Research and application of profile control and water shutoff technology in fractured sandstone reservoir based on system analysis method

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Abstract. Huoshaoshan Oilfield is a sandstone reservoir with severe heterogeneity. After years of enhanced water flooding, the reservoir conditions have changed greatly. Based on the research results of fine reservoir description, the key to successful industrial application of large-scale water shutoff and profile control is to select suitable water shutoff and profile control agents and improve injection technology and evaluation technology. This technology has become a leading technology for improving water flooding recovery in the development of extra-high water cut stage in Huoshaoshan Oilfield, with remarkable economic benefits. In this paper, the main factors affecting the performance of pre-gel system and the flow experiment used to test its performance index are described by systematic analysis method, and the construction effect of well group H1194 is briefly introduced.

Keywords: Systematic analysis; Fractured sandstone; Profile control and water shutoff

1. Introduction
Huoshashan Oilfield is a layered low-ultra-low permeability sandstone oilfield complicated by fractures, with fracture widths ranging from tens of microns to 3,000 microns. The application of water control and plugging technology has played an important role in improving the development effect of Huoshashan Oilfield and completing the annual crude oil production task [1]. Sand production is very serious in the development process, and it is easy to form large channels, which seriously affects the normal production of Huoshan Oilfield. Sand control and profile control and water shutoff are two major technical problems faced by Huoshan Oilfield [2]. In the past, separate injection, chemical profile control and other water injection adjustment measures have achieved certain results in improving the development of the whole block. However, due to the high formation temperature in this block, the effect of these measures gradually deteriorates at about 70℃. In order to improve the water flooding recovery ratio of Huoshaoshan Oilfield, which is already in the very high water cut stage, the application research of profile control and water shutoff technology in fractured sandstone reservoir is carried out based on the system analysis method.

2. Discussion on mechanism of sand control and water shutoff
Dry cement sand is a mixture of cement and quartz sand according to a certain proportion. The cement
used is generally G-grade high-resistance oil well cement. According to different types of cement, appropriate additives are added in the formula to improve the bonding strength between cement and quartz sand. According to the molar ratio of phenol to formaldehyde and the catalyst used, the speed and products of addition and polycondensation are also different [3]. On the plane, the water injection condition at the side edge of the facies belt is poor, the water flooding degree is low, and the remaining oil is rich; The remaining oil near the reservoir boundary fault is rich; The remaining oil potential is great in areas with poor water injection and poor control of injection-production well pattern. Cement in dry cement sand has formed cement slurry with sand-carrying fluid. When entering oil layer, the cement slurry follows the principle of preferential entry into large pore channels and high permeability layers, so more cement slurry is sucked into large pore channels or high permeability layers. After the cement slurry entering into high permeability strips and large pore channels under formation conditions is consolidated, the main water outlet layer is blocked to achieve the purpose of water plugging and water content reduction.

3. Laboratory study on deep profile control agent

3.1. Study on crosslinking time of new phenolic resin gel

Six newly prepared phenolic resin cross-linking agents were injected with water according to the ratio of polymer concentration of 0.5%+ cross-linking agent concentration of 0.8%, and then placed at a constant temperature of 70°C to observe the cross-linking time. Because of the different lithology, physical properties and control degree of injection-production well pattern in each longitudinal rhythm layer, there are obvious differences in water flooding between layers, and there are still potential layers with relatively low water flooding degree and relatively rich remaining oil. According to PI values of blocks and water injection wells, profile control is carried out for water injection wells below the block average, and injection wells above the block average are increased, while water injection wells near the block average are generally temporarily not treated [4]. with the increase of water content, sand production increases, and the permeability is extremely poor, so that thousands of cement sands easily enter the high-permeability water production zone, and the water shutoff efficiency increases, but the oil increase decreases with the increase of recovery degree and the decrease of remaining oil volume.

3.2. Study on series plugging agent

Through indoor evaluation and field application, there are 14 kinds of water shutoff and profile control agents suitable for water injection wells in Huoshaoshan Oilfield, and the selection of profile control agents is mainly based on the P value. The corresponding relationship between PI value and profile control agent can be obtained by indoor and field experiments [5-6]. Screen out the most suitable well points and plugging agent types for profile control, and predict the development index and the input-output ratio of profile control [7].

The calculation formula of pressure index of water injection well is:

\[
PI = \frac{1}{t} \int_{t_0}^{t'} p(t)dt
\]  

(1)

The formula for calculating the dosage of profile control plugging agent is:

\[
W = \beta h \Delta PI
\]  

(2)

The formula for calculating the dosage of profile control plugging agent is:

\[
FD = \frac{1}{P_0} \int_{t_0}^{t'} p(t)dt = \frac{PI}{P_0}
\]  

(3)

In which:

PI —— Pressure index of water injection well, MPa;
$p_0$ —— Water injection pressure of water injection well before shut-in, MPa;
$t$ —— During shut-in, min;
$p(t)$ —— Change value of wellhead pressure with time after shut-in, MPa;
$W$ —— Dosage profile control agent, t;
$\beta$ —— Dosage coefficient profile control agent, t / (MPa · m);
$h_f$ —— Sand thickness of water injection well, m;
$\Delta PI$ —— Scheduled pressure index increase value profile control well, MPa;
$FD$ —— Full degree.

On the basis of pressure index calculation of water injection wells and other test data (indicating curve and water absorption profile of water injection wells), qualitative and quantitative research is made on the characteristics and discrimination methods of full profile control of water injection wells. Put the system to be measured into a test tube with stopper scale, and insert it into the gel slowly with a clean 1 ml pipette, and connect the pipette with a vacuum pump. This is mainly due to the thick and well-developed oil layers of sedimentary facies, high oil-water well connectivity, strong heterogeneity and easy entry of dry cement sand into high permeability zone.

### 3.3. Effects of additives

The main function of additive XSN is to improve the overall strength of gel. The gap between polymer and cross-linking agent is used to form a network structure with high cross-linking degree on polymer chain, which improves the strength of plugging agent. RE decision-making technology [8] is used to make multi-factor comprehensive decision-making according to permeability, water absorption profile, injection performance and wellhead pressure drop curve [9]. The high displacement pump pressure indicates that the thickness is large, the heterogeneity is strong, and the permeability is extremely poor. The dry cement sand can easily enter the high permeability layer or large pore channel, and finally realize the plugging, give full play to the potential of the low permeability interval, and have long effective period and good oil increase effect. However, when the sealing radius increases to a certain value, the increase of recovery degree is very small. Through calculation, it is found that the sealing effect is better when the sealing radius of high permeability strip is 1/5~1/3.

### 3.4. Determination of breakthrough pressure in cracks

In each group of tests, a certain amount (usually 10 ~ 20 ml) of gel solution is injected into the fractured core at an injection rate of 3 ml/min, then the core is sealed for several days, and then the formation water is injected to determine the permeability change value. In the injection equipment, the injection pump is changed from a vertical electric pump to a 3HB 2 100 three-cylinder piston pump, which is equipped with a double-pump double-process system and an automatic metering and monitoring system for plugging agent preparation. Test and draw pressure drop curves of all water injection wells in this block, and calculate and regulate PI values of single wells and blocks; To demonstrate and adjust the necessity of profile control in blocks and single wells. Then, by adjusting the flow rate of the water injection pump at a speed of 0.12 MPa/min, the pressure is increased until the first drop flows out from the outlet end, and then there is a continuous outflow of liquid. Read out that the pressure at the inlet end is the breakthrough pressure. The results are shown in Table 1.

With the increase of the quality of additive XSA, the crosslinking time is shortened and the crosslinking strength of gel is increased accordingly, which is beneficial to the crosslinking effect of new phenolic resin gel. Therefore, XSA is selected as the additive component of new phenolic resin gel.
Table 1 Measurement results of fractured core breakthrough pressure

| Blocking agent formula | Core length / cm | Break through pressure /MPa | Break through the pressure gradient/MPa · m⁻¹ |
|------------------------|------------------|----------------------------|---------------------------------------------|
| I                      | 7.3              | 3.6                        | 50                                          |
| II                     | 7.3              | 4.2                        | 62                                          |
| III                    | 7.1              | 1.2                        | 15                                          |
| IV                     | 7.1              | 1.6                        | 21                                          |

4. Evaluation of water shutoff and profile control effect

Through the PI decision-making overall profile control of well h 1194 in Huoshaoshan oilfield, the water absorption situation in this block has been improved obviously. The production of crude oil tends to be stable, the rising rate of water cut slows down, and the recovery factor of water drive is greatly improved. The p value of profile control well rises. After overall profile control by PI decision, the pi value of the block is increased. The average value of PI is 2758 MPa before profile control and 3375 MPa after profile control.

![Figure 1](image-url)  
Fig.1 Overall profile control effect curve of Well H 1194
After the overall profile control of Well H 1194, the water cut rising rate is effectively controlled (see Figure 1), and the average annual water cut rising rate is controlled within 0.5%. The decline rate of output obviously slows down, and the annual natural decline rate is controlled within 10%. According to the calculation of water drive law, the water drive recovery ratio is increased by 3.8% after profile control, and the recoverable reserves are increased by $80.2\times10^4$ t (see Figure 2).

![Fig.2 Water drive curve of Well H 1194](image_url)

By analyzing and comparing the changes of development indexes such as water cut rise rate, natural decline rate and water flooding recovery ratio before and after profile control, the overall effect of water shutoff and profile control in the block is evaluated. After the profile control measures were implemented, the injection water pressure increased by 4MPa with the injection volume basically unchanged before and after the measures, indicating that the high permeability layer was effectively blocked and controlled, and the original production interval with low or no water absorption began to absorb water. For wells with low fluid volume before plugging, the effect of plugging with dry cement sand is poor. Invalid wells are mainly due to poor liquid supply capacity and low liquid volume of the oil well itself, and the liquid volume drops or does not supply liquid after water plugging, or because the formation is not fully filled during construction, thus failing to achieve the purpose of plugging high permeability layers or large channels.

The previous profile control effect of well H 1194 is not ideal. Increasing the dosage and strength of profile control agent is the key to successful profile control of well H 1194. By using incremental comparison method, the input-output ratio and economic benefit of water shutoff profile control are calculated by comparing and analyzing the capital investment (including plugging agent cost, construction cost, operation cost, monitoring cost, etc.) and the output value created after profile control (increased oil production, reduced water production, etc.).

5. Conclusions
The industrial application technology of large-area water shutoff and profile control is a leading technology for improving water flooding recovery in ultra-high water-cut oilfield. The optimization decision-making based on the research results of fine reservoir description is the basis of success, and the research on plugging agent and its compatibility with formation is the key to success. According to the reservoir geological conditions of Well H 1194 in Huoshaoshan Oilfield, a new type of resin crosslinked gel profile control plugging agent was developed through systematic research in the laboratory, which prolonged the validity period of water plugging and improved the temperature resistance. The pre-setting time of pre-gel system decreases with the increase of polymer concentration, crosslinking agent concentration and temperature, while the pre-gel viscosity increases with the increase of polymer and crosslinking agent concentration. It is the development direction of water shutoff and profile control technology to implement multi-round profile control of the whole unit and corresponding water shutoff and profile control of oil and water wells.
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