Using Dynamic Monitoring Data To Calculate Remaining Oil Saturation

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Abstract

The dynamic remaining oil saturation of each oil layer is based on the two phase (oil/water) percolation theory. The correlation equation was established by using dynamic monitoring data and regression analysis. The dynamic parameters include the various layer water cut, interstitial oil saturation, current water saturation, etc. The accuracy and feasibility of this research results have been verified by means of numerical reservoir simulation, carbon-oxygen-log results and neutron-lifetime-log data. As the dynamic monitoring data reflect current reservoir productivity, so the remaining oil saturation (ROS) can be the real-time dynamic data. The value and distributing of ROS can be obtained whenever necessary. The field example proved the accuracy of the proposed method in X oilfield. The calculated ROS can provide quantitative evidence for the dynamic adjustment and development strategy for oilfield.

Introduction

The dynamic monitoring data is the objective reflection of the oil productivity in specific phase and working system. It has the necessary internal relationship with the dynamic parameters of the oil reservoir. This study is based on the two phase (water/oil) flow theory. With the dynamic monitoring data, the remaining oil saturation (ROS) can be calculated. The method is simple and easy to be applied.

In reservoir condition, oil, gas and water all comply with two phase (water/oil) flow theory. According to the theory, the property of reservoir fluid can be described by the fractional flow equation, which can be expressed as,

$$Q_o = \frac{AK_o}{\mu_o}\frac{\Delta P}{\Delta L} \quad (1)$$

The relative permeability is usually applied to understand fluid flowing capacity, and describe the multiphase fluid flow. It is the ratio of the effective permeability and the absolute permeability.

$$K_{ro} = K_o/K \quad (2)$$

According to the equation, the relative percentage of each-phase can be deduced. It equals the ratio of fractional flow and the total flow. In the water-oil system, the water production rate in reservoir can be given as,

$$f_w = Q_w/(Q_o + Q_w) \quad (3)$$

Integrate **Eq. 1** and **2** into **Eq. 3**, the expression can be obtained as,

$$f_w = \frac{1}{1+\frac{K_{ro}\,\mu_w}{K_{rw}\,\mu_o}}, \quad (4)$$

As for polymer injection wells, the calculation of water production rate must take the polymer residual resistance factors and the effect of the polymer concentration-viscosity into account. Depending on the research of correction coefficient by Daqing Petroleum Institute, the water production rate can be expressed as,

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$$f_w = \frac{\frac{K_{rw}}{\mu_w R_k}}{\frac{K_{rw}}{\mu_w R_k}+\frac{K_{ro}}{\mu_o}} \quad (5)$$

Jone's formula (Yong and Zhang 1996; Zhao et al. 1997; Yu 1992) about the water-oil relative permeability curves is given as,

$$K_{rw} = \left|\frac{S_w-S_{wi}}{1-S_{wi}}\right|^2, K_{ro} = \left|\frac{1-S_w-S_{or}}{1-S_{wi}-S_{or}}\right|^3 \quad (6)$$

Integrate **Eq. 6** into **Eq. 4** or into **Eq. 5**. According to the water or polymer injection, the calculation equation of water saturation can be deduced as **Eq. 7** (Zhang et al. 1998; Chen 1990), which can be used to calculate the remaining oil saturation.

$$S_o = 1 - S_w = 1 - \frac{(1-S_{wi})(1-S_{or})+L(1-S_{wi}-S_{or})S_{wi}}{L(1-S_{wi}-S_{or})+(1-S_{wi})}, \quad (7)$$

where,

$$L = \sqrt[3]{\left|\frac{1}{f_w}-1\right|\frac{\mu_o}{\mu_w R_k}} \quad (8)$$

Production profile application and parameters determination

The dynamic monitoring data includes the oil production profile and water injection profile. Oil wells and water wells have the different methods to determine the parameters. It needs to discuss respectively.

Water Production Rate in Reservoir (f_w). Reservoir production rate usually comes from interpreting production log profile. The results provide the information of effective thickness, permeability, liquid-producing capacity and water-cut, etc., of oil reservoir.

If the oil well does not have the dynamic monitoring data, water production rate can be predicted by using the comprehensive producing water data and permeability.

Referring to the research results about the development performance of heterogeneous reservoir, the high permeability part of reservoir comes to certain moisture content, the water content of the other lower permeability part depends on the ratio, which is its permeability K divide by the highest permeability Kmax. They follow inverse linear relationship. Here, K_{max} is defined as weighted average,

$$\bar{K} = \sum_{i=1}^{n} \frac{h_i \times k_i}{\sum_{i=1}^{n} h_i}, \quad (9)$$

where, K_i is permeability of layer i in the same oil well, i=1,2,⋯,n; n is number of layers; h_i is the thickness of layer i.

The water production rate f_{wi} and $\bar{K}/K_i$ follows negative linear relationship as,

$$f_{wi} = a - b\frac{\bar{K}}{K_i}, \quad (10)$$

where the coefficient a and b can be estimated by regression analysis using the log data.

Irreducible Water Saturation (S_{wi}). Irreducible water saturation mainly is affected by porosity and shale content. The more shale content in the reservoir is, the smaller the rock particles is. The narrower the pore throat is, the higher the irreducible water saturation. At present, the methods which confirm the irreducible water saturation by using the logging data are based on core analysis and logging data analysis. According to the correlation analysis of 128 cores obtained from 9 sealed coring wells in X oilfield, the original water saturation is considered as the irreducible water saturation. If the saturation data pool is insufficient, the irreducible water saturation can be estimated from the formula which regressed by the coring well data,

$$S_{wi} = 31.98\left[1.26 - lg\left(\frac{\phi}{V_{sh}} - 0.15\right)\right] \quad (11)$$

Residual Oil Saturation (S_{or}). Residual oil saturation and irreducible water saturation are opposite but related. They reflect the bending property of reservoir acting on the inner liquids. This theory has been verified by the test. Depending on the cores relativity analysis, **Eq. 12** can be obtained by using the relative permeability curves of X oilfield (**Figure 1**). The correlation coefficient is about 0.99.

$$\frac{S_{or}}{S_{wi}} = 3.158 - 9.762S_{wi} + 8.94S_{wi}^2 \qquad (12)$$

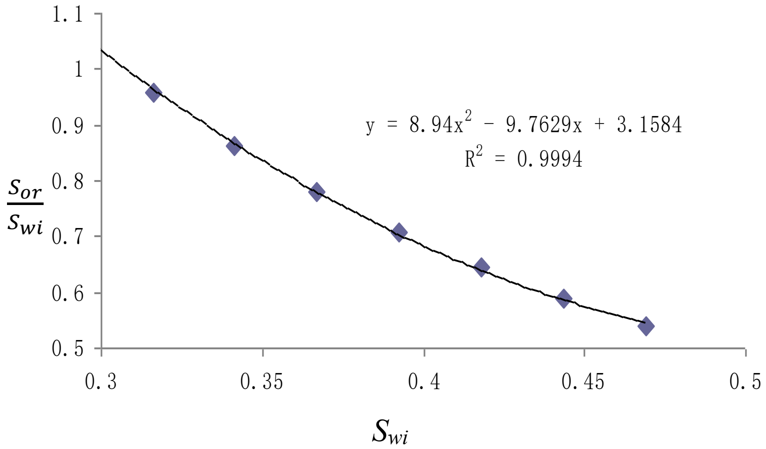

Figure 1—Irreducible water saturation versus residual oil saturation relation.

Water Saturation (S_w). With the development of the oilfield, oil saturation of the reservoir decreases gradually, water saturation increases continuously. The relationship of water saturation, irreducible water saturation and residual oil saturation can be expressed as $S_{wi} \le S_w \le 1 - S_{or}$.Water saturation can be calculated by the formula which is deduced from the water production rate and oil-water relative permeability equation (Hu and Zhang 2002). Input each parameter into the Eq. 7, the remaining oil saturation in reservoir can be calculated.

Using Injection Profile Data to Calculate the Residual Oil Saturation

The remaining oil saturation calculation methods are different between injection wells and producing wells. The residual oil saturation of injection well is dynamic. Due to water washing the reservoir in the long term waterflooding, the lithology and property of the water-absorbing layer has changed. So the residual oil saturation is not a fixed value any more, but a range (Chen 1999).

For most of injection wells, at the beginning of water injection, the residual oil saturation is regarded as the lower limit of the remaining oil saturation in waterflooding reservoir. Long term waterflooding will decrease the residual oil saturation slowly. The calculated remaining oil saturation will be the dynamic residual oil saturation.

Residual Oil Saturation Determination. In X oilfield which is an extra high water-cut reservoir, especially when each oil layer is the serious water flooded layer, the residual oil saturation can be obtained with oil/water relative permeability curve. As the residual oil saturation is regarded as zero corresponding to relative permeability of oil phase (Hearn et al. 1984). The higher the porosity and permeability are, the smaller the residual oil saturation is. Regressing the relative permeability curve data, **Eq. 13** can be obtained,

$$S_{or} = 62.440 + 1.3212\phi - 3.4028lgK \qquad (13)$$

Dynamic Residual Oil Saturation Determination. The decreasing speed of the dynamic residual oil saturation relates to many factors, such as water injection rate, reservoir heterogeneity, pressure, permeability, thickness, etc. But the accumulative water injection rate per meter reflect water absorption ability of the waterflooding layer. This parameter can be determined with all the previous water injection profile logging data. According to the data of core experiment and sidetracking well, the following formula can express the slow decreasing process of dynamic residual oil saturation in water-absorbing layer,

$$S_{orc} = S_{or}e^{-AQ/D} \qquad (14)$$

Single layer accumulative water injection rate, Q, can be obtained by using the water injection profile logging data. Factor A in **Eq. 14** is measured by the core waterflooding experiment.

In conclusion, the calculation methods of remaining oil saturation in injection wells is as follows,

- Using Eq. 13 to calculate the residual oil saturation of each oil layer when injection begins;
- To determine the accumulative water injection rate and effective thickness of each layer according to all the previous water injection profile data. Thus, current dynamic residual oil saturation can be determined. That is the value of remaining oil saturation.

Methods Verification

Take the block of X oilfield for instance to verify the feasibility of using dynamic monitoring data to calculate the remaining oil saturation.

Logging Data Method. Comparing the calculation value and logging data which were measured in 2009, including carbon oxygen log and neutron lifetime log from 4 wells, the comparison results verified the feasibility of the proposed calculation methods (**Table 1**). The errors are less than 3.3%.

Table 1—2009 Logging data and calculation value comparison.

Well	Logging Mode	Layer	Effective Thickness (m)	Permeability (μm2)	Porosity (%)	Shale Content (%)	Irreducible Water Saturation	Producing Water Rate (%)	Logging Data of DOS (%)	Calculated ROS
M1	C/O	SI 1	0.6	0.256	25.978	24.325	21.45	0.923	19.239	22.34
		SII 1+2	0.9	0.171	26.636	17.924	22.38	0.911	22.777	20.54
		SII 15+16	2.5	0.232	28.737	14.961	21.14	0.966	32.623	31.58
		SIII5+6	2.7	0.396	20.115	22.849	19.25	0.945	14.624	17.88
		PI 5-7	6.3	0.5	26.216	19.697	19.39	0.899	36.559	35.45
		GI2+3	1.8	0.052	26.618	10.694	29.18	0.901	33.583	33.456
		GI4+5	1.4	0.077	26.596	11.881	29.18	0.917	27.944	31.242
M2	C/O	SI4+5	0.8	0.124	21.521	24.107	27.45	0.846	29.397	29.041
		SII1+2	1.2	0.186	26.456	10.103	32.1	0.892	32.588	30.353
		GI1	0.7	0.053	27.813	18.34	38.16	0.948	27.562	28.034
M3	NLL	SII4	1.4	0.44	28.28	16.598	28.37	0.953	35.604	32.436
		PII4+5	1.7	0.08	25.37	20.12	30.04	0.925	41.6	40.55
		GI2	3.3	0.44	26.88	18.44	27.49	0.891	39.1	38.92
M4	NLL	SII13+14	3.1	0.34	28.02	22.57	26.89	0.904	36.1	35.46
		GI8	0.9	0.04	22.42	25.397	33.7	0.939	25.93	28.45

Numerical Simulation Method (Cheng et al. 2000). Taking a block of X oilfield as the study area, which has developed the numerical simulation in 2010, the remaining oil saturation has been understood clearly. Taking the oil layer GI1, GII^{1+2} for instance, using the data of the output profile and the injection profile from 2008 to 2010, plugging the data into the Eq. 4 through 7, Eq.13 , and Eq.14, the remaining oil saturation can be calculated. The calculated remaining oil saturation of each well match with the numerical simulation results very well. The error is only 4.6% (**Table 2**). So the numerical simulation method verified the feasibility of the proposed methods as well.

Table 2—Comparison of calculated ROS value and numerical simulation results (part of wells).

Wells	Irreducible Water Saturation	Residual Oil Saturation	Weighted Average Permeability	Permeability	Water Cut	Original Oil Saturation	Current Water Cut	Current Oil Saturation	Remaining oil
A	0.214	0.316	0.263	0.13	0.812	0.457	0.639	0.361	0.507
B	0.215	0.316	0.012	0.05	0.825	0.512	0.629	0.371	0.376
C	0.251	0.319	0.214	0.14	0.871	0.602	0.601	0.399	0.385
D	0.209	0.315	0.311	0.211	0.792	0.588	0.617	0.383	0.388
E	0.256	0.319	0.345	0.314	0.845	0.577	0.667	0.333	0.215
F	0.239	0.319	0.154	0.11	0.756	0.58	0.622	0.378	0.398
G	0.244	0.319	0.078	0.09	0.895	0.67	0.689	0.311	0.342
H	0.242	0.319	0.031	0.04	0.887	0.619	0.429	0.571	0.531
I	0.196	0.351	0.027	0.03	0.862	0.601	0.599	0.401	0.329
J	0.255	0.319	0.247	0.12	0.785	0.524	0.627	0.373	0.398
K	0.264	0.318	0.314	0.21	0.801	0.63	0.657	0.343	0.352
L	0.232	0.319	0.471	0.33	0.789	0.587	0.544	0.456	0.379
M	0.23	0.319	0.061	0.04	0.844	0.587	0.627	0.373	0.397
N	0.252	0.319	0.201	0.19	0.865	0.609	0.594	0.406	0.426
O	0.243	0.319	0.245	0.22	0.792	0.602	0.656	0.344	0.386
P	0.315	0.306	0.354	0.301	0.907	0.562	0.598	0.402	0.418
Q	0.388	0.278	0.621	0.058	0.914	0.612	0.527	0.473	0.347
R	0.291	0.313	0.175	0.251	0.868	0.411	0.615	0.385	0.397

Field Application

2D remaining oil distribution. **Table 3** is a comparison between the measured remaining oil saturation in 1994 and the calculated remaining oil saturation according to the dynamic monitoring data in 2010. The average remaining oil value equals to 0.51. At present, this oil layer remaining oil saturation is 0.37. The numerical value decreased obviously. It indicates that the remaining oil saturation will change dynamically along with the time goes on and developing adjustment. As the dynamic monitoring data reflects current reservoir productivity, so the ROS can be real-time dynamic data.

Table 3—Comparison between current remaining oil value and initial measured value.

Wells	1994 Remaining Oil Saturation	2010 Remaining Oil Saturation	Wells	1994 Remaining Oil Saturation	2010 Remaining Oil Saturation
A1	0.618	0.407	A17	0.664	0.46
A2	0.524	0.3	A18	0.377	0.3
A3	0.436	0.429	A19	0.451	0.34
A4	0.487	0.373	A20	0.467	0.375
A5	0.45	0.412	A21	0.516	0.334
A6	0.48	0.347	A22	0.49	0.409
A7	0.485	0.38	A23	0.398	0.346
A8	0.49	0.379	A24	0.42	0.408
A9	0.561	0.347	A25	0.389	0.36
A10	0.589	0.368	A26	0.452	0.36
A11	0.682	0.34	A27	0.511	0.34
A12	0.714	0.375	A28	0.498	0.382
A13	0.45	0.334	A29	0.419	0.38
A14	0.55	0.409	A30	0.419	0.385
A15	0.51	0.346	A31	0.499	0.378
A16	0.46	0.408	A32	0.736	0.339

3D remaining oil distribution. For a long term, the remaining oil in the upper part of the thick oil-layer has been described qualitatively in the oilfield. The dynamic monitoring data can be used to calculate the current remaining oil saturation in reservoir of which effective thickness is greater than two meters. Comparing current ROS with its initial value listed in **Table 4**, it shows that the remaining oil saturation of the upper and lower part in the thick oil layer changes with time. In the upper part of thick oil layer, the ROS value has decreased by 15.1%, from initial 0.47 to 0.399 at present. In the lower part, the value decreases by 50.2%, from 0.457 to 0.284. It proves that ROS will decreased along with development. Especially, the lower part of a thick oil layer will be flooded more throughoutly. As a result, remaining oil is enriched in the upper part of oil layer. It proves that ROS calculation method can describe the remaining oil quantitatively.

Table 4—Three-dimensional ROS calculation results.

Wells	Layers	Effective Thickness (m)	Initial ROS	Current ROS
01	$PII10^1$	0.8	0.369	0.353
	$PII10^2$	1.6	0.388	0.339
	$SII1+2^1$	0.6	0.477	0.39
	$SII1+2^2$	1.4	0.572	0.385
02	$GI2+3^1$	2.6	0.562	0.419
	$GI2+3^2$	0.8	0.388	0.359
03	$SI15+6^1$	1.1	0.449	0.418
	$SII5+6^2$	1.3	0.387	0.125
04	$PII7+8^1$	0.8	0.375	0.344
	$PII7+8^3$	1.2	0.592	0.187
05	$SII10+11^1$	1.3	0.699	0.432
	$SII10+11^3$	0.4	0.567	0.285
06	$GI2+3^1$	1	0.391	0.369
	$GI2+3^2$	0.6	0.422	0.212
07	$PII8+9_1$	0.4	0.439	0.411
	$PII8+9^2$	1.8	0.344	0.319

Conclusions

In conclusion, using the dynamic monitoring data, the relationship between water production rate and ROS was established in this study. The developing example has verified that the proposed method of calculating ROS by using dynamic monitoring data is feasible. As the dynamic monitoring data reflects current reservoir productivity, so the ROS can be the real-time dynamic data. It can provide quantitative data for dynamic adjustment and development strategy.

Conflicts of Interest

The author(s) declare that they have no conflicting interests.

Nomenclature

k_o = effective oil permeability, md
k_w = effective water permeability, md
k_g = effective gas permeability, md
k = absolute permeability
k_{ro} = oil relative permeability, md
k_{rw} = water relative permeability, md
k_{rg} = gas relative permeability, md

$\frac{\Delta p}{\Delta L}$ = pressure gradient upon the seepage direction

Q_o = oil rate, m^3

Q_w = water quantity, m^3

μ_o = oil viscosity

μ_w = water viscosity

R_k = correction factor

Q = cumulative water absorption per-layer, m^3

D = monolayer thickness, m

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