Mechanism experimental study on flooding control of Soft Microgel by low-field nuclear magnetic resonance

Yinzhu Ye\textsuperscript{1,a}, Xingcai Wu\textsuperscript{1}, Zhuowei Huang\textsuperscript{2}, Taifei Bi\textsuperscript{3}, Zhe Yang\textsuperscript{1,2}, Xiaocong Wang\textsuperscript{1}, Lipeng He\textsuperscript{1}, Yang Liu\textsuperscript{1,4}, Shichao Li\textsuperscript{1}

\textsuperscript{1} Research Inst. of Petroleum E&D (RIPED), CNPC.
\textsuperscript{2} China University of Geosciences, Beijing.
\textsuperscript{3} Oil Production Plant 1 of PetroChina Changqing Oilfield
\textsuperscript{4} Research Institute of Exploration and Development, PetroChina Southwest Oil&Gasfield Company, Chengdu, Sichuan 610041, China.
\textsuperscript{a} email: Yeyinzhu@petrochina.com.cn

Abstract: The research method of LF-NMR(low field nuclear magnetic resonance) combined with core displacement device has become important experiment was used to study the Water Flooding SCT(swept control technology by water flooding) of soft microgel. Besides, the transverse relaxation time spectrum and the “visual” evaluation method based on LF-NMR were used to investigate the microscopic mechanism of expended sweep volume of soft microgel in single core experiment. The displacement conformance effect of flexible microgel in parallel double-core and its displacement mechanism at different pore scales were analyzed by transverse relaxation time spectrum. The results of single core experiments show that the soft microgel can expand the sweep volume, mainly in the relatively large pore throat, with 15.43%. The results of parallel double-core experiments indicate that after SMG flooding, the recovery of low permeability core increased by 29.5%, high permeability core increased by 15.3%, comprehensive recovery increased by 22.0%, and the ratio of low permeability recovery increased by nearly 2 times that of high permeability core. The soft microgel flooding technology can effectively activate the remaining oil in different pore sizes of the core, among which the medium pore (12.1%) is more used than the large pore (5.6%) and the small pore (4.2%).

1. Introduction
In China’s waterflooding oilfields, there are some problems, such as serious reservoir heterogeneity, ineffective injection water or inefficient circulation\textsuperscript{[1-2]}. The technology of expanded water flooding with flexible microgel is an enhanced oil recovery technology developed in recent years\textsuperscript{[3]}. It has the advantages of stable chemical properties, good environmental tolerance and simple injection process. The technology is widely used and has achieved good technical and economic results\textsuperscript{[4]}. In order to study the influence of volume and profile control of flexible microgels, conventional core displacement, microscopic displacement models, CT imaging and low field NMR can be used. In comparison, low field NMR and imaging technology is more suitable for testing the fluid distribution in core\textsuperscript{[5,6]}. In this paper, the low field NMR off-line measurement method is used to study the mechanism of the flexible micro gel flooding in parallel dual pipe displacement, which provides a reference for similar chemical system to study the mechanism of profile control and flooding.
2. Principle and method of low field NMR experiment

The object of nuclear magnetic resonance is the relaxation behavior of atomic nuclei (such as hydrogen nuclei) at different resonance frequencies. In the process of NMR experiment, the measured signal is the signal of hydrogen element in the fluid in the core, and the signal quantity measured by NMR reflects the fluid content in the core. NMR results show that the transverse relaxation time is proportional to the signal amplitude, and the transverse relaxation time is proportional to the pore throat size. That is:

\[ r = 0.735T_2/C \]  

(1)

Where:
- \( r \) — pore radius, \( \mu m \);
- \( T_2 \) — NMR relaxation time, \( ms \);
- \( C \) — conversion coefficient, nearly \( 1.71 \, ms/\mu m \).

According to the relaxation mechanism of NMR, the NMR signal with longer relaxation time on T2 spectrum corresponds to the fluid in larger pores, and the NMR signal with shorter relaxation time on T2 spectrum corresponds to the fluid in fine pores. The relationship between transverse relaxation time and pore size is defined as that the pores corresponding to transverse relaxation time \( (T_2) \leq 10 \, ms \) are small pores with pore radius \( \leq 4.3 \mu m \). T2 between 10-100 ms, the corresponding pore is medium pore, and the pore radius is 4.3-43.0\( \mu m \). \( T_2 \geq 100 \, ms \) is macropore with pore radius \( \geq 43.0 \mu m \). According to the principle of NMR technology, the longer the relaxation time is, the larger the pore size of simulated core is; the larger the integral area of signal amplitude is, the higher the water saturation of porous media is.

Magnetic resonance imaging is to apply three mutually vertical controllable linear gradient magnetic fields on the target object to achieve the spatial positioning of the magnetic resonance signal, collect the amplitude of the magnetic resonance signal and the corresponding spatial position information, and obtain the magnetic resonance image of the sample after certain processing.

3. Experimental process

3.1. Experimental materials

The chemical agent used in the experiment is micron grade SMG, and the median particle size is determined by laser particle size analyzer. The basic physical and chemical performance parameters are shown in Table 1.

| Performance parameter | Median of original particle size \( \mu m \) | Median particle size after swelling \( \mu m \) | Swelling ratio |
|------------------------|---------------------------------------------|---------------------------------------------|---------------|
| Evaluation results     | 3.2                                         | 28.6                                        | 7.9           |

The experimental water is the formation water from an oil field in Bohai Sea, and the salinity is 9374.13 mg/L. The composition is shown in Table 2.

| Ionic composition content, mg/L | Na\(^+\) | K\(^+\) | Ca\(^{2+}\) | Mg\(^{2+}\) | CO\(_3^{2-}\) | HCO\(_3^{-}\) | SO\(_4^{2-}\) | Cl\(^-\) |
|--------------------------------|---------|--------|------------|------------|-------------|-------------|-------------|---------|
| content, mg/L                  | 3091.96 | 276.17 | 158.68     | 14.21      | 311.48      | 85.29       | 5436.34     |         |
Conventional simulated oil or water can produce hydrogen signal. In order to distinguish T2 spectrum signal of transverse relaxation time, deuterium water is used to prepare bound water in single pipe extended sweep volume experiment, deuterium water is from isowater company, D content is 99.9%; fluorine oil is used to replace simulated oil in parallel double pipe profile control and displacement experiment, and fluorine oil is from 3M company.

Experimental core: artificial standard columnar core, with cross-sectional area of 4.91 cm². Other parameters are shown in Table 3

| Core number | length /cm | Gas logging permeability /mD | porosity /% |
|-------------|------------|------------------------------|-------------|
| 1-1(Single tube) | 5.03       | 960                          | 27.6        |
| 2-1(Hypertonic)   | 5.32       | 1965                         | 26.5        |
| 2-2(Hypotonic)    | 5.28       | 485                          | 23.8        |

3.2. Experimental equipment
The experimental instruments used in the low field NMR core displacement experiment include Nantong Huaxing constant pressure and constant speed double cylinder pump, pressure collection system, Nantong Huaxing mixing intermediate vessel, intermediate vessel, oven, measuring cylinder, oven, Suzhou newmai large aperture NMR imaging analyzer Macro MR12-150H-I (magnetic field intensity 0.5T, resonance frequency 21MHz, probe coil diameter 70mm), etc.

3.3. Flooding experiment steps
Two cores with different permeability were dried in oven at 80℃ for 24 hours, then the cores were taken out and vacuumized for 12 hours to saturate the fluorine oil and calculate the porosity. The low field nuclear magnetic "off-line test" method was used to measure the initial signal of two cores, and the T2 spectrum of the core was obtained. The experimental temperature of core displacement is 65℃.

A water flooding experiment: Put the high and low permeability cores in the core holders respectively, and carry out the parallel double-pipe oil flooding experiment. Simulated water was injected at an injection rate of 1.0 mL/min to record the fluid and oil production of high- and low-permeability cores. Until the water content of the production end of the high-permeability core reaches more than 98% (take three stable points). After that, the core was taken out, and the signal after water flooding of the high and low permeability core was measured under low-field nuclear magnetic conditions to obtain the T2 spectrum of the core.

Flexible gel flooding and subsequent water flooding: injecting 1.0 PV of SMG chemical system at 1.0 mL/min displacement rate, recording injection pressure, and producing liquid and oil yield of core. Until the water content of core production end reaches above 98% (take three stable points). After that, the core is taken out, and the signal quantity of high and low permeability core after SMG profile control and displacement is measured by low field nuclear magnetic "off-line test" method, and the T2 spectrum of the core is obtained.

4. Results and discussion
According to the relationship between the different water content in the control substance (glass bottle) and the intensity of the nuclear magnetic signal, the water marking line is obtained, as shown in Figure 1. Use this curve to calculate the change of the water content in the core during the oil displacement process, so as to calculate the change of the recovery factor during the oil displacement process. The NMR T2 test data of high-permeability and low-permeability cores in different displacement stages of parallel double pipe experiment are shown in Figure 2, the data processing results of oil recovery efficiency of different pores in high-permeability and low-permeability cores are shown in Figure 3, and the comprehensive oil recovery efficiency of parallel double pipe flooding is shown in Table 4.
It can be seen from Fig. 5 and Fig. 6 that compared with water flooding, after SMG profile control and flooding, the follow-up water flooding $T_2$ spectrum curves of high permeability core and low permeability core move to the left and increase compared with water flooding curve, which is more obvious in low permeability core. The results show that after SMG profile control and flooding, both high permeability core and low permeability core use smaller pores in varying degrees, and the low permeability core is more obvious.

The $T_2$ spectrum curve of low permeability core increases obviously in the range of less than 100ms (medium and small pores). In water flooding stage, the recovery factor of high permeability core mainly comes from macropores, which is 37.9%, and the cumulative recovery factor of water flooding is 51.2%; The recovery rate of low-permeability cores is mainly from large and medium pores, which is 20.1%, of which the cumulative recovery rate of water flooding is 23.8%. After SMG control and flooding, the production of small pores in high-permeability cores is still limited, only 8.7%, and the cumulative recovery rate of high-permeability cores is 15.3%; However, the production degree of small pores in low-permeability cores has increased significantly, reaching 25.1%, and the cumulative recovery rate of low-permeability cores has been increased by 29.5%. After comprehensive consideration of the experimental results of large and small pore throats of high and low permeability cores, it is found that after SMG profile control and flooding, the comprehensive macropore recovery of high and low permeability cores is increased by 5.6%, the medium pore by 12.1%, and the small pore by 4.2%.

It can be seen from Table 4 that in the parallel double-pipe experiment, after SMG profile control and flooding, the recovery rate of high-permeability cores increased by 15.3%, the recovery rate of low-permeability cores increased by 29.5%, and the comprehensive recovery rate increased by 22.0%.

![Figure 1: Calibration curve of NMR experiment](image1)

![Figure 2: $T_2$ spectrum of high and low permeability cores in parallel dual tube core flooding experiment](image2)
Combined with the above experiments, it can be found that the displacement fluid is mainly along the high permeability area in the water flooding stage. After SMG profile control and flooding, SMG aqueous dispersion is effectively retained in the high permeability core, and the subsequent injected SMG aqueous dispersion enters into the low permeability core and continuously migrates to the deep part of the core, and the medium and small pores with rich residual oil are activated. At the same time, the SMG water dispersing liquid entering into the high permeability core improves the producing degree of the remaining oil in the pores of the high permeability core (mainly Acting in the medium and large porosity), and finally greatly improves the comprehensive recovery. Therefore, SMG dispersion system has a good role in deep profile control and flooding, especially for heterogeneous reservoirs. In the SMG profile control and flooding stage, the injected SMG dispersion system will
preferentially enter the high permeability layer, and play an effective role in plugging and deep profile control and flooding in the high permeability layer. At the same time, it will carry liquid into the medium and low permeability layer to improve water sweep efficiency and further improve water flooding effect(10). Compared with the traditional core displacement experimental method, the low field NMR method can characterize the start-up position and profile control and displacement effect of remaining oil in different pore sizes.

5. Conclusion
(1) SMG can effectively inhibit the seepage capacity of high-permeability reservoirs and activate low-permeability reservoirs. The enhanced value of low-permeability recovery factor (29.5%) is greater than the enhanced value of high-permeability core recovery factor (15.3%), which is close to 2 times. Considering the comprehensive recovery factor of high- and low-permeability cores, the contribution of enhanced recovery in a waterflooding stage mainly comes from the large pores. The contribution of enhanced oil recovery after SMG flooding mainly comes from mesopores.

(2) The in-depth study of this experimental method is expected to further reveal the expanding sweeping volume mechanism of flexible microgels or similar chemical agent systems, the starting mechanism of remaining oil at different pore scales, and the evaluation of profile control and flooding effects.

References

[1] Wang Yupu, Liu Yikun, Deng Qingjun. Current situation and development strategy of the extra high water cut stage of continental facies sandstone oil fields in China[J]. Journal of Northeast Petroleum University, 2014. 38(1):1-9.

[2] Yuan Shiyi, Wang Qiang. New progress and prospect of oilfields development technologies in China[J]. Petroleum Exploration and Development, 2018, 4594); 637-667.

[3] Wu Xingcai, Han Dakuang, Lu Xiangguo, et al. Oil Displacing Mechanism of Soft Micro gel Particle Dispersion in Porous Media[J]. Earth science, 2017. 42(8):1348-1355.

[4] Wu Xingcai, Xiong Chunming, Han Dakuang, et al. A New IOR Method for Mature Waterflooding Reservoirs: “Sweep Control Technology”[R]. SPE-171485-MS, 2014.

[5] Wu Xingcai, Qu Debin, Xu Hanbing, et al. The Economic Analysis and Application Strategies of EOR Technology in Low-Oil-Price Period---8 Case Study of a New Polymerflooding Technology[R]. SPE-182145-MS, 2016.

[6] Yi Zhe. Study on Profile-control Flooding Mechanism of Polymer Microsphere[J]. Advances in fine petrochemicals, 2013. 14(6):1-4.

[7] Di Qinfeng, Zhang, Jingnan, Hua Shuai, et al. Visualization experiments on polymer-weak gel profile control and displacement by NMR technique[J]. Petroleum Exploration and Development, 2017, 44(2): 270-274.

[8] Lei Qin, Luo Jianhui, Peng Baoliang, et al. Mechanism of expanding swept volume by nano-sized oil-displacement agent[J]. Petroleum Exploration and Development, 2019, 46(5): 937-942.

[9] Zhang Jingnan, Di Qinfeng, Hua Shuai, et al. Nuclear magnetic resonance experiments on foam flooding and evaluation of foam dynamic stability[J]. Petroleum Exploration and Development, 2018, 45(5): 853-860.

[10] Cheng Yichong, Di Qinfeng, Gu Chunyuan, et al. Visualization study on fluid distribution and end effects in core flow experiments with low-field mri method[J]. Journal of Hydrodynamics, Ser. B, 2015, 27(2):187-194.