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NO$_x$ and soot emissions trends for RME, SME and PME fuels using engine and spray experiments in combination with simulations

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ABSTRACT

This study includes engine tests with neat FAME fuels and blends of 7% and 30% of RME in European Diesel, EN590 (non FAME added). The study was also completed with spray studies and numerical simulations for a deeper understanding of the engine results.

The engine was operated at four operational points (A25, B50, B75 and C100) taken from the European Stationary Cycle, ESC cycle. The A25 case was also extended to achieve information how the soot emissions varies with the operational parameters; start of injection (SOI), NO$_x$ level (regulated by EGR) and needle opening pressure (NOP). The spray studies were performed in a high temperature/high pressure spray chamber at relevant conditions. For the numerical simulations the KIVA 3-V code was used with detailed chemical kinetics.

The results shows that the neat FAME fuels lower the soot emissions by up to 90% compared with Diesel fuel. Moreover, even low blend ratios lowers the soot emissions significantly. Among the FAME fuels, combustion with PME had the lowest amount of soot emissions due to its lowest amount of di- and tri-unsaturated fatty acids (i.e. less double bonds) in comparison with SME and RME.

The NO$_x$ emissions were increased for the neat FAME fuels in relation the Diesel fuel. The increase in NO$_x$ emissions for the neat FAME fuels is due to the higher flame temperature for the FAME fuels which could be a result of the oxygen content which causes a lower equivalence ratio (ϕ), i.e. leaner local reacting mixture.

The A25 operational case showed that the most important factor to decrease soot emissions for Diesel fuel was NOP, while for the FAME fuels SOI had the greatest impact. Further, at constant level of NO$_x$ emissions for the included fuels it was observed that the FAME fuels still reduced the soot emissions significantly.

The study shows that FAME fuels and Diesel blends with FAME fuels, can be a tool to meet future emission legislation, since low soot emissions levels can be reached for low NO$_x$ emissions and the fact that FAME fuels are renewable, the global warming impact is lower than for Diesel.

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1. Introduction

Limited oil reserves and environmental issues are strong motivations for research in alternative fuels. Moreover the directive from the European Parliament inform that the energy used in the transport sector should by year 2020 be minimum 10% renewable energy [1].

Further, has the emission standards over the years became even stricter and to meet these close-to-zero levels combined research in fuels, combustion and aftertreatment strategies are important.

Fatty Acid Methyl Ester (FAME) fuels are commonly used as blends in conventional Diesel fuels. FAME fuels are often called Biodiesel. Biodiesel is produced by transesterification of a vegetable oil with an alcohol (generally methanol) in the presence of a catalyst. Glycerol is a by-product in the transesterification process and can either be used as animal food or in the chemical industry.

Different biodiesels has the common effect of reducing the soot emissions in relation to conventional Diesel due to the presence of oxygen in biodiesel [2–4].

NO$_x$ emissions on the other hand are increasing when Biodiesel are used in neat form. Although, when blends with Biodiesel and

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Abbreviations: CA50, Crank angle position where 50% of the heat is released; CA70, Crank angle position where 70% of the heat is released; CFPP, cold filter plugging point; CO$_2$, carbon dioxide; FAME, fatty acid methyl ester; FBP, final boiling point; IBP, initial boiling point; NOP, needle opening pressure; NO$_x$, nitrogen oxides; PM, particulate matter; PME, palm oil methyl ester; RME, rapeseed methyl ester; RME7, blend of 7% RME and 93% diesel fuel; RME30, blend of 30% RME and 70% Diesel fuel; SME, soy-bean methyl ester; SOI, start of injection.

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conventional Diesel are used the operating mode and design of the engine (driving-cycles, load and speed cases) and type of injection system are important factors. Using a conventional pump-line-nozzle fuel injection system, the bulk modulus of the fuel impacts the injection timing. An higher bulk modulus advances the injection [5]. The advance in fuel injection does then increase the NO$_x$ emissions. However, in common rail injection systems the bulk modulus does not affect the start of injection [6].

Highly saturated Biodiesel has higher cetane number in comparison with low saturated Biodiesel. The high cetane number results in shorter ignition delay and less time for pre-heating of the reactants and then lower in-cylinder temperature and hence lower NO$_x$ emissions [7,8].

Blends of Biodiesel in conventional Diesel fuel are commonly used, especially in low blending ratios and increasing biodiesel blend ratio in conventional Diesel, often shows an increase in engine out NO$_x$ emissions [6] but there are studies when the increase is not significant. The ambient temperature, for example, has been shown to be an important factor. At -5 °C the increase in NO$_x$ emissions is not significant [3]. In a report from the National Renewable Energy Laboratory [9] different vehicles and driving cycles were investigated for B20 fuels and there were no significant trend that Biodiesel increases the NO$_x$ emissions.

The fact that Biodiesel produces less soot during combustion due to its oxygen content has the effect that the radiative heat losses are the lower for Biodiesel and thereby results in higher in-cylinder temperature and increased NO$_x$ formation than conventional Diesel fuels. Neverthless, this radiative effect is not the only effect [10].

The flame lift-off length is defined as the distance from the injector orifice exit to the upstream-most extent of the diffusion flame (flame stabilization point). The flame lift-off allows air to be entrained into the core of the burning spray and thus the fuel and air to premix before reaching the initial combustion zone. If the fuel–air premix is increased (i.e. longer lift-off) the soot formation is decreased [11,12].

In a recent study by Mueller [10], the flame lift off was studied for Biodiesel and a conventional Diesel fuel. It was shown that the Biodiesel had shorter lift-off than the Diesel fuel despite of this the Biodiesel shows lower soot formation. However in Mueller's study the reference Diesel and the Biodiesel had cetane number of 45 and 50 respectively and higher cetane number shortens the flame lift-off.

This study includes heavy-duty engine test and spray studies combined with CFD simulations of Biodiesel blends with European Diesel. The emissions trends and also the combustion are studied in order to find relations for the fuel properties and blend ratios on emissions formation.

2. Methodology

The methodology part is divided into fuel, experiments and simulation information sub-chapters.

2.1. Fuels

The fuels included in this study were three different FAME fuels; Rapeseed Methyl Ester (RME), Soy-bean Methyl Ester (SME) and Palm oil Methyl Ester (PME) and a reference Diesel fuel, EN590 (European Diesel). The RME fuel was also blended per volume with the Diesel fuel in the following concentrations; RME7 and RME30. The FAME fuels has 13% lower heating value than the reference Diesel fuel which result in an energy content of the blends in relation to Diesel fuel of 99.1% for the 7% blends and 96.1% for the 30% blend.

Table 1
Fuel specifications.

	Methods	Unit	EN590 (EU Diesel)	RME	SME	PME
Density	D-4052	kg/m^3	841	883	885	875
Sulfur	D-5453	mg/kg	23	NA	NA	NA
Aromatics	D-6591	%wt	24	NA	NA	NA
CFPP	IP 309	°C	−29	−16	−3	13
Viscosity @ 40 deg C	D-445	mm^2/s	2.7	4.5	4.2	5.1
Cetane nr	D-613		53	53	50	61
Heating value (net)	D-240	MJ/kg	42.8	37.3	37.3	37.0
Carbon	D-5291	%wt	86.5	77.5	77.3	77.5
Hydrogen	D-5291	%wt	13.5	12.2	11.9	12.3
Oxygen	CHNS-0	%wt	–	10.0	9.8	10.1
IBP	D-86	°C	185	317	321	315
FBP	D-86	°C	334	346	337	344
Oxidation stability	EN 15751	h	–	8.7	5.7	6.8

Table 2
Engine and injector specification.

Engine type	Single cylinder AVL 501
Displacement	2022 cm^3
Bore	131 mm
Stroke	150 mm
Cylinder head type	Volvo Powertrain D12C 4 valves, low swirl, (swirl ratio appr. 0.2)
Compression ratio	17
Injection system	Electronic controlled unit injector (EUI)
Nozzle	6 orifices
Spray umbrella angle	152°
Flow rate	2 l/min
Injection pressure	Strain gauge

Table 3
Measuring equipment.

HC meter	Rosemount CLD 1000089 Flame ionization detector
CO meter	Rosemount CLD 1000546 Non-dispersive infrared detector
CO$_2$ meter	Maihak S710 Non-dispersive infrared detector
CO$_2$ meter (for EGR)	Maihak UNOR 6 N Non-dispersive infrared detector
NO$_x$ meter	Rosemount CLD 1000079 Chemiluminescence Detecor
Smoke meter	AVL 415, variable sampling volume
Soot meter	AVL 483 Micro Soot Sensor
Fuel balance	AVL 733S
In-cylinder pressure sensor	Kistler 7061B
Data acquisition system	D2T OSIRIS
Design of experiments	Modde, software from Umetrics

The properties of the Diesel fuel and the FAME fuels are listed in Table 1. As shown in the table, the density of the FAME fuels is significantly higher than the reference Diesel fuel which together with the higher boiling points causes longer spray penetration before evaporation and therefore air entrainment in the spray increases and this contributes to the lower the soot emissions.

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