Diesel Fuel's Role as a Lubricant

As the demand for environmentally safe fuels increases, so will the call for cleaner burning engines. Texaco's Yvonne Thiel examines how a diesel fuel's lubricity is a measure of its ability to prevent or minimize wear in the components that utilize the fuel as a lubricant.

Protecting fuel injection systems

Fuel delivery systems in compression ignition engines depend on fuel to lubricate and cool sliding contacts. A diesel fuel’s lubricity is a measure of its ability to prevent or minimize wear in the components that utilize the fuel as a lubricant. Obviously, components with the greatest dependence on the fuel for lubrication demand a higher lubricity fuel. For example, in-line fuel injection pumps that are lubricated by a combination of the engine’s crankcase oil and the fuel are far less sensitive to the diesel fuel’s lubricity than rotary/distributor type fuel pumps that rely solely on the fuel for lubrication.

Lubrication mechanisms

The sliding surfaces in fuel injection pumps are protected from wear by hydrodynamic and boundary lubrication mechanisms. In the hydrodynamic regime, a film of fluid prevents contact between the sliding surfaces. The lubricant’s ability to keep the surfaces separated is governed by its viscosity.

In boundary lubrication, asperities (rough spots) on the sliding surfaces are just touching, but the lubricant still supports most of the load. The fuel’s effectiveness as a boundary lubricant is dictated by its chemistry. Diesel fuel molecules with polar groups will adhere to the metal surfaces, while the non-polar portion of these molecules will occupy space between the surfaces. These non-polar “tails” effectively trap additional lubricating medium to reduce the degree of contact, thereby protecting the surfaces from wear.

<table>
<thead>
<tr>
<th>Year Established</th>
<th>Country</th>
<th>Maximum Sulfur (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>Sweden (MK 1 fuel)</td>
<td>10</td>
</tr>
<tr>
<td>1993</td>
<td>Sweden (MK 2 fuel)</td>
<td>50</td>
</tr>
<tr>
<td>1994</td>
<td>USA (EPA) USA (CARB)</td>
<td>500</td>
</tr>
<tr>
<td>1994</td>
<td>Canada (winter and summer)</td>
<td>500</td>
</tr>
<tr>
<td>1994</td>
<td>Europe</td>
<td>2000</td>
</tr>
<tr>
<td>1996</td>
<td>Europe (CEN)</td>
<td>500</td>
</tr>
<tr>
<td>1996</td>
<td>Korea</td>
<td>500</td>
</tr>
<tr>
<td>1996</td>
<td>Japan (Grade 2)</td>
<td>500</td>
</tr>
<tr>
<td>1996</td>
<td>Hong Kong</td>
<td>500</td>
</tr>
<tr>
<td>1998</td>
<td>Thailand</td>
<td>500</td>
</tr>
<tr>
<td>1999</td>
<td>Taiwan</td>
<td>500</td>
</tr>
<tr>
<td>2000</td>
<td>Europe</td>
<td>350</td>
</tr>
<tr>
<td>2000</td>
<td>Philippines</td>
<td>500</td>
</tr>
<tr>
<td>2003</td>
<td>Australia</td>
<td>500</td>
</tr>
<tr>
<td>2003</td>
<td>New Zealand</td>
<td>500</td>
</tr>
</tbody>
</table>

Lubricity and environmental challenges
There is constant pressure on the petroleum industry to reduce sulfur levels in diesel fuels; this will be discussed further in a future issue of PE&T. The stringency of worldwide fuel regulations is based on the recognized detrimental impact of sulfur on emissions [1]. The chronology and geography of low-sulfur standards for diesel fuel are shown in the following Table, taken from Fuel Lubricity Reviewed, SAE 982567, 1998, Lacey, P.I., Howell, S.A. [6].

An example of sulfur’s detrimental impact on emissions is its effect on the performance of automobile exhaust systems. The catalysts used in exhaust systems will absorb sulfur, thus compromising the catalysts’ efficiency and increasing the levels of hydrocarbons and carbon monoxide in exhaust emissions. Sulfur compounds directly contribute to emitted particulate matter and may account for as much as 20 percent of a particulate [2]. Furthermore, emitted gaseous sulfur compounds are a factor in acid rain.

To achieve reduced sulfur and aromatic levels, unconventional refining/severe hydroprocessing schemes are typically required at the refinery. These processes not only decrease the sulfur content but also decrease the level of naturally-occurring lubricity agents (certain polyaromatic and polar compounds) in diesel fuel. Consequently, the diesel fuel so produced may have inherently low lubricity quality that, if not corrected with lubricity additives, can cause fuel distribution system failures.

The impact of plummeting fuel lubricity was demonstrated in well-documented field problems [3, 4, 5, 6]. The introduction of low-sulfur fuels in Sweden, (MK 1 and MK 2; see Table) was accompanied by an extraordinary increase in rotary-type injection pump failure. These fuel pumps are used in light-duty vehicles and rely entirely on diesel fuel for lubrication. In contrast, in-line fuel pumps in heavy-duty diesel vehicles did not experience this type of fuel-lubricity-related failure.

In 1993, the United States followed Sweden’s low-sulfur initiative with federal regulations limiting sulfur content of all highway diesel fuel to 500 ppm. That same year, the California Air Resources Board further stipulated that aromatics levels in diesel fuel could not exceed 10 percent. The resultant more severely refined, lower lubricity diesel fuels were responsible for a significant increase in rotary pump failure in North America in 1993.

The solution to these diesel fuel lubricity problems took its lead from experience in the aviation industry. In the 1950s, corrosion inhibitors were added to jet fuels to protect fuel systems from corrosive wear induced principally by entrained water [7]. In November 1965, the mandate to use corrosion inhibitors in jet fuel (JP-4) was lifted when certain inhibitors were linked to fuel filter plugging. Eliminating corrosion inhibitors in jet fuel resulted in fuel delivery system problems that were attributed to a deficiency in fuel lubricity. The use of approved corrosion inhibitors in JP-4 was re-established within four months after the mandate was lifted—under the premise that these additives function as lubricity agents.

**Additives and efficacy testing**
Several generations of lubricity additives have been developed since the early aviation studies. Fuel additive suppliers have broadened the spectrum of lubricity supplements beyond conventional corrosion inhibitors to compounds that include acids, amines, amides and esters, to name a few.

The effectiveness and, therefore, the treat rate—meaning the dose or concentration— of lubricity additives are determined by the responsiveness of a given diesel base fuel. Two diesel base fuels having the same initial lubricity may be treated with the same additive at the same dosage, yet one fuel’s lubricating properties may be enhanced substantially compared to the other fuel’s. Typically, the additive supplier recommends lubricity additive treat rates that will improve a fairly broad range of diesel base fuels.

Various tests have been designed to measure the lubricity characteristics of diesel fuel. The most commonly used bench tests include the High Frequency Reciprocating Rig test (HFRR), the Scuffing Load Ball-On-Cylinder Lubricity Evaluator test (SL BOCLE), and the Ball-On-Three-Discs test (BOTD). Descriptions of these methods follow.

**HFRR**: The HFRR test consists of a flat steel disc immersed in a bath of the test diesel fuel that is maintained at 60°C. A 200-gram load is applied to a 6-mm steel ball as it oscillates across the steel disc at a stroke frequency of 50 Hz for 75 minutes. At the end of the test, the wear scar generated on the steel ball is measured. The wear scar “passing” limit is 450 microns. Certain low-sulfur diesel fuels that are not treated with lubricity additives can yield wear scars greater than 700 microns.

**SL BOCLE test**

**SL BOCLE:**

The SL BOCLE apparatus monitors the load required to induce a wear scar, rather than measuring the wear scar created by a constant load. A steel cylinder rotates at 525 rpm in a bath of test diesel fuel maintained at 25°C. Variable loads are applied to a stationary ball that is in contact with the rotating cylinder and the coefficient of friction is monitored. The load that causes the friction coefficient to surpass a value of 0.175 is defined as the scuffing load. A fuel is considered to have good lubricity characteristics if the scuffing load is greater than 3,000 grams.

**BOTD**: The BOTD test method is still undergoing some modifications and has yet to be ASTM-certified. In its current form, a ceramic ball rotates at 60 rpm against three steel disks that are held in a cradle immersed in the test diesel fuel maintained at 25°C. A load of 2.5 kilograms is applied to the ceramic ball for 45 minutes. At the end of the test, the wear scars created on the three disks are measured and their average is calculated. Presently, high lubricity diesel fuels generate average wear scars that are less than 400 microns and low lubricity fuels yield average wear scars that are over 500 microns in the BOTD test.

While bench tests are time efficient, cost effective, and will show trends in lubricity quality, their correlation to field data is spurious. Pump rig tests are intended to reproduce field conditions under a
high level of repeatability; however they are time consuming and expensive. A pump rig test uses an actual fuel injection pump mounted on a stand. Diesel fuel re-circulates continuously throughout the fuel injection pump for 500 hours. The pump is then disassembled and various internal parts are measured for wear. A review of accepted pump rig tests was done by K. Mitchell in 1998. [8]

“No-harm” performance issues
Commercially available lubricity additives should be put through a battery of no-harm testing prior to their introduction in the market. Tests include examining the lubricity agent’s effect on the performance of other additives in the diesel fuel and the impact of mixing lubricity additives with engine oils. The latter situation is non-trivial, given that fuel additives can enter the engine oil in a number of ways.

First, the higher molecular weight species present in diesel base fuel and some fuel additives can reach the cylinder wall before combustion and, thereby, enter the crankcase. In-line fuel pump design affords another opportunity for fuel additives to mix with engine oil. Finally, while never recommended, some consumers have been known to add engine oil to diesel fuel under the misguided belief that the lubricity of the fuel will be enhanced in this manner.

In the past, cases have been documented in which the interaction between certain lubricity additives and engine oil has been detrimental. Problems included deposits forming in in-line fuel injection pumps [9], “black sticky gel” plugging fuel filters and deposits forming on injector tips.

In light of these field observations, lubricant compatibility tests were developed to screen for potentially harmful effects on lubricant performance induced by lubricity additives. Some methods monitor precipitate, or gel formation, in blends of engine oils and diesel fuel treated with lubricity additive at elevated temperatures. Other approaches involve blending the neat lubricity additive into the motor oil and noting any changes in the oil’s appearance over time. Tests have also been devised to measure the change in fuel filterability when blended with a lubricity additive and engine oil. Excellent reviews of the most common no-harm bench tests are available in the literature [1, 10].

Prognosis
Compression ignition engines will continue to undergo design changes as the push for reduced emissions persists. The demand for more environmentally friendly fuels will accompany the call for cleaner-burning engines. Recent history shows that the processing changes that enable fuels to meet tougher environmental standards can negatively influence other fuel performance characteristics. It is the responsibility of additive suppliers to develop next generation fuel additives that will compensate for secondary base fuel performance deficiencies that can arise as refining methods are modified.

REFERENCES


Yvonne Thiel is a Senior Research Chemist with Texaco Additives International R&D in Beacon, New York.