Study on deep profile control technology and field evaluation of water flooding thick layer in Lamadian Oilfield

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Abstract. Nine wells are on deep profile control in SaⅢ1-7 layer of Lamadian Oilfield North West block. Flexible diverting agent are be used to carry out high-dose and long slug deep profile control. Injection profile of injection wells are improved, the radius of plugging is expanded and the plugging efficiency is improved. It has certain adaptability to the profile control of thick layers, and can improve the condition of reservoirs absorption. It can reserve technology for large scale deep profile control on water flooding, and create a new way for high efficiency development the ultra-high water cut oilfield.

Keywords: deep profile control; Flexible diverting agent; reserve technology.

1. Introduction
After the oilfield entered the stage of ultra-high water cut development, water out of all kinds of reservoirs are very serious, especially in thick layers. According to the data of water washing in closed coring wells, in the upper part of the rhythmic field, the proportion of unwashed thickness is 34.94%, the proportion of feebleness watering thickness is 11.65%, the displacement efficiency is 27.20%, and the average recovery is 25.71%. In the lower part of the rhythmic field, the proportion of strongly washed thickness is 33.08%, the displacement efficiency is 65.30%, and the average recovery is 45.01%. The upper part of rhythmic field is 20 percentage points lower than the lower part. Inefficient and low efficient cycle in thickness layer is serious, which lead to low recovery, production cost rising and oilfield development benefit decline. It is the main adjustment direction of water control and potential tapping. Therefore, control inefficient circulation is a revolution in the oilfield at ultra-high water cut stage.

2. The generality of the test area
2.1. Principle of well selection and layer selection
(1) The drilling rate of sand body in the selected well area is over 90%, and the sand body connectivity rate is over 85%;
(2) The reservoir heterogeneity is serious, and the permeability level in layer or interlayer is more than 6;
(3) The difference in profile utilization is large. In most profile control wells, the ratio of the thickness of high permeability and high water absorption layer to the total thickness is below 30%, and the absorption strength is above 8m3/m.d.

(4) The water injection starting pressure of injection wells is less than 4.5MPa

(5) The water cut of more than 80% of the oil well in profile control area is more than 90%.

(6) Wells are in good condition, without casing damage, channeling and interlayer leakage.

Determination of deep profile control layer: Combined with logging curves, core analysis and other results in profile control wells and based on the water injection profile of the target well, the high permeability and high water absorbent layer with good connectivity at the bottom of thick layer is given priority. Based on the above principles, it is determined that the 6-PS2004 area is test area. Target layer is SaⅢ1-7 layer and depth is 990m to 1180m. It is divided into 4 sedimentary units. The average sandstone thickness of test area is 14.1m, the effective thickness is 9.7 m, the average effective permeability is 0.611μm², and the geological reserves is 37.14 x 10⁴t. The test area of five spot well pattern consisted of 9 injection and 16 production wells.

3. Parameter determination of profile control technology

3.1. Determination of profile control agent amount

3.1.1. Determination of the steering radius of flow. According to the results of numerical simulation and water flooding profile control test, a better profile control effect can be achieved by selecting 1/2 to 1/3 of the corresponding well spacing of oil and water wells as profile control radius. According to the actual situation, the profile control radius of 1/2 to 1/3 well spacing is 44m. The actual calculation is based on 45m, the profile control radius can realize the purpose of deep fluid diversion.

3.1.2. Determination of the steering area of flow. Calculation formula:

\[ S = 3.14 \times R^2 \times \beta_n \times n/4 \]

\( S \)—Profile control area, m²; \( R \)—Profile control radius, m; \( \beta_n \)—Area coefficient of profile control; \( n \)—Profile control direction.

Considering that the direction of profile control is basically four directions, according to the direction of profile control, the area coefficient of profile control is determined to be 0.86.

3.1.3. Determination of fluid diverting agent amount. Calculation formula:

\[ V = \sum_{i=1}^{n} Hi \times Si \times \phi \]

\( V \)—profile control agent amount, m³; \( Hi \)—Profile control thickness, m; \( Si \)—Profile control area, m²; \( \phi \)—Average porosity of profile control layer

3.2. Injection mode of profile control agent

The injection mode is nontarget profile control. The profile control agent is squeezed by profile control pump from oil pipe. The profile control agent is mixed with the mixing water through the charging hopper and then entered the mixing liquid pool.
3.3. Profile control agent formulation and slug design

3.3.1. Selection principles of profile control agents. In order to ensure that the non-profile layer is not polluted, the selection of particle size of the profile control agent should follow principles.

First, the selection of particle size for profile control agent should be based on the increase of injection pressure and adopt the principle of “from small to large”.

Second, the particle size must be compatible with the formation throat radius. When the particle size is 1/9 to 1/3 of the throat radius, the plugging effect is the best.

Third, the profile control agent has uniform particle size, good sorting grade and sufficient strength. Combining with the actual situation of the reservoir, nanometer-micron microsphere particles, SR-3 flexible steering agent which particle size is 3mm to 5mm, and millimeter level volume expanding profile control agent are used.

3.3.2. Design principles of profile control slugs. According to the test block condition, the slug was optimized. Based on the flexible particle steering agent, profile control plugging was designed to three stages. 100 m$^3$ sealing agent were added into main agent slug 1 and main agent slug 2 to enhance the effect of profile control. According to the geological design schemes, second scheme was selected as the implementation scheme. According to laboratory displacement results and site construction experience, combined with the parameters of pore throat, porosity and permeability of the test block and under the designed injection pressure condition, the concentration of 0.3 to 0.5% microspheres was selected as the main slug 1. SR-3 flexible particle diversion agent with a concentration of 1.3% and a particle size of 3mm to 5mm, and a concentration of 6150mg/L volume expanding profile control agent were selected as the main slug 2. Finally, 100m$^3$ sealing agent was injected as sealing plug.

SR-3 flexible particle steering agent with a particle size of 3mm to 5mm account for 60% of the main agent (the concentration is about 1.3 %). Microspheres and volume expanding particles account for 40% of the main agent. The specific injection volume is split according to the ratio of each single well designed in table 1.

(1) First, the microspheres with 0.3% to 0.8% concentration were injected into the deep of the high permeability layer to temporarily plug. Slow down the migration velocity of subsequent injection main slug to prevent the main slug entering the relative low permeability layer too much and weaken the plugging effect.
(2) The 3 - 5mm SR-3 flexible steering agent with a concentration of about 1.3% and volume expanding particles with a concentration of about 6150mg/L are injected sequentially. According its own deformation to migration and through the throat, flexible steering agent migrated into deep of layer.

(3) Single well was injected into 100m³ calcium lignosulfonate composite gel with a concentration of about 5% as sealing agent for preventing profile control agent spitting back. It enhanced the anti-scouring ability of profile control agent and ensured the effect of water subsequent flooding.

Table 1. Design scheme of profile control slug

| wellname  | Total injection (m³) | nano-microspheres (m³) | nano-microspheres (%) | Scheme Two | flexible steering agent (m³) | flexible steering agent (%) | volume expanding particles(m³) | volume expanding particles(%) | sealing agent(m³) |
|----------|----------------------|------------------------|-----------------------|------------|-----------------------------|-----------------------------|-------------------------------|-------------------------------|-----------------|
| L6-PS1938 | 4740                 | 1402                   | 30.24                 |            | 2785                        | 60                          | 453                           | 9.76                          | 100             |
| L6-PS2002 | 4130                 | 1356                   | 33.68                 |            | 2420                        | 60                          | 254                           | 6.32                          | 100             |
| L6-PS2008 | 5210                 | 1368                   | 26.76                 |            | 3065                        | 60                          | 677                           | 13.24                         | 100             |
| L6-PS1936 | 3820                 | 1067                   | 28.64                 |            | 2230                        | 60                          | 423                           | 11.36                         | 100             |
| L6-PS2004 | 5210                 | 1589                   | 31.08                 |            | 3065                        | 60                          | 456                           | 8.92                          | 100             |
| L6-PS2006 | 4280                 | 1336                   | 32.00                 |            | 2510                        | 60                          | 334                           | 8.00                          | 100             |
| L6-PS1928 | 4590                 | 1413                   | 31.48                 |            | 2695                        | 60                          | 382                           | 8.52                          | 100             |
| L6-AS2012 | 4130                 | 1064                   | 26.44                 |            | 2420                        | 60                          | 546                           | 13.56                         | 100             |
| L6-AS2018 | 7070                 | 1814                   | 26.00                 |            | 4180                        | 60                          | 977                           | 14.00                         | 100             |
| Total     | 43180                | 12408                  | 25370                 |            | 4502                        |                             |                               |                               | 900             |

4. Comprehensive evaluation of overall profile control in site implementation

4.1. Increasing injection pressure

There are 9 injection wells in the test area. The average number of shooting layers is 5.0. The sandstone thickness is 14.5m and the effective thickness is 11.1m. The injection pressure before the profile control is 5.5MPa, the average daily water injection per well is 42m³, and the apparent injectivity index is 7.6m³/d · MPa. After profile control in the same injection strength situation, the injection pressure increased gradually, and the apparent injectivity index decreased. The starting pressure increased from 3.3MPa before profile control to 5.6MPa after profile control, and increased by 66.7%. The injection pressure increased from 5.5MPa before the profile control to the current 8.4MPa, increased by 52.7%. The apparent injectivity index decreased from 7.6m³/d·MPa before profile control to 3.9m³/d·MPa after profile control, and decreased by 48.7%.

Fig. 2 Water injection curve of profile control well
4.2. Water injection profile improvement

By comparing the isotope water injection profile before and after profile control, the profile of water injection well after profile control was obviously improved. The relative water absorption of the high permeability layer was decreased by 28.6%, and the water absorption of the low permeability layer was increased by 32%. By comparing the oxygen activation profile measured for the first time after profile control with that before profile control, it can be seen that the profile of water injection well has been improved obviously after profile control. The relative water absorption of the high permeability layer was decreased by 26.8%, and the water absorption of the low permeability layer was increased by 34.9%.

| wellname      | Water absorption reduction of high permeability layer(%) | Water absorption increases of low permeability layer(%) |
|---------------|----------------------------------------------------------|-------------------------------------------------------|
|               | isotope | oxygen activation | isotope | oxygen activation |
| L6-AS2012     | 33.2    | 26.4              | 31.4    | 26.1              |
| L6-AS2018     | 31.8    | 16.8              | 31.8    | 37.4              |
| L6-PS1928     | 23.1    | 15.8              | 23.0    | 34.4              |
| L6-PS1936     | 39.0    | 28.0              | 28.2    | 29.4              |
| L6-PS1938     | 29.0    | 34.1              | 34.0    | 36.6              |
| L6-PS2002     | 27.5    | 34.1              | 43.6    | 42.0              |
| L6-PS2004     | 27.6    | 24.3              | 24.3    | 28.1              |
| L6-PS2006     | 16.5    | 46.8              | 31.0    | 52.0              |
| L6-PS2008     | 29.4    | 14.9              | 41.1    | 28.3              |
| Average       | 28.6    | 26.8              | 32.0    | 34.9              |

4.3. Effective on increasing oil and decreasing water

Through the profile control of 9 injection wells in the test area, the effect of increasing oil of 16 oil wells around was obvious. It can be seen that the comprehensive water cut of test area dropped from 96.7% before the profile control to the current 88.9%. It dropped by 7.8 percentage points. The daily oil production rate increased from 15.7t before the profile control to the current 46.7t, which increased average daily oil production of 1.9t. The daily liquid production rate decreased 56t compared with that before the profile control, and the decrease amplitude was 11.7 percentage points, which achieved better profile control effect.

![Fig. 3 Recovery curves of 16 wells in the vicinity of profile control wells](image)
5. Conclusion and cognition
(1) Reasonable well selection and layer selection, optimum formulation of profile control agent, structure of profile control slug and dynamic adjustment during profile control are the keys to successful profile control.

(2) Multi-slug combination profile control overcomes the shortcomings of single plugging agent. The effect of profile control can be improved to the greatest extent. It can achieve deep profile control, expand the plugging radius and improve the plugging efficiency.

(3) Flexible steering agent SR-3 profile control technology can greatly improve the recovery of Class II Reservoirs after water flooding, and achieve the expected effect of overall deep profile control, which has a certain popularization value.

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