

Effect of Multifunctional Fuel Additive Package on Fuel Injector Deposit, Combustion and Emissions using Pure Rape Seed Oil for a DI Diesel

Hu Li, Amanda Lea-Langton, Patrick Biller, Gordon E. Andrews,
Seyed Hadavi and Alex Charlton
The University of Leeds

Paul Richards
Innospec Limited
UK

Copyright © 2009 SAE International

ABSTRACT

This work investigates the effect of a multifunctional diesel fuel additive package used with RapeSeed Oil (RSO) as a fuel in a DI heavy duty diesel engine. The effects on fuel injectors' cleanliness were assessed. The aim was to maintain combustion performance and preventing the deterioration of exhaust emissions associated with injector deposit build up. Two scenarios were investigated: the effect of deposit clean-up by a high dose of the additive package; and the effect of deposit prevention using a moderate dose of the additive package. Engine combustion performance and emissions were compared for each case against use of RSO without any additive. The engine used was a 6 cylinder, turbocharged, intercooled Perkins Phaser Engine, fitted with an oxidation catalyst and meeting the Euro II emissions limits. The tests were conducted under steady state conditions of 23kW and 47kW power output at an engine speed of 1500 rpm. The in-cylinder pressure, gaseous and particulate exhaust emissions were measured. The injectors were inspected using SEM (Scanning Electronic Microscopy). The results show that the use of the multifunctional fuel additive package reduces the ignition delay (ID), increases the premixed combustion duration (PCD) and improves the combustion stability. The multifunctional fuel additive package also reduced the deposit build up on the fuel

injectors and prevented the deterioration of engine-out particulate, CO and hydrocarbon emissions

INTRODUCTION

A problem encountered when using straight vegetable oil (SVO) as a substitute for diesel fuel is the formation of deposits within the combustion chamber after continuous operation [1].

In Germany, Schoedder [2] tested raw rapeseed oil continuously for 100 h and found that the engine output was comparable to diesel, but difficulties arose due to deposits on piston rings, valves and injectors. It was suggested that the fuel would have to be pre-treated or adjustments made to the engine.

Worgetter [3] tested Rapeseed Oil (RSO) on a 47kW tractor engine. After 400 h of operation the test had to be aborted due to unfavorable operating conditions. Heavy carbon deposits had formed on the injector tips and pistons. Upon dismantling the engine it was found that the power loss was due to the deposits on the pistons, rather than those on the fuel injectors.

Wagner and Peterson [4] operated a small single cylinder engine on a blend of 70% RSO and 30 % diesel continuously for 850 h and did not observe any engine

performance issues. However, they also reported that running the engine on pure sunflower oil caused severe piston ring gumming and engine failure when running the engine long-term. Research carried out on Biodiesel (Fatty Acid Methyl Ester) suggests that the main causes for deposit formation are through condensation and cracking reactions at nozzle temperatures of around 300° C. Birgel et al's review [5] on injector hole deposits suggests that zinc in the fuel, injector hole design and residual fuel remaining in the nozzle hole after the end of the injection process could all be contributing factors to the mechanisms accelerating injector deposit formation. However it is recognised that the physical and chemical processes are not well understood due to their complexity [6].

Deposits in the orifices reduce the hydraulic diameter, which reduces the hydraulic flow through the nozzle. This in turn affects the fuel flow and spray properties and as a result, adversely affects the combustion and exhaust emissions. To overcome these problems associated with deposit formation, fuel additives could be used.

Caprotti et al investigated the impact of high doses of diesel fuel additives on vehicle performance under severe driving conditions [7]. They used a variety of additives available for their research with a standard diesel fuel: diesel detergent, demulsifiers, anticorrosion additive, ester based lubricity additive and a cold flow additive. After 50,000 km operation, the fuel injection equipment was analysed. Emission measurements were also taken throughout the tests. It was concluded that the high additive treatment did not have any negative affect on the Fuel Injection Equipment (FIE) or the exhaust emissions. No detrimental effects were observed on the pump, fuel lines, injector body, injector spray holes and the nozzle tip. This would indicate that high dose levels, and also standard dose levels, of the additive technologies tested are effective in preventing deposit formation.

In another study Caprotti et al investigated the behaviour of Rape Methyl Ester (RME) in current and future FIE [8]. The injector deposits using RME were analysed in swirl chamber injection systems for: indirect fuel injection; current common rail and; future common rail systems. Running the DW10 engine on B10 RME (10% RME with 90% diesel fuel) for 16 h showed a moderate deposit formation, resulting in about 3 % power loss. A further test was designed to try to understand what happens when B10 RME is run for an extended period of 48 hours. The result showed that the deposit formation continued at approximately the same rate and probably beyond, reaching a drop in torque of 24% as can be seen in figure 1. The graph also shows the impact of B10 RME fuel doped with 3 ppm of a soluble zinc salt or with a current commercial diesel detergent on deposit formation. The appropriate detergent levels were shown to control the level of deposit formation. Results also indicated that RME can generate higher deposit levels on old indirect injection engines with swirl chamber.

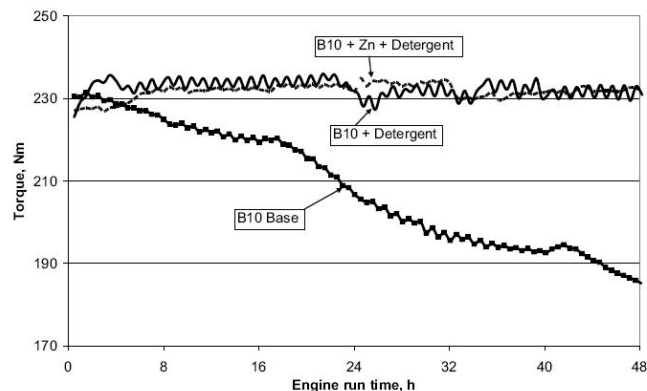


Figure 1: B10 RME, B10 RME+detergent & B10 RME+detergent+zinc torque variation over 48 hours [8]

In another piece of work Caprotti et al evaluated the impact of fuel additives on a modern passenger car equipped with advanced common rail FIE [9]. It was observed that advanced FIE, that is characterized by high injector tip temperatures, can lead to particularly stubborn injector deposits. Standard diesel fuel in the engine tests showed no significant levels of deposits. However in the presence of trace amounts of zinc, deposit formation was quite severe. It was also shown that current diesel detergent technology can control deposits at an elevated treatment level. Interestingly their later work [9] showed that in practice zinc was not present in the fuel in practical situations.

In similar studies carried out by Caprotti in [10, 11] also investigated the deposit formation on advanced FIE. It was shown that base diesel fuel shows no deposits with current and future FIE systems [10, 11]. Deposition only occurred when the fuels contained Zn and future-experimental injectors appear more sensitive to metal contamination. Commercial detergents were able to slow the deposit formation but not entirely eliminate it, even at high rates. Future FIE required for EURO 5 emission limits are shown to be prone to injector coking when the fuel contains zinc but commercial diesel detergents can help control these injector deposits.

Sem compared the effects of different fuels on injector tip deposits in transport refrigeration units [12]. Both laboratory and field testing revealed hard, black deposits interfering with optimum spray pattern on the injectors after 1000 h of operation. For the investigation B100 (100% biodiesel) and B20 soybean biodiesel was used, with and without a fuel detergent additive. Results showed that the fuel detergent additive added to B100 did not have any effect to reduce the injector tip deposits on the transport refrigeration unit diesel engine. The unit running on B20 soybean biodiesel showed significantly less accumulation of injector deposits, but was not able to eliminate the formation. Baseline tests with standard diesel fuel revealed dry, flaky, black deposits which didn't interfere with the four nozzle holes and the spray pattern was still good. Analysis of the deposits revealed they

comprised mostly of carbon (70 % wt) and oxygen (20 % wt) with less than 1 % wt of aluminium, calcium, chlorine, iron, magnesium, phosphorus and sulphur. SEM analysis suggested that the two most likely sources of the deposits were from thermal decomposition of the methyl ester and/or the glycerine. The certificate of analysis revealed 0.134 % total glycerine in the soybean biodiesel. Further SEM analysis suggested decomposition of soybean biodiesel occurs at temperatures of 430°C to 480°C so it could decompose during the ignition delay period resulting in the injector tip deposits.

Barbour et al examined injector fouling tendency in a range of engine technologies, fuels, current and future detergents [13]. They tested standard diesel fuel, B10 RME with a variation of zinc doping and detergent doping on three different DI light duty diesel engines. Injector fouling with the baseline diesel fuel was relatively low and could successfully be reduced to a negligible level with a standard dose of a currently available detergent. The researchers also doped the diesel with low amounts of zinc to investigate the fouling tendencies. The results showed a sharp increase in fouling from 0.1 to 0.6 ppm Zn but only a moderate increase at 1 ppm Zn. Tests with the conventional detergents showed that one of the detergents performed well on all three engines while the second one only performed well on the old engine with old-style indirect injection, confirming that detergents have to be well formulated for specific engine types. The tests on different detergents showed that the advances on detergents had a significant improvement in control of fouling tendencies and were possibly eliminating fouling. The paper concluded that some current commercial detergents are incapable of stopping fouling in modern engine designs while others are fully capable of providing protection. The newer novel detergents were able to provide exceptional performance in all three engines and may allow car manufacturers greater freedom in the design of FIE.

Hawthorne [14] considered the DW10 injector fouling test under development within the CEC, using a common rail, high speed direct injection engine to investigate the ability of fuel additives to maintain engine performance. Hawthorne states that the new test is more representative of current European diesel technology and is therefore a useful addition to previous performance tests. Zinc containing fuels consistently showed power loss in the DW10 test, indicating a tendency of zinc containing fuels to foul injectors. However the relevance of adding zinc salts to the fuel is yet to be shown to correlate with the field. Very high levels of deposits were observed when using B10 biodiesel fuel and commercial diesel fuel additives could offer protection against deposit formation with biodiesel. The test procedure using the DW10 engine is now a published CEC procedure [15].

Objectives of the work reported here were to evaluate the effects of a diesel fuel additive package used with a

rapeseed oil fuel on the formation of fuel injector deposits, and the effects of deposits on engine performance and engine-out emissions. Engine performance characteristics such as Ignition Delay (ID), Premixed Combustion Duration (PCD), combustion stability and fuel consumption were evaluated. Engine-out particulate and gaseous emissions were compared with and without the fuel additive.

EXPERIMENTAL

TEST ENGINE, CONDITIONS AND PROCEDURES-

The engine used was a Perkins Phaser 180Ti 6 cylinder, 6 litre, DI, turbo-charged inter-cooled, heavy duty diesel engine, fitted with an oxidation catalyst. Specifications of the engine are shown in table 1. The engine was manufactured to Euro II emissions standards.

The test was conducted under steady state conditions, 23kW and 47kW power output at an engine speed of 1500 rpm. The 47 kW power output was the dominant operation condition with additional testing at the 23 kW condition. The ignition delay, premixed combustion duration and combustion stability were monitored and reported for both power conditions. The emissions measurements were reported only for the 47 kW condition. These two power conditions represented low load and medium load conditions where the most significant effects were expected. The speed of 1500 rpm is approximately 60% of the rated power speed of 2600 rpm. The maximum power at 1500 rpm is 94 kW. Thus 23kW and 47kW conditions represent the step 3 (25% of maximum power at 60% rated power speed) and step 4 (50% of maximum power at 60% rated power speed) conditions of the ECE-R49 13 mode steady state diesel engine test cycle to which the engine would have been tested for emissions certification. For a better comparison to other engines, the BMEP of the two operating conditions are listed in table 1. The measurements were taken after cold start when the engine was fully warmed-up.

Prior to testing, the fuel injectors were removed from the engine and cleaned manually before reinstallation into the engine. Then the test started using RSO with no fuel additive package treatment (no additive package added) and the engine was run for 24 hours intermittently. This part of the testing was referred to as the 0 ppm test, which lasted for ~3 months and the predominant power condition for the engine was 47 kW with a few short periods of 23 kW runs. At the end of the 0 ppm test, one of the fuel injectors was taken out for deposit inspection by SEM. Then a one-hour run with standard diesel was carried out to enable a comparison of the gaseous emissions with standard fuel. The diesel testing was kept as short as possible to minimize the interferences with the RSO test. The RSO was then treated with 1200 ppm (v/v) of the multifunctional additive package and tested for 6.5 hours at 47kW. The purpose of this test was to

evaluate the cleansing effect of a high dose of additive package on exiting fuel injector deposits. The second SEM inspection was taken after the 1200 ppm test. The fuel injectors were manually cleaned again. A new test was started using the RSO treated with 800 ppm (v/v) of the multifunctional additive package and ran for 26 hours, which lasted for a month. The engine power during this period was mainly at 47 kW with a couple of short periods of 23 kW tests. This was followed by another inspection on fuel injectors using SEM at the end of the test.

Table 1: Engine specifications

Type	Perkins Phaser 180Ti
Displacement litre	6.0
Cylinder No.	6
Compression Ratio	17.5 : 1
Maximum Power Rating	134KW (180BHP) at 2600rpm
Aspiration	Turbo-charged and Inter-cooled
EGR	No
Fuel injection	Pump-line-nozzle
Injector hole diameter, mm	0.2
The number of holes	6
Injection timing, °BTDC	11
BMEP N/m ² , at 23kw, 1500rpm	3.07
BMEP N/m ² , at 47kW, 1500rpm	6.28

FUEL AND ADDITIVE PACKAGE-

A batch of 100% RapeSeed Oil supplied for use as cooking oil was used as the base fuel. A multifunctional additive package known as Octimise D3032 was used to treat the RSO. This additive package is designed for the use in all types of diesel fuel and is a solution of polymeric dispersant, ashless (does not contain metals) combustion improver and functional co-additives in a high flash solvent. The recommended treat rate for petroleum diesel fuels is 400 mg/kg fuel. For this work two doses were used: 800 ppm (mg/kg) and 1200 ppm (mg/kg), which is equivalent to double and triple the normal treat rate for petroleum diesel fuels. A standard ultra low sulfur diesel fuel was also used. Table 2 lists some physical properties of testing fuels and the additive package.

Table 2: Selected physical properties of the test fuels and additive package

	Diesel	RSO	Detergent package
Density @15°C kg/m ³	838	922	890
Viscosity @40°C(mm ² /s)	2.79	35.61	4
Flash Point °C	66	320	63
Oxygen % mass	0	17.5	

DETERMINATION OF IGNITION DELAY, PREMIXED COMBUSTION DURATION AND COMBUSTION STABILITY-

One of the cylinders on the test engine was fitted with a piezo-electric pressure transducer for measuring in-cylinder pressure, this was connected to a data acquisition system that could take around 100, 000 pressure readings per second. The Top Dead Centre (TDC) position was measured using an optical sensor and indentation on the flywheel at TDC. The time based pressure measurements could then be converted to a crank angle basis. The ignition delay and premixed combustion duration could then be determined in terms of crank angle. The ignition delay was defined as from the beginning of fuel injection at 11 ° BTDC until the start of premixed combustion. The PCD was defined between the end of ignition delay and the start of stratified combustion. Figure 2 shows an example of determination of ignition delay and premixed combustion duration.

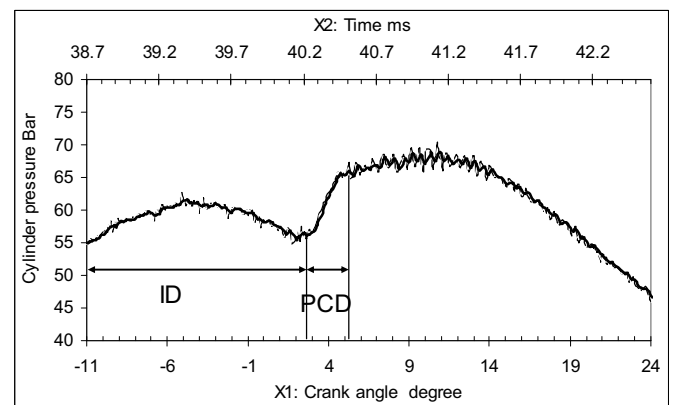


Figure 2: An example of in-cylinder pressure curve for determination of ignition delay (ID) and premixed combustion duration (PCD)

The software for pressure measurements was set up to continuously record the pressure variations for 60 seconds. This was approximately 750 firing cycles at 1500 rpm. The peak pressure of each cycle was compared to the average peak pressure and a normal gaussian distribution plotted. The value of the standard deviation divided by the mean was also calculated. Further the IMEP was calculated for multiple combustion