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The individual effects of cetane number, oxygen content or fuel properties on performance efficiency, exhaust smoke and emissions of a turbocharged CRDI diesel engine – Part 2

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ABSTRACT

The paper presents the individual effects made by the variation of cetane number, fuel-oxygen content, or widely differing properties of diesel-HRD fuel blends involving ethanol (E) or biodiesel (B) on the performance efficiency, brake specific fuel consumption, exhaust smoke and NO_x, CO, HC emissions of a turbocharged CRDI diesel engine. The dominant factors one after another operated separately to reveal their contribution to changes in operational parameters. Load characteristics were taken with a straight diesel and various (18 in total) fuel blends at maximum torque mode of 2000 rpm and additional speeds of 1500 and 2500 rpm to improve interpretation of the test results. The (bmep) characteristics were plotted as a function of relative air-fuel ratio (λ) to analyse performance and engine out emissions for relative 'lambda' values of = 1.30, 1.25 and 1.20, at the respective speeds of 1500, 2000 and 2500 rpm. Parameters obtained when using fuel blends of both E and B origins were compared with those measured with 'baseline' blends possessing normal CN rating or zero content of oxygen and a straight diesel to reveal the resulting development trends. The combustion characteristics (Part 1) were used to properly interpret the resulting changes in engine performance and emissions.

The brake thermal efficiency equally increased by 0.5%, NO_x emissions by 15.8% or 2.7%, smoke and CO decreased 1.7 times or by 34.9% and 7.2 times or increased by 18.8% when running with the most flammable (CN = 67.3) fuel blends E or B at λ = 1.20 and the high speed of 2500 rpm. The engine efficiency increased by 2.9% or 0.5%, NO_x emissions by 10.6% (1.81 wt%) or 5.0%, smoke and CO emissions decreased 3.0 times or by 46.7% and by 63.3% (3.61 wt%) or 49.5% when using the most oxygenated (4.52 wt%) fuel blends series E or B under given test conditions.

1. Introduction

The Air Pollution Control Act was the first Clean Air Act enacted by Congress of the United States to address the national environmental problem of air pollution on July 14, 1955 [1]. This was the turning point at which the entirely industrial, agricultural, and transportation infrastructure started to move towards green energy policy. At a summit in Paris agreement was signed to reduce the CO_2 emissions 40% by year 2035 and limit the global temperature rise "well below" 2.0 °C [2]. Negotiations on reduction of carbon emissions and development of solutions for a gradual switch to renewable energy systems provides review [3].

A lot of the research projects have been completed to adapt using renewable Fisher-Tropsch gas to liquid [4–7] and biomass to liquid [8–10] fuels as well as hydrotreated renewable diesel [11,12] and hydrotreated vegetable oil [13–18] or waste-cooking oil – HWCO [19,20] in diesel engines. Using Fisher-Tropsch diesel and HRD fuels in a variety of light-duty and heavy-duty engines and vehicles significantly reduces the net emissions of greenhouse gases and smoke (soot) that moderates impact on the environment. Renewable HRD fuel is less hazardous as a fossil diesel fuel, suggests ash-free combustion and long maintenance-free performance for exhaust after-treatment systems.

Effect of cetane number on the combustion process and emissions. The Finish scientists developed modern, cutting-edge technology to produce renewable, oxygen-free, low-emission diesel fuel NExBTL by using vegetable oils such as palm, soybean and rapeseed oils, as well as waste animal fats [21]. The composition of HVO is similar with that of GTL and BTL diesel fuels made by

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Nomenclature

Diesel-HRD fuel blends involving ethanol (E) or biodiesel (B) possessing the same fuel-oxygen mass content of 4.5 wt%, but still with various cetane (C) number values:

CE1	0.871 (0.770 DF/0.230 HRD)/0.129 E wt%, CN = 51.28
CB1	0.585 DF/0.415 B wt%, CN = 51.23
CE2	0.871 (0.370 DF/0.630 HRD)/0129 E wt%, CN = 60.89
CB2	0.585 (0.400 DF/0.600 HRD)/0.415 B wt%, CN = 60.89
CE3	0.871 (0.100 DF/0.900 HRD)/0.129 E wt%, CN = 67.38
CB3	0.585 HRD/0.415 B wt%, CN = 67.32

Diesel-HRD fuel blends possessing the same cetane number of 55.5, but still with various ethanol (E) oxygen (O) mass contents:

OE0	0.850 DF/0.150 HRD wt%, O = 0.00 wt%
OE1	0.974 (0.804 DF/0.196 HRD)/0.026 E wt%, O = 0.91 wt%
OE2	0.948 (0.755 DF/0.245 HRD)/0.052 E wt%, O = 1.81 wt%
OE3	0.922 (0.704 DF/0.296 HRD)/0.078 E wt%, O = 2.71 wt%
OE4	0.896 (0.650 DF/0.350 HRD)/0.104 E wt%, O = 3.61 wt%
OE5	0.870 (0.592 DF/0.408 HRD)/0.130 E wt%, O = 4.52 wt%

Diesel-HRD fuel blends possessing the same cetane number of 55.5, but still with various biodiesel (B) oxygen (O) mass contents:

OB0	0.850 DF/0.150 HRD wt%, O = 0.00 wt%
OB1	0.916 (0.835 DF/0.165 HRD)/0.084 B wt%, O = 0.91 wt%
OB2	0.833 (0.817 DF/0.183 HRD)/0.167 B wt%, O = 1.81 wt%
OB3	0.750 (0.795 DF/0.205 HRD)/0.250 B wt%, O = 2.71 wt%
OB4	0.667 (0.768 DF/0.232 HRD)/0.333 B wt%, O = 3.61 wt%
OB5	0.583 (0.733 DF/0.267 HRD)/0.417 B wt%, O = 4.52 wt%

Abbreviations

DF	fossil-origin diesel fuel (class 1)
FAME	fatty acid methyl ester
GTL	gas to liquid technology
FT	Fischer-Tropsch technology
HVO	hydrotreated vegetable oil
HWCO	hydrotreated waste cooking oil
BTL	biomass to liquid
HRD	hydrotreated renewable diesel
TDC	top dead center
ATDC	after top dead center
BTDC	before top dead center
CAD	crank angle degree
bmep	brake mean effective pressure, MPa
bsfc	brake specific fuel consumption, g/(kWh)
bte	brake thermal efficiency
NO	nitric oxide, ppm
NO_2	nitrogen dioxide, ppm
NO_x	total nitrogen oxides, ppm
CO	carbon monoxide, ppm
CO_2	carbon dioxide, vol%
THC	total unburned hydrocarbons, ppm

Fischer Tropsch synthesis from natural gas and gasified biomass [22]. Therefore, using HVO (HRD) in a heavy-duty DI diesel engine reduces CO, THC, NO_x emissions, and smoke (soot). In contrast to ester-type biodiesel fuels, HRD differs as having better storage stability, excellent cold starting and clean combustion properties due to high CN rating and low C/H atoms ratio, does not create deposits in the crankcase, prevents engine oil from rapid aging and, finally, – production of renewable fuels by using HRD technology contributes to utilisation of biological residues.

Bhardwaj et al. [18] studied utilization of pure HVO, petroleum diesel, and RME fuel properties in a high efficiency combustion system. Researchers noted that the HVO fuelling results in about 50% reduction in smoke emissions and 43% reduction in gravimetric PM flow, while the reduction with RME was 78% and 62%, respectively. Singh et al. [12] conducted dynamometer tests by using 13 modes European Stationary Cycle on a heavy-duty, DI diesel engine fuelled with two biofuels HRD and Biodiesel (B100) produced from Jatrophacurcas oil feedstock. They declared substantial reduction in PM, CO, and HC emissions due to higher heating value of HRD and lower brake specific fuel consumption compared to conventional diesel. However, NO_x emissions increased by 26% for the neat HRD and 77% for B100 fuelled engine.

Effect of fuel-oxygen on mixing control combustion and emissions. The test results of a modern diesel engine showed that using HVO reduces the NO_x-particulate (PM) trade-off up to 50% compared to conventional diesel [23]. Lighter fuel A, containing 60% LO-BP (C_8H_{18}) fuel, produced a relatively homogeneous liquid phase distribution because radial dispersion of the liquid particles was faster than that of multi-component fuels B and C [24]. Whereas Lee et al. [25] measured higher NO_x emissions and low exhaust smoke in a heavy-duty diesel engine because relatively premixed combustion was predominated when using a lighter and more volatile JP-8 fuel.

Experiments with various FAME and diesel fuel blends showed that even small fractions of low volatile components have effect on the spray formation and evaporation process under realistic diesel engine conditions [26]. The higher boiling point FAME additions resulted in a higher penetration of the fuel liquid phase and area occupied by the spray patterns. Whereas the spray cone angle reached maximum value of 17° at about 50 μs after SOI and decreased to 10° at 200 μs. Tests with various biodiesel blends also showed that the higher density and viscosity of the fuel affect the profile relaxation and lead to the spray cone angle about 10% smaller than with diesel fuel, which results in an increased thermal zone for the NO_x formation [27]. However, biofuels derived from vegetable oil [28], animal fat [29], and other sustainable sources [30] provide excellent lubricity to the fuel injection system that in a long-term can reduce excessive wear of precision nozzle-needle-valve parts.

Effect of fuel properties on mixing control combustion and emissions. Because density and viscosity of the fuel affect injection characteristics well before the combustion starts in the engine cylinder, Hulkkonen et al. [31] investigated differences in fuel spray characteristics between HVO and fossil diesel fuel EN 590. Researchers noted that the maximum velocity of HVO fuel droplets was about 10–50 m/s higher and continued longer in pressurised nitrogen (N_2) gas chamber that assured somewhat better than fossil diesel fuel penetration of the fuel spray tips for a higher injection pressure range of 1000–1985 bars. Moreover, the HVO fuel spray angle did not have a conical shape and was in the range of 0.2–2.0° wider than that of a fossil fuel at ambient density of 36 kg/m^3 in the test chamber.

Ethanol is plenty oxygenated by nature and its kinematic viscosity is nearly 3.2 times lower than that of biodiesel (Table 3). This gives a chance to provide the qualitative and quantitative study on the effects made by the differing properties of the fuel on engine performance efficiency and exhaust emissions when the cetane