Mechanism of advanced water injection and its application in Yuan A well area

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Abstract. In order to explore an effective way to further increase the single well production and improve the development effect of low permeability fractured oilfield, it provides a new theoretical and practical basis for oilfield development in Taizhao area; Through the study of advanced water injection mechanism and field test in source A well area, an effective displacement pressure system is established in low permeability reservoir, which reduces formation damage caused by formation pressure drop and initial water cut of oil well, and optimizes the scheme by combining modeling and numerical prediction, water injection development adjustment and so on; Therefore, the output of the oilfield at the initial stage of production is increased; Good development results have been achieved in the early stage of production after 6 months' advanced water injection in source A well area, and it is advisable to carry out advanced water injection for 6 months in the development of low permeability fractured oilfield.

Keywords: Advance water injection; Low permeability oilfield; Pressure.

1. Introduction
In order to explore an effective way to further increase the single well production and improve the development effect of low permeability fractured oilfields, in 2011, Yuan A well area was selected as the demonstration area for increasing the single well production in Taizhao701 block. Pu I formation in development horizon of Yuan A well area. Putaohua reservoir has an effective porosity of 13.1-25.2%, with an average of 20.1%, and an air permeability of 0.41-139.0× 10^-3 m², with an average of 36.81× 10^-3 m². Putaohua reservoir belongs to a medium-pore and low-permeability reservoir, and its sand body is mainly distributed in sheet sand with good reservoir connectivity and natural fractures. By deepening the detailed description of reservoir, optimizing the design of single well scheme, carrying out advanced water injection, applying cutting-edge technology, making efforts to optimize the scheme in terms of drilling, completion methods, water injection development adjustment, etc., so as to improve the single well production and the overall development effect of the block.

2. Mechanism and function of advanced water injection
Advanced water injection refers to an injection-production mode in which injection wells are injected before the production wells are put into production, and water injection is carried out for a certain period of time, so that the formation pressure is higher than the original formation pressure. When the oil wells
are put into production, the oil saturation in the drainage area is not lower than the original oil saturation, and the formation pressure is higher than the original formation pressure, and an effective displacement system is established.

2.1. **Advanced water injection has established an effective pressure displacement system**

According to the theory of seepage fluid, within the limit oil supply radius, the utilization degree of movable oil is directly proportional to the driving pressure gradient, and the greater the driving pressure gradient, the greater the utilization degree of movable oil. Because of the small pore radius in low permeability reservoirs, the influence of boundary layer of crude oil is obvious, and pressure gradient appears in the flow process. A large number of research data show that the starting pressure gradient is inversely proportional to the permeability, and the lower the permeability, the greater the starting pressure gradient. The percolation characteristic of low permeability oilfield is non-Darcy percolation, and fluid flow needs a certain start-up pressure difference. Advanced water injection increases formation pressure, and makes the pressure gradient in more channels of oil layer larger than the start-up pressure gradient. Therefore, advanced water injection can make the formation have higher pressure gradient and larger production pressure difference, that is, an effective pressure displacement system is established.

2.2. **Advanced water injection reduces formation damage caused by formation pressure drop**

Most low-permeability oilfields are accompanied by fracture development. When the formation pressure of low-permeability reservoirs drops greatly, the reservoir porosity will decrease, the fractures will be closed and the permeability will decrease. Then the formation pressure will be restored by water injection, and the permeability will only be restored to about 70%. Advanced water injection keeps high formation pressure and reduces the damage of micro-fracture permeability caused by the decrease of formation pressure; by implementing advanced water injection to increase the pressure gradient, the relative permeability of water phase has little change, but the relative permeability of oil phase has increased. At the same time, under the action of higher water injection pressure difference, the partially closed microfractures in the reservoir are opened, thus increasing the permeability of the formation microfracture system.

2.3. **Advanced water injection reduces the initial water cut of oil wells**

According to the experimental results, when the oil-water two phases make quasi-steady seepage in low permeability formation, their respective flows conform to the linear seepage law with starting pressure gradient. Under the condition of low permeability, there is a starting pressure gradient in the seepage process, and the formation seepage is characterized by non-Darcy seepage. At this time, there are many factors that affect the water cut. Besides the oil-water viscosity ratio, the influences of permeability and ultimate shear stress of crude oil cannot be ignored. Under other conditions being the same, the lower the permeability, the larger the starting pressure gradient and the higher the water cut. Advanced water injection increases formation pressure and reduces the damage of formation pressure drop to formation porosity and permeability. After improving reservoir permeability, the starting pressure gradient decreases. When the oil well is put into production after advanced water injection, the initial water cut of the oil well will decrease, thus improving the development effect of the oil field.

2.4. **Advanced water injection always keeps high formation pressure, which is beneficial to improve ultimate recovery**

In low permeability oilfield, lagging water injection or synchronous water injection is adopted, and the injected water will preferentially rush along the higher permeability interval with small seepage resistance. In addition, the pressure drop in the production section of the higher permeability interval is relatively large, which further aggravates the rush of the injected water along the higher permeability layer, reducing the plane sweep efficiency of the injected water and lowering the efficiency of water flooding. With advanced water injection, because the formation of low permeability oilfield is in the original pressure equilibrium state before it is put into development, the pressures at all points are
basically consistent, and the injected water pushes outward in the formation around the bottom hole evenly when injecting water wells. At first, the injection water advances along the higher permeability section with small seepage resistance. When the formation pressure of the higher permeability section increases, the injection water increases. At the same time, the pressure difference between the high and low permeability sections forces the injection water to enter the lower permeability section, which increases the formation pressure of the lower permeability section and reduces the pressure difference between them. It can drive out the crude oil with finer pores, thus improving the sweep efficiency of water injection plane, increasing the oil displacement efficiency and improving the oilfield development effect.

3. Determination of technical parameters of advanced water injection

3.1. Reasonable water injection time
In the development of low permeability oilfield by advanced water injection technology, with the extension of advanced water injection time, the cumulative injection volume increases and the single well output increases in a curve trend. However, due to the limitations of surface injection equipment and formation conditions, high pressure physical properties of crude oil, well pattern, well pattern density and advanced water injection cost, the advanced water injection time cannot be extended indefinitely, that is, there is a reasonable advanced water injection time. Reasonable advanced water injection time refers to the advanced water injection time when the economic benefit reaches the maximum. The water injection time can be calculated by the following formula:

\[ t = \frac{\beta \alpha \eta p_i N B_o \omega C_e}{B_w \lambda + B_o} - 1 \]  

In the formula: \( \beta \) can be defined as follows: the crude oil produced by advanced water injection technology is \((1 + \beta)\) times that produced by synchronous water injection (from experience, the value range of \( \beta \) is generally 20% ~ 30%); \( \beta = 25\% \)

\( \alpha \)—The holding coefficient of advanced water injection pressure is constant for a specific oilfield; \( \alpha = 1.16 \)

\( \eta \)—Market price of crude oil; \( \eta = 3600 \) (Rmb/ton)

\( P_i \)—Original reservoir pressure; \( P_i = 14.18 \)Mpa

\( N \)—Original reserves of strata; \( N = 25.1 \times 10^4 \)t

\( B_{oi} \)—Original crude oil volume coefficient of reservoir; \( B_{oi} = 1.087 \)

\( C_e \)—Comprehensive elastic compression coefficient of reservoir; \( C_e = 14.23 \times 10^{-4} \)Mpa\(^{-1} \)

\( B_w \)—Volume coefficient of formation water; \( B_w = 1.01 \)

\( \lambda \)—Average water-oil ratio; \( \lambda = 1.33 \)

\( B_o \)—Volume coefficient of formation oil. \( B_o = 1.28 \)

According to the formula, calculate \( t \approx 6 \) (month)

3.2. Determination of horizontal limit of pressure maintenance
In the process of advanced water injection, the formation pressure continues to rise, but when it reaches a certain value, the formation pressure will tend to be stable. With the continuous improvement of the formation pressure maintenance level, the oil well productivity does not rise in a straight line at the initial stage of production, but when the formation pressure is maintained at 110% ~ 120%. 110% ~ 120% oil well is suitable for production.

3.3. Maximum injection pressure of injection well
When water injection is advanced, it should be injected at a larger water injection pressure as far as possible, but it should not exceed the formation fracture pressure, so as to avoid the formation of cracks. At present, there are two methods to define the highest pressure in taizhao tian area.
The first one: old district empirical formula method (2-2), according to the old district empirical formula, the average maximum allowable water injection pressure is 19.3MPa

\[ P_{\text{Maximum allowed}} = 0.13H \times 0.0981 + 0.5 \] (2)

The second type: investigate the calculation method of Yongle Oilfield in the adjacent No.8 Oil Production Plant, and its calculation formula is as follows (2-3)

\[ P_{\text{Maximum allowed}} = (P_s - P_\text{静}) \times \frac{2v}{1-v} + P_v + P_\text{阻} + S_i \] (3)

Type in: 
- \( P_s \) — Overburden pressure, MPa; (the value is 0.023H)
- \( P_\text{静} \) — Static water column pressure, MPa; (the value is 0.01 H)
- \( H \) is the middle depth of oil layer
- \( v \) — Poisson ratio; (the value is 0.24)
- \( P_\text{阻} \) refers to flow resistance loss, ground and vertical pipe loss and resistance loss during water injection, MPa, (The value of ground pipe is 0.5 MPa, the vertical pipe loss is 0.5 MPa, and the resistance loss is 1.0 MPa)
- \( P_v \) is seepage resistance, MPa (the value is 2.0 MPa)
- \( S_i \) is the tensile strength of reservoir rock, MPa (the value is 4.0 MPa)

According to the method (2), the average maximum allowable water injection pressure is 23.0MPa.

Comprehensive analysis of the characteristics of four groups of fractures developed in taizhao (Table 1), combined with two methods, the average maximum allowable water injection pressure in source a well area is finally determined to be 15.09MPa.

Table 1. Comprehensive evaluation table of grouping fracture parameters of Putaohua oil layer in Taizhao area

| Fracture orientation | EW direction crack | NW-trending fracture | SN-trending crack | NE-trending fracture |
|----------------------|--------------------|----------------------|-------------------|----------------------|
| Opening pressure of wellhead fracture (Mpa) | 15.09 | 19.58 | 27.74 | 27.92 |
| Average crack opening (μm) | 100 | 70 | 50 | 65 |
| Average permeability (×10-3μm2) | 499 | 171.2 | 62.4 | 137 |

3.4. Reasonable flowing pressure of oil production well
The oil production index of oil wells in low permeability oil fields is small. In order to maintain a certain oil well production, it is generally necessary to reduce the flow pressure and enlarge the production pressure difference. However, if the flow pressure is too much lower than the saturation pressure and exceeds a certain limit, the degassing radius of the oil well will be enlarged, the oil phase permeability will be reduced, and the oil well production will not only stop increasing, but also decrease. Therefore, there is a minimum allowable flow pressure at the bottom of the oil well.

The quantitative relationship between the minimum allowable flowing pressure of oil well and saturation pressure and formation pressure is as follows:

\[ p_{of\text{min}} = \frac{1}{1-n} \left( n^2 p_s^b + n(1-n) p_b p_R - n p_b \right) \] (4)

\[ n = \frac{0.1033a T (1 - f_m)}{293.15 B_o} \] (5)

In which: 
- \( p_{of\text{min}} \) — Minimum allowable flowing pressure oil well, MPa;
- \( p_s \) — Saturation pressure, MPa. \( p_s = 5.2 \)
- \( p_b \) — Formation pressure, MPa. \( p_b = 14.18 \)
The formula shows that the factors affecting the minimum allowable flow pressure of oil wells include formation pressure, saturation pressure, physical properties of crude oil and water cut of oil wells.

According to the formula, the minimum allowable flowing pressure of oil wells at the initial stage of development is 3.24MPa.

According to Li Daopin, a reservoir engineering expert, the reasonable flowing pressure of oil wells should be kept at about 2/3 of the saturation pressure. According to this principle, the reasonable flowing pressure of oil wells at the initial stage of development is calculated to be 3.46MPa.

According to the above discussion, for oil extraction, the reasonable flowing pressure of oil well should be to ensure the minimum allowable flowing pressure of reservoir, so as to make the oil well have the maximum oil production. It is determined that the reasonable flowing pressure of oil well should be controlled at about 3.3MPa at the initial stage of development.

4. Modeling and numerical simulation research

4.1. Establishment of fracture model

Putaohua oil layer in Yongle Oilfield has relatively developed fractures. In order to finely characterize the reservoir characteristics, reservoir geological modeling is carried out on the basis of comprehensive study of reservoir geology, imaging logging and other data. The fracture module of PETREL software is mainly used to describe the fracture with random simulation algorithm, and a discrete fracture model is established. According to geological data, the fracture density, location and opening are described to determine the porosity and permeability of fractures. Finally, the fracture network model is generated by adjusting parameters layer by layer, and the interpretation results of single well fractures are consistent with those of single well fractures. Through simulation, the maximum length of fractures in Yuan A well area is 150m, with an average of 30m, which develops in the near east-west direction and is densely distributed. According to the distribution of fractures in the plane of each sedimentary unit, the most developed fractures are PI2 and PI4, and the fractures are distributed in a large area in the well area.

Figure 1. Fracture equivalent model of fractured reservoir after coarsening in Yuan A well area
4.2. Prediction of water injection schemes in different periods

In order to ensure the operability of the scheme, synchronous water injection and different advanced water injection time schemes are designed, and the changes of formation pressure, cumulative oil production and daily oil production are compared. According to the comparison results of formation pressure, although the formation pressure drops obviously at the initial stage of perforation, with the extension of water injection time, the formation pressure will recover steadily, and the formation pressure of the two schemes of water injection for 4 months and water injection for 9 months keeps a relatively high level. In the synchronous water injection scheme, because the formation has not gone through the stage of rapid pressure increase, the additional resistance of reservoir fluid seepage channel is large, and the formation pressure has been steadily increasing. From the initial daily oil production, there is little difference in the initial oil production at different advanced water injection times, but the daily oil production at the initial stage of implementing the advanced water injection scheme is obviously higher than that of synchronous water injection, and has always maintained a relatively high level. On the whole, the formation pressure reached 1.16 times and 1.22 times of the original formation pressure when water injection was carried out for 6 months and 9 months in advance, and the initial daily oil production and cumulative oil production kept good indexes.

Table 2. Formation pressure prediction table when different water injection schemes are put into production

| Conceptual design | Formation pressure | Pressure recovery level (%) |
|-------------------|--------------------|---------------------------|
| Programme 1       | 16.11              | Advance water injection for 4 months | 113.61 |
| Option 2          | 16.52              | Advance water injection for 6 months | 116.50 |
| Option 3          | 17.32              | Advance water injection for 9 months | 122.14 |
| Option 4          | 17.46              | Advance water injection for 12 months | 123.13 |
| Option 5          | 14.18 (Original reservoir pressure) | Synchronous water injection | 100 |

Figure 2. Formation pressure variation curves at different water injection times
5. Field test results of advanced water injection

5.1. Water injection wells in advanced water injection wells
There are 7 water injection wells in Yuan A well area, and the injection was completed in the first ten days of November 2011. The average thickness of sandstone perforated by a single well is 4.3m, and the effective thickness is 2.6m, all of which adopt dynamic negative pressure perforation. Among them, there are 6 layered water injection wells and 1 general water injection well (Yong 201- Xie 63, the interlayer is stuck), with an average daily injection allocation of 21.43m³, an average injection pressure of 9.61MPa at the initial stage of injection and an average daily actual injection of 24.57m³. At present, the average injection pressure is 14.4MPa, and the daily actual injection is 21.6m³. At present, the accumulated water injection is 7 months and 3.0791×10⁴m³.

5.2. Oil well production in advanced water injection well area
There are 16 oil wells in Yuan A well area, with an average perforated sandstone thickness of 3.8m and an effective thickness of 2.4m, which was put into production in late April 2012. At present, 14 oil wells have been put into normal production. At the initial stage of production, the average daily liquid production and oil production of a single well are 5.2t and 5.2t respectively. At present, the average daily liquid production and oil production of a single well are 5.2t, 0.3386×10⁴t and 0.3386×10⁴t respectively.
5.3. **Comparison of development effect between advanced water injection well area and adjacent water injection well area**

Since the Yuan A well area was put into development, the development effect of the test well group is better than that of the adjacent well group with synchronous water injection put into production in 2011. First, the oil well has high fluid production intensity, which is 2.17t/d.m in the Yuan A well area and 0.625 t/d.m in the adjacent well group; Second, the dynamic liquid level of oil wells is high, with an average dynamic liquid level of 581m in Yuan A well area and 1256m in adjacent well groups. Third, the pressure level is relatively high, with 13.46Mpa in Yuan A well area and 8.72Mpa in adjacent well groups.

6. **Conclusions**

(1) Good development results have been achieved in the early stage of production after 6 months' advanced water injection in Yuan A well area, and it is advisable to carry out advanced water injection for 6 months in the development of low permeability fractured oilfield.

(2) According to the analysis of the characteristics of four groups of fractures developed in Taizhao, combined with the empirical formula, the average maximum allowable water injection pressure in Yuan A well area is 15.09MPa.

(3) Study on the adjustment method of water injection scheme in advanced water injection demonstration area, and explore the reasonable working system of water wells after the demonstration area is put into production.

7. **References**

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