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The Effect of Contact Surfaces on the Lubricity of Brine and Water-Based Drilling Fluid

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Abstract

The efficiency of extended-reach drilling has increased tremendously in recent years. Records are being set for the drilling time and drilled wellbore length on a regular basis. Among all the drilling fluid components, lubricant is one of the most critical in ensuring the success of drilling operations. Using the right lubricant directly impacts the rate of penetration and the subsequent length of the horizontal lateral.

In this study, the effect of contact surfaces on fluid lubricity was investigated using two instruments: a dynamic lubricity tester and a lubricity evaluation monitor (LEM). Steel-steel contacts and steel-shale rock contacts were used to simulate downhole scenarios involving cased and open-hole operations. Clear brine and solids-laden water-based mud (WBM) were used as based fluids in this study. A range of lubricants with various chemistries was evaluated for their effectiveness in reducing the contact friction. In addition, a field experiment was performed to study the effect of fluid and lubricant on operational efficiencies.

Our results show that the nature of the contact surfaces affects the measured fluid lubricity significantly. Overall, the use of lubricant in WBM achieved greater friction reduction with steel-steel contact than with steel-shale contact. This can be due to the difference in surface roughness of steel and shale rock. More friction was reduced when lubricant was used in solids-free clear brine than in solids-laden WBM. When solving friction-related problems in the field, it is important to understand the specific problem so that the most suitable lubricant can be applied accordingly.

Introduction

The efficiency of extended-reach drilling (ERD) has increased tremendously in recent years. Technologies such as multi-well pad horizontal drilling have enabled the operators to access the maximum potential of hydrocarbon reservoirs at a lower cost. In the US, longer horizonal laterals are being drilled every day at a faster pace. Record drilled length of laterals is being set on a regular basis on major US shale basins. For example, in 2019, the longest laterals drilled in the Marcellus and Permian formations were 17,935 feet and 18,683 feet respectively (Southwestern Energy 2019; Veazey 2019).

One major challenge in drilling extended-reach wells is friction control. A significant amount of energy delivered through downhole equipment is used to counter frictional resistance between the drillstring and the casing or open hole. Various strategies, including advanced mechanical tools, improved hole cleaning and using the appropriate drilling fluid system, have been employed to reduce drilling-related frictional power loss (Schamp et al. 2006).

While oil-based mud (OBM) and synthetic-based mud (SBM) are still the preferred drilling fluid choices in land-based drilling in the US for their superior performance downhole, operators have also turned to water-based mud (WBM) in many cases for economic and environmental reasons. Lubricant is one of the most critical WBM components in reducing downhole friction and ensuring drilling success. Selecting the right lubricant directly impacts the rate of penetration and the subsequent length of the horizontal lateral.

For that purpose, various lubricity meters have been used in the laboratory to evaluate the performance of lubricant (Zhou et al. 2017; Zhou et al. 2019). However, most of such fluid lubricity measurements were performed on metal-metal contact surfaces, providing useful insight on the friction between the drillstring and the casing. The design of lubricity meters and the lack of representative core samples have limited the ability to evaluate fluid lubricity on metal-rock contact surfaces.

This paper is a continuation of our previous investigation on the effect of lubricant on brines and WBMs (Zhou et al. 2019). In this study, the effect of contact surfaces on fluid lubricity was investigated using two instruments: the dynamic lubricity tester and the lubricity evaluation monitor (LEM). Steel-steel contact and steel-shale rock contact were used to simulate downhole scenarios involving cased and open-hole operations. Clear brine and solids-laden WBM were used as baseline fluids in this study. A range of lubricants with various chemistries was evaluated for their effectiveness in reducing the contact friction. In addition, a field experiment was performed to study the effect of fluid and lubricant on operational efficiencies.

Materials and Methods

Water-Based Fluids

A solids-free clear brine and a solids-laden WBM were used as the baseline fluids in this study. The brine used was a 12 wt% NaCl brine with a density of 9.0 ppg. A saturated salt mud with a density of 14.0 ppg was used as the WBM in this study. Tables 1 and 2 show the components and rheological properties of the WBM.

Table 1: Components of the saturated salt mud (Zhou et al. 2019).

WBM	Components
Saturated salt mud	Water, NaCl salt, Attapulgite clay, PAC, starch, xanthan gum, barite

Table 2: Properties of the saturated salt mud (Zhou et al. 2019).

	After hot rolling at 150ºF for 16 hours
Mud weight, ppg	14.0
Θ600/ Θ300 @120°F	87/57
Θ200/Θ100	46/33
Θ6/Θ3	13/12
Plastic Viscosity, cP	30
Yield Point, lb./100 ft^2	27
10 sec gel, lb./100 ft^2	14
10 min gel, lb./100 ft^2	23

Lubricants

Five liquid lubricants were evaluated with these water-based fluids in this study. Several of these lubricants were based on green chemistry. Table 3 shows the generic chemistry of each lubricant. Lubricants B, C, D and E were used in the 9.0 ppg NaCl brine while Lubricants A, C, D and E were used in the 14.0 ppg saturated salt mud. The lubricants were added to the baseline fluids at 3 vol%, unless otherwise stated.

Table 3: Generic chemistries of the lubricants used in this study.

Lubricant	Generic Chemistry
Lubricant A	Ester blend, fresh water and monovalent brine lubricant
Lubricant B	Ester blend, salt water lubricant
Lubricant C	Ester blend, fresh water lubricant
Lubricant D	Ester, vegetable oil and mineral oil blend lubricant
Lubricant E	Sulfonated vegetable oil

Lubricity Measurement Techniques

In this study, two instruments were employed to measure fluid lubricity: 1) The dynamic lubricity tester, and 2) The lubricity evaluation monitor (LEM). Details on the two lubricity measurement instruments can be found in Zhou et al. (2019). The fluid lubricity was measured at ambient conditions with steel-steel contact and steel-shale rock contact. The rock samples used were from the Eagle Ford formation in South Texas.

For lubricity measurements using the dynamic lubricity tester, the contact surface was horizonal and an axial loading of 30 psi was applied during the test. Three different rotational speeds were applied on the rubbing shoe: 20 revolutions per minute (RPM), 40 RPM and 60 RPM. At each speed, three measurements were taken for eight minutes each, with a one-minute interval in between so that fresh fluid can be re-introduced to the contact interface. For lubricity measurements using the LEM, the contact surface was vertical, and the loads applied between the contact surfaces were 30 lbf and 60 lbf respective. At each load, two measurements were taken for five minutes each, with a one-minute interval in between so that fresh fluid can be re-introduced to the contact interface. In the meantime, fluid was circulated by using a peristaltic pump during the lubricity test with the LEM pump (Zhou et al. 2019).

Results and Discussion

Effect of Contact Surface on Brine Lubricity

Figures 1 and 2 show the lubricity of the 9.0 ppg NaCl brine on the steel-steel and the steel-shale contact with and without lubricant measured with the dynamic lubricity tester. The lubricity of the NaCl brine was greater on the steel-shale contact than on the steel-steel contact. The coefficient of friction (CoF) of the steel-steel contact without any lubricant was 0.30, while that of the steel-shale contact was 0.20 – 0.25.

Similarly, the measurements from using the LEM also show that the NaCl brine lubricity was greater on the steel-shale contact than on the steel-steel contact when no lubricant was added. Figures 3 and 4 show that the CoF of the steel-steel contact without any lubricant was 0.30, while that of the steel-shale contact was 0.20 – 0.25. The lower measured friction on the steel-shale contact than on the steel-steel contact can be due to the surface roughness of the shale rock. A piece of shale rock has a rougher surface than a polished steel block, enabling more fluid to enter the contact interface and provide additional lubrication when the contact surfaces are moving against each other.

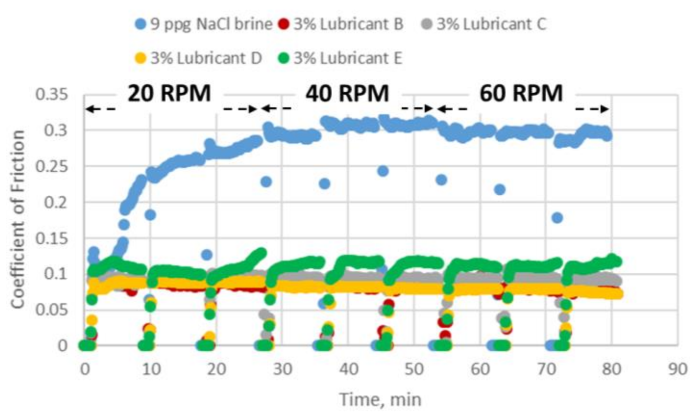

Figure 1: Lubricity of 9.0 ppg NaCl brine on steel-steel contact measured with the dynamic lubricity tester.

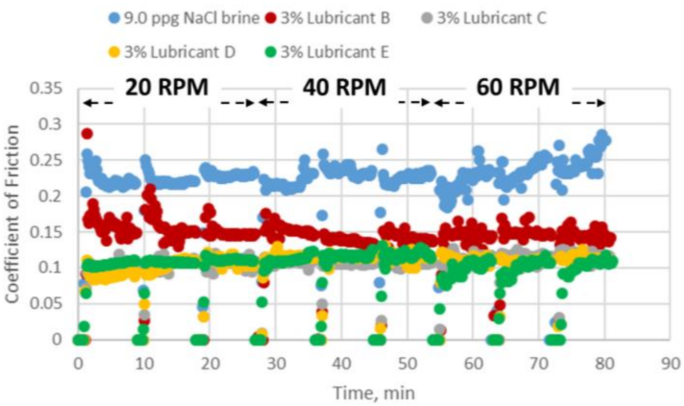

Figure 2: Lubricity of 9.0 ppg NaCl brine on steel-shale contact measured with the dynamic lubricity tester.

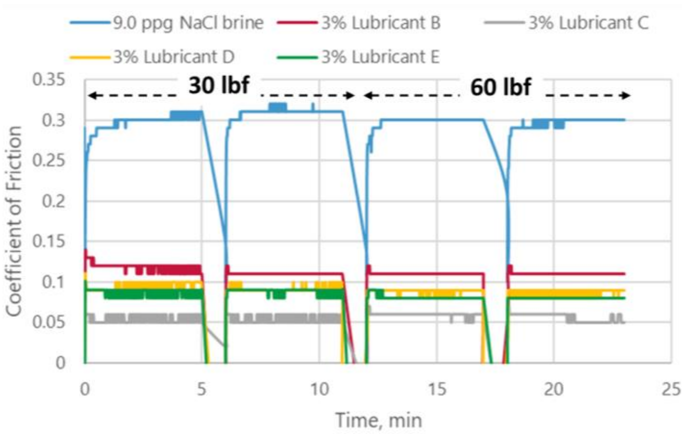

Figure 3: Lubricity of 9 ppg NaCl brine on steel-steel contact measured with the LEM.

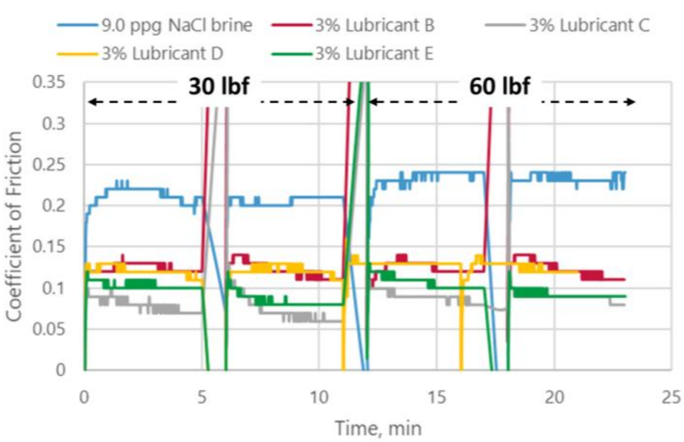

Figure 4: Lubricity of 9 ppg NaCl brine on steel-shale contact measured with the LEM.

Effect of Contact Surface on WBM Lubricity

Figures 5 and 6 show the lubricity of the 14.0 ppg saturated salt mud on the steel-steel and steel-shale contact measured with the dynamic lubricity tester. In general, the lubricity of the saturated salt mud was greater on the steel-steel contact than on the steel-shale contact. The CoF of the steel-steel contact without any lubricant was 0.17 – 0.20, while that of the steel-shale contact was 0.25 – 0.30.

In contrast, the lubricity measurements from using the LEM show that at a load of 30 lbf, the CoF of the steel-steel contact was similar to that of the steel-shale contact. However, when the load was increased to 60 lbf, the CoF of the steel-steel contact was greater than that of the steel-shale contact. At a load of 60 lbf, the CoF of the steel-steel contact was 0.23 while that of the steel-shale contact was 0.18.

The difference in the observed fluid lubricity of the WBM and the NaCl brine can be caused by the large concentration of solids in the WBM system. The presence of solids can act as a lubricating agent. In the case of steel-steel contact, even though steel surfaces appear to be very smooth, a large degree of surface asperities still exist at micro and sub-micro level. As a result, significant friction will be created when two steel surfaces move against each other. On the other hand, the solid particles in WBM were shown to have a lubricating effect between the steel surfaces. Therefore, the measured CoF of the steel-steel contact was lower in solids-laden WBM than in solids-free NaCl brine.

In comparison, the CoF of the steel-shale contact increased slightly from 0.20 – 0.25 to 0.25 – 0.30 when the fluid changed from the solids-free NaCl brine to the solids-laden WBM. In this case, since one of the contact surfaces was a natural shale rock, a greater concentration of solids in the WBM might be deposited on it. Instead of helping alleviate the friction, the excessive concentration of solids might create more friction between the steel and the shale rock when they move against each other.

In contrast, when the LEM was used to measure the lubricity of the solids-laden WBM, the CoF of the steel-steel contact at 30 lbf was about the same as that of the steel-shale contact. When the load was increased to 60 lbf, the CoF of the steel-steel contact was shown to be slightly greater than that of the steel-shale contact. This difference in the measured fluid lubricity with the solids-laden WBM can be due to the vertical orientation of the contact surfaces on the LEM. The concentration of solids between the contact surfaces on the LEM was lower than that between the contact surfaces on the dynamic lubricity tester.

In general, when using the two lubricity measurement instruments, the CoF of both the steel-steel and the steel-shale contact was reduced when the fluid was changed from the NaCl brine to the WBM. This friction reduction shows the lubricating effect of the solids in the WBM. The only exception was when the dynamic lubricity tester was used to measure the fluid lubricity on the steel-shale contact. This is probably because of the excessive accumulation of the solids on the horizontal shale surface, resulting in additional friction when the steel rubbing shoe moved against the shale block.

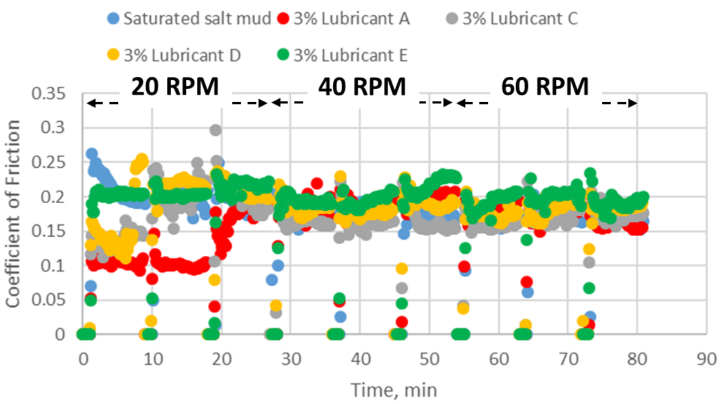

Figure 5: Lubricity of 14.0 ppg saturated salt mud on steel-steel contact measured with the dynamic lubricity tester.

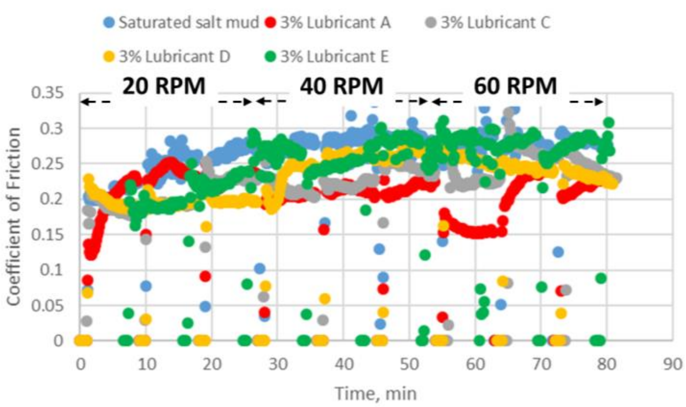

Figure 6: Lubricity of 14.0 ppg saturated salt mud on steel-shale contact measured with the dynamic lubricity tester.

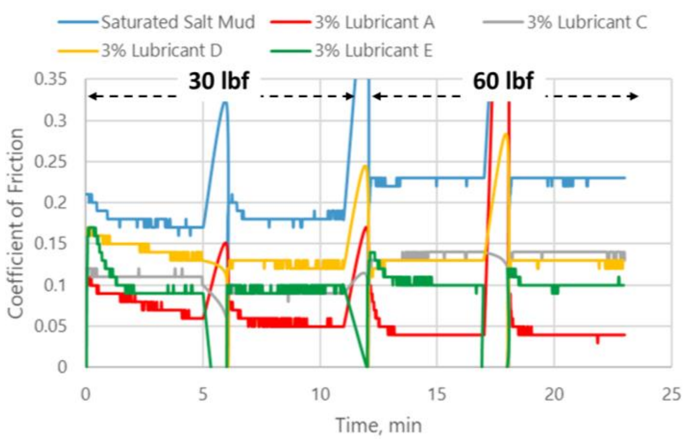

Figure 7: Lubricity of 14.0 ppg saturated salt mud on steel-steel contact measured with the LEM.

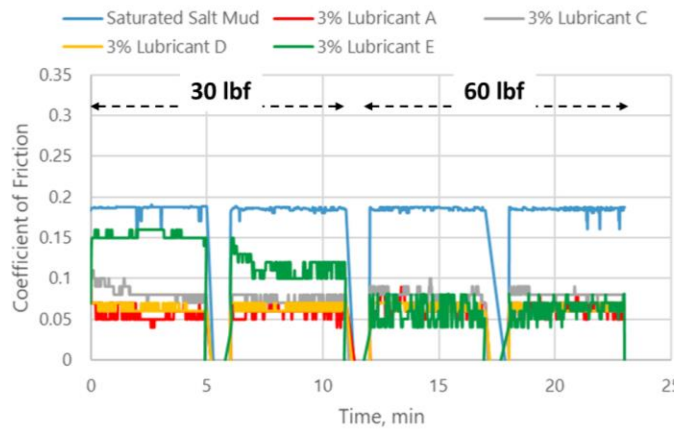

Figure 8: Lubricity of 14.0 ppg saturated salt mud on steel-shale contact measured with the LEM.

Effect of Lubricant on Brine Lubricity

Figures 1 and 2 also show the effect of lubricant on the lubricity of NaCl brine when the dynamic lubricity tester was used. With lubricant, greater friction reduction was achieved on the steel-steel contact than on the steel-shale contact. The CoF of the steel-steel contact was lowered from 0.30 to 0.08 – 0.12 when lubricant was added to the NaCl brine, a friction reduction of 60% - 73%. In comparison, the CoF of the steel-shale contact was reduced from 0.20 – 0.25 to 0.10 – 0.15, a 40% – 60% reduction in friction. This difference in friction reduction with lubricant can be attributed to the greater affinity of the liquid lubricant to the steel surface than to the shale rock surface as well as the higher CoF of the steel-steel contact with the brine. In terms of the performance of individual lubricant, these lubricants achieved similar friction reduction on the steel-steel contact. However, Lubricants C, D and E were shown to be slightly more effective than Lubricant B in reducing the friction of the steel-shale contact.

The observed difference in the degree of friction reduction between the two types of contact surfaces was also confirmed by the measurements from using the LEM. The CoF of the steel-steel contact was lowered from 0.30 to 0.05 – 0.12 when lubricant was added to the NaCl brine, a friction reduction of 60% - 80%. In contrast, the CoF of the steel-shale contact was reduced from 0.20 – 0.24 to 0.06 – 0.14, a 40% – 70% friction reduction. Similar to the lubricity measurements obtained using the dynamic lubricity tester, greater friction reduction was achieved on the steel-steel contact than on the steel-shale contact after lubricant was added to the NaCl brine. In terms of the performance of individual lubricant, Lubricant C resulted in greater friction reduction on the steel-steel contact than the other lubricants. In contrast, Lubricants C and E were slightly more effective than Lubricants B and D in reducing the friction of the steel-shale contact.

In summary, the lubricity measurements from using both instruments show that greater friction reduction was achieved on the steel-steel contact than on the steel-shale contact when various lubricants were added to the NaCl brine. This was because of the larger friction of the steel-steel contact without any lubricant as well as the greater affinity of the lubricants to the steel than to the shale rock surface.

Effect of Lubricant on WBM Lubricity

Figures 5 and 6 show the effect of lubricant on the lubricity of WBM when the dynamic lubricity tester used. Minimum friction reduction was achieved when lubricant was added to the solids-laden WBM. On the steel-steel contact, the average CoF with lubricant addition was 0.15 – 0.20, down from 0.20 – 0.25 when no lubricant was used in the WBM. Similarly, on the steel-shale contact, the average CoF of the WBM was reduced from 0.25 – 0.30 to 0.20 – 0.25 when lubricant was added. The degree of friction reduction when the WBM was used was much smaller than that when the NaCl brine was used. The results suggest that when the solids-laden WBM was used for lubricity measurement, lubrication was provided mainly by the solids in the WBM rather than the lubricant film. Since lubricant film was not working with the WBM, no significant friction reduction was observed when lubricant was added to the WBM.

On the other hand, Figures 7 and 8 show that the degree of friction reduction with the WBM was greater when measured with the LEM than with the dynamic lubricity tester. This suggests that the lubricant was more effective in enhancing the lubricity of the WBM when using the LEM rather than using the dynamic lubricity tester. This can be due to the presence of lower concentration of solids in the contact interface when the LEM was used. The vertical contact interface on the LEM prevents the excessive accumulation of solids during lubricity measurement. Thus, the CoF of the steel-steel contact without any lubricant in the WBM was greater when measured with the LEM than with the dynamic lubricity tester. However, the lubricating effect of the liquid lubricant was quickly realized when the lubricity of the WBM was measured using the LEM, significantly reducing the CoF of the steel-steel contact.

Overall, Figures 5 and 6 show no significant difference among all the lubricants in their effectiveness in reducing the steel-steel and steel-shale frictions with the WBM when the dynamic lubricity tester was used. In comparison, Figure 7 shows that Lubricant A achieved greater steel-steel friction reduction with the WBM when the LEM was used. On the other hand, at 30lbf contact load, Lubricants A, C and D reduced more friction on the steel-shale contact than Lubricant E when the WBM was used with the LEM. When the contact load increased to 60 lbf, all the four lubricants were able to achieve similar friction reduction of 60% on the steel-shale contact.

Field Case

Based on the positive results in the laboratory that show the effect of liquid lubricant on the friction reduction, a field experiment was conducted in a shale formation in West Texas. A horizontal well was drilled using a rotary steerable drilling system for more precise steering of the bit. Table 4 shows the maximum value of several parameters of the drilling system.

Table 4: Maximum value of several parameters of the drilling system.

Torque	34000 ft lb
Weight on bit (WOB)	50000 lb
Differential pressure	1000 psi

9.0 ppg NaCl brine and Lubricant B were used as the baseline drilling fluid and the lubricant respectively. pH was kept at 9.0 – 9.5 with the use of caustic soda. The lubricant was added only when drilling through the horizontal section of the wellbore. 20-bbl lubricant sweeps with a lubricant concentration of up to 2.4% were pumped down the annulus. The subsequent lubricant concentration in the fluid system was measured to be 1.0% – 1.5%.

Figure 9 shows the effect of pumping lubricant sweeps on several drilling parameters. Lubricant sweeps were pumped when drilling through two sections of the wellbore: 1) 13000 ft – 14000 ft, and 2) 15000 ft – 16000 ft.

When drilling from 13000 ft to 14000 ft, the continuous pumping of lubricant sweeps also coincided with an overall increase of 50% in torque from ~20000 ft lb to ~30000 ft lb. This resulted in the increase of WOB, rate of penetration (ROP) and differential pressure. The WOB increased by 50% from 32000 lb to 47000 lb. The ROP and differential pressure increased from 124 ft/hr and 400 psi to 220 ft/hr and 1000 psi respectively, a rise of 77% and 150% for these parameters. The greater degree of increase in the ROP and differential pressure than that in the torque suggest that the lubricant reduced the friction and improved the drilling efficiency.

When drilling from 15000 ft to 16000 ft, a maximum torque of 34000 ft lb was maintained while lubricant sweeps were pumped. After adding the lubricant to the fluid system, the WOB was raised from 30000 lb to 50000 lb without further increasing the torque. The corresponding ROP and differential pressure increased from 100 ft/hr and 440 psi to 180 ft/hr and 850 psi. In this wellbore section, the effect of the lubricant on the friction reduction was even more pronounced than that shown at 13000 ft – 14000 ft. Without introducing additional torque, the ROP and differential pressure increased by 80% and 93% respectively.

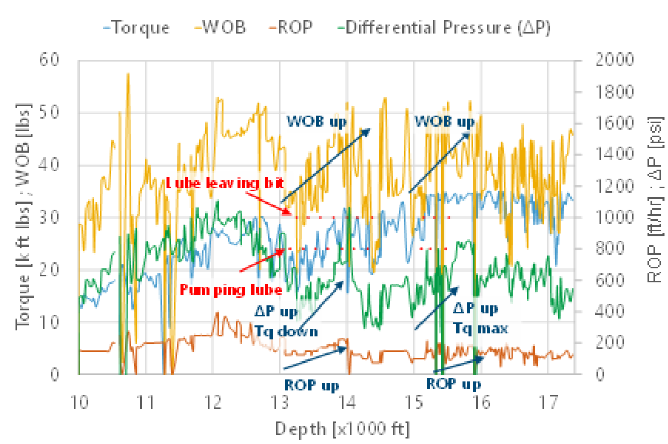

Figure 9: Effect of pumping lubricant sweeps on several drilling parameters.

Conclusions

This study investigated the effect of contact surfaces on the lubricity of brine and water-based drilling fluid. The dynamic lubricity tester and the LEM were utilized to better understand the friction on the steel-steel and steel-shale contact. The main conclusions of this study are as follows:

1. The lubricity of the solids-free NaCl brine was greater on the steel-shale contact than on the steel-steel contact. This can be attributed to the greater roughness of the shale surface than the steel surface, enabling more fluid to enter the contact interface between the steel and the shale rock to provide lubrication.
2. The lubricity of the solids-laden WBM was greater than that of the solids-free NaCl brine when no lubricant was used with the baseline fluids. This was because of the lubrication on the contact interface provided by the large concentration of solids in the WBM.
3. The lubricity of the solids-laden WBM was shown to be greater on the steel-steel contact than on the steel-shale contact when the dynamic lubricity tester was used. However, the opposite trend was observed when the LEM was used. This can be due to the accumulation of the solids on the contact surface when the dynamic lubricity tester was used.
4. When a lubricant was added to the baseline fluid, the degree of friction reduction with the WBM was much smaller than that with the NaCl brine. This was probably due to the fact that the solids contributed to reducing the friction before a lubricant was introduced. Lubricants further decreased the friction to a level similar to the NaCl brine.
5. Greater friction reduction was achieved on the steel-steel contact than on the steel-shale contact when various lubricants were added to the NaCl brine. This was because of the larger friction of the steel-steel contact without any lubricant as well as the greater affinity of the lubricants to the steel than to the shale rock surface.
6. The field experiment in West Texas shows that Lubricant B can effective reduce the friction and increase the ROP and the differential pressure when added to the clear NaCl brine. When torque management becomes a challenge in the field, liquid lubricants such as Lubricant B can be a viable choice for friction reduction downhole.

This study shows that the frictional interaction between contact surfaces is a complicated process. The characteristics of the surface of contact play an important role in the degree of friction experienced when surfaces move against each other. For example, when the surface asperity is at micron level, the capillary pressure can limit the fluid from entering the contact interfase and provide lubrication. Having a lubricant in a water-based system might change the surface tension and the wettability of the contact surfaces, subsequently making it easier for fluid to enter the contact interface. Other factors such as the type of lubricating fluid as well as the orientation of the contact interface can also affect the frictional power loss.

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