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The Development and Application of Novel Water-Based Drilling Fluid for Complex Pressure System Formation in the South China Sea

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Abstract: The Y oilfield reservoir is characterized by ultra-depleted reservoir and multiple pressure systems in each well section. If conventional PLUS/KCL drilling fluid is used in directional drilling, the following problems are found: the rheological stability of drilling fluid is not sufficient, resulting in increased viscosity and thickening after aging, and the single plugging material may cause loss-circulation when the drilling differential pressure is more than 26 MPa, resulting in poor reservoir protection effects. To solve the above problems, based on the conventional PLUS/KCL drilling fluid formula, a PLUS/KCL drilling fluid system suitable for directional drilling in multi-pressure systems was formed by optimizing the addition of a treating agent to improve the rheological stability of the drilling fluid, optimizing the plugging agent and compound combination to improve plugging ability, and optimizing the particle size distribution of a temporary plugging agent to improve the reservoir protection effect. The laboratory test evaluation showed that the optimized PLUS/KCL drilling fluid had fine plugging pressure capacity, and the intrusion depth was only 4.1 cm on the natural core at 120 °C/35 MPa/12 h, effectively reducing the risk of loss-circulation. The permeability recovery rate of the core after cutting off the polluted end was more than 90%, indicating that the reservoir protection effect was good. The drilling fluid performance was stable, and the cuttings rolling recovery rate was over 90%. Field application showed that the optimized PLUS/KCL drilling fluid was used without any loss-circulation or wellbore instability, and the production of all wells was over-matched, effectively solving the problem of ensuring drilling safety and reducing reservoir damage under the differential pressure of multiple pressure systems.

Keywords: complex pressure system; water-based drilling fluid; loss-circulation; reservoir protection; pressure bearing capacity

1. Introduction

For various reasons, the Y oilfield reservoir is characterized by ultra-depleted reservoir and multiple pressure systems existing in each well interval. It is estimated that the formation pressure coefficient is 0.67–1.33, and the maximum drilling differential pressure can reach 35 MPa. Therefore, safe drilling and reservoir protection face great challenges [1,2]. Conventional PLUS/KCL drilling fluid was used in the five directional wells in the early stage of the field. Two of the directional wells were drilled into the normal pressure reservoir, and the operation process was smooth. The other three directional wells all encountered the multi-pressure system reservoir, the drilling differential pressure reached 26 MPa, the reservoir protection effect was poor, and the production after perforation was lower than the production allocation. Furthermore, the conventional PLUS/KCL drilling fluid system became viscous after aging in all five directional wells, resulting in a high density of equivalent circulating drilling fluid at the bottom hole and a high risk of loss-circulation. In view of the above problems, domestic and foreign scholars have carried out relevant research. Some domestic scholars have improved the temporary plugging

technology of protective reservoirs [3–5], especially in terms of material type, particle size distribution, and proportion optimization of temporary plugging agents [6–9], which strengthened the temporary plugging performance of the system, improved the bearing capacity, and successfully solved the problem of easy loss-circulation of low-pressure reservoir. Domestic scholars chose the plugging agent and its compound combination that matched the formation of the reservoir segment to achieve a good plugging effect, form a high-quality filter cake around the shaft wall, improve the pressure bearing capacity of the formation, and reduce the risk of loss-circulation [10–16]. Many foreign drilling fluid companies have developed high-performance water-based drilling fluids that can replace the oil base, such as the ULTRADRIL system of the M-I company, the DYDRO-GUADR system of HALI-BUR-TON [17,18], and the BAKER HUGHES's PERFORMAX system [19,20]. Foreign studies on high temperature-resistant drilling fluids mainly include formate-free solid phase-resistant drilling fluids [21], bentonite-free high temperature-resistant drilling fluids [22], and high temperature-resistant silicate drilling fluids [23]. Nanotechnology has been applied to drilling fluid abroad [24,25]. The above research provides a reference for solving the drilling fluid optimization problem of multiple pressure systems. However, the drilling fluid optimization problem of the Y oilfield cannot simply copy the previous experience. Solutions should be found according to the reservoir characteristics of the Y oilfield, such as porosity, permeability, mineral composition, and content, while taking into account the economic benefits. The above research provides a reference for solving the drilling fluid optimization problem of multiple pressure systems.

2. PLUS/KCL Drilling Fluid Formula Matching Test

Y oilfield reservoir mainly includes deltaic deposits with strong heterogeneity of pore structure and inter-layers. The average porosity of the main oil group ranges from 14.3% to 18.8%, and the average permeability ranges from 7.6 to 78.3 mD. It is categorized as a medium-low porosity and low permeability reservoir, requiring a wide range distribution of temporary blocking agent particle sizes to effectively protect the reservoir [6,7]. Through quantitative analysis of the total amount of clay minerals and common non-clay minerals in the reservoir, it can be seen that the content of clay minerals in the shale is about 40%, the content of illite/smectite formation is about 20%, and the content of kaolinite is about 15%, which has certain expansion properties and enhances the inhibition of the drilling fluid system. Furthermore, in response to the problems of the existing PLUS/KCL drilling fluid in the Y oilfield, namely, that it cannot meet the safety requirements of boreholes under significant differential pressure, poor reservoir protection effects, and viscosity increases and thickening after aging, the plugging pressure-bearing performance is improved by optimizing the compounding combination of plugging agent. Furthermore, the rheological stability is improved by optimizing treating agent addition, and the reservoir protection performance of drilling fluid is improved by optimizing the particle size distribution of temporary plugging agent so that it can meet drilling requirement.

2.1. Matching Test of Particle Size Distribution of Temporary Plugging Agent

The success of temporary plugging technology for reservoir protection relies on the rapid development of a tight filter cake on the borehole to prevent filtrate and the solid phase in the drilling fluid from penetrating into the reservoir under high differential pressure and to easily remove the filter cake before production [3–5]. Therefore, this research sought to optimize the particle size distribution of the temporary plugging agent according to the D90 rule, that is, when the d_{90} value of the cumulative distribution curve of the particle size of the temporary plugging agent is equal to the maximum pore throat diameter of the reservoir section, an ideal temporary plugging effect can be obtained [8,9].

- (1) Select a core from the Y oilfield and cut it into thin sections; then analyze the particle size distribution of the pore throat to obtain the maximum pore throat diameter—108.36 μm of the reservoir;

- (2) Select ultra-fine calcium carbonate with high acid solubility, good compatibility with the reservoir, wide distribution, and a low price as the temporary plugging agent;
- (3) According to maximum pore throat diameter of the reservoir, apply the reservoir damage assessment and protection technology system of a complex structure well to optimize the particle size distribution of ultra-fine calcium carbonate. The mass ratio of the selected 800 mesh and 400 mesh calcium carbonate was 3.35:1.

2.2. Matching Test of Plugging Agent Combination

Plugging agents and compound combinations that matched the reservoir section formation in the Y oilfield that could yield good plugging effects and a high-quality filter cake around the borehole were selected. Therefore, the formation pressure-bearing capacity could be improved, and thus the risk of loss-circulation could be reduced [10–16]. Plugging agents PF-QWY (calcium carbonate), PF-GBL (white asphalt), PF-LSF (resin), PF-LPF H (film-forming agent), PF-DYFT (sulfonated asphalt), and PF-ZP (filtration loss agent) were commonly used plugging agents in the Y oilfield, with high acid solubility, good compatibility with the formation, and good economical and applicable features. Especially with plugging agents PF-QWY (calcium carbonate) and PF-GBL (white asphalt), the acid solubility rate could go up to 90% or more directly as a basic pressure-bearing material. For acid solubility, a rate of less than 40% of PF-ZP (zero filtration loss agent) would not be considered. Therefore, it was decided to add PF-LSF (resin), PF-LPF H (film-forming agent), and PF-DYFT (sulfonated asphalt) to the base formulation after compounding—2% seawater bentonite slurry + 0.25% Na₂CO₃ (sodium carbonate) + 0.2% NaOH (sodium hydroxide) + 0.6% PF-PAC-LV (filtration loss reducer) + 3% PF-GJC (polymeric alcohol) + 0.4% PF-PLUS (coating agent) + 0.15% PF-XC (viscosifier) + 2% PF-GBL (white bitumen) + 5% KCl + 3.5% PF-QWY (calcium carbonate, 800 mesh and 400 mesh calcium carbonate in a mass ratio of 3.35:1) + barite, to determine the rheological properties, filtration loss, and plugging properties of drilling fluids under different compounding combinations (Table 1) and pressure-bearing properties (Table 2) to determine the optimal combination of plugging agents.

Table 1. Rheological properties, filtration loss, and depth of sand bed intrusion of drilling fluids under different combination of plugging agents.

Plugging Agent	Status	AV (mPa·s)	PV (mPa·s)	YP (Pa)	Φ_6/Φ_3	API Filtration/mL	HTHP Filtration (mL)	Sand Bed Intrusion Depth (cm)
Before matching test	BH	45.5	29	16.5	8/6	3.2	7.0	
PLUS/KCl	AH	77	50	27	14/10	2.6	6.2	3.3
1.5% PF-DYFT +	BH	57	34	23	9/6	4.2	8.0	
1.5% PF-LSF	AH	86	52	34	15/12	3.8	7.4	4.0
1.5% PF-DYFT +	BH	53	32	21	8.5/6	3.6	7.2	
1.5% PF-LPF-H	AH	84	51	33	15/11	3.1	6.5	3.5
1.5% PF-LSF + 1.5%	BH	46	30	16	7.5/5.5	3.0	6.8	
PF-LPF-H	AH	77	50	27	14/10	2.5	6.0	3.0

Remarks: ① The experimental conditions were aging at 120 °C for 16 h, rheological properties before and after aging were measured at 50 °C, and HTHP filtration loss was measured at 120 °C. ② The sand particle size of the sand filling pipe experiment was 40–60 mesh, under room temperature and 0.7 MPa. ③ AV—apparent viscosity, PV—plastic viscosity, YP—yield point, HTHP—high temperature and high pressure. Status: BH—before hot-rolling, AH—after hot rolling.

The experiment results from Tables 2 and 3 showed that each combination of plugging agents had a small amount of filtration, a thin filter cake, and a shallow drilling fluid intrusion depth into the core. The optimal combination of blocking agent was 1.5% PF-LSF (asphalt resin anti-caving agent) + 1.5% PF-LPF-H (hydroxyl film-forming agent). Therefore, the PLUS/KCL drilling fluid system was initially determined as follows: 2% seawater bentonite slurry + 0.25% Na₂CO₃ (sodium carbonate) + 0.2% NaOH (sodium hydroxide) + 0.6% PF-PAC-LV (filtration loss reducer) + 3% PF-GJC (polymeric alcohol) + 0.4% PF-PLUS (coating agent) + 0.15% PF-XC (viscosifier) + 2% PF-GBL (white asphalt) + 5% KCl (potassium chloride) + 3.5% PF-QWY (calcium carbonate, 800 mesh and 400 mesh

calcium carbonate in a mass ratio of 3.35:1) + 1.5% PF-LSF (asphalt resin anti-caving agent) + 1.5% PF-LPF-H (hydroxyl film-forming agent) + barite.

Table 2. Pressure-bearing capacity of drilling fluids under different combinations of plugging agents.

Type of Base Slurry		1.5% PF-DYFT + 1.5% PF-LSF	1.5% PF-DYFT + 1.5% PF-LPF-H	1.5% PF-LSF + 1.5% PF-LPF-H
Core Number		Core G138	Core G135	Core G137
Pressure (MPa)	Pressure Time (h)	Filtration Loss (mL)		
5	0.5	3.8	3.0	2.6
10	0.5	4.2	4.2	3.8
15	0.5	5.0	4.6	4.4
20	0.5	5.8	5.6	5.0
25	12.0	12.4	9.2	9.0
Filter Cake (mm)		5.0	3.5	3.0
Intrusion Depth of Drilling Fluid (cm)		5.6	4.5	3.8

Table 3. Parameters of test core.

Core Parameters			
Core Number	Core G138	Core G135	Core G137
Length (cm)	7.70	6.80	6.90
Diameter (cm)	2.50	2.50	2.49
Gas Permeability ($10^{-3} \mu\text{m}^2$)	70	72	78

2.3. Treating Agent Matching Test

The results summarized in Table 1 showed that the viscosity of all the composite systems and the PLUS/KCl system before the matching test increased after hot rolling, indicating that temperature resistance performance needs to be optimized. Therefore, it was decided to improve the rheological properties of the system by optimizing the addition of treating agents PF-PAC-LV (filtration loss reducer), PF-PLUS (coating agent), and PF-XC (viscosifier) [26]. The test results are shown in Table 4.

Table 4. Effect of dosage variation of treatment agent on rheology.

Formula Number	Experiment Scheme	Status	AV (mPa·s)	PV (mPa·s)	YP/Pa	Φ_6/Φ_3	API Filtration Loss (mL)
1	0.6% PF-PAC-LV + 0.4% PF-PLUS + 0.15% PF-XC	BH	46.0	30	16.0	7.5/5.5	3.0
		AH	77.0	50	27.0	14/10	2.5
2	0.6% PF-PAC-LV + 0.3% PF-PLUS + 0.15% PF-XC	BH	32.0	24.5	7.5	5/3	3.5
		AH	45.0	33	12.0	6/4	3.0
3	0.6% PF-PAC-LV + 0.3% PF-PLUS + 0.10% PF-XC	BH	37.5	26	11.5	5/4	3.0
		AH	67.5	44	23.5	10/7	2.5
4	0.3% PF-PAC-LV + 0.3% PF-PLUS + 0.10% PF-XC	BH	38.0	27	11.0	6/4	3.4
		AH	45.0	30	15.0	7/4	3.0

Remarks: ① The experiment conditions were aging at 120 °C for 16 h, and the rheological properties before and after aging were measured at 50 °C. ② AV—apparent viscosity, PV—plastic viscosity, YP—yield point. Status: BH—before hot-rolling, AH—after hot rolling.

The experimental results showed that the drilling fluid of Formulation 4 was stable before and after aging, with good temperature resistance, and the addition of treating agents PF-PAC-LV (filtration loss reducer), PF-PLUS (coating agent), and PF-XC (viscosifier) were reduced to some extent, thus reducing drilling fluid cost. Therefore, the PLUS/KCL drilling fluid system after the matching test was 2% seawater bentonite slurry + 0.25% Na_2CO_3 (sodium bicarbonate) + 0.2% NaOH (sodium hydroxide) + 0.3% PF-PAC-LV (filtration loss reducer) + 3% PF-GJC (polymeric alcohol) + 0.3% PF-PLUS (coating agent) + 0.10% PF-XC (viscosifier) + 2% PF-GBL (white asphalt) + 5% KCl + 1.5% PF-LSF (asphalt resin anti-caving agent) + 1.5% PF-LPF-H (hydroxyl film-forming agent) + 3.5% PF-QWY (calcium carbonate) + barite. The calcium carbonate used was compounded by 800 mesh and 400 mesh calcium carbonate in a mass ratio of 3.35:1.

3. Performance Evaluation

3.1. Inhibition

A shale cuttings recovery experiment was used to evaluate the inhibition of drilling fluid. The cuttings from different depths of wells A1, A2, A3, and A4 in the Y oilfield were selected for rolling recovery experiments, and the results are shown in Table 5. The experiment results showed that the rolling recovery rates of cuttings from different depths in PLUS/KCL drilling fluid (before and after matching test) were above 90%, indicating that PLUS/KCL drilling fluid had better inhibition before and after the matching test, and the reduction of PF-PAC-LV, PF PLUS, and PF-XC dosages had little effects on the inhibition performance, which met the operational requirement of strong inhibition of shale hydration dispersion.

Table 5. Experiment results of rolling recovery of optimized PLUS/KCL drilling fluid.

Well Name	Cuttings Well Depth (m)	Status	Recovery Rate (%)
A1	2512	Before matching test	93.49
		After matching test	91.21
A2	2656	Before matching test	95.54
		After matching test	92.29
A3	3175	Before matching test	94.42
		After matching test	91.25
A4	3266	Before matching test	91.36
		After matching test	90.95

3.2. Temperature Resistance

The performance of optimized PLUS/KCL drilling fluid after aging was tested at 120 °C/16 h and 130 °C/16 h. The experiment results are shown in Table 6. The experimental results showed that the optimized PLUS/KCL drilling fluid at 120/130 °C maintained viscosity, shear force, and API&HTHP filtration loss at stable conditions, indicating that the optimized PLUS/KCL drilling fluid had good temperature resistance.

Table 6. Effect of aging temperature on rheological properties of the system.

Aging Temperature (°C)	Status	AV (mPa·s)	PV (mPa·s)	YP/Pa	Φ_6/Φ_3	API Filtration Loss (mL)	HTHP Filtration Loss (mL)
120	BH	42	30	12	7/6.5	2.0	5.2
	AH	47	33	14	8/7	2.0	
130	BH	44.5	30.5	14	8.5/6	2.6	5.5
	AH	46	31	15	6/4	2.4	

Remarks: ① AV—apparent viscosity, PV—plastic viscosity, YP—yield point, HTHP—high temperature and high pressure. Status: BH—before hot-rolling, AH—after hot rolling.

3.3. Contamination Resistance

The Y oilfield drilling operation required drilling fluid to be resistant to calcium, bentonite, and sodium chloride, so the contamination resistance of optimized PLUS/KCL drilling fluid was tested and evaluated.

(1) Anti-calcium contamination performance

The rheology and filtration loss changes of the optimized PLUS/KCL drilling fluid after the addition of different amounts of calcium chloride into the fluid were evaluated. The results are shown in Table 7. The experiment results showed that when the optimized PLUS/KCL drilling fluid was contaminated by calcium chloride, the apparent viscosity of the system decreased, and the API filtration loss increased. When the calcium chloride content reached 1.5%, the apparent viscosity of the system decreased slowly, and the dynamic shear force could still reach 8 Pa, but API filtration loss did not change much. This indicated that the optimized PLUS/KCL drilling fluid had a certain ability to resist calcium contamination.

Table 7. Optimized PLUS/KCL drilling fluid anti-calcium contamination performance.

Calcium Chloride Addition (%)	Status	AV (mPa·s)	PV (mPa·s)	YP/Pa	Φ_6/Φ_3	API Filtration Loss (mL)
0	BH	42.0	30	12.0	7/6.5	2.0
	AH	47.0	33	14.0	8/7	
0.5	BH	41.0	26	15.0	11/9	2.8
	AH	42.5	39	8.5	5/4	
1.0	BH	39.0	24	15.0	13/10	3.8
	AH	34.0	24	10.0	5/4	
1.5	BH	37.0	23	14.0	14/12	4.0
	AH	30.0	22	8.0	5/3	

Remarks: ① AV—apparent viscosity, PV—plastic viscosity, YP—yield point. Status: BH—before hot-rolling, AH—after hot rolling.

(2) Anti-bentonite contamination performance

The rheology and filtration loss of optimized PLUS/KCL drilling fluid after being contaminated by bentonite at room temperature and pressure were tested. The results are shown in Table 8. The experiment results showed that when the optimized PLUS/KCL drilling fluid was contaminated by bentonite, the apparent viscosity of the system increased, and the API filtration loss of the system decreased, but the variation was not significant, which met drilling requirements, indicating that the optimized PLUS/KCL drilling fluid had a certain ability to resist bentonite contamination.

Table 8. Optimized PLUS/KCL drilling fluid anti-bentonite contamination performance.

Bentonite Addition (%)	Status	AV (mPa·s)	PV (mPa·s)	YP/Pa	Φ_6/Φ_3	API Filtration Loss (mL)
0	BH	42	30	12	7/6.5	2.0
	AH	47	33	14	8/7	
5	BH	40	28	12	10/9	3.2
	AH	46	30	16	6/4	
10	BH	41	28	13	11/10	3.0
	AH	51.5	36	15.5	7/5	
15	BH	45	29	16	13/11	2.8
	AH	52	37	15	7/5	

Remarks: ① AV—apparent viscosity, PV—plastic viscosity, YP—yield point. Status: BH—before hot-rolling, AH—after hot rolling.

(3) Anti-sodium chloride contamination performance

The rheology and filtration loss values of the optimized PLUS/KCL drilling fluid after being contaminated by sodium chloride were tested. The results are shown in Table 9. The experiment results showed that when the optimized PLUS/KCL drilling fluid was contaminated with sodium chloride, the apparent viscosity of the system decreased, and the API filtration loss increased. When the sodium chloride addition reached 15%, the plastic viscosity and yield point of the system both decreased to a certain extent, but the range of variation was not significant, which met the drilling requirements, indicating that the optimized PLUS/KCL drilling fluid had a fair ability to resist sodium chloride contamination.

Table 9. Evaluation of optimized PLUS/KCL drilling fluid anti-sodium chloride contamination performance.

Sodium Chloride Addition (%)	Status	AV (mPa·s)	PV (mPa·s)	YP/Pa	Φ_6/Φ_3	API Filtration Loss (mL)
0	BH	42.0	30	12.0	7.0/6.5	2.0
	AH	47.0	33	14.0	8.0/7.0	
5	BH	36.0	23	13.0	8.5/7.0	3.3
	AH	37.0	28	9.0	5.0/3.0	
10	BH	37.5	24	13.5	9.0/7.5	3.4
	AH	35.0	27	8.0	4.0/3.0	
15	BH	37.5	24	13.5	9.0/7.5	3.8
	AH	36.5	28	8.5	3.0/2.0	

Remarks: ① AV—apparent viscosity, PV—plastic viscosity, YP—yield point. Status: BH—before hot-rolling, AH—after hot rolling.

3.4. Reservoir Protection Performance

A shale core from well A5 in the Y oilfield at a vertical depth of 3350 m was selected to evaluate the reservoir protection performance of PLUS/KCL drilling fluid (before and after matching test) by using the ZDY50-180 core dynamic contamination apparatus with reference to the oil and gas industry standard SY/T6540-2002 [27,28]. Firstly, the oil phase permeability of the core with saturated formation water was tested, and then PLUS/KCL drilling fluid was used to contaminate the core for 2 h at 120 °C and 3.5 MPa. After the core was contaminated by the high differential pressure, the permeability recovery value was tested by cutting off the contaminated end by 0.5 cm to simulate perforation. The results are shown in Table 10. The experiment results showed that the core permeability recovery value of PLUS/KCL drilling fluid before the matching test was below 80%, and the reservoir damage was great. The core permeability recovery rate of the optimized PLUS/KCL drilling fluid was above 90%, and the reservoir protection performance was greatly improved to meet the requirements of reservoir protection.

Table 10. Results of core contamination experiments before and after the PLUS/KCL drilling fluid matching test.

Core Number	Drilling Fluid	Gas Permeability (mD)	Oil Phase Original Permeability (mD)		Permeability Recovery Rate after Cut of Contaminated End (%)
			Before Contamination	After Cut of Contaminated End	
30	Before matching test	44.77	29.85	22.77	76.28
34		53.45	29.82	22.16	74.31
17	After matching test	62.58	31.29	28.52	91.14
15		67.23	42.02	38.08	90.62

3.5. Pressure Sealing Performance

A core with gas permeability of 64.87 mD was selected, and a JLX-2 dynamic plugging tester was used to evaluate the plugging capacity of the optimized PLUS/KCL drilling fluid [29]. At 120 °C, 26 MPa and 35 MPa for 12 h, the optimized PLUS/KCL drilling fluid formed filter cake with thicknesses of 2.0 mm and 3.5 mm on the core, invasion core depths were 2.5 cm and 4.2 cm, and filtration losses were 8.5 mL and 9.6 mL, respectively. The results showed that the optimized PLUS/KCL drilling fluid had a strong plugging capacity and could meet the requirements of directional drilling in the same reservoir with multiple pressure systems.

4. Field Application

The Y oilfield adopted optimized PLUS/KCL drilling fluid for directional drilling on four multi-pressure system intervals. There were three wells in this oilfield when the conventional PLUS/KCL drilling fluid was applied before the matching test to the reservoir section of the multi-pressure system. The drilling fluid density that maintains the stability of wellbore was high, and the maximum drilling differential pressure during the drilling process was 26–28 MPa. They were caused by insufficient plugging capacity, and the loss-circulation rate was about 5–15 m³/h, and the actual drilling period was 2–3 d longer than the designed drilling period. Moreover, the particle size of the previous PLUS/KCL drilling fluid temporary plugging agent was not suitable for the reservoir in this oilfield, and the reservoir protection effect was poor, with the skin factor usually reaching more than 15.0. The novel PLUS/KCL drilling fluid optimized the plugging agent combination, enhanced the plugging capacity, optimized the treatment agent addition, improved rheological stability, and ensured stable bottom hole ECD, and no loss-circulation occurred when drilling depleted reservoir. After optimizing the particle size distribution of the temporary plugging agent, the reservoir protection performance was promising. The skin factor of the four wells was −2.0–1.0, and the actual production of all wells exceeded the production distribution. The application of the optimized PLUS/KCL drilling fluid was illustrated by taking Well S of the Y oilfield as an example.

Well S in the Y oilfield was drilled into the reservoir section by using a $\phi 215.9$ mm bit with a maximum well inclination of 58° and an expected bottom pressure coefficient of 0.67–1.33. The optimized PLUS/KCL drilling fluid was used for the operation, and the following maintenance treatment measures were taken to ensure that the performance of the drilling fluid met the requirements of directional drilling in reservoir with multiple pressure systems:

- (1) The drilling fluid density was strictly controlled, and the spud density was 1.26 g/cm^3 . According to the actual conditions of drilling and shaker return, the drilling fluid density was adjusted to 1.30 g/cm^3 when reaching TD and 1.34 g/cm^3 before tripping to ensure wellbore safety during operation.
- (2) During the operation, the concentration of plugging agent in each operation stage was strictly controlled. Before entering the reservoir section, the concentration of PF-LSF (asphalt resin anti-caving agent), PF-GBL (white asphalt), PF-LPF (hydroxyl film forming agent), and PF-QWY (calcium carbonate) were controlled to 40 kg/m^3 , 30 kg/m^3 , 10 kg/m^3 , and 40 kg/m^3 , respectively. After entering the reservoir section, the concentration of each plugging agent was adjusted in time, and the concentrations of PF-LSF (asphalt resin anti-caving agent), PF-GBL (white asphalt), PF-LPF (hydroxyl film forming agent), and PF-QWY (calcium carbonate) were controlled to 40 kg/m^3 , 30 kg/m^3 , 10 kg/m^3 , and 60 kg/m^3 , respectively.
- (3) Lubricants (PF-GRA, PF-LUBE) were added in time according to the field requirements to improve the quality of the filter cake and ensure that the HTHP filtration loss was under control within 4.5–6.0 mL and the API filtration loss was 2.0–2.5 mL. Therefore, filtration into the formation could be minimized in order to protect the reservoir.
- (4) An API 170 mesh/200 mesh screen was used with the shaker, and 1–2 centrifuges were run according to the situation, using solid control equipment to remove the solid phase in order to achieve the purpose of protecting the reservoir.
- (5) Appropriate drilling parameters (pump rate: 2100–500 L/min, rpm: 120–140 r/min) were used to ensure hole cleaning. At the same time, operations were conducted carefully in order to reduce downhole pressure spikes and ensure that the bottom-hole ECD remained stable to prevent downhole loss-circulation.

Six formation pressure systems were encountered in Well S with formation coefficients 0.43, 0.5, 0.63, 0.71, 1.03, and 1.16, respectively. There were no downhole problems such as loss-circulation in the depleted reservoir and well control problems in the high-pressure zone. The skin factor was -1.0 , and the actual production was 150% more than expected. The reservoir protection effect was good, indicating that the plugging performance and reservoir protection performance of the novel PLUS/KCL drilling fluid was significantly improved, which met the requirements of directional drilling in the reservoir section of the multi-pressure system.

5. Conclusions

- (1) The PLUS/KCL drilling fluid formulation was improved by optimizing the combination of plugging agent, the addition of treating agent, and the particle size distribution of the temporary plugging agent. The results of the laboratory evaluation showed that novel PLUS/KCL drilling fluid had fine pressure bearing capacity and sealing for its invasion depth into natural core, which was only 4.2 cm at $120^\circ\text{C}/35 \text{ MPa}$ for 12 h, indicating it could significantly reduce downhole loss-circulation. The laboratory performance evaluation results showed that the inhibition and temperature resistance of the optimized PLUS/KCL drilling fluid met the requirements for directional drilling of multi-pressure system reservoirs in the Y oilfield.
- (2) A field application showed that the optimized PLUS/KCL drilling fluid could solve the problems of aging and thickening, downhole loss-circulation of depleted reservoir, and serious reservoir contamination under a high differential pressure under directional drilling of a multi-pressure system in the Y oilfield.

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