

Using 2d Infrared Imaging for the Analysis of Non-Conventional Fuels Combustion in a Diesel Engine

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ABSTRACT

The common realization of the necessity to reduce the use of mineral sources is promoting the use of alternative fuels. Big efforts are being made to replace petroleum derivatives in the internal combustion engines (ICEs). For this purpose it is mandatory to evaluate the behavior of non-conventional fuels in the ICEs.

The optical diagnostics have proven to be a powerful tool to analyze the processes that take place inside the engine. In particular, 2d imaging in the infrared range can reveal new details about the effect of the fuel properties since this technique is still not very common.

In this work, a comparison between commercial diesel fuel and two non-conventional fuels has been made in an optically accessible diesel engine. The non-conventional fuels are: the first generation biofuel Rapeseed Methyl Ester (RME) and an experimental blend of diesel and a fuel with high glycerol content (HG). Both a CCD visible camera and an infrared camera have been used to record images from the combustion chamber. The infrared range investigated is from 1.5 to 5 μm ; moreover, a band pass filter at 4.2 μm has been used to impress the radiation of the CO_2 molecules while a filter at 3.9 μm has been used to visualize the fuel location in terms of HCs, and the reacting spray by intermediate products of the combustion process. The engine mounts the head of a real Euro5 diesel engine and a Common Rail injection system with solenoid injector. The engine head is placed on an elongated piston and an optical access in the piston provides the bottom view of the combustion chamber. Images are taken by means of a 45° IR-mirror located in the elongated piston. The engine runs in two operating points of the New European Driving Cycle in order to investigate the mixing process in conditions similar to those of the real engine.

The infrared imaging has proven to give important information about the in-cylinder reactions. The pilot injection vaporization and mixing has been evaluated. The interaction between the main injection and the reacting fuel has been analyzed. Finally, CO_2 plumes appear at the end of main injection and they are isolated on the tip of the jets and close to the chamber wall.

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INTRODUCTION

The compression ignition (CI) engine is the most common propeller for civil and commercial transport. In the last years CI engines have been strongly improved to reduce pollutant emissions and fuel consumption. In order to meet these requirements various modifications in the engine hardware have been made and different alternative fuels have been used. In order to reduce the crude oil dependency, the research for renewable fuel sources has led to an increasing use of biodiesel. The first generation biodiesel includes a wide range of methyl ester blends produced from vegetable oils and animal fats through the thermo-chemical process of transesterification [1]. Several studies have been made to evaluate the effects of biodiesel on the performances and exhaust emissions of a CI engine [2, 3, 4]. For example, the lower heating value (LHV) of biodiesel is lower than diesel and this produces less torque related to diesel fuel at fixed injection strategy [5]. Biodiesel could be a cleaner fuel for ICEs compared to the diesel one. Engines fuelled with biofuels emit lower

carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM) [6]. As a result of the increasing biofuel production, also the production of glycerol, which is the main by-product of the transesterification process, is grown. Using the glycerol surplus as alternative fuel in ICEs would be the best solution. Unfortunately, because of its detrimental physical and chemical properties, raw glycerol is not suitable as alternative fuel in ICEs. Studies from literature [7] have proven its potential use as fuel additive. Blends of diesel/biodiesel and oxygenated compounds derived from glycerol etherification can improve engine performance and reduce PM, HC, CO and unregulated aldehydes emission [8]. In particular, blends with ethers of glycerol can improve the low temperature properties for diesel fuel and reduce the viscosity for biodiesel fuel.

Complex technologies are used to monitor the processes involved in the ICEs. Optical diagnostics provide considerable insight for the development of modern engines. While the investigation of the

infrared (IR) spectrum has been performed mainly by means of spectroscopic emission [9, 10], 2d infrared imaging is still not very common. In previous works [11, 12, 13], authors set up an IR camera to analyze the combustion process in an optically accessible diesel engine. The tests pointed out the potential of this technique and the need for further investigations.

The aim of the present work is to make a comparative analysis of the combustion process in a diesel engine fuelled with non-conventional fuels by means of 2d infrared imaging. The non-conventional fuels are: the first generation biofuel Rapeseed Methyl Ester (RME) [14, 15] and an experimental blend of diesel and a fuel with high glycerol content (HG) [16]. For the acquisition of in-cylinder images both a charge coupled device (CCD) visible camera and an IR camera have been used. The infrared range investigated is from 1.5 to 5 μm ; moreover a band pass filter at 4.2 μm has been used to impress the radiation of the CO_2 molecules [17] while a filter at 3.9 μm has been used to visualize the fuel location in terms of HCs and the reacting spray by intermediate products of the combustion process [18]. The optical engine mounts the head of a real Euro5 diesel engine and a Common Rail injection system with solenoid injector. The engine head is placed on an elongated piston and an optical access in the piston provides the bottom view of the combustion chamber. Images are taken by means of a 45° IR-mirror located in the elongated piston. The engine has been run in two operating points of the New European Driving Cycle characterized by a double injection strategy in conditions similar to those of the real engine. The imaging analysis in the infrared range has given important information about the effect of fuel properties on combustion reactions.

EXPERIMENTAL APPARATUS AND PROCEDURES

Optical Engine

The optical single-cylinder engine used for combustion diagnostics was equipped with the combustion system architecture and injection system of a Euro5 compliant four cylinders engine. The single-cylinder engine lay-out is shown in Figure 1. Moreover, the engine specifications are reported in Table 1.

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° fixed IR-visible mirror inside the extended piston. Even if the bowl bottom is flat, the combustion bowl volume and the bowl wall shape were kept the same as the production engine by reducing the bowl bottom distance. Figure 2 shows the original and modified combustion chamber. Since the heat conductivity of sapphire is about 5 times lower than that of aluminum while the one of the quartz is about 100 times lower than the aluminum [19], the window was made of sapphire to minimize the heat release differences between metal and optical engine [20]. 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 filtered and dehumidified. Thanks to the dehumidification, the measure of the air mass flow, depending on the volume flow, the pressure and the temperature, is not affected by the uncertainties

related to the presence of water. Then, the air was heated up to a desired inlet temperature that ensures the same rate of heat release of the metal engine [20, 21]. A reliable measure of the air mass flow before the mixing with the recirculated gases allows calculating the effective recirculation of exhaust gases (EGR) percentage. The engine was also equipped with a Common Rail injection system managed by a fully opened electronic control unit (ECU). The ECU allowed controlling 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. A solenoid driven injector was used, more specifications about the injection system have been reported in Table 2. To analyze the current profile, a Hall-effect sensor was applied to the line of the solenoid of the injection. Moreover, to record the in-cylinder pressure in motored and fired condition, a piezoelectric pressure transducer (AVL GH13P) was set in the glow plug seat of the engine head.

Table 1. Optical engine characteristics.

Engine type	4-stroke single cylinder
Bore	85 mm
Stroke	92 mm
Swept volume	522 cm^3
Combustion bowl	19.7 cm^3
Vol. compression ratio	16.5:1

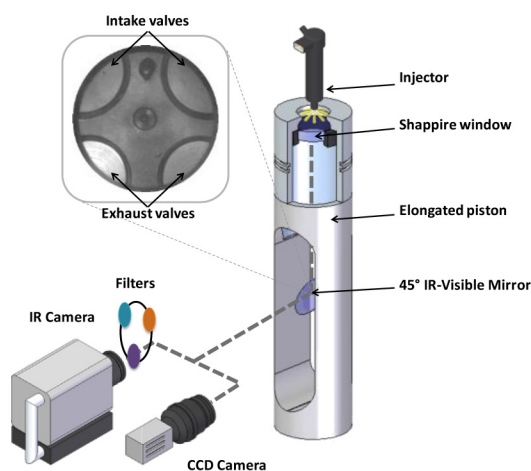


Figure 1. Single-cylinder engine optical setup.

Table 2. Injection system characteristics.

Injection system	Common Rail
Injector type	Solenoid driven
Number of holes	7
Spreading angle of fuel jet axis	148°
Hole diameter [μm]	141

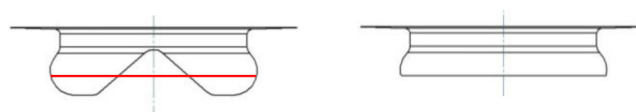


Figure 2. Original (left) and modified (right) geometry of the combustion chamber.

For each operating condition investigated, the cylinder pressure and the signal of the drive injector current were digitized and recorded at 0.1 crank angle degree ($^{\circ}\text{CA}$) 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 indicated mean effective pressure (IMEP). The heat release rate was calculated from the ensemble-averaged pressure data using the first law of thermodynamics and the perfect gas model [22].

Optical Setup

Visible Imaging

In [Figure 1](#), a scheme of the optical setup has been reported. Visible imaging analysis was performed by a charge coupled device (CCD) camera through the 45° mirror. The camera used is the PixelFly VGA COLOR; it has 640×480 pixels (pixel dimensions of $9.9 \times 9.9 \mu\text{m}^2$) and a high sensitivity over a wide visible range. It was used in order to take images during the injection and combustion processes. A visible lens, Nikkor 55 mm f/3.5, was used. Due to speed limitation of CCD camera, only one image was recorded in a given cycle. The size of the images was 460×460 pixels with a resolution of 0.1 mm per pixel. 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 recorded up to the end of visible injection. For the measurement of the spray global quantities, five repetitions were performed. The number of repetitions is limited by the fouling of the sapphire window; however, test performed with a cycle resolved camera have shown a low cycle to cycle variability of the injection process. No lamps were used to record the combustion phase because of the luminosity of the flames. 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 to 0.5°CA of the shaft encoder at 1500 rpm and 2000 rpm, respectively. In order to evaluate the in-cylinder soot for each crank angle, two-color pyrometry has been performed using the software AVL Visioscope. The analysis has been made on color images of the combustion event using the red and green channels of the CCD camera [23].

Infrared Imaging

IR imaging was performed using the FLIR Phoenix fast camera (320×256 pixels) able to detect light in the range 1.5-5 μm . The IR camera had a sensor made of Indium Antimonide and it was equipped with a 25 mm lens, f/2.3. The cycle resolved camera was used at 3003 Hz that corresponds to an angular step of 3°CA and 4°CA , at 1500 rpm and 2000 rpm, respectively. The size of the images was 128×49 pixels with a resolution of 1.1 mm per pixel. Images from IR camera were detected with an exposure time of 10 μs . However, it was necessary to use a Neutral Density filter with 10% attenuation (ND1) to prevent the saturation of the detected images. Moreover, two band pass filters at 3.9 μm and 4.2 μm have been used; their bandwidth is $\pm 150 \text{ nm}$.

The spectral range of the IR camera is quite wide (1.5-5 μm). Several species related to the combustion process emit in this band, e.g. CO , CO_2 , CH , OH , H_2O et al. [18]. Beside the collection of the IR emission in the whole camera range, two band pass filters have been selected to visualize single chemical species. Since the asymmetric stretch vibrational mode of the CO_2 molecule correspond to wavelength 4.2 μm [17], a band pass filter at this wavelength has been used to visualize the in-cylinder distribution of CO_2 . The second band pass filter used is at the wavelength 3.9 μm .

From the chemical point of view, the wavelength 3.9 μm corresponds to the wavenumber 2564 cm^{-1} . This is not characteristic of a particular species; however it is affected by the presence of other species whose signal is centered close to 2564 cm^{-1} . For example, the range $3300\text{-}2500 \text{ cm}^{-1}$ is where acid OH emits (center at 3000 cm^{-1}). The OH peaks due to carboxylic acids (COOH) show a very broad and less intense peak between 2500 and 3500 cm^{-1} . The alkyl C-H has a peak between 3000 and 2800 cm^{-1} . And the aldehyde C-H has two medium intensity peaks on the right hand shoulder of the alkyl C-H's (2850 and 2750 cm^{-1}) [18]. Hence, the band pass filter at 3.9 μm has been used to visualize HCs and the intermediate products of the combustion reactions.

Fuels

Diesel fuel has been used as reference fuel; in addition, two non-conventional fuels have been tested to analyze the advantages of using alternative fuel in a modern diesel engine. The first non-conventional fuel is pure Rapeseed Methyl Ester (RME), a first generation biofuel derived from edible oil. The second one, denoted as HG, is a blend of commercial diesel fuel (80% v/v) and an experimental fuel with high glycerol content (20% v/v) obtained from etherification of glycerol with tert-butyl alcohol and isobutylene [24]. Properties of the tested fuels have been reported in [Table 3](#).

Engine Operating Conditions

The data presented in this paper were taken with the optical engine operating in continuous mode. The engine operating conditions investigated were representative of the engine behavior installed on a D-class vehicle during the New European Driving Cycle (NEDC). They corresponded to the calibration points at 1500 rpm at 2 bar of brake mean effective pressure (BMEP) and 2000 rpm at 5 bar of BMEP; hereafter referred to as “1500 $\times$ 2” and “2000 $\times$ 5”, respectively. A collection of engine load/speed values recorded during the NEDC has been reported in [Figure 3](#). The engine operating conditions selected for this work correspond to the red dots. In motored conditions, temperature and density at Top Dead Center (TDC) were estimated assuming the pressure at the bottom dead center (BDC) equal to the intake manifold pressure and a polytropic transformation with a coefficient of 1.36 [22]. This value was chosen after a validation procedure considering a sample of motored data at different intake pressures and engine speeds. Starting from the intake pressure, the pressure at the TDC was calculated using the polytropic transformation. The calculated value was compared to the one measured by the pressure transducer. Using the exponent 1.36, errors were inside the range $\pm 3\%$. Finally, since no significant differences in the calculated ROHR curve were observed across the TDC using

lower values of the polytropic exponent, the exponent value 1.36 was adopted for the calculation of the temperature and density at the TDC. The absolute intake air pressure and temperature, the in-cylinder temperature and density at the TDC in motored conditions have been reported in Table 4. The injection strategies consisted of two events per cycle, pilot and main; the injection pressure for each engine point has been reported in Table 4. Since the engine is operated in continuous mode, true recirculation of exhaust gases (EGR) was performed using the hot gases of each combustion cycle. The EGR is used in order to reduce the emission of nitrogen oxides (NO_x); values used for each engine operating point have been reported in Table 4.

Figure 4 reports the combustion signals of the two selected operating points (1500×2 and 2000×5) for the reference fuel. In particular, the pressure signal, the calculated rate of heat release (ROHR), and the injector current have been reported for the optical engine (solid line with symbols) and the real engine (dashed line). The current signals are the same for both engines since the same injection strategies have been used.

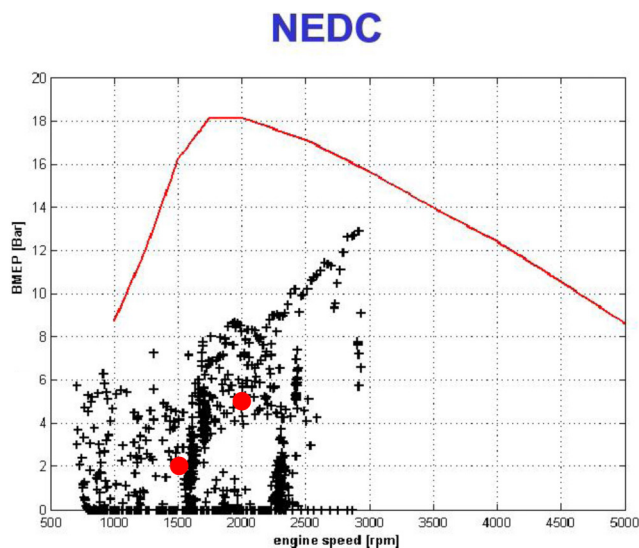


Figure 3. Load-speed diagram of the NEDC. The red line is the engine operating limit. The red dots correspond to the two engine operating condition investigated.

The injection strategies have been reported in Table 5. It reports also the effective start/end of injection detected from the visible images. The delay between the start of injection (SOI) from the ECU and the effective SOI has been calculated and it is around 300 μs for all the injections and engine conditions. In both operating points, the pressure values at the top dead center (TDC) in the optical engine are close to the real engine ones. This fit has been obtained using higher intake pressures in the optical engine to compensate for its blow-by losses and lower compression ratio (CR). The effect of higher intake pressure is evident in Figure 4; the pressure trace of the optical engine is the highest during the compression stroke. The low CR is also responsible for the low peak pressure in the optical engine. The main target was to overlap the ROHR trace in order to reproduce the same combustion behavior [20, 25]. Figure 4 shows a good fit of the ROHR curves of real and optical engines. By managing the intake

temperatures, it was possible to match the SOC of the optical engine with the real engine one. The combustion of the pilot injection releases a small quantity of energy; it generates a local peak with low intensity. On the other hand, the combustion of the main injection releases the main energy and it is characterized by a fast increase of heat release typical of premixed combustion. At 1500×2, the slope of the ROHR trace is the same for optical and real engine and the two peaks overlap; this indicates that the same combustion rate has been reached. On the contrary, at 2000×5, the peak of the ROHR is reached earlier in the optical engine denoting a faster combustion. Increasing the engine speed, the combustion frequency increases, and hence the in-cylinder temperature increases too. For the optical engine, the temperature is higher than in the real engine due to lower heat conductivity of optical parts, and this promotes combustion reactions. Finally, optical engine demonstrated to reproduce the combustion cycle of the real engine in a reliable way. And this is mandatory for the analysis of in-cylinder processes by means of optical diagnostics.

Table 3. Fuel properties.

Feature/Method	Units	Commercial Diesel	HG	RME
Density @ 15 °C (EN ISO 12185)	[kg/m ³]	829	838	882
Cetane Number (EN ISO 5165)	[-]	51.8	46.5	53.1
Low Heating Value (ASTM D3338)	[MJ/kg]	42.4	40.3	37.4
Flash Point (ASTM D93/IP 34/ EN ISO 2719)	[°C]	72	52	-
Kinematic Viscosity 40°C (ASTM D445)	[mm ² /s]	2.7	3.3	4.5
Cloud Point (ASTM D2500)	[°C]	-2.2	-2	-2/1
Cold Filter Plugging Point (EN 116)	[°C]	-19	-18	-10
Lubricity 60°C (ISO 12156-1)	[μm]	382	235	119
Distillation (ASTM D86)	IBP [°C]	159	146	316
	10%vol. [°C]	194	196	347
	50%vol. [°C]	268	255	350
	90%vol. [°C]	333	308	353
	95%vol. [°C]	350	321	356
	FBP [°C]	361	330	365
Carbon (ASTM D5991)	[mol%]	~85.5	~79.9	~77.8
Hydrogen (ASTM D5991)	[mol%]	~13.5	~11.9	~11.4
Oxygen (ASTM D5991)	[mol%]	~1.4	~8.2	~10.4

Table 4. Parameters of the engine operating conditions.

Operating Condition	Absolute intake air pressure [bar]	Intake air temperature [°C]	Temp @ TDC [°C]	Density @ TDC [kg/m ³]	Injection pressure [bar]	EGR [%]
1500×2	1.25	48	551	18.6	615	58
2000×5	1.42	60	581	20.3	891	29

Table 5. Injection strategies.

Operating Condition	SOI Pilot [°CA]	ET Pilot [μs]	SOI Main [°CA]	ET Main [μs]	Start/End of Pilot injection from visible images [°CA]	Start/End of Main injection from visible images [°CA]
1500x2	-15.8	290	-5.8	545	-13/-11	-3.5/2
2000x5	-18.6	257	-2.4	560	-15/-12.5	1.5/9

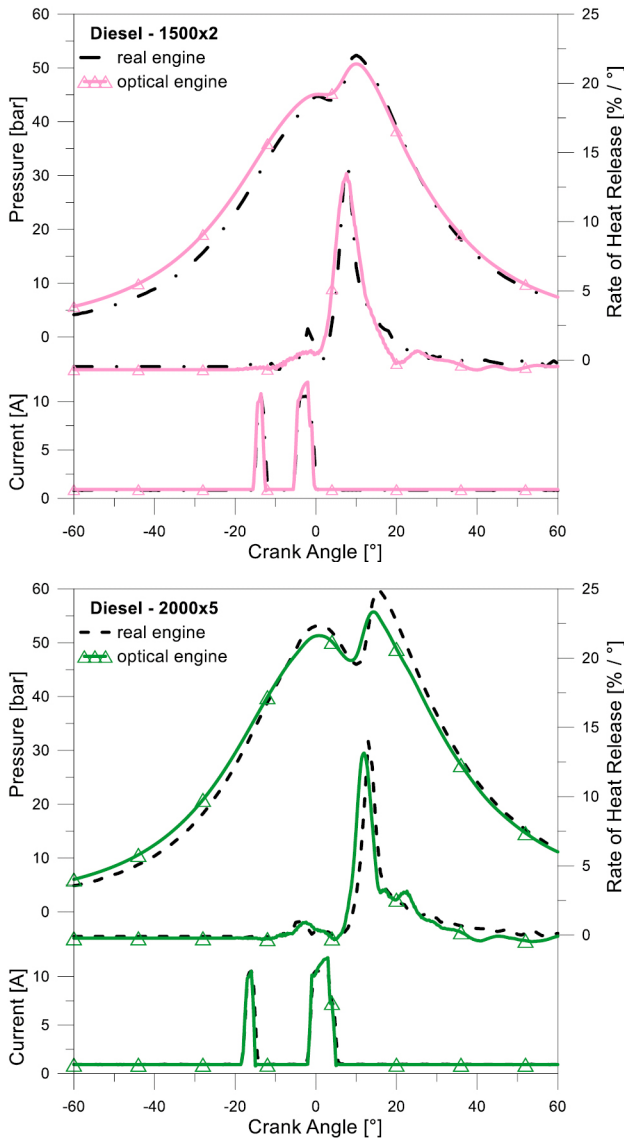


Figure 4. In-cylinder pressure, ROHR and injector current for diesel fuel at 1500x2 and 2000x5 in both real and optical engines.

RESULTS AND DISCUSSION

2d imaging in the visible and infrared spectrum has been performed in an optical diesel engine fed with commercial diesel fuel and two non-conventional fuels: RME and HG, a blend of diesel and a high glycerol content fuel. The work is divided in four sections: first, only commercial diesel is used and a comparison between two engine operating points is carried out to highlight the advantages of infrared imaging. Then, the results of the infrared imaging obtained with RME and HG are presented separately. Finally, the three fuels are compared in terms of infrared emission curves and cyclic variation.

1. Characterization of Diesel Fuel

The analysis of in-cylinder signals is useful to measure the combustion parameters. Analyzing the ROHR curve in Figure 4, the start of combustion (SOC) has been detected as the instant when the energy release begins to exceed the energy losses due to the fuel evaporating process [22]. At 1500x2, the SOC of the pilot and main injections occur at -10°CA and 0.5°CA, respectively. At 2000x5, they occur at -9°CA and 5°CA, respectively. On the other hand, optical engines give the advantage to obtain additional information about the combustion process through the direct visualization of the phenomena that take place inside the cylinder. 2d imaging during the injection and combustion phases has been performed in both the engine conditions of Figure 4. Moreover, two-color pyrometry technique has been applied to obtain the qualitative soot concentration. Figure 5 shows visible and processed images of the injection and combustion phases at 1500x2 and 2000x5 for diesel fuel. During the pilot injection, two lamps have been used to light the fuel jets. At 1500x2, the first luminous flames have been detected at the TDC (indicated as Start of visible combustion in Figure 5); since the main SOC occurs later, the flames are due to the pilot combustion that started at -10°CA. Hence, in the visible range it is not possible to detect the reactions that take place immediately after the SOC of the pilot. The same happens at 2000x5 where the first luminous flames can be detected at the TDC while the SOC of the pilot is at -9°CA. In this case, it is more evident that the flames are not due to the SOC of the main injection that occurs 5°CA later. The main combustion at 1500x2 is characterized by a two phases. In the first, the flames are localized on the jet axis; the fuel burns with very intense luminous emission and soot production, this phase is evident at 8°CA. Then, the flames distribute along the chamber wall, where additional fuel is supposed to be available for the combustion (from 16°CA to 20°CA). The luminous flames emission is visible until 40°CA (indicated as End of visible combustion), after this point no light is detectable from the combustion chamber. In the processed images, sharp gradients of the soot concentration have been detected because almost the whole area where soot appears is characterized by the maximum value of soot concentration (105 a.u.). Therefore, images with lower soot amount will be characterized by small soot regions. To reduce the local soot concentration, a more efficient mixing with the available air is required. Combustion behavior of the main injection at 2000x5 is different from the previous case because it is characterized by on-wall combustion with the formation of a hole in the center of the bowl. The combustion has a longer angular duration due to the higher engine speed. The last crank angle where luminous flames are still visible is 55°CA. Soot formation images are helpful to highlight the critical issues of this process. The ring shape observed in the visible images is well defined in the processed images (20°CA). Large soot regions are detectable and, as the previous case, the soot value is the maximum in almost the whole area. Due to the longer combustion duration, regions with low soot concentration can be detected in the expansion stroke up to 40°CA. During this phase, the oxygen in the cylinder reduces part of the soot previously formed. To overcome the limitations of optical diagnostic in the visible range, infrared imaging has been performed in the same engine conditions and a comparison of experimental results has been carried out.