Dynamic Imbibition Process Optimization for Ultra-low Permeability Sandstone Reservoirs

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Abstract. Reservoir space of ultra-low permeability sandstone reservoir has complex and special physical properties. The development performance and effects of water flooding in ultra-low permeability sandstone reservoir are determined by the permeability effect. The physical model of imbibition oil recovery is an important experimental method to optimize the formula composition of imbibition system and imbibition technology. Through a lot of oil sands static imbibition experiments for ultra-low permeability sandstone reservoir, three better imbibition agent systems are screened out. The dynamic imbibition oil recovery technology of the reservoir is optimized by using the core dynamic imbibition experiment and comparative experimental study.

1. Introduction
There are great differences in permeability between matrix rock blocks and fractures in low permeability reservoirs. It will cause the serious flooding and water channeling phenomena in reservoir exploitation by regular water injection method, and will affect the effective development of reservoirs. It is one of the effective measures to exploit ultra-low permeability sandstone reservoirs for oil recovery by imbibition mechanism at present.¹⁻⁵ The improvement of oil displacement efficiency by the use of chemical imbibition agent to change the wettability of rock pore surface and the fluidity of crude oil has become a general consensus among domestic and foreign researchers⁶⁻⁸. This paper finds out the better imbibition agent system through oil sands static imbibition experiments for ultra-low permeability sandstone reservoir, and optimizes the dynamic imbibition and recovery technology of the reservoir by using the core dynamic imbibition test.

2. Oil Sand Static Imbibition Experiment
Static imbibition means that to measure the amount of oil released in static and certain temperature when core or partially enclosed core be placed in the imbibition instrument. Static imbibition can be used to study the influence of core size, core physical properties (wettability, permeability, oil saturation), fluid properties (properties of crude oil, physical properties and activity of water, viscoelasticity, etc.) and external environmental factors on the imbibition effect. The core static imbibition experiment needs to takes a long time from core pretreatment to the completion of the imbibition process, which is not conducive to the screening of imbibition agents. Therefore, the methods of graded oil sands static imbibition method are used to study on the influence of fluid
properties and infiltration strength on imbibition effect, and also used to screen roughly the imbibition effect.

2.1. Experimental materials

2.1.1. Oil used in Experimental. A ultra-low permeability sandstone reservoir belongs to lithological structural reservoir, with an average permeability of 3 x 10^-3 um 2, a porosity of 12%, and an oil saturation of 55%. It belongs to medium-low porosity, ultra-low permeability and fine throat reservoirs. The content of saturated hydrocarbons in crude oil is about 68%, which belongs to paraffin-based crude oil.

2.1.2 Water used in Experimental. The salinity of formation water is 21377.5 mg/L, and the water type is NaHCO3. According to the ion content of the produced water, the corresponding formation simulated water is allocated for laboratory experiments.

2.1.3 Surfactant used in the experiment. Experiments were conducted using anionic, non-ionic and anionic non-ionic surfactants.

2.2 Experimental Method

The oil sands static imbibition experiment is based on the invention patent "Quantitative evaluation method of imbibition and recovery effect of an imbibition agent", which is used to evaluate the imbibition oil recovery effect of agent for the target reservoir[9].

2.3 Experimental Results

According to the physical properties of the test area, ten kinds of surfactant agents were selected and prepared with different concentrations for wide-range screening. Finally, the agents FP03, FP05 and FP08 had the most obvious effect, the static core permeation recovery rates were 56.23%, 53.31% and 49.76%, respectively. Therefore, these three formulations were selected for core dynamic core permeability test.

3. Core Dynamic Imbibition Experiment

3.1 Experimental material

Prepare the aging of saturated water, saturated oil more than 2 weeks in ultra-low permeability core. First, carry out dynamic imbibition test, and then take out of core for static imbibition. The physical properties of the selected cores are shown as below.

| No. | Length, cm | Diameter, cm | Permeability, 10^3μm^2 |
|-----|------------|--------------|------------------------|
| Core 1 | 9.99 | 2.51 | 1.75 |
| Core 2 | 10 | 2.51 | 1.75 |
| Core 3 | 9.98 | 2.51 | 1.62 |
| Core 4 | 9.97 | 2.51 | 1.74 |
| Core 5 | 9.98 | 2.51 | 1.72 |
| Core 6 | 9.96 | 2.51 | 1.54 |
3.2 Experimental Method

The set of 6 dynamic imbibition experiments were carried out by using three formulation systems, alternating injection of agent and water, and shut-in well method (0.2-0.6 PV agent-closed well 24-72 hours after water flooding). In search of the best solution which imbibition agent can play a role to improve the recovery efficiency in the process of displacement and shut-in well, the imbibition agents were injected with difference sequence in these set of 6 experiments.

The steps are as below:

- **Core treatment**: Take ultra-low permeability cores with similar permeability (see Table 3-6 for physical properties) and dry them in an oven at 105°C for 4 hours, reaching constant weight.
- **Saturated water**: Put the drying core into the holder and inject the simulated water into the intermediate container. Vacuum the holder and container until vacuum degree is 0.1. Then add water let the core fully saturated with water, and calculate core porosity by volume of saturated water.
- **Saturated oil**: Start to oil displace water, according to the volume of the displaced water to control the displacement of oil in about 60%, and make the remaining water is about 40% and produce bound water in the core;
- **Water flooding**: Start displacement experiment, constant-speed water flooding by simulated water until the water cut reaches 98%, that is, almost no oil at the outlet end;
- **Agent flooding**: start to inject imbibition agent, constant-speed displacement with injection volume of 0.5 pore volume (0.5PV);
- **Shut-in well**: In order to make best of the imbibition effect, the middle shut-in well process was set up.
- **Second water flooding**: Constant-speed water flooding, injection of 1PV of water
- **Slug flooding**: Replace another chemical imbibition agent and repeat steps from (5) to (7); with three slugs per core

3.3 Experimental Results

For these six set of cores, the average recovery of first water flooding is 24.78%, recovery of dynamic imbibition is 12.37% and total recovery is between 55.98% and 60.32%. In order to explore the potential of recoverable oil by dynamic imbibition, a static imbibition experiment at atmospheric pressure was carried out after dynamic imbibition. After static imbibition for 3 to 15 days, the recovery was increased by 10.37%~19.65%, and the recovery of dynamic-static combination increased by 27.15%.

![Comparison of water flooding, static imbibition and dynamic imbibition in six cores](image)

Figure 1: Comparison of water flooding, static imbibition and dynamic imbibition in six cores

On figure 1, it shows that first water flooding is more effective for oil displacement efficiency, but oil recovery is still improving when entering the dynamic imbibition flooding process. This will help to enhance the oil recovery.

The oil recovery is further improved after dynamic imbibition of core move to static imbibition. This just shows the necessity of shut-in well in the process of dynamic oil displacement, not only helps to reduce economic consumption in oil recovery process, but also further improves oil recovery.
According to the dynamic imbibition effect, the below scheme has a highest recovery efficiency and dynamic imbibition recovery increase by 15.78%. Therefore, this scheme is recommended.

Scheme: water flooding-injection agent (FP05) – shut-in well (52h) - after water flooding (CR = 0.05mL/min) - injection agent (FP03) - shut-in well (52h) - after water flooding (CR = 0.05mL/min) - injection agent (FP08) – shut-in well (52h) - after water flooding (CR = 0.05, 0.1, 0.15mL/min).

4. Conclusion

Based on core static imbibition experiment, three imbibition systems (ys503-5-1, ys622-2 and ys705-1 with core static imbibition recovery 50.13%, 46.46% and 51.11% respectively) were verified that they have good imbibition effect.

The results of 6 set of cores dynamic imbibition experiments show that: Dynamic imbibition has good oil displacement effect with average oil recovery increased by 10.90%. The total recovery of first water flooding, dynamic imbibition and static imbibition is 25.28-66.88%, and the dynamic-static imbibition recovery increased by 31.39% on average.

According to the oil recovery effect of dynamic imbibition, the oil displacement scheme was got as below suitable for low permeability reservoir.

Water flooding-injection agent (FP05) - shut-in well (52h) - second water flooding (CR = 0.05 mL/min) - injection agent (FP03) - shut-in well (52h) - second water flooding (CR = 0.05 mL/min) - injection agent (FP08) - shut-in well (52h) - second water flooding (CR = 0.05, 0.1, 0.15 mL/min).

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