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Comparison of performance and emissions of a CRDI diesel engine fuelled with biodiesel of different origin

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ABSTRACT

In the present paper, laboratory produced, animal origin biofuels (swine lard and turkey lard had been used as raw material for biofuel production) were evaluated in terms of physicochemical parameters and compared with commercial mineral diesel fuel and its mixture with rapeseed oil methyl esters. Basing on the results of physicochemical parameters assessment, mixtures containing 75% share of bio-component were preselected for further engine tests. The engine tests were performed on a medium-duty, turbocharged, Common Rail, Direct Injection (CRDI) diesel engine, using factory control maps. The scope of experiments included steady state measurements for two rotational speeds (1500 and 3000 RPM), for which full load sweep had been performed. Two injection strategies were utilized: single pulse (for 3000 RPM) and multi-pulse injection (1500 RPM). The research covered evaluation of engine performance parameters and full exhaust emissions. Furthermore, detailed combustion analysis was performed.

The study confirmed that high quality fuel can obtained from waste fatty material. The mixtures containing up to 75% of bio-component are suitable for modern CRDI combustion engines, though slight deterioration of engine performance parameters can be expected. An average brake specific fuel consumption increased by 13% compared to reference, for biodiesel mixtures derived from animal fatty material. At the same time a 3% increase against rapeseed oil/diesel mixture was recorded. This was correlated with a minor reduction of brake fuel conversion efficiency, but the average drop didn't exceed 2% for all examined biodiesels.

A significant reduction in exhaust gas emissions was observed, when comparing biofuel operation to reference diesel. The use of swine lard methyl ester/diesel mixture caused average reduction of hydrocarbon concentration (THC) by 13%, carbon monoxide (CO) by 22% and carbon dioxide (CO_2) by 7%. The turkey biodiesel emission results were respectively: 9%, 20% and 6% reduced. NOx emission increased on average by 7% for both animal origin biofuels.

1. Introduction

Nowadays, over 20% of global demand for energy is used for transportation [1]. The sector is largely dominated by compression ignition (CI) engines, which are used as prime movers in heavy duty road, rail and waterborne transport vessels. CI engines have gained popularity due to their higher thermal efficiency compared to spark ignition (SI) engines, large energy density, high torque and the possibility of being powered by a wide range of fuels, including those obtained from renewable sources. All those advantages, together with special requirements of heavy duty transport sector, allow to state that, despite rapidly progressing electrification, CI engines will retain its

Abbreviations: AC, air cooled engine; BDC, bottom dead centre piston position; BFCE, brake fuel conversion efficiency; BSFC, brake specific fuel consumption; BTE, brake thermal efficiency; CA, crank angle degrees; CFPP, cold filter plugging point; CHR, cumulative heat release rate; CI, compression-ignition engine; CN, cetane number; CO, carbon monoxide; CO_2, carbon dioxide; CR, engine equipped with Common Rail injection system; CRDI, Common Rail direct injection; DI, direct injection; DME, di-methyl ether; DOC, diesel oxidation catalyst; ECU, engine control unit; EGO, exhaust gasses opacity; EGR, engine equipped with exhaust gasses recirculation; FID, flame ionization detector; HHV, higher heating value; HPDI, high pressure direct injection; HRR, heat release rate; IC, engine equipped with intercooler; MD, commercial diesel fuel; NA, naturally aspired engine; NEDC, the new European driving cycle test; NOx, oxides of nitrogen; PM, particulate matter; PPM, parts per million; PPt, parts per thousand; PRR, pressure rise rate; R75, biodiesel mixture obtained from 75% of rapeseed methyl esters and 25% of commercial diesel fuel (by volume); RCCI, reactivity controlled compression ignition; RME, rapeseed methyl esters; RPM, revolutions per minute; S75, biodiesel mixture obtained from 75% of swine lard methyl esters and 25% of commercial diesel fuel (by volume); SI, spark-ignition engine; SLME, swine lard methyl esters; SOC, start of combustion; SOI, start of injection; T75, biodiesel mixture obtained from 75% of turkey lard methyl esters and 25% of commercial diesel fuel (by volume); TC, engine equipped with turbocharger; TDC, top dead centre piston position; THC, total hydrocarbons; TLME, turkey lard methyl esters; UDC, the urban driving cycle test

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Nomenclature

A	crank shaft rotation angle [CA]
$\dot{m}$	mass flow rate [kg/h]
N	engine rotational speed [RPM]
n	engine torque [Nm]
η_v	volumetric efficiency [%]
P	in cylinder pressure [bar]
P_e	engine power [kW]
Q	heating value [J/kg]
ρ	density [kg/m^3]
T	temperature [K]
Te	engine torque [Nm]
V_d	engine displacement volume [dm^3]

Subscripts

air	air
fuel	fuel
inj	injection
id	ignition delay
avg	average
r	relative

important position [2].

In recent years intensive development of CI engines, directed towards meeting more and more strict emission norms, was observed. Introduction of advanced technology in injection control and exhausts aftertreatment resulted significant reduction of exhaust gasses emission [3]. However, with the current state of the art, clean CI combustion is occupied with high technological complication level which makes the units expensive in production and maintenance. Still upcoming future legislation for heavy duty road transport will re-direct the focus towards vehicle CO_2 footprint (CARB2020) keeping strict Euro 6 requirements for emissions. Meeting those requirements is considered difficult with already established technologies [4] which creates a room for more advanced development [5–7].

A parallel development roadmap of modern CI engine is focused on fuel related topics. Different fuels were researched in order to do both: increase the share of renewable sources in energy balance or further enhance engine efficiency and emissions. This was done either by – pre-preparing dedicated fuel blends or by in-cylinder blending using various dual and multi-fuel strategies. From the later, different combinations of diesel-gasoline [8], diesel-natural-gas [9–12], and other admixes including di-methyl ether (DME) [13] or ethanol [13,14] were examined. Recently Banerjee et al. presented a technology to improve the performance and emissions of a CI engine by supplementing the fuel mixture with hydrogen direct injection [15]. The above mentioned research also considered different CI based combustion concepts: from conventional dual-fuel [10], through so-called High Pressure Direct Injection (HPDI) [11], to low-temperature Reactivity Controlled Compression Ignition (RCCI) [8–12].

In general, the supplementation of a fuel mixture with additional components can be used to improve engine efficiency and/or reduce the amount of toxic compounds in the exhausts. However, such treatments usually require substantial changes in the engine fuel system as they involve the installation of additional elements and also, in the vast majority of cases, modifying the injection system of conventional fuel. Another, less invasive strategy to reduce exhaust emissions seems to be the replacement of mineral fuel with counterparts of renewable origins [16]. This can be done in the pre-processing stage and the fuel can be prepared in such a way to meet the requirements of the existing engine hardware.

Biodiesel as a renewable alternative to mineral diesel fuel can be obtained from different types of fat material [16–18]. The properties of biodiesel, such as non-toxicity, biodegradability and the ability to mix with mineral fuel in any proportion are important reasons for its popularization. Furthermore, biodiesel is characterised by increased safety in storage due to its higher flash point compared to mineral diesel fuel.

Currently, there is increased interest in the use of post-production or post-processing waste products (the so-called 2nd generation raw material) for biofuel production. The use of feedstock of this type does not cause ethical objections related to the processing of food for fuel, and provides reasonable opportunities for the disposal of products considered as waste in other sectors of economy. Economic considerations are strong as well. The high supply of materials considered to be waste, and the need to recycle them provides easy access to feedstock far below the price of the competing first-generation bio-materials. Note that biodiesel obtained from waste can sometimes be characterised by worse physical and chemical properties compared to the product obtained from previously unprocessed feedstock [19,20]. It means that obtaining a high-quality biofuel requires additional work related to preparation of the feedstock and use of more sophisticated production techniques. These steps are necessary when using biodiesel in modern Common Rail injection systems (CR), which require high-quality fuels [21]. For this reason, there is no possibility of the regular use of fuels with properties that do not meet the quality requirements laid down by the relevant standards (EN 590 and EN 14214).

In the literature, a lot of work has been devoted to studying the biodiesel obtained from feedstocks of plant origin [22,23], or waste frying fats [24,25]. The fuels obtained from a fat material of animal origin deserve special attention as potential second generation biofuels. In meat processing plants the fat material is often considered waste. These wastes, are only partially re-used as an additive during the production of fodder for farmed animals, while the major part is subjected to costly utilisation via high temperature processing (bio-waste furnace disposal). An attempt to make the material recyclable through use as bio-component for powering combustion engines seems attractive and winsome.

A review of the most important research in the field of the use of biofuels of animal origin to power CI engines was presented in the earlier work of the authors' [26]. The main conclusions of all the analyzed research were similar. Although the studies focused on the fuels obtained from different feedstock, which were analyzed using different methods, all of them demonstrated similar trends. None of the authors indicated any malfunctioning in the operation of the engine when it was powered by animal fat origin fuel. In contrast, the attention was drawn to the observed reduction in the exhaust emissions (for most toxic gas components, excluding NOx), when the engine was powered – even partly – by biofuels. Apart from the positive aspects of using biodiesel, a slight deterioration in engine performance parameters was observed, and explained by the lower calorific value of biofuels relative to mineral diesel fuel (MD) [25,27–30].

The authors' earlier paper [26] substantially bridges the gap resulting from the lack of test results for modern engines equipped with new-generation injection systems powered by high-percentage biodiesel mixtures produced from animal fat. Apart from confirming the fundamental conclusions presented above, the authors prove that MD admixed with swine lard methyl esters (SLME) were characterised by higher heat release rates during combustion. Also, the use of SLME-MD fuel mixtures lead to a considerably reduced auto-ignition delay. Furthermore, the authors showed that using SLME-MD fuel mixtures reduces ppm wise emissions, proportionally to the biocomponent share. Particular effects have been observed for CO and THC emissions, where the average reduction levels amounted to 29% and 52%, respectively