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Study on the Contribution of Different Pore Throat Sizes to Oil Displacement Efficiency in Fracture-Pore Tight Sandstone Reservoir

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Abstract: The pore throat and fracture system of tight sandstone reservoir are complex, the reservoir is highly heterogeneous, and the production often decreases rapidly, the development degree is low, and the development effect of water injection is poor. CO_2 injection is an important means to supplement formation energy and achieve efficient reservoir development in tight reservoirs. Based on nuclear magnetic resonance technology (NMR) and high temperature and high pressure physical flow simulation experiment system, the contribution of different scales of pore throat and fracture to the improvement of oil recovery in different phases of CO_2 -crude oil system is studied. The results show that the contribution of mesopores, macropores and fractures to oil displacement efficiency in the supercritical CO_2 displacement stage reaches 74.58%. In immiscible CO_2 displacement stage, the contribution of micropores, small pores and medium pores to oil displacement efficiency reached 73.27%. In the miscible CO_2 displacement stage, the contribution of micropores and small pores to oil displacement efficiency reached 52.32%. In the supercritical CO_2 displacement stage, the contribution of oil displacement efficiency is mainly provided by macropore throats and fractures. The contribution of immiscible and miscible CO_2 displacement stage to oil displacement efficiency mainly comes from small pore throat with smaller scale.

Keywords: Tight Sandstone; Different Scale Hole Throat; Oil Displacement Efficiency; Contribution of Degree.

1. Introduction

Tight oil and gas are a very important unconventional resource in the world, which is an important force to replace conventional oil and gas energy and support the oil and gas revolution. In recent years, the development experience of tight reservoirs at home and abroad has shown that tight sandstone reservoirs with micrometer-nanometer-level pore-throat scale, complex pore-throat fracture system and strong reservoir heterogeneity will lead to poor reservoir development effect, rapid production decline and low development degree, making conventional reservoir development methods such as water injection development no longer applicable[1]. Laboratory research results and field practice experience show that CO_2 injection is an effective means to supplement formation energy and achieve efficient reservoir development in tight reservoirs. Compared with other gases, CO_2 gas has obvious technical advantages. After entering the formation, it can form mismixing with crude oil under certain conditions, realizing the advantages of reducing crude oil viscosity, reducing oil and gas interface tension, expanding crude oil volume, slowing down CO_2 viscous pointing, and slowing down gas channeling. After application, the productivity of a single well has been significantly improved.

However, the complex pore-throat system and strong microscopic heterogeneity of unconventional tight sandstone reservoirs seriously affect the percolation characteristics of CO_2 -crude oil system. At present, the microscopic seepage characteristics of different phases of CO_2 -crude oil system in micro and nano pore throat fracture system are not clear, and the contribution mechanism of different scale pore throat and fracture in the dual medium space (fracture-micro and nano pore throat) to the improvement of oil recovery needs to be revealed. Therefore, based on nuclear magnetic resonance core detection technology (NMR) [2], combined with high temperature and high pressure physical flow simulation experiment system, this paper evaluates the microscopic oil displacement and seepage characteristics of water and CO_2 in tight sandstone reservoir in fracture-pore dual media [3]. The contribution mechanism of pores and throats of different scales to enhanced oil recovery in the flow process of different phase CO_2 -crude oil system is clarified, so as to provide theoretical support for the efficient development of tight sandstone reservoirs and the realization of "dual carbon" goal.

2. Part of Experiment

2.1. Principle of Experiment

Nuclear magnetic resonance (NMR) is a rapid and nondestructive core detection method, which has been widely used in reservoir evaluation, pore seeping, and quantitative characterization of microscopic pore structure. This experiment is based on NMR technology and high temperature and high pressure physical flow simulation system to study the mechanism of the contribution of fracture-pore dual media to improving oil recovery in tight rock reservoirs. The basis of NMR technology is that the pore size of reservoir rocks is directly proportional to the relaxation time of hydrogen nuclei, that is, the smaller the pore throat radius is, the faster the relaxation rate of hydrogen nuclei is, and the corresponding relaxation time T_2 is shorter. The quantitative analysis of the occurrence characteristics of microscopic pore-throat mobile fluid in tight sandstone samples before and after the experiment was achieved by comparing the coverage area difference (the difference of T_2 spectrum signal amplitude accumulation value) of cores under different states before and after the experiment. The relaxation time difference of different pore-throat structures in tight sandstone can show different spectral peak characteristics on T_2 spectrum, which can be used to judge the characteristics of pore-throat structures. At the same time, it can determine the occurrence state of free mobile fluid and bound immobile fluid in tight sandstone pores, and clarify the utilization of crude oil and the mechanism of contribution degree of pore throat at different scales[4].

In this experiment, the natural core of Chang 6 tight sandstone reservoir of Yanchang Formation in Xuecha block, Wuqi area of Ordos Basin was selected to prepare the experimental core plunker samples (diameter 2.50cm, length 8.00cm, porosity 12.25%, permeability 0.359mD). The crude oil samples were taken from the Chang 6 Formation reservoir in Ordos Basin, which were the same well and the same layer as the sample core. The actual salinity of formation water is 47195.79mg/L, which is $CaCl_2$ water type. $MnCl_2$ aqueous solution (salinity of 25000mg/L); The purity of CO_2 gas is 99.99%. The experimental equipment (Fig. 1) is the high temperature and high-pressure physical flow simulation experimental system and Oxford NMR online testing system, and the temperature is set at 60°C. The minimum miscibility pressure (MMP) of crude oil samples with CO_2 in Chang 6 sandstone reservoir of Yanchang Formation in Xuecha Block, Wuqi area was 17.8MPa. Therefore, the CO_2 injection pressure is set as 8MPa, 14MPa and 18MPa, so that the CO_2 crosses the supercritical point, the immiscible phase of the CO_2 -crude oil system and the miscible phase of the CO_2 -crude oil system. The microscopic displacement and seepage characteristics of CO_2-assisted crude oil and the distribution law of remaining oil in the fractured dual media model with different phases of CO_2 are completely evaluated. It further reveals the contribution mechanism of pores, throats and fractures of different scales to the improvement of oil recovery in the flow process of CO_2-crude oil system with different phases[5,6].

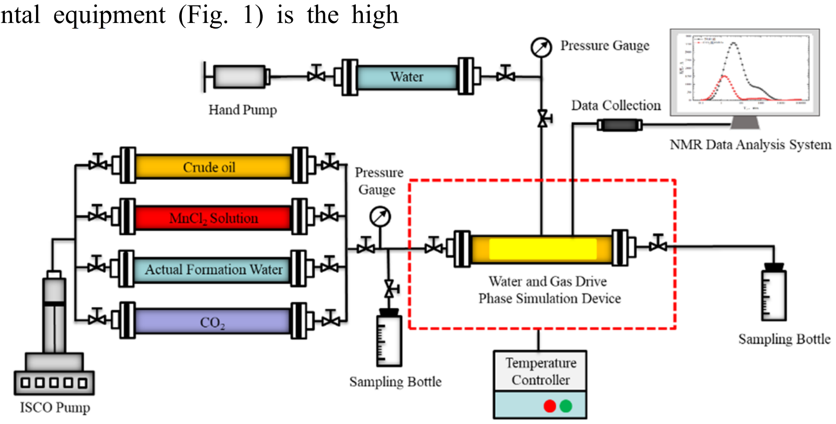

Fig 1. Experimental system of physical flow simulation at high temperature and high pressure

2.2. Procedure of Experiment

(1) Oil washing and drying: the selected core samples were screened, classified and numbered, and the core was deeply washed with the 3:1 ratio of benzene and ethanol. After the cleaning, the core was placed in a thermostat for drying, and the rock samples were dried for 24h at 80°C.

(2) Physical property test: the core was cut and polished and made into experimental core plunger samples with length of 8.0cm× diameter of 2.5cm, and the core was numbered for physical property parameter analysis and other test work.

(3) Establish the original formation water distribution model: The core plunker samples were put into the high temperature and high pressure physical flow simulation experimental device system, and the actual formation water (salinity of 47195.79mg/L, $CaCl_2$ water type) was displaced to the depth of the core by ISCO pump. The temperature was constant at 60°C, the displacement velocity was 0.05mL/min, and the displacement pressure was 12MPa. In order to establish the original formation water distribution model of the experimental core, the confining pressure was set to 14MPa with an annular pressure tracking pump, and the saturation was stopped when the injection volume reached 5PV.

(4) Saturated $MnCl_2$ aqueous solution: An ISCO pump was used to displace $MnCl_2$ aqueous solution (salinity of 25000mg/L) to the depth of the core at a constant temperature of 60°C, a displacement velocity of 0.05mL/min, and a displacement pressure of 12MPa. An annular pressure tracking pump was used to set a confined pressure of 14MPa, and saturation was stopped when the injection volume reached 5PV. Mn^{2+} in manganese water is used to shield the interference of hydrogen signal in water.

(5) Establish the original oil-water distribution model: ISCO pump was used to displace the formation water /$MnCl_2$ aqueous solution deep into the core at a constant temperature of 60°C, displacement speed of 0.05mL/min, displacement pressure of 13MPa, and circumferential pressure tracking pump was used to set the enclosed pressure of 15MPa until the oil content of the output liquid was 100%. Saturated oil NMR T_2 spectrum sampling was performed. To establish the original formation oil and water distribution model of the experimental core.

(6) Water flooding stage: the actual formation water is displaced to the depth of the core at a constant temperature of 60°C, the displacement velocity is 0.05mL/min, and the displacement pressure is 12MPa. The circumferential pressure tracking pump is used to set the confined pressure to 14MPa. When the water content of the output liquid at the outlet is 100%, the magnetic resonance T_2 spectrum sampling is carried out in the water flooding stage.

(7) Gas flooding stage: The temperature was constant at 60°C, and the ISCO pump was used to set the CO_2 injection pressure as 8MPa, 14MPa and 18MPa respectively, so that the CO_2 crossed the supercritical point, the CO_2 immiscible phase and the CO_2 miscible phase, and the physical flow simulation experiment of CO_2 flooding was carried out. The flooding was stopped when the quality of the output liquid at each stage stopped changing. In order to sample different phases of CO_2 displacement NMR T_2 spectrum.

(8) Data recording: Accurately record the injection time, displacement velocity, water/gas injection volume, inlet pressure, and outlet oil production rate during the experiment,

and clearly identify the microscopic oil displacement and fluid flow characteristics of different phase CO_2 in the fractured dual-medium model, further revealing the contribution degree of different scale pore-throat-fracture to enhancing oil recovery.

3. Analysis and Discussion

Fig. 2 shows the NMR T_2 spectrum of prefabricated longitudinal fracture core samples for water flooding and gas flooding experiments. The NMR T_2 spectrum samples were sampled after saturated oil flooding, water flooding and CO_2 displacement with different phases respectively, and the pore throat distribution scale and oil displacement efficiency were defined as shown in Table 1. Comparing the curve of saturated oil stage (red) with the curve of water flooding stage (blue), the crude oil in medium and large pores is mainly used in water flooding stage, with the utilization degree reaching 91.26%, and the crude oil in fractures reaches 17.2%. However, some crude oil seeping into micro and small pores increases the crude oil content in micro pores and throat, with the utilization degree reaching -15.95%. The overall oil displacement efficiency in the water flooding stage is 25.68%. Comparing the curve of the water flooding stage (blue) with the curve of the supercritical CO_2 flooding stage (pink), the supercritical CO_2 flooding stage mainly uses the crude oil in the macropores and fractures, and the utilization degree reaches 58.1%. Meanwhile, the CO_2 diffuses into the micropores, small pores and middle pores, and the utilization degree of this part of crude oil reaches 29.72%. The overall displacement efficiency of supercritical CO_2 displacement stage is 16.36%.

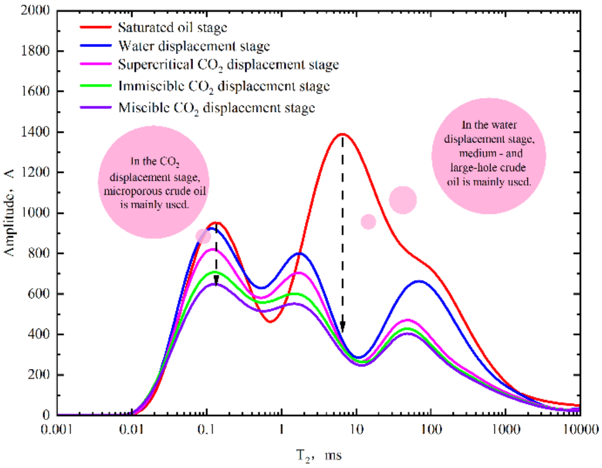

Fig 2. NMR T_2 spectra of prefabricated longitudinal through-crack core samples at different experimental stages

Comparing the supercritical CO_2 displacement stage curve (pink) with the immissibility CO_2 displacement stage curve (green) (Fig. 2), the immissibility CO_2 displacement stage mainly uses the crude oil in micropores, small pores and middle pores, and the utilization degree is 29.21%, while the utilization degree of the crude oil in macropores and fractures is low, only 17.02%, because the CO_2 displacement pressure increases. Some of the CO_2 in the small pore throat spread to increase the displacement of crude oil, and some of the rapid flow and escape along the fracture channel weakened the displacement effect in the fracture and the large pore, and the overall displacement efficiency in the immiscible CO_2 displacement stage was 9.35% (Table 1, Fig. 3).

Table 1. Distribution of pore throat at different scales and oil displacement efficiency

Serial number	Type	T_2/ms	Displacement efficiency/%			
			Water	Supercritical CO_2	Immiscible CO_2	Miscible CO_2
1	Micropore	[0.001-0.1)	-9.52	9.69	8.95	7.89
2	Ostiole	[0.1-1.0)	-6.43	9.57	8.91	7.93
3	Mesopore	[1.0-10)	44.27	10.46	11.35	8.10
4	Macropore	[10-100)	46.99	23.43	8.02	5.24
5	Crack	[100-10000]	17.02	34.67	9.00	4.87
6	Entirety	[0.001-10000]	25.68	16.36	9.35	7.11

Comparing the immismisable CO_2 displacement stage curve (green) with the mismisable CO_2 displacement stage curve (purple) (Fig. 2), the mismisable CO_2 displacement stage mainly uses crude oil in micropores, small pores and middle pores, and the utilization degree reaches 23.92%, while the utilization degree of crude oil in macropores and fractures is low, only 10.11%. This is because as the CO_2 displacement pressure continues to increase, CO_2 preferentially flows rapidly along the cracks of the hyperosmotic channel, and then gradually diffuses and spreads to the marginal matrix area far away from the cracks. Part of CO_2 rapidly advances in the micro pore throat and advances in the form of finger-like tongue, forming a special mismixing zone and forcing the displacement of the crude oil of the micro pore throat. At this time, the diffusion and spreading range reaches the maximum. Some of them quickly escape along the fracture, which weakens the displacement effect in the fracture and macropore, and the overall displacement efficiency in the miscible CO_2 displacement stage is 7.11% (Table 1, Fig. 3). It should be noted that the overall oil displacement efficiency in the mismixable CO_2 displacement stage is not the average value of the previous pore throat displacement efficiency at different scales, but the ratio of the coverage area difference between the green NMR T_2 spectrum and the purple NMR T_2 spectrum to the green NMR T_2 spectrum area, and the overall oil displacement efficiency in other stages is similar.

On the basis of clarifying the oil displacement efficiency, the area difference of T_2 spectrum between saturated oil stage curve (red) and water flooding stage curve (blue) in the range of [0.001-0.1) is further calculated. The ratio of this difference to the area difference between the saturated oil stage curve (red) and the water flooding stage curve (blue) in the range of [0.001-10000] is the contribution of micropores to oil displacement efficiency in the water flooding stage, and the contribution of different sizes of pores and throat in other stages to oil displacement efficiency is the same. Accordingly, the contribution degree of pore throat of different scales to oil displacement efficiency in different experimental stages is calculated (Fig. 4).

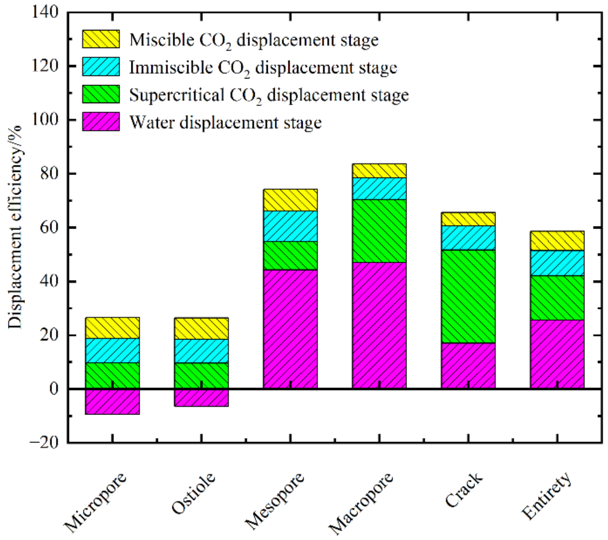

Fig 3. Oil displacement efficiency of hole throat at different scales

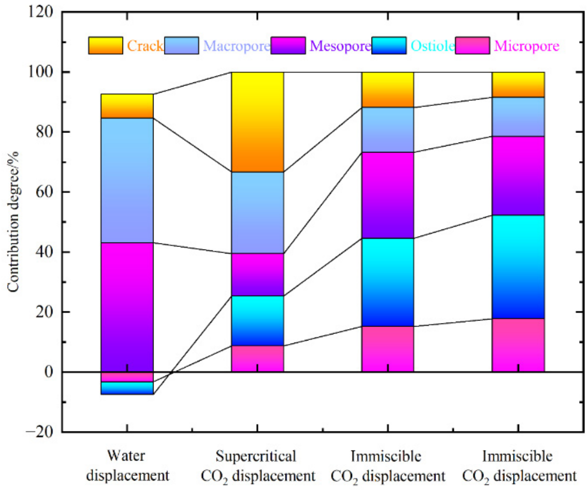

Fig 4. Contribution of different pore throats to oil displacement efficiency

It can be seen from Fig. 4 that in the water flooding stage, medium and large holes have the largest contribution to oil displacement efficiency, which are 50.61% and 48.77% respectively. The fractures are relatively small, and the crude oil content in micro and small holes increases, so the contribution to oil displacement efficiency is negative. In the supercritical CO_2 displacement stage, the contribution of micro pores and small pores to oil displacement efficiency increases significantly due to CO_2 diffusion to micro pores and throats, and the contribution of fracture, middle pores and large pores to oil displacement efficiency is the largest, and the sum of the three reaches 74.58%. In the immiscible CO_2 displacement stage, due to the relatively small amount of remaining oil in the large pores and fractures, the increase of pore throat contribution is relatively low. On the other hand, due to the diffusion of immiscible CO_2 to the small pores and throats, the forced displacement of the crude oil in the small pores and throats, the contribution of the small pores and throats to the oil displacement efficiency is large, up to 44.65%. In the miscible CO_2 displacement stage, CO_2 continues to spread and spread in the micro pore throat, and advances in a finger-like form to form a special miscible zone, which effectively replaces the micro pore throat crude oil. In this stage, the contribution of the micro pore throat to the oil displacement efficiency reaches 52.32%, while most of the CO_2 escape along the fracture, and the suction effect on the fracture and the big hole is weakened. The contribution rate is only 21.43%.

4. Summary

(1) In the water flooding stage, the oil utilization degree in the middle hole and large hole is the highest, reaching 91.26%, and the oil displacement efficiency is 25.68%; In the supercritical CO_2 displacement stage, the utilization degree of crude oil in large pores and fractures is the highest, reaching 58.1%, and the oil displacement efficiency is 16.36%. In the immiscible CO_2 displacement stage, the oil utilization degree in the large pores and fractures is low, only 17.02%, and the oil displacement efficiency is 9.35%. The oil utilization degree in micropores, small pores and middle pores reached 23.92%, and the oil displacement efficiency was 7.11%.

(2) In the water flooding stage, the contribution of middle hole and large hole to oil displacement efficiency is the largest, reaching 99.38%; The contribution of mesopores, macropores and fractures to oil displacement efficiency reached 74.58% in the supercritical CO_2 displacement stage. In immiscible CO_2 displacement stage, the contribution of micropores, small pores and medium pores to oil displacement efficiency reached 73.27%. In the miscible CO_2 displacement stage, the contribution of micropores and small pores to oil displacement efficiency reached 52.32%.

(3) During water flooding and supercritical CO_2 flooding, the contribution of oil displacement efficiency is mainly provided by macropore throats and fractures. With the increase of displacement pressure, the contribution of oil displacement efficiency in immiscible and miscible CO_2 displacement stages mainly comes from the smaller pore throat.

Acknowledgments

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References

[1] Longwei Qiu, Xiangji Mu, Hao Li, et al. Influence of diagenesis of tight sandstone reservoir on the porosity development of Lower Shihezi Formation in Hangjinqi area,Ordos Basin. Petroleum Geology and Recovery Efficiency. Vol.26 (2019) No. 02, p. 42-50.

[2] Hailong Dang, Xiaofeng Wang, Pengxing Cui, et al. Research on the characteristics of spontaneous imbibition oil displacement with the low permeability tight-sandstone oil reservoir using the Nuclear Magnetic Resonance (NMR) technology. Progress in Geophysics (in Chinese). Vol.35 (2020) No. 05, p. 1759-1769.

[3] Weiyun Ma, Kai Huang, Peng Wang, et al. Mechanism of waterproof locking in tight sandstone gas reservoir based on low field nuclear magnetic resonance technology. Science Technology and Engineering. Vol.24 (2024) No. 04, p. 1459-1470.

[4] Chen Wang, Hui Gao, Yuan Gao, et al. Influence of Pressure on Spontaneous Imbibition in Tight Sandstone Reservoirs. Energy&fuels. (2020) No. 34, p. 9275-9282.

[5] Xiaoyu Gu, Chunsheng Pu, Hai Huang, et al. Micro-influencing mechanism of permeability on spontaneous imbibition recovery for tight sandstone reservoirs. Petroleum

Exploration and Development. Vol.44 (2017) No. 06, p. 948-954.

[6] Xing Huang, Tiantai Li, Xiangzeng Wang, et al. Distribution characteristics and its influence factors of movable fluid in tight sandstone reservoir: a case study from Chang-8 oil layer of Yan-chang Formation in Jiyuan oilfield,Ordos Basin. Acta Petrolei Sinica. Vol.40 (2019) No. 05, p. 557- 567.