DISCUSSION ON NEW TRIBOLOGY TESTS AND UPDATED INSTRUMENTATION FOR THE PETROLEUM INDUSTRY

INTRODUCTION

Tribology is a vital study in the petroleum industry. It concerns the macro and molecular-scale interactions between two surfaces in motion.[1] It is an especially important area of study since nearly every mechanical product experiences frictional effects. For example, a car's engine could experience irreparable damage over time due to infrequent oil changes or incorrect oil rating use. An entire range of petroleum products is specifically devoted to lubrication, from the thinnest motor oil to the thickest grease. Tribology is not just important in lubricants; for example, airplane fuel with insufficient lubricity decreases engine component lifespan due to unnecessary friction.[2] Therefore, it is imperative to determine the tribological effects of petroleum products before scale-up and mass production occurs.

Figure 1. Suncor Energy Lubricants Centre, a lubricant manufacturing plant. [3]

Tribology Background

Tribology has been studied and utilized for millennia. The Ancient Greeks recognized the friction-reducing effects of olive oil while the Ancient Egyptians used animal fat as a lubricant for chariot wheels.[4] The mathematician Archimedes studied mechanics and observed what would eventually become the laws of friction.[4] However, the greatest advancements in tribology occurred within the past 300 years due to the Industrial Revolution and its aftermath. The development of advanced machinery and components such as shafts and bearings created a high demand for friction mitigation.[4] During the 20th Century, Dr. H. Peter Jost researched tribological studies, being commissioned by the British government in 1964 to make a report on the state of lubrication research, education, and industry demand.[5] By 1966, his group determined that approximately £515 million ($628 million) could be saved annually by implementing widespread tribological improvements throughout industries.[6] Coined the "Jost Report", it marked the beginning of modern tribology, inspiring other researchers to produce their own advancements. Their reports discussed a range of subjects, including saving between 11-22% of energy consumption when looking into tribology; such reports accounted for transportation, industrial machinery, power generation, and energy-intensive sectors such as mining and paper production.[7] These numbers are very significant even as rough estimates since they translate to billions of dollars saved. Dr. Jost concluded based on the reports that industrial nations could save 1.0-1.4% of their gross national product if they improved tribological processes and invested in research and development (R&D) at a fraction of the savings rate.[7] Tribology has a profound effect on mechanical efficiency and, in turn, has widespread economic and environmental implications.

In a 2011 analysis of global energy consumption via friction losses, researchers concluded that the average car uses ⅓ of its energy just to overcome friction.[7] In addition, researchers noted that implementing state-of-the-art tribology advancements in vehicles could cut frictional energy losses by 61% over the next 15-25 years.[7] This corresponds to an annual €576 billion ($608 billion) saved and 960 million tonnes of CO2 unreleased.[7] These numbers show how large of an impact tribology has on energy efficiency. Tribological R&D funding could lead to major advancements in climate change mediation, conservation, and bountiful economic returns.

Standardized tribological testing equipment ensures petroleum products maintain lubricity under various conditions. The American Society for Testing and Materials (ASTM) has produced several test methods specifically designed for tribological units. The following examples listed below are ASTM-conforming devices produced by Koehler Instrument Company: the High Frequency Reciprocating Rig (HFRR), the Automated BOCLE Tester, and the Benchtop Four Ball Wear and EP Tester. Their respective ASTM methods test a wide variety of petroleum products, such as jet fuels and lubricating greases. For the petroleum industry, these methods are paramount for ensuring quality lubricants.

K93405/K93495 High Frequency Reciprocating Rig

The High Frequency Reciprocating Rig (HFRR) falls under two ASTM test methods: the D6079 method for "Evaluating Lubricity of Diesel Fuels by the High-Frequency Reciprocating Rig (HFRR)"[8] and the D7688 method for "Evaluating Lubricity of Diesel Fuels by the High-Frequency Reciprocating Rig (HFRR) by Visual Observation".[9] An example of the HFRR is shown below.

Figure 2. K93495 High Frequency Reciprocating Rig (HFRR)

The test methods cover a wide range of diesel products, including 1D, 2D, their low sulfur derivatives,[8] and biodiesel blends.[9] The methods specifically examine the wear scar of the fuel tested. A crucial industry standard for fuels and lubricants, the wear scar test determines relative lubricity by moving a ball bearing along a metal disk at a high frequency. The friction between the two objects results in an abrasion scar (wear scar) on the ball, but the disk is submerged in test fuel. A fuel with higher lubricity will lessen the effects of friction, thereby decreasing scar size.[10] The U.S. standard for commercial diesel fuel is a maximum diameter of 520 microns, with the Chicago-based Engine Manufacturers Association standard being 460 microns.[10] These test methods have significant implications on diesel engines, which consequently affects worldwide commerce. Engine components, such as injectors and injection pumps, experience the lubricating properties of the fuel, creating insufficient lubricity that correlates to a decreased lifespan.[8] Therefore, this test is important for any company that produces fuels or fuel additives.

The K93405/K93495 unit is specifically designed to perform the wear scar test. It requires the assembly of several components, all cleaned before testing. The ball and disk are both placed into their respective holders with tweezers and screwed finger-tight into place. The temperature probe is placed into the hole in the disk holder along with the test fuel, and a 200 g weight hangs from the support cord. The USB-linked program allows for the input of a desired temperature, set at 60℃ in accordance with ASTM D6079.[8] The humidity can also be controlled through the program with the use of a control cabinet. Testing commences after all inputs are complete.

The ball is lowered into the fuel holder until it makes contact with the disk; at that point, it starts rubbing against the disk at 50 Hz for 75 minutes. The ball, which is still in the holder, is then removed from the device, washed with cleaning solvent, and dried with a lint-free tissue. The ball-holder combination is placed under a 100x microscope, and the major/minor axes are

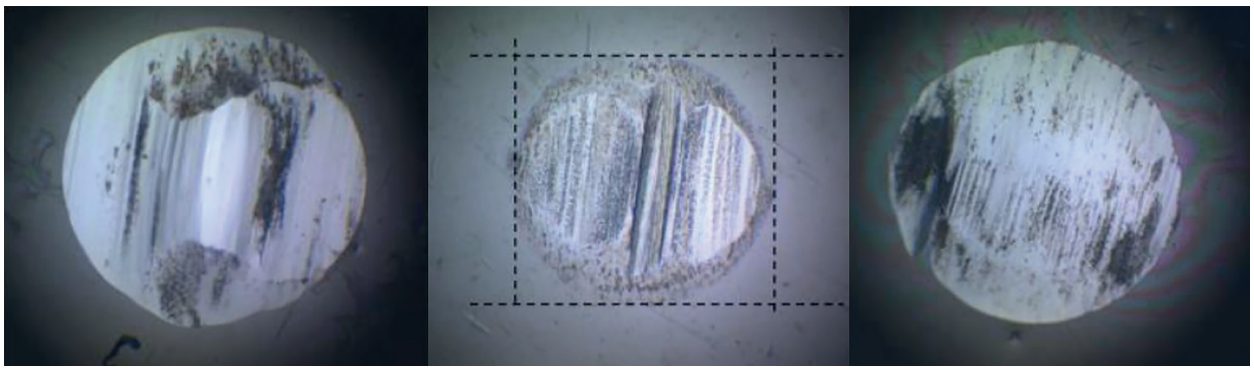

Figure 3. Wear Scar Examples

measured to the nearest 0.01 mm.[8] An average measurement is taken and used as the wear scar diameter.[8] Calculating the wear scar diameter concludes this test. Figure 3 visualizes typical wear scar formations after testing.

K94100/K94190 Automated BOCLE Tester

The Ball-on-Cylinder Lubricity Evaluator test is like the HFRR test; however, it is intended for jet fuel instead of diesel. The specific method is ASTM D5001, "Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)".[2] An example shown in Figure 4 is the Koehler K94100 Automated BOCLE Tester which has built-in digital capabilities.

Figure 4. K94100 Automated BOCLE Tester

A similar result as from the HFRR test occurs: a ball is moved against a metal surface submerged in test fuel, and the result is a wear scar that is measured to determine the fuel lubricity.[2] The primary difference between the two methods is the test mechanism. While the HFRR moves the ball horizontally at a high frequency against the surface, the BOCLE keeps the ball stationary while a rotating ring creates the necessary friction.[2] The method is significant to the aviation industry in the same way HFRR test methods are to diesel engines. Airplane fuel pumps and controls experience excessive friction and a shortened lifespan when the fuel lacks lubricity.[2] This is also the case for some fuel system hardware components,[2] making it vital for passenger safety and airline cost efficiency.

The Koehler BOCLE unit requires installation and setup similar to the HFRR. The BOCLE has a built-in humidifier to keep the test humidity standard; it must be filled with DI water. After the power is plugged in and the water is topped off, compressed air is added to the system through an inlet. The test ring is assembled using a spacer, adaptor, clamp, and screw; from there, the fuel bath is added and the thermocouple is inserted through a small hole. The fuel is added to the bath, air tubes are connected, and the test ball is positioned and tightened in the holder (located bottom-middle in Figure 4). A 500 g weight is added to the end of a lever arm to secure the holder (located bottom-right in Figure 4).

After the device is activated, the fuel will be conditioned through the air tubes for 15 minutes, followed by a 30-minute test. The 100x microscope is included with the unit and it is seamlessly integrated into the test software. Overall, this digital device has more features than the HFRR, but both units fulfill their niche within their respective ASTM specifications.

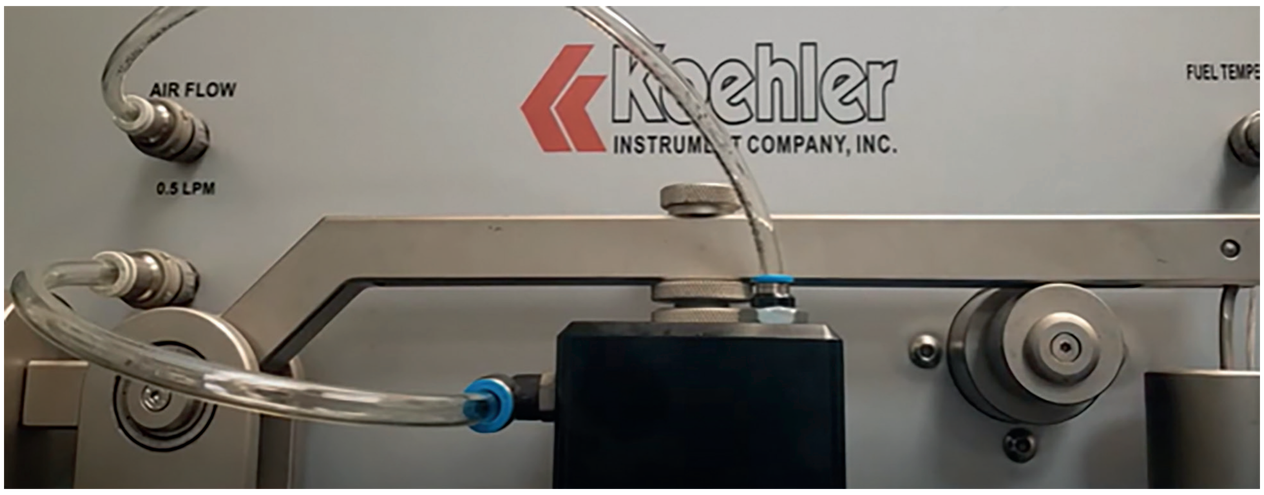

Figure 5. Fully Secured Holder with Lever Arm and Weight

K93170-PN/K39179-PN Benchtop Four Ball Wear and EP Tester

The Four Ball Tester is a versatile unit designed for a range of test methods. The example pictured below is the Koehler K93170 Benchtop Four Ball Wear and EP Tester. It is a fully digital unit with the ASTM test methods pre-programmed into its software, and it offers a custom test functionality as well. It has graphing and data analysis capabilities, and test results can be exported using its USB port.

Figure 6. K93170-PN Benchtop Four Ball Wear and EP Tester

Unlike the previous two devices that determine fuel lubricity, the Four Ball Tester is specifically designed for oils and greases. The ASTM methods are as follows:

ASTM D2266: "Standard Test Method for Wear Preventive Characteristics of Lubricating Grease (Four-Ball Method)"[11]

ASTM D2596: "Standard Test Method for Measurement of Extreme-Pressure Properties of Lubricating Grease (Four-Ball Method)"[12]

ASTM D2783: "Standard Test Method for Measurement of Extreme-Pressure Properties of Lubricating Fluids (Four-Ball Method)"[13]

ASTM D4172: "Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method)"[14]

ASTM D5183: "Standard Test Method for Determination of the Coefficient of Friction of Lubricants Using the Four-Ball Wear Test Machine"[15]

In summary, the unit tests lubricity, extreme-pressure properties, and frictional coefficients of oils and greases. Each test uses three stationary balls covered in lubricant and a rotating "top ball" pushed into them using a fixed amount of pressure.[11],[12] Although they all create wear scars, only the wear test is specifically intended to measure the scar diameters, similar to the HFRR and BOCLE devices.[11] The extreme pressure test places increased loads on the top ball until failure, which is when the balls weld together.[12] The coefficient test is also performed until failure from increased loads, but the wear scar diameter is used in addition to the final load force to calculate the coefficient of friction.[15] The significance of the ASTM four-ball wear and friction methods is similar to that of the HFRR and BOCLE methods: they determine the ability of the tested products to minimize abrasion in the systems they interact with. This is especially important since the four-ball is specifically designed to test lubricants, unlike the other units that test fuels. The extreme pressure test is crucial for lubricants designed for high-load applications; such products are often used in universal joints and chassis joints, as those mechanisms experience constant pressure and wear.[16]

The setup for the K93170-PN/K93179-PN unit is similar for every test. The balls are assembled and tightened, and test lubricant is added to the chamber.

Figure 7. Fully Assembled Test Chamber

The procedure for the wear test (D2266 and D4172) is as follows. The temperature is adjusted to 75±2 ℃, and the spindle attached to the top ball is spun at 1200±60 RPM; this is performed for approximately an hour.[11],[14] After completion, the balls are either removed from the holder or left in the ball cup assembly.[11],[14] The wear scars on each ball will be measured along two perpendicular axes using a microscope, and the average of the six values will be recorded as the wear scar diameter.[11],[14] This is similar to the HFRR and BOCLE methods but more reliable since three balls are used for a more precise average.

The D2596 and D2783 extreme-pressure methods involve a completely different procedure but use the same mechanical setup as D2266 and D4172. The temperature is set to 27±8 ℃, the initial pressure is set to 784 N, and the test is run for 10±1 seconds.[12],[13] The wear scars are examined and two factors are determined: the "last nonseizure load" and "weld point".[12],[13] Table 1 below represents an adaptation from the ASTM D2596 manual used for these tests.

Table 1: Load/Scar Diameter Chart. Adapted from [12]

Column 1 Applied Load (N)	Column 2 Compensation Scar Diameter (mm)	Column 3 Compensation Scar Diameter +5% (mm)
127	0.21	0.22
157	0.23	0.24
196	0.25	0.26
235	0.26	0.27
314	0.29	0.30
392	0.31	0.33
490	0.34	0.36
618	0.37	0.39
784	**0.40**	**0.42**
981	0.44	0.46
1236	0.47	0.49
1569	0.52	0.55
1961	0.58	0.61
2452	N/A	N/A
3089	N/A	N/A
3922	N/A	N/A
4903	N/A	N/A
6080	N/A	N/A
7845	N/A	N/A

Column 1 refers to the load amount (the initial load of 784 N is bolded and underlined). After the first test is run, if the wear scar diameter is greater than the value in Column 3, the Column 1 force is reduced for the next test.[12],[13] If not, the force is increased. The highest force that doesn't result in a scar greater than the Column 3 value is the "last nonseizure load".[12],[13] From there, the tests are repeated with the force increased every time. Once the balls begin to weld together, indicated by a loud noise and a drop in the lever arm, the test immediately stops. [12],[13] That force is recorded as the "weld point".

The D5183 method combines the previous two methods to solve an equation for the friction coefficient. The temperature is 75±2 ℃, the runtime is 60±1 minutes, the top ball rotates at 600±30 rpm, and the initial load is 392 N.[15] After the test ends, the wear scar is measured. If it falls within ±0.03 mm of the machine's average (typically 0.67 mm), the next stage can begin.[15] If not, it has to be repeated with new test balls. The balls are cleaned in addition to the wear scars, and the test is repeated at a 98.1 N load in 10-minute intervals.[15] Every 10 minutes, another 98.1 N is added until the balls start to seize. [15] The friction coefficient is calculated at each interval using the following formula:

$$\mu = \frac{0.00227fL}{P}$$

Reprinted from [15]

P is the load in kg, L is the friction lever arm length in cm, f is the friction force in N, and μ is the friction coefficient.[14] The seizure load force, torque at each interval, and final wear scar diameter are also measured.[14]

Conclusion

The aforementioned ASTM test methods play a crucial role in maintaining lubricity standards for the oil and gas industry. Nearly every liquid and semi-solid petroleum product offers lubrication as a primary or secondary characteristic. Since they are used in mechanical components all over the world, the entire supply chain relies on these products to perform up to standard. Therefore, ASTM-compliant tribology testing equipment is imperative for any industrial petroleum company.

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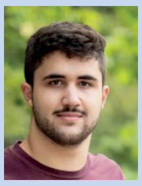

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