The research and application of compound flooding system in the block L of Huabei oilfield

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Abstract: In the three rounds of gel flooding of the block L in Huabei oilfield, better effect of watercut decreasing and oil increasing had been achieved. In order to further develop the remaining oil potential, an oil-displacement slug was added on the basis of the gel slug, to form a compound flooding system in order to improve the oil displacement efficiency. Two types of oil displacement agents were optimized through basic performance evaluation. NO.I is surfactant. When the concentration was 0.3 percent, the oil-water interfacial tension could reach $1.15 \times 10^{-3}$ mN/m and still remain within the ultra-low interfacial tension range after 150 days under formation temperature but the static adsorption loss was only 3.4mg/g. NO.II is a kind of granular oil displacement agent with certain sealing ability. The initial particle size was 189nm and the size reached 520nm after hydration for 30 days and remained stable. In the sand filled tube with a permeability of $550 \times 10^{-3} \mu m^2$, the plugging rate was up to 70.88 percent. Through the double tube with high-low permeability core experiments, the oil displacement effect of movable gel, movable gel with oil displacement agent I and movable gel with oil displacement agent II were further compared. The results showed that movable gel with oil displacement agent II could improve oil recovery by 20.95 percent compared with water flooding, 7.88 percent compared with movable gel and 5.92 percent compared with movable gel with oil displacement agent I. The composite flooding system was applied in the block L with 6 wells and the effect of watercut decreasing and oil increasing was significant. The daily oil increase in peak period was 10t, and the watercut was decreased by 5.3 percent. The accumulative oil increase was 2736 tons with 13 months validity and will continue to be effective.

1. Introduction
The geological reserves of the block L in Huabei oilfield are $158.88 \times 10^4 t$, the recoverable reserves are $32.7 \times 10^4 t$ and the recovery degree is 17.33%. The production horizon is the Neozoic Guantao formation belonging to high-porosity and high-permeability reservoir with average porosity of 28.2% and average permeability of $550 \times 10^{-3} \mu m^2$. The reservoir temperature is 76°C. Due to the strong reservoir heterogeneity and the prominent longitudinal and plane contradictions, the injected water flows along the hypertonic zone seriously and the watercut rises rapidly. The comprehensive watercut
is reaching 98.8%. From 2010 to 2014, three rounds of profile controlling were carried out. The dominant channel was effectively blocked by injecting movable gel and the swept volume of waterflooding was expanded\[1\textendash}^[3], achieving well effect of watercut decreasing and oil increasing. In order to improve the development effect of waterflooding in block L further, aiming at the highly dispersion of residual oil, an oil-displacement slug was added on the basis of the gel slug to form a compound flooding system in the fourth round in order to improve the oil displacement efficiency.

2. Basic performance evaluation of oil displacement agent

Combined with the reservoir conditions of the block L, two kinds of compound flooding modes were preliminarily chose: gel with surfactant and gel with granular oil displacement agent. The movable gel with surfactant is mainly suitable for reservoirs which are in the later stage development with strong heterogeneity and high watercut[4\textendash}^[7]. Granular oil displacement agents have a certain strength and elastic deformation capacity, which can hinder or block off water flow in the pores. It can also be deformed through the pore throat and migrate to the deep formation. In addition, the 70% of content is surfactant and organic solvent, so they also have the effect of oil displacement[8\textendash}^[10]. Through the basic performance evaluation and oil displacement experiment, the best oil displacement agent product was selected and combined with movable gel to form a compound flooding system.

2.1 Performance evaluation of surfactant

2.1.1 Experimental materials and conditions. The experiment temperature is 75°C. In the experiment, water is from injected water and oil is from dehydration of crude oil of the block L. There are 3 kinds of surfactant: NO.I-1 is betaine amphoteric surfactant, NO.I-2 is fluorocarbon surfactant and NO.I-3 is long chain alkanolamide non-ionic surfactant. Interface tensiometer TX500D and constant temperature ovenare used.

2.1.2 Experimental methods. Interfacial tension: refer to the test method for the interfacial tension of surfactant in the standard SY/T 5370, the concentration of the mixture is from 0.1% to 1%. Static adsorption capacity: the static adsorption capacity is determined by referring to the standard SY/T 6424-2014 "performance test method for compound drive system".

2.1.3 Experimental results. The interfacial tension. The three surfactants can all reach the magnitude of ultra-low interfacial tension (10^{-3} \text{mN/m}) within the concentration range of 0.1% to 1%. When the concentration was from 0.1% to 0.5%, the interfacial tension of NO.I-1 was the lowest. The interfacial tension of NO.I-3 is the highest when the concentration is from 0.6% to 1%

![Fig.1 Interfacial tension properties of three surfactants](image)

Static adsorption loss. With the increase of surfactant concentration, the static adsorption capacity of the three surfactants showed an upward trend. At the same concentration, the adsorption loss of NO.I-2 was the largest, while that of NO.I-1 was lower than that of the other two surfactants.

2
After comprehensive consideration of the interfacial tension and static adsorption loss of the three surfactants, NO.1-1 betaine surfactant is recommended. The interfacial tension value can be as low as 1.15x10^{-3} mn/m and the static adsorption loss is 3.4mg/g when the concentration is 0.3%.

2.2 Performance evaluation of granular oil displacement agents

2.2.1 experimental materials and conditions. The experiment temperature is 75 °C. In the experiment, water is from injected water of the block L. There are four kinds of particle oil displacement agents, one of which is water-soluble dispersion system, the other three are oil-soluble, and the numbers are II-1, II-2, II-3 and II-4. Laser particle analyzer HOLIBA and the constant temperature oven are used.

2.2.2 experimental methods. Solid content, initial particle size and expansion ratio: the determination method refers to the standard Q/SY HB 0191-2015 "technical specification for flexible microgel for oil displacement".

Plugging performance: expressed by the plugging rate, the calculation formula is as follows: \[ \eta = \frac{K_1}{K_2}. \]
Where, \( K_1 \) and \( K_2 \) represent the permeability to water before and after sample injection respectively. The physical simulation device with long core was used for the experiment of plugging and migration. The experimental flow is shown in Fig.3. The core permeability is close to the average permeability of block L. Firstly, the sand-filled pipe was pumped out to saturate water and water flooding was carried out at a speed of 1mL/min until the pressure at each pressure measuring point was stable. Then 0.5PV of granular oil displacement agent with concentration 0.3% was injected at the rate of 1mL/min. After hydration for 5 days, secondary water flooding was carried out. The permeability was calculated according to the pressure change and then the plugging rate was obtained.

![Fig.3 flow chart of physical simulation experiment](image)

**Fig.3** flow chart of physical simulation experiment

2.2.3 experimental results. Initial particle size and solid content. The solid content of NO.I-2 sample was the smallest, only 13.5%, but the initial particle size was not further tested. The initial particle size
of the remaining three samples was all less than 500nm.

Table 1 The basic performance test results of particle oil displacement agents

| Number | solid content, % | pH of solution | initial particle size, nm |
|--------|------------------|----------------|---------------------------|
| II-1   | 40.8             | 6.5            | 191.9                     |
| II-2   | 13.5             | 4.0            | /                         |
| II-3   | 25.4             | 7.0            | 420.5                     |
| II-4   | 42.6             | 6.0            | 263.7                     |

Expansion multiple. The expansion performance evaluation results showed that different samples showed different expansion characteristics when exposing to water. The initial particle size of II-1 sample was 189nm. It reached 520nm after hydration for 30 days, remaining stable and the expansion multiple is 2.6 at 60 days. The initial particle size of II-3 sample was 425nm and the maximum was 653nm after hydration for 30 days. The particle size reduced to 505nm after 60 days. The initial particle size of II-4 sample was 264nm and the maximum reached 571nm after hydration for 10 days. So, the particle size stability of II-1 and II-4 samples are better.

Fig. 4 The changes of particle size with time for different samples

Ability to blockoff and migration. Physical simulation experiment was conducted to obtain the change of injection pressure of three samples after injection. It can be seen that the three samples have good penetrability and certain sealing strength.

Fig. 5 Sealing performance evaluation of II-1 (left)、II-3（middle）、II-4（right）

The plugging rates of the three samples were calculated according to the formula and the results were shown in table 2. No.II-1 has the strongest plugging ability and the plugging rate is 70.88%. Therefore, No.II-1 is optimized at a concentration of 3000mg/L.

Table 2 Sealing capacity of different particle oil displacement agents

| Number | Hydration time, d | Permeability to water, ×10^-3μm² | Inject volume, PV | Concentration, % | Residual resistance factor | plugging rate, % |
|--------|-------------------|----------------------------------|------------------|-----------------|--------------------------|-----------------|
| II-1   | 5                 | 512                              | 0.5              | 0.3             | 3.43                     | 70.88           |
| II-3   |                   | 558                              |                  |                 | 1.44                     | 30.43           |
| II-4   |                   | 530                              |                  |                 | 1.68                     | 40.47           |
2.3 evaluation of oil displacement performance

2.3.1 experimental materials and conditions. With reference to the instrument of plugging experiment, three groups of experiments with the dual-pipe parallel core were carried out to compare the oil displacement effect of injecting movable gel alone, injecting movable gel with surfactant and injecting movable gel with particle oil displacement agent. The permeability of core tube is based on block L with high permeability about 1000×10⁻³μm² and low permeability about 200×10⁻³μm².

2.3.2 experimental methods. After sand filling, the sand filling pipe was pumped out and saturated with formation water. The water phase permeability and pore volume were measured. Then saturated with produced oil from block L and aged for 7 days under the condition of 76°C. Waterflooding was carried out at the speed of 1mL/min until the watercut reached 98% and the waterflooding recovery was calculated. Different types of compound profiling agent (0.2PV) were injected at the rate of 1mL/min. After full coagulation and swelling, the secondary waterflooding was carried out until there was no oil at the outlet end and the final recovery rate was calculated.

Table 3 Basic data of test core

| Number | Pore volume mL | Porosity, % | Permeability, μm² | Permeability ratio | Injecting system |
|--------|----------------|-------------|-------------------|-------------------|------------------|
| 13#    |                |             |                   |                   |                  |
| High permeability | 247       | 27.2        | 0.96              | 5.05              | 0.2PV of movable gel |
| Low permeability  | 219       | 24.1        | 0.19              |                   |                  |
| 14#    |                |             |                   |                   |                  |
| High permeability | 289       | 31.9        | 1                 | 5.26              | 0.1PV gel +0.1PV1-I |
| Low permeability  | 232       | 25.6        | 0.19              |                   |                  |
| 15#    |                |             |                   |                   |                  |
| High permeability | 266       | 29.3        | 1.1               | 5.5               | 0.1PV gel +0.1PVII-I |
| Low permeability  | 226       | 24.9        | 0.2               |                   |                  |

2.3.3 experimental results. The gel mainly enters the high-permeability zone to form blocking and the subsequent fluid enters the low-permeability layer more frequently. The swept area of the low-permeability zone increases significantly. Surfactant is used to improve oil washing efficiency. Therefore, gel flooding or gel with surfactant flooding can increase recovery by 13% to 15%. After blocking the dominant flow channel in the high permeability zone with gel, some pore canals are still unaffected in the low permeability zone. The granular oil displacement agent mainly enters the low permeability area to block part of the throat, to improve the sweep range of water flooding greatly. At the same time, it can also play the role of oil displacement to improve the oil washing efficiency of high permeability and low permeability area. Therefore, among the three flooding modes, movable gel with particle oil displacement agent has the highest recovery range, reaching 20.95%.
Table 4 Enhanced oil recovery by different flooding methods

| Displacement system | Waterflooding recovery of single tube, % | Enhanced recovery for profile controlling, % | Waterflooding recovery, % | Final recovery, % | EOR, % |
|---------------------|----------------------------------------|---------------------------------------------|--------------------------|------------------|--------|
| Movable gel         |                                        |                                             |                          |                  |        |
| High permeability   | 40.05                                  | 10.07                                       | 30.26                    | 43.33            | 13.07  |
| Low permeability    | 11.36                                  | 14.19                                       |                          |                  |        |
| Gel with surfactant |                                        |                                             |                          |                  |        |
| High permeability   | 43.88                                  | 13.25                                       | 29.16                    | 44.19            | 15.03  |
| Low permeability    | 11.07                                  | 16.89                                       |                          |                  |        |
| Gel with particle oil displacement agent | |                                             |                          |                  |        |
| High permeability   | 44.15                                  | 13.99                                       | 27.30                    | 48.25            | 20.95  |
| Low permeability    | 9.46                                   | 41.63                                       |                          |                  |        |

3. Application effect
In September 2017, 6 wells of block L were applied with the compound flooding control system with a total injectin volume of 63510 m$^3$. The movable gel effectively blocked the dominant flow channel and the oil displacement agent entered the low permeability area to displace the remaining oil to improve the oil displacement efficiency. Therefore, the effect of watercut decreasing and oil increasing was significant. The daily oil increase in peak period was 10t and the watercut was decreased by 5.3 percent. The accumulative oil increase was 2736 t with 13 months validity and will continue to be effective.

![Fig.6 The well group production relationship curve](image)

4. Conclusions
i. the experiment evaluates the basic properties of three kinds of surfactant samples and four kinds of granular displacement modifier samples and two kinds of oil displacement agent is optimized. I-1 belongs to the surfactant. The interfacial tension value can be as low as 1.15×10$^{-3}$ mN/m and the static adsorption loss is 3.4 mg/g when the concentration is 0.3%. II-1 is a granular oil displacement agent with initial particle size of 189nm. It reached 520nm after hydration for 30 days, remaining stable. The plugging rate is 70.88% when the concentration is 3000mg/L.

ii. three groups of experiments with the dual-pipe parallel core were carried out to compare the oil displacement efficiency of movable gel, movable gel with surfactant I-1 and movable gel with particle oil displacement agent II-1. Movable gel with oil displacement agent could improve oil recovery by 20.95 percent compared with waterflooding, 7.88 percent compared with movable gel and 5.92
percent compared with movable gel with surfactant.

iii. The composite flooding system was applied in the block L with 6 wells and the effect of watercut decreasing and oil increasing was significant. The daily oil increase in peak period was 10t and the watercut was decreased by 5.3 percent. The accumulative oil increase was 2736 tons with 13 months validitiy and will continue to be effective.

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