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Low Oil-Water Ratio Technology in Water-In-Oil Drilling Fluids for Cost Reduce of Unconventional Oil and Gas Drilling Fluids

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Abstract. In China's unconventional oil drilling, horizontal wells are one of the main forms of drilling， water-in-oil drilling fluid have been widely used due to their stable performance and excellent lubricating properties. To reduce the high cost of water-in-oil drilling fluids at the drilling site, further reduce the pressure of cuttings processing, and meet the requirements of environmental protection, an oil-based drilling fluid system with a low oil-water ratio was developed. Based on the research of key emulsifiers and the introduction of nanomaterials, it helps the drilling fluid system maintain the performance of the drilling fluid while increasing the water-phase ratio, and further enhances the fluid loss performance of the drilling fluid. The developed low oil-water ratio oil-based drilling fluid has been applied in the horizontal section of Jiaoye 5-3HF and Jiaoye 21-S2HF, two wells in the Fuling shale gas block in China, and successfully drilled to the designed well depth. The Marsh funnel viscosity of the drilling fluid is controlled from 63s to 78s, the plastic viscosity is lower than 40 mPa·s, the dynamic shear force is maintained at 3.5-7 pa, the high temperature and high pressure water loss is controlled below 2.6 ml, and the demulsification voltage is stable above 600v; the properties of the drilling fluid Excellent, meeting the requirements of on-site drilling construction. Compared with the conventional oil-water ratio system, the oil-based drilling fluid system with low oil-water ratio can greatly reduce the oil content, which can meet the requirements of on-site drilling and save the cost of oil-based drilling fluid to a large extent. It can reduce the pressure of environmental protection to a certain extent.

Keywords. Low oil-water ratio drilling fluid, emulsion, stability, fluid loss properties, rheological properties, water content

1. Introduction

Oil-based drilling fluid technology, as the main technical means used in horizontal wells

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in the Fuling shale gas field in China, has matured in recent years. At present, the Fuling block has put forward a new goal of reducing costs in terms of drilling, and the low oil-water ratio drilling fluid technology has been applied [1, 2]. The increase of the water-phase ratio increases the instability of the emulsion system, which has a certain adverse effect on the performance of water-in-oil drilling fluid [3-5]. The variation law of emulsion properties and the formation mechanism determine the overall properties of oil-based drilling fluids. In order to improve the stability of the emulsion, the existing low oil-water ratio drilling fluid systems usually improve the stability of the emulsion droplets by adjusting the amount of emulsifier, i.e., surfactant [6-8]. However, the low oil-water ratio oil-based drilling fluid stabilized by emulsifier will have poor properties under long-term downhole temperature aging, and it is difficult to meet the ideal requirements.

Through the development and optimization of key drilling fluid treatment agents such as new emulsifiers, fluidity regulators and organic soils, and the introduction of nanomaterials, emulsifiers and organic soils to form synergistic effects to enhance the stability of water-in-oil emulsions, Singh et al. (2015) found that the adsorption of surface-active complexes formed by nanoparticles and surfactants at the oil/water interface improved the interface properties more than surfactants or nanoparticles alone [9]. Zhou et al. (2019) found the advantages of silica nanoparticles with different wettability from both the adsorption properties of the oil-water interface and the stability of the emulsion. [10].

The formed low oil-water ratio (65/35) oil-based drilling fluid system has been proved to have high stability in laboratory experiments. The low oil-water ratio oil-based drilling fluid greatly increases the water phase content, the low-oil-water ratio oil-based drilling fluid system significantly reduces the amount of treatment agent, and the configuration method is simpler. The existing research has effectively solved the problems of unstable electrical stability and poor inhibition properties and high friction resistance in water-in-oil drilling fluid caused by excessive water content.

2. Mechanisms and Performance

The variation law of emulsion properties and the formation mechanism determine the overall properties of oil-based drilling fluids. Therefore, the key to water-in-oil drilling fluid is to improve the problem of emulsions.

2.1 Mechanisms

(1) Stability mechanism

Emulsifiers, as key treatment agents, play a significant role in the conformation of water-in-oil emulsions. Emulsifier is divided into main emulsifier and auxiliary emulsifier. By lowering the oil-water interfacial tension, a layer of composite film structure is formed on the oil-water interface to enhance the stability of the interfacial film. Nano-SiO_2 participates in the arrangement on the oil-water interface film together with the emulsifier, and forms a solid “shell” structure on the water-in-oil droplet to improve the mechanical strength of the film， as shown in Figure 1. As an oleophilic colloid, organic soil is dispersed in the oil phase to adjust the rheological properties of the drilling fluid, increase the viscosity of the oil phase, and prevent the droplets of the discontinuous phase from coalescing and becoming larger [11, 12].

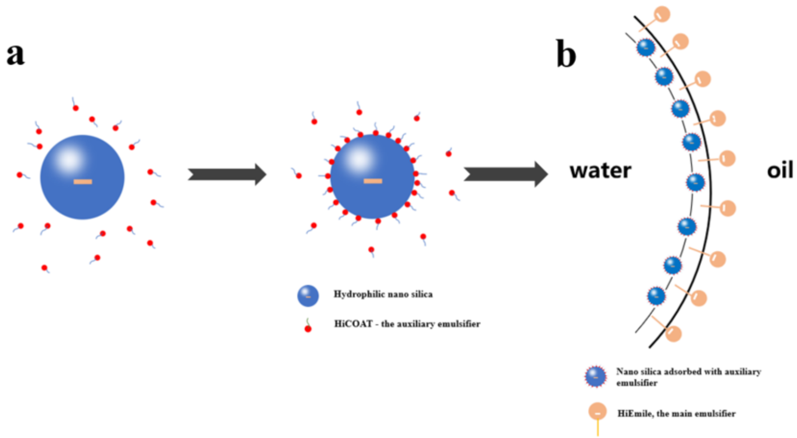

Figure 1. Mechanism of emulsifier and nanomaterial to form water-in-oil emulsion.

(2) Rheological improvement mechanism

The organic soil disperses and expands in the oil phase to form a space grid structure, which can greatly improve the viscosity and shear force of the oil-based drilling fluid. Since the nanoparticles can still maintain the stability of properties under high temperature and high pressure conditions, they can also better stabilize the properties of the emulsion, which is beneficial to improve the rheological properties of the drilling fluid [13, 14].

(3) Filter loss control mechanism

Nanometers can fill and block dense pores. Due to its nanometer size, tiny pores in shale can be plugged to improve wellbore stability. The addition of nanoparticles also effectively prevents the invasion of water-in-oil drilling fluid into the formation [15, 16].

2.2. Key Treatment Agent

The choice of emulsifier is divided into main emulsifier and auxiliary emulsifier. The main emulsifier HiEmile is an anionic surfactant with an HLB value of 3.1, and the auxiliary emulsifier HiCOAT is a nonionic surfactant with an HLB value of 5.2. From Jingzhou Jiahua Technology Co., Ltd.; the preparation of organic soil is to select cetyl trimethyl ammonium chloride to exchange and adsorb cations between montmorillonite layers to modify montmorillonite to make it hydrophilic from the surface The properties of nano-silica become lipophilic; the choice of nano-silica material is hydrophilic fumed nano-silica, and the surface contains a large number of silanol groups (SiOH). The average particle size of nano-silica is 30 nm, and the specific surface area (BET): 120m^2/g.

3. Emulsion Performance

Table 1 describes that the proportion of water phase in the emulsion is gradually increased, and the volume ratio of oil phase to water phase is from 85:15, 75:25 to 65:35.

The stability properties of the emulsion were analyzed at this point. At the same time, the stability of the formed emulsion was analyzed by adding different amounts of emulsifier or adding different amounts of nano-silica.

Table 1. Formulations of different types of emulsions.

Type	Proportion	White oil	Main emulsifier	Auxiliary emulsifier	Deionized water	Nano SiO_2
(1)	85:15	340ml	2.4%	0.6%	60ml	-
(2)	75:25	300ml	2.4%	0.6%	100ml	
(3)	65:35	260ml	2.4%	0.6%	140ml	-
(4)	65:35	260ml	4%	1%	140ml	-
(5)	65:35	260ml	2.4%	0.6%	140ml	4g
(6)	65:35	260ml	2.4%	0.6%	140ml	8g

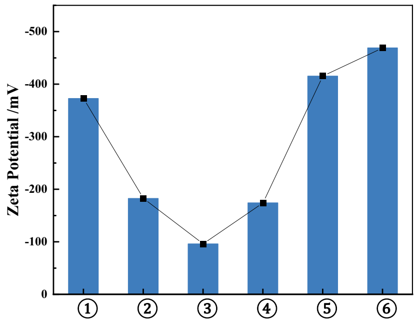

Figure 2. Zeta potential value of emulsion.

The zeta potentials of all samples are negative, which is because the main emulsifier is anionic surfactant and the added hydrophilic nano-silica is negatively charged, as shown in Figure 2. From formula (1) to formula (3), the oil-water ratio of the emulsion is from 80:20, to 70:30, to 60:40. As the oil-water ratio decreases, the droplets of the water-in-oil emulsion become larger. The absolute values of zeta potential of formula (5) and formula (6) were significantly higher than those of formula (3), which were -415.5 mV and -469.1 mV, respectively. This is due to the adsorption of negatively charged nano-SiO2 on the oil/water interface, which participates in the formation of the interfacial film, which increases the negative charge on the interface and the particles are adsorbed on the interfacial film. This structure increases the strength of the droplet interface film, which is significantly higher than that formed by the single use of emulsifier at the oil-water interface. According to the zeta potential value, adding 1 wt% nano-SiO_2 to the emulsion with a low oil-water ratio of 60:40 can help the emulsion to achieve the stability of the emulsion with an oil-water ratio of 80:20.

As shown in Figure 3, the oil-water ratio in formula (3) is 60:40, the droplet size is the largest, and the droplet size uniformity is poor, and the increase of the interfacial tension makes it difficult for the emulsion to form a uniformly dispersed system. By comparing formulas (3) and (6), it can be proved that nano-SiO_2 has a better effect on the formation of stable emulsion droplet size and the uniformity of the control size.

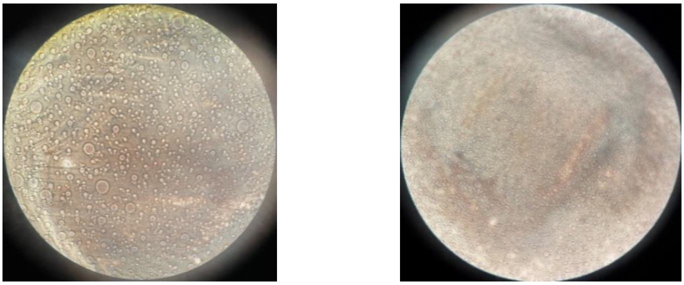

Figure 3. Microscopic images of emulsion droplets of formulas (3) and (6).

4. Oil-Based Drilling Fluid Performance

Screening of key treatment agents and selection of dosage based on previous studies. Use formula: 260ml 3# white oil + 2.4% HiEmile (main emulsifier) + 0.6% HiCOAT (auxiliary emulsifier) + 1.2% CaO + 1% MOGEL (organic soil) + 3% HIFLO (fluid loss additive) + 1 %HIROL (plugging agent) + 140ml 25% $CaCl_2$ aqueous solution + barite to 1.4g/cm^3, as the formulation of oil-based drilling fluid with low oil-water ratio. The properties evaluation of the oil-based drilling fluid was carried out.

4.1. Temperature Resistance

Water-in-oil drilling fluid are drilling fluid systems based on water-in-oil emulsions. Emulsions are thermally unstable systems, so temperature has a great influence on emulsions. Especially when the content of the water phase increases, the emulsion droplets become larger, the system tends to be unstable, and the properties of the system becomes more and more sensitive to the ambient temperature. Therefore, it is necessary to test and study the performance change law of drilling fluid at different temperatures. Test the temperature resistance of oil-based drilling fluid in the range of 80-140°C, and observe whether it can meet the requirements of the site. Experimental conditions: 80-140°C hot rolling for 16h, 50°C properties measurement, high temperature and high pressure water loss test conditions: 80-140°C×30 min×500 psi;

Table 2. Effect of temperature on the properties of low oil-water ratio oil-based drilling fluids.

State	AV (mPa·s)	PV (mPa·s)	YP (Pa)	GEL/(Pa:Pa)	ES (volts)	FLHTHP (mL)
Homeothermy	24	20	4	3/2	624	1.4
80°C	24.5	20	4.5	3.5/2.5	712	1.4
100°C	26	21	5	5/3.5	758	1.6
120°C	28	21.5	6.5	6/4	782	2.0
140°C	31	23	8	7/5.5	764	2.2

As shown in Table 2, the experimental results show that increase of temperature has little effect on the rheological properties of the drilling fluid, and the viscosity of the drilling fluid increases slightly. The drilling fluid can maintain good stability at 140℃. There is no thickening or thinning failure of the drilling fluid due to high temperature, indicating that the water-in-oil interfacial film maintains a certain strength, and the low oil-water ratio oil-based drilling fluid system can maintain good stability at temperature. The electrical stability of the low oil-water ratio oil-based drilling fluid system gradually increases and then decreases, and when it is kept above 400v, it can meet the needs of actual drilling in the field. The fluid loss of drilling fluid increased slightly with the increase of temperature, but still remained below 3ml.

4.2. Anti-pollution Performance

During the drilling process, the cuttings produced around the wellbore and the soil phase in the shale formation have a great influence on the properties of the oil-based drilling fluid. The main problem faced by drilling fluids with low oil-water ratios is their weak anti-pollution ability. Once the foreign pollutants enter, and the materials with multi-solid content enter, part of the surfactants dispersed on the oil-water interface will be adsorbed on the solid particles, reducing the stability of the emulsion. Therefore, the influence of the addition amount of foreign pollutants on the properties of water-in-oil drilling fluid with low oil-water ratio was discussed. Therefore, drilling cuttings from shale blocks are selected as pollutants, and the anti-pollution ability of drilling fluids with low oil-water ratio is verified by different dosages. And after aging at 140°C for 24 hours, the properties of the oil-based drilling fluid was tested.

Table 3. Evaluation of fouling properties of drill cuttings.

State	State	AV (mPa·s)	PV (mPa·s)	YP (Pa)	Φ6/Φ3	ES (volts)	FLHTHP (mL)
Blank	before thermal	24	20	4	3/2	624	
	90°C×16 h	25	20	5	3.5/2.5	742	2.0 ml (90°C)
5% Longmaxi cuttings	90°C×16 h	30	23	7	7/6	702	2.6 ml (90°C)
8% Longmaxi cuttings	90°C×16 h	33	24	9	10/9	684	2.4 ml (90°C)
8% Longmaxi cuttings	100°C×40 h	31	23	8	9/8	660	2.0 ml (100°C)
8% Longmaxi cuttings	120°C×40 h	32	24	8	8/7	595	2.0 ml (120°C)
8% Longmaxi cuttings	140°C×40 h	33	24	9	9/8	584	2.4 ml (140°C)

As the proportion of foreign pollutants increases, the viscosity of oil-based drilling fluid increases more and more, but the thickening behavior of drilling fluid is controlled within a certain range and kept within a safe range. As shown in Table 3, when the addition amount of shale cuttings is 15%, the demulsification voltage drops by about 100v, but it is above 500v. Although part of the emulsifier is adsorbed by the cuttings, the remaining part of the emulsifier in the low oil-water ratio water-in-oil drilling fluid under this formula can still meet the properties of stabilizing the oil-based drilling fluid. The experimental results show that the low oil-water ratio water-in-oil drilling fluid can still maintain good point stability and rheological properties under the intrusion of high content of cuttings in the drilling fluid.

4.3. Mud Cake

There are still micro- and nano-scale pore structures on the conventional drilling mud cake, which leads to the increase of drilling fluid filtration. It can be seen from Figure 4 that the filter cake formed in formula (6) is denser because the nano-SiO_2 particles penetrate the filter cake deeper and block the micro-nano pores. Nano-SiO_2 can help block the infiltration of mineral oil in the pores, further maintain the stability of the wellbore.

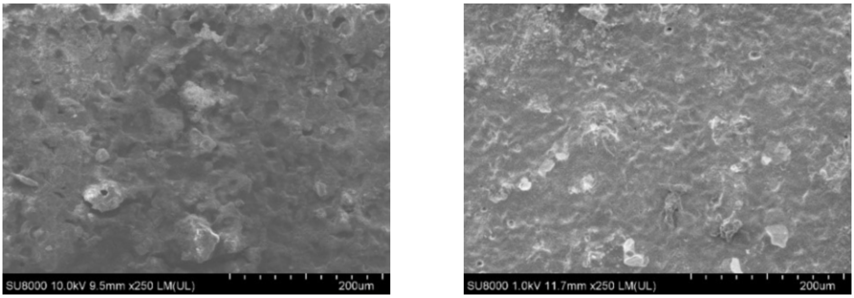

Figure 4. Structure of mud cake formed by oil-based drilling fluid without SiO_2 and with SiO_2 added.

4.4. Settlement Stability

The static settlement properties of the configured drilling fluid was tested. Based on different temperature conditions, the measuring cylinder was placed vertically in the oven for 96h. Finally, test the difference between the density of the upper part of the graduated cylinder and the density of the lower part. The sedimentation factor was quantified using equation (1). When *F* is 0.5, it means that no static settlement occurs, and if *F* is greater than 0.52, it means that the stability of static settlement is poor.

$$F = \frac{\rho_{\mathrm{lowwer}}}{\rho_{\mathrm{upper}}+\rho_{\mathrm{lower}}} \tag{1}$$

In the equation, *F* is the settlement factor, the ρ_{upper} is the average density of the upper part of the aging tank, and the ρ_{lower} is the average density of drilling fluid in the lower part of the aging tank, g/cm^3.

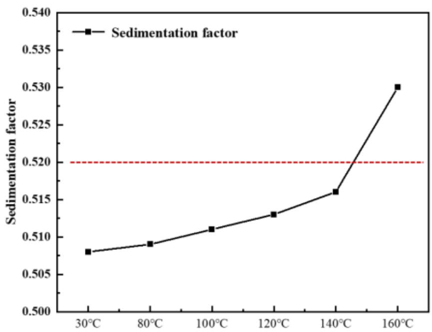

Figure 5. Static settlement process of low oil-water ratio oil-based drilling fluid at different aging temperatures.

As shown in Figure 5, from the properties of oil-based drilling fluid under different temperatures, it is obvious that oil-based drilling fluid with low oil-water ratio can maintain a certain settlement stability at 140 °C, and the maximum settlement factor is 0.516, which is less than 0.52, which is within the safe range. When the temperature reaches 160°C, the stability deteriorates, and the sedimentation factor is greater than 0.52, indicating that the low oil-water ratio oil-based drilling fluid can maintain a good stability at the formation temperature of 140°C and below.

4.5. Suppression Performance Evaluation

The well-inhibited drilling fluid system is the primary requirement for optimal control of drilling fluid in shale formations. During the drilling process of oil-based drilling fluid, irregular wellbore and virtual thick mud cake are usually caused by poor inhibitory properties of the drilling fluid, thereby increasing the probability of complex accidents. According to the drill cuttings taken out from the site, the inhibition properties was evaluated, and it was first crushed into 6-10 mesh. After drying, the rolling recovery was calculated to evaluate the inhibition properties of the shale gas oil-based drilling fluid system. Experimental conditions: 1400°C hot rolling 16 h, 50°C properties measurement.

Table 4. Suppression properties evaluation.

System status	State	AV (mPa·s)	PV (mPa·s)	YP (Pa)	Φ6/Φ3	ES (volts)	Recovery rate (%)
oil based	Before thermal	24	20	4	3/2	624	
	After thermal	32	24	8	4/3	614	98.4

From the experimental results in Table 4, it can be seen that the rolling recovery rate of the low oil-water ratio oil-based drilling fluid system reaches 98.4%, which has good inhibitory properties on shale and can meet the requirements of shale drilling for anti-collapse. Nano-SiO_2 blocks the pores in the shale and inhibits the hydration expansion effect of water relative to clay.

4.6. Field Application

The low oil-water ratio oil-based drilling fluid system has been tested on site in Jiaoye 21-XF well. The designed horizontal section of the third opening is 2190 m long. The system has been applied to the horizontal section and successfully drilled to the designed well depth. During the drilling of a well in Jiaoye, the specific properties of the low oil-water ratio drilling fluid changed with the increase of the well depth as shown in Figure 6. The specific properties changes of low oil-water ratio water-in-oil drilling fluid are shown in the following figure:

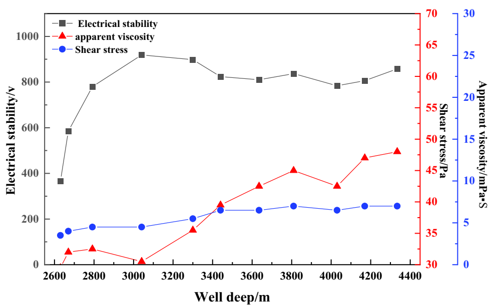

Figure 6. Actual properties of low oil-water ratio oil-based drilling fluid in a well in Jiaoye.

For the maintenance of the whole well, we ensure that the oil-water ratio of the oil-based drilling fluid is about 65/35, the viscosity is also controlled at 63 s-78 s, the plastic viscosity is less than 40 mPa·s, the dynamic shear force is maintained at about 3.5-7 Pa, and the high temperature The high-pressure filter loss is controlled below 2.6 ml, and the overall demulsification voltage is maintained above 600 v. The whole process meets the requirements of on-site drilling construction. It provides a good guarantee for the smooth progress of drilling construction, and the application effect is good.

5. Conclusion

(1) According to the properties of the low oil-water ratio emulsion, the interfacial film strength of the emulsion and the particle size of the emulsion droplets were tested. The results showed that the main emulsifier HiEmile, auxiliary emulsifier HiCOAT and organic soil MOGEL were selected as key treatments It can maintain the good stability of the low oil-water ratio emulsion,

(2) The oil-based drilling fluid with low oil-water ratio maintains good rheological properties at 140°C, the system can resist a high proportion of contaminants of 8% drilling cuttings, and can maintain a certain settlement stability within 96 h, indicating that from drilling According to the comprehensive properties of the liquid, it can meet the needs of practical application in the field.

(3) The low oil-water ratio oil-based drilling fluid system has been successfully applied in Jiaoye 21-XF well, which satisfies the on-site construction requirements, provides a good guarantee for the smooth construction, and has the value of popularization and application.

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