

Spray Formation and Combustion Analysis in an Optical Single Cylinder Engine Operating with Fresh and Aged Biodiesel

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Ezio Mancaruso, Luigi Sequino and Bianca Maria Vaglieco
Istituto Motori CNR

Claudio Ciaravino and Alberto Vassallo
General Motors Powertrain - Europe

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ABSTRACT

The present paper describes the results of a cooperative research project between GM Powertrain Europe and Istituto Motori - CNR aimed at studying the impact of both fresh and highly oxidized RME at two levels of blending on spray formation and combustion in modern automotive diesel engines. The tests were performed on an optical single-cylinder engine sharing combustion system configuration with the 2.0L Euro5 GM diesel engine for passenger car application.

Two blends (B50 and B100) blending were tested for both fresh and aged RME and compared with commercial diesel fuel in two different operating points typical of NEDC (1500rpm/2bar BMEP and 2000rpm/5bar BMEP). The experimental activity was devoted to an in-depth investigation of the spray density, breakup and penetration, mixture formation, combustion and soot formation, by means of optical techniques.

The optical engine results have confirmed that, from a combustion point of view, there is no appreciable difference between fresh and aged RME. Furthermore, the tests highlighted the higher spray penetration of RME with respect to regular diesel fuel as well as a differences in density distribution across the spray, breakup angle and soot formation. The soot evolution was lowered due to lack of aromatics precursors and the high oxygen concentration in the fuel.

INTRODUCTION

The use of alternative fuels from renewable sources has become increasingly popular in recent years and it is likely to increase its importance in the near future as a combined result of tougher CO₂ targets and energy diversity goals being set by various countries [1]. More in detail, the multiple drivers for the increasing interest in biofuels are: the need to displace expensive fossil fuel imports, their favorable well-to-wheel CO₂ balance, their reduction of the most harmful pollutant emissions coupled to easy biodegradability, and, finally, the opportunity to produce them locally with conventional technology [1, 2, 3, 4, 5, 6, 7]. These features well support why biofuels are considered a strategic opportunity for many developing countries in the Asia Pacific region, where economic drivers are of utmost importance, but they are also considered by EU policymakers as substantial contributors to meet 2020 CO₂ targets and by US as an opportunity for mid and long term petroleum displacement.

Therefore, given the interest in biofuels from EU and Asia-Pacific, two regions where diesel engines have a substantial market share, fatty acid methyl esters (FAME) have grown their importance, because of their properties promoting CI combustion; they are also known simply as biodiesel, or, depending on the feedstock source, RME (rapeseed oil methyl esters), SME (soybean oil methyl esters), PME (palm oil methyl esters), etc. Fatty acid methyl esters are usually obtained from oil seeds and are mainly used in their pure form or mixed with conventional diesel fuel in the transport sector.

Even if biodiesel is usually produced from vegetable oils, animal fats can also be used. The source oil or fat is transesterified with methanol, thus producing the methyl esters of the fatty acids together with glycerol as a by-product. Fatty acid methyl esters are relatively unstable on storage, as, like natural oils and fats, they are slowly oxidized by oxygen contained in the atmosphere. The oxidation sub-products that are formed are both corrosive towards fuel injection system components as well as prone to deposit and gum formation, both of which could cause severe engine damage. This is why the oxidation stability is an important quality criterion for biodiesel and it is regularly tracked during the production and distribution process. The oxidation process can be delayed by the addition of antioxidants [8, 9, 10, 11].

In this work, in-cylinder measurements based on optical diagnostics were applied to a transparent diesel engine equipped with the latest-generation Euro 5 production engine head. The aim is to study the impact of both fresh and highly oxidized rapeseed methyl ester (RME) at two levels of blending on spray formation and combustion behavior of a modern automotive diesel engine. In particular, B50 and B100 blending were tested for both fresh and aged RME and compared with commercial diesel fuel in two different operating points typical of NEDC (1500rpm/2bar BMEP and 2000rpm/5bar BMEP). Digital imaging was applied in order to study both injection and combustion evolution inside the cylinder through a quartz window located in the bottom of the elongated piston. Finally, the in-cylinder soot evolution was analysed by means of the two color pyrometry technique.

FUELS

Biodiesel is produced by the reaction of a vegetable oil or an animal fat with an alcohol, such as methanol, in the presence of a catalyst to yield the methyl esters (the biodiesel) and glycerine. The most commonly used catalyst, potassium hydroxide, is used in transesterification of a wide range of oils and fats, from vegetable to animal, from virgin to used, including those with the highest acid contents. One of the most important parameter to keep in consideration during the storage of the biodiesel is its stability. Freshly produced vegetable oils are protected from oxidation by the presence of naturally occurring antioxidants. However, the manufacturing process for biodiesel removes natural antioxidants, leaving the fuel unprotected from oxidative degradation. Oxidation of biodiesel by contact with air and metal surfaces results in the formation of hydroperoxides. These induce free-radical chain reactions that lead to decomposition into low-molecular-weight, highly oxidized species (aldehydes, ketones, acids) and high-molecular-weight polymeric materials (gums). Such gums are responsible for serious engine problems such as deposits on injectors and pistons. The presence of high-molecular weight insoluble gums generally leads to fuel-filter plugging [8, 9, 10, 11]. The measurement of biodiesel

oxidation stability is performed by the Rancimat test. This test consists of bubbling air through biodiesel that has been heated to 110°C. The amount of short-chain acids present in the distillate (the cleavage products of the fatty acid oxidation) is a direct indication of the oxidation stability of the biodiesel [8, 9, 10, 11].

In [Table 1](#) the specific properties of pure fuels used in the present investigation are reported. They are the most important parameters affecting the fuel injection, air/fuel mixture formation and combustion development. The reference diesel fuel is a diesel fuel provided at the refill pump. The biodiesel is a rapeseed methyl ester (RME), fresh and highly oxidized, respectively. The RME fuels properties show increases in viscosity (30%), density (6%), cetane number (up to 9%), total acid number (TAN), peroxide content (POV), and, of course, oxygen (88%) in comparison with conventional diesel. On the other hand, they have a low heating value up to 15% smaller than the reference fuel. In [Figure 1](#) the distillation curves of the pure fuels investigated are reported. The RME fuels have the distillation curves that stretched in the temperature range corresponding to the tail of the conventional diesel. These properties will allow the increase of spray penetration with respect to conventional diesel, mainly in low temperature conditions.

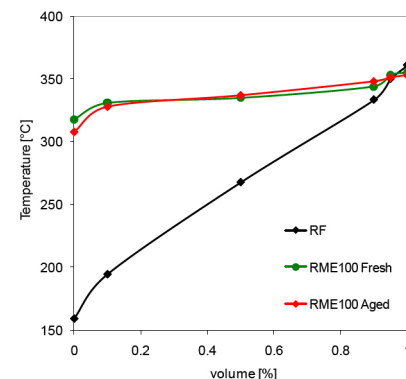


Figure 1. Distillation curves for pure fuels

EXPERIMENTAL APPARATUS

OPTICAL SINGLE-CYLINDER ENGINE

The optical single-cylinder (SC) engine used for combustion diagnostics was equipped with the combustion system architecture and injection system of a four-cylinder standard engine. The engine lay-out with the experimental apparatus is shown in [Figure 2](#). Moreover, the engine specifications are reported in [Table 2](#).

The optical engine utilized a conventionally extended piston with a piston crown window of 46 mm diameter which provided full view of the combustion bowl by locating an appropriate 45° UV-visible fixed mirror inside the extended

Table 1. Main fuels parameters

Feature	Method	RF	RME Fresh	RME Aged
Density @ 15 °C [kg/m ³]	EN ISO 12185	833.1	883.1	884.2
Viscosity @ 40 °C [mm ² /s]	EN ISO 3104	3.141	4.431	4.539
Oxydation Thermal Stability @ 110°C [h]	EN 14112	-	6.5	2.4
Oxydation stability [mg/100ml]	EN ISO 12205	-	0.6	1.2
Lubricity @ 60 °C [μm]	EN ISO 12156-01	-	179	195
Cetane Number	EN ISO 5165	51.8	52.6	57.0
Low Heating Value [MJ/kg]	ASTM D4868	42.965	37.570	37.430
A/F st		14.54	12.44	12.31
C.F.P.P. [°C]	EN 116	-	-14	-14
POV [meq O2/kg]	NGD Fa 4		16.60	68.60
TAN [mg KOH/g]	EN 14104		0.13	0.19
Carbon [%, m/m]	ASTM D 5291	85.22	77.11	76.94
Hydrogen [%, m/m]	ASTM D 5291	13.03	11.60	11.53
Nitrogen [%, m/m]	ASTM D 5291	0.04	0.03	0.04
Oxygen [%, m/m]	ASTM D 5291	1.45	11.25	11.49

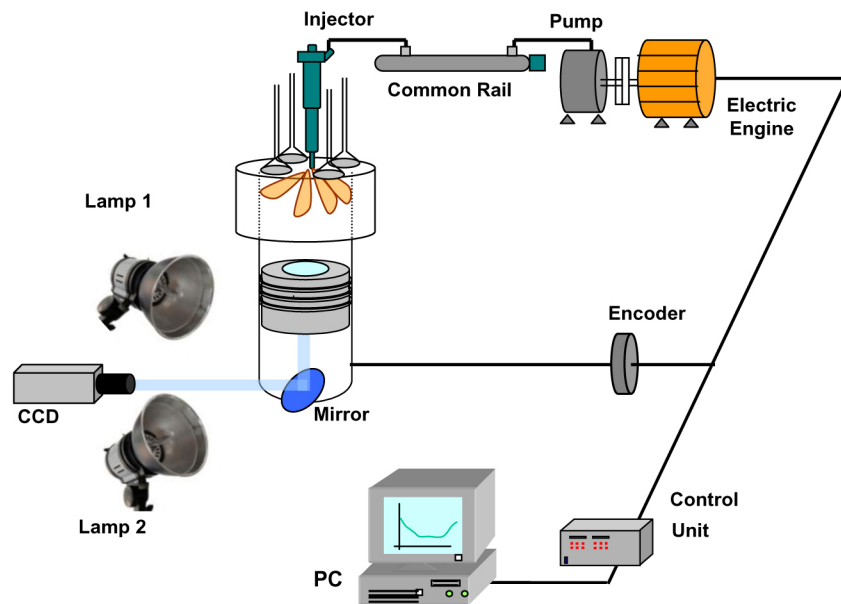


Figure 2. SC engine optical setup

piston. The window was made of UV-grade fused silica. Moreover, the combustion bowl volume and the bowl wall shape were the same as the production engine. However, the reverse cone in the center of the bowl was removed in order to have a good visualization of the phenomena. To match the in-cylinder conditions of the multi-cylinder engine tests, an external air compressor was used to supply pressurized intake air that was well filtered, dehumidified, and preheated.

The engine was also equipped with a Common Rail injection system managed by a fully opened electronic control unit (ECU). The ECU allowed to control the number of injections per cycle, the injection pressure, the injection start, the

energizing time that manage the injector as well as the dwell time between two consecutive injections. The injection system specifications are reported in [Table 3](#).

Table 2. Engine specifications

Engine type	4-stroke single cylinder
Bore	8.5 cm
Stroke	9.2 cm
Swept volume	522 cm ³
Combustion bowl	19.7 cm ³
Vol. compression ratio	16.5:1

Table 3. Injection system specifications

Injection system	Common Rail
Injector type	Solenoid driven
Number of holes	7
Cone angle of fuel jet axis	148°
Hole diameter	0.141 mm
Rated flow @ 100bar	440 cm ³ /30s

The exhaust gas recirculation (EGR) and variable swirl actuator (VSA) were managed by external devices. The amount of EGR was set at 56% @1500rpm, and 33% @ 2000rpm, respectively. In particular, in order to achieve the correct amount of EGR, a back pressure valve was fitted in the exhaust duct. This allowed to increase the pressure in the exhaust and thus to bring the exhaust gas into the pressurized intake manifold. Moreover, even if the EGR was cooled, its residual heat content was able to increase the intake temperature up to 75°C in the manifold. The variable swirl throttle actuator (VSA) system was also used. This system consisted of a set of blades mounted in the intake manifold in front of the helical shape intake duct of the engine head. The VSA controlled the swirl motion of the intake air. The high value of the VSA position induces high swirl motion to the intake air. It was positioned at 66% for 1500 rpm engine speed and at 58% for 2000 rpm, respectively.

To analyze the injection signals, a Hall-effect sensor was applied to the line of the solenoid current and a piezoelectric pressure transducer was located in the injection line between the rail and the injector. Moreover, to acquire the cylinder pressure in motored and fired condition, a piezoelectric pressure transducer (AVL GH13P) was set in the glow plug seat of the engine head. Opacity and gaseous emissions were measured with conventional systems by means of probes placed in the exhaust pipe. In particular, NO_x and O₂ concentrations were measured by means of electrochemical sensors, while HC, CO, and CO₂ concentrations were detected by means of non-dispersive infrared detectors (AVL DIGAS 4000). Finally, particulate matter concentration was monitored by means of opacimeter (AVL439). More details about the specifications of the engine are reported in [12, 13].

For each operating condition investigated, the cylinder pressure, the drive injector current and the injection pressure were digitized and recorded at 0.1 crank angle degree (CAD) increments and ensemble-averaged over 150 consecutive combustion cycles. Moreover, the cyclic variation was measured and it resulted less than 1% with respect to the maximum pressure and less than 3% with respect to the IMEP. The heat release rate was calculated from the ensemble-averaged pressure data using the typical first law and the perfect gas analysis [14].

ENGINE OPERATING CONDITION

All the data presented in this paper were taken with the transparent engine operating in continuous mode. The intake air temperature and pressure were set to 323 K and 1.21 bar @ 1500 rpm and to 318 K and 1.34 bar @ 2000 rpm, respectively. At motored condition, temperature and density at Top Dead Centre (TDC) were estimated, assuming a polytropic coefficient of 1.36 [14]. They were 823 K and 17.6 kg/m³ @ 1500 rpm, and 836 K and 22 kg/m³ @ 2000 rpm, respectively.

The engine operating conditions investigated were representative of the engine behavior on new European driving cycle (NEDC) when installed on a D-class vehicle and they are reported in Table 4. They corresponded to 1500 rpm and 2 bar of brake mean effective pressure (BMEP), and 2000 rpm @ 5 bar BMEP. Both strategies consisted of two injections per cycle, pilot and main, with an injection pressure of 615 bar @ 1500 rpm and of 891bar @ 2000 rpm, respectively.

For all the fuels investigated the injection parameters were kept fixed except for the main injection duration. In particular, the main injection duration for all RME fuels investigated was longer than the reference diesel (RF) one, in order to reach approximately the same net indicated mean effective pressure (IMEP). However, the indicated mean effective pressure of the optical engine is lower than the IMEP of the real one due to the higher displacement, higher blow by, and heat transfer. Finally, the effective percentage of EGR was computed by means of the measurement of the air at the intake manifold and the variable swirl actuator was set at same value of the real engine.

OPTICAL SETUP

Digital imaging analysis was performed by a charge coupled device (CCD) camera through the 45° mirror. The CCD camera with 640 × 480 pixels (pixel dimensions of 9.9 × 9.9 mm²) and a high sensitivity over a wide visible range was used in order to acquire images during the injection and combustion processes. A visible objective, Nikon 55 mm f/3.5, was used. Due to speed limitation of CCD camera, only one image was acquired in a given cycle. The spray parameters were investigated by means of two halogen continuous lamps that lighted the jets in the bowl via the 45° mirror. During both the pilot and main events several images from separate cycles were acquired up to the end of visible injection. Five repetitions were performed in order to carry out statistical analysis of the spray tip penetration and dispersion angle. Then, the lamps were turned off, and the whole combustion process was acquired; at each crank angle ten combustion images were analysed and the ones that better represented the whole set were subjectively selected. Through an appropriate filter, selecting fixed wavelengths in the

Table 4. Engine operating conditions

Fuel	RPM	IMEP [bar]	SOI Pil [°]	ET Pil [μs]	Δt [μs]	SOI Main [°]	ET Main [μs]	Prail [bar]	EGR [%]	VSA [%]
RF	1500	1.98	-16	290	1111	-6	545	615	56	66
RME50 Fresh	1500	1.89	-16	290	1111	-6	566	615	56	66
RME50 Aged	1500	1.87	-16	290	1111	-6	566	615	56	66
RME100 Fresh	1500	1.85	-16	290	1111	-6	587	615	56	66
RME100 Aged	1500	1.65	-16	290	1111	-6	587	615	56	66
RF	2000	4.5	-18.5	257	1348	-2.4	560	891	33	58
RME50 Fresh	2000	4.45	-18.5	257	1348	-2.4	577	891	33	58
RME50 Aged	2000	4.43	-18.5	257	1348	-2.4	577	891	33	58
RME100 Fresh	2000	4.53	-18.5	257	1348	-2.4	597	891	33	58
RME100 Aged	2000	4.45	-18.5	257	1348	-2.4	597	891	33	58

visible range, it was possible to determine the soot temperature and concentration by means of the two-colour pyrometry method [15].

The synchronization of the CCD camera with the engine was obtained by a delay unit connected with the signal coming from the engine shaft encoder. The synchronization system could be adjusted to obtain single images at a desired crank angle. In particular, the images were recorded with an exposure time of 55 μs and 41 μs that corresponded at 0.5° crank angle (CA) of the shaft encoder at 1500 rpm and 2000 rpm, respectively.

INJECTION IMAGE PROCESSING

The images of both the pilot and main injections were accurately investigated in order to evaluate the spray parameter. In particular spray tip penetration was measured in conditions very similar to those of the real engine, and the average tip penetration curves for the main injection were compared with theoretical correlations [16, 17].

Moreover, an alternative method for the investigation of the spray was developed in order to distinguish the different luminosities reflected by the jet. From a general point of view when a jet was illuminated, the denser liquid zone reflects higher intensity of light than the lower dense regions. By means of matrix manipulation and image processing a relationship between the image luminous intensity and the jet density was found. In particular, the jets shapes were cut out so that the chamber brightness would not affect the jet luminosity analysis. Injection images were acquired in 12 bit format and converted to 8 bit. The luminous levels of each image were represented by 256 gray scale intensities. A contour plot of the spray images was drawn and the light intensity along the jet axis was investigated. In this way it was possible to evaluate the spray density within the jet during the penetration in the combustion chamber.

RESULTS AND DISCUSSION

In order to characterize the combustion process of the biodiesels into a transparent Euro5 diesel engine, digital imaging was carried out using diesel fuel as reference and RME, both fresh and aged. The injection evolution and luminous flame development were recorded for the test points reported in Table 2. In particular, attention was focused on the spray spatial distribution, mixing formation, and soot production and oxidation as they occurred in the bowl.

In Figure 3 the histories of cylinder pressure, rate of heat release and drive injector current of the several fuels and speeds investigated are reported. In particular, reference diesel commercial fuel (RF), fresh RME biodiesel (RME 100 Fresh) and highly oxidized RME biodiesel (RME 100 Aged) have been tested. Regarding the injector driving current, it is evident that RME, both fresh and aged, has longer energizing time, in order to reach the same IMEP produced with the reference diesel fuel featuring a higher LHV. The combustion pressure curves are almost overlapped among the investigated fuels, even if a higher in-cylinder pressure around the top dead centre (TDC) is reached during the engine running with RF fuel. This is noted for both the engine speeds analysed, and it is due to the higher energy released by the pilot injection of the reference fuel with respect to that of the RME, both fresh and aged, as supported by the related ROHR curves. This phenomenon is occurring also on the multicylinder version of the engine, and it is caused by the lower injected energy content of pilot injection itself (which is not corrected for compensating the lower LHV of RME) as well as by its slightly lower combustion efficiency stemming from a weaker atomization of biodiesel pilot injection at low rail pressure typical of these operating conditions [12, 13, 18]. The start of combustion (SOC) is determined by the analysis of the heat release rate (ROHR) traces. From a general point of view the start of combustion is detected when the energy release begins to exceed the energy losses due to the fuel evaporating process [14]. The ROHR curve of the RF fuel shows two well resolved peaks due to the burning