Analysis on Mechanism to Improve the Recovery in Tight Oil Reservoirs by Imbibition

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Abstract: In order to explore the mechanism to improve the recovery percent in tight oil reservoirs, the mechanisms and main controlling factors of improving the recovery percent by different production mechanisms are analyzed by combining spontaneous imbibition, core displacement experiment and nuclear magnetic resonance (NMR) test. It is shown by the study that the recovery percent can be improved from 20% to more than 40% by increasing the displacement differential pressure for tight rock samples. During differential pressure displacement, the reservoir fluid in large and medium pores is mostly produced. It is proven by the pressured imbibition experiment that in the process of soaking, the fluid exchange between fractures and matrix and between large and small pores can be realized to improve the recovery percent of fine pores, and the recovery percent (mainly of fine pores) can be improved by 7-10% through pressured imbibition displacement. Large contact area caused by the complex fractures formed by stimulated reservoir volume (SRV) fracturing is the basis to improve the recovery percent by imbibition, but the recovery percent of simple fractures is limited. The research results of this paper will provide guidance for the stimulation technology and fluid system optimization to improve the recovery percent of tight oil.

1. Introduction
Tight oil plays an increasingly important role in China's energy structure, and has become an important substitute resource for oil and gas in China at present and will remain so in the future. China is rich in tight oil resources, and has a technically recoverable resource quantity of about 4.48 billion tons. As a result of learning from the advanced technology of North America, at present the tight oil in China is mainly produced by the means of horizontal well SRV fracturing combined with natural depletion. Although the production capacity of a single horizontal well can be improved by increasing its horizontal length, reducing the section spacing, and increasing the volume of fracturing fluid and proppant, problems such as rapid decline in production, low recovery percent and low accumulative production often exist with the tight oil reservoir after fracturing, and massive and cost-effective production of tight oil is faced with tremendous challenge[1]. SRV fracturing features tremendous fluid injection amount, huge stimulation volume and big fracture-matrix contact area. How to utilize the large swept area achieved by fracturing and how to use the tremendous amount of injected fluid so that the fracture-matrix imbibiton can be efficiently utilized to improve the produced percent of oil in
matrix within the stimulation extent have become the main technical measures to improve the initial production rate and the recovery percent of tight oil reservoirs after fracturing\cite{2}. However, the mechanism to improve the recovery percent remains to be further studied. This paper analyzes the different recovery mechanisms of tight oil, and clearly states the improvement degrees of recovery percent obtained by using different recovery mechanisms, which will provide guidance for the fit-for-purpose fracturing program design and fluid optimization\cite{3}.

After the SRV fracturing of a tight oil reservoir, complex fractures are developed. The matrix rocks are saturated with non-wetting phases (oil and gas), while the fracture network is saturated with wetting phases (water and fracturing fluid)\cite{4}. Under the action of capillary force and injection pressure, oil and gas in the matrix rocks are displaced into the fracture system, which means the occurrence of imbibition process. During fracturing and soaking, displacement under the action of differential pressure and imbibition under the action of capillary force occur simultaneously\cite{5}. Therefore, experimental methods were developed to simulate the processes of SRV fracturing and post-fracturing soaking.

2. Physical Simulation Experiment of Fracture Control

It has become a main measure to improve the recovery percent of tight oil by shortening the spacing between fractures to improve the control degree of fractures over a reservoir. The process of reducing the fracture spacing is simulated by means of variable displacement differential pressure\cite{6}. Meanwhile, the recovery percent of producible fluid under different displacement differential pressures is known by nuclear magnetic testing.

**Experimental materials.** Cores from a tight oil block of Xinjiang Oilfield were used in the experiment. Each core had an air permeability of \((0.2-2)\times10^{-3} \text{ μm}^2\) and a porosity of 5-12\%, and was 2.5 cm in diameter and 2.6 cm in length. Kerosene was used as the oil sample.

**Experimental equipment.** The experimental equipment comprises a nitrogen cylinder to provide gas supply, a precision pressure gauge, and a core holder and a manual pump to provide confining pressure for the core.

**Experimental procedures.**

1. A core washed off oil was dried and then vacuumed. After that, kerosene was used to pressurize and saturate the core until it was fully saturated with kerosene. At this point, the NMR T2 spectrum was tested.

2. The core was placed inside the core holder to provide confining pressure.

3. The core was then removed for weighing. After that, the core after gas drive at different driving pressures was subject to NMR T2 spectrum testing.

4. The NMR T2 spectrum curves at different displacement pressures were plotted according to the NMR results.

**Analysis of experimental results**

![T2 spectrum curves at different displacement differential pressures](image.png)
The essential of SRV fracturing is to maximize the recovery percent of reservoir fluid in matrix by increasing the displacement differential pressure. As shown in Fig. 1, the fluid produced in the process of differential pressure displacement is mainly from large and medium pores. In the range of large pores with $T_2>100\text{m}$, the produced percent is the highest, accounting for more than 50%; in the pore range with $10\text{m}<T_2<100\text{m}$, the produced percent is about 30%; in the range of small pores with $T_2<5\text{m}$, the produced percent is less than 10%. The results indicate that for a tight oil reservoir, the recovery percent of reservoir fluid in large and medium pores can be effectively improved by increasing the fracture control degree or the displacement differential pressure, but the same measure has limited effect on the recovery percent of reservoir fluid in fine pores.

![Fig. 2 Recovery percent curve of a rock with the permeability of 2 mD](image1)

![Fig. 3 Recovery percent curve of a rock sample with the permeability of 0.2 mD](image2)

In Fig. 2 and Fig. 3, the contributions of improving the displacement differential pressure for rock samples with different permeabilities to the recovery percent are compared. It can be seen that for a rock sample with good physical properties (corresponding to a low permeability reservoir), most of the fluid stored inside can be produced with a low displacement differential pressure, and the recovery percent basically remains unchanged with the continual increase of displacement differential pressure subsequently, which means that a low permeable reservoir has a low demand for fractures. However, for a tight oil reservoir, with the increase of displacement differential pressure, the recovery percent presents a trend of continual increase, which means that for a tight oil reservoir, a higher fracture control degree is demanded in order to achieve the effective production of reserves. At the same time, it is shown by the test results that with the deterioration of reservoir physical properties, less and less fluid can be produced and recovered under the action of differential pressure displacement.

3. Physical Simulation Experiment of Imbibition Displacement

It has been shown by the physical simulation experiment of fracture control that increasing the fracture control degree by shortening the fracture spacing can greatly improve the recovery percent of fluid stored in large and medium pores, but has less contribution to the recovery percent of fine pores. In a tight rock sample, most of the pores developed are fine ones. Therefore, how to improve the recovery percent of fluid stored in fine pores is the key to increasing the production rate and the recovery percent of tight oil. To this end, imbibition displacement experiment were carried out to analyze the mechanism to improve the recovery percent of the fine pores of tight rock samples.

**Experimental procedures**

1. A core washed off oil was dried and then vacuumed. After that, kerosene was used to pressurize and saturate the core until it was fully saturated with kerosene. At this point, NMR $T_2$ spectrum was tested.

2. The cylindrical surface of core was applied with heat-shrinkable sleeve of perfluoroethylene propylene (FEP) copolymer and high-strength epoxy resin, leaving only the inlet and outlet end faces. The inlet end of core was continuously injected with surfactant solution under constant pressure, and the outlet end was enclosed. The displacement differential pressure was maintained at 5 MPa, and the confining pressure was maintained at 7 MPa.
(3) The core was removed after being remained for different testing times under the displacement differential pressure. The core was weighed and tested for T2 spectrum signal after its surface had been wiped dry. Then, the curve of recovery efficiency by imbibition vs time was plotted.

**Analysis of experimental results**

![Fig. 4 T2 spectrum characteristics at different pressurized imbibition times](image)

In-house simulation of the long soaking process after fracturing was performed to study the impact of soaking imbibition displacement on stimulation results and recovery percent. Results of the physical simulation experiment of 15-day pressurized imbibition are shown in Fig. 4. According to the results, during the long-time pressurized imbibition, content of the fluid stored in fine pores decreases gradually (the envelope area of T2 spectrum relaxation time decreases), while content of the fluid stored in large and medium pores gradually increases. It is apparent that fluid exchange between fine pores and large/medium pores has occurred in this process, and the volume of fluid stored in fine pores which is difficult to produce using differential pressure displacement has been greatly reduced. This indicates that the pressurized imbibition displacement process can improve the recovery percent of fluid in fine pores.

![Fig. 5 Imbibition displacement process of soaking after fracturing](image)

The process of soaking after fracturing is shown in Fig. 5. According to the knowledge acquired from the experimental research, the fracturing fluid leaks off into the formation after the finish of fracturing under the action of displacement differential pressure, with less and less fracturing fluid remained in fractures. In this process, the fracturing fluid in fractures can displace the reservoir fluid near the fracture surfaces through spontaneous imbibition process, so that the oil saturation in fractures increases and the water saturation decreases. The fracturing fluid that has entered reservoir due to leak-off can make the fluid stored in fine pores enter large pores and the fracturing fluid in large pores enter small pores through imbibition displacement. Thus, the water saturation in the main production channels can be reduced, while the oil saturation can be increased, and the relative flow capacity
through porous media can be improved, which in turn enables the improvement in oil recovery percent.

![Fig. 6 Recovery percent by imbibition with different contact area](image)

The SRV fracturing of a tight oil reservoir can improve the recovery percent by imbibition displacement. However, different fracture shapes have a great impact on the improvement in recovery percent. Therefore, an experimental research into imbibition displacement with different contact area is carried out. In Fig. 6, the recovery percent of core by imbibition was tested respectively under the conditions of full contact, both-end contact and single-surface contact. It can be seen that with the increase of contact area, the recovery percent by imbibition increases. Therefore, for SRV fracturing, imbibition displacement as an important mechanism to improve the recovery percent has higher recovery percent under conditions that complex fractures are developed. For a reservoir that is difficult to have complex fractures developed, the recovery percent can only by improved by acquiring sufficiently big contact area through more intensive cutting.

4. Conclusions
(1) The recovery percent of tight reservoirs can improved by increasing the displacement differential pressure or shortening the spacing between fractures to improve the fracture control degree. This measure mostly produces the fluid stored in large and medium pores, but has less impact on the improvement in produced percent of fine pores.

(2) The recovery percent of fluid stored in the fine pores of tight rock samples can be improved by pressurized imbibition. In the case of nonwater-sensitive tight reservoirs, the recovery percent can be improved by the soaking imbibition displacement after fracturing.

(3) The fracture shapes caused by SRV fracturing have a great impact on the improvement in recovery percent resulted from imbibition. For complex fractures, the improvement in recovery percent due to imbibition is more obvious. For simple fractures, it is necessary to increase greatly the number of fractures developed, so that imbibition can effectively improve the recovery percent.

Acknowledgements
The paper is supported by the National Science and Technology Major Projects of China (2017ZX05070) and Science and Technology Major Projects of PetroChina (2017E-15)

Reference
[1] Li, S. et al. Solution for counter-current imbibition of 1D immiscible two-phase flow in tight oil reservoir. J. Pet. Exp. Prod. Technol. 7(3), 727–733.
[2] Fakcharoemphol, P. et al. Managing shut-in time to enhance gas flow rate in hydraulic fractured shale reservoirs: a simulation study. Present at SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, 30 September-2 October, SPE-166098-MS.
[3] Ghanbari, E. & Dehghanpour, H. The fate of fracturing water: A field and simulation study. Fuel 163, 282–294.

[4] Almulhim, A., Alharthy, N., Tutuncu, A. N. & Kazemi, H. Impact of imbibition mechanism on flowback behavior: a numerical study. Presented at the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, 10–13 November, SPE-171799-MS.

[5] Aksu, I., Bazilevskaya, E. & Karpyn, Z. T. Swelling of clay minerals in unconsolidated porous media and its impact on permeability.

[6] Bazin, B. et al. In-situ water-blocking measurements and interpretation related to fracturing operations in tight gas reservoirs. SPE Prod. Oper. 25(04), 431–437.