Laboratory experimental study on the binary combination flooding system in low permeability conglomerate reservoir

Fajun Zhao, Guangmeng Zhu, Yifan Jiang, Qinyuan Guo, Dongli Fu

Key Laboratory of Entered Oil Recovery of Education Ministry, Northeast Petroleum University, Daqing, Heilongjiang 163318, China

Abstract: In view of the poor injection-production effect of low permeability conglomerate complex fault block reservoir in Xinjiang Oilfield in the late development stage of high water cut, the indoor experimental study of binary compound flooding system was carried out. By compounding the petroleum sulfonate and polymer binary system, the viscosity and morphology parameters of the binary compound flooding system were measured. The microscopic pore structure of the core in this block was analyzed by GE Phoenix Nanotom S, and four groups of experimental schemes were designed to study the oil displacement efficiency of the whole diameter core binary compound flooding system. The experimental results showed that the binary system of surfactant and polymer showed additive synergistic effect. The performance of binary compound system is less affected by polymer molecular weight and solution concentration, which meets the viscosity requirement of low permeability conglomerate for binary compound flooding system. The porosity of samples is relatively small and the connectivity between pores is relatively poor. The experimental results of physical model oil displacement efficiency show that the oil recovery can be increased by more than 17% by injecting 0.3PV 1200mg/L polymer + 0.5% (w) surfactant binary compound system.

Keywords: Low permeability, Micro pore structure, Binary combination flooding system, Nano CT, conglomerate

1. Introduction

In recent decades, polymer flooding has been widely used in domestic oilfields, and remarkable precipitation and oil increase effects have been achieved.In order to make polymer flooding produce more economic benefits in the oilfield, it is necessary to study and master the various influence factors of polymer flooding and the change rule of each influence factor, so as to guide the field application of polymer flooding method more effectively [1].

Reservoir permeability in Daqing Oilfield is generally above 1000 m D, and polymer injection is less difficult [2,3]; however, in low-medium permeability reservoirs such as Block Jin 16 of Liaohe Oilfield [4], Block Hong 113 of Jilin Oilfield [5], Block Malingbei 3 of Changqing Oilfield [6], and Block Qidong of Karamay Oilfield [7], when polymer is injected, there is a certain degree of reservoir blockage and a sharp decline in liquid production intensity of oil wells. Therefore, it is urgent to solve the problem of mismatch between polymer flooding system and reservoir permeability [8].The injection property of binary system flooding is an important factor affecting the oil displacement effect. If the molecular weight of polymer is too large or the mass concentration is too high, it will cause reservoir blockage, continuous increase of injection pressure, resulting in subsequent injection difficulties, and even cause reservoir scrapping when serious blockage. On the contrary, when the polymer molecular weight is too small or the mass concentration is too low, the oil displacement effect is not ideal [9].

In order to improve the degree of crude oil recovery in a block of Xinjiang, this experiment uses the natural cores provided in the field, and uses GE Phoenix Nanotom S to analyze the microscopic pore structure of natural cores. The microscopic pore structure of reservoir refers to the geometric shape, size, distribution and mutual connectivity of pores and throats in reservoir rocks [10]. The microscopic pore characteristics of reservoir rocks directly affect the reservoir and seepage capacity [11].In recent years, radiation X-ray computed tomography (X-CT) has become a powerful detection method in characterizing the microstructure of tight sandstone reservoirs[12-15]. The advantage of CT scanning method is that it can quickly and nondestructively scan rock samples in all directions and in a large range. The digital core obtained by CT scanning can more intuitively study the microscopic pore characteristics of reservoirs [18-22]. The research results are helpful to improve the accuracy of quantitative evaluation of microscopic pore structure parameters in this area, provide technical support for quantitative characterization of rock microstructure, and provide basis for subsequent selection of polymer molecular weight and concentration. The core displacement experiment of low permeability conglomerate reservoir can better simulate the field conditions, enrich the displacement data of the block, and fill the experimental blank of natural core in the block. Binary composite flooding can increase the viscosity of oil displacement system to increase the sweep efficiency, which is an important method to improve oil recovery [23-25].

2. Experimental instruments and reagents

2.1 Experimental instruments

The main instruments include Quanta450 FEG environmental scanning electron microscope (FEI, USA) ; ALPHA2-4 vacuum freeze dryer (Martin Christ, Germany) ; HAAKE RS-6000 rheometer (HAAKE, Germany) ; Phoenix Nanotom S CT scanner (Sievers, Germany) ; ISCO260D pump (Teledyne Isco, USA) ; thermostat (Haian Petroleum Scientific Research Instrument Co., Ltd, China) ; core holder (Φ100mm × 300mm) (Haian Petroleum Research Instrument Co., Ltd, China).

2.2 Core model

The core used in the experiment is taken from Xinjiang Oilfield, and the physical parameters are shown in table 1. The core permeability is 20 mD, the porosity is about 10 %, and the permeability and porosity are low, which belongs to the characteristics of low porosity and low permeability conglomerate reservoir. The physical parameters of four cores are basically the same, which ensures the repeatability of subsequent experiments.

Table 1 Core physical parameters

Number	A1	A2	A3	A4
Length, cm	6.9	7	7.04	6.95
Diameter, cm	10	10	10	10
Gas permeability, mD	19.8	20.2	21.3	20
Water permeability, mD	3.42	3.42	3.42	3.42
Pore volume, cm^3	54.8	55.2	55.6	55
Porosity, %	10.12	10.19	10.26	10.15
Saturated oil, mL	31	31.2	31.5	31.4

2.3 Experimental oil, water and chemical reagents

The experimental oil is a simulated oil prepared according to the viscosity of underground crude oil. The simulated oil is prepared according to a certain proportion of dehydration and degassing crude oil and aviation kerosene in the target area of Xinjiang Oilfield. The viscosity of crude oil measured by HAAKE RS-6000 rheometer is 59.4 mPa·s.

The experimental water is standard brine, which is simulated formation water prepared by distilled water. The salinity is 9358 mg / L, which is used for sample preparation and displacement experiments.

The polymer used in the experiment was hydrolyzed polyacrylamide (Daqing Zaichuang Technology Co., Ltd.) with molecular weights of 1500×104 g·mol−1 and 2000×104 g·mol−1 salt-resistant polymers, respectively. The surfactant is petroleum sulfonate (Daqing Zaichuang Technology Co., Ltd.).

Preparation of binary compound flooding system : 4 samples of HPAM with mass concentrations of 1000 mg/L and 1200 mg/L, molecular weights of 1500×104 g·mol−1 and 2000×104 g·mol−1 respectively were prepared. A certain amount of surfactant was added to mix, and the concentration of surfactant was 0.5 wt %.

3. Experimental methods

3.1 Experimental methods of characterization

3.1.1 Environmental scanning electron microscopy analysis

Approximately 0.1 mL finely filtered injected and produced fluids before and after polymer flooding were dripped into the copper concave sample table of Quanta450 environmental scanning electron microscope to seal the sample to prevent solvent evaporation. Liquid nitrogen was used to rapidly reduce the temperature of the sample chamber to -196 °C. The sample table containing the sample was placed in the sample chamber of the vacuum freeze-drying machine. After vacuuming for 24 h, the ice in the frozen sample was completely sublimated, leaving the structure formed by the polymer in the solution. The structure was analyzed by scanning electron microscope.

3.1.2 Viscosity measurement of binary system

The solution viscosity of binary composite flooding system was tested by HAAKE RS-6000 rheometer from Germany, equipped with C60/1°Ti vertebral plate sensing system, and the shear rate was 7.34 s − 1. The data record was automatically controlled by computer, and the viscosity relationship was measured under different time conditions.

3.1.3 Core CT scan test

Put the core into the GE Phoenix Nanotom S nano CT equipment, adjust the equipment parameters for scanning. The scanned data were used to reconstruct the digital 3D model with GE Phoenix Datosx 2AcqX software. Using professional data processing software, VOLUME GRAPHICS STUDIO MAX and AVIZO 8.0 to analyze and process the reconstructed three-dimensional digital model, display three-dimensional internal view, extract core pores and analyze, extract throat model and analyze.

3.2 Displacement experiment method

Firstly, the core was vacuumed, saturated to simulate formation water, pore volume was measured, saturated to simulate oil, and bound water was established. Continuous water flooding was carried out to the core outlet water content above 98 %. According to the experimental scheme, 0.3 PV binary compound system solution was injected, and then the simulated formation water was used to drive the water content above 98 %. The end of the experiment. The experimental temperature was 60 °C and the displacement rate was 0.5 mL / min.

3.3 Experimental process of binary compound flooding system

The physical simulation experiment of enhanced oil recovery by binary compound flooding in low permeability conglomerate reservoir is carried out according to the following four groups of schemes:
Experimental scheme 1: Water flooding to comprehensive water content 98% + injection binary system (1500×104 g·mol−1, 1000mg/L polymer + 0.5 %surfactant) 0.3PV + subsequent water flooding to comprehensive water content 98 % ;
experimental scheme 2 : water flooding to comprehensive water content 98 % + injection binary system (1500×104 g·mol−1, 1200 mg /L polymer + 0.5% surfactant) 0.3PV + subsequent water flooding to comprehensive water content 98 % ;
experimental scheme 3 : water flooding to 98 % comprehensive water content + injection binary system (2000×104 g·mol−1, 1000 mg/L polymer + 0.5% surfactant) 0.3PV + subsequent water flooding to 98% comprehensive water content ;
experimental scheme 4 : water flooding to comprehensive water content 98 % + injection binary system (2000×104 g·mol−1, 1200 mg /L polymer + 0.5 % surfactant) 0.3PV + subsequent water flooding to comprehensive water content 98 %.

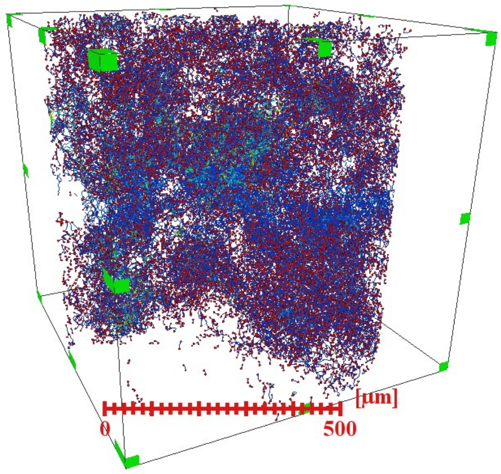
4. Results and analysis

4.1 CT scanning test of conglomerate core

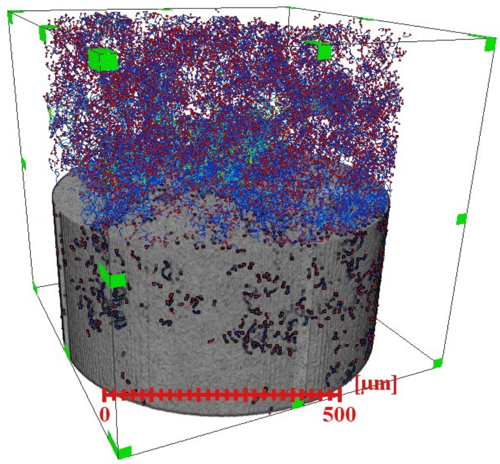
The rock samples were scanned by CT, and the scanning accuracy was 1.25 ~ 1.70 μm. The pore throat structure characteristics of tight sandstone reservoirs can be comprehensively characterized at different scales, and the structural characteristics of micropore shape, size, spatial distribution and connectivity can be clarified. It not only provides a basis for accurately understanding the microscopic structure characteristics of tight reservoirs, but also provides a new method for the study of pore throat structure of tight reservoirs. The CT scanning results are shown in table 2.

Table 2 Core CT scanning test results

Test number	Parameter	Numerical value
1	Scanning resolution/μm	1.25
2	Calculated porosity/%	8.21
3	Average pore radius/μm	4.14
4	Number of pores/×10^3	65.53
5	Pore volume/×10^6μm^3	11.85
6	Average length/μm	184.59
7	Percentage of connected volume/100	31.72



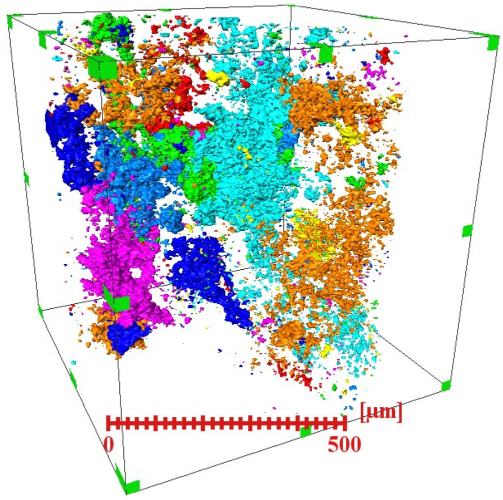
(a)



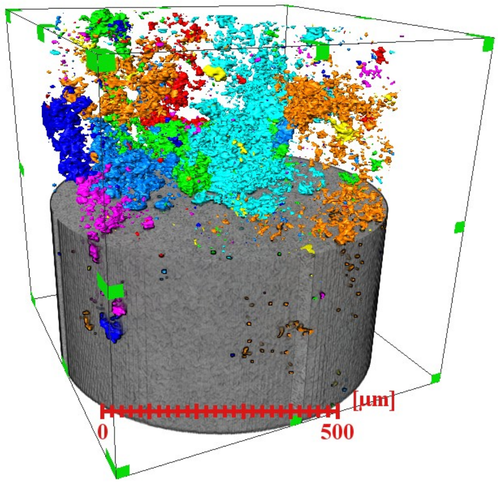
(b)

Fig. 1 Pore throat model: (a) and pore throat body (b) sectional display model of core samples

 https://doi.org/10.1051/e3sconf/202235201076

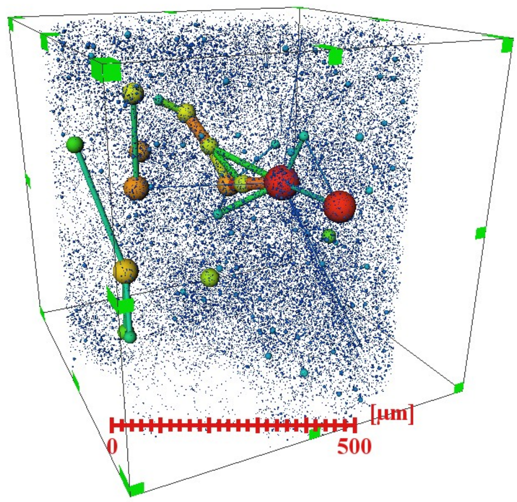


(a)

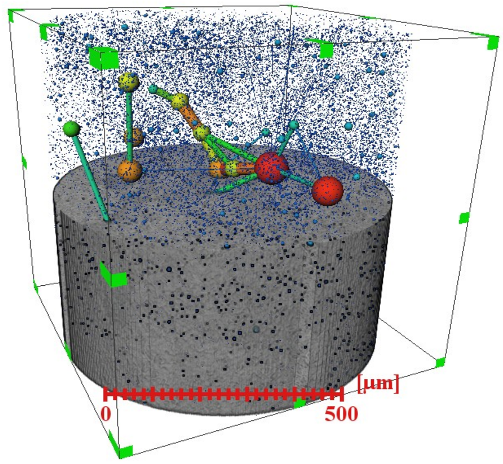


(b)

Fig.2 Connectivity model: (a) and pore connectivity (b) subsection display model of Core sample



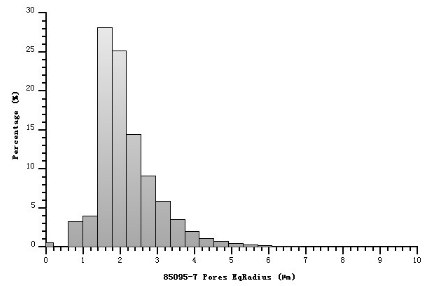
(a)



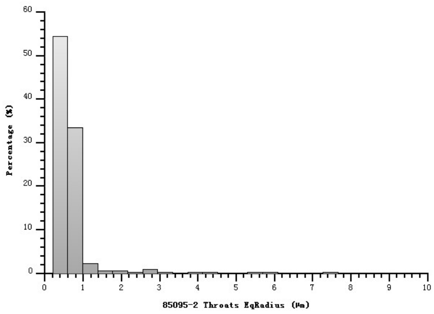
(b)

Fig.3 Pore throat ball-and-stick: (a) and pore throat ball-and-stick body (b) subsection display model of core sample

After the core CT scanning test, the three-dimensional reconstruction of the core model is carried out by AVIZO 8.0 software. The pictures are shown in Figures 1, 2 and 3. The dark black area represents the pore of the rock, and the gray and white areas represent the matrix of the rock. The pore throat diameter is mainly 1.4 ~ 3μm, and the nano pore throat overlaps with each other. The pore throat geometry is tubular and spherical, and there are micron pore throats with diameter greater than 3μm.



(a)



(b)

Fig. 4 Histogram of pore radius: (a) and throat radius (b) for core samples

Fig. 4 shows the pore radius of core samples. According to the calculation results of pore structure parameters of core samples, the pore radius of core samples is mainly concentrated in the range of 1.4 ~ 3 μm. The distribution range of pore throat radius is 0.2 ~ 7.8μm, and the peak value is 0.4μm. The average length of throat is short, the connectivity is poor, and the permeability is low. The lower the core permeability is, the narrower the throat radius distribution is, and the lower the proportion of large throat is. The smaller the average throat radius, the greater the gas seepage resistance, the greater the difficulty of development in the reservoir.

4.2 Characterization of binary composite flooding system

4.2.1 Determination of viscosity of binary composite flooding system

At 60 °C, the viscosity of binary composite flooding solution with molecular weights of 1500×104 g·mol−1 and 2000×104 g·mol−1 and concentrations of 1000 mg /L and 1200 mg /L was tested by HAAKE RS6000 rheometer system. The relationship between viscosity and concentration of binary composite flooding system is shown in Table 3 and Fig. 5.

Table 3 Viscosity of binary combination flooding system versus concentration

Polymer molecular weight.×10^4g/mol	Concentration, mg/L	Viscosity, mPa·s
1500	1000	5.8
	1200	7.2
2000	1000	14.3
	1200	17.5

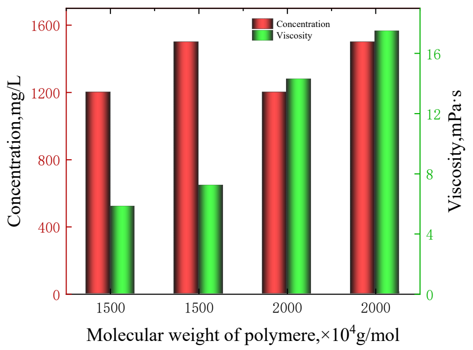


Fig. 5 Relationship between viscosity and concentration of binary combination flooding system

The relationship between viscosity and concentration of binary compound flooding system in Table 3 and Fig.5 shows that the viscosity of binary compound flooding system is affected by molecular weight and concentration at the same time. When the concentration of polymer solution in binary compound flooding system is large, the viscosity of binary system solution is large and the viscoelasticity is good. This is mainly due to the high concentration of polymer, the close aggregation of polymer molecular chains, the stronger self-similarity of the fractal growth of the network structure, the higher structural energy, and the strong ability of molecular chains to contact and entanglement.

4.2.2 Morphology test of binary compound flooding system

Field emission environmental scanning electron microscopy (FE-SEM) tests were performed using binary system solutions with molecular weights of 1500×104 g·mol−1 and 2000×104 g·mol−1 and concentrations of 1000 mg / L and 1200 mg / L, respectively. Fig. 6 is a scanning electron microscope photograph of binary compound flooding system. The magnification of the photograph is 800 times. It can be seen from Fig. 6 that the HPAM aggregate in the binary composite flooding system is a multi-layer three-dimensional network structure radiating from a certain center to the surrounding, with dense network and clear nodes.

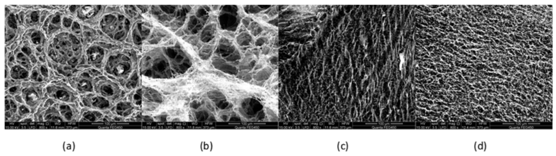


Fig.6 SEM photograph of binary compound flooding system : (a) HPAM molecular weight is 1500×104 g·mol−1, concentration is 1000 mg / L, (b) HPAM molecular weight is 1500×104 g·mol−1, concentration is 1200 mg / L, (c) HPAM molecular weight is 2000×104 g·mol−1, concentration is 1000 mg / L, (d) HPAM molecular weight is 2000×10` g·mol−1, concentration is 1200 mg / L

The carboxyl and amide groups on the macromolecular chain of HPAM are prone to cross-linking reactions within and between molecules. The imide cross-linking bridge is formed by imide reaction, and then cross-linking forms the structure shown in Fig. 6. From Fig.6 (a) to (d), it can be seen that the pore structure is gradually dense due to the gradual increase of molecular weight and concentration. At this time, the mesh holes are circular mesh holes with strong energy, and the self-similarity of their fractal growth is stronger, which can enhance their adsorption, retention and trapping ability in natural core pores, expand the swept volume and improve the final recovery degree of the core.

4.3 Oil displacement experiment of binary composite flooding system

According to the designed four groups of experimental schemes, the binary compound flooding experiments were carried out in four low permeability conglomerate full diameter cores. Using the same injection method, injection PV number (binary system slug 0.3 PV) and injection rate, the change rule and displacement effect of different binary system injection fluids in four cores with similar physical parameters were studied.

Fig. 7 and Fig. 8 are the curves of the relationship between the injection PV number and recovery factor, and the

https://doi.org/10.1051/e3sconf/202235201076

relationship between the injection PV number and water content, respectively. From fig.7 and fig.8, it can be seen that the water content decreases obviously after injecting binary composite system. In the subsequent water flooding, the crude oil in the front of the displacement continues to be produced, and the water content shows a rapid upward trend. The stage with the largest decrease in the water content of the produced liquid is also the stage with the most obvious increase in the recovery degree. The increase of polymer concentration in binary composite flooding system can effectively improve core recovery. For natural full-diameter cores, compared with the influence of polymer molecular weight in the binary system, the polymer concentration in the binary system has a greater impact on the recovery rate of low permeability conglomerate cores. The plugging effect of low concentration polymer is poor, and the spread range is small. With the increase of polymer concentration, high molecular weight polymer can better drive crude oil from natural cores.

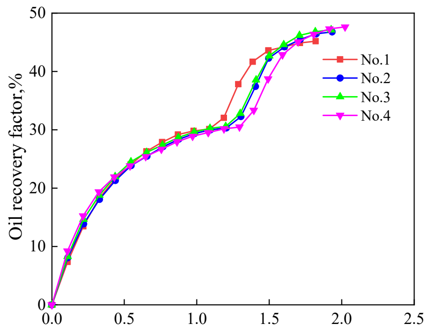


Fig.7 Relationship curve between oil recovery factor and pore volume injection PV

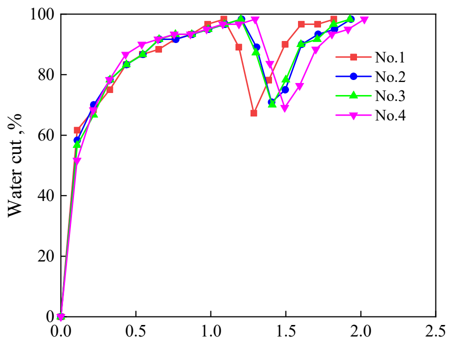


Fig.8 Relationship curve between water cut and pore volume injection PV

Fig.9 is the oil displacement effect comparison chart of four different schemes. It can be seen from Fig. 9 that the recovery degree in water flooding stage is maintained at about 30 %, indicating that under the same experimental conditions, the four groups of natural cores are repeatable. When 0.3 PV 1200 mg/L polymer + 0.5wt % surfactant binary compound system is injected, the binary compound flooding system can effectively improve the recovery of crude oil, and the final recovery is 47.62 %, which can improve oil recovery by more than 17 %, enhanced recovery effect is good.

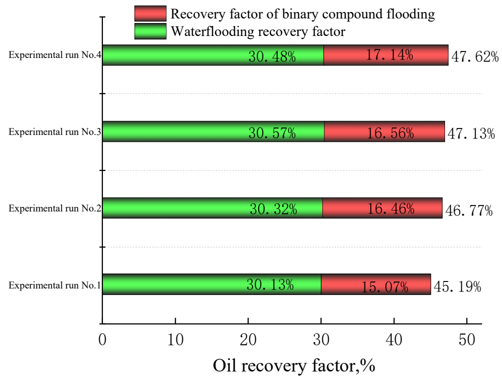


Fig.9 Comprehensive comparison diagram of displacement effect

5. Conclusion

(1) CT scanning results show that the pore radius of core samples is mainly concentrated in 1.4 ~ 3μm, the pore throat radius distribution range is 0.2 ~ 7.8μm, the peak value is 0.4μm, the average length of throat is short, the connectivity is poor, and the permeability is low.

(2) The polymer properties of binary composite flooding system are affected by the molecular weight and solution concentration of the polymer. The maximum viscosity of the polymer system used is 17.5mPa·s, which meets the requirements of low permeability conglomerate for polymer viscosity. Scanning electron microscopy analysis showed that the polymer aggregates formed a multi-layer three-dimensional network structure with a center radiating around, and its macromolecules had dendritic branching structure. Injected liquid polymer concentration is large, the mesh is dense, at this time the mesh is strong energy circular mesh, and its fractal growth self-similarity is stronger.

(3) For low permeability conglomerate reservoirs in Xinjiang Oilfield, when 0.3 PV 1200 mg / L polymer + 0.5wt % surfactant binary compound system is injected, the degree of crude oil recovery can be effectively improved, the final recovery degree is 47.62 %, and the recovery efficiency of crude oil can be improved by more than 17 %, enhanced recovery effect is good.

Acknowledgements

This work was supported by the National Science and Technology Major Projects of China for Oil and Gas (Projects No. 2016ZX05055 and 2016ZX05012).

References

1. Fu C, Yang H, Guo T Y, et al. Study on sensitivity of injection parameters of polymer/surface binary flooding in type II B reservoir [J]. China Energy and Environmental Protection, 2021,43(8):81-86.
2. Niu J G.. Practices and understanding of polymer flooding enhanced recovery technique In Daqing oilfield [J].Petroleum Geology & Oilfield Development in Daqing,2004,23(5):91-93.
3. Cheng J C, Liao G Z, Yang Z Y, et al. Pilot test of ASP flooding in Daqing oilfield [J]. Petroleum Geology & Oilfield Development in Daqing, 2001,20(2):46-49.
4. Liu Q. Research on Key Chemical Control Technology of Binary Flooding System and Its Field Application in Jin 16 Block [J].Advances in Fine Petrochemicals,2017,18(5):18-20.
5. Di S J,Liu D,Cheng H Y, et al. Analysis and evaluation of displacement efficiency of Hongbei 113 [J]. Reservoir Evaluation and Development, 2016,6(1):44-49.
6. Wang L L, Li W H, Zhang Y Q, et al. An Experiment Study on Polymer-surfactant Flooding for Bei3 Region Low Permeability Reservoir in Maling Oilfield [J]. Journal of Chongqing University of Science and Technology(Natural Sciences Edition), 2014, 16(2):82-86.
7. Xu H W, Wang H M,Liu R J, et al. Fine Multiparameter Evaluation for Polymer Flooding in Conglomerate Reservoirs and Its Application: A Case Study from Lower Karamay Formation in District Qidong-1, Karamay Oilfield [J].Xinjiang Petroleum Geology, 2018, 39(2): 169-175.
8. Wang C J,Hong L, Gao R M, et al. Status-quo and Challenges of Enhanced Oil Recovery in Low Permeability Reservoirs [J]. Unconventional Oil & Gas, 2018, 5(3):102-108.
9. Luo L T,Liao G Z,Yan We H, et al. Study on Hydrodynamic Size and Optimal Matching Injection of Polymer in the Chemical Flooding [J]. Oilfield Chemistry, 2016, 33(1):125-136.
10. Wu S H, Xiong Q H. Geology of oil and gas reservoirs [M]. Beijing: Petroleum Industry Press, 1998: 113-122.
11. Yang Z M, Jiang H Q,Li S T, et al. Characteristic Parameters of Microscopic Pore Structures of Low Permeability Gas Reservoirs—By Using Sulige and Dina Low Permeability Gas Reservoirs for Example [J]. Journal of Oil and Gas Technology,2007,29(6):108-110.
12. Prodanović M, Lindquist W B, Seright R S. Porous Sructure and FuidPrtitioning in Plyethylene Cores from 3D X-Ray Microtomographic Imaging[J]. Journal of Colloid and Interface Science, 2006, 298(1): 282-297.
13. Dewanckele J, De Kock T, Boone M A, et al. 4D Imaging and Quantification of Pore Structure Modifications Inside Natural Building Stone by Means of High Resolution X-Ray CT [J]. Science of the Total Environment, 2012, 416 : 436-448.
14. Bijeljic B, Muggeridge A H, Blunt M J. Pore-Scale Modeling of Longitinal Dispersion[J]. Water Resources Research, 2004, 40(11) : 417-427.
15. Bai B, Zhu R K,Wu S T, et al. Multi-scale method of Nano(Micro)-CT study on microscopic pore structure of tight sandstone of Yanchang Formation, Ordos Basin [J]. Petroleum Exploration and Development,2013(3) :329-333.
16. Sakdinawat A, Attwood D. Nanoscale X-Ray Imaging [J]. Nature Photonics,2010, 267(4): 840-848.
17. Attwood D. Microscopy: Nanotomography Comes of Age[J]. Nature, 2006, 442(10): 642-643.
18. Qu L, Shun W, She H h, et al. Characterization Technique of Pore Structure by 3D Digital Core Based on CT Scanning and Its Application:An Example from Sangonghe Formation of 116 Well Field in Mobei Oilfield [J]. Geoscience, 2014(1):190-196.
19. Liu X J,Xiong J,Liang L X, et al. Study on the characteristics of pore structure of tight sand based on micro-CT scanning and its influence on fluid flow [J].Progress in Geophysics,2017,32(3):1019-1028.
20. Su N, Duan Y G, Yu C S. Reconstruction of microscopic pore structure in low permeability gas reservoirs by micro-CT scanning:an example from the Upper Shaximiao Formation in Xinchang gas field [J]. Oil & Gas Geology, 2011(05):792-796.
21. Sun W, Shi C G, Zhao J Z, et al. Reconstruction of microscopic pore structure in low permeability gas reservoirs by micro-CT scanning:an example from the Upper Shaximiao Formation in Xinchang gas field [J]. Acta Geologica Sinica, 2006(5):775-779.
22. Hao L W, Wang Q, Tang J. Research progress of reservoir microscopic pore structure [J].Lithologic Reservoirs,2013(5):123-128.
23. Sun L D, Wu X L, Zhou W F et al. Technologies of enhancing oil recovery by chemical flooding in Daqing Oilfield, NE China[J].Petroleum Exploration and Development,2018,45(4):636-645.
24. Wang B, Wu T, Li Y, et al. The effects of oil displacement agents on the stability of production from ASP (alkaline/surfactant/polymer) flooding [J].Colloids & Surfaces A Physicochemical & Engineering Aspects,2011, 379(1-3):121-126.
25. Zhang X S, Ding M A. The Key Reservoir Technology Condition of Polymer Flooding in Continental Deposit Heavy Oil Reservoir [J]. Journal of oil and gas technology, 2009,31(1):127-129.