Evaluation of Oilfield Flooding Effect by Water Storage Rate and Water Flooding Index

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Abstract: Two important indicators to evaluate the water flooding effect in oilfields are water storage rate and water flooding index. According to the definitions of water storage rate and injection-production ratio and the water flooding characteristic curve, the theoretical relationship between water storage rate and recovery degree was concluded in this paper. In addition, the theoretical relationship between water flooding index and water cut was provided. For Block H, it was demonstrated that the curve of the actual water storage rate vs. water flooding index was above or at the theoretical curve indicated that the actual development index met the oilfield development plan and the water flooding effect was good, and vice versa. Finally, the next improvement measures were given for the problems in development of Block H.

1. Introduction
To develop oilfield by water flooding correctly and efficiently, it is very necessary to evaluate and adjust the water flooding quality and effect in time. The oilfields have very different development indices because of their different geologic conditions, development statuses and phases. Thus, one development index is comprehensively analyzed in different phases in order to evaluate the oilfield development effect. There are many evaluation contents and methods. To evaluate the water flooding effect and determine a rational injection-to-production ratio, the flooding effect in Block H was analyzed by plotting the water storage rate and water flooding index standard curves for oilfield to determine the rationality of water flooding.

2. Flooding Evaluation Index Selection Basis
Water storage rate, $E_i$, refers to underground water storage capacity, i.e. the ratio of water injection, $W_i$, minus water production, $W_p$, to water injection $W_i$. With increasing crude oil recovery, total water cut increases, and the injected water is continuously produced[1]. Thus, the higher water cut leads to higher water production, lower underground water storage rate, and lower flooding effect. As an index to evaluate the flooding effect, water flooding index[2] refers to underground water content in 1 t of crude oil. Theoretically, with increasing water cut, the water flooding index is a constant, 1, at the injection-to-production ratio of 1, increases at the injection-to-production ratio above 1, and decreases at the injection-to-production ratio below 1.

The water storage rate, $E_i$, is defined as:

$$E_i = \frac{W_i - W_p}{W_i} = 1 - \frac{W_p}{W_i}$$ (1)

The injection-to-production ratio is defined as:
Formulas (1) and (2) were combined to give:

\[ E_i = 1 - \frac{1}{Z \cdot \left(1 + V \cdot \frac{N_o}{W_p}\right)} \]  

The relationship between cumulative water production and cumulative oil production in Type A flooding curve is as follows:

\[ \log W_p = A + BN_p \]  

The water product formula is obtained as follows:

\[ W_p = W_{p1} - W_{p2} = 10^{(A+B \cdot N_{p1})} - 10^{(A+B \cdot N_{p2})} \]  

Formula (5) is taken into Formula (3) to obtain the theoretical relationship between water storage rate, \( E_i \), and recovery degree, \( R \), as follows:

\[ E_i = 1 - \frac{1}{Z \cdot \left[10^{(A+B \cdot N_o \cdot V)} - 10^{(A+B \cdot R_2 \cdot N_o)} + 1\right]^{-1}} \]  

- \( E_i \)-- Injection-to-production ratio.
- \( W_i, N_p, W_p \)--Water injection, oil production, and water production, \(10^4\) t.
- \( Z \)--Injection-to-production ratio.
- \( V \)--Crude oil conversion coefficient.
- \( A, B \)--Intercept and slope of the line section in the flooding curve.
- \( N_{p1}, W_{p1} \)--Cumulative oil production and water production before flooding, \(10^4\) t.
- \( N_{p2}, W_{p2} \)--Cumulative oil production and water production after flooding, \(10^4\) t.
- \( N_o \)--Geologic reserve, \(10^4\) t.
- \( R_1, R_2 \)--Recovery degrees before and after flooding.

When the total water cut reached a value during oilfield flooding, one line segment occurred in the flooding curve. If the oil recovery method in the injection and production system did not change greatly, the development tended towards this line segment. When a representative line segment occurred in the flooding curve, the oilfield data were used to plot a flooding curve. After regression, \( A \) and \( B \) values were determined, and taken along with \( N_o \), \( V \) and rational injection-to-production ratio, \( Z \), into Formula (6) to give the recovery degrees before and after flooding, \( R_1 \) and \( R_2 \) (The difference between \( R_1 \) and \( R_2 \) should be 0.5%-2%), according to which the corresponding \( E_i \) was calculated. The curve of theoretical relationship between water storage rate, \( E_i \), and recovery degree, \( R \) at different recovery degree was plotted. The water storage rate in the actual phase of oilfield was marked in the curve, and the flooding effect could be identified by comparing with standard curve. If the actual point fell below the \( E_i \) curve, the water storage rate was too low and the development effect was bad; If the actual point fell above or near the \( E_i \) curve, the water storage rate and development effect tended towards the planned objective. According to the definition of water cut:

\[ \frac{N_p}{W_p} = \frac{1 - f_w}{f_w} \]  

Formula (7) was taken to Formula (3) to give the theoretical relationship between water storage rate, \( E_i \), and water cut:

\[ E_i = 1 - \frac{1}{Z \cdot \left(1 + V \cdot \frac{1 - f_w}{f_w}\right)} \]
According to the definition of water flooding index:

\[ E_{wi} = \frac{W_i - W_p}{N_p \cdot V} = \frac{Z \cdot (W_p + V \cdot N_p) - W_p}{V \cdot N_p} \]  

(Formula 9)

Formulas (7) and (9) were combined to give the theoretical relationship between water flooding index, \( E_{wi} \), and water cut:

\[ E_{wi} = (Z - 1) \cdot \left( \frac{1}{V} \cdot \frac{f_w}{1 - f_w} \right) + Z \]  

(Formula 10)

- \( E_{wi} \)--water flooding index.
- \( f_w \)--water cut.

3. Practical Application of Evaluation Index to Block H

It was fifty years since Block H was developed in 1965. A representative line segment occurred in the flooding characteristic curve[3]. We use actual water injection time in year for analysis and calculation. Table 1 listed the development data of Block H and the calculated actual water storage rate and water flooding index. According to the plotted flooding curve, the line segment of the flooding curve of this block had the following intercept, \( A \), and slope, \( B \):

\[ A = 2.770452 \]  
\[ B = 0.000430 \]

\( A \) and \( B \) were taken into Formula (6) to obtain the water storage rate and water flooding index at different recovery degrees at a given rational injection-to-production ratio. In addition, annual actual water storage rate and water flooding index were calculated according to the actual annual water injection, annual oil production and annual water production of this oilfield. According to the above calculated water storage rate and water flooding index at the corresponding recovery degrees at different injection-to-production ratios, the curve of recovery degree vs. water storage rate and the curve of recovery degree vs. water flooding index were plotted[4].

It could be seen from the curve of water storage rate vs. recovery degree for Block H (Figure 2) that with increasing recovery degree from 1972 to 1987, the water storage rate quickly decreased to 9%, with annual average drop of 5.6%; from 1988 to 1996, the water storage rate stably increased mainly because No. 1, 2 and 3 basic well patterns put into production in 1971 were recovered by automatic spray, with low water injection; flow-to-pump of basic well patterns was comprehensively achieved in 1986, with an increase in water injection and water storage rate; No. 4 basic well pattern put into production in 1989 increased the water storage rate. With increasing recovery degree after 1996, the water storage rate tended towards 15%. it was believed that No. 1 and 2 infilled wells are drilled, basic well patterns were shut in at a large scale, and injection wells were continuously shut in, resulting in a decrease in water injection and water storage rate. After infilled wells were put into production, middle to low permeability reservoirs were drilled to control water cut and increase oil production, resulting in an increase in water storage rate; the water storage rate curve for Block H gradually tended towards to the recovery degree 45% as theoretical value, and the oilfield development tended towards a good prospect.

**Table 1. Calculated Ei of Block H**

| \( N_p \) \( \times 10^4 \) | \( V \) | time | \( N_p \) \( \times 10^4 \) | \( W_p \) \( \times 10^4 \) | \( \Delta N_p \) \( \times 10^4 \) | \( \Delta W_p \) \( \times 10^4 \) | \( Z \) | \( E_i \) % |
|---|---|---|---|---|---|---|---|---|
| 9367 | 1.3 | 1971 | 20.0909 | 111.6209 | 0.0941 | 91.5299 | 0.0941 | 0.15 | 99.4604 |
| | | 1972 | 229.3129 | 1.8898 | 117.6920 | 1.7957 | 0.66 | 98.4325 |
| | | 1973 | 343.2533 | 10.0230 | 113.9404 | 8.1332 | 1.28 | 96.8816 |
| | | 1974 | 457.6704 | 37.2232 | 114.4171 | 27.2002 | 1.24 | 93.1098 |
| | | 1975 | 588.2910 | 96.5959 | 130.6206 | 59.3727 | 1.19 | 88.1301 |
| | | 1976 | 720.3576 | 185.5399 | 132.0666 | 88.9440 | 0.98 | 82.6801 |
| | | 1977 | 838.4759 | 303.8534 | 118.1183 | 118.3135 | 1.18 | 78.1837 |
| | | 1978 | 963.6949 | 459.9871 | 125.2190 | 156.1337 | 1.26 | 74.3816 |
| | | 1979 | 1110.8478 | 654.9177 | 147.1529 | 194.9306 | 1.25 | 71.2774 |
| Year | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Value | 1260.8423 | 912.6870 | 149.9945 | 257.7693 | 67.2801 | 1408.7004 | 1222.4738 | 147.8581 | 309.7868 | 63.9550 | 1542.0867 | 1586.2747 | 133.3863 | 363.8009 | 1.12 | 67.2801 | 1666.6130 | 1994.5358 | 124.5263 | 408.2611 | 1.19 | 63.9550 | 1792.2542 | 3147.4906 | 127.6205 | 654.3797 | 0.93 | 57.7159 | 1919.8748 | 3835.2270 | 118.1141 | 687.7364 | 0.90 | 53.8874 | 2037.9888 | 1542.0867 | 1586.2747 | 133.3863 | 363.8009 | 1.12 | 67.2801 |

Theoretically, with increasing water cut at one injection-to-production ratio, the water injected into formations was continuously produced, so the water storage rate decreased; at one water cut, the higher injection-to-production ratio leaded to higher water storage rate. It could be seen during comparison of actual water storage rate and water cut curve and theoretical curve for Block H in Figure 3 that the theoretical injection-to-production ratio for Block H fell near 1.2, while the actual injection-to-production ratio for Block H was 1.1, showing Block H had higher water storage rate than theoretical value, indicating a high ratio of utilization of injected water.

The distribution scatter diagram of actual water flooding index and water cut for Block H was above the theoretical curve for water flooding index (Figure 4). The trendline of water flooding index for Block H fell between 1.2 and 1.4, and was above theoretical curve for the actual injection-to-production ratio, showing good flooding effect[5]. The water cut increment slowed down and the water flooding index increased by a series of adjustment, showing better flooding effect.
4. Water Injection Status

For the oilfield at super high water cut stage, it was very difficult to adjust various indices. The water storage rate decreased annually, the water flooding index tended towards a constant, and the injection efficiency decreased[6]. In recent years, however, Block H maintained high water storage rate and low oil production decrement, the water cut increased slowly, and the recovery degree of recoverable reserves increased by effective development and adjustment. According to the oilfield development conditions, the main problems of Block H include big high to low pressure well ratio, and poor reservoir producing status of thin & poor zones.

The corresponding control measures were made by analysis. Main technical thoughts include:

1. The unidirectional single-layer high water cut reservoirs were mainly injected with water and controlled by plane adjustment or periodic injection; the multi-directional high water cut reservoirs were mainly plugged to reduce the ineffective fluid and high pressure injectivity, control the low efficient or inefficient circulation, and increase the water storage rate[7].

2. Aiming at poor reservoir producing status of thin & poor zones, more improvement measures
were taken for oil wells, and fracturing was mainly used for oil wells; acidification measures were taken for oil reservoir pollution caused by water well; the reservoirs, to which water was difficulty injected to, would be fractured because of poor development and connectivity[8].

5. Conclusion
(1) The injection-to-production ratio was the important factor to determine the water storage rate and water flooding index. The water storage rates and water flooding indices of different reservoirs were not comparable, so the flooding effect in a phase was evaluated according to the reservoir status.

(2) The flooding status in Block H was evaluated by water storage rate and water flooding index. The next key work was to implement the adjustment measures and maintain high water storage rate and water flooding index in Block H.

(3) The applicability and reliability of water storage rate and water flooding index in oilfield flooding effect evaluation were verified by practical application to Block H.

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