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Experimental investigation of mineral diesel fuel, GTL fuel, RME and neat soybean and rapeseed oil combustion in a heavy duty on-road engine with exhaust gas aftertreatment

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ABSTRACT

The effects of mineral diesel fuel, gas-to-liquid fuel, rapeseed methyl ester, neat soybean and neat rapeseed oil on injection, combustion, efficiency and pollutant emissions have been studied on a compression ignition heavy duty engine operated near full load and equipped with a combined exhaust gas aftertreatment system (oxidation catalyst, particle filter, selective catalytic NO_x reduction). In a first step, the engine calibration was kept constant for all fuels which led to differences in engine torque for the different fuels. In a second step, the injection duration was modified so that all fuels led to the same engine torque. In a third step, the engine was recalibrated in order to keep the NO_x emissions at an equal level for all fuels (injection pressure, injection timing, EGR rate). The experiments show that the critical NO_x emissions were higher (even behind the exhaust gas aftertreatment systems) for oxygenated fuels in case of the engine not being recalibrated for the fuel. GTL and the oxygenated fuels show lower emissions for some pollutants and higher efficiency after recalibration to equal NO_x levels.

1. Introduction

In the on-road transport sector for heavy goods, diesel engines are the almost exclusively used power sources because of their advantages regarding fuel efficiency compared with spark ignition engines or other combustion-based power sources. In recent years, diesel engines gained also on importance in the passenger car sector across Europe and it is likely that other markets will follow. Compared with very low-polluting spark ignition engines using efficient exhaust gas aftertreatment systems, diesel engines have the disadvantage of emitting higher amounts of the critical components NO_x and particles. The well-known NO_x versus particle trade-off in diesel combustion leads to the need of either a NO_x or a particle exhaust gas aftertreatment system if demanding exhaust gas emission limits have to be met. Future emission limits include, besides of strict particle mass limit values, also particle number limit values which will very likely enforce the use of combined NO_x and particle exhaust gas aftertreatment systems. Continuously stricter pollutant emission values force the manufacturers to integrate more complex injection, combustion, exhaust gas recirculation and exhaust gas aftertreatment systems into their engines. Such complex engine systems are designed and calibrated to work properly with a designated fuel. In contrast to the engine's demand for fuels with defined properties to meet the emission targets, there is a society demand to use alternative fuels motivated by the reduction of the dependency on crude oil and other factors. Alternatives to mineral diesel fuel are well known and widely used. There are four important types of alternative fuels used in compression ignition engines:

(1) Fuels synthesised from fossil or biogenic gas (gas-to-liquid GTL or biomass-to-liquid BTL), usually produced with the Fischer–Tropsch process.
(2) FAME (fatty acid methyl ester), often called "bio diesel", made from different vegetable oils. A US standard (ASTM D 6751) exists since 2001; a European standard (EN 14214) exists since 2004.
(3) Neat vegetable oil. A German pre-standard exists for rapeseed oil fuel (DIN V 51605).
(4) Recycled waste-oil from fossil or biogenic sources.

This article focuses on fuels (1)–(3) which can guarantee a certain level of quality. As long as some important fuel properties (e.g. cetane number, density, viscosity, heating value, lubricity, boiling behaviour) remain close to the values of mineral diesel fuel, alternative fuels can be burned without or with only small modifications of the engine. Unfortunately, fuels (1)–(3) do have different chemical and physical properties compared to mineral diesel fuel which have to be considered. Some fuel properties required by

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the standards above mentioned are listed in Table 1. The following fuels were used for the experiments described later; their main properties are listed in Table 2:

- Market mineral diesel fuel (denoted as "diesel" from now on) meeting the European standard EN 590 as a reference fuel for this experimental study.
- Pure GTL fuel provided by Shell International Gas Limited.
- Pure rapeseed methyl ester (RME) as a FAME fuel meeting EN 14214.
- Neat rapeseed oil.
- Neat soybean oil.

The experiments described later were performed on an on-road heavy duty diesel engine with hydrocarbon, particle and NO_x aftertreatment. Its main parameters are listed in Table 3. The following questions were addressed:

Case A: How do the different fuels affect engine torque, efficiency and pollutant emissions if the injection timing and the injection duration do not differ from diesel calibration?

Case B: How do the different fuels affect efficiency and exhaust emissions if the injection duration is adapted to maintain the same engine torque for all fuels while keeping all other calibration parameters constant?

Case C: How is the engine efficiency affected if the injection pressure, start of delivery, injection duration and the EGR rate are adapted to each fuel to keep NO_x raw emissions and engine torque on the level achieved with the EN 590 diesel?

Oxygen-containing fuels such as FAME and neat vegetable oils normally increase NO_x emissions and reduce soot emissions compared to mineral diesel due to an enhanced local availability of oxygen in the diffusion-controlled flame [1,2]. Other authors report on contrary effects [3] which indicates, that the effect of the fuels on NO_x emissions depends on the combustion system (chamber geometry and size, injection system) and its calibration. It is known that GTL fuel leads to less NO_x if the engine is not being recalibrated [2,4]. Since the fuels used also have different physical properties, they induce differences in the engine's injection system which can lead to different injection rates [5] with all the consequences for the engine's efficiency and pollutant emissions. For the work discussed here, experiments were performed using a modern heavy duty diesel engine equipped with a combined exhaust gas aftertreatment system. The aim of the work was to quantify the effects of the different fuels on the engine and on the aftertreatment system according to cases A–C mentioned above.

Table 1
Required fuel properties according to European/German standards

	Unit	Diesel EN 590	FAME EN 14214	Neat rapeseed oil fuel DIN V 51605
Density at 15 °C	kg/m^3	820–845	860–900	900–930
Viscosity at 40 °C	mm^2/s	2.00–4.50	3.50–5.00	max. 36.0
Flash point	°C	min. 55	min. 120	min. 220
Lower heating value	MJ/kg	–	–	min. 36
Carbon residue	mass%	max. 0.3	max. 0.3	max. 0.4
Water content	mg/kg	max. 200	max. 500	max. 750
Sulfur content	mg/kg	max. 10	max. 10	max. 10
Cetane index	–	min. 51.0	min. 51.0	min. 39.0

Table 3
Main engine specifications

Number of cylinders	6 in line
Bore	128 mm
Stroke	166 mm
Compression ratio	17.75
Injection system	Pump-line-nozzle(adjustable injectionpressure)
Rated power	335 kW @ 1900 1/min
Rated torque	2240 N m @ 1200 1/min
Turbocharger	Fixed geometry
Intercooler	Air/water (at test bench)
EGR	Water cooled

2. Experimental setup and test program

The experiments were performed on an engine test bench as depicted in Fig. 1. Exhaust gases were sampled pre- and post the exhaust gas aftertreatment systems and analysed with a double-line Horiba Mexa 7400D system for CO, CO_2, NO_x, O_2, and total hydrocarbons (THC). NH_3 emissions after the SCR system were measured using a laser diode spectrometer whose optical path was set up directly along the exhaust gas pipe. A part of the engine's raw emissions was sampled and diluted with a heated partial flow dilution tunnel. After additional dilution, the soot mass was measured with a photo acoustic sensor. The particles were counted with a condensation particle counter with a cut-off size of 7 nm behind an evaporation tube operating at 300 °C which could be bypassed. A mass spectrometer sampled gas at tailpipe position for NO_x speciation (i.e. determining the ratio of NO and NO_2). The exhaust gas flow was fed to a full-flow constant volume sampling (CVS) system for the particle mass measurement. Fiberfilm filters were used and weighted after the tests in a low-vibration, temperature and humidity conditioned room. A second condensation particle counter with a cut-off size of 7 nm sampled from the CVS tunnel behind an additional dilution step and an evaporation tube operating at 300 °C.

Table 2
Properties of the fuels used for the experiments (bold numbers show properties that do not meet the standards)

	Unit	Method	Diesel market fuel	GTL	RME	Neat rapeseed oil	Neat soybean oil
Density at 15 °C	kg/m^3	ASTM D 4052	835	778	881	920	924
Viscosity at 40 °C	mm^2/s	EN ISO 3104	2.65	2.56	4.40	35.0	30.9
Flash point	°C	EN ISO 2719	62	87	**93**	245	260
LHV per mass	MJ/kg	ASTM D4809	43.05	44.3	37.9	36.8	36.9
Carbon residue	mass%	EN ISO 10370	<0.01	<0.01	N/A	N/A	N/A
Water content	mg/kg	EN ISO 12937	60	39	**690**	**850**	547
Sulfur content	mg/kg	EN ISO 20846	10.1	<1	2.5	3.6	2.1
Cetane index	–	ISO 5165	52	79	52	39	**36**
Nitrogen	mg/kg	ASTM D 4629	N/A	N/A	7	2	8
C mass fraction	% kg/kg	ASTM D 5291	85.2	83.6	77.3	77.9	77.1
H mass fraction	% kg/kg	ASTM D 5291	14.8	16.4	11.7	13.2	12.9
O mass fraction	% kg/kg	–	0	0	11.0	8.9	10.0
H/C (molar)	–	–	2.07	2.34	1.81	2.03	1.99