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DRILLING FLUIDS FOR HIGH TEMPERATURE WELLS

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Abstract

It is possible that the large oil and gas fields have already been discovered. The new discoveries are smaller, remote, deep water, or buried deep underground. Drilling deep wells often have to face the challenges from high temperature. It is especially challenging for drilling fluids to maintain desirable properties under a thermally-demanding environment over extended drilling time. This paper surveys the worldwide field cases of drilling fluids for high-temperature wells. According to field experiences, oil based mud and emulsion mud provides the best wellbore stability, thermal stability and rate of penetration (ROP). Water based formate mud is an alternative to oil based mud at a lower cost and less environmental impact. Formate mud also produced good wellbore integrity and good ROP. Foam mud is most suitable for drilling low-pressure formations with wellbore instability issues. The field case demonstrated foam mud was successfully implemented in a high-temperature and low-pressure well.

Keywords*: Drilling fluid; High temperature; Wellbore stability.*

1. Introduction

The growing demand for oil and gas has driven the drilling activities to very deep formations. According to US Mineral Management Services, more than 50% of proven petroleum reserves in the USA are buried deeper than 14,000 ft below seabed [1]. Deep drilling usually encounters high-temperature formations. In the Gulf of Mexico, the temperature of some formations exceeds 400°F (or 204°C). Besides, drilling deep wells often take a much longer time due to extended and complex well trajectory.

It is very challenging for drilling fluid to maintain desirable properties under high temperatures over a long period of time. The drilling mud for high-temperature wells must maintain ideal rheology to ensure the flow of drilling fluid while cuttings are transported to surface [2]. Most deep wells are directional wells or horizontal wells. Drilling fluid must provide good lubricity to reduce torque and drag. Moreover, drilling fluid must be able to maintain wellbore stability over an extended time. The last but not the least, drilling fluid should minimize the negative impact on the environment.

2. Drilling fluids for high temperature wells

Multiple drilling fluids have been successfully applied in drilling high-temperature wells, such as oil-based mud (OBM), emulsion mud, formate mud, and foam mud. These fluids have distinctive features, and their implementations in various fields are valuable lessons learnt for drilling HPHT wells in the future.

2.1. Oil-based mud

For Oil-based mud, water is the dispersed phase and oil is the continuous phase. Diesel is the most commonly-used base oil for OBM. Sometimes, mineral oil or refined white oil is used to reduce toxicity and gain better stability under high temperatures. Because OBM provides excellent lubricity and wellbore stability, OBM is widely used in drilling directional wells and shale formations [3]. However, oil-based mud is more costly than water-based mud. Besides, OBM may contaminate the environment and water aquifer if not handled properly.

2.1.1. North Sea, UK

Three HTHP wells were drilled with low-toxicity OBM at the North Sea field [4]. The mud was formulated with 89% oil and 11% water, but the detailed mud formula was not reported. For well A, the target formation pressure was as high as 17,000 psi, while the BHT (bottom-hole temperature) reached 380°F (or 193°C). Due to the failure of the top drive system, the BHA (bottom-hole assembly) was stuck, which resulted in sidetracking. While drilling the sidetrack, mud density was controlled at 18.6 lb/gal, PV was around 52 cP, YP was around 22 lb/100ft^2, and HTHP fluid loss was less than 4 ml. After completion of a sidetrack, two 90-ft cores were taken and eight open-hole logs were completed successfully while the mud was under static well conditions without gelation issues.

Well B was drilled near vertically to 18,000 ft without significant wellbore instability [4]. Stuck pipe occurred at several depths, possibly due to differential sticking, but was freed shortly. Coring and logging were carried out for 96 hours under static well conditions without mud gelation issue, despite the fact that the BHT was higher than 380°F (or 193°C). Well C demonstrated excellent wellbore stability and mud rheology under BHT of 340°F (or 171°C). Mud PV was between 60-65 cP, while mud YP was around 20 lb/100ft^2. Four open-hole logs were run under static well conditions without issues

2.1.2. Daqing Field, China

Located in northeast China, the Daqing field began producing in 1960. Till 2018, the accumulative oil output has reached 1.82 billion tons. In recent years, the annual oil production stabilizes around 40 million tons [5]. Well Pushen-1 at Daqing employed OBM to drill from 4,590 to 5,500 m, where the BHT reached 220°C. During 160 days of drilling, OBM maintains desirable rheology in the well, while mud PV was around 30-40 cP, and YP was 5-15 Pa. Multiple trips were made without difficulties. Washout was around 5% on average. Besides, multiple oil and gas zones were discovered, indicating limited formation damage [6].

Another well Gulong-1 at Daqing was completed at 6,300m depth, where the BHT reached 260°C [7]. Both well depth and BHT made records at Daqing. The mud system must achieve good stability under high temperature, excellent wellbore integrity, low filtrate loss, and low formation damage. OBM was able to meet such challenging demands. The mud formula is presented in Table 1, with low-toxicity mineral oil as the base oil. The mud also contained necessary chemicals to achieve desirable properties. After aging, mud properties remained stable, as seen in Table 2, which indicated good performance under high temperatures [8]. During drilling the well, clay was periodically added to achieve desirable viscosity and gel strength. Marsh funnel viscosity was maintained at 75-85 seconds. Fluid loss chemicals were used to control filtrate loss below 6ml. Besides, solid control equipment was operated at full capacity. The mud remained static inside well for 236 hours during logging, and both mud properties and wellbore stability were well maintained.

Table 1. Mud formula for well Gulong-1

Material	Concentration	Function
Mineral oil	90%	Base oil to provide lubricity and shale inhibition
Water	10%	Base water
Clay	6%	To provide initial viscosity and enhance emulsion stability
Surfactants	4%	To create emulsion under high temperature
Modified resin	6%	To reduce filtrate loss
Polymer	2%	To improve viscosity and gel strength under high temperature
CaO	5%	To adjust pH

Table 2. Mud properties after aging at high temperature

Mud sample	Density (g/mL)	PV (cP)	YP (Pa)	Gel strength 10s (Pa)	HTHP filtrate loss (mL)
Before aging	0.9	31	6	7	12
After aging at 250°C	0.9	30	6	7	13

2.1.3. Fuling Field, China

Located in the southwest municipality of Chongqing, the Fuling field came on stream in late 2012 and produced more than 6 Bcm (or 212 Bcf) of shale gas in 2018. The field's gas sales reached nearly 5.8 Bcm (or 205 Bcf), earning first place in both production and sales in China. By the end of 2018, the Fuling shale gas field had produced more than 21.5 Bcm (or 759 Bcf), making it the largest shale gas field outside North America [9].

Till late 2018, a totally of 438 wells had been drilled, while 321 wells were in production. Among them, more than 200 wells were drilled with diesel-based mud [10]. The typical mud formula is presented in Table 3. Laboratory aging tests were conducted with roller oven. Test results in Table 4 revealed that mud maintained stable viscosity and low filtrate loss at the high temperature of 160°C [3]. While drilling, mud YP was maintained at 10-20 Pa, marsh funnel viscosity was around 50-80 s, HTHP filtrate loss was below 3 mL, and ES (emulsion stability) was above 400 V to avoid segregation of water phase and oil phase. Excellent ROP and wellbore integrity were observed, as shown in Table 5. For well JY65-3HF, lost circulation occurred at 4,080 m (or 13,386 ft) and again at 4,096 m (or 13,438 ft). Fine carbonate particles and Nano-sized bridging materials were added into circulation to successfully battle lost circulation.

Table 3. Typical OBM formula at Fuling field

Material	Concentration	Function
Diesel	80%	Oil phase
35% $CaCl_2$ solution	20%	Water phase
Emulsifier	4.0%	Emulsify oil phase and water phase
Lime	1.5%	Adjust pH
Organic clay	1.0%	Provide initial viscosity and emulsion stability
Thickener	1.0%	Increase mud viscosity
Filtrate loss additive	3.0%	Reduce filtrate loss
Wetting agent	1.0%	Modify wettability of cuttings
Liquid asphalt	3.0%	Reduce filtrate loss
Oxidized asphalt	3.0%	Reduce filtrate loss
Plugging/sealing agent	3.0%	Reduce lost circulation

Table 4. Aging test results for OBM at Fuling field

Aging temperature (°C)	Density (g/mL)	AV (cP)	PV (cP)	YP (Pa)	Gel 10s/10min (Pa)	HTHP Filtrate (mL)
60	1.4	48	37	11	9/18	1.0
90	1.6	55	45	10	8/18	1.2
120	1.7	60	56	14	9/20	1.6
160	1.8	51	40	11	9/18	2.0

Table 5. Typical drilling performance with OBM at Fuling field

Well No.	Length of horizontal lateral (m)	Average ROP (m/h)	Average washout (%)
JY2-4HF	1,530	14.87	2.03
JY11-3HF	1,540	11.26	2.56
JY17-2HF	1,398	11.25	1.58
JY28-2HF	1,490	14.06	0.88
JY30-4HF	1,730	13.85	1.82
JY31-2HF	1,530	10.44	1.04

2.2. Emulsion mud

For emulsion mud, water is the continuous phase, and oil is dispersed in water. Emulsion mud provides very good lubricity and thermal stability. It is also less costly than OBM due to the reduced oil fraction. Because water is the continuous phase, emulsion mud has a limited impact on well logging operations.

2.2.1. Jidong Field, China

Jidong field occupies the northern part of Bohai Bay in northeast China. An emulsion mud was used to drill a horizontal well in the Jidong field [11]. The target zone is made of dolomite and limestone with developed fractures, while the bottom-hole temperature reached 220°C. The mud was formulated with 65% water, 35% diesel, 0.15% $NaCO_3$, 0.1% NaOH, 3% thickener, 5% emulsifier, 1% fluid loss additive, and 3% SMP-2. Mud specific gravity was 0.96-0.98 to achieve underbalanced conditions because the gap between pore pressure and fracture pressure was very narrow. The emulsion mud was introduced into the well NP36-P3002 at 5,593 m and drilled to a total depth of 5,738 m, where the inclination angle climbed from 73 to 81.76 degrees. Mud properties at various depths are presented in Table 6.

The drilling with emulsion mud took 13.5 days, and mud properties were stable under very high temperatures. A mudstone layer was encountered at 5,690-5,738 m. Drilling was smooth without a wellbore instability issue. Underbalanced drilling with emulsion mud led to a high ROP of 3.84 m/h, while ROP was 1.43 m/h for the nearby well drilled with KCl mud. The cost of emulsion mud was lower than OBM by 15%. Moreover, recycling 195 m^3 of emulsion mud further cut down costs.

Table 6. Properties of emulsion mud for well NP36-P3002

Depth (m)	PV (cP)	YP (Pa)	Gel 10s/10min (Pa)	HTHP Filtrate (mL)
5,601	38	9	2/4	12
5,673	42	10	3/5	11
5,701	42	11	3/4	12
5,738	36	12	2/4	11

2.2.2. Zhongyuan Field, China

Zhongyuan field is located in Henan Province of China. Emulsion mud was implemented in drilling several wells in the field. The mud was formulated with water, 30% white oil, 4% bentonite clay, 0.4% NaOH, 0.4% PAM, 0.5% LV-CMC, 4.5% TS-2, 0.7% ZR-1, and 1.5% FR-3 [12]. The mud properties for three wells are given in Table 7.

Table 7. Properties of emulsion mud for Zhongyuan field

Well No.	Funnel viscosity (s)	PV (cP)	YP (Pa)	Fluid loss (mL)	Gel 10s/10min (Pa)
Da-2	56-80	38	9	3-4	2/4
Wen23-40	63-85	42	10	3-4	3/5
Chengshen-7	52-66	42	11	1-2	3/4

Well Da-2 was designed to target 4,200 m TVD, where the bottom-hole temperature reached 160°C [12]. Mud density was maintained at 0.89-1.05 g/mL to achieve an underbalanced condition. The influx of carbon dioxide occurred when drilling progressed to 3,607 m. Mud was treated with CaO to remove carbon dioxide. No other complication was encountered. ROP was 27% higher than nearby wells.

For well Wen23-40, emulsion mud was used to drill from 3,070 to 3,400 m. The formation was a low-pressure zone with natural fractures. A nearby well could not reach design depth due to severe lost circulation. Underbalanced drilling with emulsion mud was free of trouble. ROP was 60% higher than nearby wells, and washout was only 3 mm on average [13].

For well Chengshen-7, the target was a high-temperature (170°C), low-pressure, unconsolidated sand with a high risk of lost circulation [14]. A coal zone existed at 3,040-3,046 m with a high risk of sloughing. The emulsion mud was used to drill from 2,400 to 4,269 m in underbalanced condition. Contamination of CO_3^{2-} and HCO^{3-} ions occurred at 4,000 m, but mud properties remained stable. ROP was 4.19 m/h, higher than the ROP of 3.58 m/h for a nearby well.

2.3. Formate mud

Formate brine systems were developed in the early 1990s by Shell as high-temperature fluids for drilling and completion. Since then, many additional benefits have been discovered for the fluids. The fluids were considered ideal as the base for completion and drilling fluids for a variety of demanding environments. Formate drilling fluid is most suitable when high density and low solids content fluid is required. Table 8 presents the density of formate brines. It can be seen that formate brines can reach high density with no weighting materials required.

Table 8. The density of formate brines

Product	Saturated concentration (w%)	Saturated density (g/mL)	pH
Sodium Formate	45	1.34	9.4
Potassium Formate	76	1.60	10.5
Cesium Formate	83	2.37	13.0

The various formate brines (sodium, potassium, and cesium formate) have been subject to a variety of tests by major operating and service companies, as well as environmental testing facilities. Formate brine systems have been found to possess a number of beneficial characteristics relating to oil and gas drilling and completion. The four main benefits include temperature stability, shale stability, low formation damage, good hydraulics, and high ROP due to low solids content. Other features include low toxicity and low corrosion tendency.

The temperature stability of polymers in brine-based drilling fluids has traditionally been a drawback of these systems [15]. Most brine-based fluids, particularly calcium-based fluids, will not properly hydrate biopolymer thickeners and fluid loss agents [16]. Even if they do, these fluids cannot maintain adequate fluid properties over a sufficient period of time at high temperatures over 95°C (or 200°F). Formate brines are known as high temperature fluids. In fact, this property was the primary reason for the initial development of formate drilling fluid by Shell. A large amount of research data backs up the stability of xanthan, various starches, and polyanionic cellulose (PAC) in the formate brine. Studies of transition temperatures of polymers in various formate brine indicated loss of viscosity at temperatures exceeding 190°C (or 375°F).

2.3.1. Kvitebjorn Field, North Sea

In the North Sea, Statoil drilled 7 wells with formate mud in the Kvitebjorn condensate field [17]. The challenges lied in high pressure (810 bar or 11,700 psi), high temperature (155°C or 311°F), interbedded shale, and high well inclinations. The drilling fluid was formulated with cesium formate, potassium formate, fluid loss additives (acrylamide polymer, modified starch, and PAC), and bridging material (calcium carbonate). Mud maintained the following properties during drilling: PV of 13-20 cP, YP of 1.4-3.8 Pa, and HTHP fluid loss of 6-16 mL.

The formate mud leads to low equivalent circulating density (ECD) and excellent borehole stability, even after 10-30 days of being open. ROP varied greatly at different locations and with a different types of bits. Among the 7 wells, two were completed with liners, and the others with screens. One well was completed in a record time of 12.7 days, while the average completion time is 20.9 days. The wells achieved high productivity and low skin factors.

2.3.2. Pre-Khuff Field, Saudi Arabia

The Pre-Khuff field in Saudi Arabia featured hard sandstone with interbedded shale and high formation temperature (120-177°C or 250-350°F). In 2005, Saudi Aramco drilled 3 horizontal wells at 4,237-4,450 m (or 13,900-14,600 ft) TVD with formate fluid [18]. Tinat-3 was drilled with sodium/potassium formate brine with a specific gravity of 1.47. The bottom hole static temperature reached 146°C (or 295°F). Use of formate mud significantly reduced surface mud pump pressure from a calculated 4,200 psi at 220 gpm (gallon/min) to 3,400 psi operating a high-speed steerable turbo-drill. Drag at 4,495 m (or 16,747 ft) was only 10,000 lbf compared to 50,000 lbf observed on other wells using KCl/polymer mud. Rotating torque was 20% less than another well drilled with KCl/polymer mud. The initial mud and maintenance cost to drill the 474 m (or1,556 ft) buildup/horizontal section was USD 439,000 for 2,400 bbl of formate fluid. At the end of drilling, around 1,800 bbl of formate mud was recovered for reuse, which reduced the actual mud cost for the section to USD 106,000. Tinat-3 and HWYH-201 produced excellent rates, the best seen to date in the field. After the successful trial, Saudi Aramco implemented formate mud in drilling 8 wells in Jauf field (150°C or 302°F), 16 wells in Khuff field (138°C or 280°F), and 20 wells in Unayzah field (162°C or 323°F).

2.4. Foam mud

Foam drilling employs foam as the circulating drilling fluid to transport cuttings to surface. Field experiences proved many advantages of foam mud, including high ROP, low risk of formation damage, long bit lift, low risk of lost circulation, and low mud cost. Foam mud reported a few successful field applications, such as the La Paz field in Venezuela [19], and the Tabnak field and Parsi field in Iran [20-21].

Located in east China, Shengli field began production in 1961, and annual oil production peaked at 33.55 million tons (about 250 million barrels) in 1991 [22]. Well 227-1HF at Shengli field was drilled with foam mud [23]. The target pay zone featured low pressure, low permeability and relatively high temperature (137°C). Laboratory tests revealed that the foam mud could tolerate high temperatures (180°C), while the linear swelling was very low. Foam mud was used to drill the 1,010m horizontal lateral from 3,525m to 4,534m. Detailed drilling data is presented in Table 9. Foam mud demonstrated excellent ability to stabilize wellbore and transport cuttings. The average ROP with foam mud was 6.21 m/h, while the ROP for the nearby well drilled with WBM was around 2 m/h.

Table 9. Drilling data with foam mud

Depth (m)	Liquid Rate (L/s)	Standpipe Pressure (MPa)	ROP (m/h)	Foam Half Life (min)
3,617	3.0	3.5	4.95	14
3,980	4.5	4.0	12.40	10
4,306	4.5	4.0	6.12	10
4,535	4.5	3.8	6.40	11

3. Summary and discussion

The previous section surveyed the field implementations and experiences of different types of drilling fluid for high-temperature wells. Those field cases are summarized in Table 10. According to the field cases in UK and China, OBM provides excellent rheology, lubricity, and wellbore stability under high temperatures up to 260°C for an extended period of time. Drilling with OBM also achieved higher ROP than other drilling fluids. Using mineral oil as the base fluid significantly reduces its toxicity. Despite the high costs and HSE concerns, OBM remains an excellent choice for battling high temperatures and wellbore instability.

Emulsion mud contains a lower fraction of the oil phase, therefore being cheaper than OBM. Field experiences show drilling with emulsion mud led to good wellbore stability and high ROP under high temperatures up to 220°C. Emulsion mud also provides good lubricity, even though its oil content is low. Both OBM and emulsion mud are good candidates for underbalanced drilling because the mud density can be adjusted across a wide range.

Formate mud is water-based mud (WBM) in nature. It aims to achieve good lubricity and wellbore stability at reduced costs and minimal impact on health, safety, and environment. Field cases demonstrate formate mud and MHA mud were successfully implemented under high temperatures up to 200°C. Moreover, good wellbore stability, high ROP, and high well productivity were observed. However, OBM does provide better lubricity than WBM, which is crucial for drilling directional wells. Besides, it is more challenging to customize and maintain the properties of formate mud and MHA mud to satisfy the thermal and well stability requirement of a specific formation.

Foam mud is a unique type of drilling fluid that is most suitable for drilling low-pressure formations at the underbalanced condition. The field case shows foam mud produced good wellbore stability, high ROP, and effective transport of cuttings under relatively high temperatures. The key to the success of foam mud at high temperature is a thermally-stable foaming agent that stabilizes properties of foam mud under challenging conditions.

Table 10. Summary of drilling fluids for high-temperature wells

Field Name	BHT (°C)	Type of drilling fluid	Observations
North Sea, UK	171-193	Low toxicity OBM	Good wellbore stability; Good mud rheology in static condition for 96 hours
Daqing, China	220-260	Mineral Oil Based Mud	Good mud rheology in static condition for 236 hours
Fuling, China	150	Diesel OBM	Good wellbore integrity; High ROP of 10-15 m/h;
Jidong, China	220	Emulsion mud	Good wellbore integrity; Good ROP of 3.84 h/h;
Zhongyuan, China	160-170	Emulsion mud	Good wellbore integrity; Good ROP of 4.19 m/h;
Kvitebjorn Field, Norway	155	Formate mud	High productivity and low skin factor
Pre-Khuff, Saudi Arabia	120-177	Formate mud	Low mud pump pressure; Low drag and torque; High production rates;
Shengli, China	137	Foam mud	Good wellbore stability; High ROP of 6.21 m/h;

4. Conclusion

A survey is conducted on drilling fluids for high-temperature wells. According to field cases, OBM delivered excellent wellbore stability and ROP at BHT up to 260°C. Emulsion mud produced similar lubricity and wellbore integrity at temperatures up to 220°C. Formate mud is a water-based mud that imitates the characteristics of OBM at lower costs and limited HSE issues. Field experiences demonstrated they could function at temperatures up to 200°C, but the maintenance of mud properties was more challenging than that for OBM. Foam mud achieved high ROP and good cutting transport under BHT of 137°C. It depends on thermally-stable foaming agents to extend its temperature range.

References

[1] Amani M, Jubouri M, Shadravan A. Comparative study of using oil-based mud versus water-based mud in HPHT field. Advances if Petroleum Exploration and Development, 2012; 4(2): 18-27.

[2] Gao C. Petroleum Drilling Technology, Science Press Beijing 2017, 25-35.

[3] Tan X. Application of domestic OBM in Fuling shale gas horizontal wells. Journal of Jianghan Petroleum University, 2015; 28(1): 26-29.

[4] Kabanov M, Telford E, Gray C. Designing and running a special oil-based mud for a North Sea HPHT campaign. SPE 170528 presented at Asia Pacific Drilling Conference in Bangkok 2014.

[5] Gao C. Petroleum Production Technology, Science Press Beijing 2018, 40-48.

[6] Yu X, Yao X, Lin S.Study and application of water-in-oil drilling fluid at 220°C. Petroleum Drilling Techniques, 2001; 29 (5): 45-47.
[7] Liang Y. Application of water-in-oil drilling fluid at well Gulong-1. Drilling Fluid and Completion Fluid, 2010; 27 (5), 15-17.
[8] Ren J. Application of water-in-oil mud at well GL-1 of 260°C. Exploration Engineering, 2017; 44(10): 51-54.
[9] Guo X, Li Y, Li J, Feng M. Discovery of Fuling shale gas field and its prospects. Frontiers in Energy, 2018; 13(2): 354-366.
[10] Liang W. Application of diesel based drilling fluid in development of Fuling shale gas field. Journal of Jianghan Petroleum University,2016; 29(4): 34-37.
[11] Wang W, Zhao Y, Li Z, Xie P. Application of oil in water mud at well NP36-P3002 of 200 deg. C. Drilling and Production Technology, 2015; 40 (4): 99-103.
[12] Ma W, Liu B, Lu G. Research and application of oil-in-water drilling fluid that is thermally stable at 180°C. Fault Block Oil and Gas Field, 2013; 20(2): 228-231.
[13] Zhang G, Xu J, Shi P, Wei J. Application of oil-in-water emulsion mud at Wengu-2. Drilling Fluid and Completion Fluid, 2002; 19 (3): 30-32.
[14] Shi P, Wang S, Huang D, Zheng D. Research and application of thermally stable oil-in-water drilling mud. Drilling and Production Technology, 2010; 33(1): 96-105.
[15] Gao C. Potential of welan gum as mud thickener. Journal of Petroleum Exploration and Production Technology, 2015; 5(1): 109-112.
[16] Gao C. 2016, Preliminary evaluation of gellan gum as mud thickener, Journal of Petroleum Exploration and Production Technology, 6(4), 857-861.
[17] Berg P, Pederson E, Howard S, Downs J, Harris M. Drilling and completing high-angle wells in high-density cesium formate brine – the Kvitebjorn experience 2004-2006. SPE Drilling and Production, 2009; 15-24.
[18] Simpson M, Reda S, Vice P. Application and recycling of sodium and potassium formate brine drilling fluids for Ghawar field HT gas wells. OTC 19801 presented at Offshore Technology Conference in Houston 2009.
[19] Rojas Y, Vieira P, Borrell M. Field application of near-balanced drilling using aqueous foams in Western Venezuela. SPE 74449 presented at IADC/SPE Drilling Conference in Dallas 2002.
[20] Chen G, Chen X, Liu D. Application of air and foam drilling in Tabnak gas field in southern Iran. SPE 10560 presented at Asia Pacific Drilling Conference in Bangkok 2006.
[21] Shirkavand F, Hareland G, Teichrob R. Optimized foam drilling improves drilling performance in Iranian carbonate fields. SPE 114057 presented at SPE western regional meeting 2008.
[22] Gao C, Shi J, Zhao F. Successful polymer flooding and surfactant-polymer flooding projects at Shengli oilfield, Journal of Petroleum Exploration and Production Technology, 2014; 4(1): 1-8.
[23] Ming Y, Lan Q, Zhang B. Application of foam mud in drilling a high-temperature well. Drilling Fluid and Completion Fluid, 2013; 30(5): 9-12.

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