Biodiesel Lubricity

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Introduction

The need to reduce the exhaust emissions of diesel engines has driven the development of new diesel engine technology. These innovations have focused on the development of: 1) diesel fuel injection technology, 2) exhaust after-treatment technology, and 3) diesel fuel that has been refined to higher standards. The diesel fuel injection technology of a modern diesel engine operates at higher pressures than its counterparts (1). This new technology has demanded better lubrication from the diesel fuel that has traditionally lubricated the fuel injection system of the diesel engine.

Prior to October 1993, the diesel fuel that was sold in the US had a sulfur level of approximately 5000 ppm. In 1993, the Environmental Protection Agency (EPA) mandated that all diesel fuel sold in the US contain 500 ppm or less sulfur. The petroleum refineries, largely due to special hydrotreating of the diesel fuel, produced a cleaner diesel fuel that met this requirement.

On June 1, 2006 the EPA will again lower the level of sulfur in petroleum diesel fuel. The new standard will be 15 ppm. This reduction of sulfur is projected to reduce diesel engine exhaust emissions by as much as 90% when compared to the 500 ppm low sulfur diesel fuel era. The reduction in engine exhaust emissions is projected for new diesel engines that are equipped with diesel engine exhaust catalytic converters.

Research has demonstrated that catalytic converters last longer, aromatic hydrocarbon emissions are lower, and oxides of nitrogen emissions are lower when cleaner fuels are burned in diesel engines. Unfortunately, the hydrotreating that was used to reduce the sulfur produced a fuel that sometimes failed to provide adequate lubrication for the fuel injection system of the diesel engine (1) (2) (3) (4).

Lubricity analysis using the SLBOCLE and HFRR test procedures have indicated that the new 15 ppm low sulfur diesel fuel will exhibit lower lubricity than found in 500 ppm diesel fuel (5). Engine manufacturers have proven that a single tankful of diesel fuel with extremely low lubricity can cause the diesel fuel injection pump to fail catastrophically.

Research conducted using 1-2 percent blends of biodiesel mixed with petroleum diesel fuel revealed an increase in lubricity (6). HFRR test procedures using a two percent blend of biodiesel reduced the wear scar diameter by nearly 60 percent (from 513 to 200 microns).

Background Information concerning lubricity

Lubricity can be defined in many ways. “Lubricity is the ability of a liquid to provide hydrodynamic and /or boundary lubrication to prevent wear between moving parts” (7). It can be defined as follows: “Lubricity is the ability to reduce friction between solid surfaces in relative motion”(7). LePera (2) defined lubricity as the “quality that prevents wear when two moving metal parts come in contact with each other.

Keith and Conley (8) stated that the production of a cleaner diesel fuel could in fact lower the lubricity of diesel fuel. They reported that the lubricating quality of diesel fuel dropped significantly in 1993 when the United States mandated the use of a diesel fuel that had less than 500 ppm sulfur. The petroleum industry expects the lubricity of petroleum diesel fuel to drop even lower when the limit of sulfur is lowered to 15 ppm in June of 2006.

Although the viscosity of diesel fuel has been believed to be related to lubricity (9), many researchers believe that the lubricity of the fuel is not provided by fuel viscosity (4) (8). Researchers have found that viscosity is provided by other components of the fuel such as “polycyclic aromatic types with sulfur, oxygen, and nitrogen content.” According to Mitchell (1) oxygen and nitrogen have been shown to impart natural lubricity in diesel fuel. Barbour, Rickeard, and Elliott (4) reported that oxygen definitely contributes to the natural lubricity of diesel fuel, but that nitrogen is a more active lubricity agent than oxygen. They determined that diesel fuels that were high in sulfur but low in nitrogen exhibited poor lubricity.

Some researchers stated that lowering sulfur or aromatics might not lower fuel lubricity. However, as early as 1991 hydroteating has been documented as lowering the lubricity of diesel fuel (5) (10) (11) (12). Keith and Conley (8) noted that special hydrotreating which was used to reduce the sulfur content of diesel fuel also lowered the lubricity of the diesel fuel. Keith and Conley further theorized that the components (oxygen and nitrogen) "may be rendered ineffective as a result of severe hydrotreatment to desulfurize the fuel."

It is important to note that some fuel injection systems diesel engine rely entirely upon diesel fuel to lubricate moving parts that operate with close tolerances under high temperatures and high pressure (2). Lubricity related wear problems have already surfaced in Canada, California and Texas when fleets elected to use low-sulfur fuels to reduce engine exhaust emissions (10). LePera (2) noted that rotary distributor injection pumps manufactured by Stanadyne, DENSO, Bosch, and Delphi were most susceptible to boundary lubrication wear. It is important to note that failure of injection system components have not been limited to a single manufacturer. According to Kidwell-Ross (11) Cummins, Navistar, Cat, and Mack engines experienced problems with the Buna-N seals, which ultimately led to early failure of both the fuel injection system and engine components.

There are three ways to evaluate the lubricity of a fuel: 1) vehicle test, 2) fuel injection test equipment bench test, and 3) a laboratory test (7). The least expensive and most time efficient of these tests is the laboratory lubricity test. Fuel injection equipment tests require 500-1000 hours of closely monitored operations (1-3 months). On road "vehicle tests" require a similar length of time (500-1000hrs), however, the data may not be available for as long as two years. The laboratory lubricity test provides a low cost, accurate evaluation, in less than one week.

The ASTM D 975 (13) standard specifications for diesel fuel oils in the United States as of this writing does not include a specification for lubricity. Wielligh, et al., (14) stated that there was a definite need for a diesel fuel lubricity standard. The ASTM D 6078 (15) standard for lubricity has been agreed upon by some engine manufacturers in Europe. These companies have selected test procedures to evaluate the lubricating quality of diesel fuel. For example, Cummins Engine Company has determined that "3100g or greater as measured with the US Army SLBOCLE (ASTM D 6078) test or wear scare diameter of 380 microns at 25° C as measured with the HFRR (ASTM D 6079) methods" are adequate lubricity values for modern diesel engines. Fuel with SLBOCLE values above 2800g or an HFRR wear scar diameter that is less than 450 microns at 60° C, or less than 380 microns at 25° C, usually perform satisfactorily (7). According to LePera (2) ASTM D 975 will incorporate a lubricity standard by the year 2006, the next planned reduction in sulfur.

Munson and Hetz (12) noted that several standards existed and but that the petroleum industry was divided concerning which was the best test procedure. The tests that were available to evaluate lubricity included the: M-ROCLE (Munson roller on cylinder lubricity evaluator), SLBOCLE (scuffing load ball on cylinder lubricity evaluator), HFRR (high frequency reciprocating rig), and the SRV (optimal reciprocating rig).

The SRV test has a machine with a 10 mm steel ball sliding against a 25 mm diameter disc, in an off center mode. The ball is loaded in increments that are adjusted and the frequency and stroke of the sliding action can be changed. The friction between the ball and the disc results in torque being exerted on the disc and the torque is measured. A computer calculates the friction co-efficient based on the torque. The disc and ball are flooded by dripping the fuel onto the contracting surfaces (14).

The BOCLE and SLBOCLE test devices press a steel ball bearing against a steel rotating-ring that is partially immersed in the lubricity fluid. Weight is applied until a "scuff" mark is seen on the rotating cylinder (15). More specifically, a 12.7mm (0.5 inch) diameter steel ball is placed on a rotating cylinder. A load is applied in grams. After each successful test the ball is replaced with a new one and more load is applied until a specific friction force is exceeded. Exceeding this friction force indicates that scuffing has occurred. The grams of force needed to produce the scuff or scoring on the rotating ring is recorded as per ASTM D 6078.

The HFRR test is a computer controlled reciprocating friction and wear test system. The HFRR test consists of a ball that is placed on a flat surface (16). The ball is then rapidly vibrated back and forth using a 1 mm stroke while a 200g mass is applied. After 75 minutes, the flat spot that has been worn in the steel ball is measured with a 100X microscope. The size of the spot is directly associated with the lubrication qualities of the fuel being tested.

Lubricity test procedures that have ASTM and EuroNorme (EN) recognition

Engine companies needed a quick, dependable, cost effective solution to predict fuel performance in a real injection pump. Two tests have emerged: **High Frequency Reciprocating Rig** (HFRR), (this was a collaborative development by PCS Instruments Ltd, London and the Imperial College of Science and Technology, and the **Scuffing Load Ball On Cylinder Lubricity Evaluator** (SL-BOCLE), (developed at Southwest Research Institute – (SWI)). The SL-BOCLE was developed by modifying the existing instrument (BOCLE) at SWI that had been used to measure the lubricity of jet fuel.

European engine manufacturers and fuel injection pump manufacturers developed a round robin program in an effort to determine which of these two test procedures were most accurate. As noted earlier in the chapter, if the HFRR wear scar diameter is less than 450 microns, the fuel will usually perform satisfactorily. According to European engine manufacturers, the HFRR was found to give the best correlation to diesel fuel injection pump durability. This test procedure was adopted as the Commission on European Communities (CEC) standard in 1996. The Europeans have amended EN 590 to include a lubricity standard. The HFRR test procedure was selected with a maximum wear scar diameter of 460 microns.

In the United States, the Engine Manufacturer's Association (EMA) guideline recommends the use of the SL-BOCLE test with a 3100g minimum. The state of California recommends a 3000g (SLBOCLE) minimum. There are investigations and additional discussion among engine manufacturers in the US that will ultimately lead to a specification. However, it is important to note, that in the absence of a standard, each refiner has set its own threshold for diesel fuel lubricity.

Since the data developed from these two test procedures is not an exact science, reports can be found that specify an HFRR of 500 or 550 microns and SLBOCLE of 2800 or 3000 or 3100 and even 3150 grams. In short, comparing information taken using the SLBOCLE and HFRR is not precise. Further, most supporting information suggests that the proposed 520 micron HFRR level is not a lower lubricity value when compared to the 3,100 gram SLBOCLE level. Some engine manufactures suggest that the HFRR may be a better predictor of fuel lubricity for the engine.

According to the literature, the HFRR test method also is less operator- intensive than the SLBOCLE test method. Since much of the variation noted when using the SLBOCLE test procedure seems to be associated with operator differences / techniques, the HFRR may win out as the test of choice. The adoption of the HFRR would ultimately allow engine and fuel system manufacturers to more easily compare their test results.

Analytical variation of lubricity tests

With every analytical test procedure, the information obtained can sometimes vary from one laboratory to the next. Further, the information obtained can vary from one lab technician to the next in the same laboratory using the same analytical test equipment. Some companies report compensating for this variation of the SLBOCLE test by allowing a +/-300g range from the target weight of 3100g. The repeatability of the SLBOCLE is +/- 900g and the reproducibility is +/- 1500g (7). A similar effect, although with a smaller range is noted for the HFRR test where the repeatability of the HFRR is +/- 0.8 and the reproducibility is +/- 0.136.

Impact of using biodiesel as a lubricity additive

A study conducted at Iowa State (17) evaluated the lubricity of virgin vegetable oil. This same study provided an overview of the lubricity of number one and number two diesel fuel 500 ppm low sulfur diesel fuel. Please note Table 1 that follows:

Table 1. Lubricity test results for low sulfur diesel fuel, vegetable oil, and biodiesel blends.

Additive	F2 Commercial #2 with additives		F3 Kerosene (#1 diesel)		F4 Amoco #2 with corrosion inhibitor /no other additive	
	SLBOCLE	HFRR	SLBOCLE	HFRR	SLBOCLE	HFRR
NONE	4150	376	1250	675	4200	531
1% soybean oil	4150	365	3050	468	4550	303
1% methyl soyate	5200	251	3700	294	4775	233

Engine Manufacturer's Standards: SLBOCLE = >3150, HFRR = <450

As noted in this table, Van Gerpen noted a standard (3150g) that was marginally different from the standards establish by the ASTM for the SL-BOCLE (3100g) and HFRR test procedures. The 500 ppm low sulfur number one diesel fuel (kerosene) required a lubricity additive prior to use in a diesel engine.

When early research clearly supported the premise that biodiesel indeed had good lubricity, and that the tests conducted suggested that it was nearly two times more able to provide lubricity than petroleum diesel fuel, researchers set out to determine The primary goal was to determine if blends of the new low sulfur diesel fuel (15 ppm or less) and biodiesel (1-2%) would provide adequate lubrication for the diesel fuel injection systems of the diesel engine.

Blends of 1% biodiesel, 2% (and more), were prepared on a volumetric basis for lubricity testing. These blended fuels were analyzed by independent laboratories using ASTM SLBOCLE test procedures.

SLBOCLE tests were conducted on the number one and number two diesel fuel (Tier 2 2004) and biodiesel. The results of these tests are reported below. Williams Laboratory determined the lubricity using ASTM Test procedure D 6078.

Table 2. SL-BOCLE test results for ultra low sulfur diesel fuel and biodiesel blends.

Fuel	**0% BD (100% DF)**	**½ % BD**	**1% BD**	**2% BD**	**4% BD**	**12% BD**	**100% BD**
Number 1	1250g	N/A	2550g	2880g	2950g	4200g	5450g
Number 2	2100g	2600g	3400g	3500g	N/A	N/A	5450g

Several diesel engine manufacturers have indicated that an SLBOCLE of 3100g (Chevron reports 2800g) provides adequate lubrication for a modern diesel fuel injection system. Table 2 above reports that a one percent replacement of number two diesel fuel with biodiesel will provide adequate lubrication for the injection system of a diesel engine. The increase in lubricity for the number one diesel fuel, when additized to the level of four percent, fell short of the ASTM SL-BOCLE lubricity standard. Based on these data and information subsequently gathered at the University of Missouri during May 2004 (18), at least five to six percent biodiesel will need to be added to increase the lubricity of the new ultra low sulfur number one diesel fuel above 3100g.

Summary

The data available via engine manufacturers, ASTM, EN, CEC and private companies suggested that the lubricity of the 15 ppm low sulfur petroleum diesel fuel will be lower than the existing 500 ppm low sulfur diesel fuel. Severe hydrotreating of the diesel fuel was used to remove the sulfur from the diesel fuel. The end result was a cleaner fuel, but also one that was poor in lubricity. Petroleum distributors are planning to use a lubricity additive to prevent premature failure of the diesel fuel injection system when the new diesel fuel is mandated into use by the EPA on June 1, 2006.

The diesel fuel injection system of a modern diesel engine requires better lubrication due to higher operating pressures than previously used in diesel fuel injection technology. Several lubricity test procedures have been developed by the engine manufacturers together with the petroleum industry in an effort to ensure that the diesel fuel injection system does not fail prematurely. Two of these test procedures have emerged as bench lubricity evaluators- the SL-BOCLE and the HFRR test procedures. Although several researchers contend that the SL-BOCLE correlates more closely with injection pump durability tests (9), the HFRR test procedure appears to be gaining in popularity as the EN has adopted this test procedure as a standard EN590.

The lubricity of petroleum diesel fuel was at one time believed to be directly related to the viscosity of the diesel fuel. Although viscosity and fuel temperature tend to be correlated with a high lubricity diesel fuel, researchers have determined that other compounds are responsible for the natural lubricity of diesel fuel. They have also determined that the removal of the sulfur has not lowered the lubricity of the fuel, rather, the removal of oxygen and nitrogen during desulphurization has resulted in a diesel fuel that is low in lubricity.

Lubricity research has revealed that the lubricity of low sulfur number one diesel fuel will be lower than the lubricity of number two diesel fuel. The lubricity of number two diesel fuel was noticeably lower than what the EMA, EN, and the CEC have established as an acceptable level for diesel fuel lubricity. The addition of small quantities of Biodiesel with number one and number two diesel fuel (Tier 2, 2004) significantly improved the lubricity of the diesel fuel.

Blending as little as one to two percent biodiesel with petroleum diesel fuel increased the lubricity to an acceptable level for the new ultra low sulfur (15 ppm) number two diesel fuel. Since the new number one Tier 2 diesel fuel is not yet in production, the amount of biodiesel that will be needed to raise the lubricity to an acceptable level is unknown. However, based on lubricity research that was conducted using 15 ppm low sulfur number one fuel (with a similar distillation curve and viscosity as the present day 500 ppm number one diesel fuel), as much as five to six percent biodiesel may be needed to raise the lubricity to a level that meets the lubricity guidelines set forth by the EMA, EN, and CEC.

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