Study on the main influencing factors of oil-flood recovery factor of oilfield in extra-high water cut period

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Abstract. Recovery factor is the most important comprehensive index to measure oilfield development effect and development level. Starting from the production history data of development indicators and influencing factors, this paper mainly evaluates the oilfield development effect from the transient perspective of recovery factor. The results show that the current recovery rate is higher but the recovery factor is lower. Mathematical methods such as gray correlation analysis and reservoir engineering principles analyze the main factors that affect oil recovery and oil recovery rate. According to the current recovery factor determined by the dynamic method according to the determined typical block, compared with the similar typical block, the four influencing factors are analyzed longitudinally from the historical change trend, and the next step to improve the recovery rate of the block is given. Main adjustment countermeasures. The proposed method and analysis results have certain reference value for the theoretical research and practical application of the development of ultra-high water cut oil fields.

Keywords: Extra-high water cut period; recovery factor; influencing factors; correlation analysis; grey correlation analysis.

1. Introduction
Most of China's major oil fields have entered or are about to enter the stage of ultra-high water cut development. It is urgent to analyze the main factors affecting recovery factor in the ultra-high water cut period in order to provide a basis for the future development adjustment and decision-making of the oil field. There are many factors that affect the recovery factor, and many scholars [1-7] have conducted in-depth discussions on the factors affecting the recovery factor from multiple angles such as geological conditions and development methods. The following is based on the 12 blocks in the layered sandstone oil field in the east of China in the extremely high water cut period as an example, using the combination of objective analysis and subjective analysis to analyze and determine the main factors affecting the recovery factor.

2. Analysis of main influencing factors of recovery factor
Because there are many factors that affect recovery factor, and each index affects each other, to analyze the factors affecting recovery factor, first select the commonly used representative indicators, mainly
subjective analysis—that is, based on reservoir engineering principles and actual field experience. Mainly make judgments, take the quantitative results of mathematical methods as an important reference, and at the same time determine the comprehensive weight of each influencing factor to rank the influencing factors, then evaluate the typical blocks, and give the next adjustment countermeasures.

In quantitative analysis, the correlation coefficient method and the gray correlation analysis method can be used for comprehensive analysis. The main reasons are as follows: the correlation between the two indicators is nothing more than two-straight-line correlation and curve correlation, according to which the correlation coefficient method and gray correlation are selected. Two mathematical methods of analysis. The correlation analysis method judges the degree of mutual influence according to the correlation coefficient of the two indicators, and the gray correlation analysis method judges the closeness of the two indicators according to the correlation degree, and then refers to the quantitative analysis results, applying the reservoir engineering principles and the actual mine selection. The main factors affecting oil recovery in oilfields with extremely high water cut.

1) Principles of mathematical methods

The correlation coefficient method reflects the linear relationship between the two indicators, that is, the degree of direct correlation. According to the principle of statistics, the correlation coefficient $r$ of the two indicators ranges from -1 to 1, that is, $-1 \leq r \leq 1$. When $r = 1$ is completely positive correlation, $r = -1$ is completely negative correlation, $r = 0$ is not related. The range of $r$ between 0.3-0.5 is low correlation; the range of $r$ between 0.5-0.8 is significant correlation; the range of $r$ above 0.8 is highly correlated.

In gray correlation analysis, the gray correlation degree reflects the degree of curvature similarity of the two indicators. The greater the correlation degree, the closer the relationship between the two. The geometric meaning of the correlation degree is the similarity and consistency of the comparison sequence and the reference sequence degree, the greater the correlation, the closer the curve shape to the reference sequence, indicating the greater the degree of mutual influence between the two indicators.

2) Weight determination method

In order to accurately determine the size of each influencing factor, the method of determining its weight adopts a combination of quantitative method and qualitative method: complex correlation coefficient method, coefficient of variation method and analytic hierarchy process. The method of complex correlation coefficient indicates the absolute importance of each indicator and other indicators. The complex correlation coefficient of the $k$th indicator reflects the ability of all indicators except the $k$th indicator to replace the $k$th indicator. Therefore, the larger the $k$-th complex correlation coefficient, the smaller its effect, so the reciprocal of the complex correlation coefficient can be used as the weight (ie, the correlation weight). The complex correlation coefficient can be calculated using SPSS software.

The coefficient of variation indicates the relative importance of each indicator and other indicators. According to statistical principles, the larger the difference coefficient of each indicator, the stronger the corresponding attribute of the performance evaluation object of the index, and the more attention should be paid to the attribute index, so the corresponding index weight should be greater in theory (ie, the weight of variation).

AHP (AHP) is a systematic and hierarchical analysis method combining qualitative and quantitative. Not only does it apply to situations where there is uncertainty and subjective information, it also allows experience, insight and intuition to be used in a logical manner. The biggest advantage of the analytic hierarchy process is that it proposes the tier itself, which transforms people's judgment into the comparison of the relative importance between several factors, which greatly improves the effectiveness, reliability and feasibility of decision-making, so analytic hierarchy process The method determines the weight of each index (that is, the layer weight).

In order to avoid the one-sidedness of calculating weights by various methods, the weights calculated by the above three methods are assigned according to the level of credibility to obtain comprehensive weights.

3) Analysis results
Taking 9 development indicators related to recovery factor in 12 blocks (water cuts between 92% and 95%) of the oilfield in the ultra-high water cut period as samples (Table 1), the correlation coefficient and correlation between the recovery factor and each indicator in each block are calculated. The degree is shown in Table 2.

**Table 1. Dynamic development indicators about the super-high water cut blocks**

| Indicator \ Block | Block 1 | Block 2 | Block 3 | Block 4 | Block 5 | Block 6 | Block 7 | Block 8 | Block 9 | Block 10 | Block 11 | Block 12 |
|-------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------|----------|----------|
| recovery ratio, %  | 43.12   | 40.56   | 40.69   | 38.96   | 37.16   | 36.83   | 35.56   | 44.75   | 34.81   | 40.14    | 35.38    |          |
| fluid production index, m³/MPa | 13.04 | 5.86 | 9.70 | 12.92 | 14.40 | 6.07 | 8.16 | 5.95 | 5.74 | 6.12 | 5.36 | 2.62 |
| flowing pressure, MPa | 3.45 | 2.99 | 3.41 | 4.03 | 3.66 | 4.48 | 3.91 | 3.93 | 3.01 | 4.56 | 3.71 | 3.72 |
| oil production intensity, m³/m | 0.15 | 0.09 | 0.08 | 0.11 | 0.13 | 0.10 | 0.18 | 0.11 | 0.09 | 0.06 | 0.12 | 0.16 |
| recovery of OOIP, % | 39.11 | 32.04 | 29.22 | 33.61 | 33.57 | 25.52 | 29.69 | 22.32 | 32.33 | 25.11 | 30.15 | 22.65 |
| injector-producer ratio, f | 1.27 | 2.10 | 1.29 | 1.58 | 1.02 | 1.88 | 1.67 | 1.89 | 1.56 | 2.03 | 1.08 | 1.81 |
| Cumulative water retention, % | 37.90 | 39.52 | 41.34 | 40.41 | 47.51 | 39.28 | 42.49 | 40.19 | 42.60 | 40.99 | 38.46 | 35.12 |
| borehole flow pressure difference between injector and producer, MPa | 13.25 | 17.94 | 15.00 | 16.01 | 13.60 | 18.04 | 18.67 | 15.98 | 17.42 | 18.58 | 17.73 | 18.62 |
| Injection pore multiple, % | 1.24 | 0.73 | 1.34 | 1.02 | 0.99 | 0.82 | 0.69 | 0.59 | 0.70 | 0.69 | 0.79 | 0.75 |
| well spacing, kou/km² | 48.03 | 50.90 | 49.75 | 40.07 | 55.93 | 32.97 | 19.24 | 20.82 | 37.97 | 29.14 | 34.18 | 18.82 |

**Table 2. Quantitative analysis result of influencing factors of recovery ratio**

| Serial number | index                      | Correlation coefficient |
|---------------|----------------------------|-------------------------|
| 1             | recovery ratio             | 0.7395                  |
| 2             | Cumulative water retention | 0.7301                  |
| 3             | flowing pressure           | 0.6876                  |
| 4             | well spacing               | 0.6808                  |
| 5             | oil production intensity   | 0.6772                  |
| 6             | Injection pore multiple    | 0.6539                  |
| 7             | fluid production index     | 0.5911                  |
| 8             | injector-producer ratio    | 0.5744                  |
| 9             | borehole flow pressure difference between injector and producer | 0.5719 |

The correlation coefficient and correlation between the recovery factor and each indicator in each block are calculated.
The first four indicators with the largest calculation results of the two methods are the cumulative water retention rate, well pattern density, oil well flow pressure, and oil-water well number ratio. Oil well flow pressure and oil-water well number ratio are negatively correlated with recovery rate, that is, the smaller the flow pressure and oil-water well number ratio, the greater the recovery rate, which is in line with theoretical and practical understanding; the two indicators of well pattern density and cumulative water retention The impact on the recovery factor in the extra-high water cut period will be discussed later. Combined with the principles of reservoir engineering and actual comprehensive analysis and judgment of the mine, the main factors that affect the recovery factor in the ultra-high water cut period are the four indicators of well pattern density, oil-water well number ratio and cumulative water retention rate, and oil well flow pressure. A comprehensive quantitative method is used to calculate the weights of the four indicators, as shown in Table 3.

Table 3. Weight of influencing factors of recovery ratio

| Method \ Indicator | flowing pressure | injector-producer ratio | Cumulative water retention | well spacing |
|-------------------|------------------|-------------------------|---------------------------|-------------|
| Related rights    | 0.2572           | 0.2632                  | 0.2792                    | 0.2004      |
| Variation weight  | 0.1670           | 0.2895                  | 0.0948                    | 0.4487      |
| Hierarchy         | 0.2461           | 0.3160                  | 0.1917                    | 0.2461      |
| Comprehensive rights | 0.2284       | 0.3005                  | 0.1788                    | 0.2922      |

From the statistical results, for the oilfields with very high water cut period, the primary factor affecting oil recovery is the ratio of oil to water wells, followed by the density of well pattern and flow pressure of oil wells, and again the cumulative water retention rate.

On the basis of determining the main influencing factors of recovery factor, the following in-depth analysis takes the BD block of a typical block with high water cut as an example.

3. Evaluation of typical block recovery ratio

1) Comparison of recovery factor

Calculate the current recovery factor for the BD block using the water drive curve of 98% as the limit (see Figure 1), and compare it with similar blocks. It can be seen that the recovery rate of the BD block is 35.56%, which is lower than the adjacent area The block recovery rate is nearly 3 percentage points, indicating that the development effect of the block is not good and the potential for improving recovery rate is large.

![Figure 1. A-type curve in BD block](image)

2) Analysis of influencing factors

1) Well pattern density
It goes without saying that years of theoretical research and practical knowledge show that the most closely related to recovery factor is the density of the well pattern. The model of the relationship between the well pattern density and recovery factor proposed by the former Soviet scholar Sergey Kachov in the late 1960s based on the statistics of oilfield data [10], believed that with the increase of the well pattern density, the recovery rate decreased. The expression is as follows:

\[ E_r = E_{DR} \cdot e^{-a/s} \]  \hspace{1cm} (1)

In the formula:
- \( E_r \) —recovery, \%;
- \( E_{DR} \) —oil displacement efficiency, \%, Represents the recovery factor when the density of the oilfield well pattern tends to infinity;
- \( s \) —well spacing, kou/km²;
- \( a \) —Well pattern index, It is related to the reservoir properties and comprehensively reflects the sand body continuity, heterogeneity and fluid properties of the oil layer. Generally, the more layers of the oil layer, the worse the sand body connectivity and the more serious the heterogeneity, the greater the \( a \) value.

The empirical relationship of well pattern index:

\[ a = \frac{0.1814}{\left( \frac{k}{\mu} \right)^{0.2429}} \]  \hspace{1cm} (2)

\( k \) —Air permeability, \( 10^{-3} \) μm²;
\( \mu \) —Formation oil viscosity, mPa.s

According to the core well data since 2000, the displacement efficiency of the BD block is 47%, the calculated well pattern index is 4.53, and the calculated recovery rate changes with the well pattern density as shown in Figure 2. It can be seen that with the increase of the density of the well pattern, the increase rate of recovery factor is getting smaller and smaller. This is an important reason why the current recovery rate is lower than the target recovery rate. For mining, the density of the well pattern of each underground layer is much lower than that of the surface, so the recovery rate will be lower.

![Figure 2. The curve between recovery ratio and well density of BD block](image)

The change trend of the recovery value of the BD block under different water cut conditions for each increase in unit well pattern density since the high water cut period is shown in Figure 3.
Figure 3. The changing value of recovery ratio with the well density under the condition of different water cut

It can be seen that as the density of the well pattern increases in the high water cut period, the recovery value increases rapidly. If the oil field cannot guarantee a higher recovery rate before entering the high water cut period, then after entering the high water cut period, even the density of the well pattern has increased significantly, and the increase in recovery factor will not increase significantly. The development trend of the BD block is that the water content rises rapidly in the early stage of development, and a high recovery factor cannot be guaranteed. As a result, even if the well pattern encryption and injection-production system adjustments are carried out many times later, the recovery factor has not increased significantly. But encryption adjustment is still an important aspect of improving recovery.

2) Number of oil and water wells

For oil fields with very high water cut period, a reasonable ratio of oil to water wells is an important aspect to ensure injection-production balance and enlarge the swept volume. Reservoir engineering theory and field practice have shown that the water injection method and the ratio of the number of oil and water wells in the sandstone oilfield developed by waterflood have a great influence on the waterflood sweep volume and waterflood recovery. When the density of the well pattern and the production time of water injection are fixed, as the ratio of the number of oil-water wells decreases, the number of effective directions of the oil well increases, and the degree of water flooding control increases, the coefficient of water injection ripple will also increase; Increase, the number of effective directions of oil wells decreases, and the efficiency of multi-directional reception decreases, and the coefficient of water injection ripple will decrease accordingly. In the actual adjustment of oilfield injection and production well patterns, there have been many theoretical research results and field practices that show that when the density of the well pattern remains unchanged, the flow direction can be adjusted by changing the ratio of oil and water wells to achieve improved development effects. The purpose of increasing the recoverable reserves of waterflood and improving the recovery factor of waterflood is feasible.

In the case of a certain well pattern density, the lower the ratio of oil-water wells, the greater the recovery factor. However, as the density of the well pattern increases, the gap between the effects of oil-water well ratio on the recovery factor is getting smaller. The smaller the increase.

BD block oil-water well number ratio change curve is shown in Figure 4. The ratio of oil to water wells was gradually adjusted from as high as 2.4 in the 1980s to 2 in the 1990s, and then adjusted to the current 1.53. The higher ratio of oil to water wells is another reason for the lower recovery factor.
3) Cumulative water retention rate

For waterflooding oilfields, the recovery factor is the product of the waterflooding efficiency of the injected water and its volumetric sweep coefficient (Equation 6). The volumetric sweep coefficient of the injected water is the difference between the cumulative water injection and the cumulative water production divided by the geological reserves (Formula 7).

\[ E_h = E_{i2}gE_v \]  
\[ E_v = \frac{W_i - W_p}{N} \]  
\[ E_s = \frac{W_i - W_p}{W_i} \]  
\[ \gamma_{\phi} = \frac{W_i}{N} \]  
\[ E_c = E_{i2}g\gamma_{\phi} \]

According to the definition of cumulative water retention rate:

\[ E_s = \frac{W_i - W_p}{W_i} \]

Define the definition of cumulative injection multiple:

\[ \gamma_{\phi} = \frac{W_i}{N} \]

Available:

\[ E_c = E_{i2}g\gamma_{\phi} \]

It is not difficult to see that within a certain range, the cumulative injection pore volume multiples will not change very much, so the main factor affecting the sweep coefficient is the cumulative water retention rate. The sweep coefficient increases with the increase of the cumulative water retention rate, especially for water flooding oil fields. In general, when the increase in oil displacement efficiency is limited, the main direction for improving oil recovery is to increase the volumetric sweep coefficient. It can be seen from Fig. 5 that under the condition that the injection pore multiple is constant, as the cumulative water retention rate increases, the sweep coefficient increases, so the recovery factor also increases. According to the theoretical relationship between the deduced cumulative water storage rate and the water content [11], the actual cumulative water storage rate is nearly 7 percentage points lower than the theoretical cumulative water storage rate (Figure 6), which is also a reason for the low recovery factor.

Figure 4. The changing curve of ratio of producing wells and injecting wells about BD block
According to the previous research results, there is a critical point between the oil well flow pressure and recovery factor, that is, when the flow pressure is about 2 ~ 3MPa, the recovery factor is maximized. The current block flow pressure is 3.7 MPa, which exceeds the maximum flow rate of 0.7 to 1.7 MPa, which has a certain impact on the recovery factor.

In summary, the reasons for the low recovery factor of the BD block are: one is the internal cause-the reservoir heterogeneity is serious (permeability coefficient of variation reaches 0.6718), and the second is the external cause-the measures to strengthen mining lead to "three major The "contradiction" is particularly prominent. The infiltration and injection-production system adjustments and high flow pressures were only started during the ultra-high water cut period. This caused a rapid rise in water cuts in the early stages of development, leading to failures in well pattern encryption adjustments and injection-production system adjustments in the middle and late stages of development To achieve the purpose of increasing the recovery factor, and the cumulative water retention rate has been low, all of these reasons make it difficult to increase the recovery factor.

(3) Adjustment measures

According to the analysis of the above four aspects, the corresponding adjustment countermeasures of the BD block are formulated.

First, in terms of well pattern density, the improved Shaw's formula is used to calculate the economical and reasonable well pattern density of BD block under 60 $ / bbl to be 62well / km2, which is much higher than the current 40well / km2, and the recovery factor can be increased by 0.8-1 percentage point;
Second, in terms of improving the injection-production system, the reasonable ratio of oil to water wells is 1.20 under current conditions, and the oil recovery ratio can be increased by 0.3-0.5 percentage points by reducing the ratio of oil to water wells;

Thirdly, in terms of increasing the cumulative water retention rate, measures such as deep profile adjustment to improve the water absorption profile to reduce the inefficient and ineffective circulation of injected water, increase the water injection volume in the middle and low permeability intervals, and shut down the ultra-high water cut inefficient wells and other measures to improve underground storage Water rate can increase recovery factor by 0.1-0.2 percentage points;

Fourth, in terms of flow pressure reduction, the liquid volume of low water cut wells can be appropriately increased, and the liquid volume of high water cut wells can be controlled to further increase the recovery factor by 0.1-0.2 percentage points.

Through the above measures, it can effectively slow down the decline rate of oilfield production and increase the recovery factor by 0.5-1.9 percentage points.

4. Conclusion

Through the above research, the following understandings and conclusions are drawn:

(1) A method combining objective analysis (quantitative analysis using mathematical methods) and subjective analysis (applying reservoir engineering principles and mine practice) was proposed to statistically analyze the 20 development indicators and recovery of the oilfield in this extremely high water cut period. The relationship between the rates determines the four main factors (well pattern density, oil-to-water well ratio, cumulative water retention rate, and oil well flow pressure) that affect the low recovery factor of the oil field, which has certain reference and promotion value.

(2) Through the analysis of the application of the complex correlation coefficient method and the coefficient of variation method in typical blocks, a comprehensive weight determination method is established, which provides theoretical guidance for the development of oilfields in extremely high water cut periods; at the same time, the cumulative water retention rate and the swept volume are established. The mathematical relationship of the coefficient is also closely related to the recovery factor. The proposed method and analysis result have certain reference value for the theoretical research and practical application of the development of ultra-high water cut oil field.

References

[1] Sun Huan quan. Potential analysis of water flooding recovery on different reservoir in Shengli oil field[J]. Oil & Gas Recovery Technology, 2000, 7(1): 33-37.
[2] HU Yong le, WANG Yanling, YANG Siyu, et al. Adjustment of technical policy for water-flooding oilfield with high water cut in the late stage of development[J]. Acta Petrolei Sinica, 2004, 25(5): 65-'69.
[3] CHEN Yuan qian, ZOU Cunyou, ZHANG Feng, et al. Derivation, comparison and application of forecasting water drive sweep efficiency methods with comments on Hu Gang’s new method[J]. Xinjiang Petroleum Geology, 2014, 35(3): 293-298.
[4] DOU Hong en, ZHANG Hujun, SHEN Sibo. Correct understanding and application of waterflooding characteristic curve[J]. Petroleum Exploration and Development, 2019, 46(4): 755-762.
[5] HU Gang. A new method for calculating volumetric sweep efficiency in a water-flooding oilfield[J]. Petroleum Exploration and Development, 2013, 40(1): 103-106.
[6] WANG Jiqiang, SHI Chengfang, JI Shuhong, et al. New water drive characteristic curves at ultra-high water cut stage[J]. Petroleum Exploration and Development, 2017, 44(6): 955-960.
[7] JIA H B, ZHAO H, BAO Z J, et al. New method for evaluating water flooding development effect and its oil field application. Lithologic Reservoirs, 2019, 31(5): 101-107.
[8] ZOU C Y, YU L J. A quantization relationship between water cut and degree of reserve recovery for waterflooding sandstone reservoirs in China. Acta Petrolei Sinica, 2012, 33(2): 288-292.