For some fuel injection systems, fuel is the only source of lubrication. But delivering the right product with the appropriate injection system remains an ongoing problem.

By Maurice Le Pera
and recent environmental legislation mandating reductions in vehicular emissions, resulting in lowered levels of both sulfur and aromatics in fuels, lubricity has become an important requirement in fuel specifications, especially those for diesel/distillate fuels.

Chevron’s Technical Review of Diesel Fuels publication defines lubricity as “the ability to reduce friction between solid surfaces in relative motion, the lubrication mechanism being a combination of hydrodynamic lubrication and boundary lubrication.” More simply stated, lubricity is that quality that prevents wear when two moving metal parts come in contact with each other. Although lowering sulfur and in some instances aromatics have resulted in lubricity problems, poor lubricity has been observed in diesel fuels with very high sulfur levels.

**Diesel fuel injection equipment**

As mentioned above, the two main mechanisms for diesel fuel lubricity are hydrodynamic lubrication and boundary lubrication. The effectiveness of hydrodynamic lubrication is determined by the viscosity of the fuel and, unfortunately, one cannot increase viscosity of fuels with additives. Boundary lubrication is greatly influenced by the film thickness on the metal surface and the nature of that adsorbed film on the surface of the metal components contacting each other.

All diesel fuel injection equipment relies to some degree on the diesel fuel as its lubricant. Of the many types of fuel injector pumps manufactured commercially (e.g., the single-cylinder pump, the inline pump, the distributor/distribution pump, the common rail pump, etc.), the rotary fuel distributor injection pump is one of the more sensitive to the fuel’s lubricating quality as it provides 100% of the lubrication to the internal parts of the injection pump. As the rotary distributor injection pump is highly susceptible to boundary lubrication wear (i.e., when heavy metal-to-metal contact occurs with the fuel providing little or no lubrication), this potential wear becomes more severe with increasing ambient temperature and increasing loading on the engine. Any significant wear will lead to under-run and/or stalling annoyances and eventually premature pump failure.

The newer common rail fuel injector pump is likewise sensitive to the lubricity of fuel as it operates at higher pressures (up to about 27,500 psi or 1,500 bar), which make the injector pump very vulnerable to both lubricity and variations in fuel quality.

The remaining other types of fuel injection systems are not as highly dependent on the fuel for lubrication and, therefore, are not as sensitive to low lubricity diesel fuel.

The rotary fuel distributor injection pump is inexpensive and is used in a wide variety of both commercial and military vehicle/equipment systems typically powered by light duty diesel engines. For these pumps when using fuel having sufficiently high viscosity, the fuel will physically separate the injection system’s sliding components, preventing wear. With a lower viscosity fuel, the potential for wear will significantly increase as the surfaces of the sliding parts can begin to interact.

However, certain additives in the fuel such as corrosion inhibitors or lubricity enhancers will generate surface films that provide the needed wear protection. Although the majority of lubricity deficient problems have centered on fuel injection pumps, some fuel injectors themselves have been adversely affected by insufficient lubricity.

**Surfacing problems**

With other countries also pursuing the reduction of emissions by lowering sulfur levels in their fuels, reports of fuel injection pump wear had surfaced in Canada, Finland, Japan, and other locations. Within the United States, there were scattered problems, but the majority of problems evolved from the U.S. Army, which has since implemented a one-fuel-forward policy that involves using aviation kerosene fuels (i.e., JP-8/JP-5 or Jet A-1) in lieu of diesel fuel for all ground
vehicles and equipment powered by compression ignition engines.

No doubt, using the less viscous aviation kerosene fuel having kinematic viscosities ranging from 1.0 to 1.5 mm²/s at 40 C when compared to diesel fuel with its limits of 1.9 to 4.1 mm²/s at 40 C certainly contributed to these problems. Because of the significant number of engines in the Army’s ground vehicle/equipment fleet equipped with rotary fuel distributor injection pumps, consuming kerosene-type fuels having both insufficient lubricity and reduced viscosity (e.g., Jet A-1) created problems. These typically involved wear on transfer blades, drive tangs and roller-to-roller dimensions of rotary fuel injection pumps resulting in reduced fuel delivery rates and transfer pump pressures, both of which significantly resulted in a rapid deterioration in engine performance.

In view of these numerous problems resulting from using both low sulfur and low viscosity fuels, there were a number of investigations conducted to (1.) define the mechanism of wear and (2.) develop a suitable laboratory methodology for measuring this wear.

**Laboratory procedures**

In aviation equipment, surface oxidation had been viewed as the primary mechanism for wear when using highly refined kerosene fuels. This is when oxide layers are formed on metallic surfaces and then repeatedly formed and removed during sliding contact situations producing a high material removal rate. This type of wear (i.e., oxidative corrosion), controlled by the use of corrosion inhibitor additives, led to the development of the Ball-on-Cylinder Lubricity Evaluator (BOCLE), ASTM D5001, which is extensively used for aircraft systems.

For the wear problems occurring with the rotary fuel distributor injection pumps, the BOCLE procedure was found to be inadequate. This subsequently led to the development of the Scuffing Load Test for the BOCLE or SLBOCLE, ASTM D6078. Concurrent with the development of the SLBOCLE, European researchers developed the High-Frequency Reciprocating Rig or HFRR, ASTM D6079 for evaluating the lubricity of diesel fuels. Under the conditions of these latter tests, scuffing defines those conditions of severe friction and wear that are produced as a result of the welding of surface material resulting from failure of the boundary film or surface oxide layers.

Since the development of the above laboratory procedures, there have been a number of additional test methods for assessing the lubricity of kerosene and diesel/distillate fuels. These have included but are not limited to the following procedures: the

With the enactment of past and recent environmental legislation mandating reductions in vehicular emissions, resulting in lowered levels of both sulfur and aromatics in fuels, lubricity has become an important requirement in fuel specifications, especially those for diesel/distillate fuels.
Ball-on-Three Seats (BOTS) test, the Ball-on-Three Discs (BOTD) test, the Roller-on-Cylinder Lubricity Evaluator (ROCLE) test and the HFRR test modified to operate in a pressurized environment at higher temperatures.

This latter test, referred to as the High Pressure HFRR, revealed that when using fuels with poor lubricity, wear rates were very sensitive to both temperature and oxygen partial pressure and found to be significantly higher than under normal ambient conditions. However with fuels having sufficient lubricity (e.g., containing lubricity additives), these were insensitive to changes in either temperature or pressure.

Of all the tests listed above, the one that has received industry acceptance has been the HFRR. In the mid-1990s, the European Committee for Standardization (CEN) included the HFRR as a requirement in their EN 590 specification for automotive diesel fuel. The specific limit for this lubricity test was a maximum wear scar diameter of 460 microns at 60 C.

However in this country, the HFRR was approved in June 2004 for the ASTM D975 diesel fuel specification and became effective Jan. 1, 2005. The delay in its adoption was the result of disagreements in establishing the maximum wear scar limit for 520 microns at 60 C. In addition to the HFRR lubricity test being an ASTM procedure, it is currently listed as test method ISO 12156-1:2006 under the International Organization for Standardization.

Influencing factors
Reducing sulfur levels in diesel/distillate fuels as a means to reduce particulate emissions has been the major contributor to the lubricity issue apart from the military's increased use of the lower viscosity aviation kerosene fuels in lieu of diesel fuel. All on-road vehicles in this country equipped with 2007 or newer certified diesel engines are now required by law to use diesel fuel having a sulfur content that does not exceed 15 ppm. This fuel has been referred to as Ultra Low Sulfur Diesel Fuel (ULSD) and formally named S15 by ASTM.

Typically the refinery streams are hydrotreated to remove the sulfur compounds, but this often results in the removal of other compounds that contribute to fuel lubricity. In addition to sulfur compounds, natural lubricity is also provided by trace oxygen and nitrogen containing compounds, certain classes of aromatics and high molecular weight hydrocarbons. Regarding these other compounds that aid lubricity, research conducted in 2001 by the U.S. Navy revealed that phenols and polyaromatics were found to be the major classes of natural lubricity components found in
middle distillate fuels.

Although most of the lubricity problems that have occurred in the past originated with diesel fuel injection equipment utilizing the rotary fuel distributor type injection pump, the recent introduction of the common rail diesel fuel system into passenger car and light duty commercial vehicles has revealed its requirement for fuel having adequate lubricity. The common rail fuel system, similar to gasoline multipoint fuel systems, has a fuel pump generating the needed pressure up to 27,500 psi for injecting the fuel.

As the high-pressure pump is lubricated solely by the fuel, its lubricity becomes an important factor for the satisfactory operation of these systems. Common rail and rotary distributor injection pumps essentially require the same level of lubricity. According to Dr. Paul Henderson of GM Powertrain Diesel Fuel Systems Engineering, future common rail systems operating under higher pressures may be even more sensitive to fuel lubricity. In addition to the common rail fuel pump, new generation fuel injectors that operate under higher pressures also need adequate lubricity as the fuel is their only lubricating medium.

In addition to the above, the composition of the refined fuel itself, apart from the refinery hydrotreatment processes, has a major impact on the fuel’s lubricity. Fuels refined from either petroleum, tar sands, oil shale or coal liquids have varying degrees of lubricity. However, those fuels generated (i.e., synthesized) from gas-to-liquid or coal-to-liquid processes—typically referred to as Fischer-Tropsch (F-T) fuels due to their absence of sulfur, aromatic hydrocarbons and other heteroatoms—have been found to have poor lubricity as they are predominantly branched alkane hydrocarbons.

F-T fuels have been in use commercially in South Africa and are now part of a DOD/DOE/Industry initiative called the Assured Fuels Initiative that is championing rapid development of domestic sources of alternative fuels as a means to reduce the United States’ dependence on foreign crude sources. One important element of this initiative is the Battlefield Use Fuel of the Future (BUFF) program, which will validate and certify these F-T fuel(s) for use in tactical vehicles, aircraft, ships and advanced technology systems (e.g., fuel cells, hybrid vehicles, advanced turbine engines, etc.).

The need for lubricity additives to counter the above mentioned problems has generated other issues such as type and effectiveness of additive ingredients, impact on the distribution and handling of fuel shipments, difficulties in monitoring additive treatment levels, etc. In reality, lubricity additives encompass a diverse range of surface active materials that have an affinity for metal surfaces. This affinity allows them to form boundary films that minimize any possible metal-to-metal contact and associated wear.

Many corrosion inhibitors for petroleum fuels are based upon dimer acid technology and continue to be used to provide lubricity enhancement as well as protection against moisture-induced corrosion. These were initially utilized at the onset of the lubricity problems but have since been found to be inappropriate for use in diesel fuel. This is due to their interaction with certain additives in engine lubricating oils creating a variety of engine problems. As a result, four generic classes of lubricity additives have since evolved that are currently
in use: alkyl amines, fatty acids, fatty amides and fatty esters.

**Counteracting problems**

There have been a number of efforts underway to resolve or minimize the problems discussed above. At first glance, one might assume that the easiest approach toward resolving lubricity problems would be the additive approach. Although lubricity additives are certainly a direct solution for combating wear of diesel fuel injection equipment, the type of additives and how they are introduced can be problematic. As noted above, the dimer acid type corrosion inhibitor/lubricity enhancer additive can interact with the detergent additive(s) in the engine oil. To combat this, some effort has been expended to develop predictive models for non-acidic lubricity additives using Quantitative Structure Activity Relationships. In turn, these equations can be used as a tool for development of non-acidic lubricity additives.

The method for introducing these lubricity additives also has created some problems. In the past, most refineries introduced the additives at the refinery, allowing the fuels to then travel by pipeline to the distributor/terminal for eventual delivery to the user. As almost all major pipelines operating in this country are multiproduct pipelines, the recent introduction of ULSD has resulted in a drastic change in how the additive is introduced into the fuel. When fuel containing a lubricity additive is pumped through a pipeline, the lubricity additive coats the interior surface of the pipeline. When the next product is pumped through the line, some of the lubricity additive is then transferred (desorbed) into this fuel. This is termed “trail-back,” and with most fuels there are no major contamination problems.

However with aviation kerosene fuels, this trail-back results in an unacceptable contamination of the jet fuel. Because of this trail-back potential, most of the major pipeline carriers have prohibited use of diesel fuel lubricity additives at origin, resulting in the addition of the lubricity additive occurring at the distributor/terminal. As a result of this restriction for use in pipeline operations, the Coordinating Research Council (CRC) has initiated a study to determine if the current chemistry of the more popular ULSD fuel lubricity additives creates an increased fouling rate when tested in the high-temperature environment of turbine engine fuel nozzles and control components.

One novel means for introducing lubricity additives to ULSD has been to utilize the fuel filter as an additive source. More specifically, a lubricity-enhancing controlled-
release diesel fuel filter has been developed. To accomplish this, suitable lubricity additive(s) were incorporated into a proprietary fuel insoluble matrix that would allow a consistent and sustained release of the additive ingredients via a diffusion process into the fuel. The reported service life/interval of these filters, which are currently being marketed, is 250 hours or six months from their installation date.

Another innovation that should offer some resolution to this problem is the development of smart lubricants through tribo-polymerization. Researchers at Virginia Polytechnic Institute and Radom Technical Institute in Poland have developed an advance technology utilizing monomers to continually create films that form on surface areas that are more prone to experience wear. This technology, referred to as “smart lubricants,” has since been incorporated into lubricity additives designed to combat the problems with using ULSD.

Researchers at Argonne National Laboratory have developed yet another alternative to this problem. Instead of using additives to counter potential wear problems, their approach has been to modify the individual surfaces of the components using a near frictionless carbon film that protects against friction and wear problems. The films, 1 µm thick, were generated using plasma-enhanced chemical vapor deposition techniques and found to significantly reduce wear using a variety of laboratory test procedures such as the BOTD, HFRR, etc.

Dr. Manuch Nikanjam of Chevron Products advises that two ongoing industry cooperative efforts involve fuel lubricity. The first is a Coordinating Research Council (CRC) program that was initiated to determine the relationship between diesel fuel lubricity and diesel engine injection equipment durability for the current and near future light duty diesel injection equipment. The other is an ASTM program designed to

### References


improve the precision of the HFRR test method, ASTM D6079.

Currently, ULSD is required for all 2007 highway model engines. However starting June 1, 2010, ULSD will be required to be used not only in all on-highway diesel engines but off-highway diesel engines as well. As the use of ULSD continues to expand, coupled with the anticipated more restrictive emission requirements (i.e., increased injection pressures), one can expect fuel lubricity issues to take on greater importance. The use of a ULSD has since expanded worldwide with some countries having more stringent requirements than in the United States. For example, Sweden already has introduced a maximum sulfur limit of 5 ppm, Germany and Austria have a requirement of 10 ppm sulfur maximum, and the remaining European countries need to produce a ULSD having no more than 10 ppm sulfur by 2009, although many are already marketing ULSD below that limit.

Although not discussed previously, the inability to rapidly determine the presence and amount of a lubricity additive in fuel has and will continue to remain an obstacle. Because of the lubricity problems encountered with the use of kerosene aviation fuels, the Army awarded a Small Business Innovative Research contract in 2005 for the development of a fuel lubricity meter that would be capable of quickly and accurately measuring fuel lubricity using MicroElectro-Mechanical System technology. Unfortunately, this effort was terminated at the completion of the first phase as little progress had been made in developing the handheld technology. Possibly in the future, this technology or some other may fill the void allowing for a direct on-site measurement of fuel lubricity. <<

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