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Research Article

Research on Effectiveness and Application of Fixed-Plane Perforation Fracturing Technology in Ultra-Low-Permeability Reservoir

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Water flooding development of Chang 6 ultra-low-permeability reservoirs in Ansai lasted for more than 30 years; the front of the water drive has swept the reservoir high permeability zone. As a result, a large amount of residual oil stayed in the reservoir longitudinal low-permeability area. To recover the remaining oil in the low-permeability layers, the fixed-plane perforation fracturing technology is proposed, i.e., using fixed-plane perforation to form a sector stress concentration surface perpendicular to the axis of the wellbore, which makes hydraulic fracture expand radially along the wellbore and control the longitudinal direction of the fracture. Based on the study of residual oil distribution and variation of rock mechanics parameters under long-term injection and production conditions, we simulated and analyzed the effect of fracture initiation under different perforation phases. The optimum perforation phase angle was selected according to the size of the fracture fusion area. According to the fracture simulation under the condition of weak stress difference, the parameters of fracturing operation were optimized with controlling fracture height. A 2-fold increase in ultra-low-permeability reservoir production was achieved by fixed-plane perforation fracturing compared with traditional fracturing technology according to the production data of 78 wells. In this paper, we propose a fixed-plane injection fracturing technique to address the problem of tapping the remaining oil in the longitudinal low-permeability section of the reservoir, which can provide support for tapping the remaining oil in the low-permeability section of the extra-low-permeability reservoir.

1. Introduction

After years of water injection development, the main block of Ansai Chang 6 reservoirs has entered the medium and high water-cut development period. Affected by formation heterogeneity and microfractures, the remaining oil distribution was becoming more and more complex and it is very difficult to make oil production stabilize and enhance oil recovery. With the development of the oilfield, the focus of remaining oil recovery has gradually turned to planes, interlayers, contiguous to profile, inside-layer, and dispersion of oil. Through infilling wells, well inspection data, field outcrop materials, and logging interpretation results, it is believed that the "nonpiston" displacement effect such as channeling and bypass flow for Chang 6 rock of single sand body is very serious, resulting in the water flooding sweep efficiency being low as well as uneven displacement. Under this circumstance, 40% of the oil in the longitudinal direction of the oil layer is not washed by water, leaving much of the oil inside the low-permeability oil layer in the longitudinal direction [1]. In recent years, old wells mainly have been reoperated via conventional fracturing, which achieves the average daily oil increment of a single well less than 1.0 t/d. For some wells, after refracturing, oil production declines rapidly and the high production period is short due to low permeability in the longitudinal direction. Besides, the following research work has been done (shown in Table 1).

To recover more remaining oil in the low-permeability area and improve the effect of refracturing, we proposed a fixed-plane perforation fracturing technology to control fracture height. By changing the perforation method and combining fracturing with water control materials, the low-permeability oil layer under the condition of weak stress difference has been effectively operated by fixed-plane perforation fracturing, achieving a better stimulation effect. It provided a new technical method for refracturing old wells in ultra-low-permeability oil reservoirs for the Changqing oil field.

2. Analysis of the Oil Enhancement Potential in Ansai Chang 6 Reservoir

2.1. Remaining Oil Analysis in the Longitudinal Direction of Formation. Logging and remaining oil monitoring data show that the thickness of the seriously watered-out layer accounts for 24.7% of the reservoir thickness in Chang 6 oil-bearing beds during 20 years of water flooding development, which is one of the most important oil-bearing beds. The zone without the watering-out layer accounts for 34.4% of the reservoir, where the remaining oil saturation is as high as 48.1%. The remaining oil in the low-permeability area is relatively enriched [6] (shown in Table 2). Research results indicate that the water breakthrough of the watered-out oil well is always in the direction of some high permeability area, affected by the heterogeneity of the formation. Under current injection and production conditions, it is difficult to sweep oil in low-permeability and tight zones for water flooding left oil remaining [7].

2.2. Physical Property Analysis of the Formation. According to the properties related to the reservoir, pore throat, natural gamma, and like that, a fine classification standard of a single sand body oil reserve has been established [8] (shown in Table 3), as well as reserves classification has been carried out: the oil that belongs to Class I reserves is mainly distributed in the oil layer with good physical properties, where the permeability is greater than 0.8 mD. The Class I reserve classification possesses characteristics such as high oil recovery, easy to establish (fingering) water watered-out channels, fully displaced by water, and in the condition of high water-cut. The original reserves and the remaining reserves of Class I reserve classification account for 43.7% and 17.9%, respectively. Therefore, the remaining oil of Class I reserves is difficult to recover. The oil of Class II reserves is mainly distributed in the relatively poor physical properties of the formation layer, where permeability is about 0.2-0.8 mD. This kind of reserve classification has characteristics of slow water drive front advancing and low oil recovery. The oil layer of this type accounts for 33.4%. The remaining reserves of Class II are relatively large, accounting for about 29.7%, which is the focus of recovering the remaining oil in the future. The oil of Class III reserves is almost not flooded by water, accounting for 22.9%, which is the main direction of the research for enhancing oil production.

3. Problems of Refracturing

The oil layer thickness of Ansai Chang 6 reservoir is large, the nonhomogeneity in the layer is strong, the high permeability section of the oil layer is influenced by water injection, the water-cut reaches more than 60%, the remaining oil in the longitudinal low-permeability section of the oil layer becomes the main direction of tapping, and in recent years, also, targeted measures such as repeated fracturing and hole filling fracturing all failed to achieve the ideal effect of increasing production, and the measuring process faces many problems.

3.1. Old Fractures Do Not Work, and the Oil Production Enhancement Effect Is Getting Worse. According to the analysis of operation effect in recent years, the oil production enhancement of conventional refracturing operations shows an obvious downward trend, and the effect of refracturing operations has deteriorated year by year. The initial daily oil production increment of the single well has dropped from 1.5 t to 1.0 t. Especially for some wells under several rounds of refracturing, the daily oil production of these wells decreases gradually, while the water-cut increases continuously. Furthermore, with the continuous narrowing of well selection space, the multiround refracturing wells have reached 30% of the workload. After conducting refracturing, the daily oil production increment decreased from 0.81 t to 0.67 t, while the water-cut increased by 13.7%. Therefore, it is difficult to meet the development needs for refracturing with original fractures, and new technical approaches need to be explored.

3.2. Much of Oil Remained in the Longitudinal Direction Formation Affected by Internal Stress

3.2.1. Fracture Is Easy to Propagate through the Interlayer due to the Lower Stress Profile of the Oil Layer. Because of the relatively large thickness of a single sand body, Chang 6 oil reservoir in Ansai, long-term water flooding, and the water saturation changes of the reservoir, the parameters of rock mechanics also changed [9]. Indoor core test experiments show that the elastic modulus and Biot coefficient of rock decrease with the increase of pore pressure. Poisson's ratio of rock increases with the increase of pore pressure, but the increase is relatively small [10]. It shows that the plasticity of rock becomes strong, and the brittleness of rock becomes weak. Under the same pore pressure condition ($P_p = 8.0$ MPa), the indoor triaxial rock compression test determined that Young's modulus and Poisson's ratio in the horizontal direction of the reservoir are 19.6 GPa and 0.28, respectively, and Young's modulus and Poisson's ratio in the vertical direction are 20.3 GPa and 0.24, respectively.

Meanwhile, the heterogeneity of the reservoir has a greater impact on the rock stress, found in the process of laboratory experiments. The literature research shows that Young's modulus and the minimum horizontal principal

Table 1: Work done by researchers on hydraulic fracturing.

Author	Description
Wang et al. [2]	An improved theoretical model for the analysis of the frictional force was proposed based on microscopic contact deformation theory and a bristle model. This model can accurately describe the friction behavior and quantitatively predict the frictional resistance in horizontal drilling
He et al. [3]	This paper presents an improved RTA model of multifractured horizontal wells (MFHWs) to investigate the effects of nonuniform properties of hydraulic fractures on rate transient behaviors through the diagnostic type curves. Results indicate obvious differences in the rate decline curves among the type curves of uniform properties of fractures (UPF) and nonuniform properties of fractures (NPF)
Guo et al. [4]	The technology of directional propagation of hydraulic fracture guided by vertical multiradial slim holes is innovatively developed. The results show that directional propagation of hydraulic fractures guided by vertical multiradial slim holes is feasible
Liu et al. [5]	The effect of natural fracture development degree, in situ stress conditions, fracturing treatment parameters, and temporary plugging on fracture propagation was investigated. The results show that the NF is a key factor in determining the hydraulic fracture (HF) morphology in the tight sandstone reservoir

Table 2: Statistical analysis of water flooding in Chang 6 layer.

Water flooding classification	Formation thickness (m)	Proportion of thickness (%)	Original average oil saturation (%)	Remaining oil saturation (%)	Decrease of oil saturation (%)
Without watering-out	186.8	34.4	52.7	48.1	4.6
Watered-out	222.0	40.9	53.9	39.1	14.8
Seriously watered-out	18.5	24.7	50.5	28.5	22.0
Average	142.4	33.3	52.4	38.6	13.8

Table 3: Classification standard of a single sand body oil reserves [8].

Classification	Displacement characteristics	Porosity (%)	Permeability (mD)	Microscopic pore throat radius (μm)	Natural gamma (API)
Class I	Good physical properties, easy to form (fingering) watered-out channels, early watered-out, good displacement effect, and high oil recovery	≥14	≥0.8	≥0.25	0.3-0.5
Class II	The water flooding front advancing is slow, physical properties are relatively poor, swept efficiency is low and widely distributed, and there is high shale content	≥10-14	≥0.2-0.8	≥0.1~0.25	1.5-0.3
Class III	Belonging to the unconventional tight formation, which cannot be swept and used temporarily; the reserves can be calculated, unless developed by gas flooding in the future	<10	<0.2	<0.1	0-1.5

stress of the rock will change correspondingly under the condition of long-term injection and production. Considering the influence of rock mechanics parameters, the stress profile calculation model has been improved [11]:

$$\sigma_h = \frac{E_h}{E_V}\frac{V_V}{1 - V_h}(\sigma_V - \alpha_v P_P) + \alpha_h P_P, \quad (1)$$

where σ_h is the principal stress in the horizontal direction (Pa), V_v is the pore volume in the vertical direction (m^3), V_h is the pore volume in the horizontal direction (m^3), E_h is Young's modulus in the horizontal direction (Pa), E_v is Young's modulus in the vertical direction (Pa), σ_v is the vertical direction principal stress (Pa), P_p is the rock pore pressure (Pa), and α_h is the anisotropy coefficient of the rock horizontal plane.

Considering the effects of interlayer pore pressure changes, rock mechanical parameter changes, and heterogeneity, the results show that the stress difference of the reservoir is 2.2-3.3 MPa under the condition of long-term injection production.

3.2.2. Fracture Prone to the Longitudinal Direction under the Condition of Weak Stress Difference. To verify the characteristics of fracture propagation after refracturing under the condition of weak stress difference, the fracture propagation of the X18-06 well that conducted conventional perforation adding fracturing under the action of weak stress difference was simulated by Stimplan fracturing software. The basic

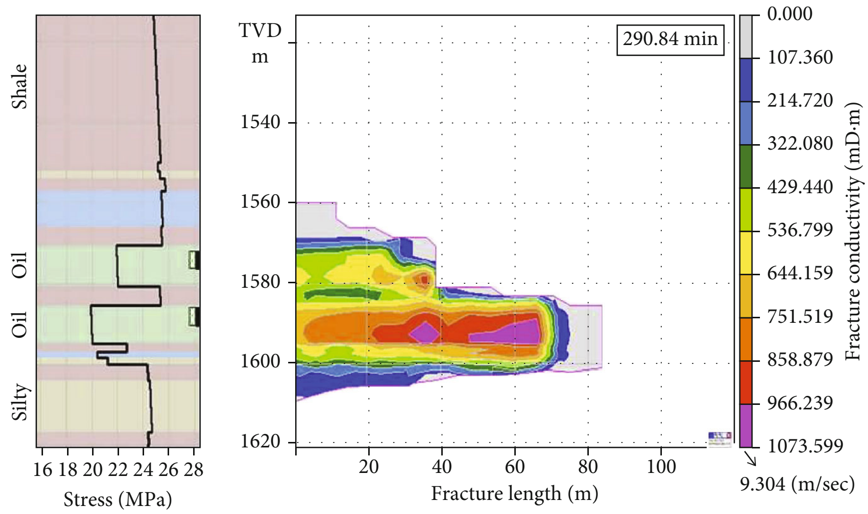

Figure 1: Fracture simulation results of conventional fracturing in well X18-06.

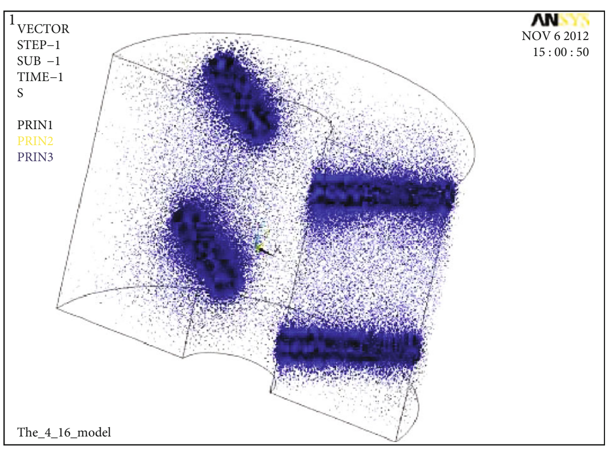

Figure 2: Stress distribution vector map of conventional spiral perforation.

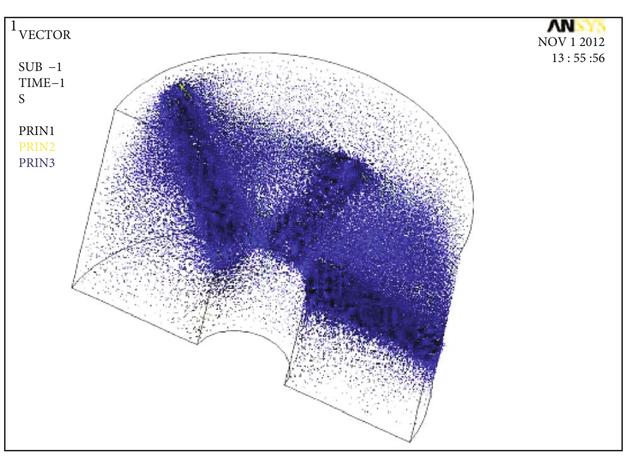

Figure 3: Stress distribution vector map of fixed-plane perforation.

parameters of the simulation model, vertical depth, effective permeability, and porosity, are 1160.00 m, 2.0 mD, and 12%, respectively. The upper oil layer is perforated with conven-

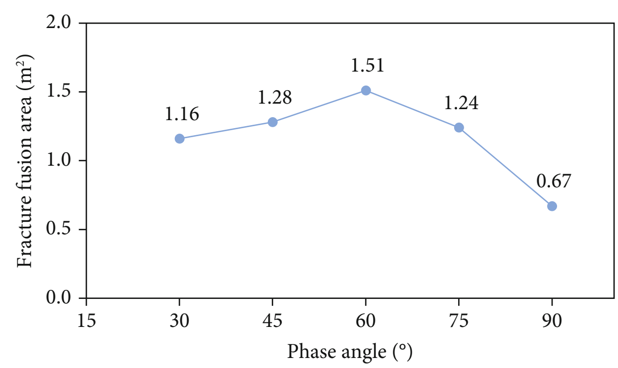

Figure 4: Fracture propagation simulation results of fixed-plane perforation fracturing.

tional spiral perforation, from 1570.00 m to 1574.00 m. The perforation section was fractured; operation parameters were as follows: sand volume is 10 m^3, fracturing fluid injection rate is 1.0 m^3/min, and total injection liquid volume is 75 m^3. The results show that 70% of fracturing fluid is filled in the old fracture (from 1555.00 m to 1595.00 m) after fracturing. The fracture height is 40.00 m, and the longitudinal channeling of the fracture is obvious. Only about 30% of the fracturing fluid filled in new fractures, displaying that the low-permeability area has not been fully fractured [12]. Simulation results indicated that it is difficult to prevent the longitudinal propagation of conventional fracturing fractures under the action of weak stress differences in a single layer (shown in Figure 1).

4. Research on Fixed-Plane Perforation and Fracturing Technology

4.1. Technical Ideas. According to the characteristics of Chang 6 reservoir in Ansai, to recover the longitudinal direction of oil layers, it is necessary to control fracture height to avoid new fracture communication with old fracture. The stress distribution of formation structure under different perforation patterns is shown in Figures 2 and 3.

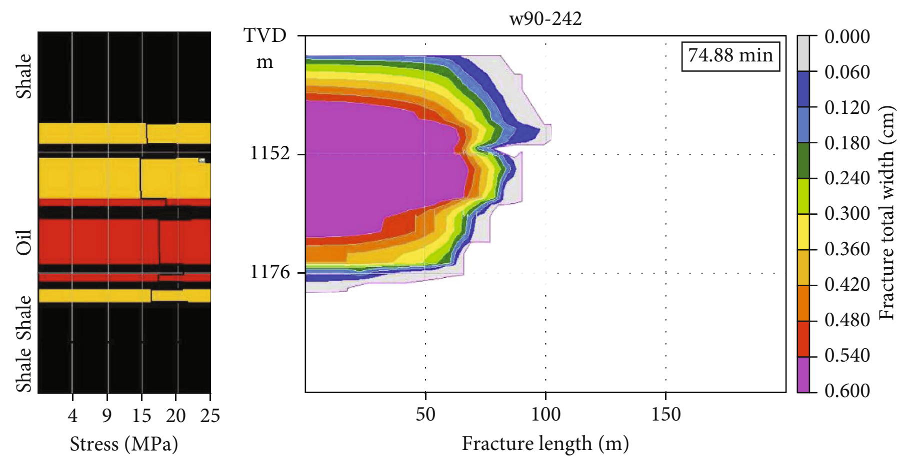

Figure 5: Simulation results of well W90-242 under fixed-plane perforation fracturing.

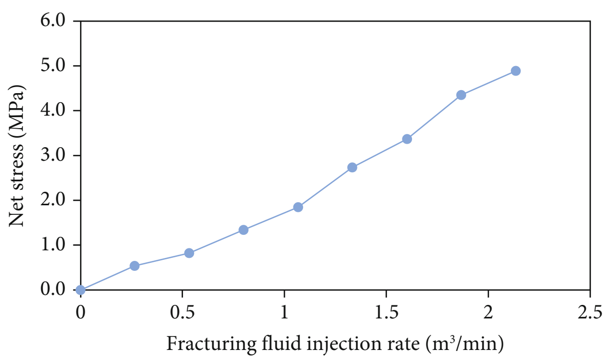

Figure 6: Net stress under different fracturing fluid injection rates.

It can be seen from Figure 2 that the conventional spiral perforation holes are mainly distributed along the vertical direction, and the points of maximum principal stress are densely distributed in the vertical direction. Under this circumstance, fractures are easy to crack and penetrate along the vertical direction, forming vertical fractures finally. It can be seen from Figure 3 that the perforations of fixed-plane perforation are distributed in a fan-shaped plane. Due to the mutual influence between the perforations in the same plane [13], the maximum principal stress points are densely distributed in the horizontal direction, forming a horizontal stress concentration surface [14]. The maximum principal stress on both sides is concentrated to the middle perforation hole, letting hydraulic fractures crack from this plane first. It extends outwards to form radial plane fracture, slowing down fractures' longitudinal cracking.

4.2. Mechanism of Fixed-Plane Perforation Fracturing

4.2.1. Fracture Extension Law. To verify the fracture extension law of fixed-plane perforation fracturing, Abaqus6 finite element software was used to simulate the rock stress field, rock deformation field, and perforation channel connection-fusion characteristics under different pressures and different perforation angles [15]. The effect of different perforation angles including 30°, 45°, 60°, 75°, and 90° on the fracture propagation law of fixed-plane perforation fracturing as the wellbore is parallel to the y-axis was investigated. The calculation results show (displayed in Figure 4) that the fixed-plane perforation fracturing fractures are mainly expanded radially along the wellbore [16]. Under the same pressure, the radial fusion area of fracture tends to increase as the phase angle increases from 30° to 60°, i.e., perforation phase increases. When the phase angle is greater than 60°, the fracture radial fusion area decreases, which is not conducive to the formation of the radial fracture surface. According to a comprehensive analysis, the fracture fusion area is the largest when the phase angle is 60°, which is more favorable for the radial expansion of the fracture.

4.2.2. Analysis on Fracture Height of Fixed-Plane Perforation Fracturing. Based on the geological parameters and operation parameters of the W90-242 well, an in situ stress profile model was established to simulate the influence of fixed-plane perforation fracturing on fracture height. The basic parameters of the stress profile model are the following: well depth is 1200 m, effective permeability is 2.1 mD, porosity is 12.8%, and reservoir stress difference is 2.0 MPa. Fixed-plane perforation was carried out in the upper low-permeability section of oil layers to study the fracture crack and propagation law of fixed-plane perforation. The operation parameters were subject to the actual oil field. The perforation section depth of this well was 1152.00-1154.00 m, using a 102-16-180-70 fixed-plane perforation gun with SDP44HMX32 perforation bullet to perforate 12 holes per meter. The perforation section was fractured; operation parameters were as follows: sand volume is 15 m^3, fracturing fluid injection rate is 1.4 m^3/min, and total injection liquid volume is 60 m^3. The results show that about 80% of the fractures propagated in the low-permeability section (1140-1160 m), which shows that the longitudinal expansion of the fractures is effectively controlled [17], and the low-permeability section of the oil layer is effectively fractured (see Figure 5).

4.3. Optimization of Fracturing Parameters. Considering oilfield actual conditions, the impact of operation parameters

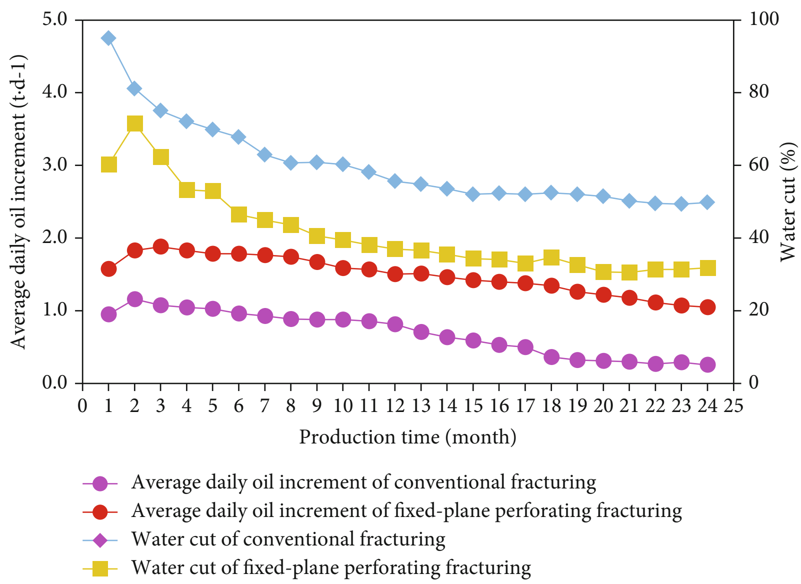

Figure 7: Production curve of fixed-plane perforation fracturing compared with conventional fracturing.

on the longitudinal extension of fractures should also be considered in the fracturing process. The new fractures should be controlled to crack in the longitudinal direction of the low-permeability reservoir as far as possible in the operation. To avoid connecting with the old fractures that have been flooded by water, the low-permeability zone of the reservoir should be fully fractured.

4.3.1. Selection of Fracturing Fluid Injection Rate. According to the study in Section 2.2 of this article, to make the fracture of the reservoir layer controlled by the reservoir barrier stress, the net pressure of fracture must be less than 3.0 MPa [18]. The relationship curve between net pressure and different fracturing fluid injection rates is obtained through theoretical calculations (see Figure 6). It can be seen that to ensure that fracture height is controlled by net pressure, the fracturing fluid injection rate needs to be less than 1.6 m^3/min. When the fracturing fluid injection rate is greater than 1.6 m^3/min, the fracture height suddenly increases and the longitudinal fracture extension of the reservoir is easily out of control, thus influencing the fracturing effect. After comprehensive consideration, the optimized fracturing fluid injection rate is 1.4-1.6 m^3/min.

4.3.2. Selection of Fracturing Fluid Liquid Volume. To take full use of hydraulic fractures and avoid production wells watering-out or water channeling due to too long fracturing fractures, it is necessary to study the influence of fracturing fluid liquid volume on hydraulic fracture lengths to determine the best hydraulic fracture parameters under different good patterns and well spacing and to guide the optimization design of oil well fracturing [19]. Taking the 300 m × 120 m rectangular inverted 9-spot well pattern of Chang 6 oil reservoir in Ansai as an example, the fracture length needs to be controlled because the water flooding front approaches old fractures during years of injection production. The simulation results show that it is easy to communicate with the water flooding front when the liquid volume is greater than 80 m^3 as well as the fracture length is greater than 90 m, i.e., the fracture penetration ratio is greater than 0.3. Therefore, the best fracture penetration ratio should be less than 0.3, the optimal fracture length is 60-80 m, and the best fracturing fluid liquid volume is 60-80 m^3.

4.3.3. Optimization of Proppant and Fracturing Fluid. To control the lift of fracture water saturation, a combination of selective wetting proppant and quartz sand proppant is used to support the hydraulic fracture. According to the reservoir closure stress and the evaluation results of proppant conductivity tests [20], the combination of 40/70 mesh selective wetting proppant and 20/40 mesh quartz sand is preferred.

To better control the net pressure of fracture and water-cut after fracturing, 10 m^3 liquid was injected in the prestage to change water and oil permeability to control the water-cut at the end of fracture. The 5-10 m^3 volume of 40/70 mesh selective wetting proppant was added at the initial stage of sanding, which uses the coating resin technology to change the phase permeability to prevent the rise of fracture water saturation. 10-15 m^3 volume of 20-40 mesh quartz sand was injected in the fracturing stage. Weak cross-linked fracturing fluid was used as sand-carrying fluid to reduce liquid viscosity and sand ratio and control fracture longitudinal extension with the sand ratio between 20% and 25%.

5. Application Effect of Fixed-Plane Perforation Fracturing

5.1. Enhanced Oil Recovery Effect. 78 wells of ultra-low-permeability Chang 6 oil reservoir in Ansai have applied fixed-plane perforation fracturing for reservoir stimulation. After the fracture, the average daily oil of a single well

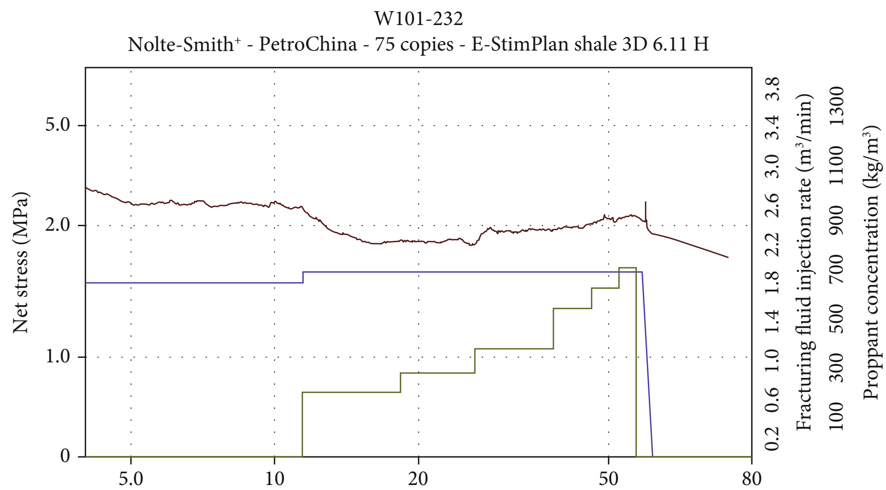

Figure 8: Nolte-Smith curve of fixed-plane perforation fracturing in well W101-232.

increased by 1.80 t/d and the water-cut decreased by 43.0%. Compared with conventional fracturing, the average daily oil increment of a single well increased by 0.70 t/d, and the water-cut is reduced by 20.0%. From the long-term production data, it can be seen from Figure 7 that the technology has obvious effects on recovering oil and controlling water. Thus, fixed-plane perforation fracturing has a good effect on stabilizing production in the long term.

5.2. Case Study. Well W101-232 is located in the middle of Chang 6 Block in Ansai. It was put into production in July 2015. At the initial stage of production, the daily oil production was 2.10 t/d, and the water-cut was 8.3%. Before fixed-plane perforation fracturing, the daily oil production was 0.68 t/d, the water-cut was 70.6%, and the cumulative oil production was 13460 t.

In June 2017, combined with the good pattern, water drive system, formation pressure, and other conditions in the area, fixed-plane perforation fracturing was implemented on the low-permeability zone of the lower Chang 6 to excavate the remaining oil in the low-permeability section. Selective wetting proppant was used to increase the flow resistance force of water and reduce the water saturation in the fractures after fracturing. The optimization design of a single well is mainly as follows: fracturing fluid injection rate is 1.4 m^3/min, injected prefluid volume is 10 m^3 to change relative permeability, 5.0 m^3 of 40/70 mesh selective wetting proppant is injected followed by sand-carrying liquid, 15.0 m^3 of conventional 20/40 mesh proppant is added for support fracture following sand-carrying liquid, and the total amount of liquid entering the ground is 75 m^3. Through the analysis of the Nolte-Smith curve, displayed in Figure 8, the net pressure in the fracture during fracture extension is about 2.0 MPa. After the low-permeability interval is fractured, the daily fluid production of this well is 2.98 m^3, the daily oil production is 1.63 t/d, and the water-cut is 35.6%. It is indicated that fixed-plane perforation fracturing is an effective and promising way to excavate the remaining oil in the low-permeability section for similar oil and gas reservoirs.

6. Conclusion and Suggestion

(1) The area nearby the old fractures of Chang 6 reservoir in Ansai has been fully flooded by water. The longitudinal low-permeability section of the reservoir is the focus of recovering the remaining oil through oil saturation and reserve analysis. New fracturing technology needs to recover the remaining oil of the low-permeability zone in the longitudinal direction of the reservoir

(2) The longitudinal low-permeability section of the reservoir is the focus of recovering the remaining oil through oil saturation and reserve analysis. The perforation pattern, fracturing fluid (including water control material), proppant, and operation parameters were optimized, forming the fixed-plane perforation fracturing technology, which solved the problem of fracturing reformation under the condition of weak stress difference

(3) From the perspective of fracture monitoring and oil field application effects, fixed-plane perforation fracturing makes the longitudinal low-permeability reservoir fully refractured, achieving significant effect to excavate more remaining oil

(4) Fixed-plane injection is an important way to induce fracture initiation along the radial direction. The relationship between rock ground stress and fracture initiation and the influencing factors will be further studied in the future to improve the application effect of this technique

(5) This numerical simulation method is in the 2D stage for fracturing simulation, while the real fracture pattern is in 3D; the relationship between the two needs to be further explored and studied

Data Availability

The results and data used to support the findings of this study are included within the article.

Conflicts of Interest

We declare that we have no conflict of interest.

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