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A Novel Solid Lubricant Uses the Principles of Tribology to Reduce the Coefficient of Friction COF in Oil- Based Muds OBM for Extended Reach Drilling Applications

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Abstract

Extended reach horizontal wells face significant challenges in drilling longer laterals with oil-base mud (OBM). A novel solid-state lubricant was developed to close the gap in limitations of liquid lubricants and OBM with respect to lubricity in long extended lateral sections. The novel solid lubricant reduces the surface contact area between the asperities (deformations) by rolling and provides a chemically bonded film on the contact areas to reduce the amount of shear stress between the surfaces.

There is limited understanding of the complex mechanisms affecting the coefficient of friction (COF). The principles of Tribology (the science of friction, lubrication and wear) were used to develop the solid-state lubricant. The Stribeck Curve describes the regimes while using a lubricant, including boundaries mixing elasto-hydrodynamic and hydrodynamic lubrication. Liquid lubricants are limited at controlling boundary conditions where the COF is ruled by asperities in contact between the surfaces. The novel solid-state lubricant works on the asperities of both the wellbore and bit/BHA. In addition, the COF is improved in the mixed and elasto-hydrodynamic lubrication regimes.

Several oil-based mud field samples were tested for lubricity using different methods including the EP Lubricity Meter and Dynamic Lubricity Evaluation Monitor (LEM). The novel solid-state lubricant was also tested using a Tribometer to produce a continuous Stribeck curve that enables evaluation of the lubricant in the entire lubricity regime. The results of the COF using EP Lubricity Meter were transformed calculating the Stribeck number to build the curve. The potential benefits of the solid lubricant were discussed using a model developed by the Stick Slip vibrations with Stribeck curves. A reduction of COF in the boundary lubrication region occurs when the asperities of the wellbore and the bit/BHA are in contact. This is explained by the adsorption and absorption of the novel solid-state lubricant onto the asperities, providing a smooth surface. The novel solid-state lubricant has a wide particle distribution (PSD) to cover different size and height of asperities. The Stribeck curves of the novel solid-state lubricant show that the lubricant can reduce COF in the boundary lubrication region where friction forces are highest, compared with a base fluid and other liquid lubricants.

Introduction

The selection and application of lubricants used to reduce the COF in oil well drilling fluids has been primarily a trial and error process. Most liquid lubricants and some solid-state lubricants are available in the market place and the performance is difficult to measure. Some lubricants work well in a drilling fluid, while others do not perform as expected. Liquid lubricants usually contain an active component diluted in a carrier and the concentration of active lubricant is difficult to determine. Some liquid lubricants used in water-base mud (WBM) present incompatibility issues, potentially leading to grease-out and interaction with the low gravity solids.

Some liquid lubricants can exhibit stability problems when exposed to varying weather conditions. The relatively low concentration of the active component for lubricity and the large volume of carrier fluid lead to an increase of volume requiring mixing and transportation. Conversely, the solid-state lubricants currently available on the market function mechanically and are inert. Their use can also require the utilization of expensive recovery systems for the solid lubricant.

Consequently, there is limited understanding in the oil and gas industry about the complex mechanisms involved in lubricity, wear, and COF factors. These complex concepts can be used to design an efficient lubricant to overcome performance limiting conditions. The expertise of other industries, using the principles of Tribology, will progressively contribute to lubricant selection as well as design optimization.

Statement of Theory and Definitions

Historically, the oil and gas industry has not widely used the principles of Tribology to design lubricants when compared to mechanical and automotive industries. The models developed in these industries can be used to study and predict the performance of lubricants in WBM and OBM. The Stribeck Curve is a better tool to evaluate the performance of lubricants in oil well drilling fluids. Tribology is a relatively new science that dates to 1966 when Australian scientists from the University of Leeds stated that a new science should be established to merge the disciplines of mechanical engineering and chemistry to better define lubrication. Below is a brief description of the analysis of lubrication.

Friction and wear

In 1699, Amonton established the first law of lubrication indicating that friction was independent of the surface area. The second law states that friction force is proportional to the normal load. Those observations were made by Da Vinci in the 15th century. Recent evaluation has established that Amonton was not completely accurate in his first law. Coulomb (1781) defines static and kinetic or dynamic friction and established the third "law," stating that kinetic friction is independent of sliding speed. From this, Coulomb began to explore asperity contact area and the relation to surface roughness. Archard (1953) introduced the theory of adhesion wear and calculated the contribution of materials' properties to the wear surface. Rabinowics (1965) added the free energy to the surface and Suh (1973) established the delamination theory of wear used as a model today. According to Suh, the high pressures in the surface contact area are resolved in the boundary condition where the surfaces are almost in contact. To summarize, Amonton, Coulomb, Archard, Rabinowicz and Suh discuss the material properties and surface characteristics and preclude the inclusion of a friction-reducing species that forces surface contact and wear. However, the function of industrial systems cannot survive under extreme wear conditions leading to the development and study of lubricating mechanisms.

Before lubricant mechanisms were completely understood, Reynolds (1886) developed the mathematical representation of the behavior of fluid in a confined space modeled after a journal bearing. He observed that the distance between rotor and stationary surface changes according to the speed and the hydrodynamic wedge that is formed between the two surfaces. The thickness of the film is controlled by the velocity and the viscosity while using a Newtonian fluid. The viscosity (ŋ) and film thickness are correlated by using the Reynolds equation. The value of ŋ represents the minimum required viscosity required to maintain the film thickness in a determined value.

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(h^3\frac{\partial}{\partial y}\right)=6U\eta\frac{dh}{dx}$$

According to the Reynolds equation, we have multiple cases for h. When h has a large value, we are in the hydrodynamic condition. The bulk properties of the system take over and ŋ (viscosity) is an important factor. Baldwin and Geibor discussed the meaning of the condition when h equaled zero and they thought it was something else in addition to the wedge; thus, they introduced the concept of the boundary condition. When a fluid is circulating in the hydrodynamic condition at least 4-8 molecular layers are present. They are aligned parallel to the direction of the flow. However, in the boundary condition a unique phenomenom occurs and the molecules start to stand up. The polymer chain was long/thin and did not occupy too much space when flowing in the hydrodynamic condition. However, when the polymer stands up, the space occupied is significantly higher, forming a pack of large amount of stiff polymer chains. The polymer cannot stand up if it does not have attraction to the surface. The tribo-film formed by the tight pack of polymer chains behaves differently than a Newtonian fluid in the boundary condition.

Raman spectroscopy[15] was used to show both the packing and orienting of liquid molecules in the thin film lubrication (TFL). Near the surface a thin adsorption film is formed which is marked as the first layer I (see Figure 6). In this case the molecules are oriented perpendiculary to the surface, owing to the influence of surface adsorption, rather than the shearing force. The layer marked III represents the fluid layer in the middle of the thin film. It could be observed the film aligned along with the flow direction. It is supposed that between Layer I and III, (marked as layer II), an ordered molecule layer would exist and the molecules in the layer oriented via an induction force. Thus, it can be summarized that molecules under a flow field confined in a small space can orient in different ways. For molecules near or on surfaces, the ordering behavior is affected significantly by the surface adsorption, whereas the alignment of molecules in the middle fluidic layer is affected by the shearing force. Diffferent materials perform different lubrication characteristics. The anionic solid lubricant forms ionic bonds with the charged metallic surfaces and formation.

Reynolds put limits in his differential equation. Infinity is not practical for lubricated contacts, but zero is significant. Baldwin and Geiber gave the name of boundary condition to the solution of λ=zero. Reynolds equation only interpreted characteristics when the λ value approaches zero.

Tribology and the Stribeck Curve

It is more than 100 years since Richard Stribeck published his famous papers.[11] The first treated the load carrying capacity of ball bearing and the second paper resolved the long standing dispute of bearing friction characteristics as a function of load, speed and lubrication. Stribeck's investigation of journal bearing friction, as a function of load and speed, was extremely important as he showed the possibility of finding a point of minimun friction for lubricated applications. He also showed that the friction for sliding bearing started at high friction at low speeds, decreased to a minimum friction when the metal to metal contact stopped, and then increased again at higher speeds, which is the well known Stribeck Curve[12]. The Stribeck curve and the Tribology are standard tools for the design of lubricants in the mechanical engineering and automotive industries. However, there are few references about the connections between these industries and the lubrication problems encountered while drilling oil wells. Typically, the coefficient of friction is considered and calculated as a single point value for the whole system.

One of the fields in which minimum friction and wear plays an important role is the oil and gas industry. Both friction and wear should be as low as possible to minimize energy loss and maximize bit life, bottom hole assembly and downhole tools. This is particularly becoming more important with the development of horizontal and extended reach hole sections. Friction is converted to loss of energy required to move the downhole motors. The associated wear reduces the life of expensive downhole tools used to navigate the horizontal sections. The productivity and economics of the well are improved by each foot gained in the extended section and it is becoming more critical to reduce the friction to reach the planned targets. As a consequence, the conditions under which the bit, BHA and downhole tools must operate become increasingly severe. Eventually, even the smooth surfaces will be too rough, resulting in too much metal-to-metal and metal-to-formation contacts and accompanying high levels of wear and friction.

The usual way of creating low friction and wear is to lubricate the borehole and BHA using oil-based mud. In the past, it was generally accepted that the COF of the OBM cannot be improved. However, we know that the lubrication properties of the oil-based mud can be enhanced.

Figure 1 illustrates the standard Stribeck Curve to describe the different regimes of lubrication. In Tribology, speed dependant film formation and changes in the frictional forces are portrayed through "Stribeck Curves". To define these system lubrication regimes, Richard Stribeck investigated the film forming properties of the lubricant in the journal bearing. He found a distinct correlation between frictional forces and films of the lubricant formed between two surfaces. The Stribeck Curve also tells us that the use of a single COF while modeling the performance of OBM or WBM lubricity is far from reality because one single point on the Stribeck Curve is not enough to describe these properties.

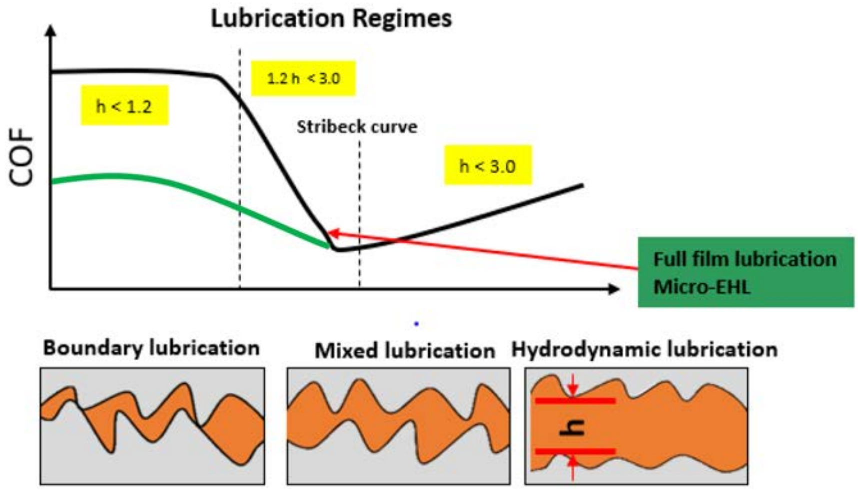


Figure 1—Stribeck Curve. This is the standard curve to describe the different regimes of the lubrication

Schematic of curve

Stribeck observed that at low speeds the two surfaces which interact determine the friction (boundary friction). This friction is represented by a COF value, which is the ratio between the frictional force and the normal force. With the increase in speed, the lubricant is transported into the space between the surfaces and the upward force of the lubricant, pushing the surfaces apart (mixed lubrication). The further the surfaces are pushed apart, the COF value will change. The minimum friction is achieved when the surfaces are no longer touching. This is the elasto-hydrodynamic friction regime. If films are formed, they prevent and reduce wear. When the sliding speed is increased, the film gets thicker. Just like in the flow curve, the internal friction of the lubricant then increases, and thus the friction of the entire tribosystem increases again (hydrodynamic lubrication).

Below, is a brief description of the different lubrication regimes in sequence: Hydrodynamic Lubrication (HL), Elasto-Hydrodynamic Lubrication (EHL) when a full lubricating film supports and creates a working clearance between surfaces, Mixed (ML), and Boundary Lubrication (BL). Specific attention has been given to the condition of BL regime as it is critical to optimize while drilling extended reach horizontal hole sections. In the BL, chemistry and mechanics play an important role that leads to the science of Tribology.

Hydrodynamic Lubrication (HL)

This lubrication regime occurs between rotation or sliding surfaces (Bit and BHA rotating in the wellbore at relative high RPM) when a full lubricating film supports and creates a working clearance between the BHA and the wellbore. (Figure 2) In order for Hydrodynamic Lubrication to be successfully and completely applied, there must be a high degree of geometric conformity between the curve of the wellbore and the bit and BHA. This lubrication regime condition occurs after the bit and the BHA have begun to rotate in the borehole and the RPM and the loads are such that a wedge of lubricating film has been formed between them. In the case of WBM or OBM the lubricating film is constituted by the whole fluid phase. It is expected that if the system is using a lubricant, this should be preferably located in the lubricating film. This wedge of fluid lifts the bit and the BHA from the wellbore. While drilling horizontal holes, the wedge pushes the bit and BHA from the lower part of the hole counteracting the gravitational force, so there is little risk of asperity contact. This is a desirable condition to avoid friction and wear. Any friction remaining is found within the lubricant itself, as the molecular structures of the oil- or water-base fluid slide past each other during the operation. This is observed in the Stribeck Curve when the COF starts to increase at higher RPM. The oil or water films are typically in the order of 2 to 100 microns thick. The films can be larger (300 microns) in large diameter holes. The lambda value, **λ** (film thickness to surface roughness ratio) is greater than 2.

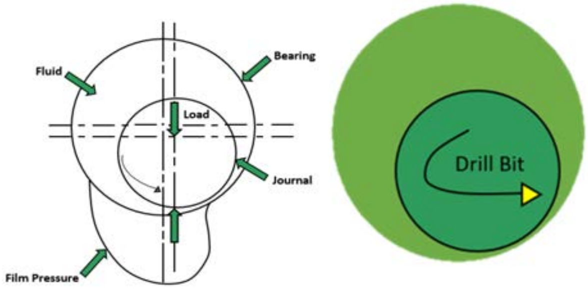


Figure 2—Friction fundamentals of journal bearing are similar to rotating drill bit

For HL to be effective, the OBM or WBM viscosity must be such that the hydrodynamic condition will be maintained under every operating condition, such as high speed and high load, high speed and low load, low speed and high load and low speed and low load. If the operating conditions cause the working clearance to be reduced too much, metal-to-metal and metal-to-formation contact will occur with the surface asperities. If the viscosity of the drilling fluid is too high (thick), the internal resistance (drag) of the molecules will reduce operating efficiency and temperatures will increase. If the viscosity is too low, the film thickness will decrease and the contact between surface asperities is more likely to occur.

It may be helpful to correlate HL to hydroplaning in a vehicle. The heavy vehicle can be supported on low viscosity fluid (water) at relatively low speeds. The vehicle loses contact with the road surface directly related to the speed of the car. Converse to the intent of oil and gas ERD applications, the automotive industry uses its understanding of Tribology to improve traction (increase the COF) to prevent the hydroplaning potential.

Elasto-Hydrodynamic Lubrication[3,4,6,7] (EHL)

Alexander M. Ertel, the founder of elasto-hydrodyamics, was the first to solve the problem of hydrodynamic lubrication while accounting for the effects of elastic deformation of the bodies in contact, as well as the impact of the viscosity of the lubricant on pressure and temperature. Elasto-hydrodynamic conditions occur when a rolling motion exists between moving elements and the contact zone has a low degree of conformity (Figure 3). The same contact occurs between the wellbore at the bit/BHA while drilling a horizontal hole, which creates a high contact pressure (thousands of psi). As the OBM or WBM enters the contact zone between the bit/BHA and the wellbore in the lower part of the hole by the rolling action, the viscosity of the fluid raises rapidly. The high pressure in the point of contact increases the fluid viscosity and load-holding ability. This concentrated load will slightly deform (flatten) the borehole in the contact zone. The deformation only occurs in the point of contact, and the wellbore elastically returns to its normal form as the rotation continues. Due to the fluid viscosity being directly affected by temperature, it is also clear that incorrect or abnormal operating temperatures will interfere with the formation of the elasto-hydrodynamic film. The fluid film thickness is often in the order of 1 micron (very thin film).

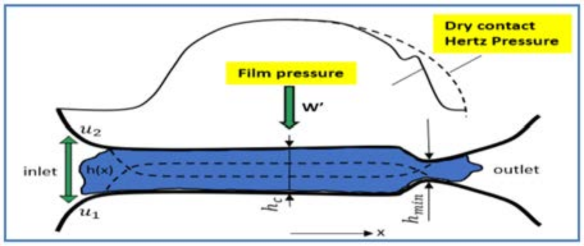


Figure 3—Design of Tribex™ ERD Additive. Elasto-Hydrodynamic Lubrication (EHL).

The conjunction zone of the typical EHL contact can be conveniently divided into three regions, as shown in the figure. The load gives rise to a pressure called the Hertzian pressure, which is distributed over a small area of contact called the Hertzian region. The viscous characteristics of the fluid, while passing through these regions, change drastically going from an easily flowing liquid to a pseudo solid and back to easily flowing liquid in a matter of milliseconds. The viscous properties of the fluid in each region are determined by the temperature-pressure and shear conditions created in each region. The hydrodynamic pressure generated in the Hertzian region contributes to the separation of surfaces, which are being forced together by the substantial pressure of the Hertzian region.

Although these hydrodynamic pressures may be much smaller than the maximun Hertzian pressure, they are still enough to separate the surfaces at the leading edge of the Hertzian region. Once this is achieved, the fluid finds that it cannot escape because its viscosity is too high and the gap between the surfaces in the Hertzian region is too thin and the time is too short. Finally, it is also clear that incorrect or abnormal operating temperatures will interfere with the formation of the elasto-hydrodynamic film.

Mixed Lubrication (ML)

ML is dramatically reduced as sliding speed increases, creating a wedge of lubricant film between the surfaces in motion. As the potential for asperity contact is reduced and film thickness increased, the COF drops dramatically to the condition known as mixed-lubrication. Some metal-to-metal or metal-to-formation asperity loading is still occurring, combined with loading (lift) on the lubricant. This is an intermediary condition between the boundary and hydrodynamic/elasto-hydrodynamic lubrication regimes. As the lubricating film thickness increases further, the system now moves into full film lubrication, either elasto-hydrodynamic or hydrodynamic lubrication.

Boundary Lubrication (BL)

The HL, EHL, and ML regimes of the Stribeck curve are areas dominated by the mechanical interaction where the COF is dynamic. This is affected by the speed of the bit and BHA in the wellbore. Those variations are illustrated by the shape of the Stribeck curve. Contrary to general evaluation methods in drilling, COF is tested and applied as a single value to the overall operating conditions. This is an oversimplification of a more complex system. As soon as the rotation is decreased or when the bit/BHA starts to rotate in the wellbore, we are entering in a new area where mechanics and chemistry define the Tribology science. The concept of viscosity as the resistance to flow developed by Reynolds explains that the performance in the HL, EHL and ML regimes starts having limitations that explain the behavior in BL conditions.

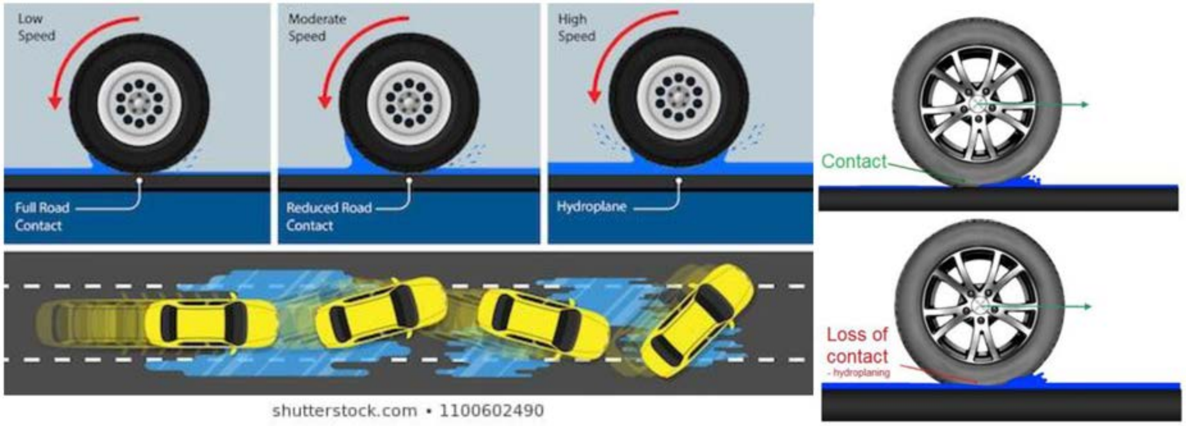
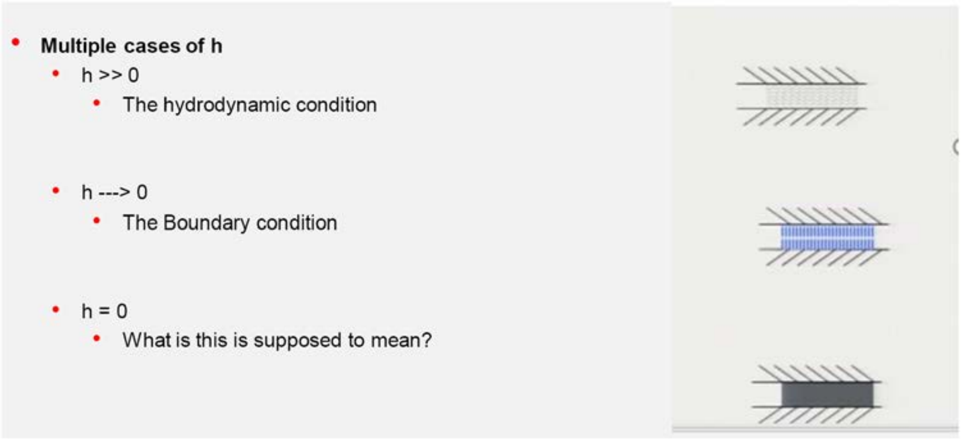


Figure 4—Hydroplanning - Elasto-Hydrodynamic Lubrication (EHL).

The boundary regime or boundary condition as identified by Baldwin and Gaber is an analysis of the Reynolds equation as λ approaches zero (surface to surface contact-Static Friction). To gain a better understanding of non-Newtonian fluids and why the lubricity profile collapses rapidly with temperature, Baldwin and Gaber evaluated what was happening beyond the viscosity wedge of the Newtonian fluids and proposed the term boundary condition. The boundary condition is where chemistry and surface interaction (Tribology) starts. In hydrodynamic conditions, we have many layers and molecules (6 to 8 molecular layers) oriented in the direction of the flow. In the boundary condition, molecules are not oriented in the direction of the flow, but stand-up because of the contact charges. The polymer chains are thin, long, and consist of 4-9 layers. If you put these molecular chains in the vertical position, they occupy a lot of space (8 to 18 carbons long or more) when standing in a tight pack forming a stiff layer. This is a different behavior as compared to the behavior of a Newtonian fluid. Now, without the attraction of the solid-state lubricant to the surfaces in contact, the molecules cannot stand up. The solid-state lubricant is anionic which allows for attraction to the surfaces of metal and formation. This attraction leads to the molecules' vertical position in the boundary condition.



- **Multiple cases of h**
  - h >> 0
    - The hydrodynamic condition
  - h ---> 0
    - The Boundary condition
  - h = 0
    - What is this is supposed to mean?

Figure 5—The Boundary Condition

Raman Spectroscopy (Figure 6) was used to show both the packing and orienting of liquid molecules in the thin film lubrication (TFL). Near the surface, a thin adsorption film is formed which is marked as the layer I. In this case, the molecules are oriented perpendicularly to the surface, owing to the influence of surface adsorption rather than shearing force. The layer III represents the fluid layer in the middle of the thin film. It can be observed that film III is aligned parallel to the direction of the flow. It is between Layer I and

III (marked as layer II) that an ordered molecule layer exists and are oriented through an induction force. It can be summarized that molecules under a flow field confined in small a space can orient in different ways. For molecules near or on surfaces, the ordering behavior is affected significantly by the surface adsorption, whereas the alignment of molecules in the middle fluid layer is affected by the shearing force. Different materials perform different lubrication characteristics.

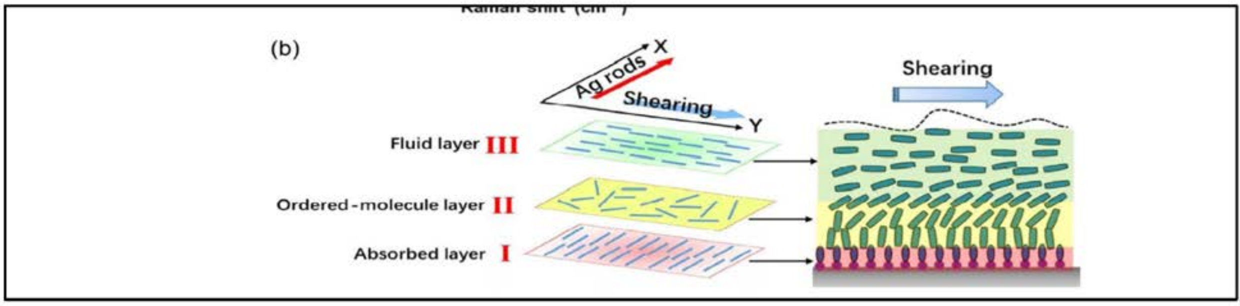


Figure 6—Raman Spectroscopy

The Reynolds equation provides an accurate calculation of the lubrication film thickness for Newtonian fluids. However, non-Newtonian fluids like paraffin oil or drilling fluids, have demonstrated limitations when using the Reynolds equation to calculate the value of film thickness. As indicated in Figure 7, the friction increases with the speed showing a perfect Newtonian behavior. The friction increases as a result of increased drag forces of more molecules of fluid while the thickness of the film is increased.

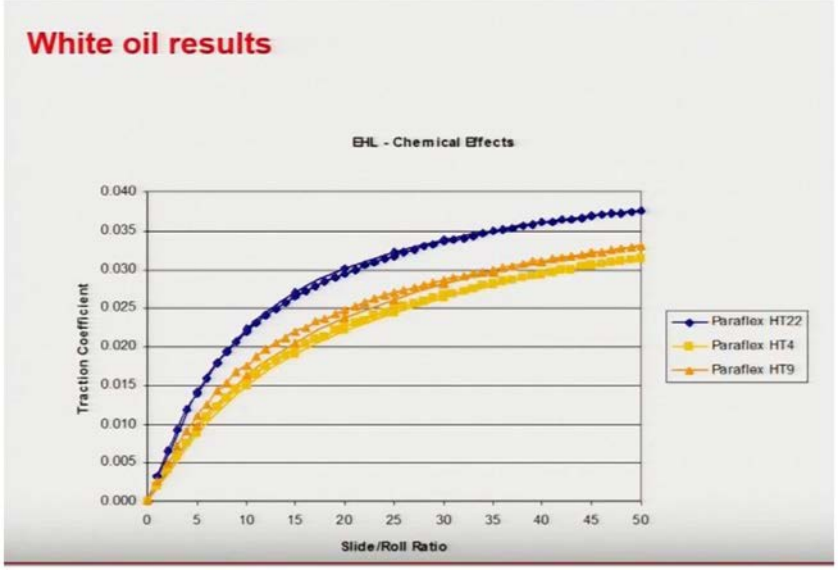


Figure 7—Newtonian Fluids and Reynolds Equation

A majority of non-Newtonian fluids (Figure 8), such as greases, glycols, esters and drilling fluids, deviate from the performance of the Newtonian fluids (Figure 7). The question of why the non-Newtonian fluids have this performance is illustrated in the Stribeck curve (Figure 1). The static COF is high in the boundary regime. The COF starts to reduce with surface rotation in the ML condition whereby reaching the minimum in the EHL regime. The shape of the Stribeck curve is more complex when using the Tribometer where the COF is measured at a very low rpm. In this case, the COF starts very low when rotating very slowly and increases to a maximum value corresponding to the static COF after reaching a point of activation energy allowing the COF to decrease. Standard lubricity meters start using a relatively high initial rpm which does not allow this part of the curve to be detected and evaluated. The Tribometer can build a continuous Stribeck curve which identifies that something different is occurring in the boundary condition (λ approaching zero). This regime is where the science of Tribology is required to explain the behavior.

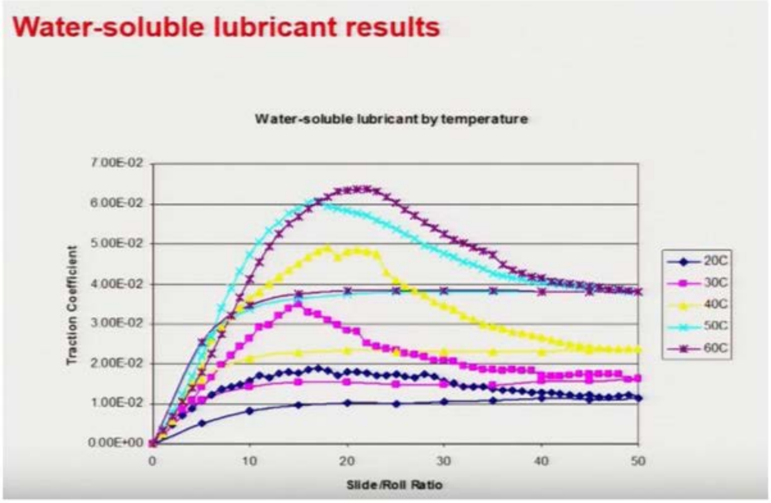


Figure 8—Non-Newtonian Fluids

The chemistry of the lubricant involves interaction with surface properties of materials in contact (metal-to-metal or metal-to- formation)[30]. The traditional definition of the viscosity used for the hydrodynamic regime is not valid in the boundary regime. In the boundary condition, the bulk physical properties (viscosity) are no longer paramount and chemical activity (molecular level properties) takes over. Helmetag propose a new property, ε, that can be defined as the friction contribution of the lubricant in the contact region. E is a function of polar intercations and adsorption that occurs and defines the boundary characteristics of the lubricant based upon its ability to adsorb onto or form polar bonds with the surface. The novel solid-state lubricant is anionic and contains double bonds that can produce a reactive layer on a surface. When the fluid is moving through the hydrodynamic region, at least 8-10 layers of molecules or lubricant are moving in the direction of the flow. The solid-state lubricant is able to attach to both surfaces (metal-to-metal and/or metal-to-formation). The formation of the reactive Tribology film, which possesses lower shear strength, has lower COF and, as a result, the surfaces in contact slide over the reactive layer efficiently. The friction forces in the boundary condition come from chemical and mechanical forces combined.

Hardy, in 1922, experimented passing electrical current through two surfaces in near contact and found cases where the current passed through the contact and sometimes did not, depending on the fluid between the surfaces. It was not until 1995 that proof of clean contact between surfaces was discovered. Boundary functionality is defined by the way the lubricant reacts with the surfaces. Boundary agents are assumed to interact with the surfaces in some way. Anionic materials and double bonded materials are typically boundary lubrication agents. The novel solid-state lubricant has both properties.

Chemical Regimes

The value of $\lambda=\infty$ defined in the HL regime allows no chemical interaction with the surface and defines the hydrodynamic characteristics of a lubricant by its viscosity. Friction forces come from internal friction of flow (kinematic viscosity). For $\lambda=0$ defined as boundary, this condition allows for polar interactions and adsorption to occur and define the boundary characteristics of a lubricant based upon its ability to adsorb to or form polar bonds to the surface. Friction force comes from chemical and physical interactions.

The new solid-state lubricant is deposited on the surface and forms a physical Tribo-film. This helps to reduce the compressive stress concentration associated with the high contact pressure by bearing the compressive force increase. The difference between the tribo-film of the solid-state lubricant and the fluid containing a traditional liquid lubricant can be demonstrated in the Stribeck curve. Figure 9 shows the influence of a solid-state boundary film on the lubrication regime. It is observed that the solid-state forms a protective boundary film via interaction with the friction surfaces to reduce the friction and wear. The low shear stress of the lubricant film gives friction reduction by means of producing a very smooth surface allowing effective full contact area separation.

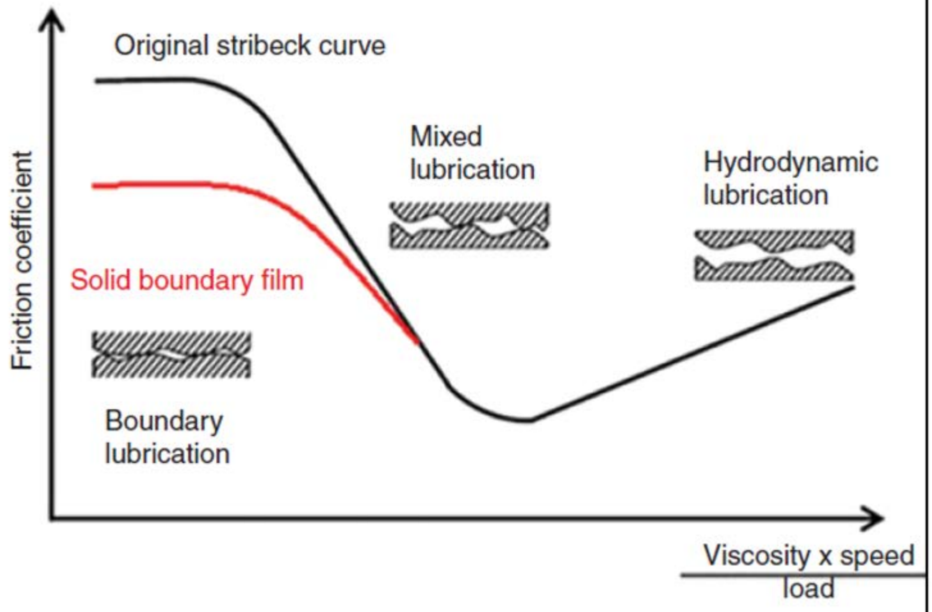


Figure 1: Influence of solid-like boundary film on lubrication regime. Reprinted (adapted) with permission from Ref. [10]. Copyright (2013) University of Hertfordshire.

Figure 9—Influence of solid-like boundary film on lubrication regime.

Over the past twenty years, thin film lubrication (TFL) theory has been used to characterize the molecular behaviors in lubrication films thinner than 100 nm, effectively bridging the gap between EHL and BL. Unfortunately, to date, the TFL molecular model proposed in 1996 has not been directly proven by experimental detection. Herein, a method based on surface-enhanced Raman spectroscopy was developed to show both the packing and orienting of liquid molecules in the TFL regime. By trapping liquid crystal molecules between a structured silver surface and a glass surface, molecular ordering states dominated by shear effect and surface effect were successfully distinguished. A nanosandwich structure consisting of an adsorbed layer, an ordered-molecule layer, and a fluid layer was demonstrated. Molecular imaging in TFL was achieved. Results illustrate the molecular behaviors and lubrication mechanisms in nanoconfined films and facilitates the lubrication design of nanoelectromechanical and microelectromechanical systems. Common industry practice is to add carbon nano-additives to lubricant oils to improve the quality. Most of those solid lubricants form a lubricant film on the surface of the metal, thereby preventing the direct contact of the metal to exacerbate wear[16]. The solid-state lubricant has nanoparticles in the range of solids particle distribution which yields the same effect. The solid additive also has film forming properties acting at the nanolevel.

Roughness

Friction lubrication and wear are a correlated circumstance of surface interaction. The presence of lubricating oil between contacting surfaces is often beneficial, as it reduces the shear stresses and thereby friction and wear. By contrast, breakdown of the oil film leads to adverse effects. A film failure is associated with surface roughness. In the case of insufficient lubrication, two sliding bodies under normal load come in direct contact first at the highest peaks (asperities) and the lubricant film breakdown is initiated at these spots. Wear is initiated at these contact spots as well. A new model was developed for the simulation of the friction coefficient in lubricated sliding line contacts[5]. The breakdown of the film in the presence of the solid-state lubricant is minimized due to the flexibility of the product and the strength of the film generated.

Since the 1970's, the effect of roughness orientation on contact and lubrication characteristics has been studied. Design manufacturing engineers have used surface pattern contact and lubrication models to gain a better understanding. Overall, the orientation effect is significant in the mixed EHL regime where the λ ratio is roughly in the range of 0.05 to 1.0. It is relatively insignificant for both the full-film EHL ($\lambda > 1.2$) and the boundary lubrication/dry contact ($\lambda < 0.025 \sim 0.5$)[10]

Implications of Stribeck Curve and Tribology in Rotary Drilling

The Stribeck curve and the science of Tribology are standard tools for the design of lubricants in the mechanical engineering and automotive industries. However, there is not much reference about the connections of these principles and the lubrictation problems encountered while drilling oil wells. The COF is considered and calculated as a single point value for the whole system. The principles of Tribology demonstarated that the COF is not solely a property of the material, but a property of the system. The Stribeck curve also identifies that the lubricant has a wide range of behavior depending on the rotation of the drilling string. Considering the more demanding conditions of drilling extended reach lateral sections, the COF is becoming more important because friction is wasted energy and more powerful motors are required to compensate for these energy losses.

Stick-slip and Whirl Interaction of the Drill String

Stick-slip is a drilling disfuction that is characterized by huge oscillations of the bit speed. It is a major disfunction because this drilling behavior induces early fatigue of equipment that can lead to failures. In addition, high bit acceleration levels can damage the wellbore and downhole electronics. To overcome these downhole conditions, increased motor power is required to free the bit when it is stalled. Unfortunatelly, this does not enhance the rate of penetration and a 12% reduction in ROP during stick-slip phase has been observed.

Dawson et al, attributes this drilling condition to a nonlinear decreasing relationship between the bit-rock friction and the rotary speed. Brett introduced the term "negative damping" in lab experiments with a polycrystalline diamond compact (PDC) bit. Together, their research has shown that nonlinear damping between the torque at the bit and the rotary speed can minimize stick-slip by increasing RPM to a higher than critical value. Tag, Dufeyte and Rapplod suggested that by adding lubricant to the mud it could change the drill bit/shale relationship with respect to friction. In general, people think that high weight on bit (WOB) and low RPM with hard rock promotes further stick-slip. Static friction is generally higher than the slipping coefficient and this is generally assumed to generate "jerky" motions.

Pavone et al. proposed a simulation to anlyze stick-slip experiments in a real well with one-dimensional and nonlinear models. This analysis found that the friction at the bit rock level is more complex. It decreases with the rotary speed and increases with the WOB. It was found that the origin of stick-slip is in the negative slope of the relationship between friction and the rotary speed. The proposed solution was an Anti-Stick-slip tool to compensate with a positive boreole friction slope.

Leine and others studied the behavior of oil well drilling strings when both torsional stick-slip and whirl vibrations are involved. It is demonstrated that the observed phenomena in experimental drill string data can be due to the fluid forces of the drilling mud. A Stick-slip Whirl model is presented that consists of a submodel for whirl motion and a submodel for stick-slip motion. The numerical results are compared with the experimental data from a full-scale drilling rig. The measured downhole friction shows the shape of the Stribeck curve. The stick-slip motion is caused by the dry friction between the BHA and the rock.

Stribeck Curve and Stick-Slip

Liu Hong proposed a Kalman estimator [22] to control stick-slip vibrations when the bit is momentarily stalled. In this condition, the driving torque acting on the bit increases to a larger value to overcome the static dry friction. However, when the bit is released, the friction torque decreases following the Stribeck Curve. As a result of this release of energy stored in the drill string, there is a large acceleration at the bit. A correlation was also made between the measurements of torque and the shape of the Stribeck curve in the measurements.

This is a very important step because for the first time, studies can associate the Stick-slip condition with properties of the drilling fluid, establishing the connection between mechanics and Tribology.

Downhole Measurements

The Trafor system[23], a reaserch tool to measure downhole and surface data to improve knowledge about drill string dynamics was used to take measurements at a full-scale rig (Figure 10). The well is nearly vertical and about 1080 m deep. Various tests with different WOB and RPM were conducted. The drill string consisted of 5 in. drill pipe, 8 in. drill collars and 12 ¼" in, roller-cone bit. Figure 11 shows a time history of the RPM (downhole annular velocity calculated from the magnetometer signals). The angular velocity at surface, WOB, and other parameters were kept almost constant during the experiment. The drillstring clearly performs stick-slip motion for t< 35 sec. At t=30 secs the stick-slip motion suddenly disappears, and backward whirl is prevalent for t> 35 secs. The stick-slip motion is caused by the dry (boundary) friction between the BHA and the rock. The friction is due to the drilling bit, but also due to stabilizers which have contact with the borehole wall. The friction curve of the BHA beneath the sensor, relating to the torque and downhole annular velocity (RPM), could be reconstructed from these measurements (Fig 12 a, b). The torque consists of the friction torque of the bit, the torque created by the contact (if present) of the drill collar beneath the sensor with the borehole wall and by viscous torque of the drilling fluid. During the stick-slip motion, this part of the friction is traversed with the negative slope. The profile shows the typical shape of the Stribeck curve used to evaluate the performance of lubricants. This demonstrates the influence of the drilling fluid in the friction torque and COF of the drilling fluid. The negative slope of the Stribeck curve causes the steady rotation of the drill string to be unstable, which induces the stick-slip motion.

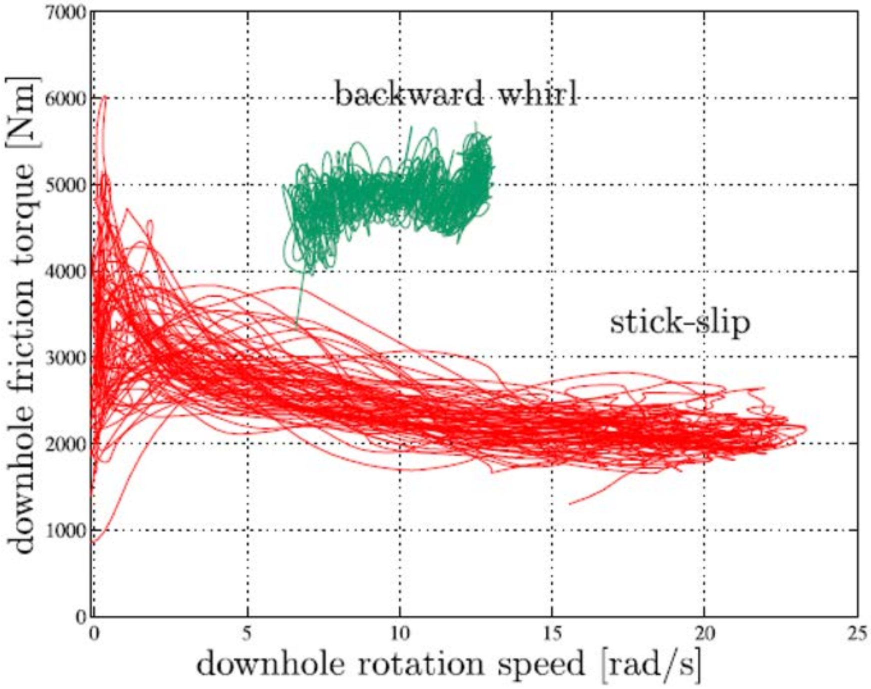


Figure 10—Measured downhole friction curves

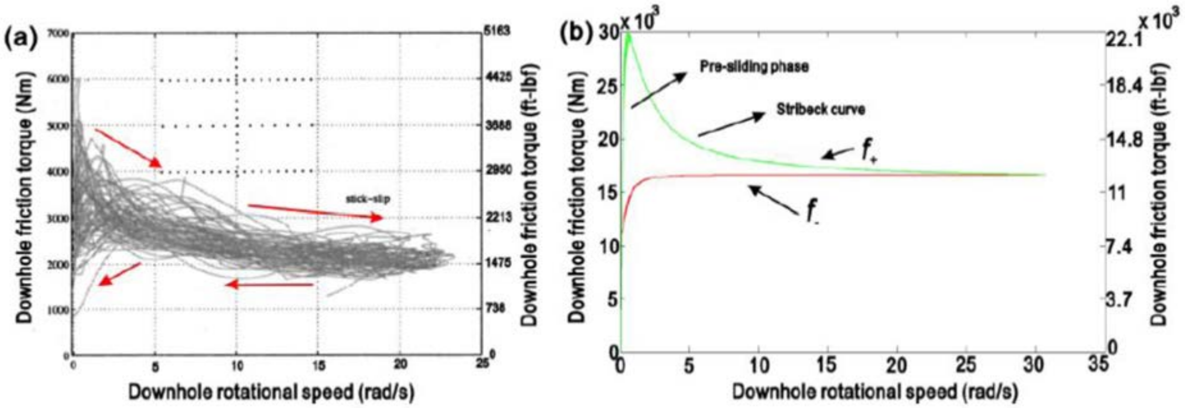


Figure 11.—a) Measurements of downhole hysteretic friction from a full research rig (reproduced from Leine et al., 2002). b) Hysteretic dry friction from the model presented in Kalman Estimator.

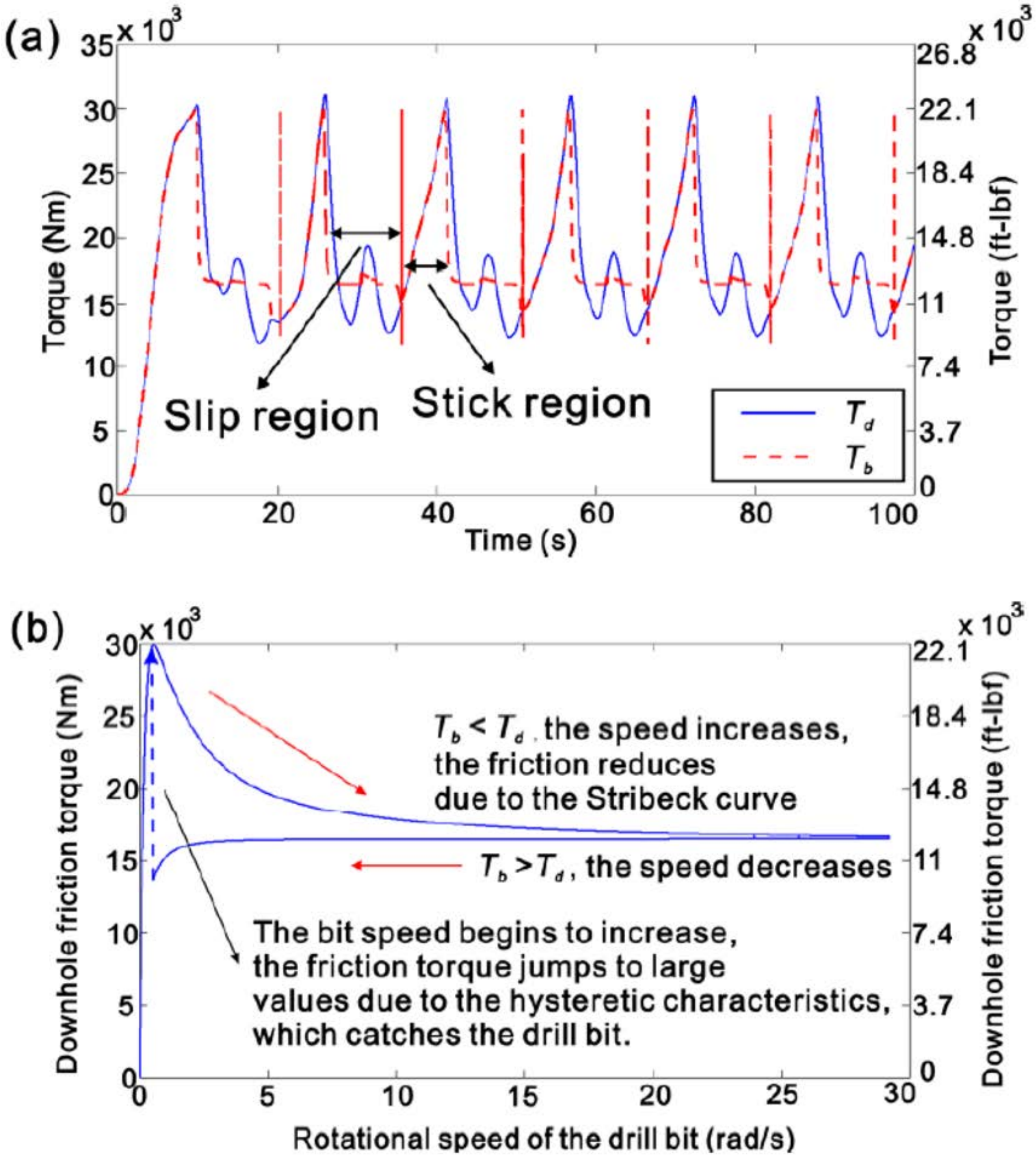


Figure 12.—a) Bit-rock interaction curve Tb and driven torque Td transmitted through the torsional string; b) Typical downhole friction torque variation with respect to the downhole speed variation during a cycle of Stick-slip vibration.

As the transition to whirl motion occurs, a switch is made to another part of the friction curve with a higher value of COF and is a slightly positive slope. The drill string is not deflected in a lateral direction during the stick-slip motion. Consequentely, the torque on the tool is experienced during the stick-slip motion due to the friction torque on the bit. The whirl motion has been identified as a backward whirl caused by the rolling of the drill collar section over the borehole wall. The drill string must be deflected during whirl motion. The torque measured in the tool will be higher during whirl motion due to the additional torque created by the contact between the drill collar and the borehole wall and the increased drag forces of the drilling fluid on the whirling drill collar. This additional torque increases with the increase in RPM.This accounts for the higher torque values and slightly positive slope of the Stribeck Curve during this motion. The slightly positive slope compensates the Stribeck effect and causes the constant rotation to be stable which prevents stick-slip motion as observed in figure 10.

The Stick-slip phenomena is produced due to the difference between the static and dynamic COF. The static COF is the one associated with the boundary lubrication condition and the dynamic with the ML, EHL, and HL lubrication regimes. A lubricant with small differences between the static (boundary) and dynamic COF would yield less tendencies for Stick-Slip conditions.

Stick-Slip in the Automotive Industry

The stick-slip phenomenon is also observed in the automotive industry[20]. The surface Tribology contact between plastic or polymer materials can exhibit a stick-slip behavior that generates noise. Tribology properties can be influenced by lubricants like bonded coatings, greases, and fluids. Well-known theories about polymer friction in the literature are useful in developing new lubricants. Theoretical results have been validated with a Ziegler Stick-Slip Test Rig. The test methods are used in the development of lubricants for automotive applications, including invisible lubricants in the interior of the car. The Ziegler Stick-Slip Test Rig used in the automotive industry can be adapted to measure the Stick-Slip phenomenon occurring while drilling oil wells. The two surfaces used in the test can be selected according to the requirements, such as metal-metal or metal-rock surfaces. The tested lubricant can be sprayed before and after to evaluate the impact of the lubricant on Stick-Slip. In the case of a solid lubricant, the OBM or WBM containing the product can be sprayed onto the surfaces.

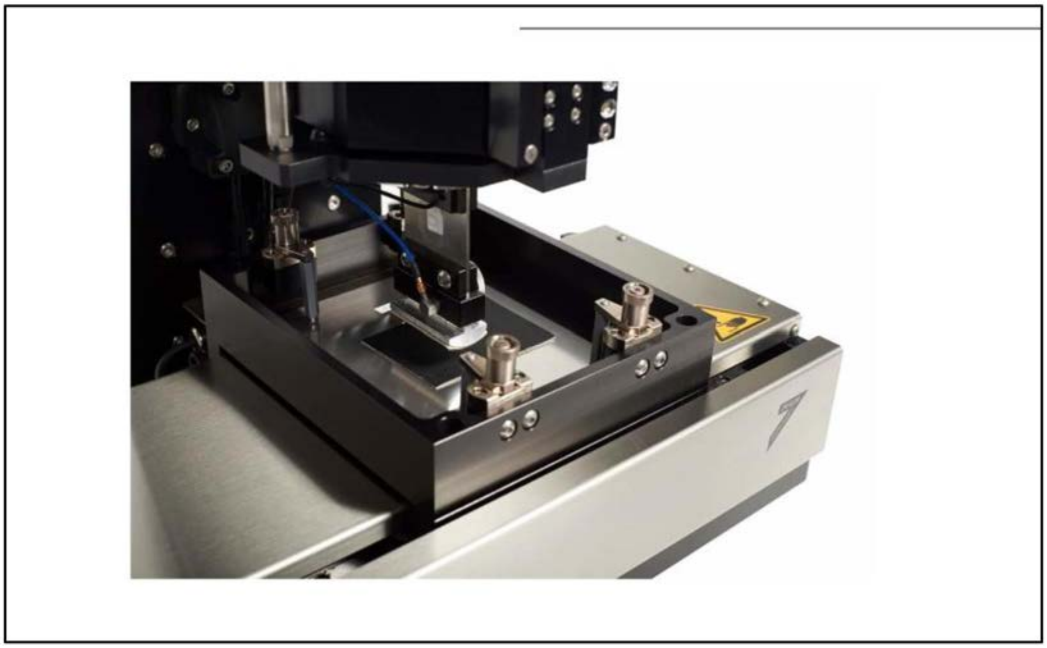


Figure 13—Ziegler Stick-Slip Rig Tester

Description of Application of Equipment and Processes Test Equipment

The novel solid-state lubricant performance was evaluated using an EP Lubricity Meter, Lubricity Evaluation Monitor (LEM), and Elasto-Hydrodynamic Tribometer.

In the initial stage of the project, the standard lubricity meter is used to calculate the COF at 150 in-lb torque loads to observe the performance of the solid-state lubricant. However, when plotting the values of the COF at different torque loads, the shape of the curves changed when using different lubricant concentrations. It was concluded that a better and more accurate observation of the lubrication behavior was required. The next step was to test the solid-state lubricant using dynamic conditions. The fluid tested in the EP Lubricity Meter remains static during the test and only one film is tested concurrently while changing the torque load. The LEM provides dynamic conditions and the film is renewed continuously. Finally, after observing the behavior and the shape of the curves in the LEM, a more accurate and comprehensive method to measure and study the performance of the solid-state lubricant was used to compare against liquid lubricants.

Below is a brief description of the different methods of evaluation of the COF

EP Lubricity Meter

The more common lubricity test measures fluid resistance of various lubricating additives. The standard lubricity coefficient test is run at 60 rpm with 150 in-lb of force (the equivalent of approximately 600 psi (4,137 kPa) pressure of the intermediate fluid) is applied to two hardened steel surfaces, a rotating ring, and a stationary block. Friction is measured as the COF (μ). The COF between two solids is defined as the frictional force of the load or the force perpendicular to the surfaces. The COF is independent of the apparent areas of contact as long as this area is not so small as to break through the film. The force to overcome friction will be the same for a small area as for a larger area. The force, F, required to slide the block and the ring surfaces across each other at a given rate is measured by the power required to turn the test ring shaft at a prescribed rate of revolutions per minute. The Coefficient of Friction, μ = Meter Reading /Load or force.

Lubricity Evaluation Monitor

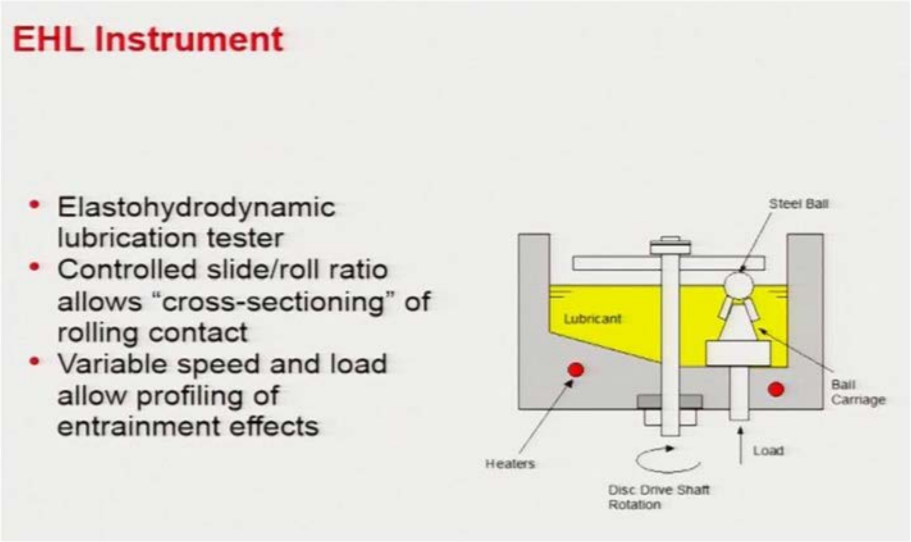
The Lubricity Evaluation Monitor (LEM) is a laboratory device designed to evaluate lubricants by direct comparison. It determines the COF between an interchangeable wellbore sample (casing, formation, sandstone, etc.) pressed against a rotating steel bob while immersed in a circulating cup of test fluid. The LEM measures relative friction factors under ambient temperature and pressure. It is purposefully designed to provide lubricity comparisons between different fluid systems and/or fluid additives. A pneumatic ram applies side load pressure to the sample while periodically refreshing the test fluid at definable intervals. The clamp allows samples of casing, formation, sandstone, etc. to be tested in the same fixture. The LEM has computerized data acquisition and control software. The user inputs rotational speed, side load, and refresh parameters. Testing archives provide access to historical data graphs which include: rotational speed (RPM), torque (in-lb), side load (lb), and COF with respect to time. The test is run, and the machine collects 600 data points or until COF values have been stabilized.

Tribometer

When lubrication is applied to reduce the wear/friction of moving surfaces, the lubrication contact at the interface can shift from several regimes such as Boundary, Mixed, and Hydrodynamic Lubrication. The thickness of the fluid film plays a major role in this process, mainly determined by the fluid viscosity, the load applied at the interface and the relative speed between the two surfaces. How the lubrication regimes react to friction is shown in what is called a Stribeck curve. The Triobometer[14] shows a method with the ability to measure a continuous Stribeck Curve. Using advanced step-less speed control, from 2000 to 0.01 rpm, within 10 minutes the software directly provides a complete Stribeck Curve. The simple initial setup only requires users to select the Exponential Ramp Mode and enter initial and final speeds, rather than having to perform multiple tests or program a stepwise procedure at different speeds requiring data stitching for the conventional Stribeck curve measurements. This advancement provides precise data throughout the lubricant regime evaluation and substantially reduces time and cost. The test shows a great potential to be used in different industrial engineering applications.

The importance of using Tribometer for Stribeck Curve Testing. The Stribeck Curve plots the COF as a function of viscosity, speed, and load. The vertical axis is the COF and the horizontal axis is a parameter that combines the other variables. Effective and efficient measurements for evaluating and developing cost-saving lubrication systems are critical for battling the friction and wear in industrial applications. The purpose of Tribology research is ultimately the minimization and elimination of energy losses resulting from wear and friction and the enhancement of production efficiency, application performance, controlled replacement breakdowns, and most importantly, the cost savings to allow industrial growth.

Measuring Objective. The Stribeck Curves were measured using two lubricant oils with different kinetic viscosities for comparison. The Pin-On-Disk Tribometer equipped with the lubrication module was used. The rotational speed decreased at an exponential rate from 2000 to 0.01 rpm to showcase the continuous Stribeck Curve measurement and the precise sensitivity of the Tribometer capabilities.



EHL Instrument

- Elastohydrodynamic lubrication tester
- Controlled slide/roll ratio allows "cross-sectioning" of rolling contact
- Variable speed and load allow profiling of entrainment effects

Figure 14—Tribometer

Presentation of Data and Results

The results of lab lubricity obtained by using EP Lubricity Meter, LEM, and Tribometer are presented in tables and Figures 9 through 14. Results of the field trials are presented in the Tables and Figures.

EP Lubricity Meter

The initial lubricity data was obtained using this standard lubricity meter. Usually the COF is defined based on the torque load of 150 in-lb while rotating at 60 rpm. However, when the COF versus torque load of the base fluid and the base fluid containing 2 and 3 ppb of solid-state lubricant are plotted, the shape of the adjusted curve shows an interesting profile. As observed in Figure 15, the solid-like lubricant presented lower COF at lower torque loads

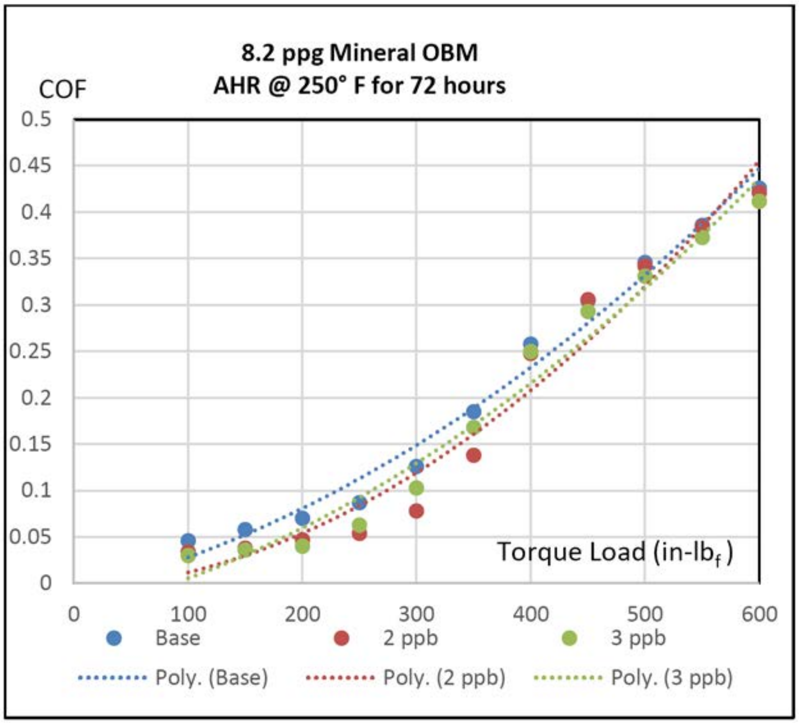


Figure 15—EP Lubricity Meter Results using mineral oil-based mud and solid-like lubricant

The results of the EP Lubricity Meter were then plotted to build the Stribeck Curve. The x-axis is the Stribeck number = ŋ*V/W, calculated using the rpm (60) and the torque load and assuming dynamic viscosity of 1, with the purpose of observing the profile of the curve in a different approach. The results appear in Figure 16, showing the behavior of the solid-like lubricant in the boundary lubrication regime at lower Stribeck numbers. The lubricant reduces the COF in the boundary condition, compared with the base fluid.

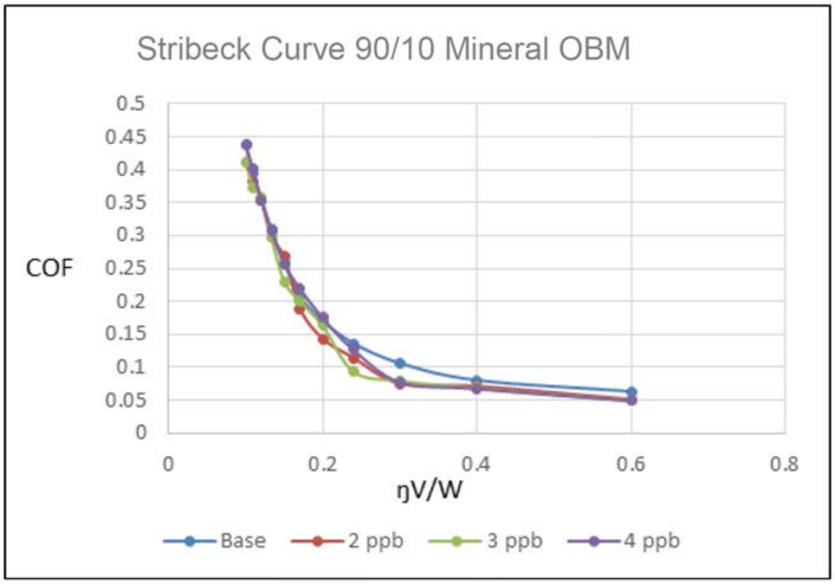


Figure 16—Stribeck Curve of mineral oil-based mud. The results of the previous tests are presented in a different way using the concept of the Stribeck Curve. The ŋ*V/W is called the Stribeck number and calculated using V=60 rpm and different torque loads. The value of ŋ=1 is centipoise.

The same method was used to calculate the Stribeck Curve of the same fluid containing 10 ppb of Rev Dust. The effect on the COF of the sample with 2.0 ppb of lubricant is clear in the presence of the simulated low gravity solids in the boundary condition.

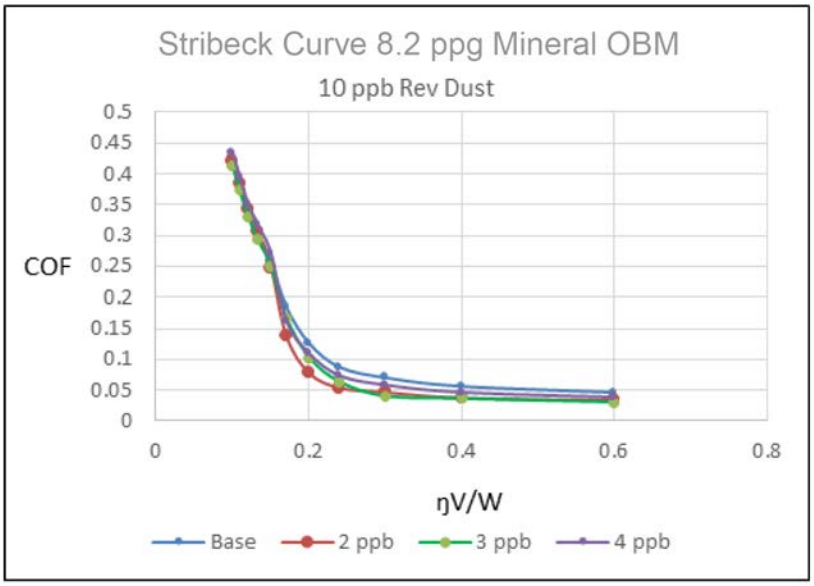


Figure 17—Stribeck Curve of mineral oil-based mud containing 10 ppb of Rev Dust

Another base fluid was used to test the lubricant and the results appear in Figure 18. Notice the effect of the lubricant on the boundary lubrication condition using 90/10 OWR Mineral OBM with 5.0 ppb of organophilic clay.

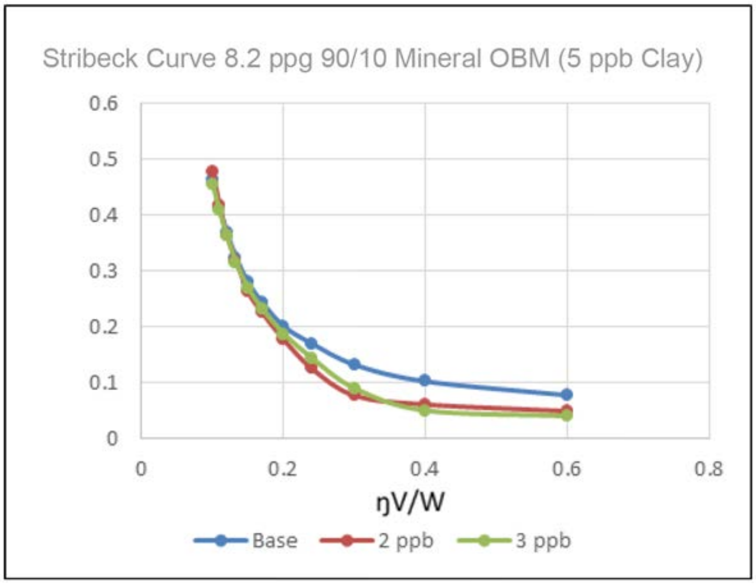


Figure 18—Stribeck Curve 90/10 Mineral OBM with 5 ppb of organophilic clay

Lubricity Evaluation Monitor (LEM)

An examination of the COF was made with a Dynamic Lubricity Meter. Contrary to the EP Lubricity Meter, where the COF was measured using the same film while increasing the torque load, the LEM contact between the rotor and the block is refreshed continuously as the fluid circulates. The tests are conducted using several stages until a stable dynamic COF is obtained. A lab sample of 85/15 OWR and 11.0 ppg Diesel

OBM and a sample of base fluid with 2.0 ppb of solid-state lubricant were tested in the LEM. Although the measured COF of both samples was 0.12, a close examination of the curves showed that the fluid containing no solid-like lubricant presented a higher COF static compared with the fluid containing the solid-state lubricant. The COF static is the maximun peak observed in the initial part of each stage while the rotor starts moving in the boundary condition.

Each stage of the graph displayed has the shape of the Stribeck Curve.

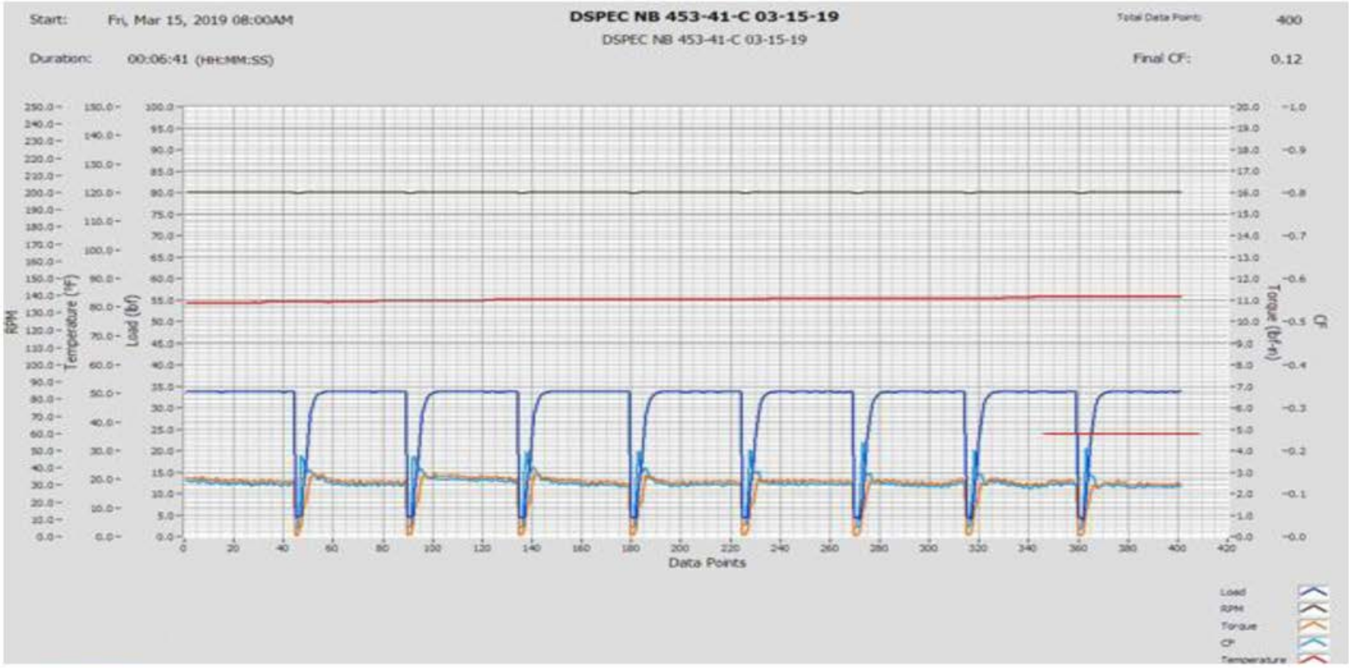


Figure 19—The lubricity curve of the base fluid containing no lubricant in the Dynamic LEM. The maximun peak COF (Static) is about 0.23

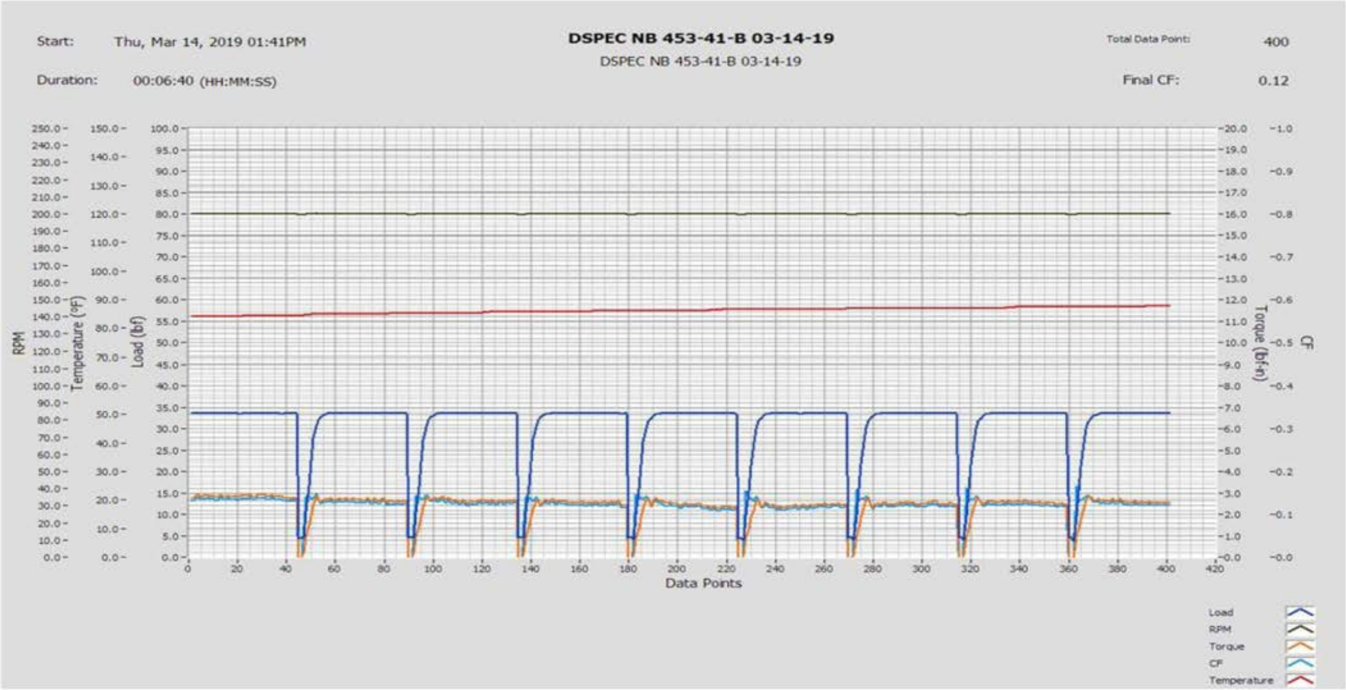
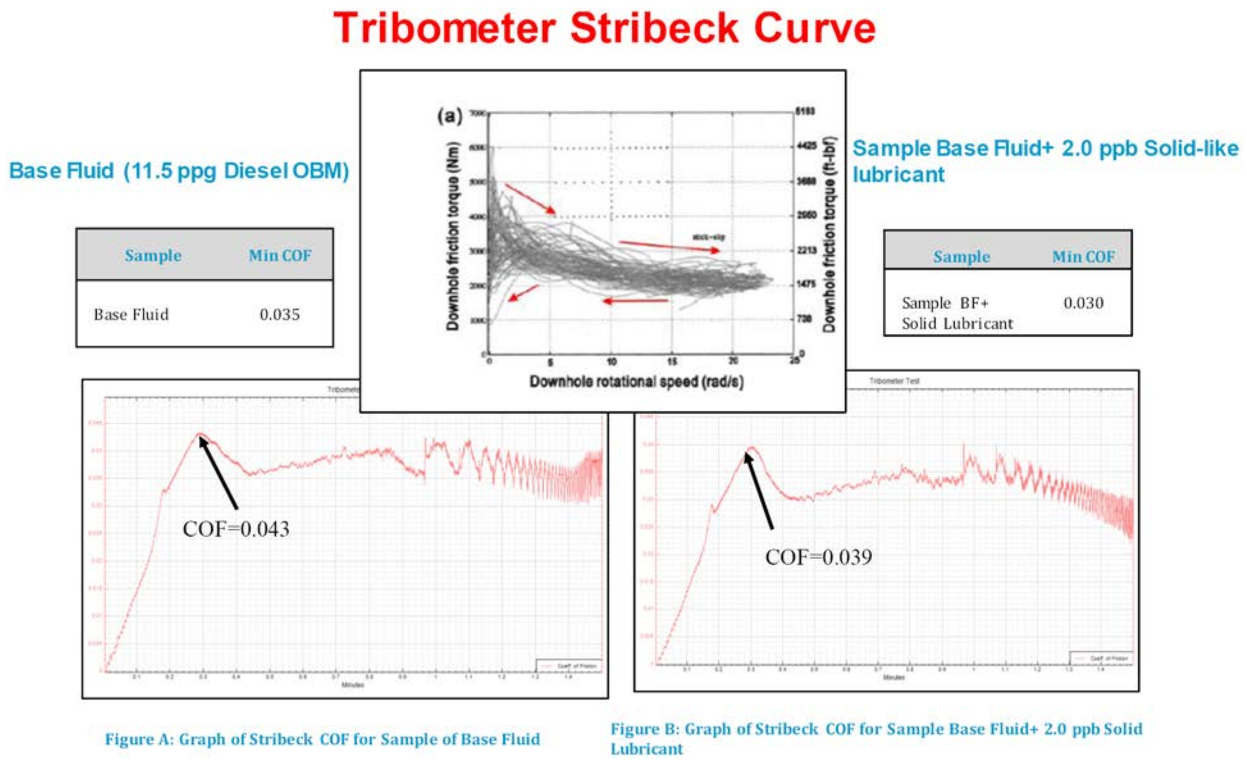


Figure 20—The lubricity curve of solid-state lubricant in the Dynamic LEM. The maximun peak of COF (Static) is about 0.15

Tribometer

The LEM results encouraged the authors to further investigate the Stribeck curves of fluids containing the solid-state lubricant, as compared to liquid lubricants and their performance under boundary conditions. The Tribometer, a novel lubricity meter, has the ability of producing a continuous Stribeck Curve while varying the rpm between 0.01 and 1000 rpm. Instrument rotation speeds between 0.01 and 250 rpm were used for practical purposes. A fixed load of 150 in-lb was also selected while measuring the COF values.

The same fluid tested in the LEM was used to build the Stribeck curves using the Tribometer. Four tests were run including the base fluid (BF) and samples of base fluid containing 2.0 ppb of solid-state lubricant and 2% by volume of two liquid lubricants. The results are displayed in the Figures 21 and 22. Lubricant 2 (liquid lubricant) showed a poor performance and caused an adverse effect on the COF of the base fluid. Lubricant 1 presented a better performance, compared with Lubricant 2, providing a slight decrease of the COF static and a similar COF dynamic. The solid-state lubricant produced both a reduction of static and dynamic COF in the entire range of rpm.



Sample	Min COF
Base Fluid	0.035

Sample	Min COF
Sample BF+ Solid Lubricant	0.030

Figure A: Graph of Stribeck COF for Sample of Base Fluid

Figure B: Graph of Stribeck COF for Sample Base Fluid+ 2.0 ppb Solid Lubricant

Figure 21—The Stribeck Curve of the BF and BF containing 2.0 ppb of solid-state lubricant. For comparison, the figure on the top displays the results of torque vs rotation on a full-scale drilling rig. Notice that the shape of the Stribeck curves built using the Tribometer correlates to the graph of Torque vs rpm of the rig data.

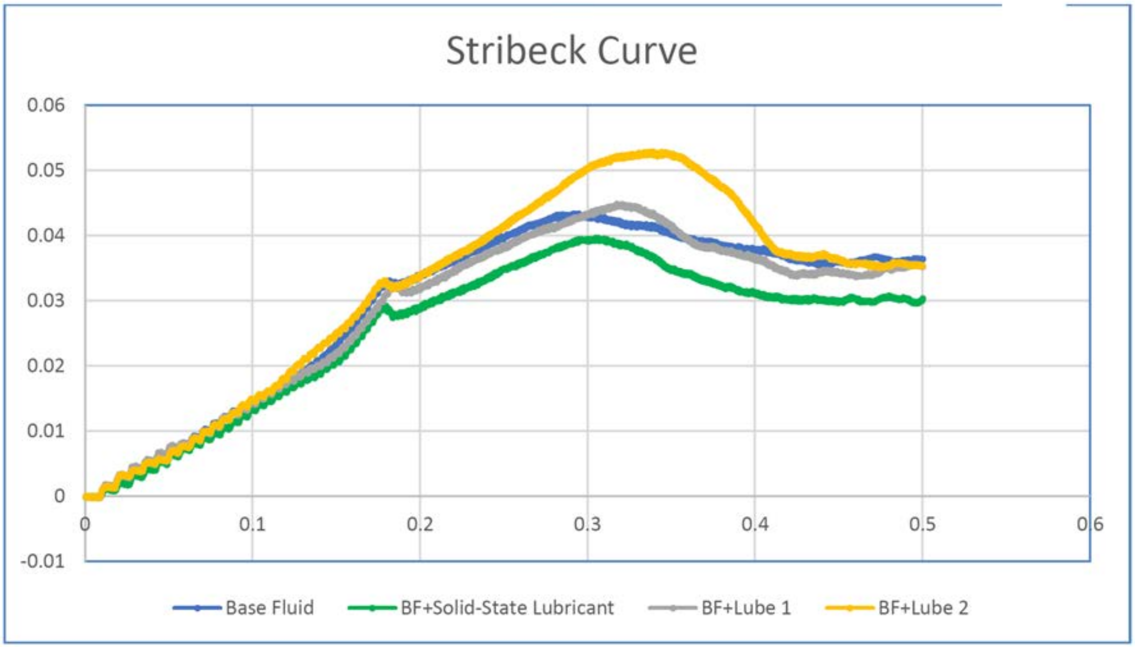


Figure 22—Stribeck curve 85/15 Diesel OBM

Field Trial Data

The first field trial using the novel solid lubricant was conducted in the Permian Basin using a Direct Emulsion Water Base Mud. The purpose of the field trial was to evaluate the potential replacement of the OBM by the Direct Emulsion system and the solid-state lubricant. The solid-state lubricant was added by pill application at a concentration of 3.0 ppb until reaching the final concentration of 3.0 ppb in the circulating system. The operator increased the concentration up to 6.0 ppb by interval Total Depth.

A snapshot of the field trial conducted in the Permian Basin is displayed in Figure 23. Notice the overall increase of the ROP with 6.0 ppb compared with 3.0 ppb of solid-state lubricant and sustaining a similar torque load.

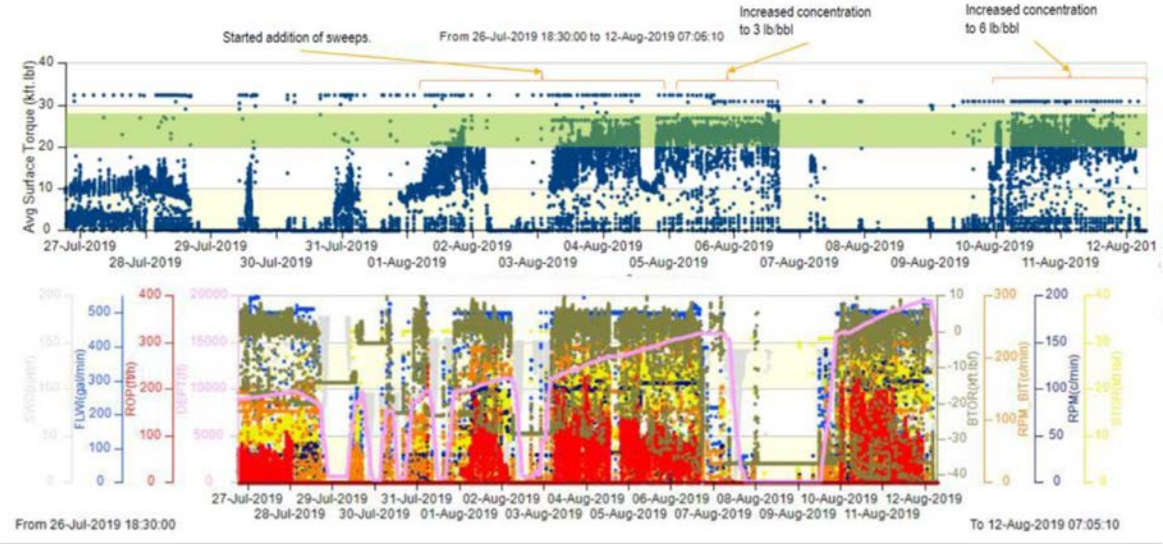


Figure 23—Snapshot of the field trial conducted in the Permian Basin with Direct Emulsion

Figure 24. The upweight and downweight were recorded along the horizontal section. One can expect an increase of both upweight and downweight as depth increases. Both curves show a decrease of both

measurements. The trend of the two curves is smooth when the concentration of the solid lubricant reached 3.0 ppb in the whole system

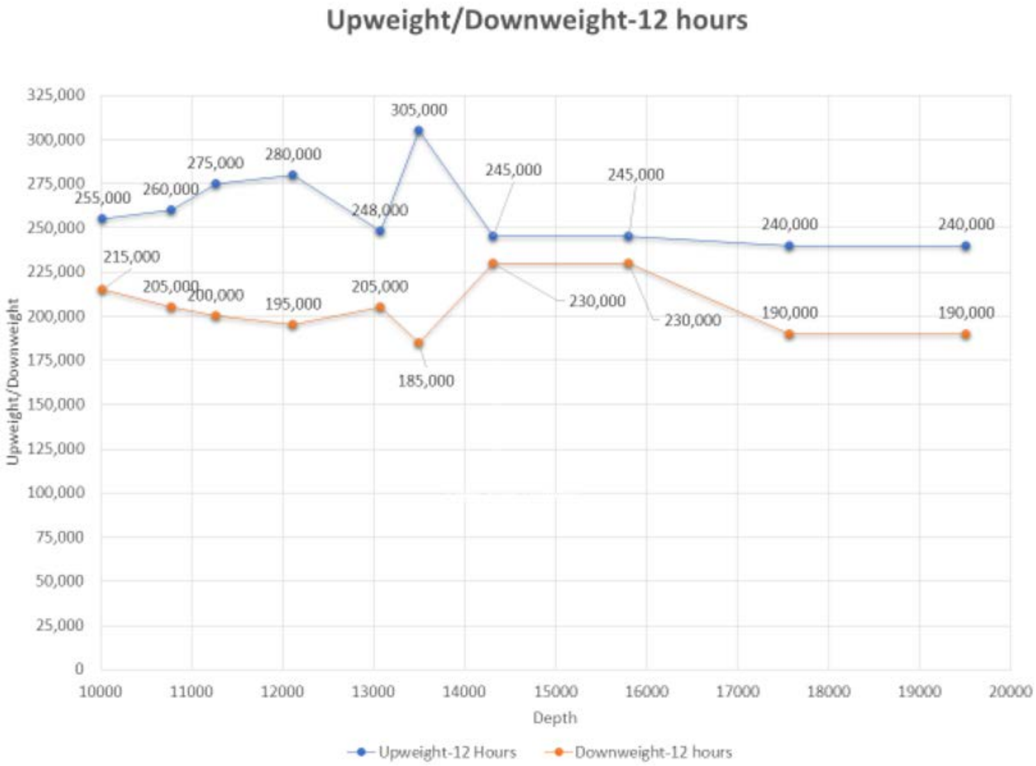


Figure 24—Upweight/Downweight Trend

Conclusions

The novel solid-state lubricant reduces both the static and dynamic COF according to the laboratory and field data results. The solid lubricant works in the boundary lubrication regime, as indicated with both LEM and Tribometer lubricity meters. The automotive and mechanical engineering industries are using the Tribometer for the design of lubricants. The oil and gas industry is not actively utilizing these new tools for the design of lubricants based upon the principles of Tribology. Stick-slip conditions are a recurrent problem while drilling oil wells and can be explained using the principles of the Stribeck Curve. The Tribometer is an essential tool for the proper design of lubricants due to its ability to display the performance of the lubricant in all 3 lubricity regimes. The COF that we use in the oil and gas industry as a single value to estimate the lubricity properties of a drilling fluid is an oversimplification of a more complex phenomenoa. The properties of a lubricant should be judge based upon the COF static and dynamic as it relates to the shape of the Stribeck Curve.

1. The Stribeck curves of the 11.0 ppg OBM sample containing 2.0 ppb of the novel solid lubricant and 2% of two liquid lubricant tested in the Tribometer showed a distinct difference in the performance. The solid lubricant has both lower static and kinetic COF.
2. The Stribeck curves of the 11.0 ppg OBM sample containing 2.0 ppb of the novel solid lubricant and 2% of liquid lubricant tested in the LEM showed similar COF of 0.12. However, the static COF of the base mud with the solid lubricant is lower than the COF static of the base mud containing the liquid lubricant. The lower peak of each stage of the LEM is clearly observed on the snapshot of the tests. Each stage of the test represents a Stribeck curve and the lower peak observed indicates that the solid lubricant is reacting with the metal surface.

3. The Stribeck curve built using the Tribometer shows that the solid lubricant reduces the static COF of the base fluid in the boundary condition, as well as the dynamic COF in the ML, EHL and HL regimes.
4. The dynamic COF of the base fluid remains stable and then starts to increased while reaching 250 rpm.
5. The dynamic COF of the base fluid with 2.0 ppb of solid lubricant decreases continuously after 1.2 minutes. Conversely, of the tested liquid lubricants, one of the liquid lubes produced no improvement on the COF, static or dynamic, and the other one produced an adverse effect on the COF, both static and dynamic
6. The above demonstrate that the solid lubricant works in the boundary lubrication regime by producing a tribofilm, which reduces the viscosity.

Acknowledgments

The authors would like to thank Chevron Phillips for the support provided to write this technical paper.

Nomenclature

ε : surface roughness
h or λ : film thickness to surface roughness ratio
ŋ* : viscosity
V : velocity
W : load per contact area
COFs : Coefficient of friction static
COFk : Coeficient of friction dynamic
Stribeck Number : ŋ*V/W

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