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Biodiesel/mineral diesel fuel mixtures: Spray evolution and engine performance and emissions characterization

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ABSTRACT

The interest in energy from biomass, in particular for transportation, is related to the need to differentiate the energy sources to improve environment and protect human health. Objective of this study is a comparative evaluation of performance and exhaust emissions of an automotive diesel engine fuelled by mixtures of rapeseed and soybean methyl ester with reference to mineral diesel fuel. The spatial and temporal jet evolutions have been characterized injecting the fuel in a quiescent vessel by a standing alone common rail apparatus at diesel-like gas density conditions. The injection strategies have been chosen as representative of different engine working conditions for several speeds and loads, injecting the fuel in a non-evaporating high-density vessel. Fuel injection rate measurements, spatial and temporal fuel distribution have been carried out processing jet images captured by a CCD camera. Engine tests have been performed on a 4-cylinder DI Diesel engine for automotive applications equipped with a common rail 7-hole nozzle electro-injector system. Engine performance, gas emissions and smoke have been measured at the engine speeds of 1500 and 2500 RPM for different loads. Two different fuel blends, RME50 and SME50, have been tested comparing their performance and emissions with the diesel ones.

1. Introduction

Biodiesels are alternative diesel fuels made from renewable sources such as vegetable oils and animal fats. They are biodegradable, nontoxic with low emission profiles [1]. Recently, the employment of first generation biodiesel in the automotive transportation has grown significantly thanks to a favorable combination of high fuel prices and fiscal policies to promote its use [2–4].

Biodiesels are ethylic or methyl esters of acids with long chain derived from vegetable oils and animal fats through a thermochemical process involving the transesterification process. They have characteristics quite similar to the common diesel fuel, particularly as regards the cetane number. Their interesting peculiarities can be summarized as renewable and biodegradable, don't contain any sulphur element and PAH, don't require changes to the engine structure and, finally, don't contribute to the accumulation of CO_2 in the atmosphere [5–7]. However, the interference of this generation of biodiesel with the human food chain as well as to the limited total producible output has oriented the efforts toward the so-called second generation of biodiesel, through a synthesis process from biomass, fossil fuels, natural gas or coal. There is evidence that biodiesel fuelling of engine can have a strong impact on performance and pollutant emissions, in particular for the last generation of electronically controlled diesel engines [8,9].

There is a wide agreement in the literature that biodiesel and its blends generally decrease the emissions of both CO and HC. It is also suggested that higher CO and HC emission reductions are seen at higher engine loads. Due to the lack of sulphur and PAHs, biodiesel usage decreases the carbon particulate emissions and increases the SOF (Soluble Organic Fraction), resulting in reduced visible smoke and opacity. SOF is probably increased due to reduced spray penetration of biodiesel, especially at low engine loads [10,11]. The shift of PM toward higher SOF content, as well as the absence of sulphur, makes biodiesel compatible with diesel oxidation catalysts, which can maximize PM benefits.

NO_X emissions are in most cases increased with biodiesel, mainly due to the high oxygen content of the fuel. In general, the cetane number and fuel volatility are the two most important fuel properties controlling the amount of premixed combustion and, thus, the combustion rate. Due to its higher bulk modulus at low injection pressures, its compressibility is reduced compared to petroleum diesel, and an injection advance is observed that leads to a higher initial rate of combustion, higher gas temperatures in the cylinder

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Nomenclature

BSFC	Brake Specific Fuel Consumption
BMEP	Brake Mean Effective Pressure
CAD	Crank Angle Degree
CN	Cetane Number
CO	Carbon monoxide
DI	Direct Injection
EGR	Exhaust Gas Recirculation
HC	Hydrocarbons
LTC	Low Temperature Combustion
NO_x	Nitrogen Oxides
PAH	Polycyclic Aromatic Hydrocarbons
PECU	Programmable Electronic Control Unit
PM	Particulate Matter
RME	Rapeseed Methyl Ester
RMS	Root Mean Square
RPM	Revolution per Minute
SF_6	Sulphur Hexafluoride
SME	Soybean Methyl Ester
SOF	Soluble Organic Fraction
SOI	Start of Injection
TDC	Top Dead Center

and increased NO_X production. However, at higher injection pressures (above 70 MPa) the bulk modulus is similar to petroleum diesel and the differences in injection timing are not significant [12].

Current literature reports numerical studies with multi-component fuels that have investigated the overall mixture formation process demonstrating as spray atomization, droplet evaporation, ignition, combustion and pollutant emissions formation may be significantly influenced by the composition of the fuel. The CFD predictions, supported by experimental measurements to investigate spray behaviour and mixing, may serve as a basis for engine optimization in order to examine a wide range of potential solutions, without the restrictions of time consuming and costly experiments at the engine test bench. Several of the main processes affecting ignition and combustion have been evaluated in recent literature. Rakopoulos et al. [13,14] have reported the development of a multi-zone model for combustion and pollutants formation in direct injection diesel engine equipped with a mechanical pump and supplied with vegetable oil and biodiesel pointing out as the different properties of the tested fuels affect the spray formation, ignition, combustion mechanism and emissions. Yuan et al. [15] have reported results from KIVA-3V code, with detailed numerical models for spray atomization, ignition, combustion and NO_x formation. They have evaluated strategies for NO_x reduction and showed the potential worth of using numerical simulation in guiding engine manufactures and biodiesel users to get the most effective approach to reduce NO_x emissions. Golovitchev and Yang [16] have investigated the combustion mechanism of rapeseed methyl ester (RME) proposing detailed and reduced combustion models validated using shock-tube ignition delay data under diesel-like engine conditions. According to this approach, experiments of non-evaporating and evaporating fuel sprays, injected in a high-pressure ambient, are essential to provide experimental measurements for the validation of the spray atomization and evaporation models. The same experiments made on engines with multi-component fuels may be used for the calibration of the ignition, combustion, and emission formation models.

As well known, in diesel engines exhaust emissions, soot and NO_x, can be controlled by promoting premixing of fuel with air and lowering the combustion temperature. This combustion mode, known as low temperature combustion (LTC), requires high EGR rates that are applied to the intake charge to reduce the flame temperature [17–20]. This mechanism may be established if high level of EGR and retarded start of injection are realized. In fact, the exhaust gas recirculation contributes to reduce the in-cylinder oxygen concentration and consequently the flame temperature with a higher smoke production. To solve this problem, it is strategic to start the combustion following a long ignition delay that may strongly improve the mixing of fuel and oxygen. The potential of considering biodiesel within diesel engines operating close to LTC conditions has suggested the authors to perform experiments at high EGR levels, comparing the combustion characteristics of diesel and biodiesel fuels.

In summary, it appears that there is a potential to reduce gaseous and smoke emissions using biodiesel blends, when an engine and its auxiliary systems (injection system, EGR) have been optimized for the specific blend. The effects of supplying diesel engines with biofuels must be studied both in terms of fuel spray characterization and mixture formation to make engine performance and exhaust emissions fulfill the incoming pollutant restrictions.

Aims of this study are to decouple the dynamic and thermodynamic processes of injecting rapeseed and soybean mixtures with reference to mineral diesel fuel. The fuel injection of blends has been fully characterized in terms of fuel injection rate and spatial-temporal evolution of the jets in a quiescent vessel at engine-like gas density conditions. In addition, engine tests at different loads have been carried out to characterize performance and emissions of a d.i. diesel engine equipped with a turbocharger and common rail injection system able to manage multi-injection strategies.

2. Experimental apparatus

2.1. Injection apparatus test rig

Objective of the present activity is to verify the effects of physical and chemical properties of the most promising alternative renewable diesel fuels on the injection process and combustion and, therefore, on performance and pollutant emissions. The

Table 1
Specifications of the engine.

Engine type	
4 Cylinder, 4 Valve, DI Diesel Engine	
Bore	82 mm
Stroke	90.4 mm
Connecting rod	145 mm
Displacement	1910 cm^3
Compression ratio	17.5:1

Table 2
Main Fuel properties of Diesel, RME50 and SME50.

Fuel Properties	Diesel	RME50	SME50
Density @ 15 °C [kg/m^3]	840	861.9	862.3
Viscosity a 40 °C [mm^2/s]	3.2	3.675	3.46
Cetane Number	52	55.5	54
Net Heat Value [MJ/kg]	42.5	40.15	40.1
Carbon content [%, m/m]	87.	81.90	82.34
Hydrogen content [%, m/m]	12.6	11.95	12.22
Distillation [°C] 50% Vol.	280	320	319
Distillation [°C] 90% Vol.	338	339	337