Design and Evaluation on a New Dynamical Lubricity Tester

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Abstract. Development of modern drilling has placed greater demands on lubricity inspection. The traditional lubricity testers appear to be very limited due to a lack of real-time measurement in the high temperature high pressure (HTHP) conditions. In the present work, a novel HTHP dynamic lubricity tester has been specially designed. This tester comprises five main parts: a driving part, a set of HPHT actuators, a loading unit, a test chamber, and a computational control part. Special friction interfaces encountered in downhole can be effectively simulated. Testing temperature and pressure can be controlled up to 150°C and 10MPa, respectively. The applicability of the tester has been evaluated by measuring lubricity of the typical PRD fluid in the pressure range of 1.5MPa~3.5MPa. This newly designed lubricity tester can provide instructive information on optimization of modern drilling process.

1. Introduction

Modern drilling, e.g., non-vertical drilling, multilateral drilling, and extended reach drilling, has opened up new oil & gas reserves that have previously been unreachable, which also presents new and particular problems for economic and safe operation[1]. In addition, modern drilling easily encounters adverse downhole conditions, e.g., high temperature high pressure (HTHP). Obviously, these new technologies, on one hand, can prompt the exploitation of oil & gas and keep the stable production; on the other hand, they can still have a series of application limits [2], e.g., large friction and torque, which is inevitable to present new problems.

One of the most significant problems is failure of drill bit to penetrate a particular formation, resulting in stuck pipe or drilling stoppages. Excessive friction between the wellbore and the drill or pipe is the usual culprit in such drilling failure, which will have serious impact on the safe and economic operation [3]. Most friction forces encountered in drilling are due to hole conditions and geometry. Also, friction resistance is commonly referred to as drag in the content of non-vertical wellbore. Therefore, much attention has been paid to inspect and reduce the downhole friction, which will be meaningful for improving ROP (rate of penetration) in the modern drilling [4].

The lubricity is essential to estimate the ability of fluids to reduce friction resistance (i.e., drag and torque force). The lubricity of working fluids is important for enhancing the economics of drilling and completing high angle bores. Lubricity is a measure of the coefficient of friction (COF) between a moving part and a surface in contact with the part. The lower the COF, the greater the lubricity. The measurement of lubricity may provide valuable information for optimizing casing runs, the well profiles, and chemical additives.

To examine lubricity of drilling fluids (or lubricants), a series of lubricity measuring instruments were reported by the petroleum and other industries[5~8]. The earliest apparatus for lubricity testing is
the Timken lubricity tester, which is adapted from an industry standard extreme pressure (EP) torque measuring instrument. It is widely used to determine the friction coefficient under high loads and extreme pressures. Subsequently, the Fann lubricity instrument was developed to test lubricity under substantially vertical conditions. Such instrument uses a steel block to simulate the borehole wall. The block is pressed against a rotating steel ring by a torque measuring arm. The coefficient of friction is measured by the amount of current required to drive the rotating ring at a given rpm while the steel block is immersed in the fluid. Another common lubricity tester is the Lubricity Evaluation Monitor (LEM). Differing from the Fann instrument, the LEM induces a cycle system of fluids and enables continuous circulation across the test surfaces. Besides, the LEM can simulate different friction interface by changing core materials such as shale, sandstone, and metals. While the steel shaft rotates against the given core under the designed load, variation of torque with time can be recorded, which is indicative for the interface friction. Obviously, the dynamic friction formed between drill pipe and borehole wall can be tested with LEM. At present, the LEM is seldom applied on-site because of the worse portability and application limitation at HTHP.

In this paper, we presented a novel lubricity tester that can simulate the pipe rotation and side load in the downhole environments, with which the coefficient of HTHP dynamic friction can be attained.

2. Action Mechanism

In the friction process, surface lubricity is, in principle, caused by a pressure resistant film that is derived from the chemical reaction at the contact area. Obviously, the lubricity can reflect the friction in nature. In petroleum industry, the COF (\(u\)) is induced to describe the interface friction at the contact area. COF is defined as the ratio of the tangential variable torque(F) to the vertical(or side) load(W) at the contact area, as shown in Eq.1:

\[
 u = \frac{F}{W}
\]  

(1)

Torque of testing shaft under a certain normal load can be revealed the COF variation. In drilling friction, W denotes the side load, which is perpendicular to the tangential velocity of rotational rod; F is the shear resistance between the rotational rod and rock core. There are three points that need to be noticed: (1) the rod remains rotational at a given rate to simulate the rotary drilling pipe; (2) the side load, W, is used to simulate the pressure between drill pipe and borehole, which is here realized by artificially pressing the rod onto the core at a constant value(about 60 rpm); (3) the shear resistance, F, that is closely contacted with dynamic friction, is calculated based on the contact area in the rotational process.

Using the traditional lubricity testers, only the static lubricity of drilling fluids at a given time is simply evaluated. Although the testing mechanism is partly in accordance with that of traditional lubricity testers, the newly designed HLT enables continuous examination of lubricity. That is, the friction variation with time can be effectively stated, and especially the lubricity of drilling fluid in the whole drilling process, e.g., the filtrate loss and mudcake formation, is systematically described by friction of metal-to-metal and metal-to-sandstone. In addition, a HTHP actuator has been inserted to simulate the temperature and pressure in the downhole environments. Therefore, the HTHP dynamic friction can be exhibited by the continuous lubricity test. However, it should be noted that \(u\) measured at HTHP needs to be further modified and standardized based on benchmark tests.

3. Design and evaluation of HLT

3.1. Working mechanism of HLT

There are five basic parts in the newly designed HLT, including a driving part, a set of HPHT actuators, a loading part, a test chamber, and a computational control part, as shown in Figure 1. The primary parts are described in some details.
3.1.1. The driving component. The driving component consists of an electric driving motor, a rotate sensor, pulleys and drive belts. With the variable-speed electric driving motor, the rotational speed of the center rod 24 can be controlled in the range of 0~600rpm, which is enough to simulate the actual rotational speed of drilling pipes (about 60rpm) in the field. A torque transducer is mounted between the motor and the shaft to record the torque. It is worth noticing that the driving capability is closely related with F in Eq. 1, which contributes large to the accuracy of u.

3.1.2. The HPHT actuator. The HTHP actuator contains an electrical heater and a N2 cylinder, and is used to control the temperature and pressure in the testing cell. The electrical heater that covers the testing cell has the thermogenic action, with which the cell temperature can be increased up to 150°C. Additionally, the cell pressure can be raised to 10MPa by high pressure N2 source, which is enough to simulate different pressure of 3.5MPa between drilling fluids and formation.

3.1.3. The load unit. With the loading part, side load are applied on the casing so that the inside of the casing is pressed against the steel shaft (see Figure 2 and 3). The load components contain a core holder. The load unit comprises a load ring, a clamp ring, a force sensor, a compression rod, and a tie rod, which can offer a force up to 10kgf against the center rod. The dynamic friction of drill pipe can be effectively simulated. Also, lubricity of drilling fluids can be continuously illustrated. The real-time torque data upon filtration can be collected, and the dynamic friction of different surface can also be evaluated by varying the core materials (i.e., the steel and sandstone).

Figure 1. Picture of the designed HLT.

Figure 2. Top schematic of normal load unit.
3.1.4. The testing cell. The testing cell is made of stainless steel, and mainly contains a testing chamber, a rotating assembly, and a compression cover, as may be seen in Figure 3. The testing chamber may be entirely sealed by the compression cap and the tie block interposed between the magnetic plates. Notice that, the magnetic plate pair is attached to the rod that acts as the driving component to turn the rod. While the motor starts work, two collinear magnetic plates can rotate, and simultaneously drive the output rod rotate at the same speed. With the collinear magnetic rotor pair, the center rod and testing chamber, the rotary state of drill pipe in the wellbore can be effectively simulated.

3.1.5. The computer package. The computer package is used for data collection, classification and calculation. The computer is directly connected with the designed HLT. The computational software has been compiled to collect the temperature and pressure data, and to analyze u, which enables real-time inspection of dynamic friction.

3.2. Application evaluation of HLT

3.2.1. Testing methods and materials. The dynamic friction of fluids may be predicted by the real-time simulation upon drilling. To evaluate the applicability of the designed HLT, the protecting reservoir drill-in fluid (PRD) was employed here. The PRD system is chiefly used in reservoirs, which can be cleared by acidolysis to reduce the potential reservoir damage. The formula of PRD is: Seawater+0.35wt.% (Na₂CO₃+NaOH)+1.5wt.% PF-FLO + 0.75wt.% PF-VIS + 11wt.% KCl+ 2wt.% PF-JLXB +2wt.%LUBE. All of the additives are commercial.

In the testing process, the pressure and temperature of chamber were controlled at 3.5MPa and the required temperature, respectively. The general procedure started with a two-minute run without any pressure to find the tare torque. Given differential pressure between pipes and hole, the side load was set to be 10 kg (0.26MPa equivalent pressure) in the friction interfaces. The center rod remained rotational at 60 rpm to simulate rotation of drill pipes. While the device worked stably, the COF values were collected at the given condition for 10min.

3.2.2. Analysis on Lubricity measurement. To validate adaptability of the designed device, lubricity of the PRD fluid was measured within different conditions. Herein, the dynamic lubricity of PRD was
separately measured with a side load in the pressure range of 1.5MPa–3.5MPa. The testing results are given in Figure 4. It is worth referring that each test was run for 30min, and only stable test data of 10min are shown.

Figure 4 compares the variation of lubricity for the PRD fluid with load at 1.5MPa, 2.5MPa, and 3.5MPa, and the average COF values of the PRD fluid are 0.564, 0.549, and 0.524, respectively. Undoubtedly, the boundary lubrication contributes mainly to the dynamic lubricity because the COF values are larger than 0.5. Besides, the average COF values decreases by 7% as the pressure varies from 1.5MPa to 3.5MPa, indicating that increasing pressure is useful to reduce the dynamic friction. This variation trend should be attributed to that a proper increment of environmental pressure can prompt redistribution of lubricant on the rough surface and, in this regard, the lubricant loss can be supplemented to keep the integrated cover on the material surface. In the initial stage, however, the average COF values of the PRD fluid increases with pressure. For instance, the average COF value measured at 0 MPa is 0.430, which increases by 31.2% than that tested at 1.5MPa. This variation should be ascribed to the relation of pressure and viscosity. The larger the pressure, the larger the viscosity of continuous phase, the larger the friction should be. On the basis of these findings, one can reasonably conclude that there is a inflection point for the COF value with increasing pressure. Prominently, the designed HLT can accurately collect the lubricity data and indicate the friction state, which can effectively reveal the influence of pressure on lubricity property.

4. Conclusion
In this work, a HTHP dynamical lubricity tester has been designed and developed for meeting the testing requirements of lubricity in the deviated wellbore. The testing mechanism of lubricity was described for the new tester, and the primary parts of lubricity tester were systematically reported. The HTHP dynamical lubricity tester is portable, and its most advantage is to allow the real-time inspection on lubricity for the different surfaces of metal-to-metal and metal-to-sandstone in the filtrate loss and mudcake formation. Applicability of the HTHP dynamical lubricity tester was preliminarily evaluated by measuring the lubricity of the PRD fluid. This newly designed lubricity tester will provide instructive information on optimization of drilling process in modern drilling.

Acknowledgments
This work was financially supported by National Science and Technology Major Project (No. 2016ZX05060-015).

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