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Research Article

Study on Micropore Throat Fluid Seepage Characteristics and Oil Displacement Efficiency in Tight Reservoir

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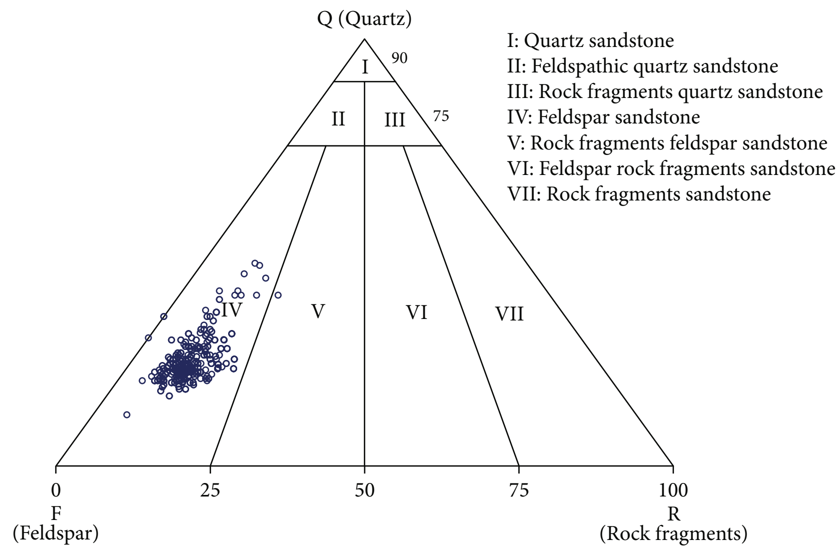
In order to overcome the problems including complicated pore throat structure, changeable seepage characteristics, and difficulty to find seepage law in the tight reservoir, this study simulated the water flooding development process of oilfield reservoir, and the water flooding seepage experiment of real sandstone microscopic model was carried out in a laboratory. Thin slice identification, constant velocity mercury injection, physical property analysis, scanning electron microscope, and other test data were combined to study the reservoir microscopic water flooding characteristics. The relationships between physical properties, water displacement efficiency, displacement pressure, pore structure, wettability, and water injection ratio are discussed. The study showed that the tight reservoir fluids were uniform displacement and reticular displacement seepage that occurred more than finger-reticular displacement. Meanwhile, displacement types affected oil displacement efficiency. Specifically, the uniform displacement type displayed the highest oil displacement efficiency, whose average value was 62.15%. The lowest oil displacement efficiency was finger displacement type, which is 26.89%. Additionally, 79% of the residual oil was cluster and film, and the corner and isolated distribution are less; the change of permeability has a greater effect on oil displacement efficiency than porosity. With the increase of water injection ratio, the oil displacement efficiency was improved. The oil displacement efficiency increases greatly and tended to be smooth and stable, when the water injection increased by 3 PV. There is an exponential relationship between throat radius and oil displacement efficiency.

1. Introduction

The Chang 6 reservoir in Jiyuan Oilfield, Ordos Basin has played an important role in increasing production. After years of water flooding development, there are some problems in oil wells, such as low production per well, block of rising water cut, and the difficulty of water injection, resulting in a short stable production cycle and low recovery degree. Previous studies on the block were mainly focused on reservoir description, development performance, and reservoir engineering evaluation [1–4]; however, the research for the relationship between oil-water seepage in oil reservoir and its influencing factor was relatively weak, and the law of oil-water seepage in the reservoir was not clear. The characteristics of oil-water two-phase seepage and residual oil types in tight reservoir rocks were analyzed through the microscopic water flooding model experiment of real sandstone in this paper, combined with physical properties, casting, and other data and experimental conditions. This paper discussed the relationship among physical properties, wettability, water injection multiple, pore structure, and displacement type and oil displacement efficiency to find out the internal relationship between the fluid flow characteristics and micropore throat characteristics and put forward some suggestions for increasing the effect of oil displacement in tight reservoir. Meanwhile, it also provided a theoretical description for describing the formation mechanism and distribution characteristics of remaining oil. [5–7].



(a) The table of rock type

(b) Y179, 1838.45 m, fine feldspar sandstone

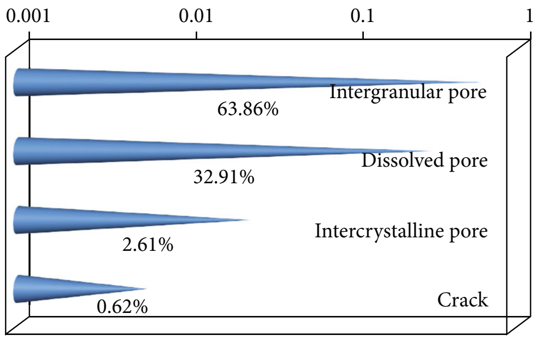
FIGURE 1: Rock type of Chang 6 reservoir.

2. Regional Geological Survey

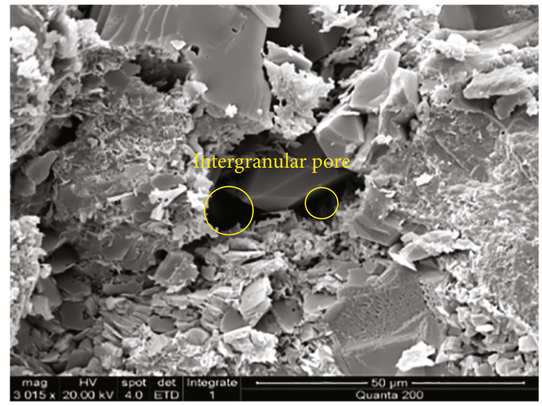
Jiyuan Oilfield is most located in Yanchi County, Ningxia and Dingbian County, Shaanxi Province. The area has a low amplitude nose uplift structure in the eastward direction, and the two wings of the nose-cutting structure are approximately symmetrical. The dip angle is less than 2 degrees, the closure area is less than 10 square kilometers, the closure degree is generally 10-20 meters, most of the nose-shaped structures are irregular, and faults are not developed [8, 9]. The Chang 6 reservoir is the main oil-producing layer, the porosity is mainly concentrated at 3.24%-19.21%, with an average of 11.03%, and the permeability is $0.004 \times 10^{-3}\,\mu m^2$-$11.68 \times 10^{-3}\,\mu m^2$, with an average of $1.21 \times 10^{-3}\,\mu m^2$, which is a typical tight reservoir. Thin section identification and scanning electron microscope analysis indicated that the reservoir lithology of Chang 6 formation is light gray, gray, fine-grained, and very fine-grained lithic feldspathic sandstone (Figure 1). The reservoir's average pore diameter is 31.16 μm, and the average areal porosity is 3.62%. Residual intergranular pores and skeleton grain solution pores (feldspar solution pores and lithic solution pores) are the most pore types of the reservoir, and local intergranular micropores and microfissures are rarely seen (Figure 2).

3. Microscopic Seepage Experiments of Water Flooding

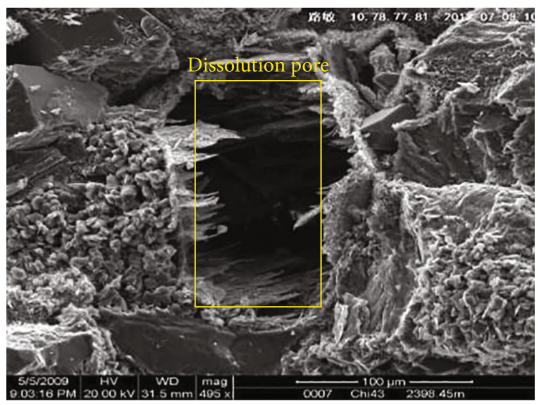
3.1. A Brief Introduction to the Method of Seepage Experiment. The experimental equipment adopted the real sandstone water flooding instrument independently developed by the Geology Department of Northwestern University. Through a series of technological processes of core slicing, oil washing, drying, grinding, and cementation, a sandstone model with a length, width, and thickness of 2.5 cm × 2.5 cm × 0.07 cm was made. The pressure range was between 0.2 MPa and 0.3 MPa, and the temperature resistance was about 100°C. The experimental oil sample was the wellhead sample (viscosity is 1.55) adding a small amount of oil dissolved red, and the water sample was the actual formation water adding a small amount of methyl blue, showing blue [10, 11]. The permeability of the model was measured by test tube gas, and then the model was vacuumed (Figure 3(a));



(a) Percentage of different pore types



(b) The intergranular pore



(c) The dissolution pore

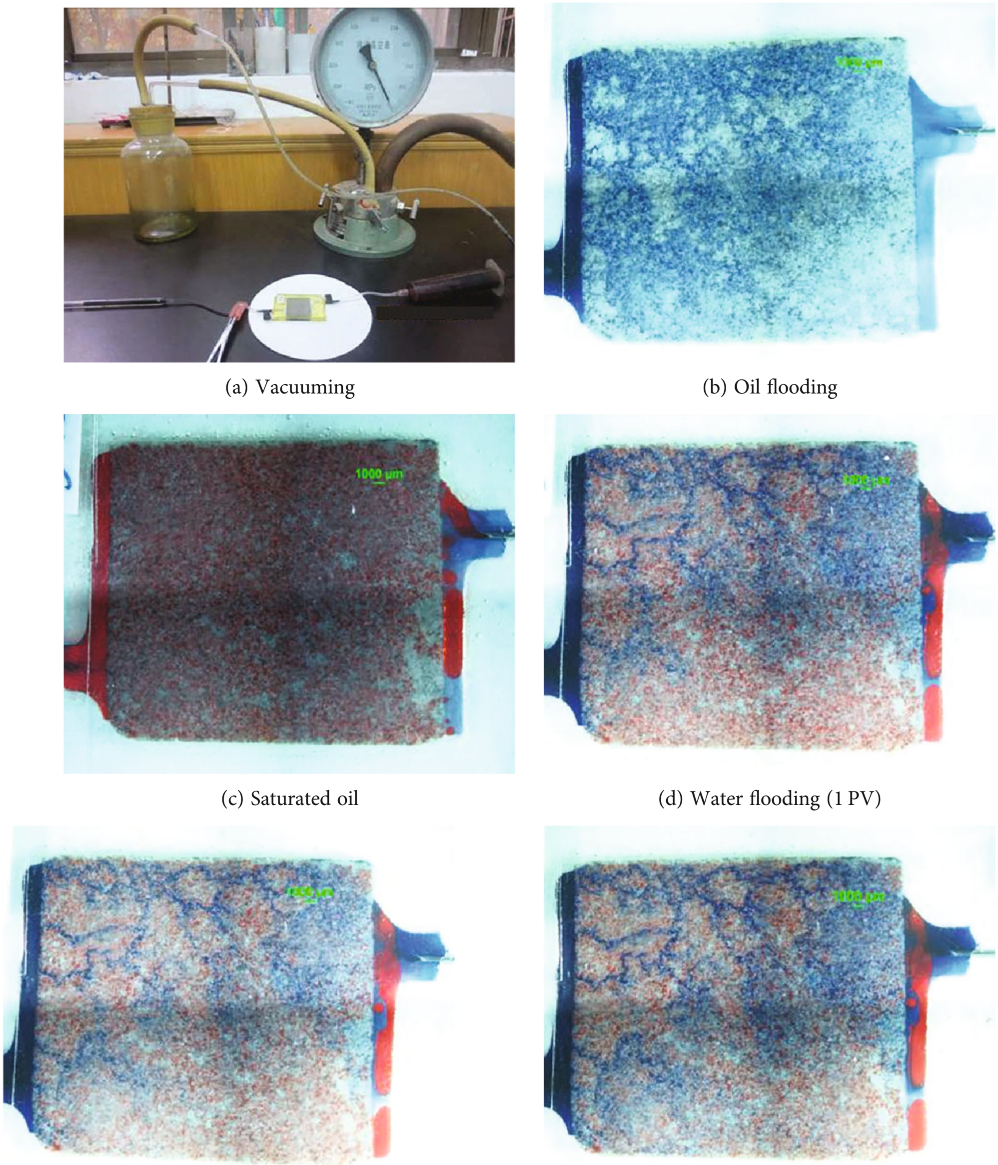
Figure 2: The distribution diagram of pore type.

then, saturated water (Figure 3(b)), then oil flooded water (Figure 3(c)), and finally water flooding simulation experiments were carried out (Figures 3(d)–3(f)). In the course of the experiment, the pressure increased gradually from 0.001 MPa to 0.1 MPa, and the water flooding images were observed and recorded every 30 minutes. At the same time, the experimental data such as pressure at the entrance and outlet were accurately recorded, and the images of 1 PV, 2 PV, and 3 PV under the water flooding mirror were recorded by microscopic equipment, and finally, the data were collected and processed.(Red represents oil, blue represents water, and gray represents rock.)

3.2. Seepage Characteristics of Microscopic Water Flooding. The microwater flooding experiment of real sandstone was carried out on 14 cores of Chang 6 reservoir in Jiyuan oilfield. The core model had a wide range of distribution, covering the whole study area; the physical properties of the model were inconsistent, the range of porosity was 5.22%-14.43%, and the range of permeability was $0.234\text{-}2.135 \times 10^{-3}\,\mu m^2$, reflecting the complex geological characteristics of the reservoir. Owing to the weaker physical properties and strong heterogeneity of the core model, the reservoir fluid seepage path was inconsistent and residual oil types were different [12]. The oil displacement efficiency was different with different displacement paths. The specific core parameters and oil displacement characteristics are shown in Table 1 and Figure 4.

The injected water did not enter the experimental model when the pressure was less than 20 kPa (starting pressure). When the pressure exceeded 20 kPa, the injected water began to enter the saturated oil model slowly. In the course of the experiment, the injected water entered the model along multiple seepage paths at the leading edge of water flooding, and the injected water of each path advanced parallel at a relatively stable speed, and the injected water velocity of each path was different, but the difference was not obvious. The whole was in a uniform advancing state (Figure 5(a)). The amplitude of the injected water seepage path gradually widened, and the water flooding path extended around the original path when the displacement time and displacement pressure increased. The swept area was enlarged, and the seepage channel was intricate and interactive into a reticular structure. This kind of model has developed pores and good pore-throat connectivity, and the final swept area is larger; the average displacement volume is higher than 0.063 cm^3, and the final displacement efficiency is 63.08% (Figure 4).

Microscopically, after the visual injection of water enters the saturated oil model along the inlet, multiple injection waterlines moved irregularly in the form of serpentine interaction [13, 14], and the water drive path was in the shape of a reticular and pushed to the exit end layer by layer. When



(a) Vacuuming

(b) Oil flooding

(c) Saturated oil

(d) Water flooding (1 PV)

(e) Water flooding (2 PV)

(f) Water flooding (3 PV) (PV stands for multiple of pore volume)

Figure 3: The image of real microcosmic water flooding.

the displacement time and displacement pressure increased, the displacement path widens, and the injected water spread around along the original path, forming a dendritic fine path, which expanded the swept area. After water was seen at the outlet, the model displacement path showed a multimorphological and irregular reticular structure (Figure 5(b)). The physical properties of the model were good, the average displacement volume was higher than 0.041 cm^3, and the final displacement efficiency was 42.36%.

In this kind of model, the sorting of rock particles was poor; meanwhile, the pore size and the throat thickness were different. The injected water began to enter and displace along the large throat under the starting pressure and quickly reached the exit end. When the displacement pressure increased, the injected water spread around it along the fingering displacement path [15, 16] formed a reticular displacement route and showed finger-reticular displacement characteristics as a whole (Figure 5(c)). The pore development of this kind of model was poor, the pore throat connectivity became worse, the average displacement volume reached 0.026 cm^3, and the displacement efficiency reached 33.6%.

Under the action of driving pressure difference, the injected water will flow forward along the large throat with less capillary resistance and gradually occupy the large throat and the connected pores, forming a single seepage channel with finger distribution. With the progress of water flooded, the water flooding path of finger oil gradually became wider, and part of the paths was connected. The overall advance of water flooding in this kind of model was uneven, forming an obvious sudden infiltration path, which was easy to flow around to form a large residual oil area

Table 1: Pore structure parameters and displacement path of sandstone.

Well name	Porosity (%)	Permeability ($\times10^{-3}$ μm^2)	Oil displacement efficiency (%)	Displacement path
C146	9.23	0.4001	37.28	Finger-reticular displacement
C335	9.19	0.3441	40.4	Finger-reticular displacement
L27	12.42	2.1355	63.07	Uniform displacement
C250	10.56	0.4771	32.75	Finger displacement
C57	9.1	0.4023	41.22	Reticular displacement
C95	10.76	0.6566	43.16	Reticular displacement
X29	8.14	0.5652	38.26	Finger-reticular displacement
J71	9.87	1.7737	58.33	Uniform displacement
Y179	13.43	0.6903	37.54	Reticular displacement
Y263	5.22	0.3891	24.28	Finger displacement
J116	11.17	1.2337	37.75	Uniform displacement
J43	11.73	1.0385	38.2	Reticular displacement
Y245	9.37	0.3966	38.61	Reticular displacement
J68	7.72	1.0447	44.67	Finger-reticular displacement

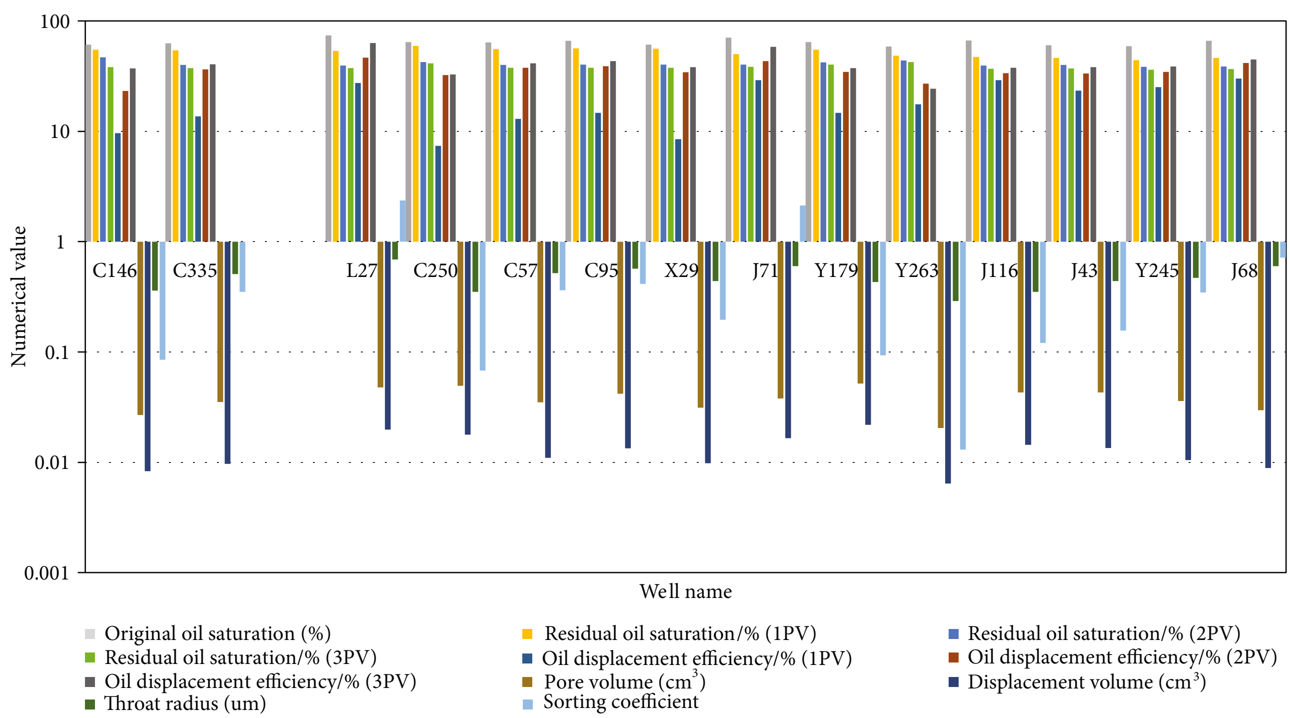


Figure 4: Characteristics of water flooding.

(Figure 5(d)). This kind of model had poor pore development, poor pore-throat connectivity, and low oil displacement efficiency. Its displacement volume was only 0.009 m^3, so its oil displacement efficiency is only 27.71% in the end.

The pore structure, surface properties, reservoir physical properties, displacement conditions, and other factors affected the retention state of the remaining oil. Microscopic visible residual oil types were usually cluster, oil film, isolated, corner, and other forms (Figures 5(e) and 5(h)). Statistics of 14 experimental models showed that clusters and oil film were the main types of residual oil, and clusters accounted for about 50% of the total residual oil. Oil film accounted for about 30% of the total. Cluster and oil film residual oil types were common in the uniform displacement and reticular displacement models, and the average residual oil volume was 0.027 cm^3 and 0.023 cm^3, respectively. Corner and isolated residual oil types were common in the finger-reticular displacement and finger displacement models, and the average volume of residual oil was

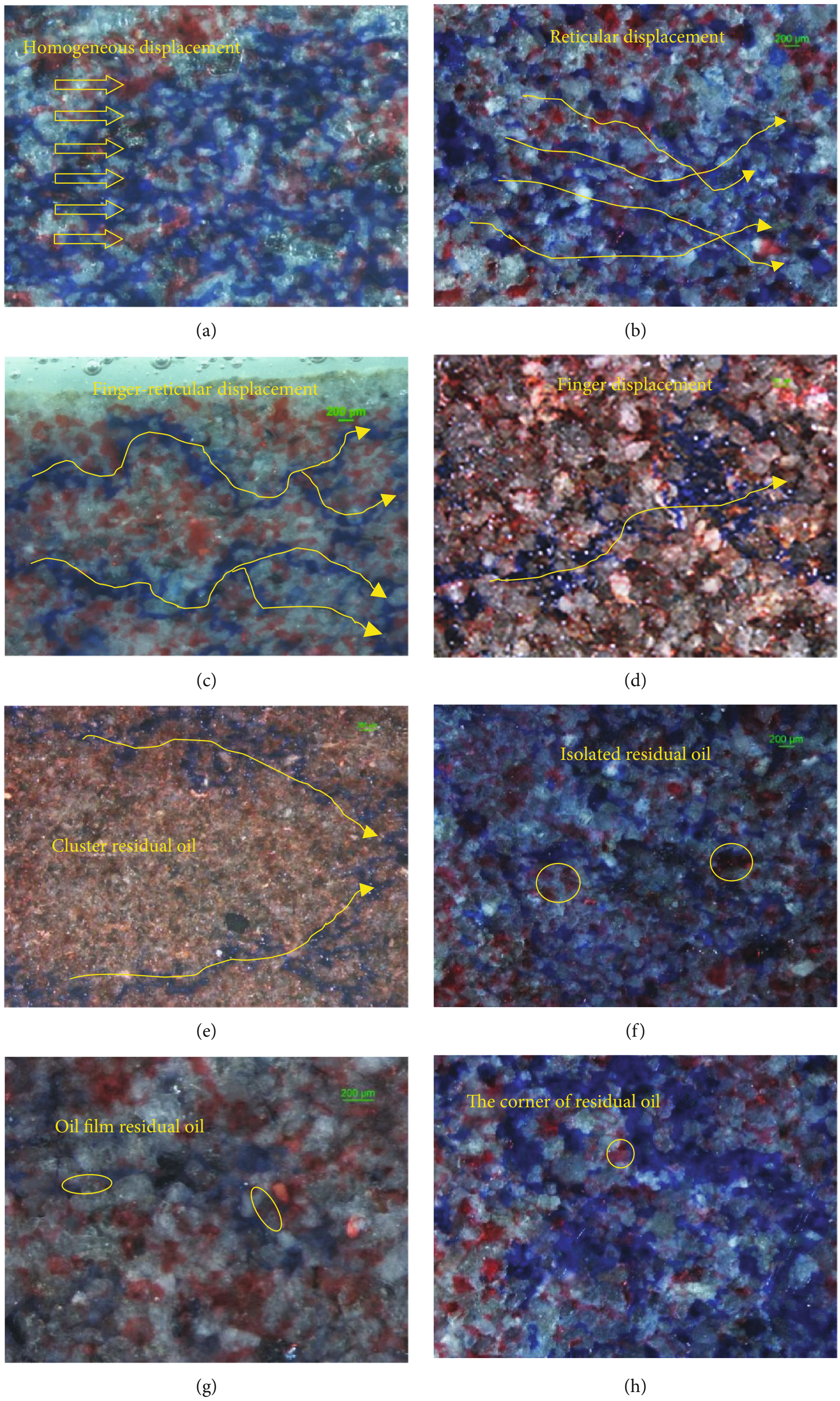
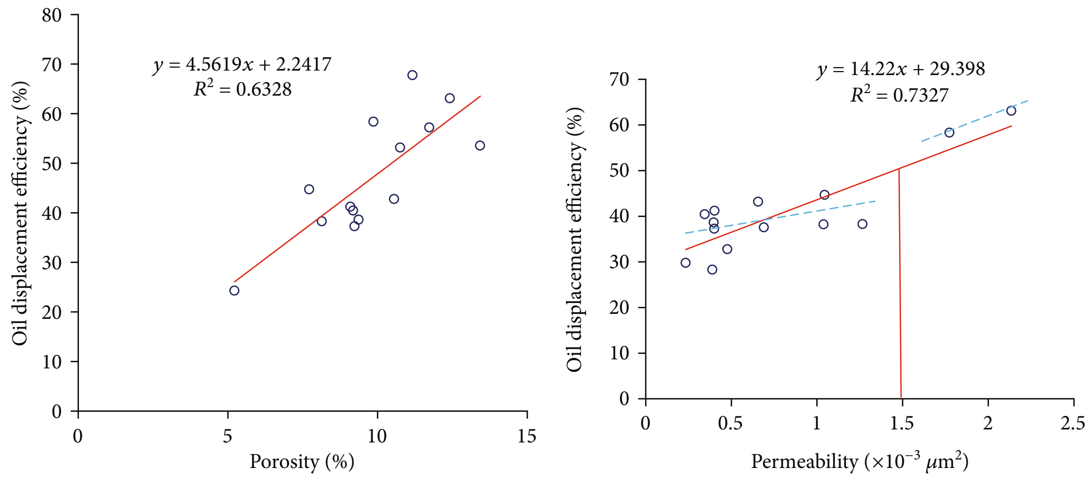
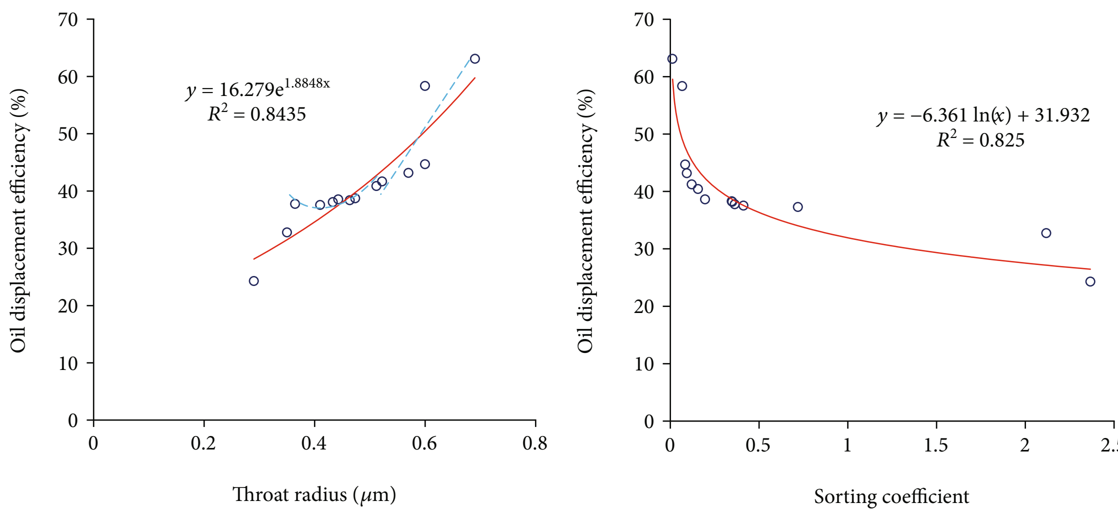


Figure 5: The characteristics of microscopic photos in water flooding experiments with the real sandstone micromodel. (a) Uniform displacement (Y245, 2111.60 m); (b) reticular displacement (J116, 2101.96 m); (c) finger-reticular displacement (Y215, 2118.47 m); (d) finger displacement(X29, 2331.00 m); (e) cluster residual oil (J43, 2041.93 m); (f) isolated residual oil (C335, 2303.72 m); (g) oil film residual oil (L37, 2285.47 m); (h) the corner of residual oil (J43, 2028.91 m).



(a) (b)

FIGURE 6: The relationship between physical parameters and oil displacement efficiency..



(a) (b)

FIGURE 7: The relationship between pore throat parameters and oil displacement efficiency.

0.046 cm^3 and 0.041 cm^3, respectively. In a word, in the model, when there are more pore-shrinking throat and necking throat, it is generally uniform displacement; when there are more flake throat, it is reticular displacement; when there are more curved throat, it is finger-reticular displacement; and when there are more pipe-bundle throat, it is finger displacement, and the oil displacement efficiency becomes worse in turn.

4. Analysis of Influencing Factors on Seepage Characteristics of Water Flooding Oil

There are many factors affecting oil displacement efficiency, including production system (displacement pressure, displacement rate, and water injection ratio), fluid properties (water-oil viscosity ratio, injected water quality, and displacement type), and reservoir characteristics (physical properties, pore structure wettability, oil-water phase permeability, and movable fluid) [17–21]. Based on the indoor real sandstone microscopic water flooding experiment, this paper focused on the effects of reservoir physical properties, micropore throat structure, displacement pressure, water injection ratio, and other parameters on oil displacement efficiency.

4.1. Physical Factor. With the increasing of porosity and permeability, the final oil displacement efficiency relationship increased. This showed that the physical properties of the reservoir would affect the final oil displacement efficiency of the reservoir (Figure 6). It was found that both porosity and permeability were positively correlated with oil displacement efficiency. And the correlation between permeability and oil displacement efficiency ($R^2 = 0.7327$) was better than that between porosity and oil displacement efficiency

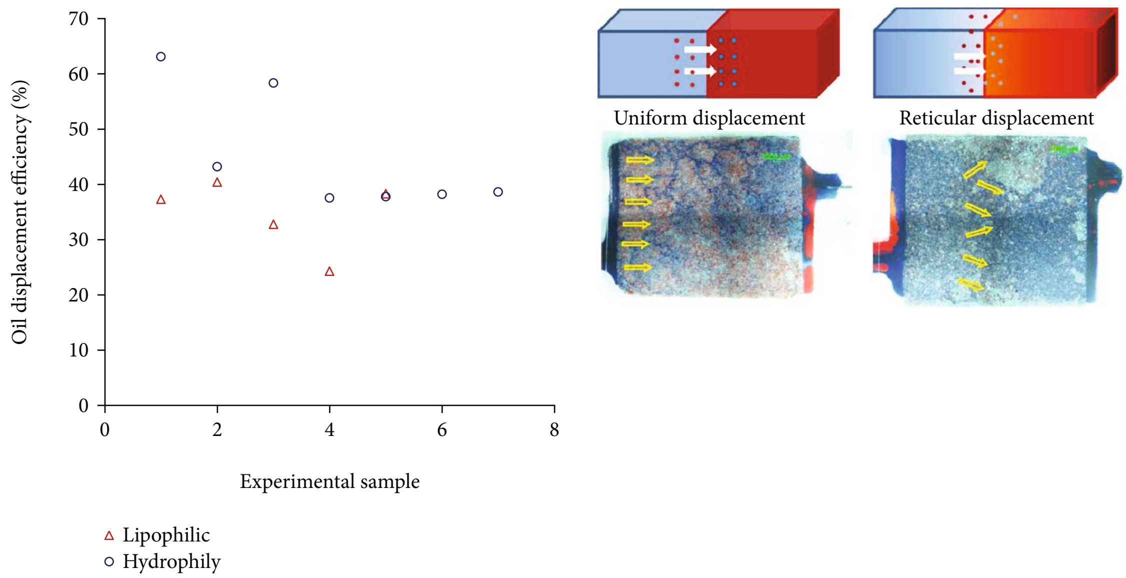


Figure 8: The relationship between different wetting phases and oil displacement efficiency (red dots represent oil and blue dots represent water).

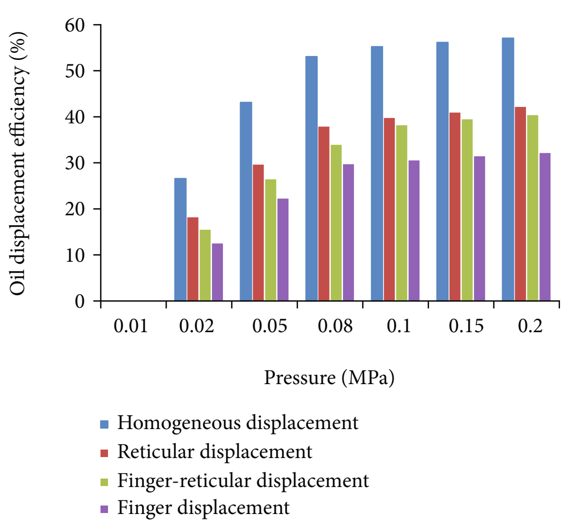


Figure 9: The relationship between displacement efficiency and displacement pressure.

($R^2 = 0.6328$). It also showed that the control of oil displacement efficiency by permeability restricted by throat width was stronger than that by porosity. When the model permeability was more than $1.5 \times 10^{-3}\,\mu\text{m}^2$, the displacement was relatively easy. In the experiment, the displacement type was mainly uniform displacement. Under the condition of increasing permeability, the final oil displacement efficiency would also increase.

4.2. Influencing Factors of Pore Structure. The correlation coefficient between throat radius and oil displacement efficiency was $R^2 = 0.8219$ (Figure 7(a)); when the throat radius increases gradually from small to small (<0.49 μm), because the throat radius is finer as a whole, the capillary resistance is stronger, the seepage resistance is larger, and the pore throat connectivity is also poor. Under the same experimental conditions, the injected water first moved along the high permeability path with the type of reticular, finger-reticular. The fitting curve of oil displacement efficiency increased exponentially, the throat radius >0.49 μm, the throat radius increases, the seepage path widens, the permeability of the effective throat reticular increases, and the swept area expands. The injected water mainly driven by uniform displacement could be observed, and the fitting curve of oil displacement efficiency increased linearly.

However, the oil displacement efficiency decreased significantly (Figure 7(b)) when the separation coefficient increased. The response relationship between separation coefficient and oil displacement efficiency was stronger than that between porosity, permeability, throat radius, and oil displacement efficiency. The separation coefficient becomes larger, indicating that the thickness of the throat was different; the heterogeneity between the throats was enhanced. Then, the injected water would burst along the large throat, resulting in finger infiltration, mainly finger displacement and forming many of the cluster residual oil. It was difficult to drive out the crude oil in the pore reticular which was poorly connected to the mainstream pore throat. As a result, the final oil displacement efficiency was low, only 28.51%.

4.3. Influencing Factors of Wettability. On the whole, most hydrophilic samples had higher displacement efficiency than lipophilic samples [22–25]. When the rock of the Chang 6 reservoir was lipophilic, due to the action of capillary resistance, the injected water moved forward in the center of the throat, and the throat wall absorbed thin-film oil. And in the process of fine throat driving, oil flow blockage was easy to occur due to strong interfacial tension, and the injected water was mainly finger-reticular displacement type, and the oil displacement was not complete. The average low

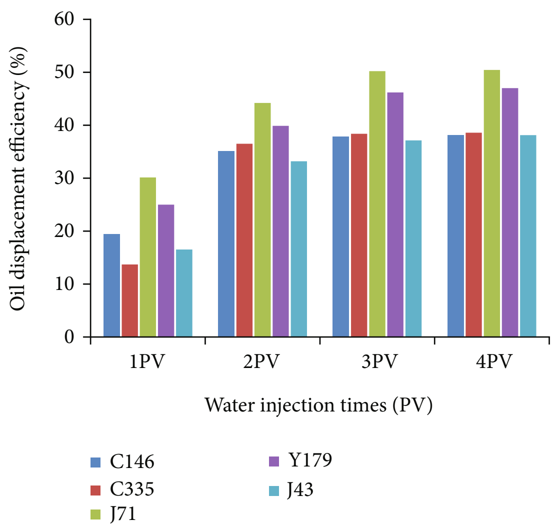


Figure 10: The relationship between water injection times and oil displacement efficiency.

oil displacement efficiency was 34.59% (Figure 8). When the rock was hydrophilic and under the condition of the injection water squeezed the oil film on the throat wall, the oil in the throat was evenly displaced, the sweep range of the injected water was expanded, the sweep volume has been large, and the final oil displacement efficiency can reach 50.53%. The oil displacement efficiency is significantly improved with the strong hydrophilicity of reservoir rocks. On the whole, the oil displacement efficiency of lipophilic reservoir is 15.94% lower than that of hydrophilic reservoir.

4.4. Influencing Factors of Displacement Pressure. The porosity and permeability of the experimental model were low, and the starting pressure was 0.02 MPa. When the pressure was less than 0.02 MPa, the injected water did not enter the experimental model because of the capillary resistance. When the pressure was greater than or equal to 0.02 MPa, the injected water began to enter the experimental model from the inlet. When the injection pressure increased continuously, the displacement speed was accelerated, resulting in the peeling off of the oil film on the pore and the throat wall and the decrease of the oil film thickness. Then, the larger displacement pressure enabled the injected water to enter the smaller pores and throats and broaden the seepage path. At the same time, the area of water flooding was further expanded, and finally, the oil displacement efficiency was improved.

The analysis of the test results indicated that the oil displacement efficiency of different displacement types increased step by step, while the displacement pressure increased (Figure 9). The average percentage increase of oil displacement efficiency of finger displacement, finger-reticular displacement, reticular displacement, and uniform displacement was 25.80%, 31.96%, 37.25%, and 38.15%, respectively. When the experimental pressure exceeded 0.1 MPa, the water flooding channel was stable, and the increase of oil displacement efficiency was weak. Meanwhile, if the displacement pressure was increased, the reservoir was prone to water flooding, resulting in a sharp increase in water cut. Therefore, the injection pressure should be kept within a certain range in the actual process of water injection.

The experimental results showed that the oil displacement efficiency increased synchronously with the increase of water injection ratio (Figure 10). When the injection volume reached 1 PV, the injection water formed a displacement path from the injection inlet along the well-connected hole and throat, reached the outlet end, and continued to inject fluid; a large amount of injected water spread irregularly around, and the oil film adsorbed on the hole wall and the residual oil would be carried out by continuous flow and erosion. When the injection water reached 2 PV, the oil displacement efficiency increased from 21.46% to 30.72%, with an increase of 43.15%, and the oil displacement efficiency of some models reached the maximum. When the water injection continued, the oil displacement efficiency tended to be stable, and when the water injection ratio reached or exceeded 3 PV, the increase of water displacement efficiency would no longer increase (3.24%). Meanwhile, the growth rate slowed down, and the water injection continued to show an invalid water cycle. The experimental results show that the water injection time has little effect on the oil displacement efficiency. The experimental study showed that for a water flooding reservoir, the increase of water injection ratio was limited, that was, the oil displacement efficiency would not increase indefinitely with the increase of water injection ratio, and the water injection multiple could be controlled at about 3 PV. When the injected water reaches 4 PV, the oil displacement efficiency is almost not improved, so it is economical and efficient when the injected water reaches 3 PV.

5. Conclusion

(1) In the water flooding seepage path of Chang 6 reservoir in the study block, the uniform displacement and reticular displacement are more than the finger-reticular displacement type, and the finger displacement type is relatively rare. The oil displacement efficiency decreased from 63.07% to 24.28% and decreased in turn. In the type of residual oil, cluster residual oil and oil film residual oil are more than isolated residual oil and corner residual oil

(2) The correlation analysis between physical characteristic parameters and oil displacement efficiency shows that permeability is better than porosity. Among the characteristic parameters of pore throat structure, the correlation between throat and oil displacement efficiency is strong. The oil displacement efficiency of hydrophilic reservoir is weaker than that of hydrophilic reservoir. With the increase of displacement pressure, water injection multiple and the oil displacement efficiency will increase significantly, and the water injection multiple increased to 3 PV is a reasonable range

(3) During the development of the Chang 6 tight reservoir, emphasis should be placed on the development of areas with good physical properties. For the areas with poor physical properties, engineering fracturing or plugging control technology can be adopted, and the injection water displacement pressure should be kept within a reasonable range to ensure sufficient water flooding energy. Meanwhile, in order to avoid the occurrence of water channeling and flooding, the amount of water injection should be strictly controlled

(4) The geological factors that affect the oil displacement efficiency of the reservoir are various, so in the development of oil and gas fields, it is very important to study the geological factors controlling the oil displacement efficiency and screen the favorable and high quality reservoirs to ensure the recovery of tight sandstone reservoirs of Yanchang formation in Changqing oilfield

Data Availability

The experimental data used to support the findings of this study are included within the manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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