An improved 3.5° single-bend positive displacement mud motor and its parameter optimization for deep short-radius open-hole sidetracking

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Received: 22 March 2021 / Accepted: 21 July 2021 / Published online: 29 July 2021
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Abstract

In order to improve the sidetracking efficiency for the recovery of old wells in the middle and later stage of oilfield, an improved 3.5° single-bend positive displacement mud motor (PDM) is designed. This novel single-bend PDM first uses the structure of 3.5° large angle PDM + cushion block, which can meet the sidetracking requirements of high build-up rate and short directional section in large curvature short-radius sidetracking wells and can significantly improve the build-up ability. Furthermore, based on the mechanical analysis and finite element numerical simulation, its parameter optimization is carried out. The optimal main parameters are determined as follows: the structural bending angle is 3.5°, the outer diameter is 95 mm, the height of the cushion block is 14 mm, the distance between the cushion block and the bending point is 120 mm, the minimum curvature radius is 35.50 m, and the weight-on-bit (WOB) should be less than 30kN. The initial section build-up rate of directional sidetracking can be increased up to 52.67°/30 m ~ 53.29°/30 m. The research results have been applied in Tahe oilfield. It proves that 3.5° single-bend PDM can sidetrack successfully at one time and increase deviation, and the overall angle change rate of bottom hole can reach 45.00°/30 m, which can meet the requirements of short-radius sidetracking with curvature radius of 40 m. The successful application of open-hole sidetracking technology with 3.5° single-bend PDM is of great significance to the production increase and efficiency improvement of old oilfields.

Keywords Short radius · Open-hole sidetracking · 3.5° single-bend positive displacement mud motor · Finite element numerical simulation · Parameter optimization

Introduction

With the continuous development of old oilfields, the well condition of oil and water wells in old oilfields is deteriorating, which seriously restricts the improvement of oil recovery. In order to enhance oil recovery, infill wells

and short-radius sidetracking horizontal wells can be used (Zhang et al. 2017). Comparing these two methods, the former has the disadvantages of long well construction period and high cost, while the latter can effectively communicate with new reservoirs through wellbore extension, which can not only save drilling cost, but also improve reservoir connectivity efficiency, enhancing oil recovery and economic benefits (Zhang et al. 2019). Sidetracking short-radius horizontal wells is an effective means to tap the latent power and increase reserves and production in old areas (Liu et al. 2013).

The sidetracking slim hole short-radius horizontal well technology is the important drilling technology developed rapidly in 1980s (Li 2020). The commonly used drilling tools for short-radius horizontal wells can be divided into two types, namely surface-driven flexible drilling system and downhole-driven articulated elbow chain motor system. In the mid-1970s, the Eastman Whipstock company of the USA developed a short-radius deflecting drilling system through eight

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years of research and test, which is widely used in the Knparnk oilfield of Canada. Since 1983, Eastman Christenden company has made further improvement and has sidetracked more than 300 short-radius horizontal wells in recent years. The articulated positive displacement mud motor (PDM) developed by the Petroleum Exploration and Development Research Institute of Sinopec has the deflection rate of 90° – 150° /30 m and the curvature radius of not greater than 18 m, which can change the wellbore from vertical to horizontal within 28 m wellbore length (Chen et al. 2010). Shengli Oilfield has carried out the scientific research of the sidetracking for short-radius horizontal well, the core of which is designing the articulated PDM, and it can realize the average deflection rate of 33° /30 m (Jiang 2004). The Drilling Institute of Daqing Oilfield adopts the steering elbow to control the direction, and the rotary table drives the articulated flexible drill pipe to drill. The build-up rate can reach 69.9° /30 m, and the curvature radius is not greater than 25 m (Yang et al. 2014). The depth of sidetracking point of short-radius horizontal wells in Tahe oilfield is generally about 5500 m (Yu 2009), its vertical distance from the target formation is less than 70 m, and the average curvature radius can reach 40 m or even smaller. This kind of short-radius horizontal well is deep and has large curvature, which makes it difficult to control the well trajectory, select the deflecting tools and predict the deflecting ability (Chen et al. 2007; he et al. 2003; Lu et al. 2017). On the other hand, after long-term production, the old well has high hole enlargement rate (Ma et al. 2007). All these will increase the difficulty of sidetracking. Taking a sidetracking horizontal well in Tahe oilfield as an example, the original sidetracking point is 5720 m, and there are undeveloped reservoirs under this sidetracking point at a vertical depth of 40 m in different azimuths. The downhole temperature reaches about 120° and the hole size of the original open-hole section is 165.1 mm. After 7 years of production, the measured hole diameter is 203.8 mm, and the hole enlargement rate reaches 23%.

According to the specific situation of Tahe oilfield, deep-well short-radius sidetracking technology is proposed to reduce cost and increase production in Tahe oilfield. To achieve the sidetracking success of the deep short-radius open hole, the improved 3.5° positive displacement mud motor (PDM) with cushion block is proposed. Then based on the mechanical analysis and finite element numerical simulation, its key parameters are calculated and optimized. It can realize high build-up rate and one-time sidetracking, which will provide an effective technical scheme for subsequent production and efficiency of old well.

Overview of sidetracking design

Sidetracking project

For sidetracking technology, there are two widely used construction methods: casing sidetracking and open-hole sidetracking (Zhang et al. 2015; Ma et al. 2020). During the implementation of open-hole sidetracking, different sidetracking methods can be adopted for different down-hole specific working conditions, including open-hole inclinometer sidetracking, conventional open-hole sidetracking, etc. (Sun 2016). In Tahe oilfield, the conventional open-hole sidetracking construction method with cement backfill is adopted in a sidetracking well. This method not only avoids the disadvantage of difficult control of suspended sidetracking, but also has the advantages of simpler construction, less tool adjustment, and more cost savings than the downward inclinometer sidetracking.

The selection of sidetracking points is a control work that affects the success of sidetracking. Its determination should not only consider the geological conditions and avoid the poor geological conditions, but also combine the directional drilling and completion construction after sidetracking to reduce the difficulty of subsequent construction. Furthermore, it is necessary to choose the right orientation for sidetracking in old wells, so as to reduce the workload of twist orientation in the whole drilling process and improve the drilling efficiency.

Before tripping in sidetracking drilling assembly, the pressure bearing test of cement plug should be carried out to ensure the quality of cement plug and meet the requirements of sidetracking and old well packer.

Well structure design

The sidetracking point is 5730 m, the top boundary of Yiji-anfang group is 5724.5 m, the upper casing is 193.7 mm, the casing is connected back to the wellhead, the casing diameter is 165.1 mm, and the casing shoe is 5704.78 m. The original well deviation point is 5720 m, the designed sidetracking point is 5730 m, the well deviation is 8.17° , and the designed build-up rate is 38.53° /30 m. The designed well depth is 5876.47 m (inclined)/5774 m (vertical). The well structure is shown in Fig. 1.

Technical difficulties in initial construction stage of Sidetracking

There are many construction technical difficulties in the initial stage of sidetracking, as follows:

Fig. 1 Schematic diagram of well structure design

(1) After two acid fracturing, one acidizing and three rounds of water injection in 5704–5770 m well section, the original formation structure of the well section is damaged to a certain extent, and there are risks such as low build-up rate and unstable wellbore in the initial stage of sidetracking. Optimizing PDM and deflecting tool is necessary to strengthen technical support.

(2) The sidetracking point of 5730 m has a certain deviation of 8.17°. It is an important prerequisite to ensure the success of sidetracking to observe the changes of various drilling parameters during plug sweeping.

According to the actual working conditions of Tahe oilfield and the technical difficulties, combined with the existing sidetracking technical scheme and further research, the optimal sidetracking scheme and supporting technology suitable for the specific situation of Tahe oilfield are proposed.

Improvement of deflecting tool with high build-up rate

Design basis for structural parameters of single-bend PDM

Although there are many factors that affect the build-up rate of drilling tools, the structural parameters of curved

joint PDM are dominant (Zhang et al. 2007). Given the expected build-up rate of the drilling tool, any structural parameter can be obtained according to the build-up rate relation. In this paper, the calculation methods of the structural bending angle (γ), the length of the first span (L_1) and the clearance between the lower stabilizer and the wellbore (δ) are given.

The calculation formula of structural bending angle is:

$$\gamma = \frac{L_T}{60} \cdot \frac{k - k\delta}{\lambda} \quad (1)$$

The calculation formula of the first span length is:

$$L_1 = \sqrt{b^2 + 2c} + b \quad (2)$$

in which

$$b = \lambda \frac{30\gamma}{k} - 0.5L_s + \frac{c}{L_s}, \quad c = \frac{5.4}{\pi k} \delta \quad (3)$$

The calculation formula of clearance is as follows:

$$\delta = \frac{\pi}{10.8} \left[kL_s - 60\gamma \frac{L_3}{L_T} \right] L_1 \quad (4)$$

In particular, when $\delta = 0$, there is

$$L_1 = \lambda \frac{60\gamma}{k} - L_s \quad (5)$$

where k is the geometric build-up rate of the drilling tool, $^{\circ}/30$ m; γ is the structural bending angle, $^{\circ}$; L_1 is the distance from the lower stabilizer to the bit, m; L_2 is the distance from the bending elbow to the lower stabilizer, m; L_3 is the distance from the bending elbow to the upper stabilizer, m; L_T is the total length of the drilling tool from the upper stabilizer to the bit, m; L_s is the length of drilling tool between stabilizers, m; λ is the influence factor of bending angle position, dimensionless; δ is the clearance between the lower stabilizer and the wellbore.

Design results of improved single-bend PDM

According to the design and construction requirements of a sidetracking well in Tahe oilfield, the structure of single-bend PDM is improved as shown in Fig. 2 to meet the high build-up rate of construction requirements.

According to the structural analysis of single-bend PDM, the build-up rate of single-bend PDM is mainly determined by many factors, such as the size and position of structural bending angle, the size and position of stabilizer (cushion block) and weight-on-bit (WOB) (Sun et al. 2004). The control variable method (Zhang et al. 2016) is used to analyse the influence trend of various factors on the build-up rate of single-bend PDM. The same increasing variable factors include structural

bending angle and outer diameter of lower stabilizer (cushion block); the different increasing variable factors include the distance from lower stabilizer (cushion block) to bending angle. Especially, increasing WOB can increase build-up rate without considering bottom layer factor, otherwise, it will decrease. Based on the above principle, the single-bend PDM is improved, and the improvement results of each structural parameter are shown in Table 1. According to the modified three-point circle determination method and limit curvature method (Liu et al. 2004; Su, 1997; Li et al.; Tang et al. 2000), the prediction results have high accuracy. Combined with Wang et al. (1994), the incremental expression of build-up rate caused by eccentric cushion block was derived by using energy method, which can predict the limit build-up rate of 43.89–48.45 ($^{\circ}/30$ m) of the improved 3.5° single-bend PDM

Table 1 Parameter results of improved single-bend PDM

Parameters	Value
Upper end of bend point L'_1 /m	3.04
Distance between bending point and bit L'_2 /m	1.1
Outer radius D /m	0.095
Structural bending angle γ' / $^{\circ}$	3.5
Distance of cushion block d /m	0.12
Height of cushion block δ /m	0.014
Limit build-up rate/ $(^{\circ}/30$ m)	43.89–48.45
Minimum curvature radius/m	35.5

Fig. 2 Structural diagram of single-bend PDM. **a** Original single-bend PDM. **b** Improved single-bend PDM

with considering formation factors, and the build-up rate can reach 52.67–53.29 (°/30 m) without considering formation factors. The actual build-up rate is limit build-up rate, which is less than simulated/designed value. The key lies in the influence of formation factors. Formation factors are very complex and changeable and have obvious regional characteristics. In order to simplify the calculation of numerical simulation, some assumptions are made.

Optimization of WOB

From the above factors, it can be seen that in the actual construction process, the specific influence of WOB on the 3.5° single-bend PDM build-up needs to be further studied. WOB provides the power for drilling, and appropriate WOB provides drilling speed. If the WOB is too small, the PDM cannot break the rock and the drill string cannot drill in the process of sidetracking; If the WOB is too large, it will cause the buckling of the drill string, and the friction resistance caused by the excessive buckling will increase, so that the WOB cannot be transmitted to bottom hole and the phenomenon of drag will appear. Therefore, the selection of appropriate WOB is the premise to ensure the success of sidetracking. Making WOB as the representative of drilling parameters, the appropriate value of the improved PDM is optimized by the numerical simulation method.

Model simplification

In the actual sidetracking operation, there is a small azimuth change in the well trajectory, which inevitably leads to a certain spiral bending in the geometric structure of the well, distortion of the geometric standard circle in the radial section, and non-ring shape in the longitudinal section of the well. In order to simplify the calculation process, the wellbore trajectory is simplified as a thin-walled hollow cylinder structure in the two-dimensional plane. In the process of drilling tool lowering, the tool surface and the center line of wellbore trajectory are in the same plane.

The internal structure and material composition of each part of high-angle PDM are complex. If the internal structure and material properties of each part are considered, the calculation is large and the process is complex, which has little effect on the WOB of the whole drilling tool. Further, according to the outline size, each part of the drilling assembly is simplified into a three-dimensional thin-walled hollow string structure.

In addition, there are some assumptions as follows:

(a) The wellbore is regular, and the hole enlargement and wellbore roughness are neglected.

(b) The influence of cuttings blockage and bit sticking is not considered in the calculation,

(c) The influence of the fluid pressure fluctuation in the wellbore on the drill string is ignored.

Model establishment

In opening the window of sidetracking stage, the drilling assembly is as follows: 120.65mmPDC + 95mm3.5° single-bend PDM + single flow valve + 88.9 mm non-magnetic pressure bearing drill pipe + 105mm MWD sub + 88.9 mm non-standard drill pipe + 88.9 mm weighted drill pipe + 88.9 mm drill pipe + 114.3 mm drill pipe. According to the actual size and type of drill string, the three-dimensional model of the lower 20 m drill string is established as shown in Fig. 3.

With the help of ANSYS software, the numerical simulation analysis can be carried out. Firstly, according to the design trajectory parameters of a sidetracking well in Tahe oilfield as shown in Table 2, the wellbore model is established as shown in Fig. 4.

In the numerical model, the dynamic and implicit analysis step is used to simulate the tripping in of nonlinear drill string. The analysis of the contact force applies face-to-face contact, and its friction coefficient is 0.05 according to the performance of the drilling fluid in Tahe oilfield. The top surface of the drill pipe is loaded by point-surface coupling. The tripping in speed is 2 m/s. The outer side and bottom of the wellbore are set as full constraints.

Then the 3D stress element, namely C3D8R, is used to calculate the model. The wellbore and drill pipe parts in the model are divided by hex hexahedron mesh, and the cushion block part of single-bend screw is divided by TET tetrahedron mesh. The minimum unit size of wellbore is 10 mm and the maximum is 20 mm, and the minimum unit size of drill pipe is 10 mm and the maximum is 18 mm. The meshing results of wellbore and drilling string are shown in Fig. 5.

Result analysis

When 3.5° single-bend PDM is tripped in the wellbore, the variation of its lateral displacement and corresponding stress nephogram with the tripping in depth is shown in Figs. 6

Fig. 3 Establishment of drill string model

Table 2 Design trajectory parameters of a sidetracking well in Tahe oilfield

No	Well depth/m	Well deviation/°	Azimuth/°	Vertical depth/m	North	South/m	East	West/m	Apparent displacement/m	Closed azimuth/°	Closed distance/°	Wellbore curvature/° (°/30 m)
1	5730.00	8.17	215.15	5729.56	-31.52		10.51		32.52	161.56	32.21	0.00
2	5736.88	9.00	176.39	5736.36	-32.45		10.26		33.42	162.46	34.03	25.00
3	5740.00	13.01	176.39	5739.43	-33.04		10.30		34.01	162.69	34.61	38.53
4	5750.00	25.85	176.39	5748.84	-36.35		10.50		37.33	163.88	37.84	38.53
5	5760.00	38.70	176.39	5757.27	-41.67		10.84		42.65	165.42	43.06	38.53
6	5770.00	51.54	176.39	5764.32	-48.73		11.29		49.71	166.96	50.02	38.53
7	5780.00	64.38	176.39	5769.61	-57.17		11.82		58.16	168.32	58.38	38.53
8	5790.00	77.23	176.39	5772.89	-66.58		12.41		67.57	169.44	67.72	38.53

and 7. According to Figs. 6 and 7, with the increase in tripping in depth, the whole drilling assembly is bending continuously, and the bending stress also increases. With the increase in WOB and tripping in depth, there is the risk of backing pressure.

When the WOB is 20kN, driving the whole drilling tool into the hole, the stress distribution of drilling assembly is shown in Fig. 8, and the stress distribution of 3.5° single-bend PDM is also enlarged. It can be seen from the calculation results that under the WOB of 20kN, the support reaction force between drill string and wellbore is small. From the initial stage of drill string running to the stable deviation section, the stress fluctuation of string is relatively stable and the value is small. Part of the force mainly exists in the contact part between the bending part and the wellbore, which is also the main force that causes the bending and inclination of the drill string due to the support reaction force. The tripping in speed of the drill string is always stable and slow, but it will not lead to the sticking, that is, the drill string can trip in smoothly.

When the WOB is increased to 30kN, the stress distribution of drilling assembly is shown in Fig. 9. At this time, the support reaction force between the drill string and the wellbore increases, the initial tripping in speed is faster, and the stress on the drill string increases faster. The later tripping in speed of the drill string decreases significantly, and the drill string can still trip in, but it is less than the tripping in speed under the low WOB condition of 20kN. It is now difficult for the drill string to trip in, and the stress on the drill string rises sharply, reaching the initial value of instability. The stress nephogram of drilling assembly shows that the drill string has undergone large plastic deformation and occurs buckling, the transmission of WOB is limited, and the drill string is in a disadvantageous state at the beginning of tripping in.

Based on the above numerical simulation results, the drill string can be tripping in under the WOB of 20kN–30kN. If the WOB is higher than 30kN, the risk of buckling will occur when the drill string is tripping in, which may cause problems such as difficulty in passing the drill string.

Sidetracking field application

This sidetracking well is formally drilled from 5728 m, the sidetracking tool face is 20–30° smaller than the target azimuth (the original wellbore azimuth is 214° and the target azimuth is 176°), the time control is 3–4 h/m, and the sliding drilling is carried out. In order to protect the sandwich wall, the times of drilling tool movement are reduced as far as possible and the drilling is stable. During the drilling, the geological sand bailing monitoring is carried out. Each 0.5 m sand bailing is evaluated once.

Fig. 4 Wellbore model **Fig. 5** Meshing results of wellbore with PDM+cushion block

The cuttings content increases rapidly, reaching 10% in the first 1 m, 60% in the third 3 m, and more than 80% in the 5732 m, which is judged that the sidetracking is successful. After successful sidetracking, if the drilling tools are not pulled out of the hole and continue drilling with the deviation increasing, the phenomenon of backing pressure may occur in the drilling process. By controlling the WOB

at 20–30kN, the possible deformation and bending of the bottom hole can be reduced, and the hole can be drilled to 5745 m smoothly. The bottom hole deviation and the change rate of full angle can be predicted, and the PDM can be replaced after pulling out. The calculation formula of overall angle change rate and curvature radius during drilling measurement (Chen et al. 2000) is as follows:

Fig. 6 Lateral displacement of 3.5° single-bend PDM

Fig. 7 Stress nephogram of 3.5° single-bend PDM

Fig. 8 Stress nephogram of drill string in tripping in process when WOB is 20kN including the partial enlarged view of 3.5° single-bend PDM

$$K_{ab} = \frac{30}{\Delta L_{ab}} \sqrt{(\alpha_a - \alpha_b)^2 + (\Phi_a - \Phi_b)^2 \sin^2 \left(\frac{\alpha_a + \alpha_b}{2} \right)} \quad (6)$$

$$R = \frac{1719}{K_{ab}} \quad (7)$$

where K_{ab} is the overall angle change rate of well deviation between measuring points A and B, °/30 m; ΔL_{ab} is the length of well section between measuring points A and B, m; α_a, α_b are the well deviation angle at measuring point A and B, °; Φ_a, Φ_b is the azimuth difference between measuring points A and B, °; R is the curvature radius between measuring points A and B, m.

In the process of this drilling survey, according to the well depth of 5728 m at the initial position, and increasing drilling deviation to the well depth of 5745 m, the well depth, well deviation, azimuth, overall angle change rate and bottom hole overall angle change rate measured at two points are shown in Table 3.

According to the calculation results, in the case of sidetracking deep short-radius open hole with high build-up rate, short directional section and low sidetracking success rate, 3.5° single-bend PDM with cushion block can be selected. The sidetracking overall angle change rate can

reach 38.19°/30 m, which can improve the sidetracking success rate.

Conclusions

1. 3.5° single-bend PDM with outer diameter of 95 mm and cushion block has high build-up rate, and its theoretical build-up rate can reach 52.67–53.29 (°/30 m). Considering formation factors, its limit build-up rate can reach 43.89–48.45 (°/30 m), and its minimum curvature radius can reach 38.20 m, which can meet the requirements of short-radius sidetracking with curvature radius of 40 m.
2. The cushion block of 3.5° single-bend PDM is located at PDM bending point, which greatly increases the deviation making capacity of the PDM. It is sensitive to WOB, so the WOB should be less than 30kN, avoiding the occurrence of backing pressure problem.
3. Combining with the short-radius sidetracking technology, using the improved 3.5° single-bend PDM with outer diameter of 95 mm and cushion block can greatly improve the efficiency of open-hole sidetracking and the success rate of.
4. The improved 3.5° single-bend PDM with cushion block has good adaptability and applicability for realizing

Fig. 9 Stress nephogram of drill string buckling in tripping in process when WOB is 30kN including the partial enlarged view of 3.5° single-bend PDM

short-radius sidetracking horizontal well in deep wells. However, in practice, the tool face should be adjusted to be consistent with the wellbore orientation in the full round trip operations. At the same time, further research is needed on the adaptability of this drill tool in the case of tripping in resistance, hole enlargement and actual geological conditions.

Ethical statements

The manuscript is submitted to only this one journal for consideration.

The submitted work is original and has not been published elsewhere in any form or language (partially or in full).

This study will not be split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time.

Results are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation (including image-based manipulation). Authors adhere to the discipline-specific rules for acquiring, selecting and processing data.

The author has not plagiarized other people's data, text or theory and has given appropriate recognition to other reference works and has made a clear citation mark in the text.

Table 3 Design trajectory parameters of a sidetracking well in Tahe oilfield

Parameters	Value	
Well depth/m	5728	5745
Well deviation $\alpha/^\circ$	6.36	28.00
Azimuth $\Phi/^\circ$	161.15	163.50
Overall angle change rate $K_{ab}/(^\circ/30\text{ m})$	38.19	
Overall angle change rate of bottom hole $K'_{ab}/(^\circ/30\text{ m})$	45.00	
Minimum curvature radius R/m	38.20	

Funding The project is supported by the Sinopec key scientific and technological projects “Research on quality increasing and speed-up drilling and completion technology for No. 5 fault zone of Shunbei District 1” (No. P20002), “Technical demonstration of extra-deep drilling and completion engineering in Tarim Basin” (No. P21081-6), and the National Natural Science Foundation of China (Grant No. 51874098).

Declarations

Conflict of interest On behalf of all the co-authors, the corresponding author states that there is no conflict of interest.

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References

- Chen S, Guo DT, Sun YL (2010) Progress Status and Development Trend Of Positive Displacement Motor. *J Yangtze Univ (nat Sci Edit)* 7(03):317–319
- Chen SC, Wang SC (2007) Slim hole sidetracking and short-radius horizontal well drilling technology. *Oil Drill Prod Technol* 29(03):11–14
- Chen TG, Guan ZC (2000) Drilling engineering theory and technology. China University of Petroleum Press, Dongying
- He L, Chen YJ (2003) The short-radius horizontal sidetracking technology in Tahe Oilfield. *Petrol Drill Techniques* 31(06):63–65
- Jiang S (2004) Trajectory controlling technology about window milling sidetracking horizontal well in slim hole. *Offshore Oil* 43(06):31–34
- Li FX (2020) Sidetracking slim hole short-radius horizontal well technologies applied in OMG723 Algeria. *Drill Prod Technol* 4(01):80–84
- Liu SY, Wang L, Mao X et al (2013) Drilling technologies of sidetracking short radius horizontal well in no. 6 block of Tahe oilfield. *Drilling & Production Technology* 36(03):21–23
- Liu XS, He SS, Zou Y (2004) Study on the geometric build angle rate of steerable motor. *Acta Petro Lei Sin* 25(06):83–87
- Lu FF, Li F, Hu GQ et al (2017) Drilling and completion technology for sidetracked slimhole in carbonate reservoir in Tahe Oilfield. *China Petrol Mach* 45(09):37–41
- Ma CJ, Wang HX, Fan XL et al (2007) Drilling technology of ultra deep slim hole and short radius sidetracking horizontal well in Tahe Oilfield – Taking TK318CH well as an example. *Petrol Geol Eng* 21(01):66–68
- Ma HY, Kong FG, Yang JS et al (2020) Sidetracking technique of slim hole in AT-6X well of ultra-deep and ultra-high temperature buried hill gas well. *Oil Drill Prod Technol* 42(02):143–149
- Su YN (1997) A method of limiting curvature and its applications. *Acta Petro Lei Sin* 18(03):112–116
- Sun ML, Zheng YB, Pan JS et al (2004) Application of steering drilling system in high angle well in henan oilfield. *Drill Prod Technol* 27(05):14–16
- Sun XB (2016) Optimizing slim-hole sidetracking assembly for extra-deep and hard formations in Yuanba 10–1H well. *Natural Gas Technology and Economy* 10(04):33–35+75
- Tang XP, Chen ZX, Wang GT et al (2000) Study on prediction methods of build -up rate of PDM with bent housing for middle -short radius horizontal well. *Drill Prod Technol* 23(03):15–20
- Wang JJ, Zhang SK, Di QF et al (1994) Prediction method of the influence of eccentric pad on the deviation making ability of explicit dynamics drill. *China Petrol Mach* 22(12):25–27
- Yang ZG, Sun QR, He JC et al (2014) Current status and development direction of the horizontal well drilling techniques in Daqing Oilfield. *Petrol Geol Oilfield Development Daqing* 33(05):226–230
- Yu FC (2009) Research and application of ultra deep sidetracking horizontal well drilling technology in Tahe Oilfield. *J Oil Gas Technol* 31(05):312–317
- Zhang H, Zhang RP, He J et al (2016) Study on build-up capacity of Positive Displacement Drill (PDD) wit single bend. *J Yangtze Univ (natural Science Edition)* 13(02):41–46
- Zhang JW, Wang GY, He K et al (2019) Practice and understanding of sidetracking horizontal drilling in old wells in Sulige Gas Field. *NW China Petroleum Exploration and Development* 46(02):384–392
- Zhang SL, Sun Q, Li T et al (2017) The low cost ultra-short radius sidetracking technology in produced wells based on flexible drill pipe. *China Petrol Mach* 45(12):18–22
- Zhang XH, Feng D (2007) Analysis on structural deflecting characters of downhole assembly for steering drilling. *J Oil Gas Technol* 29(02):138–140
- Zhang XM (2015) Study and application of short radius horizontal well drilling technologies. *J Yangtze Univ (natural Science Edition)* 12(11):47–51

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