Application of high-performance water-based drilling fluid system in Mahu oilfield

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Abstract. The Baikouquan Formation in Block 18 of Mahu Oilfield, Xinjiang, is easily hydrated with mud shale; it exhibits poor cementation speed, low mechanical drilling speed, and high accident and complexity rates during drilling. The existing water-based drilling fluids show poor inhibitory properties, insufficient lubrication and anti-seize, and insufficient plugging ability for pores and micro-fractures, so it cannot easily satisfy construction requirements. In the present study, a strong inhibitor YZFS-1 and a wall-fixing agent GBFS-1 are introduced based on the existing water-based drilling fluid system to build a set of high-performance water-based drilling fluid system that has successful applications in a well. As revealed from the results of its field application: XZ high-efficiency water-based drilling fluid system exhibits stable rheology, low filtration loss, robust suppression ability and regular well diameter, and without the presence of downhole complex accidents. As compared with adjacent wells, the system of this study exhibits high drilling speed, a short cycle, low cost and significant effects, providing a solid technical guarantee for safe and efficient development in the area.

Key words: drilling fluid; high-performance; inhibitor; polymer; wall-fixing agent

1. Introduction

Over the past few years, the number of deep wells and ultra-deep wells drilled by Xinjiang Oilfield Company has showed a year-on-year growth. Xinjiang Mahu oilfield is located in the belly of Xinjiang Junggar Basin. Such well area often suffers from severe jamming for deep reservoir burial, significant formation pressure variations and complex lithology. For downhole complex conditions (e.g., malignant leakage and overflow wells), low drilling speeds and high accident and complex time rates were caused [1-4].

Deep oil and gas wells are becoming increasingly applied in the industry to cover the high demand for energy around the globe. Given cost, environmental protection and other factors comprehensively, the oil-based drilling fluid has been unable to satisfy the requirements of the current large-scale development of tight reservoirs [5, 6]. A water-based drilling fluid capable of satisfying the construction requirements of the long horizontal section of MaHu Oilfield is required. High-performance water-based
drilling fluid refers to a novel type of drilling fluid system adopting amine-based inhibitor as the main treatment agent; it can achieve strong inhibition.

Over the years, rigorous studies have been conducted to enhance the properties of the water-based drilling fluids. A range of additives have been developed, including polymers adopted to enhance drilling mud rheology, bentonite employed to promote hole cleaning capacity of the mud, and bridging agents used to control formation damage, etc. [7-9]. Eny Kusrini synthesised Graphene oxide (GO) and phosphorylated graphene oxide (PGO) from graphite electrode waste (GrW) or spent pot lining (SPL) from industrial aluminium wastes [10]. Using GO as additive in water-based drilling fluids achieved better rheology properties, an enhancement in fluid loss control performance, as well as an increase in lubricity ability [11]. Qi Chu introduced a series of amidocyanogen silanols (HASes) modified by methacryloxy propyl trimethoxyl silane (MPS) with polyethylene polyamine as potential shale inhibitors; accordingly, the development and application of high-temperature resistant shale inhibitors were facilitated in water-based drilling fluids. Badr S. Bageri delved into the potentials of perlite as a filtration control agent under high pressure [12]. A. H. M. Muhayyidin explored rheological and filtration performances of water-based drilling fluid (WBDF) using tannin as deflocculant and fluid loss additive at high pressure and high temperature [13]. To enhance the higher temperature resistance of water-based drilling fluid system, Jin-hua Huo synthesised a type of polymer Poly (SSS/AM/AMPS) with 2-acrylamido-2-methylpropanesulfonic acid (AMPS), acrylamide (AM) and sodium p-styrenesulfonate (SSS) by inverse emulsion polymerization. However, the existing water-based drilling fluids are poorly inhibited; they exhibit poor anti-seize ability, and their capacity to block pores and micro-fractures cannot effectively satisfy construction requirements, which has become a factor limiting the economic development of deep oil and gas in the region [14, 15].

Based on the existing water-based drilling fluid, a strong inhibitor YZFS-1 and a wall-fixing agent GBFS-1 were introduced in this study to develop a novel technology, namely, high-performance water-based drilling fluid. The strong inhibitor YZFS-1 refers to a small-molecule organic substance, which can be embedded in the layers of clay; besides, the molecules and the clay surface form strong hydrogen bonds significantly higher than the ordinary hydrogen bond strength, so YZFS-1 can be firmly adsorbed on the inner surface of the clay and clamp the phase. Adjacent to the two layers, this wall-fixing agent acts as a micro-reinforcement, and it is capable of inhibiting the hydration and dispersion of the clay. Wall-fixing agent GBFS-1 refers to a high-molecular polymer, adopted to spontaneously solidify on the surface of the rock near the wall during drilling to form a relatively dense, water-resistant shell, blocking and strengthening micro-fractures. High performance water-based drilling fluid system can maintain the stability of the borehole wall using “shale suppression”, “loss reduction” and “reinforcement”, while expanding the safety density window, reducing or avoiding reservoir damage, and solving Friction. This high-performance water-based drilling fluid has been successfully applied in 9 wells in the 18 well block of Mahu Oilfield. It can remedy several defects (e.g., poor water-based drilling fluid inhibition, insufficient lubrication and anti-seize capabilities, and insufficient pores and micro-fracture plugging capabilities). The downhole complexity significantly declines, and significant economic benefits have been achieved.

2. Materials and methods

2.1. Mechanism of the strong inhibitor YZFS-1

X-ray diffraction analysis of bentonite adsorbed with YZFS-1 (Figure 1), and its inhibition mechanism was studied. Experimental conditions: working voltage 40kV, working current 40mA, continuous scanning mode, step size 0.02, scanning rate 0.5° / s.

As shown in Figure 1, the bentonite without YZFS-1 adsorption achieved the interlayer spacing (d_{space}) of 1.17 nm; with the increase in the amount of YZFS-1 adsorption, the interlayer spacing of bentonite increases continuously; at the concentration of YZFS-1 of 1%, the interlayer distance reaches a maximum value of 1.54 nm. With the continuous increase in the concentration of the YZFS-1 solution, the interlayer distance remains basically unchanged, suggesting that the adsorption saturation of the
YZFS-1 molecule is saturated. It is therefore demonstrated that this small-molecule biomimetic inhibitor can be embedded between the lamellar structures of clay. On the surface, the embedding of YZFS-1 expands the layer spacing of the clay and makes the clay “swell” relative to the non-embedded layer. However, the layer spacing after embedding is significantly smaller than the layer spacing (seepage water) that can even reach 13nm. Moreover, after embedding, YZFS-1 molecules are capable of forming stronger hydrogen bonds with stronger strength than ordinary hydrogen bonds on the adjacent clay surface (even at 150 °C), and connecting adjacent clay sheets closely via bridging.

![Figure 1. XRD spectrum of bentonite adsorbed by YZFS-1.](image)

2.2. Mechanism of the wall-fixing agent GBFS-1

The bionic wall-fixing agent GBFS-1 spontaneously adsorbs on the near surface of mud shale while chelating and cross-linking with Ca\(^{2+}\), Mg\(^{2+}\) and other metal ions on the surface of the mudstone via "bionic groups"; meantime, it solidifies to form a coagulation with strong adhesion and cohesion. The “bionic crust” can increase the cementation strength of mud shale and subsequently strengthen the shale. Morphological observation of shale shavings immersed in 5% GBFS-1 solution at different times (Figure 2) qualitatively reveals the wall-fixing mechanism of the bionic wall-fixing agent GBFS-1.

![Figure 2. Shale morphology changes immersed in GBFS-1 solution. a: initial; b: 1 d after; c: 3 d after; d: 7 d after.](image)

Figure 2 suggests that in the initial state, the surface of the cuttings is immersed in the light brown clear solution of GBFS-1 is free from any other substances. After immersing for 1 d, the surface of the cuttings begins to form light yellow adhesive, and the adjacent small pieces of cuttings are glued together.
to a certain extent. Then, the bulk solution remains clear. After a longer time (3 d), the pale-yellow adhesive on the surface of the cuttings covers a wider area, and the adhesion becomes stronger. Then, the bulk solution slightly away from the cuttings remains clear. After 7 days, since the water in the GBFS-1 solution has basically evaporated, the stickies are formed in all solution areas regardless of location, and the cohesion turns significantly large. This phenomenon basically reveals the wall-fixing mechanism of the wall-fixing agent GBFS-1, i.e., "the spontaneous solidification of the wall-fixing agent on the rock surface". To be specific, the wall-fixing agent GBFS-1 can be spontaneously cured on the rock surface under the catalysis of the rock surface, thereby forming a bionic shell, namely the mentioned light-yellow adhesive. The bionic crust exhibits mechanical properties not available in films formed by general film-forming agents; it can strengthen the rocks in contact with them via adhesion and cohesion, so the rock, especially the shale, undergoes hydration during hydration and expansion. The force is weakened or offset by the cohesive force of the bionic shell, thus maintaining the stability of the well wall. Moreover, due to the fixed-point solidification characteristics of GBFS-1, the rheology of bulk drilling fluids far from the well wall will remain unaffected, ensuring its availability in the practical drilling process.

2.3. Preparation of water-based drilling fluid
A high-performance water-based drilling fluid was employed in this study. The composition of the optimized formula of drilling fluid and initial formula of drilling fluid are listed in Table 1. The density of the drilling fluid is 1.70 g/cm³.

| Name      | Initial formula | Optimized formula |
|-----------|-----------------|------------------|
|           | Unit Addition   | Unit Addition    |
| Water     | mL 300          | mL 300           |
| Bentonite | g 9             | g 9              |
| Na₂CO₃    | g 0.6           | g 0.6            |
| NaOH      | g 1.5           | g 1.5            |
| XZ-FJL    | g 6             | g 6              |
| TC-DBY    | g 1.8           | g 1.8            |
| YZFS-1    | g -             | g 9              |
| GBFS-1    | g -             | g 6              |
| CaO       | g 0.9           | g 0.9            |
| KCl       | g 21            | g 21             |
| NaCl      | g 30            | g 30             |
| Barite    | g 650           | g 650            |

2.4. Filtration property test
High-Pressure High-Temperature (HPHT) fluid loss test is performed to implement mud invasion and filter cake formation at a laboratory scale. These tests are performed to compare the filter cake quality and filtration properties of the drilling fluid containing YZFS-1 and GBFS-1 with the blank sample. The test is performed at a temperature of 120 °C and differential pressure of 300 psi (inlet pressure of 500
psi and outlet pressure of 200 psi). The filter cake is formed over the filter paper samples; subsequently, filtration volume and filter cake thickness are measured.

2.5. **Hot rolling recovery of cuttings measurements**

The cuttings (6-10 mesh) from the Baikouquan Formation in Mahu oilfield are exploited to assess the rolling recovery of the cuttings. 20g of cuttings are added to the drilling fluid, and after hot rolling at 120 °C for 16h, the cuttings are poured out, washed and then dried. Besides, the weight of the cuttings is tested.

2.6. **Rheological properties of drilling fluids test**

The properties of the base drilling fluid and the drilling fluid containing different weights of perlite are listed in Table 2. The drilling fluid rheological properties are ascertained using ZNN-D6 Viscometer® at 30 °C. Plastic viscosity, apparent viscosity and yield points are calculated from the dial readings at 300 and 600 RPM ($\Phi_{300}$ and $\Phi_{600}$) by Eq. (1), (2), and (3), respectively, while gel strength is computed directly from the dial reading at 3 RPM after the static gel time.

\[
\text{Apparent viscosity (AV)} = \frac{\Phi_{600}}{2} \\
\text{Plastic viscosity (PV)} = \Phi_{600} - \Phi_{300} \\
\text{Yield point (YP)} = \Phi_{300} - PV 
\]

\[\text{Eq. (1), (2), and (3)}\]

3. **Results and discussions**

3.1. **Properties of drilling fluids**

Table 2 presents that the original formula exhibits good rheology after aging, whereas the filter loss is overly large, and the viscosity coefficient is high; the optimized formula exhibits good rheology after aging and maintains the good rheology and filtration loss after long-term aging. The filtration is obviously reduced, and the shear force is increased. The viscosity coefficient is low, and high lubricity is achieved, thereby satisfying the performance requirements of the site.

**Table 2. High-performance water-based drilling fluid composition.**

|                  | Hot rolling | AV (mPa·s) | PV (mPa·s) | YP | Gel Pa | $\Phi_3/\Phi_1$ | FL API (ml) | FL HT (ml) | Viscosity coefficient |
|------------------|-------------|------------|------------|----|--------|----------------|-------------|-------------|-----------------------|
| **Initial formula** | Before 16h  | 40         | 33         | 7  | 1/1.5  | 2/1           |             |             | 0.12                  |
|                  | After       | 33         | 28         | 5  | 0.5/1  | 2/1           | 2.6         | 12          | 0.12                  |
|                  | Before 16h  | 54         | 45         | 9  | 1.5/3.5| 4/3           |             |             | 0.08                  |
| **Optimized formula** | Before 16h  | 50         | 42         | 8  | 2/4    | 4/3           | 2.1         | 7.4         | 0.08                  |
|                  | After 72h   | 49         | 41         | 8  | 2/4    | 3/2           | 2.3         | 7.6         |                       |

3.2. **Pollution resistance of drilling fluids**

The experimental results in Table 3 indicate that after adding 10% and 15% cuttings to the optimized formula, the viscosity, filtration loss, and shear force change are overall small; the apparent viscosity and plastic viscosity after the addition of 1% calcium chloride increase; the filtration loss and shear force
remain almost unchanged, and the optimized formula exhibits good resistance to rock cuttings and calcium chloride pollution.

Table 3. The performance of Optimize formula of drilling fluid after being contaminated.

| Property                  | AV (mPa·s) | PV (mPa·s) | YP (Pa) | Gel (Pa) | $\Phi_6/\Phi_3$ | FL-API (ml) | FL-HTHP (ml) |
|---------------------------|------------|------------|---------|----------|----------------|-------------|--------------|
| Optimized formula         | 52         | 45         | 7       | 2/4      | 4/3            | 2.2         | 7.2          |
| After aging               |            |            |         |          |                |             |              |
| Optimized formula +10% cuttings | 58         | 50         | 8       | 3/5      | 6/5            | 2.0         | 7.0          |
| After aging               |            |            |         |          |                |             |              |
| Optimized formula +15% cuttings | 63         | 54         | 9       | 4/7      | 8/7            | 1.9         | 6.8          |
| After aging               |            |            |         |          |                |             |              |
| Optimized formula +1% CaCl$_2$ | 60         | 52         | 9       | 5/8      | 9/8            | 2.0         | 7.2          |
| After aging               |            |            |         |          |                |             |              |

3.3. Inhibitory evaluation

The inhibition of drilling fluid was tested by rolling recovery rate experiment. The experimental results are shown in Table 4. As can be seen from Table 4, the cuttings rolling recovery rate reaches over 95%, and the suppression effect is significantly enhanced. The optimized drilling fluid exerts a stronger inhibiting effect than the optimized drilling fluid.

Table 4. The performance of Optimize formula of drilling fluid after being contaminated.

| Drilling fluid                             | Rolling recovery, % |
|--------------------------------------------|---------------------|
| Water + cuttings                           | 10.48               |
| Initial formula of drilling fluid + cuttings | 82.52               |
| Optimized formula of drilling fluid + cuttings | 95.26               |

3.4. Field application

High-performance water-based drilling fluids are popularized and employed in nine wells of MaHW6104/6105, MaHW6135/6136, MaHW6114/6115, MaHW6231, MaHW6233, and MaHW6240 in the 18 wells of Mahu Oilfield. Such system exhibits robust rock carrying and wall-fixing capabilities, smooth start-up and downhole drilling, as well as a significant reduction in downhole complexity.

The Baikouquan Formation of MaHW6105 well, mud shale is susceptible to hydration and poor cementation, and the wall of the well is easy to collapse.

1. Mud shale is easy to hydrate for pulping, resulting in high system viscosity, high ban content, and poor stability of drilling fluid system;
2. Carbonate and bicarbonate encountered when drilling into formations will easily contaminate the drilling fluid, thereby increasing the difficulty in rheological control;
3. Mud shale exhibits poor cementation, and the wellbore is easy to collapse.
Introducing strong inhibitors and wall-fixing agents in the system can effectively reduce the shale swelling and hydration, while enhancing the plugging and strengthening of the shaft wall. Field application effects include:

| Well depth (m) | Viscosity (s) | density (g/cm³) | YP (Pa) | Gel (Pa/Pa) | FL_{API} (mL) | FL_{HTHP} (mL) | Cl⁻ (mg/l) | CO₃²⁻ | HCO₃⁻ |
|---------------|--------------|-----------------|--------|-------------|--------------|---------------|------------|-------|-------|
| 3328          | 48           | 1.41            | 5.5    | 1/4         | 2            | 140000        | 7.2        |       |       |
| 3636          | 50           | 1.56            | 5      | 1/3         | 1.8          | 140000        | 5.8        |       |       |
| 3769          | 51           | 1.56            | 4      | 1/3         | 1.6          | 145000        | 8          |       |       |
| 3944          | 54           | 1.57            | 6.5    | 1.5/5.5     | 1.6          | 140000        | 3360       | 3904  |       |
| 4321          | 67           | 1.6             | 14.5   | 6/21        | 3.3          | 140000        | 2640       | 32452 |       |
| 4440          | 66           | 1.6             | 17     | 6/18.5      | 3.6          | 135000        | 9.4        |       |       |
| 4805          | 65           | 1.6             | 17.5   | 6/22        | 3.8          | 135000        | 4320       | 36112 |       |
| 5233          | 54           | 1.61            | 10     | 3.5/12.5    | 3.4          | 120000        | 9          | 3600  | 47824 |
| 5337          | 50           | 1.61            | 11.5   | 3/11.5      | 3.4          | 130000        | 8.2        | 4080  | 48312 |
| 5515          | 54           | 1.61            | 11.5   | 3.5/15.5    | 4.2          | 130000        | 8.4        | 3600  | 48800 |

From Table 5, the optimized formula drilling fluid has stable rheological properties with little fluctuation between 3328 m and 5515 m. The fluid loss is less than 10 ml, and the fluid loss performance is stable.

The application of high-performance water-based drilling fluid in the three well sections of Well 18 in Mahu oilfield narrows the average drilling cycle by 21 to 36 d and decreases the average total drilling cycle by more than 20 d. The comparison table of different drilling fluid drilling cycles is listed in Table 6.

| Drilling fluid system                  | Average drilling cycle (days) | Average period third section of well (days) | Drilling speed (m/h) |
|---------------------------------------|-------------------------------|---------------------------------------------|----------------------|
| High-performance water-based drilling fluid | 85.4                          | 59.365                                      | 5.58                 |
| Organic salt drilling fluid            | 162.3                         | 95.33                                       | 4.02                 |
| Potassium calcium polyamine organic salt drilling fluid | 118.6                         | 79.98                                       | 5.925                |
| Reverse permeability drilling fluid    | 105.7                         | 80.21                                       | 5.87                 |

4. Conclusion
The following conclusions can be drawn based on this study:
1. High-performance water-based drilling fluid exhibits good rheology, filtration loss and wall-building properties, strong inhibition, good lubrication and anti-seizure ability, low cost, as well as environmental protection.

2. High-performance water-based drilling fluids have been field-promoted and applied in 9 wells in the 18-well area of Mahu Oilfield. Its well diameter expansion rate is low, the drilling fluid performance is stable during construction, and the drilling is normal, and no block collapse phenomenon occurs, as compared with those of horizontal wells of the identical well type, indicating that it exhibits excellent anti-collapse effect.

3. Since the use of a high-performance water-based drilling fluid system, the drilling cycle has been narrowed, the mechanical drilling speed has been significantly stimulated, and the downhole accidents have been significantly simplified. It can achieve safe and fast drilling, which is conducive to lowering costs and gaining economic benefits.

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