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Study and Application of Diagnosis Curves of Water Channeling Patterns for Horizontal Well in Bottom-Water Heavy Oil Reservoir

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Abstract

Researches on the water breakthrough patterns and laws of horizontal well are weak. Based on this, a typical model was established by using the geology and reservoir parameters of the heavy oil reservoir with large bottom water in the Bohai Sea. Generally, there are 4 water-out patterns for horizontal well in bottom-water heavy oil reservoir, including punctiform breakthrough waterflooding in a local horizontal section, punctiform breakthrough waterflooding in several local horizontal sections, linear breakthrough waterflooding in the whole horizontal section, and water channeling along high permeability zone. Then, the typical diagnosis curves of these water breakthrough patterns were drawn by studying WOR (water-oil ratio) and its first-order time derivative. However, there are usually value errors in the actual production data, so the interference of noise signals in production data would reduce the accuracy and reliability of water output diagnosis. Using wavelet transform method to denoise dynamic data can simultaneously guarantee both the smoothness and approximation of derivative curves. Finally, the effective measures of different water flooding modes were put forward by the case study of 22 horizontal wells in LD bottom-water reservoir. It has reference significance for efficient development of bottom-water reservoir with horizontal wells in high water cut stage.

Key words: Production performance; Heavy oil reservoir; Horizontal well; Diagnosis curve; Water control and oil increase

INTRODUCTION

As an advanced technology for oil and gas field development, horizontal wells have been applied to most oil and gas reservoirs (Xiong, et al, 2007). However, horizontal well would be watered out and even be shut in because of the invasion of edge or bottom water along high permeability zone or fractures with the time, which is one of the difficult problems in exploitation by horizontal well at present (Tang, et al, 2005; Jiang, et al, 2009). Aiming at the weak research on water breakthrough pattern and law of horizontal well, a typical model was established on the basis of the geology and reservoir parameters of a heavy oil reservoir with bottom water in Bohai Sea. Then, several typical water channeling patterns, including punctiform breakthrough waterflooding in a local horizontal section, punctiform breakthrough waterflooding in several local horizontal sections, linear breakthrough waterflooding in the whole horizontal section, and water channeling along high permeability zone, were studied and diagnosed by WOR and the first-order derivative of WOR. This study provides a new idea to recognize the water channeling pattern by using the dynamic production characteristics and to put forward reasonable measures.

1. INTRODUCTION OF TIME DERIVATIVE CURVE OF WOR

The type "A" water drive characteristic curve is constructed with the cumulative oil production as the abscissa and the cumulative water production as the ordinate (logarithmic coordinates). This curve presents a distinct straight line segment in the middle and late stages of development, and the slope of the line is usually represented by b. The characteristic function equation is:

$$\lg W_\mathrm{P} = \mathrm{a} + \mathrm{b} N_\mathrm{P} \quad (1)$$

Where, W_p is cumulative water, $10^4\mathrm{m}^3$; N_p is cumulative oil, $10^4\mathrm{m}^3$; a and b are constants.

The current geological reserves under the water drive performance can be calculated by using the slope of the straight line segment. The correlation commonly used is:

$$\mathrm{N} = 7.5/\mathrm{b} \quad (2)$$

Where, N is the current geological reserves under the water drive performance, 104m3.

According to the discussion in reference (4), the derivative curve of water drive characteristic curve can be obtained by simultaneously differentiating Np on both sides of the formula (1), it is shown as follows (Yang, et al, 2008):

$$\frac{\mathrm{d}\lg W_\mathrm{P}}{d\lg N_\mathrm{P}} = \mathrm{b} \quad (3)$$

The numerator and denominator of the left side of equation (3) is derived from time:

$$\frac{\mathrm{d}\lg W_\mathrm{P}/dt}{d\lg N_\mathrm{P}/dt} = \mathrm{b} \quad (4)$$

Because $\mathrm{d}W_\mathrm{P}/dt = Q_W$ and $\mathrm{d}N_\mathrm{P}/dt = Q_o$, equation (4) can be:

$$\frac{\mathrm{WOR}}{W_\mathrm{P}} = \mathrm{b} \quad (5)$$

Where, WOR is water-oil ratio, WOR=$Q_\mathrm{w}/Q_\mathrm{o}$; Q_w and Q_o are stage water production and stage oil production respectively, $10^4\mathrm{m}^3$.

Equation (5) means that the WOR of the cumulative water production per unit is a constant, if there is no large scale stimulation in the high water cut stage. Besides, the derivative curve consists of 2 factors, current production performance (WOR) and overall production performance (Wp), which not only has important significance for evaluating the effect of current measure, but also plays a significant role in the middle and late stage (Yang, et al, 2008).

2. STUDY ON TYPICAL THEORETICAL DIAGNOSIS CURVES

Production stabilization and water-cut control is the main job during the development of reservoirs driven by strong edge and bottom water, so the key is to judge aquifer water multiple and water channeling pattern. Some researchers used the production data to analyze the production characteristics of oil wells, and summarized the water invasion mode. Moreover, oil and water production data were directly used to divide the production stage and water breakthrough stage of oil wells. Although this method can determine the type of water breakthrough to a certain extent, it depends to a large extent on experience. What's more, the identification mark has multiple solutions (Liu, 2008). K. S. Chan et al employed the time derivative of WOR to analyze the production data (Chan, 2008) to explore the potential information existing in the data. This method has more clear judgment symbol and better maneuverability for the judgment of water channeling pattern.

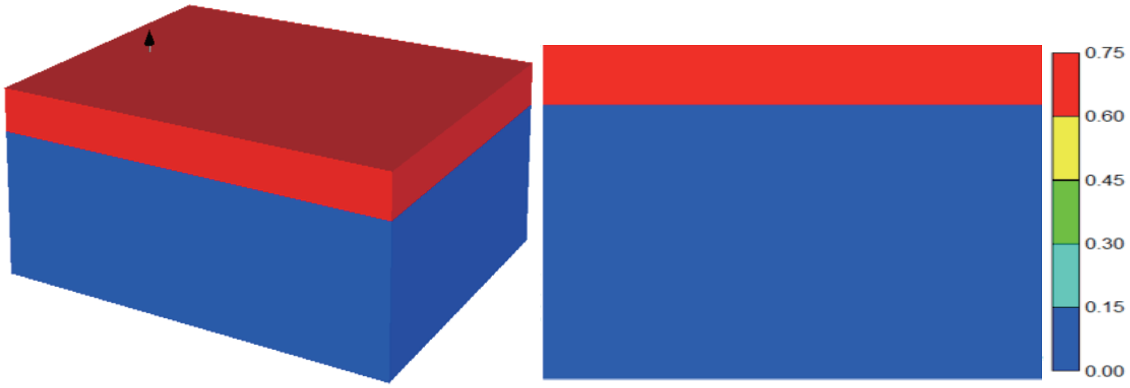
2.1 Establishment of Homogeneous Model of Bottom Water Reservoir

According to the geology and reservoir parameters of typical heavy reservoir LD oil filed in Bohai Sea, a homogeneous model of heavy oil reservoir with bottom water was built. The parameters of the model are shown in Table 1. In this model, the grid number in the X direction is 40, the gird step is 10m and the total length is 400m; the grid number in the Y direction is 21, the gird step is 15m and the total length is 315m; in the Z direction, there are 30 layers, of which 1 to 10 are oil layers, the grid step is 3m and the total thickness of the oil reservoir is 30m, and the layers of 11 to 30 are water layers, the gird step is 5m, and the total thickness of the water layers is 100m.

Table 1
Basic Parameters of Typical Model

Parameters/unit	Value
Depth of formation/m	1500
Thickness of reservoir/m	30
Initial pressure of reservoir/MPa	15
Porosity	0.35
Original oil saturation	0.75
Initial temperature of reservoir /℃	61
Formation oil viscosity/(mPa•s)	450
Horizontal permeability/(10-3μm2)	3000
Vertical permeability /(10-3μm2)	0.3
Aquifer water multiple	5.0

Oil wells are simulated through three-stage control conditions: the first control is constant liquid production ($200\mathrm{m}^3$/d), the second control is constant production pressure drop (The maximum production pressure drop is 4MPa), and the third control is constant bottom hole pressure (The minimum bottom hole pressure is 2MPa).

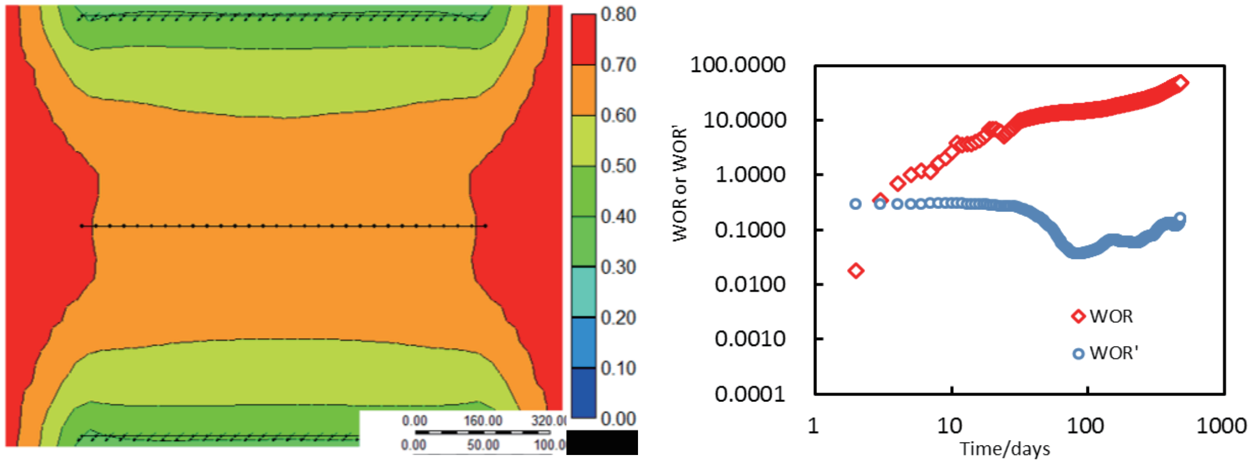


(a) (b)

Figure 1
Schematic diagram of oil saturation of a numerical homogeneous model for (a) three-dimension graph, (b) the profile of J-K.

2.2 Injected Water Channeling Along High Permeability Zone

In order to compare and study the water distribution characteristics of bottom water reservoir, the injected water channeling along the high permeability strip is simulated in this section. This study can provides a reference for the different water breakthrough modes during the development of bottom water reservoir. To simulate the injected water channeling along the high permeability strip, a model, with one horizontal well deployed in the middle and two horizontal injection wells deployed in the sides of reservoir, is built. And, the eighth layer in the longitudinal direction is set as a barrier in the model. It can be seen from Figure 2 (a) that the oil saturation field of the horizontal well is uniform when water floods along the high permeability strip. From figure 2 (b), the slope of WOR curve is positive, and the slope of WOR derivative curve appears upward after the inflection point.

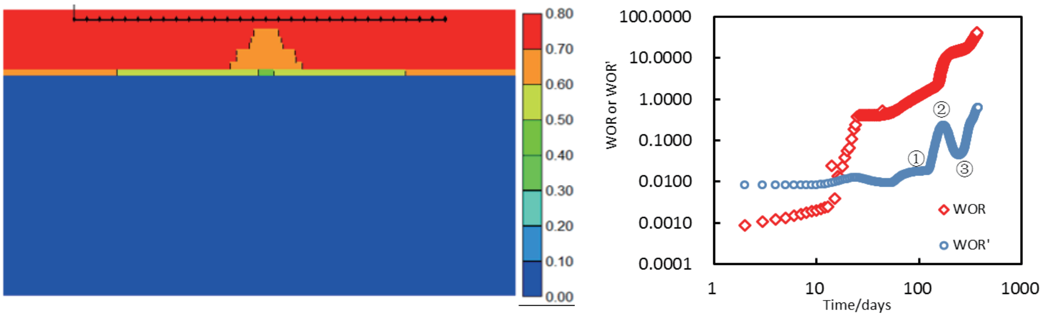


(a) (b)

Figure 2
The water breakthrough mode of injected water channeling along high permeability strip for (a) oil saturation field, (b) WOR curve and its derivative curve.

2.3 Punctiform Breakthrough Waterflooding in a Local Horizontal Section

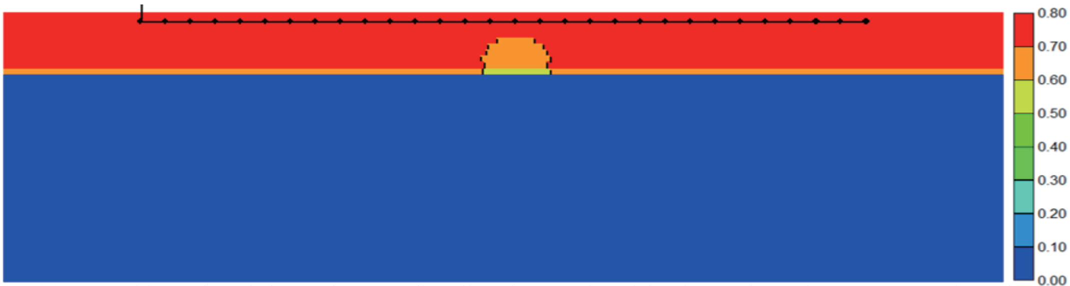
In this section, a model is set to simulate punctiform water cone and waterflooding in a local horizontal section. In this model, a high permeability zone is evenly set along the 300m horizontal section, and the eighth layer of the longitudinal direction is set as an interlayer. The simulation result is shown in Figure 3. It can be seen from Figure 3 (a) that bottom water breaks through one local horizontal section first and then uplifts as a whole. According to Figure 3 (b), the slope of WOR curve is positive, but there are obvious inflection points. Besides, the "upward-drop" change of WOR derivative curve indicates that the horizontal well has different waterflooding modes.



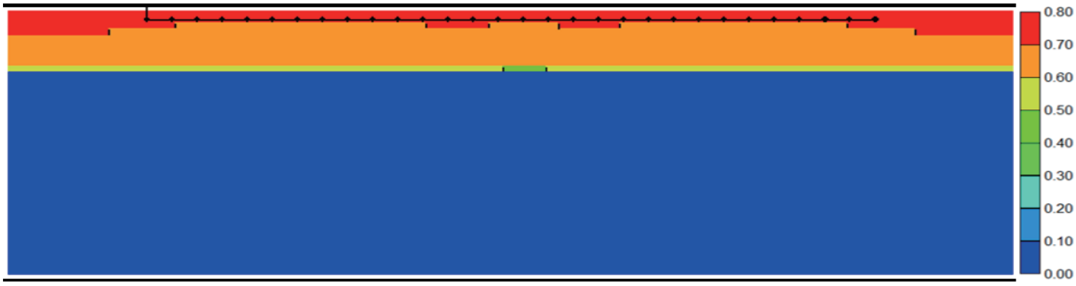
(a) (b)

Figure 3
Punctiform breakthrough waterflooding in a local horizontal section, (a) oil saturation field, (b) WOR curve and its derivative curve

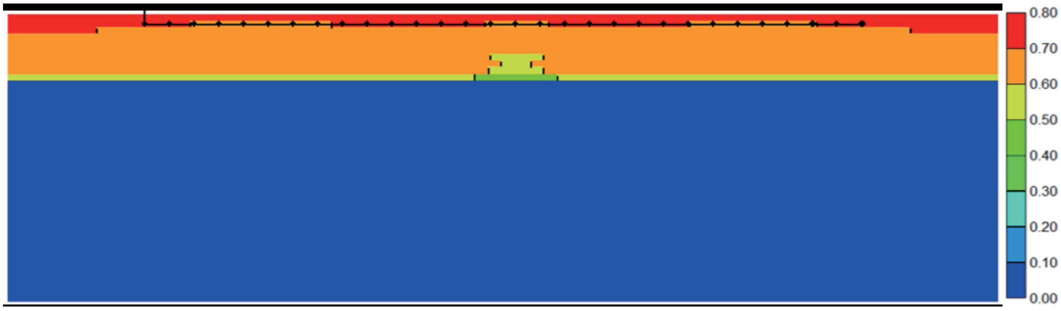
In order to study the waterflooding modes corresponding to the 3 inflection points of WOR derivative curve in Figure 3 (b), the oil saturation fields of corresponding time are drawn, as shown in Figure 4. From Figure 4 (a), the first inflection point indicates that bottom water channels along a local horizontal section, the WOR derivative curve turns upward after this point. From Figure 4 (b), the second inflection point states that the barrier has lost its water blocking effect and secondary bottom water formed, and the WOR derivative curve goes downward after this point. From Figure 4 (c), the third inflection point represents that the linear breakthrough of secondary bottom water in the whole horizontal section, and the WOR derivative curve goes upward after this point.



(a) Punctiform breakthrough waterflooding in one local horizontal section, expressed as the WOR derivative curve going upward (corresponding time: the first inflection point)



(b) The barrier has lost its water blocking effect and secondary bottom water formed, expressed as the WOR derivative curve going downward after this point. (corresponding time: the second inflection point)



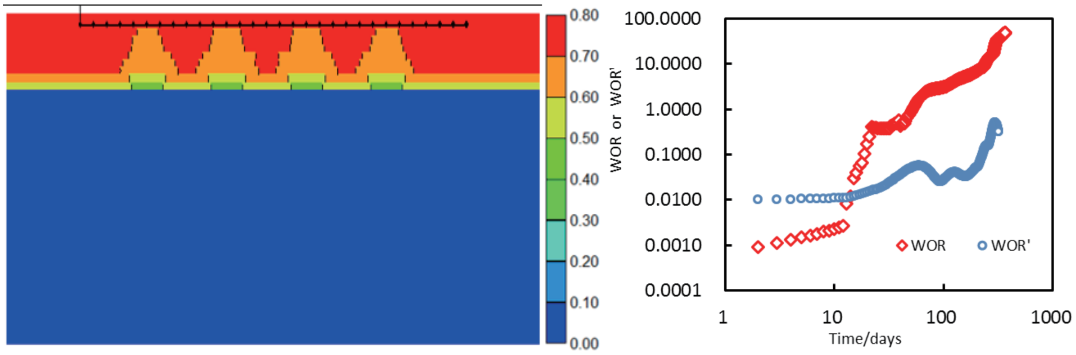
(c) Linear breakthrough of secondary bottom water in the whole horizontal section, showed as the WOR derivative curve going upward after this point. (corresponding time: the third inflection point)

Figure 4
Oil stauration field graphs under different water out behaviors of punctiform water breakthrough

2.4 Punctiform Breakthrough Waterflooding in Several Local Horizontal Sections

In this section, a model is set to simulate punctiform water cone and waterflooding in several local horizontal sections. In this model, 4 high permeability strips are evenly set along the 300m horizontal section, and the eighth layer of the longitudinal direction is set as an interlayer. The simulation result is shown in Figure 5.

According to Figure 5 (a), bottom water breaks in 4 local horizontal sections first and then uplifts as a whole. Figure 5 (b) shows that there are 4 obvious inflection points on the WOR derivative curve, and its slope shows the fluctuations of "negative-positive-negative-positive". For punctiform water out, the remaining oil concentrates in the places far from the high permeability zones.

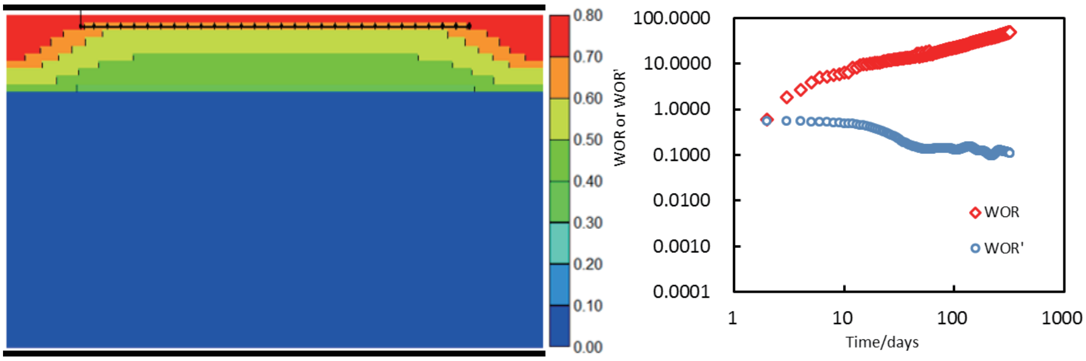


(a) (b)

Figure 5
Punctiform breakthrough waterflooding in several local horizontal sections, (a) oil saturation field, (b) WOR and WOR derivative curve.

2.5 Linear Breakthrough Waterflooding in the Whole Horizontal Section

If there is a long continuous high permeability strip along the horizontal section, the water channeling mode is usually linear breakthrough waterflooding in the whole horizontal section. It can be seen from Figure 6 (a) that water production along the horizontal section is relatively well-distributed, and bottom water would uplift as a whole after linear breakthrough of water. Figure 6 (b) is the diagnosis curve of linear breakthrough waterflooding in the whole horizontal section, which shows that the slope of WOR curve is positive, and that of WOR derivative curve is negative.



(a) (b)

Figure 6
Linear breakthrough waterflooding in the whole horizontal section, (a) oil saturation field, (b) WOR and WOR derivative curve.

3. PRODUCTION PERFORMANCE ANALYSIS OF TYPICAL HEAVY OIL FIELDS

3.1 Geological Reservoir Characteristics and Development Characteristics of LD Heavy Oil Field

The structural morphology of LD oilfield is composed of a small bounded fault block and its adjacent faulted semi-anticline (Figure 7). The reservoir type of this oilfield is a structural reservoir controlled by faults with several oil-water systems vertically and horizontally. The porosity distribution ranges from 15.0% to 42.0%, with an average value of 35.0%. The average permeability is 10000.0mD, which is characterized by high porosity and high permeability. The formation crude oil density is 0.936 ~ 0.937g/cm^3, and the formation crude oil viscosity is 437.00 ~ 559.60mPa·s, belonging to heavy oil.

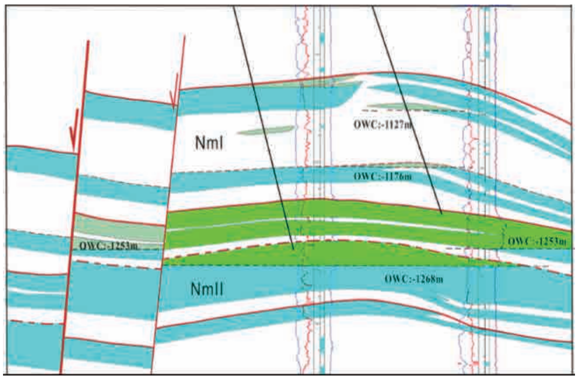


Figure 7
Reservoir profile of LD oilfield Figure 8 structure location map of LD oil field

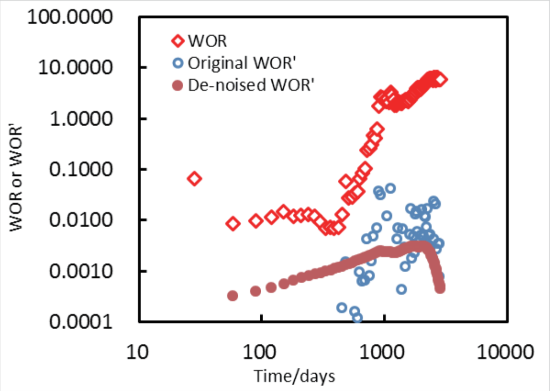
LD oilfield has been put into production since July 2010. At present, there are altogether 24 development wells in the oilfield, including 22 production wells and 2 water injection wells (Figure 8). The daily production of field has fallen from a peak of 967m^3/d to the current 240 m^3/d. Since the water breakthrough in April 2011, the water cut increased rapidly, and by June 2012, the comprehensive water cut of the oilfield increased to 80%. And the recovery degree of reserves in the two stages of water-free oil production period and low-medium water cut period was only 2.7%. By the end of 2016, the water cut of the oil field has risen to 94.7%, and the recovery degree of geological reserves is only 7.0%, and the final oil recovery is predicted to be 14.0%.

3.2 Difficulties and Major Problems in Oilfield Development

Since 2014, the surface water treatment process of LD oilfield has reached the upper limit of treatment capacity of 6000m^3/d, with the result that the oil wells have to be limited to liquid production. According to the theoretical dimensionless productivity index and dimensionless liquid production index, the heavy oil reservoir driven by edge and bottom water has great potential of enhancing fluid in the high water-cut stage. The relation curve between recovery degree and water cut rate indicates that the proportion of oil production in the high water-cut stage is large. From the perspective of production stability, the oil field has a large demand for enhancing fluid. However, the production capacity in the high water-cut stage cannot be released due to the restriction of water treatment capacity of platform.

3.3 Research of Noise Reduction by Wavelet Transform

In the actual measurement process of production dynamic data, there are inevitable interferences of various noise signals, which makes the jump of the diagnosis curve very large and even difficult to identify (Chen, et al, 2007). Therefore, it is necessary to preprocess the production dynamic data before judging water channeling type of oil wells and eliminate the noise signals contained in the dynamic data, so as to improve the accuracy and reliability of diagnosis (Zhan, 2001).



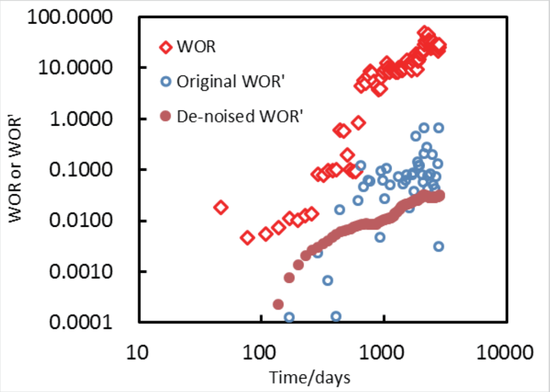
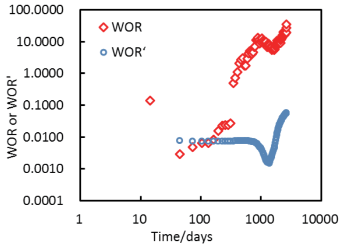
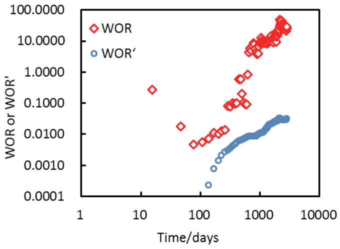
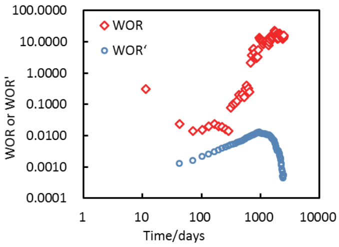
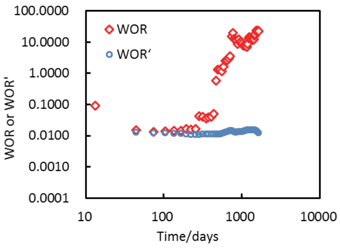


Figure 9
WOR and its derivative of LD-A3H Figure 10 WOR and its derivative of LD-A6H

In this paper, MATLAB software is used to reduce the noise of the first-order derivative of water-oil ratio. Firstly, the data of the WOR derivative are input and converted into signals. Then, extending the signal or reducing the length of the signal. And then the noise is reduced by wavelet transform. As can be seen from Figure 9 of well LD-A3H, after de-noising by wavelet transform, the slop of WOR derivative and the time relation curve is positive at the beginning and negative at the end. As a result, it can be diagnosed as abnormal water out mainly caused by bottom water coning. As can be seen from Figure 10 of well LD-A6H, the slop of relation curve between WOR derivative and time is basically positive, so it can be diagnosed as abnormal water out mainly caused by water channeling along the high permeability strip.

Table 2
Classification of Horizontal Well Water Channeling Types and Typical Diagnostic Curves of LD Bottom Water Heavy Oil Reservoir in Bohai

Water Channeling Pattern	typical diagnostic curves	Curve description	Typical Wells	Corresponding measures
Punctiform breakthrough waterflooding in a local horizontal section		Although the slope of the water-oil ratio curve is positive, there is an obvious inflection point of the slope. The slope of derivative curve of water-oil ratio appears "upward-down-ward".	A08H, A13H, A19H, A20H, A23H	Pressure Cone or Water Plugging
Water channeling along high permeability strip		Slope of derivative curve of water oil ratio is always positive.	A4H, A05H, A06H, A09H, A10H, A21H	Replace Larger Pump or Water Plugging
Linear breakthrough waterflooding in the whole horizontal section		Slope of water-oil ratio curve is positive, slope of derivative curve of water-oil ratio is negative.	A03H, A7H, A12H, A16H, A17H, A22H, A28H	Replace Larger Pump
Entire breakthrough waterflooding in the whole horizontal section		The slope of water-oil ratio curve is positive, and the derivative curve of water-oil ratio is basically a straight line.	A11H, A27H, A30H, A31H	Little Potential

3.4 Classification of Water Breakthrough Modes of Horizontal Wells in LD Oilfield

According to the above research results, the production performance data of all opened horizontal wells (22 in total) in Bohai LD heavy oil reservoir were analyzed. Screening the production data firstly, and the data of monthly average daily oil production and monthly average daily water production were taken to calculate the WOR and its derivative data. Then, the noises were reduced by wavelet transform. Finally, four typical water-channeling modes were obtained, and the corresponding measures were proposed based on the production dynamics, which was shown in table 2.

4. ANALYSIS OF FIELD CASE

There are 22 oil Wells in LD oilfield. Based on the analysis of the diagnosis curves of water channeling, combining with the structure location and the distribution law of the interlayers, four wells have been replaced with large pumps in the past two years. Due to the limit of water treatment process of platform, 15 well times of adjusting the makeup of liquid production structure have been operated, such as shut-in for continuous coning control. The effect of the measures is shown in table 3.

Table 3
Statistical Data of the Measures Taken in Bohai LD Bottom Water Heavy Oil Reservoir in the Past Two Years

Well Name	Measures Type	Implement Period	Before taking measures			After taking measures		
			daily fluid production rate	daily oil production rate	water cut	daily fluid production rate	daily oil production rate	water cut
A4H	Increase drainage	2016.8	693	38	94	1581	94	94
A5H	Increase drainage	2018.3	230	7	97	997	85	91
A8H	Increase drainage	2018.3	522	17	97	1336	75	94
A12H	Increase drainage	2017.12	190	12	94	1270	88	93
A19H	Pressing cone		225	21	91	256	23	91
A20H	Pressing cone		54	3	94	117	25	79
A23H	Pressing cone		108	3	97	169	15	91

Under the guidance of the diagnosis curve of water channeling, the production strategy of developing oil one after another in sequence by big pump is put forward. The measures mentioned above can make the liquid of oil wells unrestricted under the liquid limit of platform. Four wells have been implemented to enhance liquid and good results were obtained (shown in table 3). Among them, A4H, A5H and A8H belong to the second category and A12H is in the third category.

In August 2016, A4H well was replaced large pump during pump detection, and the pump displacement was increased to 1500m3/d. After operation, oil production increased from 38m3/d to peak production of 97m3/d, and by the end of May 2018, cumulative oil production increased by 1.68×104m3 (shown in Figure 11).

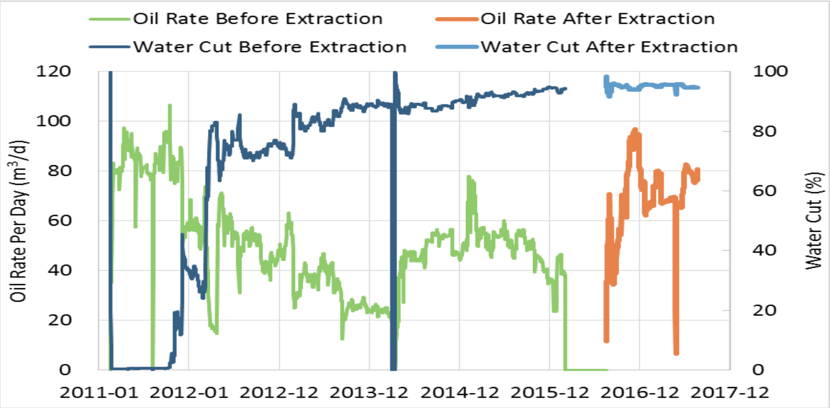


Figure 11
Production curve for increase fluid production rate of well A4H

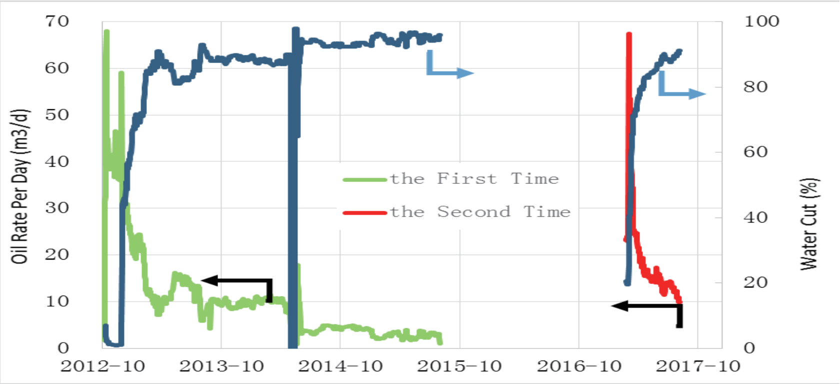


Figure 12
Production curve for pressing cone of well A20H

The A20H well was shut in for controlling water cone and reopened in March 2017. The daily oil production rose from 2m3/d before shut-in to the peak value of 68m3/d, and the water cut decreased from 96% to 20%. As of the end of May 2018, the oil production was 13 m3/d, with water cut of 89%, still in effect. The average daily oil increase of the shut-in coning control in this round is 15m3, and the cumulative oil increment is 0.48×104m3 (Figure 12).

CONCLUSIONS AND SUGGESTIONS

(1) The water-flooding mode of a horizontal well can be judged by the relationship curve between WOR, WOR derivative and production time. Several typical water breakthrough modes, such as point-like ridges flooding, point-like ridges flooding, line-like ridges flooding, and injected water channeling along hyper permeability zone, can be identified by the first-order derivative of WOR and WOR.

(2) The wavelet transform method can better remove the noise signal in the actual production dynamic data. After noise reduction, the relation curve of WOR derivative and production time not only reproduces the real information contained in production dynamic data, but also makes the positive and negative slope more obvious, which improves the accuracy and reliability of diagnosis.

(3) The case of LD bottom water reservoir shows that, the mode of punctiform breakthrough waterflooding in a local horizontal section can get better results by means of pressure cone or water plugging; The mode of water channeling along the high permeability strip through replacing big pump or water plugging can achieve better results; The effective measure of linear breakthrough waterflooding in the whole horizontal section is replacing large pump; The potential of the mode of overall breakthrough overall flooding is small.

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