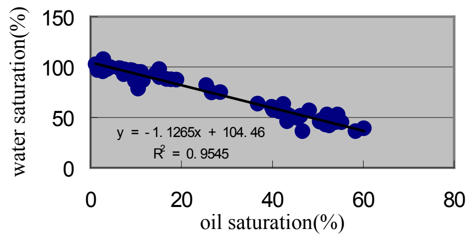

Fig.3 Relations between oil saturation and water saturation in Well M006

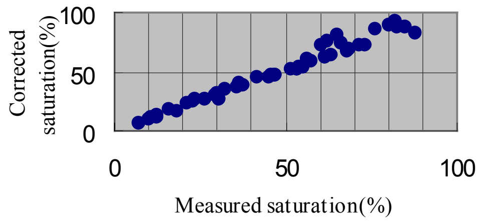

Fig.4 Measured saturation vs corrected saturation in S004 and S007

Fig. 1, 2 and 3 show the relations between oil saturation and water saturation from the Jurassic Badaowan formation in Well S007, the Carboniferous Shixi Oilfield in Well S004, and the Jurassic Baikouquan formation in Well M006 respectively. The figures show that the correlation coefficient of Well S004 is relatively low with 0.7789, and the coefficients of Well S007and Well M006 are 0.9164 and 0.9545 respectively. All these experimental data are reliable. The remaining rate of oil and water in Well S007 are 0.919 and 0.985

respectively, those in Well S004 are 0.931 and 0.898, and those in Well M006 are 0.927 and 1.044. On the basis of these data, we are able to gain correction factors of oil saturation and water saturation.

Fig.4 shows the relationship between the measured saturation and the corrected saturation of water and oil in Well S004 and Well S007. After correction, the sum of water saturation and oil saturation in same sample becomes 100%. Additionally, the saturation data of wells of M006, G8, S112, Sq113, J003 have also been corrected. Thus, the saturation percents of 8%~24% have exactly been corrected.

RESULTS AND DISCUSSION

After substituting the corrected oil and water saturation and the porosity and resistivity values of the corresponding depth into the formula (5) a regression calculation was carried out. Regression equations of saturation analysis data from Well G8, S112, SQ1113, J003 and M006 are shown in table 1.

Table 1 Saturation equation and Archie parameters

Well No.	Regression equation	*m*	*n*	abR_w
S004	$\log S_w=-1.0135-0.1561\log R_t+0.3916\log\Phi$	1.55	3.61	0.0992
S007	$\log S_w=-1.0037-0.2770\log R_t+0.4301\log\Phi$	2.51	6.41	0.0969
M006	$\log S_w=-0.3993-0.4330\log R_t+0.7919\log\Phi$	1.83	2.31	0.3987
G8	$\log S_w=-0.2894-1.6691\log R_t-1.8730\log\Phi$	1.12	0.60	0.5136
S112	$\log S_w=-0.4506-0.0168\log R_t+1.3233\log\Phi$	4.02	7.30	0.3543
Sq1113	$\log S_w=-0.4370+0.2566\log R_t-0.5490\log\Phi$	2.14	3.90	0.3656
J003	$\log S_w=-1.2549-0.5795\log R_t-1.8164\log\Phi$	3.13	1.73	0.0556

In general, the cementation factor m varies from 1.3 to 3.0[5] with which values for m in table 2 are consistent. The saturation exponent n is usually very close to 2[6], but the values for n in table 2 vary from 0.6 to 7.3. Results in literature show that n for water-wet rocks ranges from 1.7 to 2.5, but for oil-wet rocks n ranges from 2.5 to 20[7]. Based on these results, Garrouch et al. indicate that wettability and saturation exponent have a linear relations[8]. Apparently, saturation exponents obtained from saturation analysis reflect the influence of wettability.

Additionally, the product of abR_w should be discussed. In Archie's equation, abR_w is substituted after a, b and R_w are determined. In the saturation regression formula, we only need to calculate abR_w as a whole. This simplifies the procedure and avoid the difficulties to measure R_w and meet the demands of Archie's parameters as well. At present, two main methods are used to determine the water resistivity. One is calculated by a formula obtained from logging data (e.g. *SP*), the other is gained from analytical water samples in the lab. *SP* should be corrected because of the influence of well bore and drilling mud. The method mentioned by Chen[9] can be used for correction, but the procedure is relatively complex. Water samples from boreholes might be contaminated by mud filtrate and surface water, which will result in too high values of R_w, and influence the accuracy of saturation interpretation. Compared with these methods, saturation regression analysis gives more accurate results.

CONCLUSION

Archie parameters obtained by saturation regression analysis reflect variations of pore structure of rocks and distribution of oil and water saturation, which can meet the demands of logging interpretation. The results of the regression analysis indicate that there is an influence of rock wettability on the saturation exponent. With this method, we can avoid the difficulty to figure out R_w. Therefore, it is of great value.

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