Research and Application of Optimized Integrated Profile Control in Wang 36 Well Area of Wangjiawan Oilfield

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Abstract. Aiming at the problems of serious heterogeneity of reservoirs in Wang 36 well area of Wangjiawan Oilfield, rapid rise of water cut in the oilfield, poor waterflooding development effect and unsatisfactory effects of conventional single profile control measures. Based on PI decision-making, a comprehensive profile-adjustment decision-making technique based on factors such as heterogeneity of water absorption profile and rising rate of water cut is developed. Field application shows that the overall profile adjustment of the block effectively improves the water flooding effect of Wang 36 block. This method has the characteristics of fastness, practicality and strong operability, and has important guiding significance for comprehensive treatment of similar oilfields.

1. Introduction
Wangjiawan Oilfield is a heterogeneous reservoir with low permeability and microfractures. After years of waterflood development, oilfield injection water penetrates into the low-pressure and high-permeability zone or fracture zone of the reservoir, resulting in poor waterflooding effect [1, 2]. Because the conventional single-well profile control technology in the field has a short validity period and poor results, exploring the overall profile adjustment using blocks as a unit has become an important requirement for oilfield development [3].

The Wangjiawan Oilfield is located in the middle of the Yishan slope in the Ordos Basin. The main oil-bearing layer is 2 oil layers long and belongs to fluvial sediments. The average porosity of the reservoir is 11.95%, and the average permeability is $7.96 \times 10^{-3} \text{m}^2$. The average formation temperature is 40 °C, the original formation pressure is 9 Mpa, the average degree of formation water salinity is 32000 mg/L, the water type is mainly CaCl₂, and the reservoir driving type is elastic and weak hydraulic pressure driving. Water injection development began in this area in 2005. At present, there are 486 oil wells and 163 water injection wells, with a daily output of 2646 m³, a daily output of 494.3 t, and a comprehensive water content of 81.7%. Among them, the average daily well production fluid is 5.5 m³, the daily oil production is 1.1 t, and the water injection pressure is 5.6 MPa. Wang 36 well area has 7 water injection wells and 17 oil wells.

The main factors affecting the profile decision [2, 3]
There are many factors that influence the decision of profile selection and well selection, mainly from the following aspects:
(1) Parameters reflecting water absorption capacity of water injection wells: including apparent water absorption index per meter, water absorption index per meter, wellhead pressure drop, etc;

(2) Parameters that reflect the heterogeneity of the reservoir, such as the coefficient of variation of permeability and the heterogeneity of the water absorption profile;

(3) Parameters that reflect the dynamics of surrounding wells, such as changes in fluid production and water cuts in connected wells.

From the above influencing factors of profile adjustment decision, it can be seen that factors such as formation permeability, wellhead pressure drop, water absorption profile, and injection dynamics are recognized as the basis for well selection. However, in practical applications, these factors are not easy to accurately grasp. According to the study by Li Yikun of China University of Petroleum, the $PI$ value (pressure index) of water injection wells has a specific relationship with formation permeability, formation thickness, daily water injection volume, and viscosity of the injected fluid, which can reflect the seepage characteristics of the formation. The $PI$ decision technology is based on the wellhead pressure drop curve of the injection well, and the $PI$ value is the technology of the overall profile decision parameter of the block, which can simply, quickly, and quantitatively select the well accurately. In order to facilitate field operations and simplify decision-making parameters, the average $PI$ value and $PI$ level difference of the block are used as the basis for the overall profile adjustment of the block. The pressure index, the water rise rate of the well group, and the percentage breakthrough coefficient of the water absorption profile were used as the basis for selecting the profiled well layer.

2. Holistic profile control decision method

2.1. Calculation of $PI$ value

The $PI$ profile control technology is an important technique to determine the profile adjustment timing and well selection decision based on the pressure index ($PI$) value obtained based on the pressure drop curve of the injection well. The $PI_t$ value is calculated from the pressure drop curve of the injection well according to its definition. Figure 1 shows the pressure drop curves of three typical injection wells. Curves I, II, and III are obtained by connecting the injection well with the high-permeability, middle-permeability, and low-permeability layers [4, 5].

![Pressure drop curve of typical injection well](image)

**Figure 1.** Pressure drop curve of typical injection well

In order to quantify the pressure drop curve of the injection well as a decision parameter, it can be calculated from the area integral under the curve when the shut-in time is $t$ (Figure 2), then calculate the $PI_t$ value from equation (1):

$$PI_t = \frac{\int_0^t p(t) dt}{t}.$$ (1)
$PI_t$-Pressure index of water injection well, MPa; $p(t)$-Pressure at shut-in time $t$, MPa; $t$-Shut-in time, min.

It can be seen from equation (1) and Figure 2 that under the same condition of closing time $t$, the smaller the $PI_t$, the higher the permeability of the water-injection formation.

![Figure 2. Schematic diagram of pressure change over time after well closure](image)

2.2. Calculation of $PI$ rounding value

Because the water injection intensity ($q/h$) of each injection well is different, the $PI_t$ value of each injection well is not comparable. In order to make the $PI_t$ value of the injection well comparable with the $PI_t$ value of other injection wells in the block, each injection The $PI_t$ value of the well is rounded to the same $q/h$ value. The same $q/h$ value can select the nearest rounded value of the $q/h$ average value of the block injection well. The rounded value $PI_t^G$ of $PI_t$ can be obtained from equation (2).

$$PI_t^G = \frac{PI_t}{G} \cdot q/h$$

$PI_t^G$- Rounded value of $PI_t$ value, MPa; $q/h$-Water injection intensity of water injection well, m$^3$·d$^{-1}$·m$^{-1}$; $G$- Rounded value of $q/h$ average value of block water injection wells, m$^3$·d$^{-1}$·m$^{-1}$.

2.3. Calculation of profile fullness (FD value)

The degree of profile adjustment can be judged by the fullness (FD value) calculated from the pressure drop curve of the wellhead of the injection well. The fullness is equal to the ratio of the area under the pressure drop curve of the injection well to the area of $P_0 \cdot t$ (Figure 3).

![Figure 3. Conceptual diagram of fullness of pressure drop curve of injection well](image)
Fullness $FD$ is defined by:

$$FD = \frac{\int_0^t p(t)dt}{p_0 t} = \frac{1}{p_0} \int_0^t \frac{p(t)dt}{t} = \frac{PI_t}{p_0}. \quad (3)$$

$FD$—Fullness; $P_0$—Water injection pressure for injection well before shut-in, MPa; $t$—Elapsed time after closing the well, min; $PI_t$—The pressure index value when the shut-in time is $t$, MPa. It can be seen from equation (3) that the fullness can be calculated from the $PI_t$ value and the water injection pressure $P_0$ of the injection well before shut-in. Under normal circumstances, the $FD$ value of the profile adjustment well is less than 0.65 before the profile adjustment, and after profile adjustment, the $FD$ value is generally between 0.65 and 0.95.

2.4. Necessity judgment of overall block profile adjustment

The block for overall profile selection must be a block with high water cut and low extraction, with large inter-layer differences and poor development effect. There are two criteria for judging the profile adjustment of a block in Table 1. The first is the average $PI$ value of the block. The smaller the average $PI$ value, the more profile adjustment is required. According to field statistics, blocks with average $PI$ values below 10 MPa need to be profiled; the second is the extremely poor $PI$ between the injection wells in the block. The $PI$ value range is the difference between the maximum and minimum $PI$ values of the block’s water injection wells. The larger the value, the more the profile adjustment is required. The block with the range exceeding 5 MPa needs profile adjustment.

Seven water injection wells in the Wang 36 well area measured in July 2015. After 90 minutes, the wellhead pressure drop curve and the pressure index was $PI_{90}$. The corrected value of $PI_{90}$ was corrected with the rounded value of 6.5 m$^3$·d$^{-1}$·m$^{-1}$ and recorded as $PI_{90}^{6.5}$. From Table 1, the maximum, minimum, the range, $PI_{90}$ rounding value and $FD$ value are 7.73 Mpa, 0 Mpa, 7.73 MPa, 1.98 MPa, 0.17, respectively. The range of $PI$ values in the well area exceeds 5 MPa, so profile adjustment is needed.

| Pound sign | Date        | Water injection layer thickness (m) | Daily fluence (m$^3$·d$^{-1}$) | Water injection pressure (MPa) | $PI_{90}$ (MPa) | $FD$ (m$^3$·d$^{-1}$·m$^{-1}$) | $PI_{90}^{6.5}$ (MPa) |
|------------|-------------|----------------------------------|--------------------------------|--------------------------------|----------------|--------------------------------|----------------------|
| 1 Wang36-6 | 2015.7.12   | 2                                | 18.24                          | 0                              | 0              | 0                              | 9.12                 |
| 2 Wang72-2 | 2015.7.12   | 2                                | 8.83                           | 3                              | 0.04           | 0.01                          | 4.41                 |
| 3 Wang82   | 2015.7.12   | 2                                | 26                             | 3                              | 0.13           | 0.04                          | 13                   |
| 4 Wang82-4 | 2015.7.12   | 8                                | 10                             | 3.1                            | 0.1            | 0.03                          | 1.25                 |
| 5 Wang82-1 | 2015.10.6   | 14                               | 15                             | 5                              | 0.19           | 0.04                          | 1.07                 |
| 6 Wang36-2 | 2015.10.17  | 2                                | 14.64                          | 7.5                            | 4.86           | 0.64                          | 7.32                 |
| 7 Wang53-6 | 2015.9.29   | 2                                | 19.2                           | 8.9                            | 11.41          | 0.45                          | 9.6                  |
| Average    |             | 4.57                             | 25.27                          | 4.36                           | 2.39           | 0.17                          | 6.5                  |

2.5. Determination of profile control well

Based on the use of overall profile adjustment technology to determine whether a block or unit needs profile adjustment, the main basis for choosing a profile adjustment point is the $PI$ rounding value of the injection well, the heterogeneity of the water absorption profile, and the dynamic response of injection and production. According to the research, a water injection well with one of the following characteristics can be determined as a profile adjustment object:

Water injection well whose $PI$ rounding value is significantly lower than the average $PI$ value of the block; The heterogeneity of the water absorption profile is strong, manifested by the peak-shaped water absorption characteristics in the layer or the water absorption of the high-permeability layer and the poor
water absorption of the low-permeability layer. Water injection well; Through the dynamic adjustment and analysis of the water volume of the injection wells, the fluid volume and water cut of the corresponding effective oil wells have changed significantly, and the monthly water cut rate of the effective oil wells is higher than 2% [7, 8].

3. Profile selection and dosage

3.1. Profile Modifier Selection

The choice of profile control agent for injection wells is mainly based on the PI value of the injection well, the salinity of the formation water, the formation temperature, and the location of the plugging agent. Under the conditions of formation temperature and injection salinity of Block Wang 36, three kinds of gelatin microsphere dispersions with particle sizes ranging from nanometers to millimeters were obtained by different polymerization methods in accordance with orthogonal test methods, respectively SD-310, SD-320, SD-350. The microsphere dispersion can deform and move under the pressure fluctuations of the formation, resulting in multiple plugging, which has the characteristics of "plugging without death"; The cross-linking agent is an organic chromium cross-linking agent SD-107 and an inorganic chromium cross-linking agent SD-101 with controlled freezing time and strength and good stability.

According to the characteristics of different PI values of the water injection wells and the dynamic analysis of the water seepage characteristics of the effective oil wells, different intensity profile control agents were used for classification and profile control. For well groups whose PI value is less than 4, and the water rising speed is accelerated, the high-strength microsphere particles, double gel crosslinker, and low-medium strength microsphere particle formulation profile control plug profile control system are designed; For well groups with PI values greater than 4, the predominant channels are not developed, but the plane contradictions are more prominent, and the water content is rising slowly, a low-strength small-particle microsphere profile control system is selected (Table 2).

| Category | $PI_{90}$ range (MPa) | Water injection well number | Process countermeasures |
|----------|------------------------|-----------------------------|-------------------------|
| 1        | 0~4, the dominant channel is developed, and the rising rate of water content is accelerated | Wang82, Wang82-1, Wang82-4, Wang36-6, Wang72-2 | Fully profile for gel and particle profile, then deep profile for microspheres |
| 2        | Above 4, the dominant channel is not developed, the water content rises slowly, and the contradiction in the plane is more prominent | Wang53-6, Wang36-2 | Deep profile adjustment of jelly microspheres |

3.2. Calculation of the amount of profile modifier

(1) Dosage of frozen gel profile:

$$V_1 = \beta h \Delta PI$$  \hspace{1cm} (4)

$V_1$-dosage of profile modifier (m$^3$); $\beta$-dosage coefficient, select a value in the range of 5~50 m$^3$·MPa$^{-1}$·m$^{-1}$ for test injection; $h$-shooting layer thickness of water injection well (m); $\Delta PI$-the difference between the expected value of $PI_{90}$ and the current value of $PI_{90}$, increase the $PI$ value by 2~5 Mpa. The calculation of 5 water injection wells in the block shows that the total amount of block gel profile adjusting plugging agent in the block is 2700 m$^3$. 

(2) Dosage of microsphere profile:
\[ V' = \pi (R_2^2 - R_1^2) h \phi \alpha \gamma \]  

(3) \( V' \)-Estimated dosage of profile modifier, \( \text{m}^3 \); \( R_2 \)-The radius of the profile control agent outside the high permeability layer, \( \text{m} \); \( R_1 \)-The radius of the profile control agent in the high permeability layer, \( \text{m} \); \( h \)-Stratum thickness, \( \text{m} \); \( \phi \)-Porosity; \( \alpha \)-Fraction of high permeability layer thickness in water injection layer thickness; \( \gamma \)-The direction coefficient of profile control agent injection is 0.25–1. The calculation of 2 water injection wells in the block shows that the total amount of block microsphere deep profile modifier is 1260 \( \text{m}^3 \).

3.3. Field application effects
Overall profile adjustment of 7 water injection wells in Wang36 well area from 2015-9-26 to 2015-11-7. The statistical data before and after profile adjustment of water injection wells show that the wellhead pressure drop curve of the block after profile adjustment significantly moves up and slows down (Figure 4, Figure 5). The water injection pressure in the block tends to be similar, and the average water injection pressure increased from 4.36 MPa before profile adjustment to 6.46 MPa. The average PI value of the water well increased from 1.98 MPa to 16.66 MPa, and the FD value increased from 0.17 to 0.80. The sharp increase in PI value indicates that the high-permeability zones and large channels of the block have been effectively blocked, and the seepage conditions in the longitudinal and planar reservoirs have been improved. After the profile adjustment, 12 wells were effective, with a daily increase of 3.2 t, and the water cut decreased by 5.2%. As of the end of June 2016, the cumulative oil increase was 615.9 t, and the input-output ratio reached 1:1.21, achieving good economic benefits.

Figure 4. Pressure drop curve of water injection well before profile adjustment

Figure 5. Pressure drop curve of water injection well after profile adjustment

4. Conclusion
Based on the dynamic and static data of the oil and water wells in the actual block and combined with the PI decision-making technology, the overall profile adjustment effect is significant and the site operability is strong; Through the overall profile control of Wang 36 block, the waterflooding condition has been significantly improved, the water injection pressure has been increased, and the rising rate of water cuts has been suppressed, providing a theoretical basis for similar oilfields.

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