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High Performance Water-based Drilling Fluids—A High Efficiency Muds Achieving Superior Shale Stability While Drilling Deepwater Well with HPHT in South China Sea

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Abstract: In deepwater drilling operation, low temperature, high pressure, gas hydrate, narrow density window are the major challenges for drilling fluids to meet, and with the increasing depth drilled, high temperature and high pressure condition was occurred in deepwater well. In the other side, Oil based muds (OBM) and synthetic based muds (SBM) are limited in using because of the strict environment rules in the South China Sea. In deepwater HTHP well, shale hydration, dispersion and Equivalent Circulation Density (ECD) caused by rheology change with high temperature difference are the two critical problems. Therefore, petroleum service institutes and companies take much time and money on research to develop a high performance water-based mud system (HPWBM) to solve these problems and improve drilling efficiency. In the paper, a new method to estimate amine derivatives was proposed, the specific test steps was introduced in detail, and secondly a High efficiency muds (HEM) are selected and the main properties were evaluated in lab such as rheological properties at lower temperature, shale inhibition and anti-accretion. Finally, the system was applied successfully in LS project in the South China Sea. The results showed that HEM system delivered high drilling performance such as shale stability, high pressure and high temperature (HPHT) resistance, lubricity and high rate of penetration (ROP) with no wellbore problems, and the system is suitable for deepwater HTHP well operation.

Keywords: Deepwater, HTHP, HPWBM, Inhibition

1. Introduction

With the increasing demand for oil & gas and the development of ocean petroleum industry, many oil companies have focused on oil and gas buried in deepwater and ultra-deepwater reservoir [1, 2]. Low temperature, high pressure, narrow density window between fracture and pore pressure, gas hydrate and rich shale in drilled formation are the major challenges for drilling fluids [3-5]. In order to satisfy the requirements of deepwater drilling operations, many petroleum service institutes and companies take much time and money on research to develop a High Performance Water-based Mud (HPWBM) to drilling shale formation in deepwater and too much money to improve drilling efficiency [6-9].

In the past 20 years, hundreds of wells had been drilled, and various Non-Aqueous Drilling Fluids (NADF) and Water-based Mud (WBM) have been used in deepwater zones [10-14]. But NADF have some undeniable disadvantages, such as high cost, environmental limitations, disposal problems, and health and safety issues. Therefore, WBM had a wide development and applications in the past year, such as PERFORMAX, ULTRADRILL and HYDROGUARD. They all have the following criteria:

i. Maximum shale inhibition and wellbore stability
ii. Low accretion and bit balling tendencies
iii. Good, stable and easy to maintain properties
iv. Flexibility in density and base brine selection
v. Thermal stability from low temperature to high
vi. Environmental friendly

In this paper, a high efficiency muds (HEM) was selected based on an excellent amine derivative, and a new methodology was introduced to evaluate the inhibition of amine inhibitor. We also address operator's criteria of evaluating the HEM system, and finally summarize the whole achievements of the HEM system's drilling campaign.

2. Filed Background

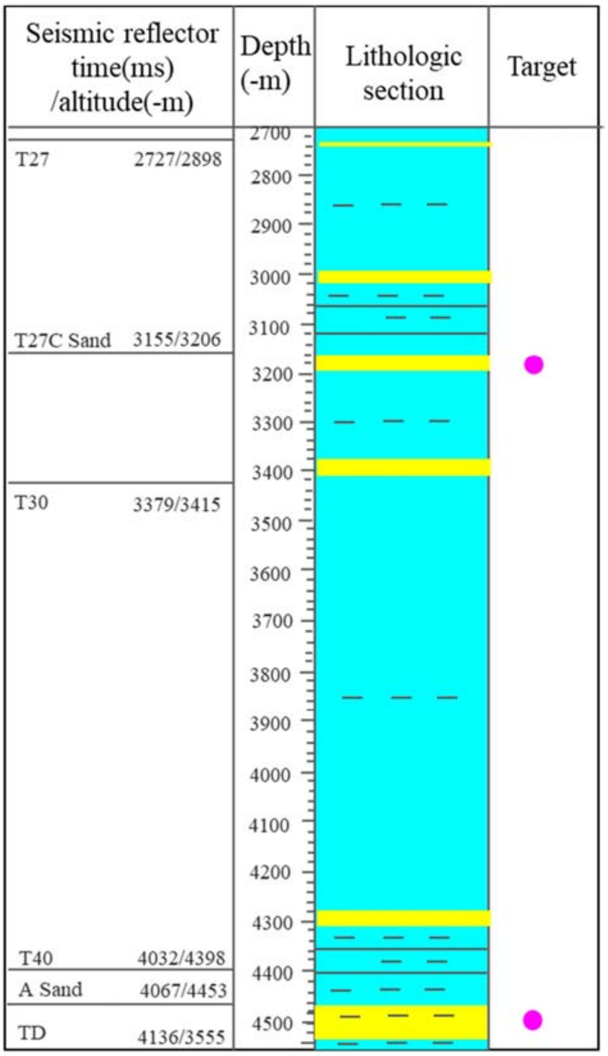

Figure 1. *Lithology of target well.*

The target well drilled is a vertical deepwater well with high pressure and high temperature (BHT is 156°C). Yinggehai group, Huangliu group and Meishan group have been drilled successively; the lithology (Figure 1) of the formation is mainly rich dark grey claystone and silty claystone, partially with siltstone and fine sandstone. The formation pressure coefficients are as follows: above 2,000m is 1.00, 2,000-3,200m is 1.00 to 1.22, 3,200-4,400m is 1.22 to 1.70 and 4,400-4,555m is 1.70 to 1.83.

3. Selection Criteria for HEM

The primary reasons driving the operator to switch drilling fluids from SBM to WBM was the increasing environmental awareness and few application case of SBM in this area. When OBM or SBM system is used in offshore, the rigorous design investigation and environmental assessment by government department must be done, and the operator do not be inclined to OBM or SBM [15-16]. Meanwhile, there is a stronger restriction on ocean discharges of SBM and oil-contaminated cuttings. If the local government leans toward a zero discharge limit, the operator must transfer the oil-contaminated drilling cuttings to land for further management and treatment. The combined costs of SBM, solid control, waste transportation treatment and management will diminish the attractiveness of SBM system.

The secondary consideration was that the operator has already be costumed to using HEM system for shale inhibition in South China Sea, approximately 20 deepwater exploratory wells were drilled in the past 10 years. The system has showed success in achieving high shale inhibition, preventing clay and cutting hydration, and reducing bit balling without any hole-related problems.

4. HEM Design and Properties

HEM system is a high performance water-based muds (HPWBM) for deepwater and ultra-deepwater well drilling without bentonite, which could achieve the requirement of drilling operation and environmental protection by an exclusive, extra-inhibition approach. The basic formula of HEM was listed in Table 1.

Table 1. *The basic formula of HEM.*

Product name	Primary function	Dosage
PF-UHIB	Shale stabilizer	2~4% V/V
PF-UCAP	Clay-dispersion inhibitor	0.5~1%
PF-HLUB	Anti-accretion, lubricity and ROP enhancement	2~3% V/V
PF-FT-1	Well stability	1~2%
PF-XC	Rheology control	0.1~0.3%
PF-FLOTROL	Filtration control	1.5~2%
NaCl	Hydrate inhibitor/Weight material	As needed for mud weight
KCl	Inhibitor	5~7%
Barite	Density control	As needed for mud weight

4.1. Inhibition Test of PF-UHIB

From the lithology information, we can see that upper section is rich in shale and clay and easy to disperse and swell which is the main reason to wellbore instability. An amine derivative PF-UHIB was adopted to improve the shale inhibition, minimize bit balling and accretion. In the paper, a new methodology called water separation percent (WSP) was put forward to test the properties of amine inhibitor [17], It's definition is a percent of free water separated with total slurry volume. and is calculated by the following formula.

$$WSP = \frac{V_{fw}}{V} \times 100\%$$

V_{fw} - the volume of free water separated, mL;V—total volume, mL.

In WSP experiment, different concentration bentonite was added to distilled water (DW) contained 3% amine derivatives, then the slurry was aged at 100°C for 16 hours, then poured the slurry in 250mL cylinder to let stand 6 hours. Figure 2 and figure 3 show the contrast of WSP in different concentration of bentonite slurry. They showed that WSP decrease with the increasing bentonite in slurry and PF-UHIB inhibitor has an excellent inhibition to shale.

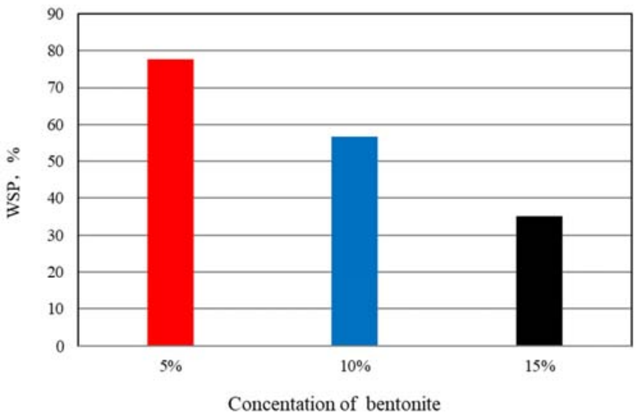

Figure 2. *WSP of PF-UHIB in different concentration of bentonite slurry.*

Figure 3. *Contrast of WSP in different concentration of bentonite slurry.*

The influence of polyamine inhibitor on clay surface was tested by scanning electron microscopy (SEM). The results are shown in figure 4 and figure 5. It illustrates that the inhibitor can absorb clay layers and makes them closer to each other. When adding inhibitor, the microstructure of clay is more compact, while the clay without inhibitor is granular, and the distance between them is larger.

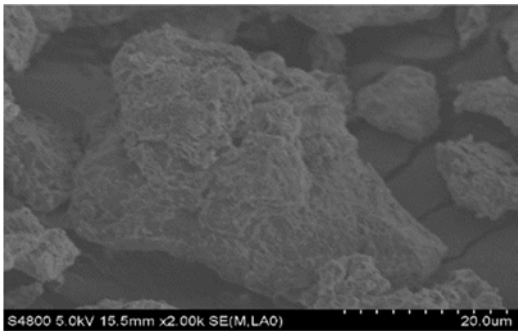

Figure 4. *Clay SEM photo with no inhibitor (×2000).*

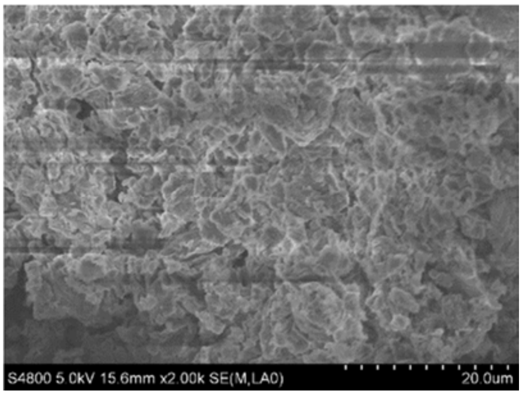

Figure 5. *Clay SEM photo with 1.5% inhibitor (×2000).*

4.2. Laboratory Experiments on HEM

4.2.1. Rheological Properties at Low Temperature

Drilling fluids used in deepwater drilling operation was cooled in riser and warmed up in formation bellow mud line, these two opposite states alternate ceaselessly in drill-in operation. Drilling fluids had different properties with temperature, increasing with high temperature and decreasing with low temperature, which effected well cleaning, cutting suspending, annular hydraulics and mud treatment directly. Based on FanniX77 Automatic Rheometer, Rheological properties at different temperatures (4°C, 8°C, 15°C, 25°C, 40°C, 50°C) between cooling and warming-up were recorded in lab. Figure 6, Figure 7, Figure 8 showed the test results, which demonstrated HEM had a good rheological properties at low temperature and superior thermal stability from lower to higher.

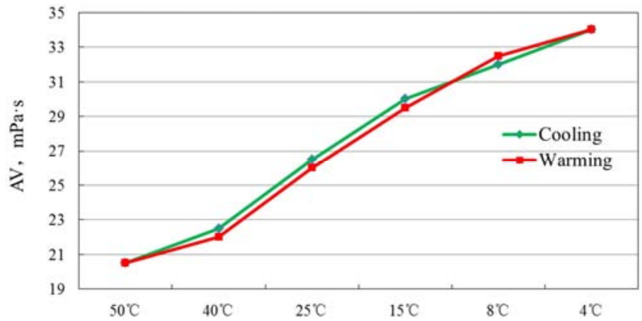

Figure 6. *AV curve of HEM between cooling and warming-up stage.*

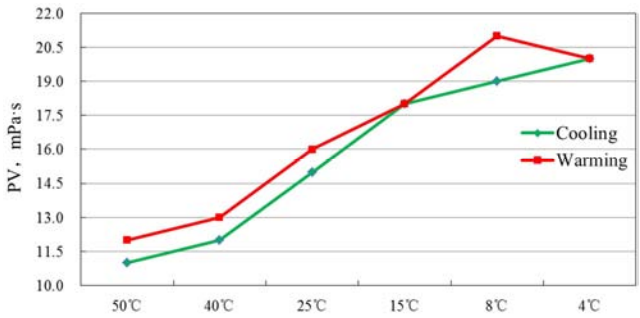

Figure 7. *PV curve of HEM between cooling and warming-up stage.*

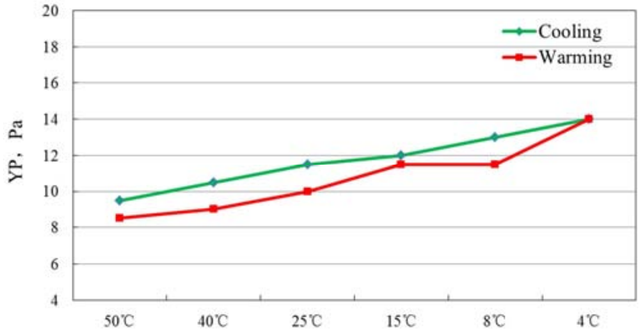

Figure 8. *YP curve of HEM between cooling and warming-up stage.*

4.2.2. Shale Inhibition

Qualitative shale recovery test was done on HEM to evaluate qualitatively of shale inhibition performance with easily dispersed shale named HolePLUG. The same test was carried out on PHPA/KCl system which was widely used in China BoHai zone. The results can be seen in Figure 9. What can be seen from the results was that HEM had higher shale recovery than PHPA/KCl no matter Hot Recovery, Durability Recovery or Second Recovery. Therefore, HEM was a good WBM for drilling deepwater formation contained high dispersing shale. Figure 7 showed the Second recovery of each mud in distill water, HEM had a higher integrity than PHPA/KCl system.

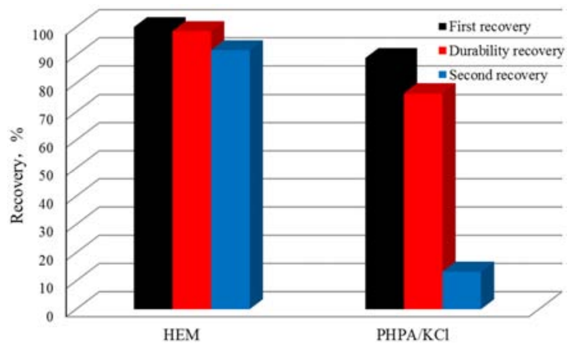

Figure 9. *Recovery results of HEM and PHPA/KCl.*

4.2.3. Anti-accretion

Shale formation could easily produced mud-ball in drill-in operation, which caused higher torque, effected Rate of Penetration (POP) and hole stability. The lab bit-balling test showed HEM had little gumbo phenomenon compared with PHPA/KCl, only 3.13%, see Figures 10 and 11. The main reason was that PF-HLUB added in the syestem can form a film between clay and bit interface to reduce the adhesion of the clay to bit.

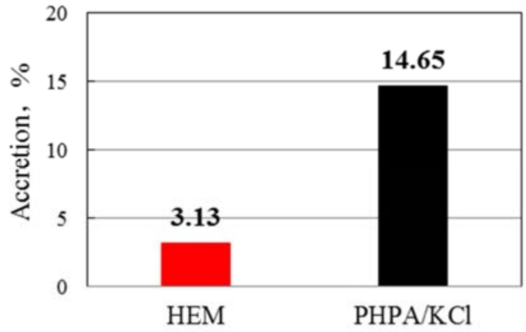

Figure 10. *Anti-accretion results of HEM and PHPA/KCl.*

Figure 11. *Anti-accretion results of HEM and PHPA/KCl (Left HEM, right PHPA/KC).*

5. Application

LS1-1 well was an exploratory vertical deepwater well drilled in 2015 with 988 m water depth, and there were four sections (17*20 in, 14-3/4*17-1/2 in, 12-1/4 in and 8-3/3 in) drilled with HEM, the 36 in and 26 in section were drilled with sea water (SW) and pre-hydrated bentonite (PHB). The ROP in the section drilled with HEM was average 11.7m/h, the well TVD was 4448 m with 1.94 SG mud weight. Figure 12 was the well structure.

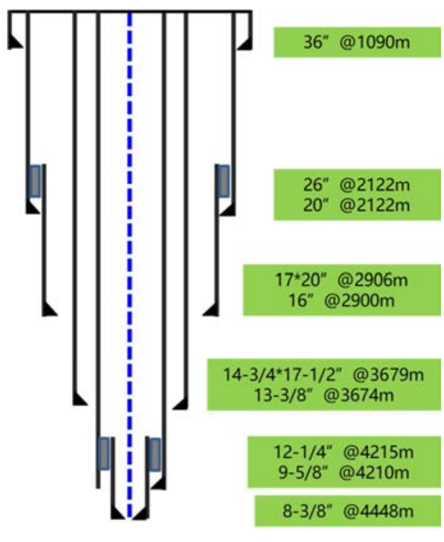

Figure 12. *Well structure.*

Table 2 illustrates system properties at the final TD, the results show that the HEM system provides good rheological properties with low MBT and filtration. In field application, the system showed good inhibition to shale and excellent flow pattern (figures 13, 14, 15, 16).

Table 2. *End properties of the HEM system.*

Name	Value
Mud weight, SG	1.94
FV, s	69
PV, mPa·s	66
Gel 10"/10´, lb/100 ft^2	4/9
MBT, kg/m^3	11
API filtration (mL)	2.0
HTHP filtration @150℃ (mL)	12.0
pH	11

Figure 13. *Drilling cuttings.*

Figure 14. *Flow state of HEM system curve.*

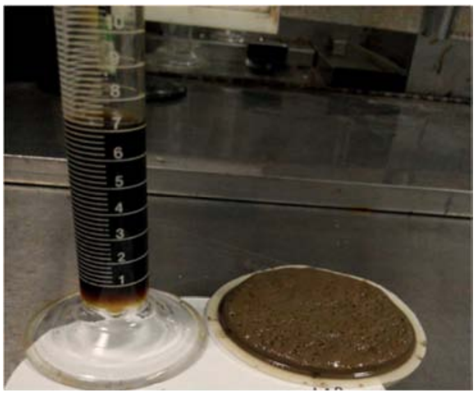

Figure 15. *Filtration and cake.*

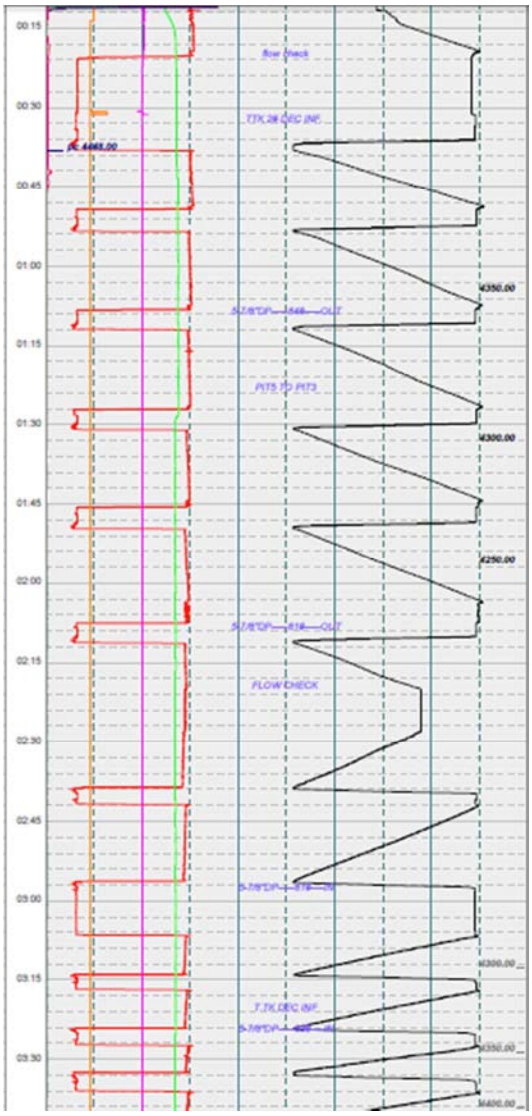

Figure 16. *Tirp curve.*

6. Conclusion

A new methodology named WSP was introduced to evaluate shale inhibition of amine derivative and the new method was used to evaluate PF-UHIB which showed a good inhibition to bentonite slurries. HEM system is suitable in South China Sea deepwater well drilling operation, and the well application proved that HEM system selected is an excellent alternative to OBM or SBM. The system delivered high drilling performance such as shale stability, clay inhibition, lubricity and high rate of penetration (ROP) with no wellbore problems, and the system provide improved HSE and eliminated the rig costs associating with drilling and waste management.

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