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A Comprehensive Study of Lubricant Performance in Brines and Water-Based Drilling Fluids

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Abstract

Lubricant is one of the most important components in drilling fluids, especially for extended reach drilling. A good lubricant can effectively minimize the frictional force between the wellbore and the drill strings, thus maximizing the rate of penetration (ROP) and the subsequent well productivity. However, selection of the optimal lubricant for field operations remains challenging for the industry. It is often difficult to correlate the field performance of lubricants to the laboratory lubricity measurements.

In this paper, we present a comprehensive study of fluid lubricity measurements using three instruments: 1) An extreme pressure (EP)/lubricity tester; 2) A dynamic lubricity tester; 3) A lubricity evaluation monitor (LEM). The lubricity of various brines and water-based muds (WBMs) was studied. A range of lubricants with various chemistries was evaluated for their effectiveness in improving the fluid lubricity.

Our results show that these lubricants were able to reduce the friction in metal-metal contact when added to brines and WBMs. Greater friction reduction was achieved in clear brines than in solids-laden WBMs with lubricants were used. The solids in WBMs also helped provide lubrication when no lubricant was present. Cations with a small hydrated radius helped reduce the friction when using clear brines. It is important to evaluate the lubricant-fluid compatibility to ensure that the measured lubricity reflects its actual performance.

Introduction

Increasing oil and gas productions from unconventional shale reservoirs have helped meet the world's growing energy demand in recent years, thanks to the improved horizontal drilling and multi-stage hydraulic fracturing technologies. Extended reach drilling is one of the key engineering strategies that shale operators employ to improve the well productivity and the overall well economics. Records are being set on a regular basis on the length of the laterals drilled and the number of days needed to drill these horizontal sections. The world's longest land-based horizontal lateral of over 20,000 ft was drilled in the Utica shale in just 13 days in 2017 (Prado, 2018).

The advancements in drilling fluid technology is a big reason why operators are able to drill longer and faster. In many cases, water-based muds (WBMs) or even solids-free brines are the preferred choices to drill part of the horizontal well because of cost and environmental constraints. Lubricant is one of the most critical components in these water-based wellbore fluids, whose performance significantly affects the efficiency of horizontal drilling.

Excessive friction between the drillstring and the casing or the wellbore wall during drilling can greatly limit the rate of penetration (ROP) and create enormous equipment stress (Growcock, 2017). As a result, both solid and liquid lubricants have been used to reduce such friction and improve drilling efficiency. Common solid lubricants include long-chain copolymers, graphite and composites (Growcock, 2017); on the other hand, long-chain hydrocarbons and fatty acids have been widely used as lubricants in WBMs. However, due to environmental concerns and increasingly stringent regulations, ester-based and naturally occurring vegetable oil-based lubricants have become popular choices in water-based mud formulations (Knox and Jiang, 2005). These liquid lubricants work by adhering to the surface of the metal or rocks and thus enhancing the surface lubrication. The focus of this paper is on the performance of liquid lubricants.

During drilling operations, there lacks a method that specifically evaluates the performance of lubricant in drilling fluids. Instead, the combined effect of lubricant and other mechanical means to counter frictional power loss can be analyzed using the term friction factor, which describes the loss of transitional power while drilling a well (Redburn et al., 2013). However, more often than not, such data is not made available to drilling fluids providers for fluid optimization. A lubricant or a fluid system is assumed to be working if the operator does not encounter major drilling problems that prevent them from reaching the target zone and length.

As a result, the extreme pressure (EP)/lubricity tester is still widely used in the field to measure the fluid lubricity. However, the industry is well aware of the fact that this type of lubricity measurement is unable to provide useful insights on the lubricant performance for field operations. In the meantime, there have been growing efforts in the industry to develop methodologies to evaluate lubricant performance under downhole conditions.

In this paper, we present a comprehensive study of fluid lubricity measurements using three instruments: 1) An EP/lubricity tester; 2) A dynamic lubricity tester; 3) A lubricity evaluation monitor (LEM). The lubricity of various brines and

WBMs was studied. A range of lubricants with various chemistries was evaluated for their effectiveness in improving the fluid lubricity. The importance of lubricant-fluid compatibility was demonstrated to ensure that the measured lubricity reflects its actual performance.

Materials and Methods

Brines and Water-Based Muds

As mentioned earlier, due to cost and environmental concerns, WBMs and even clear brines have gained popularity as the fluids of choice in recent years for drilling long horizontal wells in unconventional plays in the US. In this study, two clear brines and three WBM samples were used as the baseline fluids. The two brines selected were 10 wt% $CaCl_2$ (9.05 lb/gal at 68ºF) and saturated NaCl (10.01 lb/gal at 68ºF). The three WBMs included a PHPA polymer mud, a saturated salt mud and a generic bentonite mud. The WBMs were mixed in the laboratory and dynamically aged at 150ºF for 16 hours. The rheological properties of the WBMs were measured according to API 13-B1 (API, 2009). Table 1 shows the density of each fluid. The components and properties of the WBMs will be discussed later.

Table 1: Density of water-based fluids used in this study.

Baseline fluid	Density (lb/gal)
10 wt% $CaCl_2$ brine	9.05
Saturated NaCl brine	10.01
PHPA polymer mud	9.0
Saturated salt mud	14.0
Generic bentonite mud	12.0

Lubricants

Five lubricants were evaluated with these water-based fluids in this study. Several of these lubricants were based on green chemistry. Table 2 shows the generic chemistry of each lubricant. They were added to the various baseline fluids at 3 vol%, unless otherwise stated.

Table 2: Generic chemistries of the lubricants used in this study.

Lubricant	Generic Chemistry
Lubricant A	Ester blend, fresh water 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

Lubricant/Fluid Compatibility Screening

Before any lubricity measurement is performed, it is imperative that the lubricant of interest is evaluated for its compatibility with the baseline fluid. Incompatibilities such as lubricant cheesing/emulsification can have significant adverse effects on drilling operations, including a reduction in the active concentration of the lubricant in the fluid, damage of the production zone and even plugging of the sand screens (Knox and Jiang, 2005). More severe lubricant incompatibility with drilled solids can even result in sidetracking the well. Lubricant that is incompatible with the baseline fluids should be avoided for field applications.

In this study, lubricant incompatibility was evaluated based on foaming and cheesing after high-speed mixing with the baseline fluid for five minutes. The lubricants that did not exhibit incompatibility with the baseline fluids were then used in any subsequent lubricity measurement.

Lubricity Measurement Techniques

In this study, three instruments were employed to measure fluid lubricity: 1) An EP/lubricity tester; 2) A dynamic lubricity tester; 3) A lubricity evaluation monitor (LEM). The fluid lubricity was measured at ambient conditions with steel-steel contact. The features and characteristics of each instrument are described in the following section.

1. EP/Lubricity Tester

EP/lubricity tester has been widely used in the oilfield to measure fluid lubricity and evaluate lubricant performance. The instrument employs a ring and block configuration, where a hardened steel block is pressed against a rotating hardened steel ring during lubricity measurement (Figures 1 and 2). Typically, the ring rotates at 60 RPM with a torque of 150 in-lb (Fann Instrument Company, 2009). The load needed to overcome the friction between the ring and the block is displayed on the torque arm and is used to calculate the fluid lubricity.

Due to its small size and relative ease to operate, the EP/lubricity tester is suitable for both laboratory and field use. However, it is only able to measure fluid lubricity at ambient conditions. The measured lubricity has not shown a good correlation with the field performance of lubricants (Redburn et al., 2013).

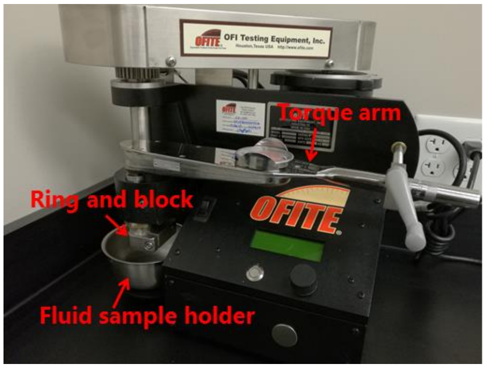

Figure 1: EP/lubricity tester.

Figure 2: Ring and block for the EP/lubricity tester.

2. Dynamic Lubricity Tester

The dynamic lubricity tester has the capability of measuring fluid lubricity at elevated temperature and pressure conditions. This is especially beneficial to evaluate lubricant for actual field applications. The temperature and pressure ratings of the instrument are 500ºF and 2000 psi respectively. The dynamic lubricity tester also utilizes a ring and block set-up, however with a different orientation compared with the EP/lubricity tester (Figures 3 and 4). During a measurement, the cylindrical rubbing shoe rotates against the top of a steel block or a core sample in the testing fluid. The measured torque is then used to calculate the coefficient of friction. More details on the dynamic lubricity tester can be found in Zhou et al. (2017).

In this study, the rotational speed used was 40 RPM and 60 RPM. The axial loading between the rubbing shoe and the test block was kept at 30 psi, equivalent to a force of about 150 lbf.

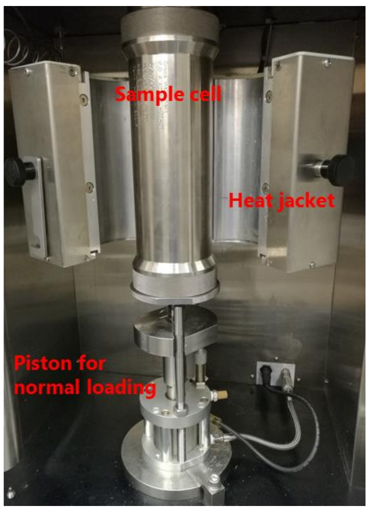

Figure 3: Dynamic lubricity tester.

Figure 4: Rubbing shoe and steel block set-up inside the sample cell.

3. Lubricity Evaluation Monitor (LEM)

The lubricity evaluation monitor (LEM) is designed to measure fluid lubricity between a rotating steel bob and an interchangeable block, which can be made of steel or an actual rock. This mimics the frictional contact in the rotational lateral direction downhole during the drilling process. During a test, the bob is pressed against the sample block fully submerged in the testing fluid by applying a pneumatic ram. The testing fluid is continuously circulated using a peristaltic pump. The block and the bob also disengage periodically to ensure fresh testing fluid in the contact interface. The rotational speed and the load of the bob on the test block can be varied. In this study, the rotational speed of the bob was 150 RPM. 30 lbf and 60 lbf of loads were used when measuring fluid lubricity. Similar to the EP/lubricity tester, the LEM is designed for ambient conditions only. Temperature can be monitored continuously throughout the test. The torque generated during a test was used as a friction indicator in this study. Figures 5 and 6 show the overall instrument set-up of an LEM and the configuration inside the sample cell.

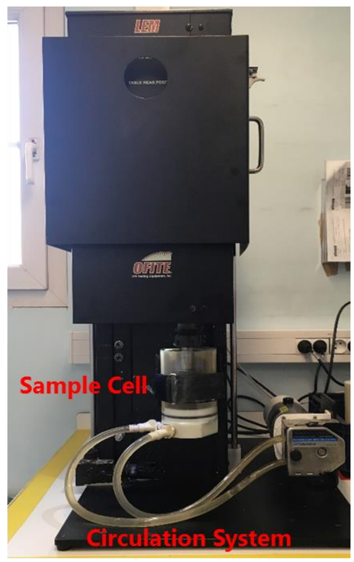

Figure 5: Lubricity evaluation monitor (LEM).

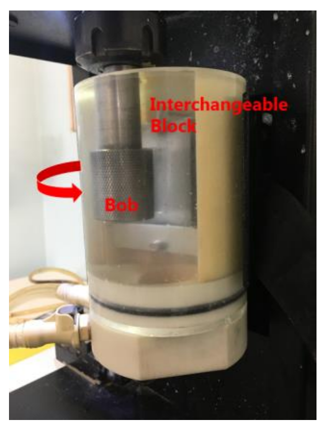

Figure 6: Configuration of the LEM sample cell with the testing block and the rotating bob.

Results and Discussion

Lubricant/Fluid Compatibility Screening

Figure 7 shows that Lubricant A cheesed out in 10% $CaCl_2$ brine. A thick layer of "cheese" was formed on the top of the brine-lubricant mixture after five-minute mixing. As mentioned earlier, lubricant cheesing is highly undesirable for drilling operations, causing problems such as the reduction in active lubricant concentration in the fluid and damage of the productive zone. Further testing also shows that Lubricant A cheesed out in saturated NaCl brine. Similarly, cheesing was observed with Lubricant D in 10% CaCl2 brine and saturated NaCl brine. These observations confirm that lubricants A and D were not designed for use in clear brine systems. Hence, these two lubricants were excluded in subsequent lubricity measurements with the brines. However due to time constraints these two lubricants were not tested in salt water based mud systems. On the other hand, no foaming was observed with any of the five lubricants in the two brines.

Figure 7: Cheesing of Lubricant A in 10% $CaCl_2$ brine.

Effect of Cation on Brine Lubricity

Figure 8 shows the lubricity of 10% $CaCl_2$ brine and saturated NaCl brine measured with the EP/lubricity tester. The coefficient of friction (CoF) of 10% $CaCl_2$ brine was greater than that of saturated NaCl brine. This agrees with the lubricity measured with the dynamic lubricity tester and the LEM (Figures 9 and 10). In fact, the CoF of the $CaCl_2$ brine was twice that of the NaCl brine when measured using the dynamic lubricity tester.

The difference in the measured lubricity of the two brines can be due to the different size of their hydrated radii. The hydrated radius of a Ca^{2+} cation was 9.6 Å whereas that of a Na^+ cation was 7.9 Å (Zhang, 2005). It might be more difficult for the larger Ca^{2+} cations than for the smaller Na^+ cations to enter the tiny space between the metal-metal contact to provide lubrication during a lubricity test. Therefore, the $CaCl_2$ brine showed a higher CoF than the NaCl brine.

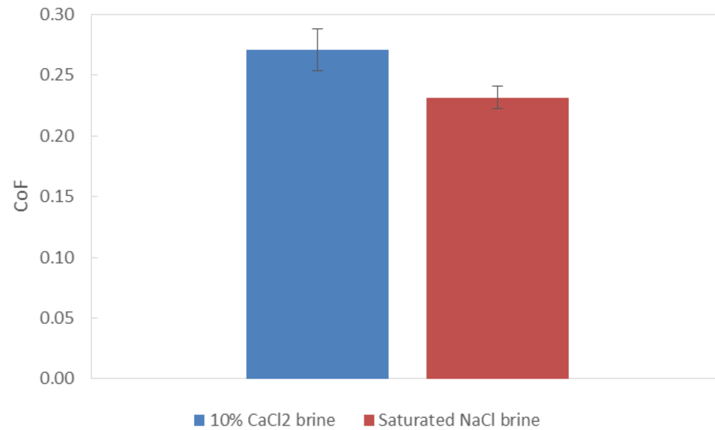

Figure 8: Lubricity of 10% $CaCl_2$ brine and saturated NaCl brine measured with the EP/lubricity tester.

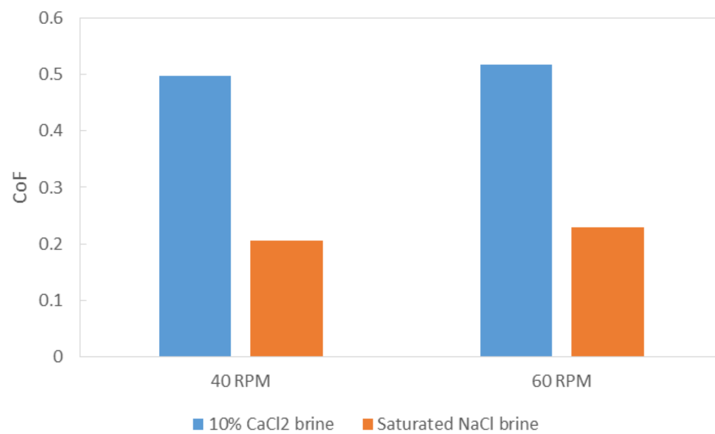

Figure 9: Lubricity of 10% $CaCl_2$ brine and saturated NaCl brine measured with the dynamic lubricity tester.

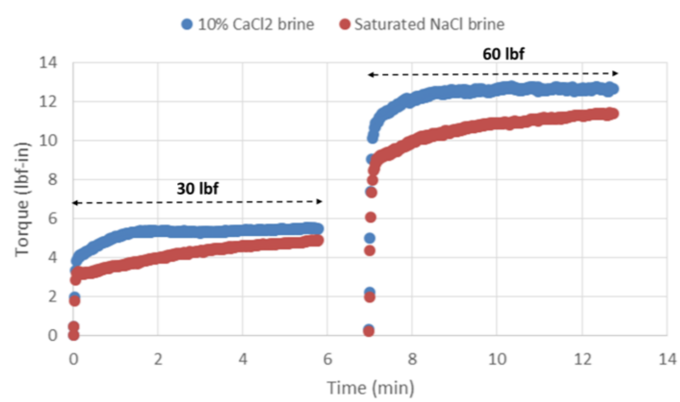

Figure 10: Lubricity of 10% $CaCl_2$ brine and saturated NaCl brine measured with the LEM.

Effect of Lubricant on Brine Lubricity

Figure 11 shows the effect of lubricant on the lubricity of 10% $CaCl_2$ brine and saturated NaCl brine measured with the EP/lubricity tester. The lubricant concentration used was up to 5 vol%. It is evident that all the lubricants were effective in reducing the CoF of the two brines. Even with 0.5 vol% lubricant, the CoF of the saturated NaCl brine was reduced from 0.23 – 0.25 to less than 0.1, a reduction in CoF of more than 55%. In general, friction was reduced with increasing lubricant concentration. However, the improvement on the friction reduction with lubricant concentration over 1 vol% was marginal. Typically, a fluid with a measured CoF smaller than 0.1 is viewed as having sufficient lubricity for downhole applications. On the other hand, the lubricity tester might have reached its limit on accuracy when the CoF is as small as less than 0.05.

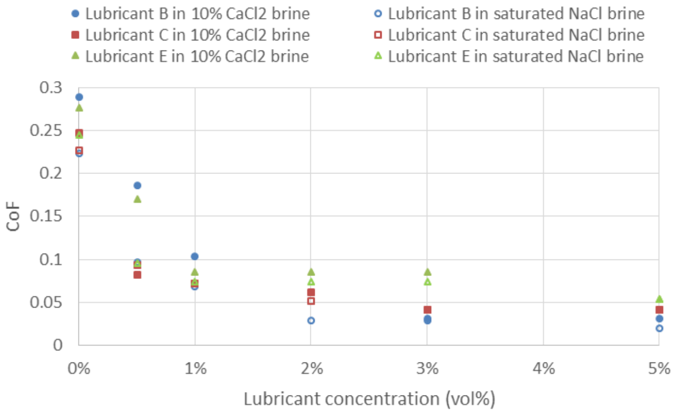

Figure 11: Effect of lubricant on the lubricity of 10% $CaCl_2$ brine and saturated NaCl brine measured with the EP/lubricity tester.

Figures 12 and 13 show the effect of 3 vol% lubricant on the lubricity of 10% $CaCl_2$ brine and saturated NaCl brine measured with the dynamic lubricity tester. Similar to the results obtained using the EP/lubricity tester, the lubricants were shown to be effective in friction reduction with both brines. The CoF of the 10% $CaCl_2$ brine was reduced from about 0.5 to less than 0.2 when the three lubricants were added. More specifically, the CoF of 10% $CaCl_2$ brine with Lubricant C was lower than that with Lubricants B and E. On the other hand, the CoF of the saturated NaCl brine was reduced from over 0.2 to 0.08 – 0.12 when the three lubricants were added. Lubricant E appeared to be slightly more effective than Lubricants B and C in reducing the contact friction.

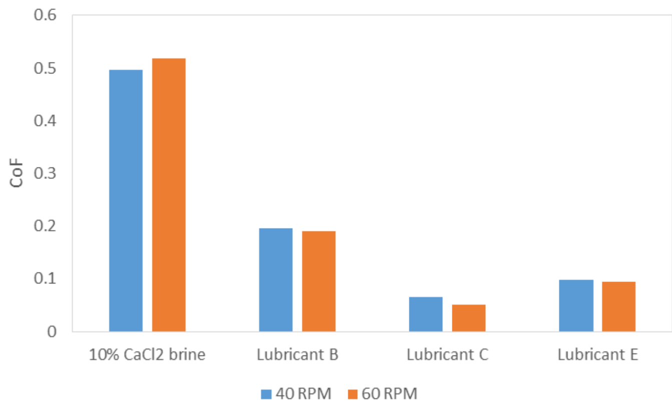

Figure 12: Effect of 3 vol% lubricant on the lubricity of 10% $CaCl_2$ brine measured with the dynamic lubricity tester.

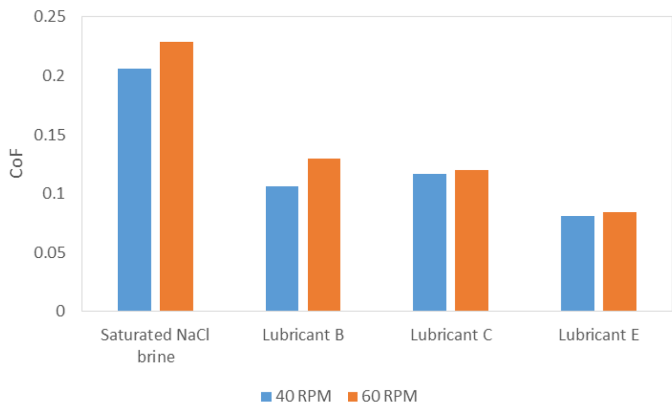

Figure 13: Effect of 3 vol% lubricant on the lubricity of saturated NaCl brine measured with the dynamic lubricity tester.

Figures 14 and 15 show the effect of 3 vol% lubricant on the lubricity of 10% $CaCl_2$ brine and saturated NaCl brine measured with the LEM. Similar to the results with the EP/lubricity tester and the dynamic lubricity tester, the lubricants were shown to be effective in friction reduction with both brines. Friction was reduced by more than 50% when the lubricants were used. Lubricant C was especially effective in improving the lubricity of the two brines, reducing the friction by an order of magnitude.

Overall, all the three lubricants were shown to be effective in friction reduction in 10% $CaCl_2$ brine and saturated NaCl brine using the three lubricity measurement techniques. The friction was reduced by at least 40% when lubricant was added to the brines. Among the three, Lubricant C appeared to have the highest friction reduction ability when used in these two brines.

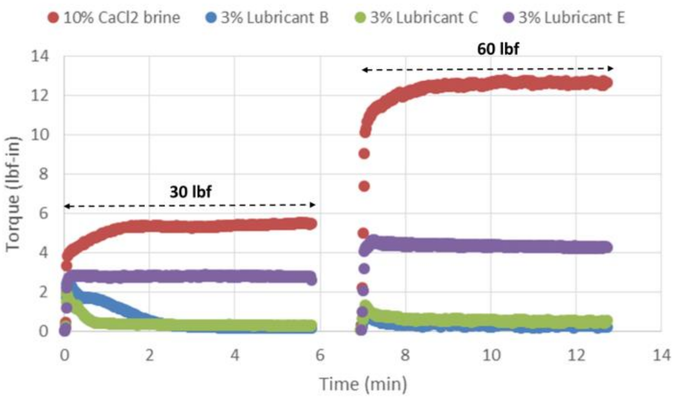

Figure 14: Effect of 3 vol% lubricant on the lubricity of 10% $CaCl_2$ brine measured with the LEM.

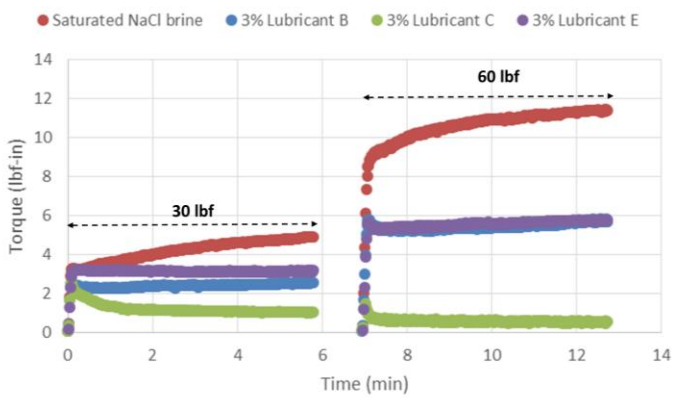

Figure 15: Effect of 3 vol% lubricant on the lubricity of saturated NaCl brine measured with the LEM.

Effect of Lubricant on WBM Lubricity

Tables 3 and 4 show the components and properties of three WBMs. Their densities varied from 9.0 ppg to 14.0 ppg. The PHPA polymer mud and the saturated salt mud had very similar rheological properties. The generic bentonite mud was less viscous than the other two WBMs.

Table 3: Components of the three WBMs.

WBM	Components
PHPA polymer mud	Water, bentonite, PAC, starch, xanthan gum, PHPA, barite
Saturated salt mud	Water, NaCl salt, Attapulgite clay, PAC, starch, xanthan gum, barite
Generic bentonite mud	Water, bentonite, seawater, lignosulfonate, lignite, pH buffer, PAC, starch, xanthan gum, barite

Table 4: Properties of the three WBMs.

	PHPA polymer mud	Saturated salt mud	Generic bentonite mud
Mud weight, ppg	9.0	14.0	12.0
Θ600/ Θ300 @120°F	80/56	87/57	76/45
Θ200/Θ100	46/33	46/33	33/21
Θ6/Θ3	13/13	13/12	7/5
Plastic Viscosity, cP	24	30	31
Yield Point, lb./100 ft^2	32	27	14
10 sec gel, lb./100 ft^2	17	14	7
10 min gel, lb./100 ft^2	34	23	15

Figure 16 shows the effect of lubricant on the lubricity of the three WBMs measured with the EP/lubricity tester. The lubricants were shown to be effective in reducing the CoF of the WBMs. The degree of friction reduction in the WBMs was not as much as that in the two brines. In general, the CoF decreased from about 0.25 to about 0.10 after 3 vol% and 5 vol% lubricant was added to the WBMs. This might be due to the presence of large amount of solids in the WBMs. The optimal concentration of lubricant appeared to be 3 vol%, above which very little additional friction reduction was achieved. Greater variation in the measured CoF was also observed when the lubricants were added to the WBMs than to the brines at different concentrations. Specifically for the PHPA polymer mud, Lubricant A resulted in greater CoF reduction than other lubricants, when used at concentrations above 2 vol%. The CoF decreased to about 0.05 at 3 vol% and 5 vol% concentrations.

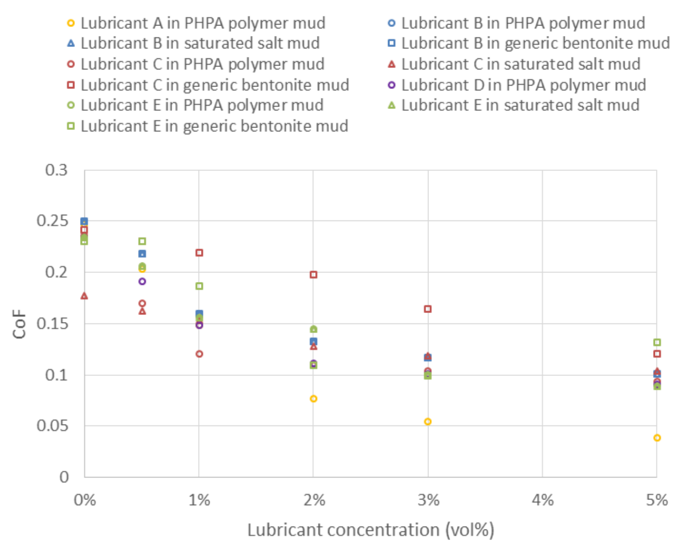

Figure 16: Effect of lubricant on the lubricity of the three WBMs measured with the EP/lubricity tester.

Figure 17 shows the effect of 3 vol% lubricant on the lubricity of the three WBMs conditions measured with the dynamic lubricity tester. 60 RPM rotational speed was used during the measurement. However, not much additional benefit in lubrication was realized after adding lubricants to the saturated salt mud and the generic bentonite mud. The slight increase in the CoF of the generic bentonite mud after adding lubricant might be caused by the movement of solids in the mud and between the contact surfaces during the lubricity measurement.

The difference in the observed effect of lubricant on the lubricity of the saturated salt mud and the generic bentonite mud obtained using the EP/lubricity tester and the dynamic lubricity tester might be due to the orientation of the ring and block for the two instruments. For the EP/lubricity tester, the contact between the ring and the block is vertical. A very small amount of solids will be in that tiny space during a test. On the other hand, the rubbing shoe of the dynamic lubricity tester rotates on top of the block. A great amount of solids may have already settled on the surface of the block before it comes into contact with the shoe. In this case, if the solids are able to provide lubrication initially without any lubricant, the lubrication in the metal-metal contact even after lubricant is added might still be largely due to the presence of solids.

Overall, the results using the dynamic lubricity tester show that Lubricants C and E resulted in greater friction reduction than Lubricants B in the PHPA polymer mud. On the hand, for the saturated salt mud, Lubricant C was able to reduce the CoF the most among the three lubricants. In contrast, none of the three lubricants were able to result in noticeable friction reduction when used with in the generic bentonite mud.

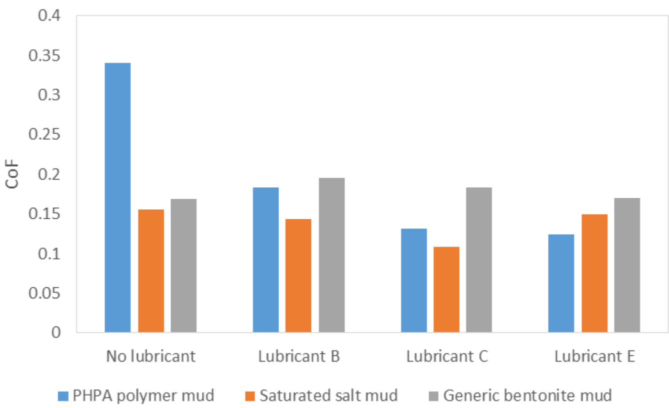

Figure 17: Effect of 3 vol% lubricant on the lubricity of the three WBMs measured with the dynamic lubricity tester.

Figures 18 – 20 show the effect of 3 vol% lubricant on the lubricity of the three WBMs measured with the LEM. All the lubricants were shown to be effective in reducing the metal-metal friction. Greater friction reduction was experienced when the lubricants were added to the PHPA polymer mud than to the saturated salt mud and the generic bentonite mud. The effect of lubricant was more pronounced when the load was increased from 30 lbf to 60 lbf. Lubricant C reduced the friction in the PHPA polymer mud the most when fluid lubricity was measured with a load of 60 lbf, bringing the measured torque down by almost 40%.

On the other hand, based on the results from the LEM measurements, Lubricant E provided the most friction reduction at a load of 60 lbf when added to the saturated salt mud and the generic bentonite mud. In comparison, at a load of 30 lbf, no significant friction reduction was achieved with the use of the lubricants in the two WBMs.

Overall, the results from the three lubricity measurement techniques show that the lubricants were effective in friction reduction when used in the three solids-laden WBMs. Among the lubricants evaluated, Lubricants C and E appeared to be more effective in improving fluid lubricity. On the other hand, smaller degree of friction reduction was achieved in the WBMs than in the clear brines. The presence of large amount of solids in the WBMs likely played a big role in controlling the contact friction.

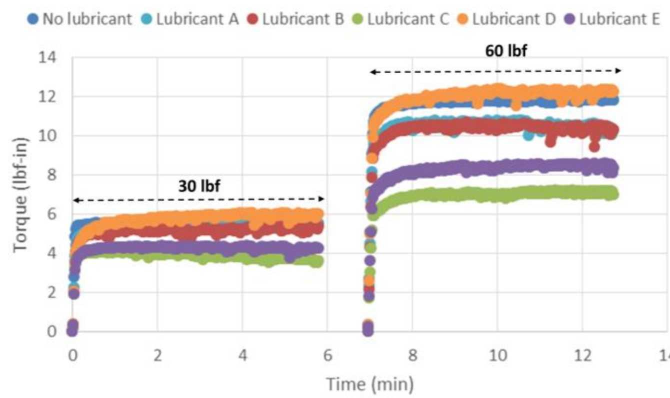

Figure 18: Effect of 3 vol% lubricant on the lubricity of the PHPA polymer mud measured with the LEM.

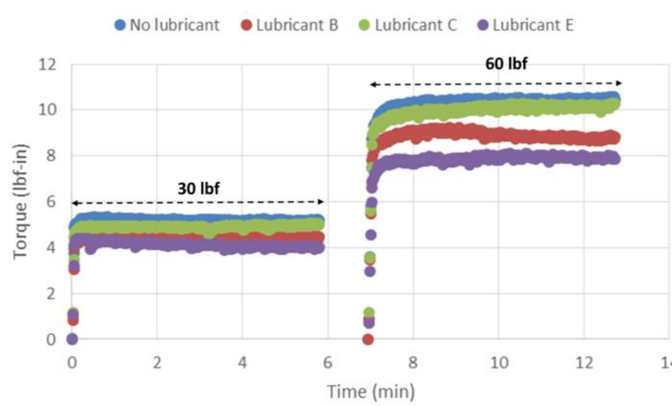

Figure 19: Effect of 3 vol% lubricant on the lubricity of the saturated salt mud measured with the LEM.

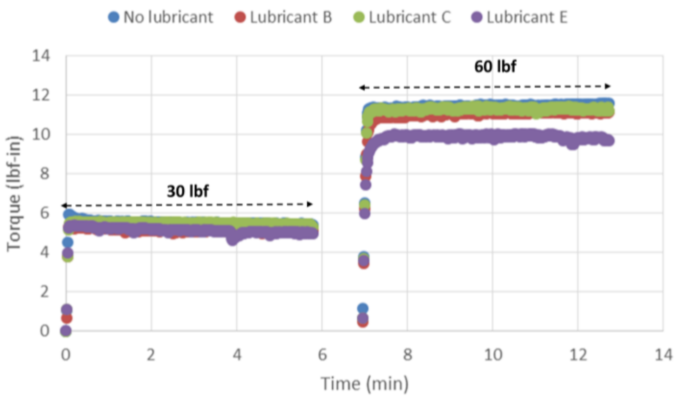

Figure 20: Effect of 3 vol% lubricant on the lubricity of the generic bentonite mud measured with the LEM.

Conclusions

This paper presents a comprehensive study of the effect of lubricant on the lubricity of brines and water-based drilling fluids. Three lubricity measurement techniques were utilized to better understand the performance of various lubricants. The main conclusions of this study are as follows:

1. It is imperative to evaluate the compatibility of lubricant with the fluid of choice. A lubricant that shows incompatibility with the baseline fluid should not be used for field operations.
2. The hydrated radius of the cation in clear brine significantly affects the fluid lubricity. The cation with a small hydrated radius tends to improve the fluid lubricity by providing more lubrication between the contact surfaces.
3. Overall, the lubricants evaluated in this study were effective in reducing the friction between contact surfaces. Greater friction reduction was achieved in clear brines than in solids-laden WBMs with the use of lubricants. This might be due to the presence of large amount of solids in WBMs.
4. The effectiveness of a lubricant in improving the fluid lubricity depends on both the lubricant chemistry and the composition of the water-based fluid system.
5. The lubricity measurement results from using the three lubricity testers correlate with each other to a certain extent. The observed difference might be due to the design of the lubricity testers, the testing conditions, and whether the baseline fluid contains large amount of solids.

In order to evaluate lubricants for field applications, the effect of temperature and the metal-rock contact on the fluid lubricity will need to be investigated in the future as well. This will offer more insights on the performance of lubricants when used in downhole environments.

Acknowledgments

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Nomenclature

CoF = *Coefficient of friction*

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