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Standard article

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Biofuel blend late post-injection effects on oil dilution and diesel oxidation catalyst performance

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Abstract

In the present paper, the effects of different biofuel-diesel blends on engine oil dilution and diesel oxidation catalyst (DOC) performance during late post-injections were investigated. The engine tests were made with an off-road diesel engine under low load conditions at 1200 rpm engine speed. During the experiments, oil samples were periodically taken from the engine oil and later analyzed. Emissions and temperatures before and after the DOC were also measured. The fuels studied were fossil EN590:2013 diesel fuel, 30 vol-% biodiesel (FAME) and 30 vol-% hydrotreated vegetable oil (HVO), which is a paraffinic diesel fuel fulfilling the EN15940 specification. The novelty of the study is based on two parts. First, similar late-post injection tests were run with blends of both HVO and FAME, giving a rare comparison with the fuels. Second, oil dilution and the fuel exit rates during normal mode without the late post-injections were measured. The results showed the oil dilution and the DOC performance to be very similar with regular diesel and HVO blend. With the FAME blend, increased oil dilution, smaller temperature rise in the DOC and higher emissions were measured. This indicates that during DPF regeneration by late post-injections, FAME blends increase fuel consumption and require shorter oil change intervals, while HVO blends require no changes when compared with regular diesel.

Keywords

Paraffinic diesel, HVO, FAME, Late Post-injection, Oil dilution, Emissions, Oxidation catalyst, DPF regeneration

Introduction

Background

Many new energy sources and fuels have been introduced as alternatives to traditional transportation fuels in order to reduce greenhouse gas emissions. Simultaneously, particulate matter (PM) and nitrogen oxide (NOx) emissions are increasingly regulated. This has led to a situation where new engines, nowadays also off-road engines require modern aftertreatment technologies such as diesel particulate filters (DPFs), diesel oxidation catalysts (DOCs) and selective catalytic reduction (SCR). These technologies bring about new challenges when the fuel specifications are changing in parallel as the alternative diesel fuels and their blends are introduced to markets. While biodiesel (fatty acid methyl ester, "FAME") is still the most common alternative to fossil diesel, the use of paraffinic fuels such as Fischer-Tropsch diesels and hydrotreated vegetable oil (HVO) is increasing. These alternatives decrease both local emissions and well-to-wheel greenhouse gas emissions simultaneously.

In diesel engines, DPF accumulates particulates from the exhaust gas flow. To avoid choking the flow, particulates are removed from the filter during the regeneration cycle, in which the DPF temperature is raised to remove the soot. The DPF regeneration method of interest here is the late post-injection (LPI), conducted by modifications of post-injection parameters with respect to those set for normal vehicle operation. The late post-injected fuel is meant to evaporate in the cylinder and reach the DOC in the exhaust line. The fuel oxidizes in the DOC, causing a temperature rise. Thus, in the DPF downstream of the DOC in the exhaust system, soot is burned.¹ Because of low in-cylinder temperatures and pressures during the LPI, the LPI fuel is prone to contact the cylinder walls and cause oil dilution². The dilution has negative impact on lubrication oil and thus results in increased wear in the engine.^{3,4} Typically the electronic control unit (ECU) controls the post-injection duration to target the soot oxidation temperature of ~600 °C upstream of the DPF. The occurrence of the regeneration is usually controlled via monitoring the pressure difference over the DPF and vehicle mileage or engine running hours.^{5,6}

The fuel used has an effect on the optimum interval, timing, and quantity of late postinjections. First, higher PM emissions increase the required frequency of the regeneration process. Second, with low heating value fuels the oxidation in the DOC generates less heat. Thus, the amount of fuel required for the post-injections is increased. Third, with high cetane number (CN) fuels, to avoid ignition in the cylinder, the start of the LPI may have to be delayed. This affects the in-cylinder temperature and pressures during the injection.¹ These, as well as the physical properties of the fuel, have an impact on the fuel spray, the amount of fuel impinging the cylinder walls, and therefore, oil dilution. High surface tension, viscosity, density, and distillation temperatures have been found to increase the spray length.⁷⁻¹² Additionally, low volatility of the fuel fraction in the oil slows the vaporization process and thus, the exit rate of fuel from the oil.^{7,9}

Previous studies

During recent years, the research on alternative diesel fuels has been diverse and abundant. The effects of FAME on exhaust emissions have been studied extensively. When compared to regular diesel, FAME has been shown to decrease particulate (PM) and hydrocarbon (HC) emissions¹¹⁻¹⁶ and, in most cases, to increase NOx emissions slightly ^{11, 12, 14–16}. FAME has also been found to be related to injector fouling and faster deterioration of engine oil. ¹⁶ High density, viscosity, surface tension, and low volatility typical for FAME, have been shown to increase fuel spray penetration. ^{14–18} This increases the risk of cylinder wall wetting and thereby possible oil dilution. HVO is a purely paraffinic renewable diesel fuel derived from bio-oils and fats via hydrotreatment and its properties are very similar to synthetic diesel fuels. ^{15, 19–23} HVO has been found to decrease all regulated emissions in most cases, including NOx.^{21–23} HVO properties and fuel spray characteristics have been found to be beneficial to LPIs.^{24–25}

Many studies^{5, 8–9} have concluded that high fuel distillation temperatures cause oil dilution with LPIs. Tschoke et al.⁵ found that using 30% biodiesel blend doubled the amount of fuel in oil compared to 7% biodiesel (B7), which meant about 30% viscosity decrease. Their conclusion was that high distillation temperatures of the fuel increase oil dilution. Ye et al.⁸ found that if post-injection timing was 45° after top-dead center (ATDC), significant combustion occurred with a FAME blend. At 60° ATDC or later, only slow fuel oxidation occurred and more fuel escaped the cylinder into the exhaust channel. Only esters, and paraffins with a carbon number higher than 14 were observed to dilute into the lubricant. This was attributed to smaller molecules vaporizing at high temperatures rather than condensing and dissolving into the lubricant. Andreae et al.⁹ found oil dilution rates to be

higher with 20% biodiesel blend than with regular ULSD diesel, due to the higher distillation temperatures of FAME.

In addition to the oil dilution, also fuel evaporation from the diluted oil during normal operation has been studied. Song et al.²⁶ studied oil dilution and fuel subtraction from the oil with regular diesel, reaching 10% oil dilution after two hour post-injection mode run (5% is the usual limit for oil change). He also used engine oil from the post-injection tests (oil dilution 10%) and engine oil blended with 15% diesel in 500-hour evaporation tests. With the used oil, the oil dilution dropped from 10% to 6%. With the fresh oil with 15% diesel blended in, oil dilution decreased to 8%. The minimum fuel content no longer decreased after 20 hours, apparently because the engine temperatures were insufficient for fractions of fuel with high distillation temperatures (370 °C) to evaporate. However, Wattrus⁷ found that high back-end volatility did not affect oil dilution, whereas high viscosity, density, and surface tension and low front-end volatility increased the dilution rates. Fuel subtraction rates from the oil followed the derivative of the back-end of a fuel's distillation curve. Paraffinic diesel resulted in significantly reduced oil dilution when compared to FAME, and an experimental low viscosity diesel showed virtually no oil dilution. It was found that the FAME component remained in the engine oil, whereas the diesel component was subtracted out during higher load operation. The oil total base number (TBN) dropped significantly during the testing of 20% FAME blends.

There are only very limited number of studies focusing on oil dilution with HVO. However, Pflaum et al.²⁷ made oil dilution tests with HVO. In his study, HVO increased wall impact and oil dilution compared to standard diesel. This was attributed to an increased volume of the LPI due to lower volumetric heating value and high CN, which lead to a decrease in the amount of unburned HCs and caused a lower DOC oxidation temperature. They also found that with an increased HVO content the amount of large droplets (and therefore the spray penetration) increased. This increased wall wetting and thereby oil dilution. In contrast, in their research with an optical engine, Hulkkonen et al.² studied the effect of fossil EN590 diesel fuel and its blends with 30% FAME and 30% HVO on late post-injection spray properties. They found that differences in the spray characteristics are not significant between the fuels. However, all the studied late post-injection timings led to cylinder spray/wall interaction and wall-wetting consequently diluting the engine oil.

The focus of the present research is on off-road diesel engine late post-injections with biofuel blends (30% FAME and 30% HVO), and their effect on engine oil dilution, DOC

performance and emissions. The research was performed with a six-cylinder off-road diesel engine. The objectives of the present study are to:

(a) compare regular diesel, 30% HVO blend and 30% FAME blend effects on oil dilution during similar late post-ignition mode engine operation;

(b) compare the diluting fuel exit rates from oil during normal engine operation with regular diesel, 30% HVO blend and 30% FAME blend;

(c) monitor the emissions and temperature increase in the DOC during late post-injection mode operation with regular diesel, 30% HVO blend and 30% FAME blend.

The results of this study give information on how modern aftertreatment technologies and fuels impact the requirements for engine use and maintenance as well as the functioning of the oxidation catalyst and emission performance of the engine.

Methods

Fuels and engine oil

The studied fuels were regular EN590:2013 diesel fuel without any biocomponent (B0) and its blends with 30 vol-% HVO (HVO30) and 30 vol-% FAME (B30). Blends with 30% biofuel were chosen for the tests, because EU biofuel targets require commercial fuels with high biocontent and have led to pressure for a commercial B30 grade biofuel blend, especially for heavy-duty use. Depending on the HVO component characteristics, a blend of up to 30% HVO can meet both the EN590 diesel fuel standard^{28, 29} and the advanced requirements for emission control and fuel efficiency according to the Worldwide Fuel Charter (WWFC) category 5 standard³⁰. Depending on the biodiesel component, blended fuel properties of up to 30% FAME can meet the blended fuel standard ASTM D7467 requirements.³¹

The regular diesel fuel and the fuel blends were analyzed and the analysis results can be seen in Table 1 with relevant EN590 standard values for comparison.

Property	Unit	EN590, standard	Diesel	HVO 30	B30
Oxygen content	wt-%	-	0	0	3.6
Density (15°C)	kg/m ³	820-845 (>800 ²)	835.7 ¹	815.1 ¹	849.3 ¹
Viscosity (40°C)	cSt	2.0-4.5	3.141 ¹	2.991 ¹	3.3851
Cetane number		>51	53.8 ¹	62.9 ¹	54.1 ¹
Lower heating value	MJ/ kg	42–44	43.6	43.7	41.6
Distillation range	°C	-	172–355 ¹	176–349 ¹	178–353 ¹
Total aromatics	wt-%	-	18.9	13.6	13.0
Polyaromatics	wt-%	<8	1.6	1.2	1.1

Table 1. The fuel blends studied in the project. Standard EN590 values are given for reference.

¹Fuel analysis result

²Winter grade

The properties of the diesel and biofuel blends are from fuel analyses or calculated from typical properties of pure biofuels according to fuel specifications and previous studies²¹⁻²², ²⁹. The FAME was rapeseed methyl ester (RME) according to EN14214:2008. B30 did not meet EN590 because the density was over 845 kg/m³ and the FAME content was over 7 vol-%. Because in this case, the HVO30 density was lower than 820 kg/m³, it did not meet WWFC or regular EN590 standards. However, the winter-grade EN590 standard was met.

The distillation curves of the fuel blends used in this study were obtained by atmospheric distillation (according to EN ISO 3405:2000) and can be seen in Figure 1. The distillation curves are relatively close to one another because of the moderate blending ratios that caused EN590 to dominate the evaporation rates. While FAME-fuels commonly have higher final boiling points than standard diesel, here the B30 has a distillation end point lower than the other fuels, slightly over 350°C. This implies that a high-grade FAME component was used

in the B30 blend. The distillation curve derivatives for all the fuels were also included. Their significance is discussed in chapter "engine oil condition".



Figure 1. The distillation curves and their derivatives for the studied fuels.

The engine oil used in the study was fully synthetic, with a viscosity class SAE 10W40 and classifications ACEA E9 and API CJ4/SN. Engine oil fossil diesel and FAME contents, viscosities, total acid numbers (TANs – a measure of acidity of the oil), and total base numbers (TBNs – a measure of the corrosion protection properties of the oil, achieved and maintained with additives) were analyzed by a third party laboratory. With fuel and FAME content, the repeatability of the analyses was the absolute maximum difference of two repeated test results with a probability of 95%. With the other analyses, the repeatability was the difference between results, relative to their average with a probability of 95%. The lower

measurement limit of fuel content and biodiesel content was 0.3%. The analyses and the methods used in the analyses are compiled in Table 2.

Property	Unit	Repeatability	Methods
Viscosity (100°C)	cSt	14%	ASTM D 445, DIN 51562
TAN	mgKOH/g	11.7%	ASTM D 664
TBN	mgKOH/g	5%	ASTM D 664
FAME content	m-%	0.4%	DIN 51451
Fuel content	m-%	0.4%	DIN 51451, JOAP

Table 2. Engine oil properties and analysis methods.

Research apparatus

The engine used was an Agco 8.4 liter six-cylider diesel engine (fulfilling the emission regulation stage 3B) connected to a Schenk W400 eddy-current dynamometer equipped with a force transducer. The engine was modified for these tests by replacing the original exhaust gas after-treatment system (DOC+SCR) with only DOC. The DPF was not installed, since only DOC performance during the LPI cycle was studied, not the DPF regeneration itself. The DOC was a typical (l = 5 in, d = 10,5 in) catalyst package from a commercial catalyst manufacturer with medium PGM loading and Pt/Pd –ratio. The experimental setup is described in Figure 2 and the basic engine data is shown in Table 3.



Figure 2. A schematic of the engine and the measurement system.

Table 3. Basic engine data.

Property	Unit	
Rated power	kW	240
Nominal speed	r/min	2200
Rated torque (1500 rpm)	Nm	1500
Cylinders		6
Displacement	1	8.4
Cylinder bore	mm	111
Stroke	mm	145
Compression Ratio		17:1
Aspiration		Turbocharged, charged air cooled
Emission certification		EU Stage3B / EPA Tier3 ¹
Injection system		Common Rail
EGR		No
DPF		No
DOC		Yes
SCR		No

¹ Before modifications to exhaust gas system

The THC emissions were measured with a J.U.M. VE7 analyzer, based on the hydrogen flame ionization detector (FID) method. A Sick Sidor multi-component analyzer measured

 O_2 utilizing a paramagnetic cell, while CO and CO_2 were measured using a non-dispersive infra-red (NDIR) technique. NO_x emission measurements were made with an Ecophysics CLD 880 chemiluminescence analyzer. Smoke emissions were measured using an AVL 415S Smoke Meter. An AVL Fuel Meter 733 was used to measure fuel mass flow. The measurement inaccuracies are presented in Table 4.

Measurement	Unit	Inaccuracy
Load	Nm	±0.1%
Speed	rpm	±0.1%
Temperature	°C	±1.0
СО	ppm	±3
THC	ppm	<30
NO _x	ppm	<40
Smoke	FSN	±0.005
Pressure	bar	±0.1%
Fuel mass flow	kg/h	±0.12%

Table 4. Engine measurement inaccuracies.

Test run procedure and experimental conditions

The engine parameters during the test runs are in Table 5. In the test runs, two modes of running were used: regeneration mode with LPI and normal mode without LPI. First the engine oil was changed and the engine was operated with the selected fuel with normal injection parameters at 1200 rpm. After two hours, the regeneration mode was switched on and run for four hours, the run-time being similar to other studies^{4, 26, 27}.

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Parameter	Unit	Normal mode	Regeneration mode
Speed	rpm	1200	1200
Injection pressure	bar	900	900
Load	Nm	375	375
Load	%	38	38
Intake air temperature	°C	20	20
Oil temperature	°C	91	91
Main injection timing	° BTDC	4.8	4.8
Post-injection	mg	4	10 ¹
Post-injection timing	° ATDC	7.8	80 ¹

¹LPI

To test how prone the different fuels were to exit the oil, the test was continued in normal mode for two hours. Oil samples were periodically taken during the run, according to Figure 3. Temperatures were measured immediately after the cylinder, as well as at the inlet and outlet of the DOC. Emissions were measured after the DOC. The post-injection doses were kept constant during the regeneration mode.



Figure 3. The test run procedure.

Based on the previous studies, the post-injection fuel mass was evaluated to be low enough to avoid engine problems and high enough to cause significant oil dilution. Both the timing and the doses of the post-injections were close to parameters used in previous research^{2-5, 7, 8}. The engine conditions and injections were kept as similar as possible with the authors' previous study with an optical engine². In this project it was decided to keep the LPI mass smaller than would have been needed to reach typical regeneration temperature of 600°C after the DOC, since the engine did not have OEM DPF and regeneration parameters, and thus not optimized regeneration. With higher LPI masses there would have been risk of overestimating the negative effects of LPI on oil dilution. However, this was not seen as significant, since the focus of the present work is on the effects of late post-injections on

engine oil and DOC, not the DPF regeneration itself, and thus the differences between fuels should be visible even with smaller injection masses.

Results and discussion

Engine oil condition

The fuel content in engine oil (i.e. oil dilution) is shown in Figure 4. The standard diesel hydrocarbon content and in the B30 case also the FAME content are included. EN590 and HVO30 had very similar oil dilution behavior, the differences being within errors of margin. With B30, oil dilution was found already after the pre-run. Due to this unexpected finding, the B30 test was repeated and similar dilution result was found again. After the LPI runs, there was a significant difference with B30 oil dilution, about 40% more after the regeneration mode than with EN590 and HVO30. The increase of oil dilution with LPI's is due to the lower in-cylinder gas temperatures and pressures before LPI than before the main injection. With decreased cylinder charge density, the resistance of the air is also decreased and the spray length increased. Additionally, the mean droplet size of the fuel spray is increased according to an empirical expression for Sauter Mean Diameter (SMD)⁷:

$$SMD = C \left(\frac{\mu_f \sqrt{\left(\frac{\omega}{\rho}\right)f}}{u_g^2 \rho_g} \right)^{2/3} \tag{1}$$

where fuel μ_f is fuel viscosity, ψ_f fuel surface tension, ρ_f fuel density, ρ_g cylinder charge density, u_g the velocity difference between fuel and C cylinder charge empiric correction factor.

With smaller SMD, a lower net droplet surface area will be in contact with the cooler than normal in-cylinder air. Thus, the evaporation of the fuel droplets is decreased and the liquid fuel contact with the oil film on the cylinder wall is increased.^{2,7} This was verified with a numerical model in our previous study², where the droplet evaporation time was found to be very long compared to the characteristic wall contact time. Conditions needed to evaporate the droplets before the cylinder wall require high gas density and very small droplet sizes not attained with very late injection strategies. The oil dilution variations between the fuels are due to fuel property differences leading to higher quantity of liquid fuel contacting the cylinder wall with B30:

1. According to equation (1), the higher density and viscosity (see table 1) as well as the typically higher surface tension of $B30^{14-18}$ lead to increased fuel droplet sizes in the LPI spray. The higher droplet momentum leads to an increased spray length.^{2, 7}

2. As can be seen in the distillation curves (figure 1), the front-end volatility is much lower with B30 (\sim 70%) than with HVO30 and EN590 (\sim 90%). The front-end volatility is defined by Wattrus⁷ to be the volumetric percentage of fuel distilled in temperatures found in the cylinder during the LPI event. Here the temperatures are approximated from measurements in the exhaust line immediately after the cylinders, slightly below 330 °C with B30 and slightly above with the other fuels. The case is similar to what was reported by Wattrus⁷: the implication is that with B30, fewer fuel components evaporate off the fuel droplets during LPI's.

While fuel is usually entering the oil only during the LPI mode, fuel is removed from the oil by evaporation continuously. The evaporation rate is a function of temperature (speed and load of the engine) and the concentration of fuel in oil. Fuel component evaporation from oil increases with the oil temperature, which is limited by the cooling system. The fuel evaporation rate from oil increases with the oil dilution. Thus, if the LPI mode had been continued long enough, an equilibrium oil dilution would have been reached. As can be seen from figure 4, the B30 evaporation rate from the oil was slightly higher than with the other fuels. This is usually not the case with fuels containing FAME, due to the FAME components with very high boiling temperatures not evaporating.⁵ However, in this case, there are few components with very high distillation temperatures in the B30, as end of the distillation curve of B30 had even lower temperature than those of HVO30 and EN590 (see table 1). Thus, the slightly higher rate of evaporation found for B30 is to be expected. Wattrus⁷ found that fuel subtraction rates from the oil correlated with the derivative of the back-end (above the exhaust gas temperatures after the cylinder) of a fuel's distillation curve, which gives an indication of the evaporation rate as the temperature is increased. This seems to be the case here also, as B30 had distinctly higher distillation rates (see figure 1) above the measured exhaust temperatures of ~330°C.



Figure 4. Fuel contents in engine oil.

In the B30 runs, the oil dilution was a combination of FAME and EN590 hydrocarbons (see Figure 5). The FAME portion of the oil dilution after a normal mode pre-run was 0%, after 2 and 4 hours of regeneration mode 42.7% and 44.3% respectively, and after the final normal mode run 42.6%. The evaporation rates of the fuels from oil were similar within measurement accuracy. The FAME portion of the oil dilution was generally higher than 30% (FAME portion in B30), which means that the FAME components of B30 were more likely to dilute the engine oil, probably due to FAME properties affecting liquid fuel spray length and fuel droplet evaporation rate. The exception was the sample after the pre-run, in which FAME levels were below the measurement limit of 0.3% and thus could not be analyzed. If the FAME levels were assumed to be close to 0.3%, it would mean 38% portion of the oil dilution in the pre-run sample case.



Figure 5. Oil dilution consisting of regular diesel and FAME: case B30.

In the B30 runs, the sample taken after the preliminary run contained 0.5% of regular diesel fractions. This initial dilution could be due to several possible reasons:

1. Analysis uncertainties are improbable as the B30 test-runs and analyses were done twice and similar oil dilution was found in both cases. As the repeatability of the oil dilution measurements was 0.4 percentage points of absolute difference between results, the B30 ref sample dilution was significant.

2. Leftover oil in the engine after the oil change. The amount of drained oil during oil changes varied between 21.2 kg and 22.2 kg, while the estimated total amount of oil was 22.5 kg. This would mean 5% of used and diluted oil (or $\sim 0.2\%$ oil dilution) in the ref sample at

maximum. However, this can be considered a partial explanation at most, since the phenomenon did not occur with the other fuels although the oil change procedure was similar in all cases.

3. Used oil left in the sample line. The maximum portion of this leftover oil in the sample (calculated from the sample line and sample volumes) is $\sim 1.5\%$, having an effect of less than 0.1 percentage points on the oil dilution measurement result.

4. B30 caused oil dilution in normal mode. The fuel content in the oil samples taken after the preliminary run was not seen with standard diesel or HVO30, which implies that leftover oil is not the probable cause for the ref sample's dilution. The main injection fuel droplets will usually evaporate completely. With B30, this may not have been the case, probably due to higher density and viscosity and lower volatility of B30 leading to worse fuel spray quality, as discussed earlier. It is notable, that with B30 pre-run phase, dilution was found in two separate but similar test-runs. Thus it can be stated that B30 seems to increase oil dilution and may enter oil more rapidly, even during normal operation, especially when the engine is still cold.

The engine oil viscosities at 100°C can be seen in Figure 6. Unless there are other factors (e.g. soot contamination, oxidation, polymerization of unsaturated fuel components of FAME in used oil) affecting the engine oil viscosity, it will decrease with increasing oil dilution, due to the lower viscosity of the fuel.⁷ The viscosity of the unused engine oil (viscosity grade SAE 10W-40) was 13.6 cSt at 100°C. With regular diesel fuel the viscosity at 100°C remained the highest and with B30 it decreased the most during the tests. With HVO30 and regular diesel the viscosity drop was ~8% (to about 12.2–12.3 cSt), with B30 the viscosity decreased almost 12% (to about 11.8 cSt). The viscosity grade SAE 10W-40 after 4 hours of regeneration mode with any of the fuels. It is noticeable that in evaporation mode, with regular diesel and especially B30, the viscosity continued to drop (possibly due to oil shearing)²⁶, while with HVO30 the oil viscosity started to recover. However, the error margin of the measurements was 1.6% (~0.2 cSt), meaning that the EN590 and HVO30 differences and the recovery of HVO30 are within measurement variability.



Figure 6. Engine oil viscosities during the test runs.

The engine oil Total base number (TBN) and Total acid number (TAN) development during the tests can be seen in Figure 7. TAN measures the quantity of base required to neutralize the acidic components in the oil. It will increase when the oil is oxidized or acidic contaminants enter the oil. TBN is a measure of engine oil reserve alkalinity, indicating the capability of oil additives to neutralize acids. If a fuel containing oxygenates (e.g. FAME) dilutes the engine oil, premature oil oxidation may occur, seen as TAN increase and TBN decrease .^{7,9} In the tests, TBN declined very slowly (as opposed to findings by Wattrus⁷), but remained high and similar between the fuels. The TAN remained at the same levels and no significant differences between the oils analyzed could be seen. In this case, the similarity of the results between the fuels can be explained by the relatively short duration of the test runs

(when compared with Ye et al.⁹) and low oil dilution rates (when compared with study by Wattrus⁷). The TBN and TAN measurement repeatability (the difference between results, relative to their average) were 5% and 11.7%, respectively. Therefore, the differences between the fuels were negligible.



Figure 7. The engine oil TBN and TAN development during the tests.

Exhaust gas temperatures

The exhaust gas temperatures in the exhaust line before and after the DOC during regeneration mode can be seen in Figure 8. Between the EN590 and HVO30, the differences in temperature before the DOC are small, while B30 had slightly lower (8–10°C) values. This is due to the lower heating value of B30, as it can be assumed based on previous research³²,

that the fuel energy utilization by the engine (thermal efficiency) is not significantly higher with B30. The temperature rise in the DOC is caused by exothermic HC oxidation reactions. With HVO30 and regular diesel, the rise is very similar, but for B30 the temperature rise is significantly (~12°C) smaller, which can be mainly attributed to the lower heating value of FAME causing less energy to be released in the DOC. As the injected fuel mass remains the same with all the fuels, the ratio between the table 1 fuel heating values (e.g. H_f, B30/H_f, EN590) should be equal to the ratio between temperature increases in the DOC from figure 8 (ΔT_{B30} / ΔT_{EN590}). Calculating from these values, ΔT_{B30} should be 148,4 °C, as opposed to 144 °C seen in figure 8. The lower measured ΔT_{B30} can be explained by incomplete B30 oxidation in the DOC, which results in a slightly decreased energy release. The incomplete oxidation is indicated by the higher B30 HC and CO emission results (later presented in figures 10 and 11). Together with the lower temperature before the DOC, the lower ΔT_{B30} means that with B30, the temperature after the DOC was ~20 °C lower than with other fuels. In order to reach the same temperature levels with the other fuels, more B30 blend should be injected during LPI cycle, which could possibly lead to increased oil dilution.



Figure 8. The temperatures measured (the average of measurements made once every hour during the regeneration mode) in the exhaust channel before and after the DOC, and the temperature increase in the DOC during the runs. T before DOC is the exhaust channel temperature measured right before the DOC, T after DOC is the exhaust channel temperature measured right after the DOC, and ΔT is the temperature rise in the DOC.

Emissions

The NOx emissions during the normal and regeneration modes with the fuels studied can be seen in Figure 9. In normal mode, B30 and HVO30 NOx emissions were very similar, while regular diesel gave the lowest values. In regeneration mode, NOx emissions remained at the same level with HVO30, increased slightly with EN590 and significantly with B30, leading to ~10% higher total NOx emissions with B30 than with the other fuels. The increase in NOx emissions for the fuels containing FAME are often attributed to higher local flame temperatures with FAME (e.g. Johansson et al.³³). However, the reasons behind the higher

flame temperatures are still debated, and several other explanations for the high NOx phenomenon with fuels containing FAME have been suggested.³⁴



Figure 9. NOx emissions in ppm and the portions of NO and NO₂ of total NOx (the average of measurements made once every hour).

The NO-NO₂ ratio during the regeneration mode can also be seen in Figure 9. The LPI reduced the NO₂ emissions significantly while NO emissions increased, the NO–NO₂ ratio being very similar for all the fuels in the LPI mode. This is a consequence of the natural NO–NO₂ balance moving towards NO as the temperature rises.³⁵ Additionally, the presence of CO and HC may inhibit the NO conversion to NO₂, which may in some cases be secondary to hydrocarbon oxidation in the catalyst. ³⁶⁻³⁷ The NO–NO₂ balance change was most remarkable with HVO30. B30 had much higher NO emissions than regular diesel and HVO30 during normal mode. With B30 the normal mode NO₂ emissions were smaller and

also the relative NO₂ decrease was less pronounced when the mode was changed. This may be explained by the hydrocarbons measured with B30 also during normal mode (see figure 10), which may have inhibited the NO conversion to NO₂ to some extent. ³⁶⁻³⁷ Moreover, the lower local equivalence ratios in the cylinder due to FAME oxygen may lead to higher production of NO₂.³⁵ It is notable, that NO-NO₂ ratio after DOC is very important for optimum SCR system performance, and thus the changes on this ratio may lead to reduced NOx conversion rate in SCR, which may cause further increase of NOx emission or ammonia slip.³⁸



Figure 10. The hydrocarbon emissions (the average of hourly measurements).

The HC emissions (measured after the DOC) can be seen in Figure 10. The regeneration mode increased the emissions as a small part of the LPI hydrocarbons escaped the DOC. With regular diesel and HVO30 the HC emissions were negligible (1-2 ppm), even during

regeneration mode, while with FAME the emissions were higher. It must be noted that the regeneration mode emissions were still very low when compared with measurement inaccuracy.

The CO emissions (measured after the DOC) can be seen in Figure 11. During the normal mode, the CO emissions were negligible. During the regeneration mode, the CO values were over 50 ppm with all tested fuels. With B30, the CO emissions were the highest (73 ppm). A smaller temperature rise in the DOC and the higher CO and HC emissions during the regeneration mode with B30 indicate incomplete oxidation of FAME in the DOC.



Figure 11. The carbon monoxide emissions during the test runs (the average of measurements made once every hour).

The opacity results as filter smoke number (FSN) measured after the DOC can be seen in figure 12. The smoke number results, indicative of PM emissions, were very low and similar with all the fuels during both regeneration and normal modes. The values are negligible and the differences within measurement accuracy.





Conclusions

In this study the effects of late post-injections (used in the DPF regeneration cycle) on oil dilution, DOC temperature increase, and exhaust gas emissions after DOC were investigated. The engine tests were done with regular EN590 diesel and its blends with 30% FAME (B30)

and 30% HVO (HVO30) at a speed of 1200 rpm, with a 375 Nm load, and both with and without 10 mg LPI (at 80 ° ATDC) in regeneration mode. Lubrication oil samples were taken periodically and both oil dilution and fuel exit rates from the oil were analyzed.

The main conclusions of the present study are summarized as follows:

1. Oil dilution and viscosity were found to be very similar with HVO30 and regular EN590 diesel, within measurement accuracy. With B30, the oil dilution increase and viscosity decrease were more pronounced compared to the other fuels.

2. The portion of FAME was higher than 30% of the oil dilution with B30 in all the oil samples taken during and after regeneration mode, indicating that FAME has an increased tendency to dilute oil compared to the EN590 diesel portion of the fuel blend.

3. HC and CO emissions were low and similar with HVO30 and regular diesel and increased significantly with B30 during regeneration. This indicates that FAME is less prone to oxidize completely in the DOC.

4. The total NOx emissions were relatively similar in both modes with all fuels, except the B30 regeneration mode case, where NO_x was approximately 9% higher. In normal mode NO-NO₂ ratio was rather similar between EN590 (49.1% NO) and HVO30 (45% NO), but with B30 the ratio (75.4% NO) was clearly different from the two other fuels. The regeneration mode changed the NO–NO₂ ratio towards NO, resulting in similar portions of NO for all the fuels, but the total NO_x was still highest with B30.

5. The temperature increase in the DOC during regeneration mode was similar with HVO30 and regular diesel and noticeably lower with B30. This is estimated to be due to both the lower heating value of B30 and incomplete oxidation of FAME in the DOC.

In conclusion, while HVO30 behavior during regeneration is very similar to regular diesel, B30 is more prone to dilute the engine oil. Moreover, there is a need for larger quantities of B30 LPIs during DPF regeneration events, which will increase fuel consumption and lead to increased oil dilution. Thus, for high FAME portion fuel blends, more frequent oil changes may be needed. However, in most studies, both FAME and HVO reduce particulate emissions. This means that the interval of the regeneration events could be longer, which decreases both the consumption and oil dilution, compared to regular diesel. Moreover, by optimizing the engine calibration for the biofuel blends, emissions and oil dilution could probably be reduced, as the engine parameters are based on experiences with regular diesel. Furthermore, the optimization of the LPI would be beneficial with all the fuels: the earliest possible injection timing with no ignition in the cylinder ensures the highest in-cylinder temperature and pressure during the LPI's. This increases the fuel spray quality and reduces

the amount of liquid fuel contacting the cylinder walls, and therefore, oil dilution. Due to its high CN, HVO30 will ignite in lower pressure and temperature, which reduces the LPI timing optimization potential.

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