Study on Characteristics of Phase Permeability Curve of Xingbei Development Zone During Extra High Water Cut Period

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Abstract: The relative permeability curve is an important basic data for the preparation and dynamic analysis of oilfield development (adjustment) schemes. Due to the different types of relative permeability curves in different water cut stages, there is a large deviation in the prediction of oilfield development indexes in the ultra-high water cut stage according to the relative permeability curve in the early stage of development. In order to study the change of relative permeability curve in the development process, based on the analysis of the morphological characteristics of 118 relative permeability curves in the ultra-high water cut stage of 28 coring wells in Xingbei development area after more than 50 years of water injection development, the influence of injection multiple on the relative permeability curve, and the influence of long-term water injection development on the average pore radius, the changes of morphological characteristics and characteristic parameters of relative permeability curves after entering the ultra-high water cut stage were studied, and a correction method for the changes of oil phase and water phase of relative permeability curves according to the changes of relative permeability curves in different water cut stages was proposed to better reflect the changes of relative permeability curves in the whole process of water injection development. It provides a basis for accurately predicting the index of water injection development oilfield.

1 Introduction

Xingbei development zone is located in the northern part of Xingshugang structure of Daqing placanticline. The southern part is adjacent to Xingba area of Xingnan development zone. The northern part is bounded by Sa 'nan development zone, and the eastern and western parts are bounded by Sa II outer oil-bearing boundary line. The oil-bearing combination oil layer of the development series is the target layer of this study. The Saertu oil layer, Putaohua oil layer and Gaotaizi oil layer in the middle of Songliao Basin are buried at a depth of about 1000 m. It was put into development in 1966.After 50 years of water flooding development, basic well pattern, primary infill well pattern, secondary infill well pattern and tertiary infill well pattern have been deployed successively. At present, the comprehensive water cut has reached 94.44 %, and it has entered the development stage of ultra-high water cut stage. At present, it has entered the stage of ultra-high water cut, in which the relative permeability curve is used as an important data for various calculations related to oilfield development calculation, dynamic analysis and water flooding [1-3]. The relative permeability curve is affected by many factors such as water injection intensity, pressure gradient, crude oil viscosity and pore structure [4-6].From the initial stage of water cut to the ultra-high water cut stage, the relative permeability curve will change under the influence of various factors after long-term water injection development [7-10]. At this time, the relative permeability curve of the early stage of development can not accurately reflect the permeability of the rock to each phase fluid in the ultra-high water cut stage. Similarly, the current relative permeability curve can not accurately reflect the permeability of the rock to each phase fluid in the early stage of development. Therefore, the change of relative permeability curve in different water cut stages of Xingbei development zone is studied [11-13], and a method for calculating the dynamic relative permeability curve of the whole process is provided, which can explain the influence of long-term water injection development on relative permeability curve and relative permeability characteristic parameters.It provides a theoretical basis for subsequent reservoir numerical simulation and actual production.

2 Effect of long-term waterflood development on phase permeability curve

2.1The main types of interinfiltration

The morphological characteristics of 118 relative permeability curves in high / ultra-high water cut stage of

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28 coring wells in Xingbei development area are analyzed. The variation trend of oil phase relative permeability curve is basically the same, while the shape of water phase relative permeability curve is obviously different. The relative permeability curves are mainly divided into three types : concave, linear and concave. Among them, the number of samples with concave water phase is the largest, with a total of 69 relative permeability curves, accounting for 58.47 % of the total number of samples. The irreducible water saturation is low, and the relative permeability of the oil phase decreases rapidly in the early stage, and the decline rate gradually slows down with the increase of water saturation, while the relative permeability of the water phase increases with the increase of water saturation, and the increase gradually increases. The maximum relative permeability of the water phase corresponding to the residual oil saturation is higher. There are 29 linear relative permeability curves in the water phase, accounting for 24.58 % of the total number of samples. The irreducible water saturation is high. With the increase of water saturation, the relative permeability of water phase shows an approximate linear variation law. The relative permeability of water phase corresponding to residual oil saturation reaches the maximum value, but the value is low. The number of samples with concave water phase is the least, with a total of 20 relative permeability curves, accounting for 16.95 % of the total number of samples. The irreducible water saturation is higher, and the relative permeability curve of oil phase is similar to that of water phase, but the decline rate is faster. At the high water saturation section, the increase of relative permeability of water phase decreases gradually and the curve tends to be gentle. The relative permeability of water phase corresponding to residual oil saturation reaches the maximum value, but the value is low.

2.2Effect of injection multiple on phase permeability curve

Long-term high-intensity water injection development is an important factor affecting the relative permeability curve. In order to quantitatively describe this change, the injection multiple is introduced to study the change law of injection multiple, and the relationship between injection multiple, permeability and average pore radius is established. The influence of injection multiple on permeability and relative permeability curve. According to the relative permeability data, the change of oil-water seepage capacity of relative permeability curve is studied, and the relationship between the sum of oil phase relative permeability and water phase relative permeability and water saturation is drawn, as shown in Fig.1.

It can be seen that the injection multiple of long-term water injection development increases. With the increase of injection multiple, long-term water injection development increases the average water saturation of the reservoir, changes the oil-water seepage capacity, reduces the oil phase seepage capacity, and increases the water phase seepage capacity. The oil-water fluid

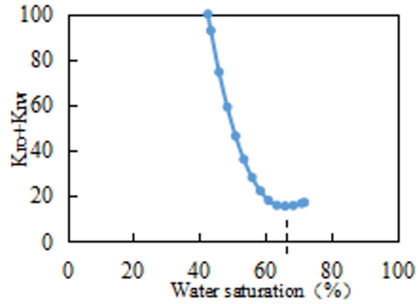

Fig.1 Relation between oil-water seepage capacity and water saturation

seepage capacity Kro+Krw shows a trend of decreasing first and then increasing. Before the isotonic point, the oil phase change characteristics play a leading role. The oil-water fluid seepage capacity Kro+Krw decreases rapidly with the increase of water saturation. After the isotonic point, the water phase change characteristics play a leading role, and the oil-water fluid seepage capacity Kro+Krw increases slowly with the increase of water saturation.

The calculation method of injection multiple was studied in combination with reservoir engineering methods [14-16]. The injection multiple was calculated using Buckley-Leveret front equation, and the injection multiple was the reciprocal of the derivative of water cut. The ratio of cumulative water injection to pore volume was used to calculate the injection multiple. According to Buckley-Leveret front equation and Welge integral equation, the injection multiple formula was calculated as:

$$\frac{W_i}{V_p}=\frac{\int_o^t Q_t dt}{\phi A\left(x_e-x_o\right)}=\frac{1}{f_w^{'}\left(S_{we}\right)}, \quad (1)$$

In formula: W_i is the cumulative injection water volume, V_p is pore volume, and S_{we} is water saturation

According to the oil-water flow equation, the water content is calculated. Combined with the relative permeability data and Formula 1, the variation law of injection multiple of relative permeability curve is studied. The water content and injection multiple of relative permeability curve are shown in Figure 2.

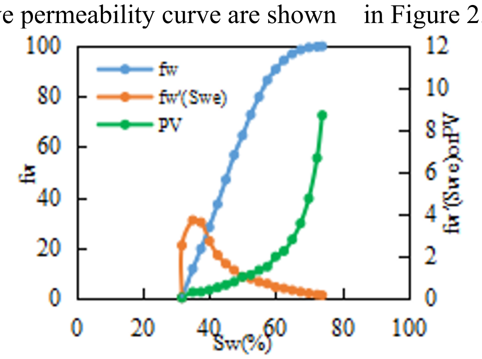

Fig.2 Relative permeability curve injection multiple

As can be seen from the figure, the average water saturation of the reservoir is low in the early stage of oilfield development, and the injection multiple of injected water is relatively low. With the continuous waterflooding development of the oilfield, the average

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water saturation of the reservoir increases, and the water cut increases gradually. When entering the ultra-high water cut stage, the average water saturation is high, and the injection multiple increases exponentially. The higher the injection multiple, it is highly consistent with the phenomenon of serious ineffective circulation in the high permeability layer.

2.3Effect of long-term waterflood development on average pore radius

Long-term water injection in the oilfield scour the pores of the reservoir, which directly affects the average pore radius. Especially after entering the ultra-high water cut stage, the water injection increases exponentially and the average pore radius changes more obviously. Therefore, 1,548 records of micro-pore structure parameters at different core-taking times were collected from 14 core Wells in Xingbei Development Zone. The influence of long-term waterflooding development on the average pore throat radius of cores of three permeability levels was studied respectively, and then the relationship between the average pore radius and permeability was established. Combined with the influence of long-term waterflooding development on the average pore radius, the changes in reservoir permeability caused by changes in microscopic pore structure were quantified, as shown in figure 3 and figure 4.

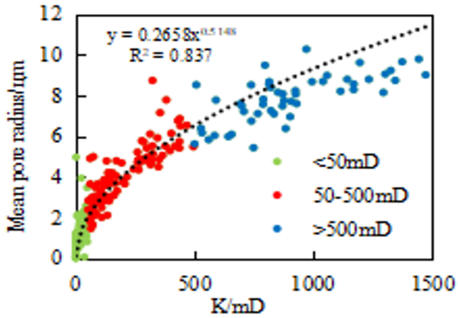


Fig.3 Permeability varies with average pore radius

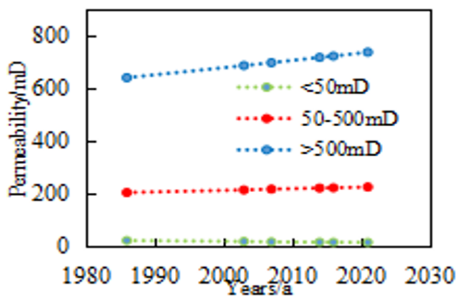


Fig.4. Permeability changes with long-term waterflood development

It can be seen that with the continuous development of the oilfield, long-term waterflooding causes changes in the micro-pore structure of the reservoir, which is also the reason for the changes in oil-water seepage characteristics in the late period of ultra-high water cut. The average pore radius shows a power exponential relationship with the increase of permeability, and the pore structure changes of different permeability levels are different. The permeability level is less than 50×10^{-3}μm2, and the clay particles washed away in the long-term waterflooding development clog the throat. The proportion of small pores increases significantly, the average pore radius decreases, and the permeability decreases by 29.75%. With the permeability level of 50-500$\times10^{-3}$μm^2, the proportion of macropores increased slightly after long-term waterflooding, and the permeability increased by 10.20%. The permeability level of 50-500$\times10^{-3}$μm^2 is different from that of 50-500$\times10^{-3}$μm^2, and the dominant seepage channel is formed by long-term waterflooding. The proportion of large pores increases significantly, the average pore throat radius increases, the flow resistance decreases, and the permeability increases by 15.11%.

3 Characteristics of phase permeability curve in extra high water cut period

3.1Change of phase permeability type

According to the facies permeability data, the variation of reservoir facies permeability curve types in different development stages (low water cut stage, extra high water cut stage) with the same permeability level was studied. Typical phase permeability curves of different development stages with the same permeability level were selected respectively, and the comparison of phase permeability curves was shown in Figure 5.

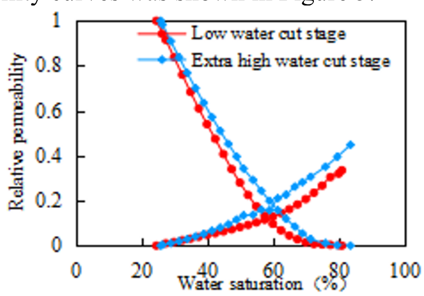
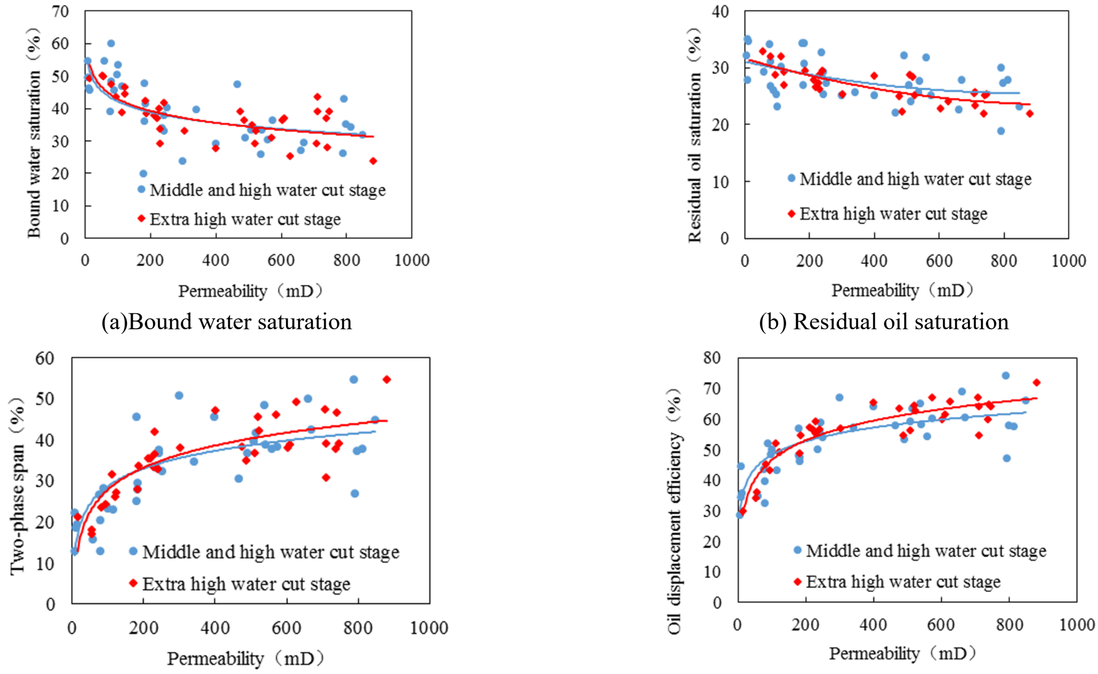


Fig.5 Comparison of relative permeability curves at different development stages

It can be seen that the shape and type of the relative permeability curve do not change basically after the influence of various factors of long-term waterflood development. However, the variation of oil phase and water phase in different permeability levels is not completely consistent.

3.2Characteristic parameter change

Further study the changes of bound water saturation, residual oil saturation, two-phase span, oil displacement efficiency and other characteristic parameters of the phase permeability curve at the ultra-high water cut stage. According to the phase permeability data, study the changes of characteristic parameters of phase permeability at different water cut stages, as shown in Figure 6. Characteristic parameters such as bound water saturation, residual oil saturation, two-phase span and oil displacement efficiency of phase permeability curves at different water-bearing stages and permeability levels were calculated, as shown in Table 1.



(a)Bound water saturation (b) Residual oil saturation

(c) Two-phase span (d) Oil displacement efficiency

Fig.6 Phase permeability curve changes at different development stage

Table 1 The characteristic parameters of phase permeability curve change in different development stage

Permeability level (10-3μm 2)	Water-bearing stage	Bound water saturation(%)		Two-phase span(%)		Two-phase span(%)	Oil displacement efficiency(%)	
		Range	Average	Range	Average		Range	Average
1-50	Medium-low/medium-high	31.50-55.70	45.77	14.91-32.22	29.86	58.65	39.00-60.26	53.42
	High/extra high	28.6-54.7	44.92	23.3-47.5	29.24	58.17	41.91-66.53	52.8
50-500	Medium-low/medium-high	16.40-47.80	40.13	14.60-54.70	32.01	57.09	34.93-70.98	55.48
	High/extra high	25.1-59.27	40.06	17.92-52.1	34.16	57.32	40.46-73.48	57.33
>500	Medium-low/medium-high	17.84-47.10	34.22	22.14-51.87	38.17	56.28	37.54-70.60	58.26
	High/extra high	17.2-43.52	31.1	13.1-52.33	42	57.02	34.78-72	60.59

By comparing the relationship between phase permeability parameters and permeability in the middle and ultra-high water cut stages, it can be seen that the bound water saturation has little change in different water cut stages. Under the influence of long-term waterflooding development, the residual oil saturation increases first and then decreases with the increase of permeability, while the span of two-phase flow and oil displacement efficiency decreases first and then increases with the increase of permeability. When the permeability is lower than $50\times10^{-3}\mu m^2$, the bound water saturation decreases, the residual oil saturation increases, and the two-phase span and oil displacement efficiency decrease. When the permeability is higher than $50\times10^{-3}\mu m^2$, the bound water saturation increases, the residual oil saturation decreases, and the two-phase span and oil displacement efficiency increase.

4 Dynamic phase permeability curve of the whole waterflood development process.

The influence of long-term waterflooding development on the phase permeability curve is mainly reflected in two aspects: one is that long-term waterflooding leads to changes in the micro-pore structure of the reservoir, thus changing the original permeability of the reservoir; the other is that development factors such as waterflooding intensity and displacement pressure gradient lead to changes in the utilization conditions of remaining oil, thus reducing the residual oil saturation of water flooding. In order to quantitatively describe the influence of long-term waterflood development on the phase permeability curve, a dynamic phase permeability curve correction method was proposed.

According to the Willhite empirical formula [17-20], the relative permeability of oil and water phases can be expressed as:

$$K_{ro} = K_{ro}\left(S_{wc}\right)\left(1 - S_{wd}\right)^{\alpha}, \tag{2}$$

$$K_{rw} = K_{rw}\left(S_{or}\right)S_{wd}^{\ \beta}, \tag{3}$$

$$S_{wd} = \frac{S_w - S_{wc}}{1 - S_{or} - S_{wc}}, \tag{4}$$

In formula: K_{ro} is the oil phase relative permeability, Kr_w is the water phase relative permeability, α and β are the coefficients.

In order to describe the variation law of dynamic relative permeability, based on the formula of relative permeability curve, the expression formula of dynamic relative permeability is established by combining formula 2, formula 3 and formula 4.For the relative permeability curve of low water cut stage and the relative permeability curve of extra high water cut stage, two sets of fitting parameters can be obtained, and the relative permeability formula of dynamic water phase and oil phase can be defined as

$$K_{ro} = K_{ro1} + \left(K_{ro2} - K_{ro1}\right)S_{wd}, \tag{5}$$

$$K_{rw} = K_{rw1} + \left(K_{rw2} - K_{rw1}\right)S_{wd}, \tag{6}$$

In formula: K_{ro1} is the oil phase relative permeability, Krw1 is the water phase relative permeability, K_{ro2} is the oil phase relative permeability, K_{rw2} is the water phase relative permeability.

According to different types of oil-water relative permeability curves, formula 5 and formula 6 are used to establish the influence of long-term water injection development on dynamic relative permeability. The dynamic changes of water phase and oil phase in the whole process relative permeability curve are shown in figure 7 and figure 8.

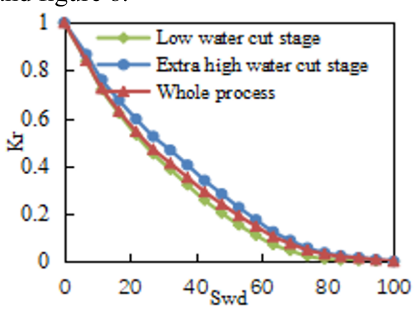


Fig.7 Dynamic simulation of water phase curve of relative permeability

It can be seen from the figure that the established dynamic phase permeability curve of the whole process is consistent with the phase permeability curve of low water saturation at low water saturation and with the phase permeability curve of extremely high water saturation at high water saturation, which can interpret the influence of long-term waterflooding development on different types of relative permeability curves and phase

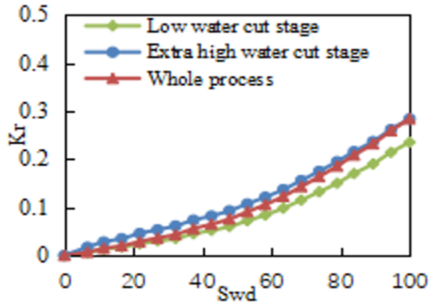


Fig.8 Dynamic simulation of oil phase curve with relative permeability

permeability characteristic parameters. In the actual production process, the phase permeability curve is mainly obtained from the core experiment carried out by the core taken out of the core well in the early stage of oilfield development. When the oilfield enters the ultra-high water cut stage, the lithology changes after a long period of water injection. At this time, the phase permeability curve measured by the core obtained in the early stage of development will lead to certain deviation in predicting the production dynamics of the oilfield. Therefore, the phase permeability curve obtained from the core experiment can not fully reflect the real flow state of underground fluid. Therefore, the changes of water phase and oil phase in the phase permeability curve are corrected by using the core phase permeability data in the early stage of development and the core phase permeability data after entering the ultra-high water cut stage, so that the changes of oil phase and water phase can better reflect the changes of phase permeability curve in the whole process of waterflooding development.

5 Conclusion

(1)The relative permeability curve of Xingbei development zone is mainly divided into three categories, concave type, concave type, linear type, mainly concave type.

(2)In the early stage of oilfield development, the average water saturation is low, the injection multiple of injected water is low, and the water content increases gradually. After entering the ultra-high water cut period, the average water saturation is high, and the injection multiple increases exponentially.

(3)For the reservoir with low permeability, the proportion of small pores increases significantly and the average pore throat radius decreases after long-term water injection development. For the reservoir with high permeability, the long-term water injection erosion forms the dominant seepage channel, the proportion of large pores increases significantly and the average pore throat radius increases.

(4) After entering the extra-high water cut stage, the relative permeability curve type of different permeability levels has not changed, but the long-term water injection development directly affects the characteristic parameters of the relative permeability curve. The irreducible water saturation in different water cut stages has little change. Affected by long-term water injection development, the residual oil saturation increases first and then decreases

with the increase of permeability. The two-phase span and oil displacement efficiency decrease first and then increase with the increase of permeability.

(5)Therefore, the dynamic relative permeability curve of the whole process is established for the change of the relative permeability curve, which provides a theoretical basis for improving the prediction method of oil production.

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