Journal of Petroleum Exploration and Production Technology (2020) 10:2447–2452
https://doi.org/10.1007/s13202-020-00907-3

LETTER-- PRODUCTION ENGINEERING

# Glycol mud improves drilling performance in Chinese fields

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Received: 20 March 2020 / Accepted: 5 May 2020 / Published online: 12 May 2020


**Abstract**
Growing demand for oil and gas has driven drilling activities to deep formations and complex well structures. Drilling fluid must be able to maintain wellbore integrity and thermal stability over extended drilling time. Besides, drilling fluid should produce high rate of penetration (ROP) and low damage to formation rock. Glycol mud satisfies these criteria thanks to its unique cloud point phenomenon. When temperature exceeds cloud point temperature, glycol starts precipitate from mud by forming micelles, coats the rock surface, and plugs the small fractures in rocks. As a result, the flow of mud into rocks is restricted and wellbore stability is improved. This paper surveys more than 40 wells that were drilled with glycol mud. Field cases reported good wellbore integrity, thermal stability, high ROP, and low formation damage. Glycol mud is an excellent choice for battling well instability and high temperatures.

**Keywords** Drilling fluid · Glycol · Wellbore stability · Shale · Survey

## Introduction

Despite many years of research and practices, wellbore instability remains a major challenge for drilling oil and gas wells (Gao 2019). Wellbore instability may result in well pack-off, stuck pipe, lost borehole, and costly sidetracking. Wellbore stability is controlled by the complex mechanical and chemical factors such as earth stresses, rock strength, pore pressure, mud pressure, and mud chemistry (Bol et al. 1994). The problem of wellbore instability due to reactive shale is well known in the drilling industry. It is estimated that 75% of the formations consist of shale rocks. Shales are mainly composed of mud, silts, and clays. Clay minerals are flaky, mica-type crystalline in nature. Among the clay minerals, smectite has a high cation exchange capacity (CEC); therefore, it is prone to swelling and dispersion when in contact with water (Li et al. 2012). Illite, chlorite, and kaolinite have low CEC and low tendency to swell. However, another type of illite is produced by the transformation of smectite under high pressure and high temperature. This mixed layer illite has more tendency to swell than its original form.

Oil-based mud (OBM) is widely used for drilling through troublesome shale formations (Gao 2017). OBM contains small fraction of water, therefore reducing the swelling and dispersion of shale due to water invasion. However, the use of OBM is often restricted due to its environmental impacts (particularly in offshore drilling), high costs, and safety issue (Amani et al. 2012). Therefore, the design and development of water-based mud (WBM) with OBM performance is currently seen as an area of great interest in the oil industry.

One of the high-performance WBMs is glycol mud. A glycol is soluble at low temperatures, but starts to form micelles (molecular agglomerates) as the temperature is raised, thus becoming cloudy. The temperature at which this phenomenon occurs is named the cloud point temperature (CPT). Glycols, usually polyethylene glycol (PEG), are often used as shale inhibitors. The purported mechanism is that the glycol clouds out at higher downhole temperatures, coating the surface of clays and preventing shale hydration (Wang et al. 2009). Research also revealed that glycol effectively improved the thermal stability of certain polymers, thus reducing fluid loss and enhancing wellbore stability under high temperatures (Hu et al. 2003).

The cloud point temperature is influenced by glycol concentration. When glycol concentration increases, CPT first declines and then recovers, as shown in Fig. 1. Accordingly, glycol concentration of 2–5% is recommended in field implementation to take advantage of low CPT (Wang et al. 2009). Moreover, inorganic salts depress the CPT of glycol. For instance, when NaCl concentration increases to 10%,

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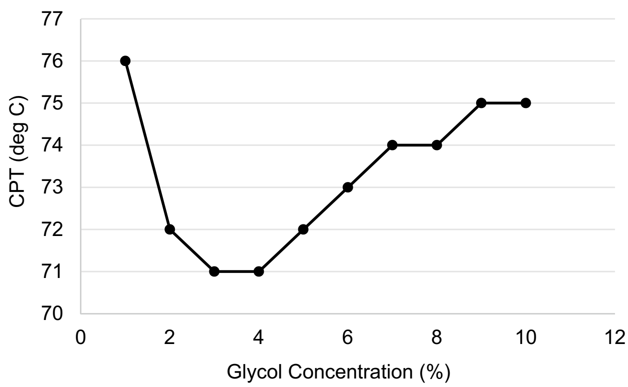


**Fig. 1** Effect of glycol concentration on CPT

**Table 1** Drilling program for Boshen-8

| Casing program | Casing setting depth (m) | Bit size (mm) |
|---|---|---|
| Conductor casing | 357 | 444.5 |
| Surface casing | 3228 | 311.2 |
| Intermediate casing | 4860 | 177.8 |
| Production casing | 5307 | 165.1 |

CPT drops from 75 to 65 °C. When $CaCl_2$ concentration reaches 10%, CPT is depressed to 60 °C.

## Field cases

In recent years, glycol mud gained popular field implementations, especially in China. Some typical field cases are surveyed in this section. These valuable field experiences can improve our understanding of glycol mud and serve as the guidance for future implementations of glycol mud.

### Bohai Bay, China

Well Boshen-8 was an exploration well drilled by Sinopec in Bohai Bay. The well was completed at 5,307 m, where the bottom-hole temperature reached 200 °C (Niu 2010). The drilling program is given in Table 1. Brittle shale was encountered below 3200 m TVD, which resulted in high risk of shale sloughing. Therefore, the mud system must effectively reduce filtrate loss and inhibit shale swelling. Moreover, relatively low pore pressure zone lays above the shale zone. High density mud may fracture the upper zone and result in lost circulation. As a result, mud density must be controlled carefully not to exceed formation fracturing pressure (Gao 2018).

Base mud contained clay and mud additives for HTHP applications, as shown in Table 2. The polymer and resin additives were applied to reduce filtrate loss, improve shale stability, and provide lubrication for drill bit and drill string. The base mud samples were aged at high temperatures for 16 h, and the mud properties were tested and are presented in Table 3. Test data revealed the base mud maintained high viscosity and moderate filtrate loss. In other words, the base mud was able to function properly under high temperatures.

Glycol and salt, such as NaCl and KCl, are often added to mud to inhibit shale swelling. Their effects on mud properties are presented in Table 4. After NaCl was added, both mud gel strength and filtrate loss increased. On the other hand, filtrate loss declined after glycol is applied, which revealed glycol reduced shale swelling by effectively reducing filtrate loss. With the selected mud system, the filtrate loss remained less than 12 ml during drilling, which lead to good wellbore integrity. The mud achieved good stability and lubricity at 200 °C. As a result, the drilling and tripping operations were smooth without incidents.

Three wells were drilled at Yuedong block of Bohai Bay from an artificial island (Liao et al. 2014). It was a challenge to maintain wellbore stability because unconsolidated mudstone was encountered at several depths. The drilling mud contained 3% PEG, 4% KCl, and necessary additives to control filtrate loss under 4 ml. While drilling, mud funnel viscosity was around 56–62 s, and

**Table 2** Base mud formula

| Material | Concentration | Function |
|---|---|---|
| Clay | 3% | To provide initial viscosity |
| PA-1 (modified polyamide) | 2% | To reduce filtrate loss at HPHT |
| SPNH (lignite resin) | 1% | To inhibit shale and provide lubrication |
| SPC (modified resin) | 3% | To reduce filtrate loss at HPHT |

**Table 3** Effect of temperature on mud properties

| Test sample | Aging conditions | PV (cp) | YP (Pa) | Gel strength 10 min (Pa) | Filtrate (ml) |
|---|---|---|---|---|---|
| Base mud | No aging | 30 | 3 | 4 | 5 |
| Base mud | 180 °C/16 h | 20 | 2 | 1 | 4 |
| Base mud | 220 °C/16 h | 32 | 6 | 5 | 4 |
| Base mud | 250 °C/16 h | 25 | 11 | 5 | 7 |

**Table 4** Effect of salt and glycol on mud properties

| Test sample | Aging condition | PV (cp) | YP (Pa) | Gel strength (Pa) | Filtrate loss (ml) |
|---|---|---|---|---|---|
| Base mud | 250 °C/16 h | 25 | 11 | 5 | 7 |
| Salt mud (base mud + 5% NaCl) | No aging | 23 | 10 | 35 | 9 |
| Salt mud (base mud + 5% NaCl) | 250 °C/16 h | 44 | 27 | 50 | 7 |
| Glycol mud (base mud + 5% glycol) | No aging | 12 | 2 | 25 | 2 |
| Glycol mud (base mud + 5% glycol) | 250 °C/16 h | 13 | 2 | 23 | 3 |

**Table 5** Comparison of glycol mud and oil-based mud

| Well No. | Mud Type | Interval | Inclination angle (deg.) | ROP (m/h) | Mud specific gravity |
|---|---|---|---|---|---|
| A7 | Glycol mud | 3636–4206 | 20.25 | 18.00 | 1.46 |
| A11 | Glycol mud | 3483–4106 | 24.87 | 16.93 | 1.45 |
| A23 | Glycol mud | 3728–4181 | 46.00 | 13.32 | 1.15 |
| A17 | Glycol mud | 3847–4860 | 36.91 | 10.58 | 1.54 |
| A15 | Glycol mud | 4038–5060 | 47.80 | 11.78 | 1.52 |
| A1 | OBM | 3654–5010 | 36.32 | 10.47 | 1.53 |
| A2 | OBM | 3442–4398 | 21.00 | 9.91 | 1.54 |
| A5 | OBM | 3077–4073 | 0 | 9.51 | 1.61 |
| A18 | OBM | 3277–3730 | 12.22 | 4.00 | 1.52 |

mud YP was around 11 Pa. Solid control equipment was operated at high capacity. The wellbore drilled with PEG mud measured lower washout (15–18%) than nearby wells drilled with other muds (23–25%). It proved that PEG was effective at enhancing wellbore stability.

Seven directional wells were drilled with glycol mud at BZ251 block in Bohai Bay (Liu and Guo 2014). The reservoir featured low porosity, low permeability, and abnormal pore pressure. Drilling was faced with high risks of formation damage and lost circulation. The mud was formulated with sea water, 3% glycol, 5% potassium formate, and other chemicals. While drilling, mud funnel viscosity was 40–45 s, mud PV was 14–24 cP, mud YP was 9–15 Pa, API filtrate loss was below 3 ml, and HTHP filtrate loss was less than 10 ml. Drilling was successful without accidents. Among the seven wells, five wells were flowing naturally upon completion, which indicated that glycol mud effectively protected formation permeability. Glycol mud achieved higher ROP than nearby wells drilled with OBM, as shown in Table 5.

**Table 6** Drilling program for Nanpu-54

| Casing program | Casing setting depth (m) | Bit size (mm) |
|---|---|---|
| Conductor casing | 300 | 660.4 |
| Surface casing | 2340 | 444.5 |
| Intermediate casing | 4421 | 311.2 |
| Intermediate casing | 5359 | 215.9 |
| Production casing | 5500 | 152.4 |

## Jidong field, China

Jidong field occupies the northern part of Bohai Bay. Well Nanpu-54 at the field was completed at 5,500 m TVD, where the bottom-hole temperature reached 195 °C (Zhu et al. 2009). The drilling program is given in Table 6. Drilling through layers of unconsolidated sands and brittle shales presented challenges for drilling mud. The drilling mud must generate low filtrate loss and high competence in shale stability. As such, the mud was formulated with sea water, formate salt, and glycol to achieve the desired performance. The detailed mud formula is presented in Table 7.

Mud samples were aged at 200 °C for 16 h in laboratory, and the mud properties are presented in Table 8. After aging, the mud still demonstrated good performance, especially the very low filtrate loss. During drilling, mud samples were taken at various depths and the properties were measured and are presented in Table 9. While drilling progressed deeper, mud plastic viscosity and yield point declined, but remained at an acceptable level, while the mud filtrate loss remained low. The drilling, logging, and cementing operations were successful without accidents. Caliper log showed the wellbore was only 1.8–4.5% larger than bit size, indicating excellent wellbore integrity.

## Jilin field, China

Four wells at Jilin field in northern China were drilled with solid-free glycol mud (Li and Li 2012). The sandstone field was characterized with low porosity (4%), low permeability (50 md), and high bottom-hole temperature (160 °C). Therefore, a solid-free mud was designed to drill through the

**Table 7** Mud formula for Nanpu-54

| Material | Concentration | Function |
|---|---|---|
| Clay | 5% | To provide initial viscosity |
| Potassium formate | 5% | To inhibit shale swelling |
| Glycol | 2% | To inhibit shale swelling and reduce filtrate loss |
| SMP | 2% | To reduce filtrate loss |
| SPNH | 2% | To inhibit shale swelling and provide lubrication |
| DSP | 2% | To reduce filtrate loss |
| A-20 | 0.1% | To maintain mud performance at high temperature |
| SP-80 | 0.3% | To maintain mud performance at high temperature |

**Table 8** Mud properties after aging

| Mud sample | Density (g/ml) | PV (cp) | YP (Pa) | Gel at 10 min (Pa) | Filtrate loss (ml) |
|---|---|---|---|---|---|
| Before aging | 1.5 | 80 | 24 | 8 | 3 |
| After aging | 1.5 | 45 | 12 | 20 | 4 |

**Table 9** Mud properties at various depths

| Well depth (m) | PV (cp) | YP (Pa) | Gel strength (Pa) | Filtrate loss (ml) |
|---|---|---|---|---|
| 4600 | 40 | 20 | 12 | 5 |
| 4800 | 40 | 17 | 18 | 4 |
| 4900 | 45 | 16 | 11 | 4 |
| 5000 | 33 | 10 | 5 | 6 |
| 5200 | 26 | 9 | 5 | 6 |

**Table 10** Mud properties at various temperatures

| Test temperature (°C) | PV (cp) | Filtrate Loss (ml) | Gel 10 s (Pa) |
|---|---|---|---|
| 25 | 25 | 6.0 | 0.5 |
| 120 | 30 | 5.6 | 1.5 |
| 140 | 31 | 5.8 | 1.5 |
| 160 | 32 | 5.9 | 2.0 |

pay zone to reduce formation damage. The mud was formulated with water, 3% glycol, sodium formate, biopolymer as thickener, and PAM as filtrate depressant. The mud was first tested in laboratory, and the results are given in Table 10. It can be seen the mud system maintained good viscosity and low filtrate loss at high temperature. The mud also demonstrated good performance under contamination of calcium ions, as shown in Table 11.

The wells were drilled to 4,100 m. While drilling the wells, mud properties were carefully controlled with mud

**Table 11** Mud properties under effects of aging and calcium ions

| Test sample | Test condition | PV (cp) | Filtrate loss (ml) | Gel at 10 s (Pa) |
|---|---|---|---|---|
| Base mud | 25 °C/no aging | 23 | 6.0 | 1 |
| Base mud | 160 °C/24 h aging | 28 | 6.0 | 2 |
| Base mud + 2%CaCl2 | 25 °C/no aging | 23 | 6.5 | 1 |
| Base mud + 2%CaCl2 | 160 °C/24 h aging | 30 | 6.0 | 2.5 |

additives. The mud properties at various depths are presented in Table 12. Moreover, the mud density was controlled at 1.05–1.15 g/ml to achieve underbalanced drilling condition. The solid-free mud system required solid control equipment working at high efficiency. On the other hand, corrosion inhibitors were applied to reduce corrosion from sodium formate. Compared with nearby wells drilled with clay mud, glycol mud achieved high ROP and high gas production rates after wells came on stream, as shown in Table 13.

## Huaz field, China

The Huaz field is located in Jiangsu basin in southeast China. The field features thin pay zones with low permeability. At early stage of field development, KCl-polymer mud was used in drilling, but 3 wells experienced severe lost circulation, and 6 wells encountered wellbore sloughing, which resulted in stuck pipe, formation damage, and more than 100 h of non-productive (He et al. 2009).

In 2007, glycol mud was used in drilling 21 wells at the field. The mud was made of 5% clay, 3% glycol, and other chemicals. While drilling, mud funnel viscosity was controlled at 45–50 s, mud PV was 18–20 cP, and fluid loss was below 5 ml. The mud solid content was controlled below 10% with solid control equipment. With glycol mud, average drilling time reduced by 10 days, wellbore washout was less than 6%, and very low formation damage was observed.

**Table 12** Mud properties at various depths during drilling of well No. 6

| Depth (m) | Density (g/ml) | PV (cp) | YP (Pa) | Gel at 10 s (Pa) | Funnel viscosity (s) | Filtrate Loss (ml) |
|---|---|---|---|---|---|---|
| 3100 | 1.05 | 22 | 8 | 0.5 | 75 | 7 |
| 3500 | 1.10 | 29 | 11 | 1.5 | 86 | 5 |
| 3800 | 1.11 | 31 | 12 | 1.5 | 82 | 4 |
| 4200 | 1.11 | 32 | 13 | 2.0 | 85 | 4 |

**Table 13** Comparison of clay mud and glycol mud

| Well no. | Mud type | Solid fraction (%) | ROP (m/hour) | Gas production rate (1000 m3/day) |
|---|---|---|---|---|
| 101 | Emulsion mud | 17 to 31 | 1.65 | 110 |
| 301 | Polymer mud | 15 to 26 | 1.26 | 89 |
| 006 | Glycol mud | 0 | 1.95 | 150 |
| 304 | Glycol mud | 0 | 2.01 | 120 |
| 204 | Glycol mud | 0 | 2.03 | 130 |

## Changning Field, China

The Changning and Weiyuan shale gas fields are located in south Sichuan basin, west to the city of Chongqing with 10 Bcm gas reserve (Xie 2018). The primary producing zone is the Longmaxi (LMX) formation about 300–400 m in thickness. XRD analysis showed the mineralogy was mainly clay, quartz, and dolomite. Drilling started in 2009, and 127 wells were producing a total of 8.14 million $m^3$/day of gas from the two shale plays in late 2018.

Even though OBM has dominated the shale drilling market, innovations in WBM lead to a few successful field applications at major shale plays (Deville et al. 2011). Well Ning206 was drilled with a mud made of 3% clay, 4% glycol, 10% organic salt, and other chemicals. The glycol mud was used to drill from 1680 m to 1920 m. While drilling, the funnel viscosity was around 41 s, mud PV was 12–16 cP, mud YP was 1–4 Pa, and fluid loss was less than 4 ml. Mud rheology was stable over long drilling time. Glycol mud produced very good wellbore stability with 1.2% washout and high rate of penetration (ROP). PDC bit achieved ROP of 11 m/h with glycol mud, while ROP was 6.3 m/h with three-cone bit (Xiao et al. 2011).

## Summary and discussions

The field cases surveyed are summarized in Table 14. According to the field cases, glycol mud demonstrated 4 advantages. (1) The primary purpose of glycol mud is to battle wellbore instability. Most field cases reported that glycol mud produced excellent wellbore integrity. When temperature exceeds CPT, glycol separates from mud, coats rock surface, and plugs the small fractures in shales. This process reduces the contact between mud and reactive shale, thus enhancing wellbore stability. (2) Several field cases reported that glycol mud maintained excellent stability under high BHT up to 200 °C. This proves glycol is able to enhance the thermal stability of mud chemicals. (3) Some wells drilled with glycol mud reported excellent ROP. The high ROP is attributed to the good lubricity, low solid contents, and

**Table 14** Summary of field cases with glycol mud

| Location | Number of wells | Challenges | Drilling results |
|---|---|---|---|
| Bohai Bay | 1 | High temperature (200 °C); brittle shale; high risk of lost circulation | Good well stability; good lubricity |
| Yuedong block in Bohai Bay | 7 | High risk of wellbore instability | Good wellbore integrity |
| BZ251 block in Bohai Bay | 7 | High risks of formation damage; high risk of lost circulation; | ROP higher than OBM; low formation damage; |
| Jidong field | 1 | High temperature (195 °C); | Excellent wellbore integrity |
| Jilin field | 4 | High temperature (165 °C); low porosity and low permeability | High ROP; high production rates |
| Huaz field | 21 | Low permeability; lost circulation; wellbore instability | Good wellbore integrity; reduced drilling time; low formation damage |
| Changning field | 1 | Reactive clay; shale sloughing | High ROP; good wellbore integrity |

reduced bit balling when glycol mud is used. (4) Several field cases reported low skin factors and high production rates. After glycol forms a barrier on rock surface, the flow of mud into the rock is restricted, leading to low formation damage and low skin factors.

## Conclusions

Glycol demonstrates a unique cloud point phenomenon. When temperature exceeds CPT, glycol separates out from mud. Glycol then forms a coat on rock surface and plugs the small rock fractures. As a result, contact between mud and rock is reduced and wellbore stability is enhanced. In recent years, glycol mud gained popularity in Chinese fields. This paper surveys more than 40 wells drilled with glycol mud. According to field experiences, glycol mud led to excellent wellbore integrity, good thermal stability, high ROP, and low formation damage.



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