

Diesel Lubricity Requirements of Future Fuel Injection Equipment

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ABSTRACT

This paper looks at the underlying fundamentals of diesel fuel system lubrication for the highly-loaded contacts found in fuel injection equipment like high-pressure pumps. These types of contacts are already occurring in modern systems and their severity is likely to increase in future applications due to the requirement for increased fuel pressure.

The aim of the work was to characterise the tribological behavior of these contacts when lubricated with diesel fuel and diesel fuel treated with lubricity additives and model nitrogen and sulphur compounds of different chemical composition. It is essential to understand the role of diesel fuel and of lubricity additives to ensure that future, more severely-loaded systems, will be free of any wear problem in the field.

The lubricity with the High-Frequency Reciprocating Rig (HFRR) and the critical load of incipient scuffing (load-carrying capacity) in the High-Temperature Oscillating Machine (HiTOM) using real components of a Common Rail (CR) pump as test samples depends on the composition of the base fuels. A content of 5 % rapeseed-methyl ester (RME) in fuel increases the load-carrying capacity and increases the lubricity. Hydrodesulphurization decreases the lubricity of gas oil by 80 - 200 μm and the load-carrying capacity by 1500 N. Model sulphur compounds benzothiophene, dibenzothiophene and 4,6-dimethyldibenzothiophene cannot restore the lubricity of a hydrotreated diesel fuel, but can increase the load-carrying capacity. The model

nitrogen compound 8-hydroxyquinoline improves the lubricity at very low concentrations (20 ppm nitrogen) whereas quinoline and acridine need a higher concentration (100 ppm nitrogen) for some lubricity improvement.

The outcome of this work has confirmed that specific lubricity additive chemistries can stretch the mixed lubrication area where highly-loaded contacts can operate safely. Specific lubricity additives with carboxylic acid-, ester- and amide based chemistries can increase the lubricity in a variety of base fuels at a concentration of 200 ppm to meet the lubricity requirement according to EN 590. These compounds can provide protection against adhesive wear by increasing the incipient scuffing load. Higher than market-typical additive concentrations can further increase lubricity, but are levelling at concentrations between 1000 ppm and 2000 ppm. The ester-based additives level at a lower value than the acid and amide based additives and so can provide further protection to FIEs. The load-carrying capacity of test fuel - ULSD 1 - can be increased by 4500 N by an ester content of 1000 ppm. The acid can only provide an increase of 2500 N. The ester-based additive at 200 ppm can already provide an improvement of the load-carrying capacity by 3000 N at a fuel temperature of 90 °C.

Tribological investigations with the HiTOM showed an excellent correlation between the results of this test and the HFRR results.

INTRODUCTION

The composition of diesel fuel has a strong impact on the wear of fuel injection equipment and model wear specimen in tribological test rigs [1,2]. The adverse effect of severely hydrodesulphurized diesel fuel on distributor type injection pumps has been pointed out in several studies [2-6]. In order to restore the lubricity of hydrotreated diesel fuels, several different types of lubricity additives have been developed and are added to the fuel. These additives are added to the base fuel together with other additives, e.g. detergents, defoamers and cold flow additives. It has been confirmed in field tests that a careful selection of the additive technology can completely restore the level of protection needed to ensure proper field operations without failure and performance loss due to wear [7,8]. Furthermore it has also been emphasized that the chemistry has to be carefully selected to avoid negative interactions with other additives that may lead to injector deposits or increase in cylinder bore polish [9,10].

Fuel injection equipment (FIE) systems for Euro 5 and beyond will have to generate extremely high fuel pressure and controlled injection events to meet stringent emissions legislations [11]. Such performance will be required for the effective life of the vehicles, ranging from 150 to 500 thousand kilometres for passenger cars depending on their application. It is therefore imperative that the FIE systems maintain their top performance during the entire life of the vehicle. In order to achieve this, new contacts and materials are being considered. At the same time new fuels are appearing in the market place that could have an impact on the performance of such FIE systems like fuels containing 10 ppm sulphur and fatty acid methyl ester (FAME) as a blend component. These new fuels are likely to increase the overall severity for the FIE environment. The best combination of new FIE contacts for Euro 5 type and beyond, fuels and fuel additives is one way to ensure that the goal of meeting future more stringent emissions legislation can be met without field issues.

MAIN SECTION

1. OBJECTIVE OF THE TEST WORK

Modern diesel engine cars are no longer equipped with distributor type fuel pumps. Instead, Common Rail fuel injection systems are used which allow the car manufacturers to meet more stringent noxious emission limits [12]. In the future, more restrictive emission legislations will put even greater demands for performance and durability on FIE which may result in more severe tribological conditions leading to higher fuel temperatures in the FIE and higher contact pressures. Although the HFRR test (see Chapter 4.2) is a suitable test for the assessment of fuel lubricity today, it does not provide information about the lubricating operational

limits of diesel fuel as the lubricant of future more advanced and highly stressed FIE (e.g. its load-carrying capacity). Therefore, the objective of this investigation was to:

- increase the knowledge of the tribological behaviour and the failure mechanism of different fuel compositions in a highly-loaded contact. This will provide information on whether current fuels and lubricity additives can provide wear protection under more severe tribological conditions.
- assess whether the HFRR test has the potential to reproduce these more severe tribological conditions.

2. EXPERIMENTAL SETUP

2.1 BASE FUELS AND ADDITIVES

Base fuels

In this work four different commercial base fuels have been tested. All fuels are free of any additive and their characteristics are listed in **Table 5** (Appendix). They include two ultra-low sulphur diesel fuels (ULSD 1, ULSD 2), one ULSD with a biodiesel content of 5 % (Rapeseed-Methyl Ester or RME) and one Swedish Class I diesel fuel (Class I). The Class I fuel contains an antistatic additive as this is routinely added to the fuel during production. Beside these fuels, three gas oils have also been tested (Appendix Table 6). These samples were taken from the gas oil product stream that feeds the hydrodesulphurization (HDS) plant, hence have relatively high sulphur content - and from the stream coming out of this plant that have very low sulphur content. Hydrotreated gas oil, the refinery term for middle distillate petroleum fractions, is the main blending component of diesel fuel. The light gas oil (LGO), medium gas oil (MGO) have been provided by a German refinery and the gas oil (GO) has been provided by a different German refinery. These samples differ by their boiling range (LGO 5 % volume evaporated distillation at 180 °C and 95 % at 300 °C; MGO: 5 % at 200 °C and 95 °C at 360 °C; GO: 5 % at 211 °C and 95 % at 358 °C) and their kinematic viscosity (LGO 1.6 mm²/s; MGO 3.3 mm²/s; GO 2.8 mm²/s at 40 °C).

Lubricity additives

The typical chemical structure of a lubricity additive consists of a polar functional group attached to an oleophilic part R_i . Typical functional groups are carboxylic acid (Acid), carboxylic acid ester (Ester) and carboxylic acid amide (Amide) (Table 1). An ester for northern regions has also been tested that has the same functional group as the regular ester, but with a different oleophilic part for an increased solubility in diesel fuel at cold temperatures (high solubility ester - Hi.Sol.Ester). The market-typical treat rates of these additives to

achieve the required lubricity of 460 μm in an ULSD range from 50 ppm to 300 ppm. For our investigations four different commercial lubricity additives were selected. They comprise an acid, an ester, an ester designed for regions with extremely cold climates and an amide. All the lubricity additives tested do not contain any other active chemical, like detergents and cetane improver.

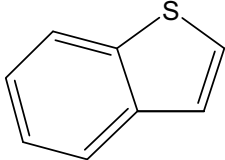
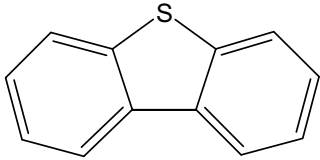
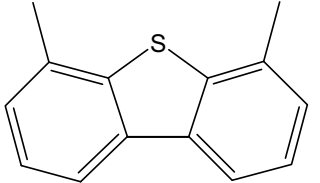
Table 1: Functional groups of lubricity additives [12]

Carboxylic acid	$\text{R}_1-\text{C}(=\text{O})-\text{OH}$
Carboxylic acid ester	$\text{R}_2-\text{C}(=\text{O})-\text{O}-\text{R}_3$
Carboxylic acid ester (northern regions)	$\text{R}_4-\text{C}(=\text{O})-\text{O}-\text{R}_5$
Carboxylic acid amide	$\text{R}_6-\text{C}(=\text{O})-\text{N}(\text{R}_7)-\text{R}_8$

Model sulphur compounds

Sulphur compounds, which are present in a considerable amount in unhydrotreated diesel fuel, could have an impact on the lubricating properties of the base fuel. In order to assess this, we needed to select the sulphur compounds that are the main components present in diesel fuel. Sulphides, disulphides, mercaptans, alkylated derivatives of thiophene, benzothiophene and dibenzothiophene, are the main types of sulphur compounds that occur in gas oil [14]. In low sulphur diesel dibenzothiophene (DBT), benzothiophene (BT) and 4,6-dimethyldibenzothiophene (4,6-DMDBT) (Table 2) are the main sulphur compounds present because they are the most difficult to remove by hydrodesulphurization [15,16]. These compounds are therefore the only sulphur compounds that can contribute to the difference in lubricity between ULSD and low sulphur diesel. These were the components selected for our investigation.

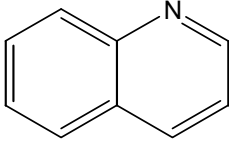
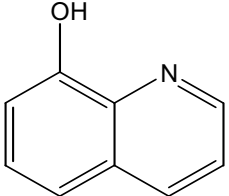
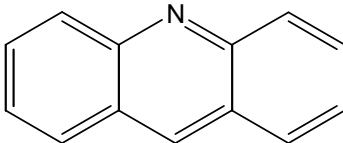
Table 2: Sulphur compounds [16]

benzothiophene	
dibenzothiophene	
4,6-dimethyl-dibenzothiophene	

Model nitrogen compounds

Beside sulphur compounds, other polar compounds like nitrogen-containing compounds - found in untreated gas oil and removed by HDS - may affect lubricity [16]. Typical nitrogen compounds which can be found in crude oil fractions comprise derivatives of aniline, pyrrole, pyridine, quinoline, acridine, indole and carbazole [15-19]. It has been demonstrated that pyridine, pyrrole, quinoline and indole showed a wear decrease pattern at 10000 ppm in a hydrotreated diesel fuel in a pre-version of the HFRR (among others differences fuel temperature 20 °C, stroke length 0.5 mm) from wear scar diameters of 0.35 mm (base fuel) down to values between 0.15 mm and 0.22 mm [20]. For 8-hydroxyquinoline, this effect could also be seen at a nitrogen content of 100 ppm. It was also observed that oxygen-containing derivatives of heterocyclic nitrogen-containing compounds have superior antiwear properties to the corresponding nitrogen compound [21]. The nitrogen compounds used in this work are displayed in Table 3. The nitrogen contents of the gas oils used in this work range from 15 ppm to 164 ppm before HDS (Table 5, Figure 6). Therefore, the impacts of quinoline and 8-hydroxyquinoline have been assessed at a similar nitrogen content of 20 ppm and 100 ppm. This is a factor from 500 and 100 times lower than what was investigated in the work by Wei [20]. The possible effect of acridine, another possible nitrogen-containing compound, has not been investigated in previous work, yet. Therefore, we also added this substance in our investigation.

Table 3: Nitrogen compounds [16]

quinoline	
8-hydroxyquinoline	
acridine	

2.2 TRIBOLOGICAL TEST METHODS

For the tribological characterisations of diesel fuels and lubricity additives two different test rigs were used. The HFRR test method is the standard technique for the assessment of diesel fuel lubricity and has been used to obtain a lubricity profile of all the fuels/additives tested in this study. A second test rig, the High-Temperature Oscillating Machine (HiTOM), has been the main test apparatus selected because it allows to investigate different tribological conditions. This test also allows the use of different wear specimen geometries and higher and variable loads. The highly-stressed contact is intended to represent highly-loaded contacts present in FIEs.

High-Frequency Reciprocating Rig (HFRR)

The HFRR test method for diesel fuel lubricity according to ISO 12156 [22] is used for standard lubricity assessments in our study. A detailed setup of the test rig and standard test parameters according to ISO 12156 can be found in the appendix (Figure 18). All tests were performed two times with the average corrected wear scar diameter (WS1.4) used in all the figures presented. For tests with varying fuel temperatures, WS1.4 is not defined so the mean wear scar diameter (MWSD) is used. Error bars represent the minimum and maximum values of the experiments. It has been shown that experiments with this test rig can also be assessed by measuring the wear volume of both specimens to get even more information from an HFRR test [23].

High-Temperature Oscillating Machine (HiTOM)

The test rig (Figure 1) HiTOM (High-Temperature Oscillating Machine) has been designed by BOSCH to reproduce in a controlled environment the main contacts that are present in the drive of Common Rail pumps. The machine kinetics of the chosen machine element are tribological similar to the real conditions experienced in

the high-pressure pump. The rig consists of a test chamber where the test specimens are immersed in diesel fuel that can be controlled to a temperature range from ambient to 90 °C. In the chamber a cylinder wear specimen is sliding in a reversing motion on a plate wear specimen. The oscillating motion is driven by an electric motor and a crankshaft with a frequency of 5 Hz and a stroke length of 10 mm. The normal force F_N (load) of up to 10000 N is applied to the tribological contact by a hydraulic cylinder. The resulting friction force F_F is measured at the lower wear specimen via a piezoelectric force gauge. Photographs of the test rig and the chamber are displayed in the appendix (Figure 19).

The cylinder specimen, which is an original part of a Common Rail pump, is made of annealed tool steel AISI M2. The plate as counter body which represents the raceway of a pump camshaft is made of the same annealed bearing steel AISI E-52100 as the original component with an equivalent heat treatment and surface finish. These materials are the latest used in Common Rail systems and are very likely to be the choice also for future FIE. Further details on the specimen can be found in Table 4. This test method is not standardized and is not intended to substitute the HFRR standard technique. The advantage of this technique is that it can provide information about the load-carrying capacity of different fuel compositions in highly-stressed contact environments that can be found in a real system. The load-carrying capacity has a direct link to the limit of performance of the fluid tested. In order to detect the transition from mild wear to incipient scuffing a series of tests has to be performed [24]. Each single test runs for 10 minutes at a fixed load with a fuel bath temperature of 60 °C. This results in a mean sliding velocity of 0.1 m/s.

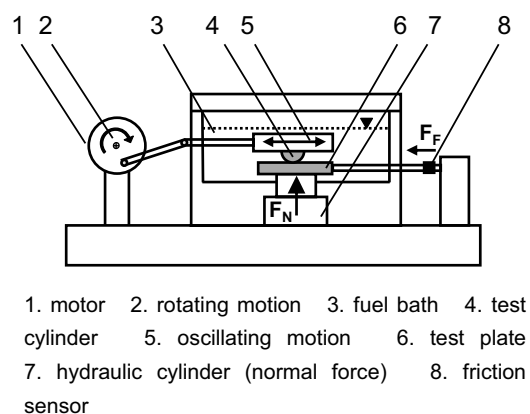


Figure 1: Setup of HiTOM test rig

Table 4: HiTOM test parameters

Parameter	Value
Test parameters	
Normal force	1000...10000 N
Stroke length	10 mm
Oscillating frequency	5 Hz
Fuel temperature	60 ± 2 °C
Fuel volume	4500 ml
Test duration	10 min
Wear specimen	
Cylinder diameter	10 mm
Cylinder length	21.5 mm
Cylinder material	AISI M2
Cylinder hardness	850 ± 70 HV10
Cylinder roughness	$R_a < 0.03$ μm
Plate material	AISI E-52100
Plate hardness	748 ± 19 HV10
Plate roughness	$R_a < 0.1$ μm
Ambient conditions	
Temperature	24 ± 2 °C
Relative humidity	50 ± 5 %
Hertzian pressure	400...1790 N/mm ²

Each test is performed twice to define a more representative value of the load-carrying capacity of the fluid under investigation. To find the transition from the mild wear regime to the scuffing regime, the wear scars of all tests are compared. A characteristic feature of incipient scuffing is the significant widening of the wear scar on the cylinder and the formation of shining bands on the plate. At a load of 1000 N the wear scar on the cylinder features a constant width of about 400 μm across the whole length of the line contact. At 1500 N and 2000 N the wear scar is significantly wider (600 μm to 700 μm) with signs of incipient scuffing which indicates that more severe wear is occurring (Figure 2).

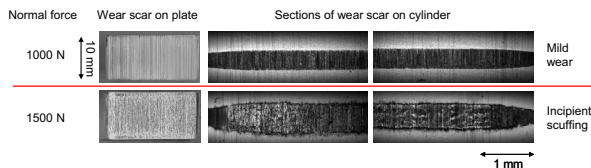


Figure 2: Wear scars on plate and cylinder at varying loads (ULSD 1; 60 °C, 5 Hz)

As a quantitative criterion for the transition from mild wear to incipient scuffing, the maximum wear scar width (WSW_{max}), the location with the widest extension of the wear scar on the cylinder, is measured with a microscope (Figure 3). The WSW_{max} values of all tests in

one series of tests for the same fuel are plotted versus the normal force (Figure 4). The load-carrying capacity for a certain fluid can then be drawn from this plot where values for WSW_{max} begin to exceed the constant level seen in experiments with lower loads. The incipient scuffing load determined in this work is the load at which at least one of the two tests measures widening of the wear scar with the constraint that no experiment at a lower load results in incipient scuffing. The load is increased from one test to the next by 1000 N. If the next higher load leads to incipient scuffing the next test will be performed 500 N below that load. This way the load interval from the last test with both “pass-runs” to the first test with incipient scuffing is reduced to 500 N. The error bars in all the HiTOM experiments represent this interval between “last pass” and “first failure”. The terms incipient scuffing load and load-carrying capacity are used with an equivalent meaning. The measurement of the widest wear scar extension instead of the average wear scar width can only provide the necessary information of incipient scuffing. Experiments demonstrate that incipient scuffing is rather a local effect and is not always occurring across the whole length of the contact. Sometimes experiments above the critical load do not show incipient scuffing. This can be explained by the fact that this is an incipient effect which is affected by slight variations of specimen material and fuel composition. FIE needs protection against the failure mechanism of incipient scuffing because this may reduce performance and lifetime.

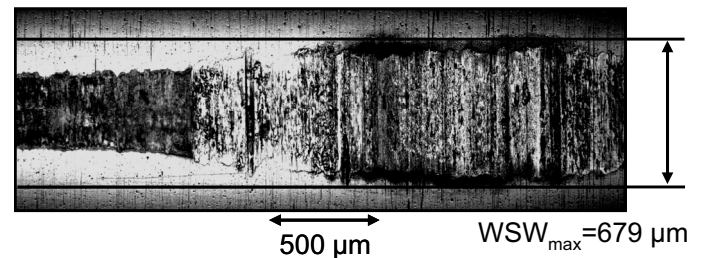
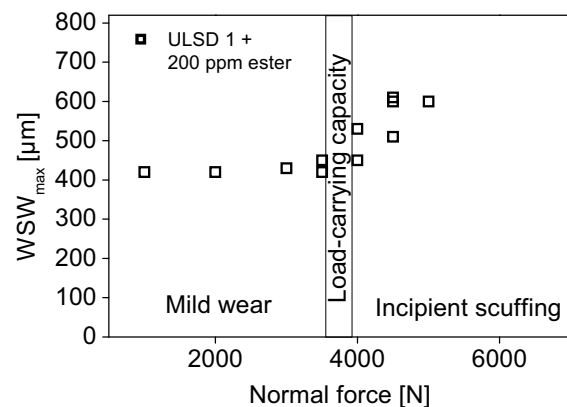
Figure 3: Measuring of maximum wear scar width WSW_{max} 

Figure 4: Plot of a test series to find one LCC