Study on Enhanced Oil Recovery Technology of Tight Reservoir Modified in Highly Deviated Well: A Case Study of the L183 Area in the Huaqing Oilfield Ordos Basin, China

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Abstract. Chang 6 sandstone reservoir in Huaqing oilfield is a typical tight reservoir. The whole reservoir presents the characteristics of obvious non Darcy seepage, widespread development of natural fractures, large proportion of low production and low efficiency wells, and low production of single wells developed by conventional vertical wells. Based on the mechanism of highly deviated wells improving oil production rate, aiming at the problems of low recovery degree and fracture development induced by water injection during the development of tight reservoirs, this paper verifies the feasibility and superiority of highly deviated wells in tight reservoirs through indoor numerical simulation and field actual effect evaluation. The research results indicate that: (1) The highly deviated wells in the study area adopt advanced fine layered water injection development method, and the regional formation pressure is maintained at a level of over 120%. By utilizing the role of closed well infiltration and displacement, the seepage range is increased and the oil recovery rate is significantly improved. (2) Through numerical simulation combined with actual field test results, it has been proven that the concept of reducing the number of fracturing sections by combining cost control in highly inclined well areas, and the optimal perforation control degree is achieved at 10–20 m per well, with a reasonable flow to saturation ratio of less than 1.0, can maximize the benefits. It is concluded that the development of highly deviated wells in the L183 area of Huaqing oilfield provides strong support for the optimization design of fracturing parameters of thick reservoirs with tight interlayer, and provides theoretical guidance and technical support for their field application.

Keywords: Tight Reservoir · Imbibition Oil Recovery · Highly Deviated Well · Enhanced Oil Recovery

1 Introduction

Huaqing oilfield in Ordos Basin has large proved reserves and developed oil resources. The main layer length of 6 is a powerful battlefield for the exploration and development of Huaqing oilfield. The reservoir in this area is a typical tight reservoir (permeability

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0.38md), with low formation pressure (pressure coefficient 0.6–0.8), large thickness of stable contiguous oil layer (23.6 m), large geological reserves controlled by a single well (106000 tons), relatively complex sedimentary environment, interaction of semi deep lake gravity flow channels in the middle, deep lake sandy debris flow mainly developed in the south, weak sand carrying capacity, interlayer development, and natural fractures in the reservoir, The maximum principal stress direction NE50° ~ NE90°. Therefore, it is urgent to explore a more suitable development mode for tight and thick reservoirs to further improve the oil recovery.

Highly deviated well means that the same oil production well can be exploited through multiple strata at the same time. At present, there is relatively little research on highly deviated wells in China [1–3]. Yang [4] proposed that reservoirs with small oil layer thickness and sufficient natural energy are suitable for long horizontal well development, with discontinuous sand body development, reservoirs with complex water drive conditions are suitable for short horizontal well development, and reservoirs with many oil layers and large thickness are suitable for highly deviated well development, Tang [5] developed the directional hydraulic injection technology to solve the technical problems of highly deviated wells, realizing the natural positioning of the spray gun and avoiding the problem of shooting through thin interlayer in the perforation process. Based on previous studies, on the basis of numerical simulation and field test analysis of Chang 6 reservoir in the L183 area of Huaqing oilfield, this paper discusses the transformation intensity, reasonable flow saturation ratio and advance water injection time of highly deviated wells, and finally realizes the scale benefit development of highly deviated wells in tight reservoirs. Its understanding has important reference significance for the benefit development of highly deviated wells in subsequent tight reservoirs.

2 Reservoir Profile

L183 area of Huaqing district is located in Huachi County, Gansu Province, with an area of about 300 square kilometers, belonging to the Loess Plateau landform. The surface is covered by 100–200 m thick Quaternary loess, with complex terrain, crisscross gullies and uneven ridges. Exposed rocks can be seen in the valley where the river cuts down deeply. The ground elevation is 1350–1660 m, and the relative elevation difference is about 310 m.

L183 area of Huaqing oilfield is located in the south of the slope of Ordos sedimentary basin in Northern Shaanxi [6]. It is a deep-water gravity flow deposit. The structure is a gentle west dipping monocline. The main development layer system is Triassic Yanchang Chang6 oil layer group. The oil layer is stable and thick. The South mainly develops deep Lake sandy debris flow with weak sand carrying capacity, small sand body development scale, thin oil layer, rapid change, interlayer development, reservoir burial depth of 2064 m, and 11.9 m oil layer, The poor oil layer is 4.6 m, the average porosity is 11.6%, the average permeability is 0.28 mD, the oil saturation is 56.87%, the resistivity is 55.41 Ωm, and the acoustic time difference is 225.8 us/m.

3 Well Pattern Transformation of Highly Deviated Well

3.1 Establishing a New Model of Imbibition Displacement in Highly Deviated Wells

According to the driving mechanism of matrix fracture network and Blasingame theory [7, 8], the unstable seepage model of highly deviated wells is derived. According to Fig. 1, the seepage area of highly deviated wells is divided into inner and outer areas. The inner area is artificial fracture network and matrix seepage, and the outer area is mainly matrix seepage. Combined with block reservoir parameters, the zonal seepage theory chart is established.

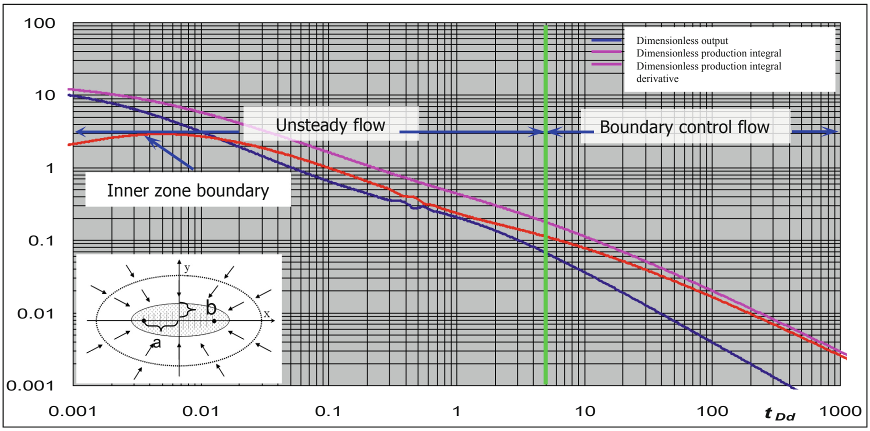

Fig. 1. Zonal seepage theory chart of highly deviated wells.

After high angle volume fracturing, a comprehensive characterization development mode of differential pressure mass transfer and imbibition displacement is established. The fracture network structure is the main control factor affecting matrix fracture mass transfer. After volume fracturing, the oil production rate is the sum of imbibition displacement and differential pressure mass transfer, that is:

$$Q_w = \Delta q + q_w \tag{1}$$

$$q_w = C_f \frac{K_w A}{\mu}(p_f - p_m) \tag{2}$$

where Q_w is the total mass transfer within the scope of large-scale volume transformation of horizontal well, m^3/d; Δq is the imbibition production rate within the scope of large-scale volume reconstruction of horizontal well, m^3/d; q_w is the differential pressure mass transfer and oil production rate, m^3/d.

Necessity of highly deviated well

The tight reservoir of the Huaqing oilfield has the characteristics of large oil layer thickness, developed interlayer, large proved undeveloped reserves, and sand body structure mainly of continuous superposition type, as shown in Fig. 2. In view of the development advantages of comprehensive vertical wells and horizontal wells in the reservoir physical properties of the study area, the development mode of highly deviated wells is innovatively proposed to make full use of each small layer, realize the development of multi-layer system, and improve the horizontal and vertical production degree of the reservoir.

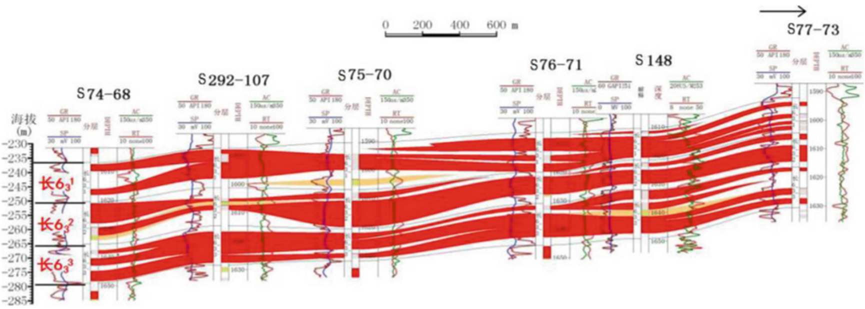

Fig. 2. Profile of Chang 6 reservoir in the L183 area of the Huaqing Oilfield.

The pressure distribution of water drive in 20a through numerical simulation in the study area is shown in Fig. 3. The figure shows that the pressure distribution of highly deviated wells is relatively uniform, and the start-up pressure gradient is higher than that of directional wells and horizontal wells. There is a wide range of low-pressure area near the wellbore of horizontal wells, and the pressure difference in the area is small. While the pressure distribution near directional wells is uneven, the pressure at the edge wells and corner wells of highly deviated wells is low, and the production pressure difference is larger than that of directional wells.

Consequently, the numerical simulation in the study area shows that the reservoirs with thick layers, multiple thin layers and relatively high permeability in Huaqing oilfield have good adaptability for highly deviated wells, greater plane sweep efficiency, greater start-up pressure gradient and more uniform seepage field.

According to Fig. 4, it can be proved theoretically that the highly deviated well on the plane has realized the transformation from conventional fracturing to single sand body volume fracturing. A single fracture is generated after conventional fracturing on the profile, while independent multiple fractures are formed in highly deviated wells.

In order to improve the production degree of reserves, oil production rate and single well production, the development mode of highly deviated wells is optimized for the thick oil reservoir developed in Huaqing Chang 6 inter-layer.

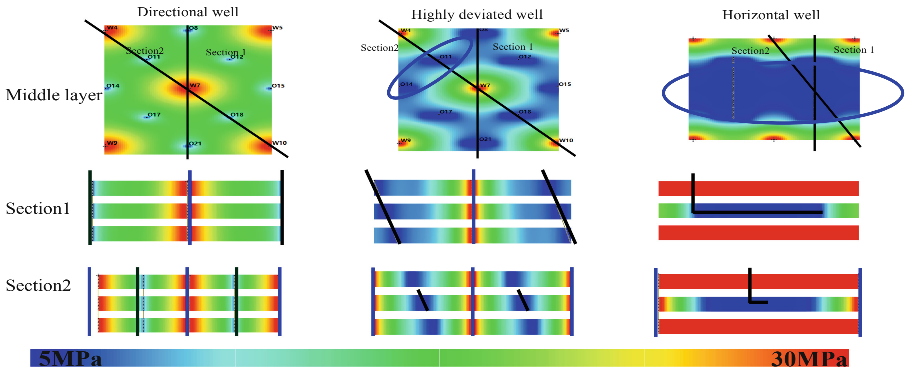

Fig. 3. Numerical simulation pressure distribution of Chang 6 in the L183 area of Huaqing oilfield (20 years of water drive).

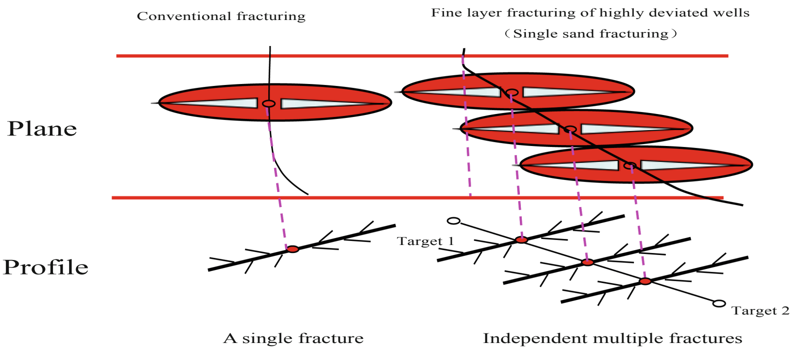

Fig. 4. Schematic diagram of theoretical volume fracturing for highly deviated wells.

3.2 Selection of Well Pattern

Selection of well pattern and well type the reservoir physical property of Huaqing oilfield is poor, and there are contradictions in the development process, such as slow establishment of effective displacement system and rapid production decline. Thus, the three well patterns of rhombus reverse nine-spot well pattern, five-spot well pattern and rectangular well pattern are optimized. The results of numerical simulation are shown in Fig. 5 and Fig. 6. The five-spot well pattern has a large number of water injection wells and a small distribution of residual oil. The rhombus reverse nine-spot well pattern and rectangular well pattern have obvious distribution of residual oil. Controlled by the well pattern, the residual oil is enriched near the corner well, but the pressure distribution of rectangular well pattern is more uniform than that of rectangular well pattern.

In combination with the development characteristics of natural fractures and the current principal stress direction in Huaqing area [9], the well pattern adjustment in this area is designed and optimized to make it easier to establish a displacement system between oil and water wells and extend the stable production time. The well pattern distribution of Huaqing tight reservoir is related to the fracture density and reservoir

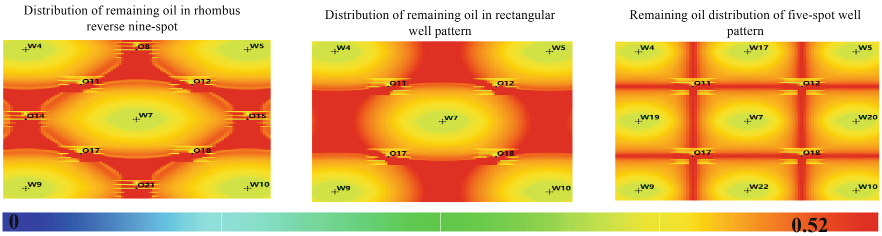

Fig. 5. Numerical simulation of Chang 6 in the L183 area of Huaqing Oilfield.

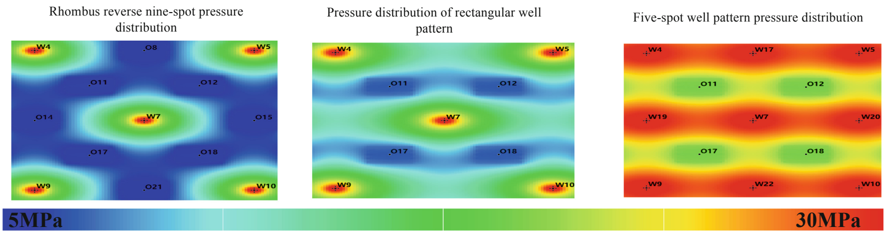

Fig. 6. Numerical simulation of Chang 6 in L183 area of Huaqing Oilfield.

matrix permeability, and the tight reservoir has obvious non Darcy seepage characteristics, Therefore, it is necessary to calculate the formation pressure distribution curves between water injection wells and oil production wells under different well row spacing. According to the starting pressure gradient under different permeability (Fig. 7), the well spacing of rectangular well pattern of highly deviated wells is determined to be 400 m. Draw the chart of the relationship between fracture bandwidth and single section production (Fig. 8), determine that the effective width of artificial fracture is about 10 m, and determine that the row spacing is 120–160 m in combination with the length of the inclined section of highly deviated wells of 80–100 m.

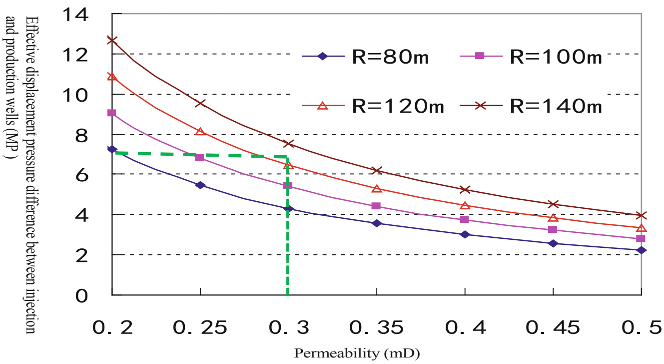

Fig. 7. Effective displacement injection production differential pressure and permeability chart.

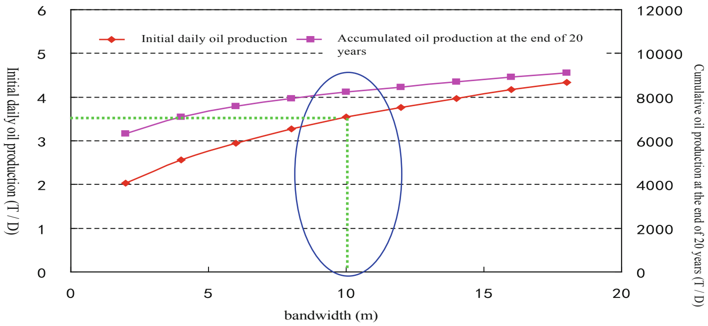

Fig. 8. Single section production with different average fracture bandwidth.

4 Large Scale Application of Highly Deviated Wells to Enhance Oil Recovery

4.1 Reconstruction Strength in the L183 Area

Referring to the idea of large-scale reservoir reconstruction of horizontal wells, aiming at the reservoir with multi-layer system production and high level of horizontal and vertical production, the technical idea of hydraulic injection, fine multi-stage and interference fracturing is adopted as a whole to form the development mode of highly deviated wells in tight reservoir of Huaqing Oilfield: (1) single point centralized perforation: the point source fracture is achieved through hydraulic multi-stage perforation, making the artificial fracture easy to be controlled and extended; (2) Vertical layered fracturing: use the reservoir at the geological "sweet spot" and the corresponding place of injection and production to realize fine multi-stage fracturing; (3) Large displacement fracturing: it is similar to multi-stage and multi cluster fracturing in the horizontal well layer, increasing the three-dimensional complexity of fractures.

By establishing the fracturing geological model in the study area, the numerical simulation software and fracturing software are comprehensively used to optimize the key parameters. See Fig. 9 and Table 1 for details, so as to realize the replacement of natural fractures by artificial fractures. Finally, it is determined that the reconstruction technology is mainly conventional hydraulic jet staged fracturing, with the fracturing fluid of biological glue and EM30 + fracturing fluid. The number of fracturing sections is 4–8, and the single well sanding section is 57–63 m^3, the discharge capacity is 4–6 m^3/min, the sand ratio is 19.0–25.0%, and the amount of liquid entering the ground is 2300–2500 m^3.

Based on the mature experience of the test of changing the water injection development mode [10] (Fig. 10), the well is blocked after fracturing. The actual average number of fracturing sections of 139 highly deviated wells in the test area is 5.6, the average sand addition per well is 352 m^3 (single section 63 m^3), the average sand ratio is 19.6%, the displacement is 5.7 m^3/min, the amount of ground fluid is 2500 m^3 (single section 446 m^3), and the average single well is blocked for more than 20 days.

It is proved that the scale of reservoir reconstruction is in direct proportion to daily oil production through the scatter relation diagram of single section fluid inflow and daily

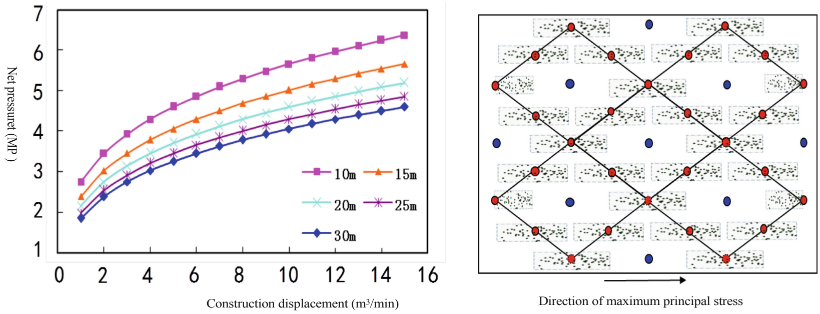

Fig. 9. Net pressure chart and large-scale molded fracture network matching chart of reservoirs with different thickness and different displacement in the study area.

Table 1. Parameters of volume fracturing in highly deviated well area.

well number	number of clusters	sand quantity m^3	sand ratio %	displacement m^3/min	fracture pressure MPa	working pressure MPa	Single section liquid inflow m^3	flowback liquid volume m^3
1	6	42.5	17.9	6.0	91.3	63.9	479.2	54.6
2	5	52.0	19.8	6.0	71.2	54.4	354.1	71.0
3	6	60.8	18.6	5.0	79.4	58.2	496.5	86.3
4	6	43.3	19.5	6.0	72.0	43.9	318.6	59.7
5	6	54.2	18.2	5.0	75.9	57.8	398.5	72.7
6	5	64.0	19.6	6.0	68.3	47.2	430.2	81.1

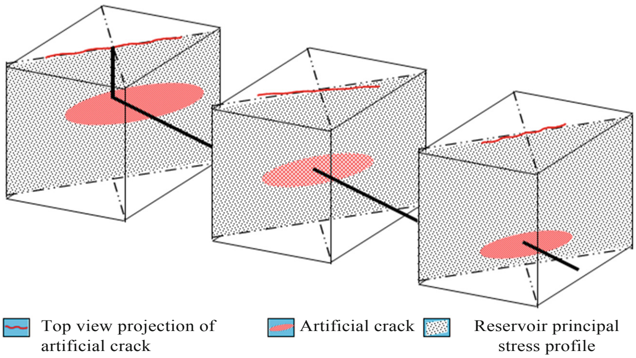

Fig. 10. Schematic diagram of highly deviated well + hydraulic jet staged fracturing process in the L183 area.

oil production and the scatter relation diagram of displacement and daily oil production (Fig. 11). Contrary to the conventional understanding, the greater the displacement in the study area, the lower the water cut. The large displacement reconstruction forms a wide fracture instead of extending the fracture to the far end. The transformation near the perforated section can be fully carried out without affecting the water cut while extracting the liquid.

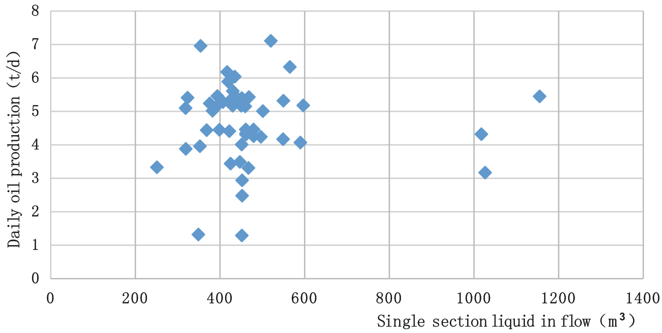

Fig. 11. Scatter diagram of single section liquid inflow and daily oil production.

The perforation control degree parameter introduced in this paper is shown in Fig. 12, that is, the effective oil layer length divided by the number of perforated sections represents that a single perforated section controls the oil layer length. The smaller the controlled oil layer length of a single perforated section, the better the reservoir reconstruction effect. Combined with the concept of reducing the number of fracturing sections by controlling the cost, the optimal result is 10–20 M/piece.

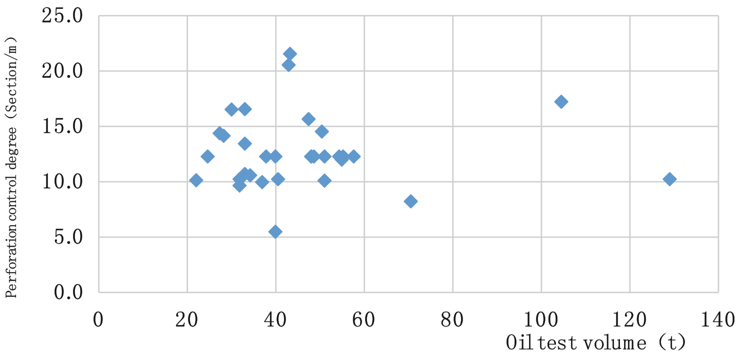

Fig. 12. Scatter diagram of perforation control degree and oil testing volume.

L183 area of the Huaqing oilfield adheres to the development technical policy of "fine layering, small water volume, long period and plane equilibrium" advanced water injection and coiled tubing + closed well. The pressure level is maintained at more than 120% (Fig. 13). The formation energy is sufficient, and all water injection wells adopt separate injection in 2–3 layers. The vertical water absorption is uniform, the water drive control degree reaches 72.4%, and the dynamic liquid level is maintained at about 1000 m.

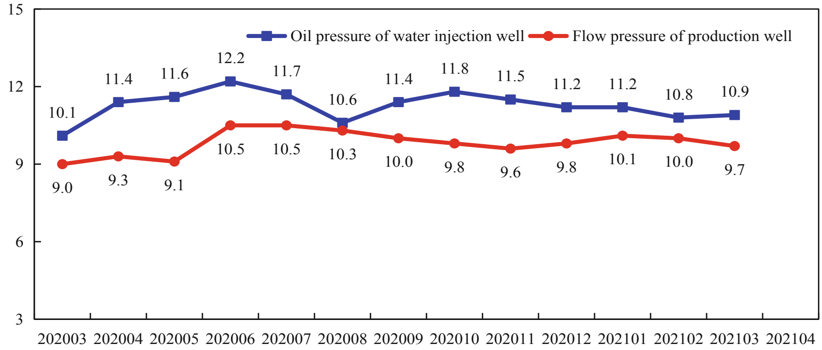

Fig. 13. Variation curve of oil pressure of water injection well and flow pressure of production well in highly deviated well in the L183 area.

4.2 Reasonable Flow Saturation Ratio in the L183 Area

The correlation analysis between the flow saturation ratio and single well production in the Chang 6 highly deviated area of the Huaqing L183 area shows that when the flow saturation ratio is less than 0.8, the single well production is between 4.0–5.0 t, and the benefit is maximized. According to the analysis of single well B299-54X, there is no obvious decline when the flow saturation ratio is about 1.0 (Figs. 14 and 15).

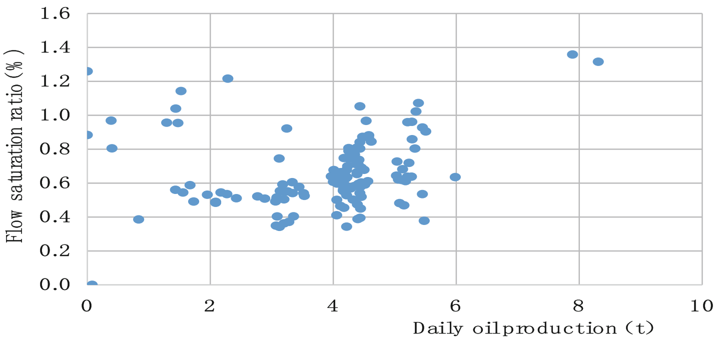

Fig. 14. Scatter diagram of well flow saturation ratio and daily oil production in the L183 area.

Through the industrial profile test (Table 2, Fig. 16), the vertical oil layers are fully utilized, and the vertical production degree of the reservoir is increased to more than 80%. Compared with adjacent horizontal wells, highly deviated wells produce 0.9t ↑ 3.5t oil in 100m horizontal section, and the initial oil production rate is 0.7% ↑ 1.8%.

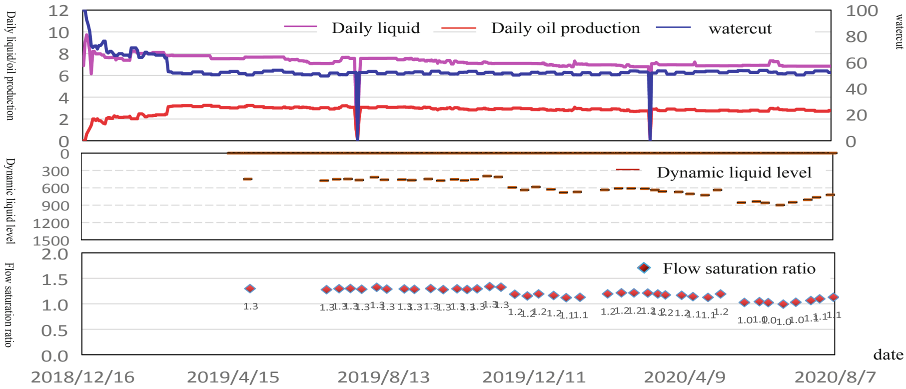

Fig. 15. Production curve of well B299-54X.

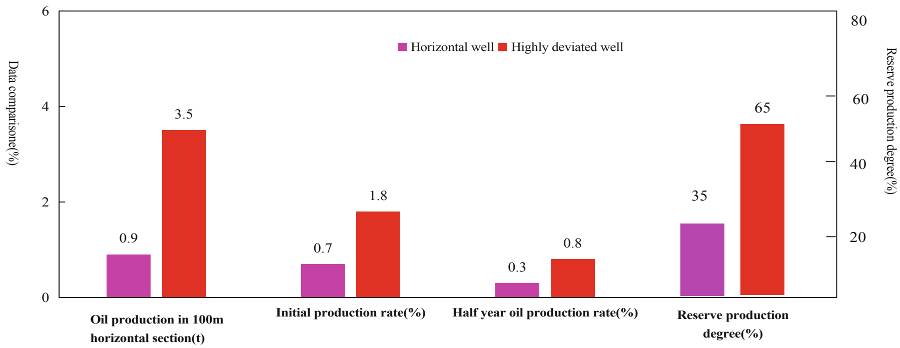

Fig. 16. Comparison histogram of highly deviated wells and surrounding horizontal wells.

Table 2. Production interpretation results of B184-107X well.

number	Perforation point m	Daily water production m^3/d	Daily oil production m^3/d	Liquid production m^3/d	Moisture content %	Relative liquid production %
1	2223.0	0.61	1.74	2.35	26.11	24.33
2	2238.0	0.47	1.36	1.83	25.63	18.94
3	2265.0	0.49	1.40	1.89	25.77	19.57
4	2281.0	0.47	1.37	1.84	25.64	19.05
5	2294.0	0.45	1.30	1.75	25.63	18.12
total		2.49	7.17	9.66	25.78	100

Production decline law in the L183 area

The production change of highly deviated wells in the L183 area conforms to the law of exponential decline, as shown in Fig. 17. The production decline is 10.9% in half a year, 30.8% in one year, and the water cut is stable at about 25%, which is in the early decline stage as a whole.

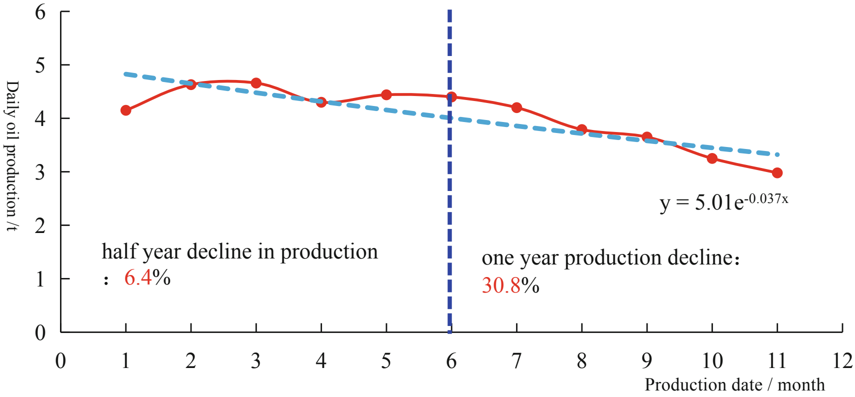

Fig. 17. Pull up curve of daily oil production and production of highly deviated wells in the L183 area.

5 Conclusion

(1) The tight reservoir in the Huaqing oilfield has poor physical properties, strong heterogeneity and natural fractures, but relatively high permeability sections are developed in many sets of small layers in the study area. The numerical simulation results show that highly deviated wells have feasibility and superiority in the development of tight reservoirs.

(2) The highly deviated wells in the study area are developed by advanced fine layered water injection, and the regional formation pressure is maintained at a level of more than 120%. The seepage range is increased and the oil production rate is greatly improved by using the imbibition displacement effect of closed wells.

(3) The development of highly deviated wells in the study area changes the relationship between reservoir reconstruction fractures and oil layers from two-dimensional level to three-dimensional level through the change of well pattern. Through numerical simulation combined with actual field test results, it is proved that the idea of reducing the number of fracturing sections in highly deviated well area combined with cost control can maximize the benefit when the optimal perforation control result is 10–20 m/well and the reasonable flow saturation ratio is less than 1.0.

(4) At the initial stage, the average daily oil production of a single well in the study area is 4.0 t, the initial production of highly deviated wells is 2.0–2.4 times that of surrounding directional wells, the initial oil production rate is increased from 0.8–1.0% to 2.0–2.3%, and the oil production rate and single well production of the block are significantly increased.

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