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High-speed infrared imaging for analysis of a diesel engine supplied with a premixed methane-air charge

Abstract

Efforts are continuously made for improving internal combustion engines (ICEs) efficiency. Lowering fuel consumption and reducing soot formation are among the challenges being addressed when seeking to improve engine designs. In this work, ICEs characterization was carried out on an elongated single-cylinder transparent diesel engine equipped with the multi-cylinder head of a commercial passenger's car and a common rail injection system. The engine uses a conventionally extended piston where part of the piston's crown is replaced by a sapphire window. In this configuration, a full view of the combustion bowl can be achieved while the engine is in operation by looking at a 45° fixed mirror located in the extended piston axis. Infrared imaging was carried out at 26 kHz, leading to a temporal resolution of about 0.35° crankshaft angle, at 1500 RPM, in the engine's reference frame. The different phases of a combustion cycle, i.e. intake, compression, fuel injection, working stroke and exhaust, were investigated using four different spectral filters (broadband, CO_2 red-spike, through-flame and hydrocarbons). In the experiment, air was replaced by a premixed air-methane charge in order to improve combustion and lower the amount of soot deposits. The results illustrate the potential of high-speed IR imaging as a diagnostic tool for ICEs.

Keywords: High-Speed Infrared Imaging.

1. Introduction

Internal combustion engines (ICEs) are part of everyday life as they are found in most vehicles around the world. Although the market for hybrid and electric cars is undergoing a sustained growth over the past decades, the majority of ICEs are still using diesel as their main fuel. Despite all the efforts made by the manufacturers to improve engines' design, fossil fuel (C_nH_y) combustion in ICEs still produces considerable amounts of soot particles (C(s)) and other pollutants like nitrogen oxides (NO_x) and partially oxidized and/or unburnt hydrocarbons ($C_nO_zH_y$), as shown in Eq.1.

$$C_nH_y + O_2 \rightarrow CO_2 + H_2O + CO + C_{(s)} + NO_x + C_nO_zH_y \qquad (1)$$

Among the strategies used to improve combustion efficiency in compression ignition (CI) engines is the use of multi-injection sequences. In such a case, the use of a pilot injection helps igniting the main fuel injection, resulting in less unburnt hydrocarbons and particulate matters in the exhaust gases. However, this did not solve the problem of the pollutant emission from a CI engine completely. For this reason, one alternative considered by researchers in this field consists in using a dual-fuel configuration engine [1]. In dual fuel CI engines operating with natural gas as primary fuel and a "pilot" amount of liquid Diesel fuel as an ignition source, the gaseous fuel is inducted along with the intake air and is compressed like in a conventional Diesel engine. The mixture of air and gaseous fuel does not autoignite due to its high autoignition temperature. A small amount of liquid Diesel fuel is injected near the end of the compression stroke to ignite the gaseous mixture. Diesel fuel autoignites and creates ignition sources for the surrounding air–gaseous fuel mixture. The pilot liquid fuel, which is injected by the conventional Diesel injection equipment, normally contributes only a small fraction of the engine power output [2].

Research activities on operating ICEs are very challenging as these fast chemical reactions are taking place in a close vessel in high-temperature and pressure conditions. In addition, diesel fuel is undergoing a rapid phase transition from liquid to gas phase before igniting [3, 4]. For these reasons, having a diagnostic tool allowing investigation under all these constraints represents an important asset. In this work, a modified diesel engine (see Fig. 1) was used in combination with a high-speed infrared camera for investigation of the various cycles of a diesel ICE supplied with a premixed methane-air charge. The various stages, i.e. intake, compression, diesel fuel injection, working stroke and exhaust, were characterized at a frame rate of 26 KHz using different attenuation and spectral filters (broadband, CO_2 red-spike, through-flame and hydrocarbons). The results illustrate the potential of high-speed IR imaging as a diagnostic tool for ICEs.

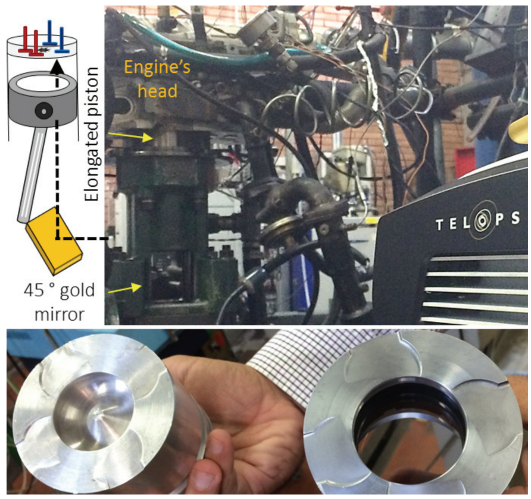

Fig. 1. Infrared imaging carried out on the optical engine

2. Experimental Information

2.1. Optical Engine

The optical engine is a single-cylinder engine equipped with the combustion system architecture and injection system of a commercial 4-cyclinder diesel passenger's car. In order to be able to carry out imaging of the combustion chamber while the engine is operating, part of the piston crown is replaced by a 12-mm thick sapphire window as shown in Fig.1. An elongated piston configuration is also used to accommodate the presence of a 45° gold mirror. The elongated single-cylinder transparent engine has the stroke and bore of 92 mm and 85 mm, respectively, and a compression ratio of 16.5:1. Commercial grade diesel fuel was used for all experiments, using a common rail injection system. The setup is equipped with a fully opened Electronic Control Unit (ECU), which allows full control on diesel fuel injection and timing. In particular, for dual fuel operation, diesel fuel was injected directly into the cylinder under a pressure of 800 bar and at a 6° crank angle before top dead center. It was a small amount with respect to the same operating conditions realized by means of diesel conventional combustion. On the other hand, the production intake manifold of the engine was modified to set an electronic port fuel injector (PFI) generally used in modern engines. It was a production one suitable for gaseous fuel. It was fed by an automotive electrical pump able to reach up to 5 bar of injection pressure and was used with methane fuel. In this work, the engine's revolution was set to 1500 RPM, the air mass flow rate to 33.5 kg/h, the methane mass flow rate to 0.385 kg/h and the Diesel mass flow rate to 0.400 kg/h.

2.2. High-Speed Infrared Imaging

The Telops FAST-IR 2K is a cooled high-performance infrared camera using a 320×256-pixel indium antimonide (InSb) focal plane array (FPA) detector covering a spectral range of (3–5.5) µm. A 50-mm Janos lens was used for all experiments. A 64×64 sub-window of the FPA was used for imaging at 26,000 frames per second. The recording time was set to 1 s. The camera is also equipped with a 4-position internal filter wheel that allows infrared imaging under different conditions [5]. The engine's operation was investigated using a total of 5 different filters: optical density (OD) 1.0, OD 2.0, bandpass 3.80 ±0.18 µm, bandpass 4.35 ±0.18 µm (CO_2 red-spike) and bandpass 3.42 ±0.35 µm (hydrocarbons). The spectral response of the different filters relative to the spectral radiance of a typical methane combustion is shown in Fig.2.

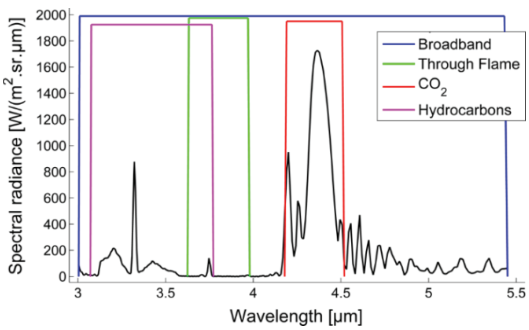

Fig. 2. Typical spectral radiance associated with a methane combustion as well as the spectral range covered by the infrared spectral filters

As shown in Fig.2, there is no almost no infrared self-emission contribution from major combustion products in the (3.6–4.0) µm spectral range. For this reason, the bandpass 3.80 ±0.18 µm filter often referred as being a through-flame filter.

2.3. Image Processing

At the engine's revolution speed, a series of 11 complete 4-stroke engine sequence was recorded. Due to the high periodicity of the phenomena and great reproducibility for cycle to cycle, the median value associated with each crank angle was computed for each experiment. For broadband imaging, a composite sequence was made by replacing the saturated pixels in the experiment carried out with the OD 1.0 with measurements carried out with the OD 2.0 filter. The atmospheric, sapphire window and gold mirror contributions were accounted according to the radiative transfer equation below:

$$L_{tot} = \left(\left(L_{comb}\tau_{saph} + L_{saph}(1-\tau_{saph})\right)\tau_{mir} + (1-\tau_{mir})L_{room}\right)\tau_{atm} + (1-\tau_{atm})L_{atm} \quad (2)$$

where L_{tot} is the measured spectral radiance, L_{comb}, the spectral radiance associated with the combustion inside the chamber, τ_{saph}, the transmittance of a 12-mm-thick sapphire window, L_{saph}, the self-emission associated with the sapphire window (estimated to 450 K), τ_{mir}, the transmittance of unpolarised radiation on the gold mirror at 45° (derived from its reflectivity curve), L_{room}, the self-emission associated with the surroundings under ambient conditions, τ_{atm}, the atmospheric transmittance and L_{atm}, the self-emission associated with the atmosphere. Calculations consisted in estimating the temperature corresponding to the in-band radiance of a blackbody source in the spectral range associated with the selected filter.

3. Results and Discussion

3.1. 4-stroke Diesel ICE

The main components of a conventional 4-stroke CI engine are illustrated in Fig.3. Intake and exhaust valves move upward and downward in order to close the cylinder or establish an access to it under the action of a camshaft (not shown). The injector is responsible for spraying the fuel into fine droplets to facilitate vaporization. The upward and downward motion of the piston assembly is translated into a gyration movement by means of a crankshaft. As a matter of fact, the engine's reference frame is often expressed in terms of crank angle (° CA) where the 0° CA position corresponds to the top dead centre (TDC). In the present work, the temporal resolution corresponds to 0.35° CA per frame. Detailed investigation of all four strokes of the diesel ICE is presented in the following sections.

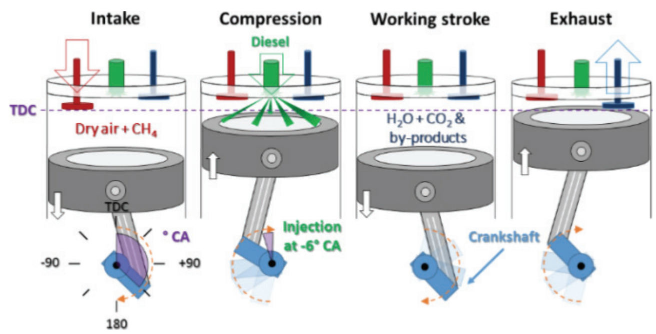

Fig. 3. Schematic representation of a typical 4-cycle diesel ICE

3.2. Intake

During the intake stroke, intake valves are fully opened while the piston is going downward (0–180° CA) in order to fill the combustion bowl with a methane-dry air blend. In the present experiment, both the dehumidified, heated up, and filtered air and gaseous fuel (i.e. CH_4) enter the combustion chamber at the same time. The intake pressure was managed in order to achieve high air mass flow rate at fixed engine speed.

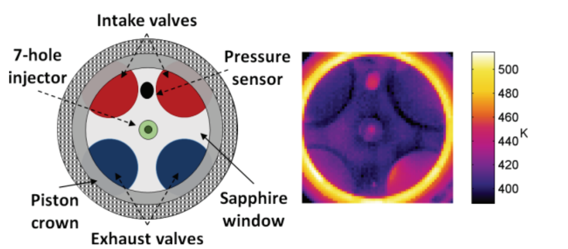

Fig. 4. Schematic view (left) and infrared image (right) of the combustion chamber

A schematic view of the investigated region and a typical infrared image recorded during the intake stroke are presented in Fig.4. Weak thermal contrast, resulting from air-methane intake, was observed during the experiments (data not shown).

3.3. Compression

During the compression stroke, all valves are closed while the pressure gradually increases as a result of the upward motion of the piston and of the compression ratio of the engine (180–0° CA). The mechanical work is not fully converted into a pressure increase as poor thermal exchanges are taking place between the system and its surrounding [6]. Therefore, the gas temperature increases significantly as a result of nearly adiabatic compression, as shown in Fig.5. Since the charge contains both CO_2 (from the air) and CH_4, the highest thermal contrast associated with adiabatic compression is seen through the CO_2 and hydrocarbon spectral filters. Since compression is not purely adiabatic, a weak temperature increase can still be seen in the through-flame spectral filter as a result of grey-body self-emission from the different components.

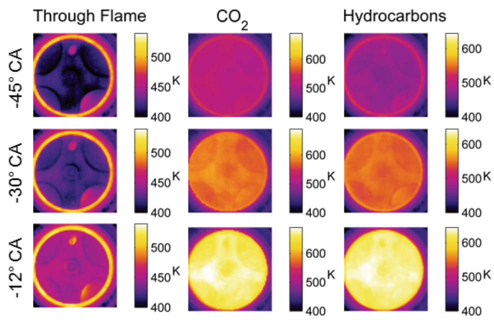

Fig. 5. Infrared imaging carried out at various stage of the compression cycle using a through-flame (left), CO_2 red-spike (center) and hydrocarbon (right) spectral filter

It should be noted that the temperature differences of the same event observed at different spectral bands do not correspond to actual thermodynamic temperature differences. The gas temperature appears differently as a function of wavelength due to spectral absorption/emission features (see also Fig. 2). The temperature corresponds to the in-band radiance of a blackbody source in the spectral range associated with the selected filter. Further flame simulation work (e.g., computer fluid dynamic, CFD) is required in order to estimate the actual gas temperature.

3.4. Diesel Injection

While approaching TDC, the temperature in the combustion chamber increases more and more. At this stage (–6° CA for these experiments), diesel fuel is injected into the combustion bowl under high-pressure conditions, as shown in Fig.6. In the early stage, diesel fuel is still in a liquid phase. Under these conditions, liquid fuel behaves like a grey-body. Consequently, the greatest thermal contrasts associated with liquid fuel can be seen using both the broadband and through-flame channels. The highest contrasts among all is observed using the through-flame spectral filter, since no contribution from the hot compressed CO_2 and CH4 gases occurs in this spectral band. As the fuel vaporises, it starts behaving like a semi-translucent media with distinct absorption features in the (3–3.5) µm common to all hydrocarbons. For this reason, thermal contrasts associated with diesel fuel in the gas phase are better observed in the hydrocarbon bandpass filter. When looking at the “star” shape created by the 7-hole diesel fuel injector, it can be seen that the “arms” of the star are significantly larger in the hydrocarbon spectral channel than in the through-flame due to the lateral diffusion of gaseous fuel. As expected, very weak contrast associated with diesel fuel, in the liquid or gas phase, is observed in the CO_2 bandpass filter other than its grey-body contribution in this spectral range.

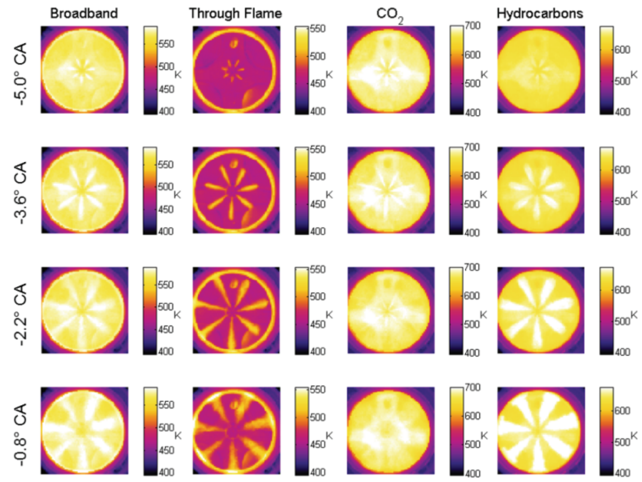

Fig. 6. Various stages of the diesel fuel injection investigated during the end of the compression cycle using an infrared broadband, through-flame, CO_2 red-spike and hydrocarbon spectral filter respectively

3.5. Working Stroke

At this point, temperatures are sufficiently high so that the little amount of diesel fuel ignites spontaneously along with the methane gas. As seen in Fig.7, ignition starts from the piston bowl wall, although the temperature of the compressed gas, prior to ignition, appears to be quite homogeneous. This likely illustrates that diesel fuel must evaporate in high-temperatures condition in order to ignite properly. As combustion occurs, methane and diesel molecules are rapidly transformed into much greater amounts of gaseous CO_2 and H_2O. Since this large volume change takes place in a close vessel, this results into a significant heat release, a pressure increase and a downward motion for the piston (0 – 180° CA). This can also be observed in Fig.7, where the contrast associated with CO_2 greatly increases upon ignition, while the contrast associated with liquid fuel and hydrocarbons decreases at the same time.

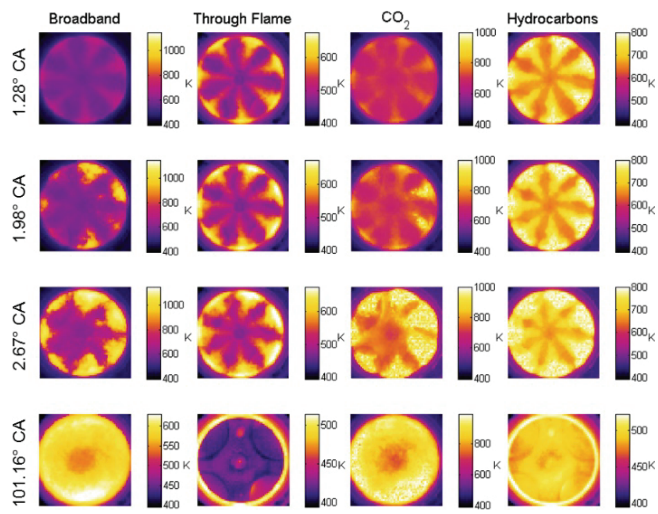

Fig. 7. Working stroke investigated at various stages using an infrared broadband, through-flame, CO_2 red-spike and hydrocarbon spectral filter respectively

3.6. Exhaust

During the exhaust stroke, exhaust valves are fully opened, while the piston is going upward (180 – 0° CA) in order to empty the cylinder before starting a new combustion cycle. Combustion gases exiting the combustion chamber through the two exhaust valves located in the lower part of the cylinder can be clearly seen in Fig. 8.

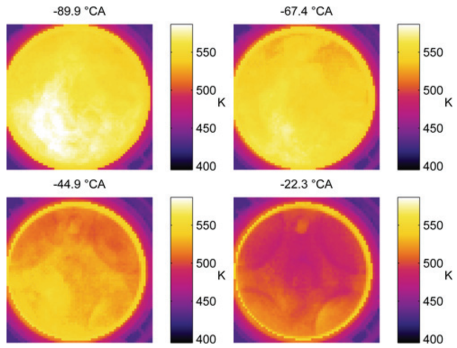

Fig. 8. Exhaust cycle investigated at various stages using a CO_2 red-spike spectral filter

4. Conclusions

The different phases of a combustion cycle, i.e. intake, compression, fuel injection, working stroke and exhaust, of a compression ignition research engine operating in dual fuel mode could be successfully investigated using high-speed infrared imaging. The use of multiple spectral filters allowed to see diesel fuel under both the liquid and gaseous phases as well as to highlight the presence of different gases involved the combustion process. High-speed infrared imaging proves itself to be an interesting diagnostic tool for research aiming for the improvement of diesel ICEs. In this regard, the dual-fuel configuration represents an interesting approach, as lowering the amount of soot particles could help slow down the clogging of after-treatment filters in the exhaust systems.

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