Mechanism of Enhanced Oil Recovery for In-Depth Profile Control and Cyclic Waterflooding in Fractured Low-Permeability Reservoirs

Daiyin Yin¹,² and Wei Zhou¹,²

¹Department of Petroleum Engineering, Northeast Petroleum University, Daqing 163318, China
²Key Laboratory of Enhanced Oil Recovery (Northeast Petroleum University), Ministry of Education, Daqing 163318, China

Correspondence should be addressed to Daiyin Yin; yindaiyin@nepu.edu.cn

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When fractured low-permeability reservoirs enter a high water cut period, injected water always flows along fractures, water cut speeds increase rapidly, and oil production decreases quickly in oil wells. It is difficult to further improve the oil recovery of such fractured low-permeability reservoirs. In this paper, based on the advantages of in-depth profile control and cyclic water injection, the feasibility of combining deep profile control with cyclic water injection to improve oil recovery in fractured low-permeability reservoirs during the high water cut stage was studied, and the mechanisms of in-depth profile control and cyclic waterflooding were investigated. According to the characteristics of reservoirs in Zone X, as well as the fracture features and evolution mechanisms of the well network, an outcrop plate fractured core model that considers fracture direction was developed, and core displacement experiments were carried out by using the HPAM/Cr³⁺ gel in-depth profile control system. The enhanced oil recovery of waterflooding, cyclic water injection, and in-depth profile control, as well as a combination of in-depth profile control and cyclic water injection, was investigated. Moreover, variations in the water cut degree, reserve recovery percentage, injection pressure, fracture and matrix pressure, and water saturation were monitored. On this basis, the mechanism of enhanced oil recovery based on the combined utilization of in-depth profile control and cyclic waterflooding methods was analyzed. The results show that in-depth profile control and cyclic water injection can be synchronized to further increase oil recovery. The recovery ratio under the combination of in-depth profile control and cyclic water injection was 1.9% higher than that under the in-depth profile control and 5.6% higher than that under cyclic water injection. The combination of in-depth profile control and cyclic water injection can increase the reservoir pressure; therefore, the fluctuation of pressure between the matrix and its fractures increases, more crude oil flows into the fracture, and the oil production increases.

1. Introduction

Reserves of low-permeability reservoirs account for 60%–70% of proven reserves in China [1–3]. Generally, there are abundant natural fractures in low-permeability reservoirs. Due to the great permeability ratio between fractures and matrices, injected water may always flow along fractures in the process of waterflooding, thus making the water cut of production wells increase too rapidly [4]. When a fractured low-permeability reservoir is in a high water cut period, CO₂ injection, hydraulic fracturing, in-depth profile control, or cyclic water injection can be used to further increase oil production. For CO₂ flooding, the injected CO₂ may always flow along the fracture due to the high conductivity of fractures [5–7]. Hydraulic fracturing is a commonly used method for increasing oil production in low-permeability reservoirs [8]. However, due to the existence of natural fractures and hydraulically fractured fractures, repeated fracturing will increase fluid filtration in the targeted formation [9], making it more difficult to create fractures in the reservoir. Moreover, if high aquifers are refractured, the water cut of oil wells will rise rapidly, and the degree of oil production will be lower.
For in-depth profile control, an in-depth profile control system has been developed for fractured low-permeability reservoirs [11, 12], and the representative deep profile control agents are crosslinked polymer weak gel [13, 14], pre-crosslinked gel particle [15, 16], colloidal dispersion gel [17, 18], etc. In-depth profile control has achieved good results in the Chaoyanggou block in the Daqing Oilfield. Field tests show that in-depth profile control can effectively block fractures and high-permeability reservoirs [19, 20], and it can cause subsequently displaced fluid to flow into low-permeability reservoirs to displace residual oil [21]. Nevertheless, in-depth profile control techniques have many problems, such as short-term validity, decreased effects of enhanced oil recovery, and scale formation from the reaction between bicarbonate radical ions in weak gels and calcium ions in strata [22]. Therefore, the enhanced oil recovery of in-depth profile control is limited. Cyclic water injection is also an effective method to develop fractured low-permeability reservoirs [23]. Due to pressure fluctuations of the matrix and fractures formed during cyclic water injection, crude oil in the matrix can flow to the fractures, which can improve the oil recovery of fractured low-permeability reservoirs [24, 25]. Field tests of cyclic water injection were carried out in the Yushulin block in Daqing. The field test results show that with increasing cyclic water injection frequency, the oil production gradually decreases. Usually, after two or three cycles, the oil production of cyclic water injection is very low [26–28]. Therefore, for fractured low-permeability reservoirs with high water cuts, CO₂ injection, fracturing, deep control, or cyclic water injection has a limited potential to improve oil recovery. Therefore, to further improve the recovery rate of fractured low-permeability reservoirs at the high water cut stage, combined with the advantages of in-depth profile control and cyclic water injection, the feasibility of in-depth profile control and cyclic water injection has been investigated through core displacement experiments. The fractured low-permeability core models were made according to the geologic characteristics of Zone X. The flooding, cyclic water injection, in-depth profile control, and combination of in-depth profile control and cyclic water injection were simulated, and the enhanced oil recovery was evaluated. The enhanced oil recovery mechanism of in-depth profile control and cyclic water injection was analyzed. Research conclusions can provide some references for the development of fractured low-permeability reservoirs in the high water cut stage.

2. Materials and Methods

2.1. Experimental Agentia and Apparatus. The in-depth profile control system consists of polyacrylamide, chromium chloride, lactic acid, and thiocarbamide. The polyacrylamide concentration was 1000 mg/L, and the relative molecular weight was 16 million. Chromium chloride and lactic acid were the crosslinking agents, the concentrations of chromic chloride and lactic acid were all 150 mg/L, and they were mixed according to a molar ratio of 1:3. Thiocarbamide was the stabilizing agent, and the concentration of thiourea stabilizer was 1000 mg/L. The gel viscosity of this deep system was 2869 mPa·s.

The in-depth profile control system was prepared by the produced water of oil wells in Zone X of the Daqing Oilfield. The salinity of this produced water was 3200.93 mg/L, and the pH value was 7.5. In this produced water, the K⁺Na⁺ concentration was 1054.67 mg/L, the Mg²⁺ concentration was 9.12 mg/L, the Ca²⁺ concentration was 55.11 mg/L, the HCO₃⁻ concentration was 793.26 mg/L, the CO₃²⁻ concentration was 32.39 mg/L, the Cl⁻ concentration was 1240.75 mg/L, and the SO₄²⁻ concentration was 18.01 mg/L.

Oils used in the experiment were mixed with kerosene and crude oil according to a certain ratio, and their viscosity was 6.7 mPa·s at 45°C.

The experimental apparatus included a ZJ-HK ultra-I thermostat, an ES-120 electronic analytical balance, a KJ-1
homogenizer, an NDJ-4 viscometer, a CS-501 ultrathermostat, a HXDSY flow experimental instrument, an LB-1 constant-flux pump, and a vacuum pump.

2.2. Experimental Core. Natural outcrop cores with permeabilities of $30 \times 10^{-3} \mu m^2$ were applied to develop the fractured low-permeability core models. According to natural fractures in Zone X, the included angle between east-west striking fractures and the well drains was approximately 22.5° (Figure 1(a)). The natural outcrop plate fractured core is shown in Figure 1(b). In actual low-permeability reservoirs, the fracture morphology and strike are very complex [29]. In this experiment, the fracture is simplified. It is assumed that the angle between the fracture and the well row is approximately 22.5° in the east-west direction, and the fracture morphology and strike are consistent. Moreover,
the actual fractured low-permeability reservoir has many oil layers at different depths [30]. To study the enhanced oil recovery mechanism of in-depth profile control and cyclic water injection methods in fractured low-permeability reservoirs, only a single layer is considered in the fractured low-permeability core model.

In Figure 1(b), five east-west striking fractures with an angle of 22.5° were set (dotted lines). The plate core was cut into 6 pieces according to the directions of dotted lines, and the spaces between any two pieces were filled with ceramsite proppants and binders. The permeability ratio between the fractures and the matrix is approximately 10. In addition, 9 injection-production wells were set on the plate model to simulate the injection-production mode of the inverse 9-point well network. In Figure 1(b), P1~P8 are simulated oil production wells at the extraction end, and I1 is the simulated injection well at the injection end. To monitor the pressure in the matrix and fractures throughout the experiment, pressure monitoring points were set on the model. Specifically, Pm1~Pm3 are pressure monitoring points in the matrix, while Pf1 and Pf2 are pressure monitoring points in fractures. In addition, five electrodes were set on the model to monitor changes in the water saturation of the matrix and fractures in the experiment. Resistances between any two electrodes were measured by an ammeter in the experiment. Water saturation was measured according to the corresponding relationship between resistance and water saturation. Em1~Em3 are water saturation monitoring points on the matrix, while Ef1 and Ef2 are water saturation monitoring points in fractures. The manufactured plate fractured core is shown in Figure 2.

The above manufacture method was adopted to make the fractured plate core models, and the corresponding simulation well points and monitoring points were set. The porosity, permeability, and irreducible water saturation were measured, as shown in Table 1.

| Schemes                     | Core no. | Polymer molecular weight (×10^4) | Polymer concentration (mg/L) | Injection velocity (mL/min) | Time for in-depth profile control or cyclic flooding (water cut, %) | Amount of profile control agent (PV) | Injection cycle (h) |
|-----------------------------|----------|----------------------------------|-----------------------------|-----------------------------|---------------------------------------------------------------|--------------------------------------|---------------------|
| Waterflooding               | #5-1     | —                                | —                           | 0.3                         | —                                                           | —                                    | —                   |
| In-depth profile control    | #5-2     | 1600                             | 1000                        | 0.3                         | 80%                                                          | 0.15                                 | —                   |
| Cyclic flooding             | #5-3     | —                                | —                           | 0.3                         | 80%                                                          | —                                    | 4                   |
| In-depth profile control and cyclic flooding | #5-4     | 1600                             | 1000                        | 0.3                         | 80%                                                          | 0.15                                 | 4                   |

2.3. Experimental Method. In the displacement experiment, the experimental core was put into a high-pressure container to simulate the temperature and pressure in the reservoir through confining pressure pumps and heating devices. The experimental process is shown in Figure 3.

The experimental process is composed of a conventional waterflooding stage, an in-depth profile control stage, and a...
cyclic waterflooding stage. The oil output and water output in the experiment were recorded. Experimental steps are introduced as follows:

(1) **Saturating Water**. The core was vacuumized to a negative pressure of -0.1 MPa with a vacuum pump, and the modulated simulation formation water saturation was realized. The core porosity was tested by the "weighing method."

(2) **Saturating Oil Saturation**. The core models were injected into the simulated oil from \( P_1 \) to \( P_8 \) at a rate of 0.3 mL/min. In addition, \( I_1 \) was used as the output end. When there was no water at the output end and the pressures at the two ends of the core were stable, the valves at the inlet and outlet were closed. The irreducible water saturation in the cores was calculated, and the cores were placed in a 45°C thermostat for 3 days.
(3) **Injecting Water to Displace Oil.** First, the reverse 9-point injection well pattern was adopted to inject water to displace the oil. Water was injected from I₁ at a rate of 0.3 mL/min. P₁−P₈ were used for oil production. The injection-production well pattern changed from a reverse 9-point pattern to a linear injection-production well pattern when the water cut reached 40%. P₄ and P₈ were changed into injection ends, and waterflooding continued until the water cut reached 98%.

Later, five turns were implemented, and waterflooding continued until the water cut reached 100%.

### 3. Enhanced Oil Recovery Based on a Combination of In-Depth Profile Control and Cyclic Waterflooding Methods

To investigate oil recovery based on a combination of in-depth profile control and cyclic water injection methods, displacement experiments were carried out for injecting water, injecting an in-depth profile control agent, and cyclic water injection, as well as a combination of in-depth profile control and cyclic waterflooding methods. According to the evolution of the oil well network in Zone X, all experiments employed the inverse 9-point injection-production well pattern in the waterflooding stage. However, a linear injection-production well pattern was applied when the water cut...
reached 40%, and experiments were stopped when the water cut reached 100%. The evolution forms of the well network are shown in Figure 4.

Different displacement schemes of reservoir oil under single waterflooding, single cyclic waterflooding, single in-depth profile control, and a combination of in-depth profile control and cyclic waterflooding are designed as shown in Table 2.

The relation curves of the water cut, percentages of oil recovery, and pressures of different injection volumes in these four enhanced oil recovery methods are shown in Figure 5. Oil recoveries under different enhanced oil recovery measures are shown in Table 3.

It can be seen from the experimental results that the water cut utilizing single waterflooding increases fastest, the injection pressure is low, the highest injection pressure is approximately 0.46 MPa, the recovery is low, and the final recovery is 45.1%. The water cut of the single deep profile control decreased greatly, and the lowest water cut was 71.3%, but the injection pressure was also high. The highest injection pressure was approximately 1.3 MPa, and the final recovery rate was 50.3%, which was 5.2% higher than that of waterflooding. The reduction in the water cut in a single cycle is small, the injection pressure is also low, and the enhanced oil recovery is small. The final oil recovery is 46.6%, which is 1.5% higher than that of waterflooding. For the combined deep profile control and cyclic water injection processes, the water cut decreased greatly, and the lowest water cut was 70.2%. The oil recovery was highest at 52.2%. It was 7.1% higher than that of single waterflooding, 1.9% higher than that of the single in-depth profile control method, and 1.9% higher than that of single cyclic waterflooding. Therefore, the combination of deep profile control and cyclic water injection can give full play to the synergistic effect of deep profile control and cyclic water injection, and it can further improve oil recovery for fractured low-permeability reservoirs at the high water cut stage.

4. Mechanism of Enhanced Oil Recovery of In-Depth Profile Control and Cyclic Waterflooding

The pressures, water saturation degrees in the matrix, and fractures of different injection volumes were monitored. Compared with single cyclic waterflooding in the stopping water injection stage and restoring water injection stage, the enhanced oil recovery mechanism of in-depth profile control and cyclic waterflooding was investigated. The experimental results are shown in Figures 6–8.

It can be seen from the experimental results that the maximum injection pressure is 0.5 MPa under single cyclic water injection, and the maximum injection pressure is 1.6 MPa under in-depth profile control and cyclic water injection. Compared with the single cyclic water injection, the combination of profile control and cyclic water injection can improve the pressure of the matrix and fracture. In the stopping injection water stage, the maximum pressure difference between the matrix and the fracture is 0.2 MPa under single cyclic water injection, and the maximum pressure difference between the matrix and the fracture is 0.6 MPa under in-depth profile control and cyclic water injection. In the stage of recovery water injection, the pressure difference between the matrix and the fracture is approximately 0.2 MPa under single cyclic water injection, and the pressure difference between the matrix and the fracture is 0.7 MPa under in-depth profile control and cyclic water injection. The combination of in-depth profile control and cyclic water injection increases the pressure fluctuation range between the matrix and the fracture. It makes more oil in the matrix flow into the fracture due to the pressure difference of the matrix and fracture, and it further reduces the oil saturation of the matrix. The oil saturation of the matrix was 36.8% at the end of single cycle water injection, and the oil saturation of the matrix was 33.5% at the end of in-depth profile control and cycle water injection. Therefore, more remaining oil in the matrix can be produced by adopting the combination of
in-depth profile control and cyclic water injection methods in fractured low-permeability reservoirs. In the in-depth profile control stage, the injected in-depth profile control agent gradually gelatinizes in the process of migrating in the reservoir, and it rapidly increases the matrix and fracture pressure. The fracture pressure increases more quickly than that of the matrix. The in-depth profile control agent can block the fracture, and it greatly decreases the permeability of the fracture. In the stopping injection water of cycle waterflooding, the pressure of the matrix and fracture decrease gradually, but the fracture pressure declines faster than the matrix pressure. When the fracture pressure is less than that of the matrix, the remaining oil in the matrix flows in the fracture, and the remaining oil is produced by the oil wells. In the restoring injection water of cycle waterflooding, the pressure of the matrix and fracture rises rapidly. This causes pressure fluctuations in the matrix and fractures. The injected water flows into the matrix, and the remaining oil of the matrix is produced from the oil wells.

5. Conclusions and Discussion

(1) For fractured low-permeability reservoirs, in-depth profile control and cyclic waterflooding can be coordinated to further enhance oil recovery in the high water cut stage. The oil recovery of in-depth profile control and cyclic waterflooding is 1.9% higher than that of in-depth profile control, 5.6% higher than that of single cyclic waterflooding, and 7.1% higher than that of conventional waterflooding.

(2) In-depth profile control and cyclic water injection methods can be used to combine the advantages of in-depth profile control and cyclic waterflooding. Fractures can be blocked through in-depth profile control, and the remaining oil can flow to the fracture through cyclic waterflooding. The combination of in-depth profile control and the cyclic water injection method can effectively exploit the remaining oil of the matrix in fractured low-permeability reservoirs. The remaining oil in the matrix after the in-depth profile control and cyclic water injection is 3.3% less than that of single cyclic water injection.

(3) The mechanism of enhancing oil recovery under in-depth profile control and cyclic water injection is that in the stage of in-depth profile control, the injected profile control agent makes the pressure in the matrix and fracture rise rapidly. The fracture pressure rises more quickly than that of the matrix, and profile control blocks the fracture. Then, cycle water injection was carried out, and the pressure difference between the matrix and the fracture was greater than that of single cycle water injection without in-depth profile control. This causes more remaining oil of the matrix to flow into the fracture due to the pressure difference, which increases the oil production of fractured low-permeability reservoirs.

(4) In the actual fractured low-permeability reservoir, there are many oil layers at different depths. The fracture morphology and fracture strike are very complex. The core displacement experiment method can only approximately simulate the development effect of in-depth profile control and cyclic water injection. It cannot be used to investigate whether the injection well can reach the rupture pressure under different recovery injection volumes. This needs to be combined with numerical simulation to further determine the reasonable parameters of in-depth profile control and periodic water injection. Therefore, the feasibility of in-depth profile control and periodic water injection should be determined by combining core experiments with reservoir numerical simulations, and the injection parameters for in-depth profile control and periodic water injection should be optimized before field testing in oilfields.

Data Availability

The data used to support the findings of this study are included within the manuscript. The figures and tables are the data used to support the findings of this study.

Conflicts of Interest

No conflict of interest exists in the submission of this manuscript.

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