IR analysis of diesel combustion in a transparent Euro5 diesel engine

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Abstract

Infrared (IR) imaging (in the range 1.5-5 micron) in a transparent Common Rail Euro 5 diesel engine was performed in order to study the development of injection and combustion phases. In the same engine operating condition, IR imaging with a filter at 4.2 micron was performed in order to analyse the spatial and temporal distribution of CO₂ inside the cylinder after the main combustion event. The engine is an elongated piston provided with the head of a real diesel engine. A window was set in the bottom of the combustion chamber. This feature provides a full view into the cylinder during both the expansion and exhaust strokes of the engine. IR images were detected by means of cycle resolved FLIR camera.

1. Introduction

Modern smart engines continuously adjust combustion to give optimum output of power, fuel economy, and emissions. This is done with programmed electronic controls using information input from sensors located in appropriate engine, intake, and exhaust locations. Among other things, these sensors measure throttle position, throttle rate of change, intake manifold pressure, atmospheric pressure, coolant temperature, intake temperature, EGR valve position, crank angle, O₂ and CO in the exhaust, knock, etc. The controlled variables include ignition timing, valve timing, fuel injection duration, exhaust air pump actuation, air-fuel ratio, transmission shifting, turning on of warning lights, repair diagnostic recording, reprogramming of computer, etc [1].

Methods used by these sensors are mechanical, thermal, electronic, optical, chemical, and combinations of these. In particular, optical sensors based on the detection of the infrared thermal emission by the several in-cylinder components of a GDI engine were used. They monitored the temperature of the exhaust valve and the temperature surface of the piston that are two critical parameters of the new turbocharged small engines [2]. Moreover, IR measurements were performed in a simulated diesel environment with precombustion temperatures ranging from 700 to 950 K and pressures of approximately 3 MPa. The fuel was normal dodecane. Measurements were obtained at locations ranging from 5 mm from the spray tip to 35 mm from the tip. Soot was monitored using infrared emission between 6 and 12 µm with a custom-designed infrared spectrometer, and 9.4 µm was found to be an appropriate wavelength for quantitative measurements of soot mass in the spray. [3]

IR imaging was also performed to analyze the flame in a burner and to investigate the combustion process in the near-infrared range. The study had the aim to characterize the flame morphology and compute geometric and densitometric features useful to describe the combustion dynamics [4].
In this study the IR imaging was applied to analyze the premixed combustion in CR transparent diesel engine. In particular, an optically accessible diesel engine by means of the piston crown window and a 45° mirror was used. IR images cycle resolved was detected and compared with the images acquired in the visible range. Moreover, IR imaging with a filter at 4.2 mm was used to analyze the evolution of CO₂ during the whole combustion process.

2. Experimental setup and operating condition

The transparent 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 1. Moreover, the engine specifications are reported in Table 1.

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 was set in the glow plug seat of the engine head. For each operating condition investigated, the cylinder pressure and the drive injector current were digitalized and recorded at 0.1 crank angle degree (CAD) increments and ensemble-averaged over 150 consecutive combustion cycles.

In a previous paper, digital imaging analysis was performed by a CCD camera through the 45° mirror. The CCD camera with 640 x 480 pixels and a high sensitivity over a wide visible range was used in order to acquire the visible combustion. Through an appropriate filter, selecting fixed wavelengths in the visible range, it was possible to determine the soot temperature and concentration by means of the two-colour pyrometry method [5]. In the present investigation, IR imaging was performed using a Fast InfraRed Camera in the range 1.5-5 μm. The IR camera was able to reach a maximum recording speed up to 30 kHz and had with a sensor 320x256 pixels. It was used in order to analyze the flame fluctuations of the
natural flame emission. Moreover, by means of a filter at 4.2 μm, the CO₂ spatial distribution and temporal evolution during the combustion cycle. The sensor is made by Indium Antimonide (InSb). The synchronization of the CCD and IR cameras with the engine was obtained by a delay unit connected with the signal coming from the engine shaft encoder. Images were acquired each 6° crank angle in a single cycle.

The engine operating condition investigated was representative of the engine behaviour on new European driving cycle (NEDC) when installed on a D-class vehicle and its specifications are reported in Table 3. The data presented in this paper were taken at an engine speed of 1500 rpm using commercial diesel fuel.

### Table 3 engine operating condition

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3. Results

In Fig. 2 the history of the combustion pressure and drive injector current at 1500 rpm are reported. Moreover, the rate of heat release curve is computed from the ensemble-averaged pressure data using the typical first law and the perfect gas analysis [6]. Two injections per cycle, pilot and main, are well discernible on the drive injector current signal. Moreover, the main combustion event occurs after the top dead center (TDC corresponding to the 0° crank angle) as noted on the in-cylinder pressure signal. Finally, the start of combustion (SOC) is determined by the analysis of the heat release rate trace. From a general point of view the start of combustion was detected when the energy release begins to exceed the energy losses due to the fuel evaporating process. The ROHR curve shows two well resolvable peaks due to the burning of the two injections performed. The SOC of the pilot injection occurred at 8° before top dead centre (BTDC) while the SOC of main injection occurred at 1° after top dead centre (ATDC). At the start of main combustion a fast rate due to the exothermic reactions of combustion is observed. At 7° ATDC, the peak of heat release curve is observed. The combustion occurs
mainly in a premixed mode and its duration is considerably short with respect to a previous CR diesel standard combustion [7].

In Fig. 3, the images of the injection and combustion of the pilot are reported both in the infrared and visible range. IR images were detected each 6° crank angle in the same combustion cycle. The first image, detected at 18° before top dead center (BTDC), shows the head of the engine; in particular, the four valves, the injector nozzle in the center and the pressure transducer in the glow plug seat between the two intake ports are well distinguishable. At 12° BTDC the first droplets of fuel due to the start of pilot injection are observed. The previous images in the visible were ligthed by means of the external alogen lamps, on the other hand, no lamps were used for the IR images. At 6° BTDC, in the visible image the first luminous emission due to the start of pilot combustion is observed. On the other hand, more information can be deducted analysing the IR images; in particular, all the seven jets of the pilot injection are well resolvable because of the IR camera is able to detect the different amount of energy produced by the vaporization of the fuel. Moreover, the jets are affected from the swirl motion of the air entering in the bowl. However, the fuel doesn’t mix well with the air because the motion of the air decelerates during the movement of the piston toward the TDC.

In Fig. 4, infrared (up) and visible (bottom) images of the main injection and combustion are presented.
In Fig. 4 the images of the main injection and combustion are reported. In the IR image at TDC the jets of main injection can be observed together with the combustion of fuel previously delivered in the combustion chamber. At the tip of the jet near the bowl wall, it is also possible to observe the deviation of the burning fuel in the swirl direction. At 6° after top dead center (ATDC), the combustion is homogeneously distributed along the jet. These information are better detailed with respect to those from the corresponding visible images. IR images from 12° up to 30° ATDC show the highest intensity close to the bowl wall and the hot gases emission in the center of the combustion chamber. The burning gas had higher energy with respect to the head of the engine and, for this reason, it is not possible to recognize the valves and the injector nozzle. On the other hand the visible images show only the sooting flames as they developed during the combustion.

In Fig. 5, the IR and visible images after the main combustion are reported. They are completely different. While the visible images do not show any flame or other emission intensity, on the other hand, the IR images show a lot of information regarding the burned gas into the cylinder. First of all, the hot burned gas seems well distributed in the volume investigated, with the higher IR emission near the bowl wall that is the hottest surface in the engine due to the main combustion. Moreover, increasing crank angles, the zone at low emitted energy is on the right side of the bowl. Probably in this zone the temperature decreases earlier than on the left side.

In Fig. 6, the normalized intensities emitted in the 1.5-5 μm range and at 4.2 μm versus a complete combustion cycle are reported. In particular, 4.2 μm is a characteristic emission wavelength of the CO2 [8]. In figure, the top and bottom dead center (TDC and BDC) as well as the arrows that indicate the piston movement are signed. Finally, the intake and exhaust valves opening are showed. During the first phase, when the piston moves from the TDC to the BDC, the intake valves are open and the fresh air mixed with the exhaust gas recirculation enters into the engine and fills the volume. The temperature decreases into the cylinder and thus a reduction of the IR intensity is observed. Moreover, since the exhaust gas brings CO2 in the intake, then its emission increases during this phase. After the BDC, the intake valves close, and the in-cylinder pressure and temperature increase. The IR intensity increases, while the CO2 has different behaviour. In the IR curve it’s possible to observe a minimum in the energy detected due to the evaporation of the pilot injection, and then the combustion of main injection produces the maximum energy release in the infrared range. On the CO2 curve, the maximum of the intensity is detected with a shift of 30° crank angle, after the intensity remains quite high during the expansion phase up to 180° when the exhaust valves open.
**Fig. 6** Normalized emission intensities of IR and CO$_2$ images.

### 4. Conclusion

IR cycle resolved imaging into a Common Rail diesel engine was performed. IR images were detected also with a filter at 4.2 $\mu$m in order to follow the CO$_2$ evolution during the whole combustion cycle. The detection of IR emission has revealed a good tool to analyze the different phase of combustion. The energy absorbed during the fuel evaporation and the energy release by the burning gas after the end of visible combustion were investigated. Moreover, CO$_2$ was detected during the intake phase due to the ricirculation of the exhaust gas and its highest intensity was measured 30° crank angles later than the peak of the IR one.

### 5. Acknowledgments

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### 6. References