Infrared Imaging in Internal Combustion Engines: Advanced Techniques for Vapor Phase Visualization and CO₂ Detection

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Abstract. As the technical level of modern engines increases to fulfill the emissions requirements, the techniques used to investigate in-cylinder phenomena need to update and to improve. Optical diagnostics provide precious information about the injection and combustion processes. To visualize the fuel vapor phase, a light source with specific wavelength and energy is needed; multiple optical accesses and additional optical components are required; the techniques are susceptible to the directionality of the light source and to the fuel composition. Recently, Infrared imaging has been used to overcome some of the drawbacks of well-known optical techniques. A peculiarity of infrared imaging is the ability to detect the energy emitted by a body as electromagnetic waves, from 0.76 to 1000 μm wavelength. This work illustrates the application of infrared imaging in a compression ignition engine for the analysis of the injection and combustion processes. The diesel fuel vapor penetration is experimentally measured and then compared to a 1d model of spray injection. Another application of IR can be the evaluation of the CO₂ in the cylinder, that is a key species in the combustion process, the wavelength of 4.2 μm, relative to the asymmetric stretch of this molecule, is investigated to follow its distribution within the cylinder for different, conventional and non-conventional combustion modes.

1. Introduction
Among the phenomena that take place in a compression ignition engine some are the key processes for the formation of pollutants that creates the exhaust emissions, that are subjected to strict regulations [1, 2]. Before the combustion occurs, an inadequate air-fuel mixing can contribute to generate some pollutant precursors. The characterization of the fuel liquid and vapor phase can be obtained by optical diagnostics such as shadowgraph, Schlieren, laser-induced fluorescence (LIF) [3, 4, 5]. These techniques are generally very complex to apply. They need a light source that in some cases must be a laser beam at a specified wavelength and energy. Moreover, additional optical accesses or fuels with specific properties must be used [5]. Additionally, limited engine operating conditions can be tested.

The investigation of the infrared spectrum can be an interesting field to explore, taking advantage of the ability of each body to emit energy in the form of electromagnetic waves in the infrared (IR) band, from 0.76 to 1000 μm. Moreover, infrared diagnostics can be included among the passive optical diagnostics since the target not need to be excited. An infrared detector can detect the natural emission of the phenomena to investigate. 2d infrared imaging is not commonly used for the investigation of high-speed phenomena in the internal combustion engine. Previous works from the authors [6, 7, 8] showed the application of this technique to different aspects of the engine functioning as thermal management of the engine components, analysis of biofuels and alternative injection strategies performance, and the...
assessment of dual fuel combustion mode. In [7], optical diagnostics in the infrared spectrum between 3 – 5 µm was applied to measure the temperature of the piston head, resolved in the cycle, to evaluate the heat transfer coefficient of the inner piston surface to the hot gas. The application of thermal imaging was applied for the first time to a working piston in continuous firing mode in a research compression ignition engine. Infrared imaging was used to investigate the vapor fuel distribution of conventional diesel fuel and different blends of diesel and biofuel Rapeseed Methyl Ester [6]. The insight given by infrared imaging consisted in the availability of vapor fuel penetration data used to tune a 1d model of biofuel injection. Similarly, in [8], infrared diagnostics was used to study a novel injection strategy for the shaping of the injection profile. Also, alternative, low-emission combustion strategies as dual fuel mode were investigated. Reactivity controlled compression ignition using diesel as high reactivity fuel and a blend of diesel and gasoline (a.k.a. dieseline) as low reactivity fuel was studied in [9] highlighting the possibility to get evidence on the low-temperature reactions, not detectable in the visible spectrum. The easy application of infrared diagnostics for conventional and un-conventional combustion strategies and fuels highlights the flexibility of this technique and the potential that it can have to optimize the combustion process of the new generation of internal combustion engines.

This work aims to give a quick overview of the detectable species and the processes that can be investigated in a research compression ignition engine using infrared imaging at different wavelengths. The injection process is examined in conventional diesel combustion (CDC) mode; the experimental fuel vapor penetration is measured and compared to the results of a 1d model of spray injection. Moreover, the combustion process was investigated following the CO2, that is a key species. Measurements are carried out at the wavelength of 4.2 µm, relative to the asymmetric stretch of this molecule. Its distribution is followed within the cylinder for two different combustion strategies, the CDC and the dual fuel combustion and relevant results are obtained.

2. Experimental setup

2.1. Optical engine

The optical compression ignition single-cylinder engine used in this work is equipped with the combustion system architecture and injection system of a modern four-cylinder compression ignition engine for passenger cars. The engine layout is shown in figure 1. It has a bore of 85 mm, a stroke of 92 mm, and a swept volume of 522 cm³. The volumetric compression ratio is 16.5:1. The optical engine is equipped with a conventionally extended piston with a piston crown window of 46 mm diameter which provides a full view of the combustion bowl by locating an appropriate 45° fixed infrared-visible mirror inside the extended piston. Even if the bowl bottom is flat, combustion bowl volume and wall shape are kept the same as the ones in the production engine by reducing the bowl bottom distance. The window is 12 mm thick and is made of sapphire, material that has good transmission properties from the ultraviolet to the infrared band [10]. To match the in-cylinder conditions of the multi-cylinder engine tests, an external air compressor is used to supply pressurized intake air, that is filtered and dehumidified, then heated up to the desired inlet temperature. The engine is equipped with a Common Rail injection system managed by a fully opened electronic control unit. A solenoid driven injector with 7 holes of 0.141 mm diameter is used. For dual fuel combustion, a gasoline injector with 10 holes is installed in the intake port and connected to an automotive electric pump. To record the in-cylinder pressure in motored and fired conditions, a piezoelectric pressure transducer is set in the glow plug seat of the engine head.

The data presented are obtained with the engine operating in continuous mode. The investigated engine operating conditions are representative of the engine behavior on the Worldwide Harmonized Light Vehicles Test Cycle when installed on a D-class vehicle. The engine speed is 1500 with 2 bar of brake mean effective pressure (BMEP). The analysis is first made for the CDC strategy, characterized by two direct-injection events of long duration. Then, only for the CO2 visualization, an additional combustion strategy in dual fuel mode is performed. This condition is characterized by low flame luminosity; therefore, it is interesting to visualize the burned gas in the infrared whereas poor information can be obtained from the visible flame visualization.
2.2. Optical diagnostics

2.2.1. Visible imaging
A high-speed complementary metal-oxide semiconductor camera is used to detect the images of the liquid spray and sooting flames in the combustion chamber (Figure 1). The camera has 1024 x 1024 pixels and high sensitivity over a wide visible range (400-900 nm). It is equipped with a visible lens of 50 mm focal length. Two halogen continuous lamps light the jets in the bowl via the 45° mirror for the imaging of the injection phase. Images of 256 x 256 pixels are recorded at 30000 fps in each combustion cycle. An exposure time of 32 µs and f-stop 1.8 is used for the analysis of the injection process. Images of 128 x 128 pixels, 10000 fps, 10 µs of exposure time and f-stop 2.8 are taken for the combustion process. To carry out a statistical analysis of the spray, ten repetitions are recorded and elaborated. The number of repetitions is limited by the fouling of the sapphire window.

2.2.2. Infrared imaging
Thermal imaging is performed using a fast infrared (IR) camera (320 x 256 pixels) working in the range 3.0-5.5 µm (Figure 1). The IR camera has a sensor made of Indium Antimonide and it is equipped with a 50 mm lens that works in the range 3.0-5.0 µm. As reported in figure 2, the absorption of carbon-hydrogen (C-H) single bonds can be detected at about 3.4 µm while the CO₂ molecule asymmetric stretch absorbs at 4.2 µm [11, 12]. 3.9 µm is a wavelength where there is no absorption in the infrared. In this work, it is used to have information about background radiation that could affect the signal of the other band-pass filters. The wavelength at 3.4 µm is used as a diagnostic for fuel vapor detection [11, 12] and the one at 4.2 µm for CO₂ detection [12]. For the CDC strategy, full image resolution is selected to get the best image quality. Images are not resolved in the cycle, the acquisition frequency is 50 Hz, then, one image per cycle is recorded with a step of 0.5°C.A. The exposure time is 10 µs. An external delay unit, connected to the engine crankshaft, triggered the acquisition at each cycle. For the dual fuel combustion strategy, the detection of the CO₂ is performed using an image resolution of 64x72 pixels and an acquisition frequency of 10000 fps to get cycle resolved images. The exposure time is 66 µs.
3. 1d model of spray injection
For a deep understanding of the infrared measurements and to get more insights on the injection process, the mono-dimensional (1d) model developed by Musculus and Kattke in [13] and modified by the authors [11] is used. It consists of a 1d array of discrete control volumes in the axial direction of the jet, where mass and momentum transport are solved numerically for each control volume. The model is able to calculate the fuel liquid and vapor penetration assuming the hypothesis of mixing-limited vaporization [14]. The penetration of the liquid-phase is identified as the position from the nozzle where the fuel-to-air (F/A) ratio reaches the critical equivalence ratio for the thermodynamic equilibrium. The procedure for the determination of this value is reported in detail in [15]. In this paper, a limited domain for the simulation of the interactions between the fuel and the combustion chamber wall is set. The experimentally measured rate of injection is used to reproduce the effective fuel mass delivery in the cylinder. Finally, in-cylinder properties as pressure, density, and temperature are varied over time to consider the effect of the piston movement and the volume variation over time.

4. Results and discussion
Infrared imaging is applied for the first time in an optically accessible compression ignition engine to detect both the vapor phase of the directly injected fuels and the CO\(_2\) produced by the combustion reactions. Conventional diesel combustion and alternative, low-emission dual fuel combustion modes are investigated. To understand the advantage of the infrared imaging compared to the visible diagnostics, two images of the cylinder head via the transparent piston window are reported in figure 3. They are recorded using a visible camera and both refer to the same time, crank angle degree. The one on the left is taken with the lamps on; while, the one on the right is taken without light sources. The first image shows the seven liquid fuel jets that move from the injector, in the center, toward the chamber wall. The valves and the pressure transducer (center-top side) are also visible. On the other side, the second image is completely dark because of the lack of self-luminosity of the investigated objects, which are the fuel jets. This difference between the two images highlights the limits of the visible imaging, that cannot be applied without a light source; moreover, it can detect only the fuel liquid phase.
To overcome these limitations, infrared imaging is performed at selected wavelengths. Figure 4a reports images of the injection process in the visible spectrum and in the infrared at 3.4 µm and 3.9 µm, at two characteristics crank angles. The images in the infrared are taken with the light off. The visible image at -10.5°CA shows the fuel liquid jets moving from the injector holes, in the center of the combustion chamber, to the periphery. At the same time, the image in the infrared taken with the band-pass filter at 3.4 µm shows the fuel jets having a longer and wider extension because it can detect also the fuel vapor that surrounds the liquid jets. Gradients of fuel concentration can be observed from the core of the jet to the boundaries. The signal at 3.9 µm, last row, is affected by noise; likely from the species that emit at the close wavelengths. This is particularly visible in the combustion chamber periphery. Concerning the fuel jets, their shape is similar to those of the visible image and no fuel concentration gradients can be observed. In the other investigated crank angle, -8°CA, the injection process is finished and liquid fuel is no longer detectable from the visible image. Conversely, the infrared image at 3.4 µm is still able to impress the fuel that is vaporized and is spreading in the combustion chamber. The jets have a wrinkled contour because of the air entrainment. Moreover, the contours have lower intensity (refer to the color bar on the side) because of the lower fuel concentration after the mixing with the air. The image at 3.9 µm is strongly affected by noise and no particular observations can be made. To further understand the information provided by infrared imaging. The experimental results have been coupled to the 1d model of fuel spray presented in the previous section [16]. The jets penetrations are measured from the images in the three optical configurations. The curves are reported in figure 4b with circle symbols. At the same time, the model of spray injection is run to simulate the fuel liquid and vapor penetrations, solid lines in the figure. The comparison of the model and experimental results shows that the curves of penetration of the jets in the visible spectrum and at 3.9 µm fit the fuel liquid penetration curve. While the curve of the images at 3.4 µm matches the fuel vapor penetration curve. This comparison supports the ability of the infrared imaging at 3.4 µm to follow the evolution of the vapor fuel. The resemblance between the data of visible, 3.9 µm wavelength and model liquid penetration suggests using this infrared wavelength as a tracer of liquid fuel working in the infrared spectrum.

![Figure 4](image-url)
Concerning the combustion process, CO\(_2\) is the main product of combustion and then it is used as an indicator of combustion efficiency. The detection of CO\(_2\) directly inside the cylinder is useful for combustion optimization. Infrared imaging at 4.2 µm is performed to detect the CO\(_2\) molecules during both conventional diesel and dual fuel combustion. Figure 5 reports a collection of the most significant images recorded in the infrared at 4.2 µm during the conventional diesel combustion (CDC) mode. This strategy, as seen in the injection images of figure 4a, is characterized by long injection events that deliver the fuel from the center towards the combustion chamber periphery. Here, there is the highest fuel concentration at the end of the injection process [6]. The flames in the CDC are generally located along the jets axes and occupy the whole chamber. At -5°CA, the CO\(_2\) detected in the center of the image is likely ascribed to the recirculated exhaust gas that emits because of the high in-cylinder pressure. Then, at 2°CA, the first combustion reactions take place, the image shows some isolated high-intensity areas close to the chamber periphery. This indicates the formation of CO\(_2\) from the reaction of air and fuel. Moving to the image at 5°CA, the isolated spots turn into well-defined, big areas. They correspond to the reaction zones of the seven fuel jets; they are indeed placed at the end of the jet axes. The small differences of infrared intensity between the seven areas are due to non-homogeneous air-fuel mixing. As the combustion process proceeds, the seven separate areas expand and get in contact (7°CA). At this time, gradients of CO\(_2\) concentration can be appreciated inside them. Moreover, some weaker signal is also collected from the center of the combustion chamber, where the combustion reactions are now moving because of fuel availability. The last part of the injected fuel is subjected to low injection pressure and then penetrates less in the combustion chamber, remaining close to the injector tip when the combustion reactions are already started. Images at 10°CA and 14.5°CA show the formation of a single, high-intensity ring. The CO\(_2\) that formed during the combustion process in the CDC mode is mainly located on the edge of the bowl and moves according to the swirl motion.

**Figure 5.** Infrared images of the combustion process at 4.2 µm, for conventional diesel combustion.

To develop alternative, low-emission combustion strategies, it is of interest to compare the results relative to the CO\(_2\) emission of CDC mode to the ones of dual fuel combustion. Especially because of the highly premixed combustion evolution of this strategy and the low flame luminosity [17]. Therefore, a condition with a port fuel injection of gasoline and a small direct injection of diesel is selected as previously reported in the paper. The engine aspires a mixture of fresh air, recirculated exhaust gas, and vaporized gasoline. This mixture is compressed and ignited by the small quantity of diesel fuel that auto-ignites because of its high reactivity (high cetane number). This type of combustion is characterized by a well-distributed, low reactivity fuel that burns after the high reactivity fuel has found the proper condition for the auto-ignition. The areas involved by the combustion reactions are not limited to the jets axes locations but to the whole combustion chamber. Figure 6 reports a selection of the most relevant
images of the combustion process in the visible and infrared spectra, the band-pass filter at 4.2 µm is used in the infrared. In the visible, weak luminous spots can be observed. They indicate the presence of premixed fuel in the cylinder, even if they are not well-distribute in the whole available volume because of airflow motions and direct injection asymmetry. The strongest combustion signal is at 13.1°CA, then, only a few isolated flame spots can be detected. No signal is available at 49.1°CA. This kind of combustion is indicative of low soot production [18]. Infrared imaging is performed because it can provide more information about this process. At 13.1°CA, the formation of CO2 clouds in the combustion chamber periphery can be observed. This location is where the fuel arrives at the end of the injection process, mixes with the air, and reacts. Differently from the CDC, there is no formation of isolated CO2 clouds because the amount of directly injected fuel that reaches the chamber wall is very low. In the following crank angles, from 31.1°CA to 49.1°CA, CO2 from the hot burned gas is still observable. It fills the whole available volume because of the homogenization of the charge. In these crank angles, it is possible to observe the effect of the movement of the piston on the gas. When the piston moves downwards, the volume in the cylinder increases and the gas moves upside, out of the piston bowl. This flow is caught by infrared imaging as a dark contour. It is visible at 31.1°CA, where it forms and has a wide diameter. Subsequently, the edge of the moving gas is observed to slowly shrink as more gas exits from the piston bowl.

5. Conclusions
The potential of applying infrared imaging in an internal combustion engine is proposed for the first time to analyze the injection and combustion processes in an optically accessible compression ignition engine. Infrared imaging has the advantage of an easy application even for such complex systems; overcoming the limits of the visible imaging that requires a light source. Moreover, it can provide a different kind of information according to the investigated wavelength. The fuel vapor is detected at the wavelength of 3.4 µm; a longer and wider extension of the jets can be observed because of the fuel vapor that surrounds the liquid jets. Gradients of fuel concentration are also observed from the core of the jet to the boundaries. The signal at 3.9 µm is strongly affected by noise; however, it can be used to follow the liquid fuel penetration without switching to a visible camera. A 1d model of spray injection is used to get the fuel liquid and vapor penetrations. The good agreement between experimental (infrared data at 3.4 µm and 3.9 µm) and modeled penetration supports the observation made.
The wavelength of 4.2 μm, relative to the asymmetric stretch of CO₂ molecule, is investigated to follow its distribution within the cylinder. For the CDC, high CO₂ concentration is observed on the chamber periphery in seven separated reacting areas at the end of the jets axes. For the dual fuel combustion, the areas involved by the CO₂ formation are not limited to the jets axes locations but to the whole combustion chamber because of the presence of premixed fuel in the cylinder and low amount of directly injected fuel.

In the later combustion phase/expansion stroke, it is possible to observe the effect of the movement of the piston on the burned gas. Highlighting the movement of the gas out of the piston bowl. The results obtained with the infrared technique, coupled with the well-consolidated visible imaging have allowed to better understand the in-cylinder processes. Moreover, they showed to be of easy application. Therefore, this technique is supposed to be systematically applied for the analysis of the performance of future alternative combustion modes.

6. References

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