Technology of Water Injection Development in Ultra-Low Permeability Reservoir

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Abstract. In order to further explore the technology of water injection development in ultra-low permeability reservoir, the Chang 6 reservoir in S area is taken as an example in this study to analyze the characteristics of single-phase seepage, dual-phase seepage, and water injection development in ultra-low permeability reservoir. The experimental results show that the reservoir has poor physical properties and complex pore structure. The flow of single-phase oil/water in the reservoir is non-Darcy flow; it restricts each other for the dual-phase flow, which seriously affects the effective flow capacity, resulting in high injection resistance. It is found based on the water injection experiment that the initial mining degree is relatively high, and the average water driver recovery factor in the core of ultra-low permeability sandstone is 49.9%, and the physical properties have no direct impact on the recovery level. Therefore, the technology of water injection development has certain feasibility and rationality in the exploitation of ultra-low permeability reservoir, and can be used in the practical exploitation.

Keywords. Ultra-low permeability reservoir; water injection development; percolation characteristics; water injection features.

1. Introduction
Low permeability reservoir has low permeability and high flow resistance, which increases the difficulty of oilfield development. The characteristics of the low permeability reservoir include complex structure, small pores, high seepage resistance, and strong molecular force on the solid-liquid surface. Thus, its seepage characteristics and seepage rules are very different from the medium and high permeability oil reservoir [1].

Water injection development is currently the most commonly used secondary oil recovery method used in various oilfields in the world. The commonly used experimental methods and means for water injection research include conventional core flooding, microscopic analysis of sandstone flooding, centrifugation, and combined analysis of computed tomography (CT) scanning and magnetic resonance (MR). The effect of water injection development is controlled not only by the particularity of the reservoir itself, such as heterogeneity and permeability of reservoir, and thickness of oil layer, but also by the water injection development process, such as development system, reservoir damage, and fluid-solid coupling effect [2, 3]. Some technologies such as advanced water injection, narrowed well spacing, and fracture extension for water injection have been formed under such conditions; and a certain theoretical guidance has been formed on high-efficiency water injection technologies and well layout.
methods such as seepage mechanism, water injection timing, and water injection quality. Various methods and means of pressure reducing and injection increasing are also developed, such as horizontal well, staged fracturing and acidification, pressure reducing and injection increasing by surfactant, simultaneous water injection, and advanced water injection. At the same time, scholars have also developed some new materials for pressure reducing and injection increasing [4-6]. These methods and technologies provide solid theoretical and practical basis for the development of ultra-low permeability reservoir.

Ultra-low permeability reservoir is an important type of low-permeability reservoir and it is of important theoretical and practical significance to exploit the ultra-low permeability reservoirs. The characteristics of single-phase seepage, dual-phase seepage, and water injection in ultra-low permeability reservoir are explored in this study, to provide a theoretical and practical basis for the exploitation and development of the ultra-low permeability reservoir.

2. Methodology

2.1. Characteristics of single-phase seepage of ultra-low permeability sandstone reservoir

In order to understand the water injection characteristics of the reservoir, the flow characteristics of single-phase water and single-phase oil in the ultra-low permeability sandstone reservoir are firstly analyzed to lay the foundation for the next step of water injection analysis.

The cores are taken from Chang 6 reservoir, numbered A, B, C, and D. The cores are evacuated to saturate water and oil, respectively. The experimental fluids are kerosene and simulated water. In order to avoid the fluid damage, the simulated water is the 30 g/L KCl aqueous solution. The viscosities of kerosene and simulated water are 2.17 mPa•s and 1.01 mPa•s, respectively at 20°C, 1.08 mPa•s and 0.47 mPa•s respectively at 20, and the densities are 0.80 g/cm³ and 1.03 g/cm³, respectively.

The experiment is conducted in a specific device, with a confining pressure of 10 MPa and a temperature of 60 °C. The piston container is filled with experimental fluid, driven by a constant pressure pump at a constant pressure, so that the fluid in the container enters into the core holder. The outlet end of the holder is connected with a back pressure device, so that a certain back pressure can be set on demand of the experiment. Two pressure sensors are used to accurately record the pressure at the injection end and outlet end of the core. At the beginning, it is displaced with a lower displacement pressure difference. After the flow rate at the outlet is stabilized, the flow rate is measured by the graduated cylinder for three times to take the average value, and then the single-phase fluid permeability is calculated with the stable displacement pressure difference. With such steps, the displacement pressure is sequentially increased to obtain the series displacement pressure differences and corresponding flow rates, and then the single-phase fluid permeability is calculated. The curve of correlation between permeability and pressure gradient or pressure difference is drawn, and the characteristics of single-phase water and oil seepage are analyzed.

2.2. Characteristics of dual-phase seepage of ultra-low permeability sandstone reservoir

Dual-phase seepage can better reflect the real situation of water injection and oil displacement than single-phase seepage. For this reason, it is necessary to analyze the seepage characteristics of ultra-low permeability sandstone reservoir cores with saturated oil and water simultaneously, so as to establish the foundation for analyzing the water flooding and oil displacement.

The cores are taken from Chang 6 reservoir in S area, which are brownish grey oil-soaked fine sandstones, numbered as 10-1 and 10-2. The experimental fluids include kerosene and simulated water. The experiment is carried out by using the non-steady-state method given in the industry standard SY/T5345-2012 “Determination of the Relative Permeability of Dual-Phase Fluids in Rocks”. Measuring the relative permeability of oil/water by using the non-steady-state method is to take the Buckley-Leverett one-dimensional dual-phase water injection and oil displacement as basis, ignore the
effect of capillary force and gravity, assume that the dual-phase fluid is mutually insoluble and incompressible, and the oil/water saturation is uniform in any cross section of the rock sample.

2.3. Analysis on water injection features of ultra-low permeability reservoir

On the basis of understanding the oil/water single-phase and dual-phase seepage in the core of ultra-low permeability sandstone reservoirs, the water injection features of ultra-low permeability sandstone reservoir are analyzed in this section.

The cores are taken from the ultra-low permeability sandstone reservoir Chang 6 reservoir in S oilfield, and numbered as 10C, 24B, 18C, 36A, 33A, 19B, and 17C. Before the experiment, the general physical properties of the cores are measured after they are washed to remove the oil and salt and dried. The experimental fluids are 30g/L simulated water and kerosene. The properties of fluid are the same as above.

Before the experiment, the pipeline is evacuated with fluid, the core with established saturation is weighed and placed in the core holder, the confining pressure is set to 10 MPa, the temperature is 60 °C (being close to the formation temperature), and it is driven with the constant speed pump at 0.05 mL/min to displace. During the displacement, the amount of water and oil as well as pressure at different times are recorded until the pressure difference is constant.

3. Results and Discussion

3.1. Experimental results of single-phase seepage

The following conclusions are drawn from the experiment. When the displacement pressure is low, it is difficult for fluid to flow, but the flow rate can be finally measured, and the time for the flow rate to stabilize is longer. Analysis of the results is given as below.

The curves of correlations between the test flow rate and permeability and the pressure gradient of rock samples A and B saturated with brine are given in Figure 1 and Figure 2, respectively. Pressure at the outlet of the core is atmospheric pressure.

![Figure 1 Characteristics of single-phase water-phase seepage of core A](image1)

![Figure 2 Characteristics of single-phase water-phase seepage of core B](image2)
It can be seen from the Figure 1 and Figure 2 that when the flow rate is low, the flow rate and the pressure difference have a polynomial relationship; when the flow rate increases to a certain value, the flow rate and the displacement pressure gradient have a linear relationship gradually, and the straight trend line will cross with the displacement pressure gradients curve in the abscissa. As the displacement pressure difference increases, the permeability slowly rises to a basically steady state. The lower the permeability of the core, the more obvious the nonlinear relationship at low velocity. With the increase of permeability, the non-linear seepage weakens.

The curves of correlations between the test flow rate, permeability and pressure gradient of rock samples C and D after being saturated with oil are given in Figure 3 and Figure 4, respectively. Like the trend of single-phase water flow, the flow velocity and pressure gradient are not linear at low speed. When the flow velocity increases to a certain value, the relationship between the flow velocity and the pressure gradient gradually becomes linear, and the straight trend line will cross with the pressure gradient displaced in the abscissa. As the displacement pressure increases, the permeability slowly rises to a basically stable level. The lower the permeability of the core, the more obvious the nonlinear relationship at low speed. As the permeability increases, the non-linear seepage weakens.

It can be seen from the above single-phase seepage experiment that the ultra-low permeability sandstone core requires a higher pressure gradient and a longer stability time for single-phase seepage, and the core with lower permeability corresponds to a higher pressure gradient at the flow rate, and a clear non-linear seepage can be seen at a lower pressure gradient. The single-phase seepage experiment shows that the fluid seepage capacity of the ultra-low permeability sandstone reservoir is poor. Maintaining a certain pressure at the outlet end of the core can increase the number of channels participating in the flow, indicating that it is of great significance to develop the formation pressure by water injection [7].
3.2. Experimental results of dual-phase seepage

The efficiency data on water injection and oil displacement for core 10-1 is given in Figure 5. It can be seen that when the volume of water injection is less than 0.5 PV, the oil recovery rate rises rapidly with the increase of the injection volume, the recovery degree reaches 20%, and the water content is more than 90%. If the volume of water injection is increased continually, the increase of recovery rate becomes slow. The dual-phase coexistence area is very narrow, and the saturation of the isotonic point is slightly less than 50%, indicating that the core is neutral and oily. During the process from the bound water saturation to the isotonic point saturation, because the dual-phase region is very narrow, the oil phase permeability declines very quickly, the final water-phase relative permeability is 0.255, and the water phase saturation is 55%.

![Figure 5](image-url)

**Figure. 5** Efficiency data on water injection and oil displacement for core 10-1

Core 10-1 has better physical properties, but the narrower dual-phase seepage area, earlier water breakthrough time, lower oil displacement efficiency, and faster oil phase seepage ability. On the one hand, it shows that oil wetting is not conducive to oil displacement, and the boundary layer of oil film is not easy to be driven; on the other hand, it shows that the core is highly heterogeneous, and there may be dominant channels such as large pores or micro-fractures. When water is injected, water flows along the dominant channel and quickly breaks through the water seepage. The oil phase is trapped and could not be exploited, water injection in later period is invalid, and the residual oil saturation is high.

The efficiency data on water injection and oil displacement for core 10-2 is given in Figure 6. It can be seen that the recovery degree gradually increases with the multiple of injection pore volume. Before the volume of water injection reaches 1 PV, the recovery degree rises faster, and then becomes slower. After the volume of water injection reaches 5 PV, the recovery degree is basically stable, and the final recovery rate is as high as 58.89%. The bound water saturation of the core is 38.6%, and the residual oil saturation of the core is 25.8%. Compared with the core 10-1, the dual-phase seepage area of this core is relatively wide. The water-phase seepage is close to the water saturation line, which is an upward concave type. The isotonic point saturation is greater than 50%, indicating that the core is hydrophilic. With the increase of water saturation, the permeability of the oil phase drops sharply, while the relative permeability of the water phase increases slightly.
3.3. Analysis on water injection features of ultra-low permeability sandstone reservoirs

The curves of relationship between the pressure gradient at the inlet end and the multiple of injection pore volume and the multiple of displacement pore volume during water injection are given in Figure 7 (a) and Figure 7 (b), respectively. It can be seen from Figure 7 (a) that the lower the permeability of the core, the slower the pressure rise, the longer the time to the peak pressure, and the higher the pressure at the injection end. If the pressure gradient at which the fluid starts to flow out is defined as the pseudo-starting pressure gradient, the pseudo-starting pressure gradient of the experimental core is about 50-200 MPa/m. It can be seen that the water injection is difficult to be effective, as shown in Figure 7 (b).

Figure. 6 Efficiency data on water injection and oil displacement for core 10-2

Figure. 7 Pressure gradient at the inlet end
It can also be seen from Figure 7 that the core with high permeability can reach the peak pressure at a lower injection volume, and the peak pressure is relatively low, indicating that its physical properties are good; the lower the permeability of core is, the longer the time reaching the peak pressure, and the higher the peak pressure, indicating that such core has poor physical properties.

The recovery ratios of the corresponding 7 ultra-low permeability sandstones during the water injection process are given in Table 1. The measured gas permeability of the rock sample is 0.11 Md ~ 0.73mD, the average permeability is 0.375 mD, and the recovery level is 35.9% - 57.8%, with an average value of 49.9%. It can be seen that the recovery rate obtained by the indoor water injection simulation experiment is higher, which is common to most water flooding experiments. On the one hand, there may be some errors in the calculation of oil saturation by the weighing method; on the other hand, when the oil saturation is established by the displacement method, it is easy for the oil phase to enter the well-connected pores, and the poorly connected pores are not saturated with saturated oil, so the injected water can displace the oil in individual holes. The finer the holes are, the higher the degree of oil displacement. Therefore, the overall water recovery factor under the experimental conditions is higher.

| Number | Porosity, % | Permeability, mD | Recovery factor, % |
|--------|-------------|------------------|-------------------|
| 10C    | 13.87       | 0.369            | 35.9              |
| 24B    | 10.63       | 0.167            | 47.1              |
| 18C    | 10.68       | 0.243            | 57.8              |
| 36A    | 7.98        | 0.136            | 41.9              |
| 33A    | 13.65       | 0.387            | 55.9              |
| 19B    | 14.91       | 0.752            | 56.1              |
| 17C    | 13.71       | 0.516            | 52.1              |
| Average| 12.10       | 0.375            | 49.9              |

4. Conclusion

The fine pore structure of the reservoir and its heterogeneity, sensitive minerals, and wettability of the reservoir rock are the main factors affecting the water injection pressure and injection efficacy. The main sources of excessively high injection pressure include the extremely poor physical properties of the ultra-low permeability reservoir itself, the high permeability resistance caused by the fine pore structure, the capillary resistance of the ultra-low permeability reservoir and the seepage resistance caused by the surface wetting characteristics, and the seepage resistance caused by reservoir damage. The Chang 6 reservoir studied in this study has water phase trap damage, fluid sensitivity damage, and stress sensitivity damage, which are important factors that have to be considered in the study of water injection in the ultra-low permeability reservoirs. Physical properties of the reservoir are inherent in the reservoir itself and difficult to change. Various resistances generated by interface effects can be improved or reduced by taking appropriate measures. Therefore, in the future research, it can start with various resistances produced by the interface effect to explore the method and mechanism of improving the recovery factor of the ultra-low permeability sandstone reservoir.

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