APPLICATION NOTE

High-Speed Infrared Imaging for Analysis of a Diesel Engine Supplied with a Premixed Methane-Air Charge

Efforts are continuously made to improve 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, ICE characterization was carried out on an optical engine at *Istituto Motori Consiglio Nazionale delle Ricerche (CNR)*, in Napoli, Italia. The setup consists of an elongated single-cylinder diesel engine equipped with the multi-cylinder head of a conventional car and a common rail injection system. In this system, the piston's crown is replaced by a sapphire window in order to carry out imaging of the combustion bowl. Imaging is 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 experiment, air was replaced by a premixed air-methane charge in order to improve combustion and lower the amount of soot deposits. 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, hydrocarbon and methane). The results illustrate how high-speed IR imaging can provide unique insights for research on ICEs.

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 has experienced a sustained growth, the majority of ICEs are still using diesel as their main fuel. In optimal conditions, combustion of hydrocarbon fuel should essentially produce water vapor (H_2O) and carbon dioxide (CO_2). Despite all the efforts made by the manufacturers to improve engine designs, fossil fuel ($\mathrm{C_nH_y}$) combustion in ICEs still produces considerable amounts of soot particles ($C_{(s)}$) and other pollutants like carbon monoxide (CO), nitrogen oxides (NO_x) and partially oxidized and/or unburnt hydrocarbons like aldehydes and ketones ($\mathrm{C_nO_zH_y}$), as expressed in Equation 1.

Equation 1

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

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 to ignite the main fuel injection, resulting in less unburnt hydrocarbons and particulate matters in the exhaust gases. However, this does not solve the problem of the pollutant emissions from a CI engine completely. For this reason, one alternative considered by researchers in this field consists in using a

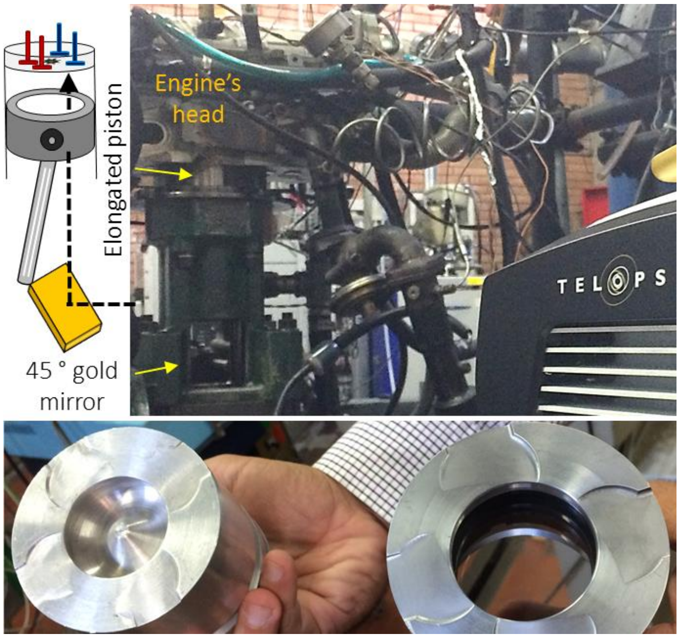

Figure 1 Infrared imaging carried out on the optical engine.

dual-fuel configuration engine [1]. In dual-fuel CI engines, natural gas serves as the primary fuel while a "pilot" amount of liquid diesel fuel is used as an ignition source. The gaseous fuel, i.e. methane (CH_4), is inducted along with the intake air and undergoes compression just like in a conventional diesel engine. The mixture of air and gaseous fuel does not autoignite as a result of the compression stroke due to its high autoignition temperature. Therefore, a small amount of liquid diesel fuel is needed near the end of the compression stroke in order to ignite the gaseous mixture. Since diesel fuel usually autoignites under these conditions, it 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 to only a small fraction of the engine power output [2].

Research activities on operating ICEs are very challenging as fast chemical reactions occur in a closed vessel, in high-temperature and high-pressure conditions. Characterization techniques must also account for changing physical and optical properties of the medium. Rapid phase transition, from the liquid to the gas state, occurs when liquid diesel fuel is injected in a high-temperature environment. For these reasons, having access to a diagnostic tool allowing investigation under all these constraints represents an important asset. In this work, a modified diesel engine (see Figure 1) was used in combination with the Telops FAST-IR 2K (see Figure 4), a high-performance cooled high-speed infrared camera, for investigation of the various cycles of a diesel ICE. The engine was operated in a dual-fuel configuration, i.e. air was replaced by a premixed methane-air charge. Phenomena taking place in each individual cycle, i.e. the intake stroke, the compression stroke + diesel-fuel injection, the working stroke and the exhaust stroke, were characterized by high-speed infrared imaging carried out at a frame rate of 26 KHz and using different filters (broadband, CO_2 red-spike, through-flame, hydrocarbon and CH_4). The results illustrate the potential of high-speed IR imaging as a diagnostic tool for ICEs.

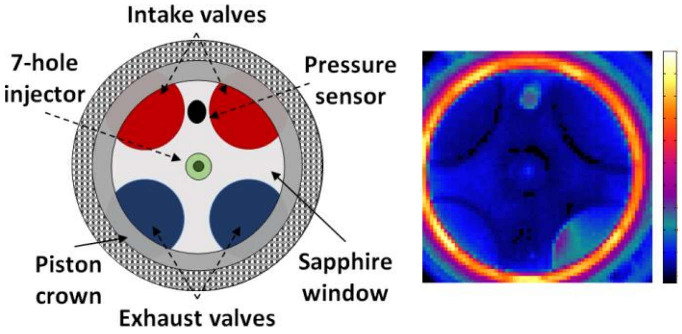

Figure 2 Schematic view (left) and infrared image (right) of the combustion chamber.

Experimental Information

Optical Engine

The optical engine is a single-cylinder engine equipped with the combustion system architecture and injection system of a 4-cyclinder diesel car. In order to carry out infrared imaging of the combustion chamber while the engine is in operation, part of the piston crown was replaced by a 12-mm thick sapphire window, as shown in Figure 1. An elongated piston configuration is also used to make space for a 45° gold mirror in the cylinder's axis. The elongated single-cylinder transparent engine has stroke and bore dimensions of 92 mm and 85 mm, respectively, and a compression ratio of 16.5:1. A schematic view of the investigated region as well as a typical infrared image recorded during the intake stroke are shown in Figure 2. Commercial grade diesel fuel was used for all experiments and injected using a common rail injection system. The setup is equipped with a fully opened electronic control unit, which allows full control of diesel fuel injection and timing. In the dual-fuel configuration used in this work, diesel fuel was injected directly into the cylinder at a mass flow rate of 0.400 kg/h under a pressure of 800 bar and at 6° crank angle before top dead center. This represents a small amount with respect to the same operating conditions realized by means of conventional diesel combustion. The production intake manifold of the engine was modified to set an electronic port fuel injector (PFI) as generally used in modern engines. It was fed by an automotive electrical pump able to reach up to 5 bar of injection pressure and was used with methane fuel. The air and methane mass flow rate were set to 33.5 kg/h and 0.385 kg/h respectively. The engine's speed was set to 1500 revolutions per minute (RPM).

High-Speed Infrared Imaging

The Telops FAST-IR 2K (Figure 4) is a cooled high-performance infrared camera using a 320×256-pixel indium antimonide (InSb) focal plane array (FPA) detector covering the 3 – 5.5 µm spectral range. A 50-mm Janos lens was used for all experiments. A 64×64 pixel sub-portion of the FPA detector was used for imaging at 26 000 frames per second. The total recording time was set to 1 sec for each measurement sequence. The camera is equipped with a 4-position internal filter wheel that allows the storing of commercially available 1-inch (2.54 cm) filters. The engine's operation was investigated using a total of five different filters: optical density (OD) 1.0, OD 2.0, bandpass 3.80 – 0.18 µm, bandpass 4.35 – 0.18 µm, bandpass 3.42 – 0.35 µm and bandpass 3.30 – 0.04 µm. The spectral response of the different filters, along with the spectral radiance spectrum of a typical methane combustion measured by midwave infrared (MWIR) remote sensing, are shown in Figure 3.

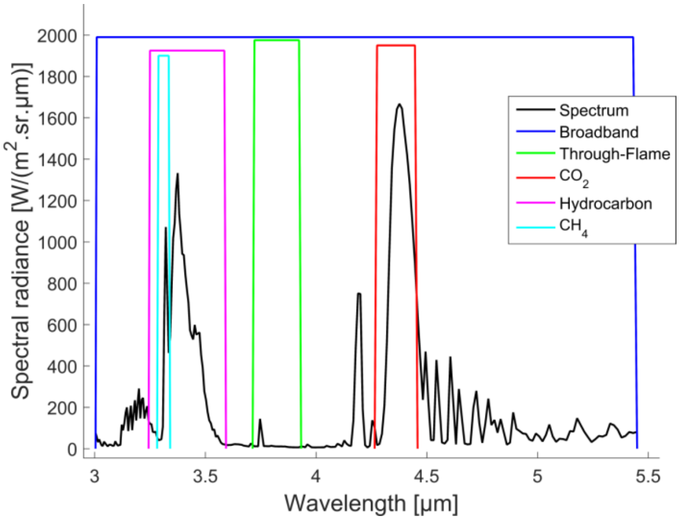

Figure 3 Typical spectral radiance associated with a methane/diesel combustion as well as the spectral range covered by the infrared spectral filters.

Due to important atmospheric absorption in the 4.2 – 4.5 µm (ambient CO_2), the CO_2 spectral features associated with combustion appear like two separate peaks: the blue (4.15 µm) and the red spikes (4.35 µm). For this reason, the bandpass 4.35 µm spectral filter is often referred to as the CO_2 red-spike filter. As seen in Figure 3, there is almost no infrared self-emission contribution from major combustion products in the 3.6 – 4.0 µm spectral range. For this reason, the broad-bandpass 3.80 µm filter is often referred to as a through-flame filter. The 3.0 – 3.5 µm spectral range is typically associated with the C–H stretching vibration spectral feature. As all hydrocarbons, including methane, contain at least one C–H chemical bound, a bandpass 3.42 µm spectral filter is often referred to as a hydrocarbon filter. Finally, the 3.30 – 0.04 µm narrow-bandpass filter is centered on the methane main absorption/emission spectral feature.

Figure 4 The Telops FAST-IR 2K.

Image Processing

At the engine's revolution speed, 11 successive 4-stroke cycles were recorded for each measurement. Due to the high periodicity of the phenomena and great reproducibility from cycle to cycle, the median value associated with each crank angle was computed. In the case of the broadband infrared sequence, a composite sequence was obtained by merging data from both the experiment carried out with the OD 1.0 and the OD 2.0 attenuation filters, where the saturated pixels identified in one experiment were replaced with the corresponding pixels from the other. The atmospheric, sapphire window and gold mirror contributions were accounted for according to the following radiative transfer equation:

Equation 2

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

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 in-band radiance associated with the combustion process for each filter.

Radiometric Temperature

It should be noted that the concept of radiometric temperature is irrelevant in presence of selective absorbers/emitters of infrared radiation like the combustion gases. The gas temperature appears differently as a function of wavelength due to the spectral absorption/emission features (see also Figure 3) and has no physical meaning. Further flame simulation work (e.g., computer fluid dynamic [i.e., CFD] simulations) is required in order to estimate the actual gas temperature from the infrared imaging measurements.

Results and Discussion

4-cycle Diesel ICE

The main elements of a conventional 4-stroke CI engine are illustrated in Figure 5. 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 in order 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 center (TDC) position. In the present work, the temporal resolution corresponds to 0.35° CA per frame. Detailed investigation of all four strokes and the liquid fuel injection of the diesel ICE is presented in the following sections.

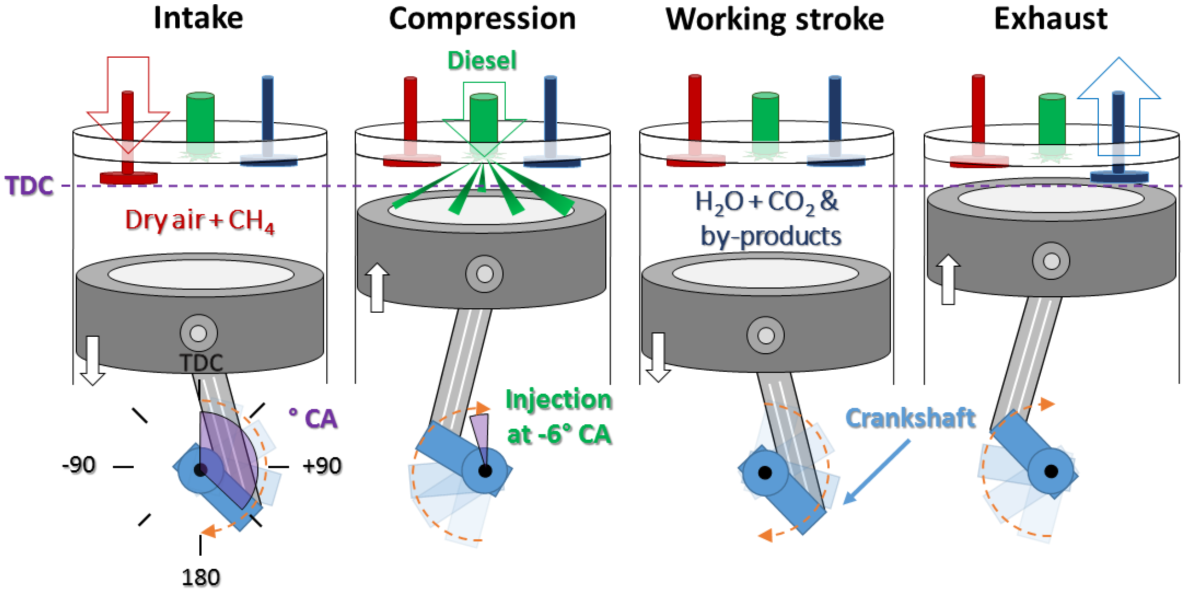

Figure 5 **Schematic representation of a typical 4-cycle diesel internal combustion engine.**

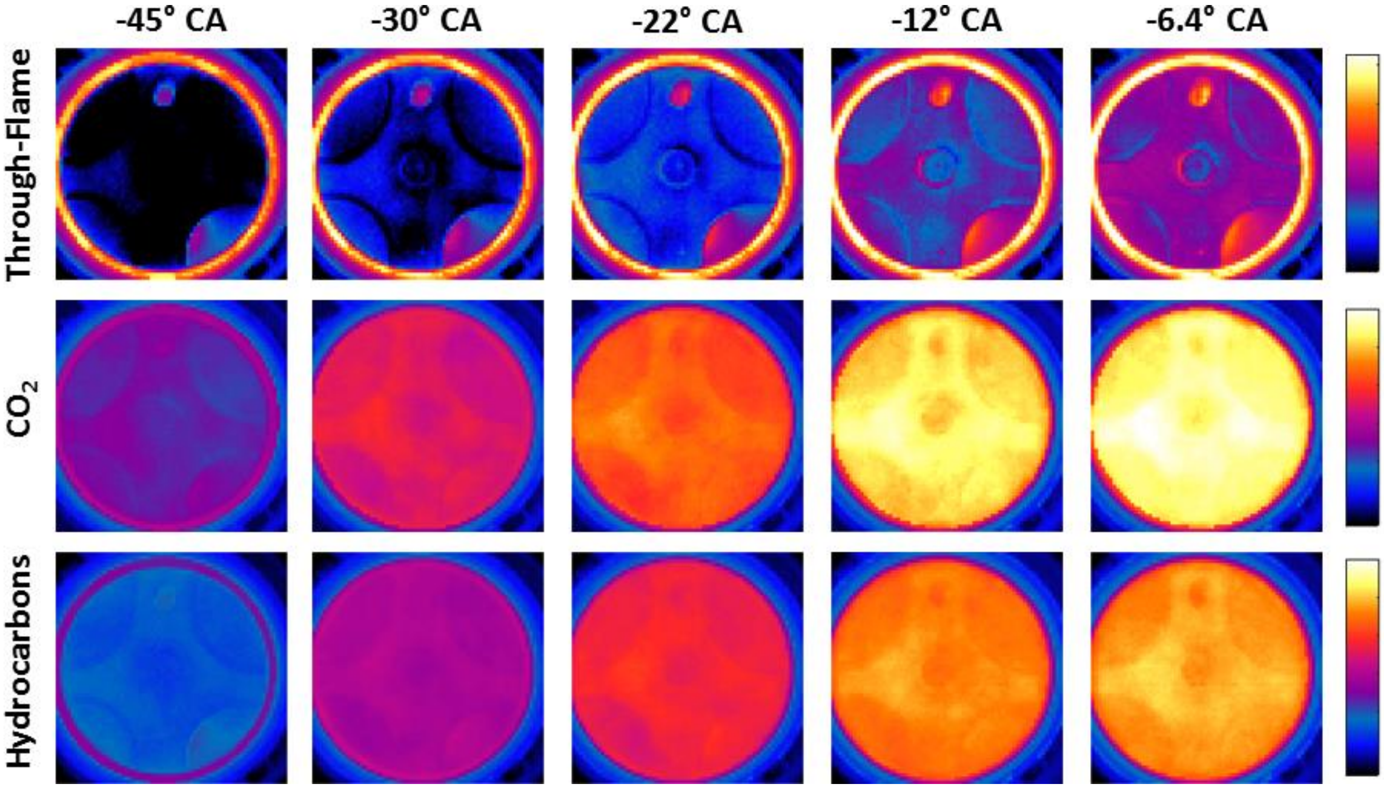

Figure 6 Various stages of the compression stroke seen through different infrared spectral bands.

Intake Stroke

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 charge. In these experiments, both the warm dehumidified 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. From an infrared imaging perspective, the intake stroke involves 2 infrared-active molecules: CO_2 from the compressed dry air and CH_4. Since their temperature is close to the cylinder's temperature as they exit the PFI, weak thermal contrasts associated with the charge induction are typically observed during the intake strokes (data not shown).

Compression Stroke

During the compression stroke, all valves are closed while the pressure gradually increases as a result of the upward motion of the piston and the compression ratio of the engine (180 – 0° CA). During the compression stroke, the mechanical work is not fully converted into a pressure increase as poor thermal exchanges are taking place between the cylinder's cavity and its surrounding. Consequently, the gas temperature increases significantly as a result of a nearly adiabatic compression, as shown in Figure 6. Since the charge contains both CO_2 (from the air) and CH_4, the highest thermal contrasts associated with adiabatic compression are seen through the CO_2 red-spike, hydrocarbon and methane (not shown) spectral filters. The hot pressurized gas mixture eventually warms up some engine parts leading to an increased grey-body-like infrared self-emission from these components. This effect can be seen using the through-flame filter near the end of the compression stroke in Figure 6. It should be noted that sufficient temperature increase upon compression is critical for good performance of CI engines, because autoignition of diesel fuel only occurs beyond a certain temperature threshold.

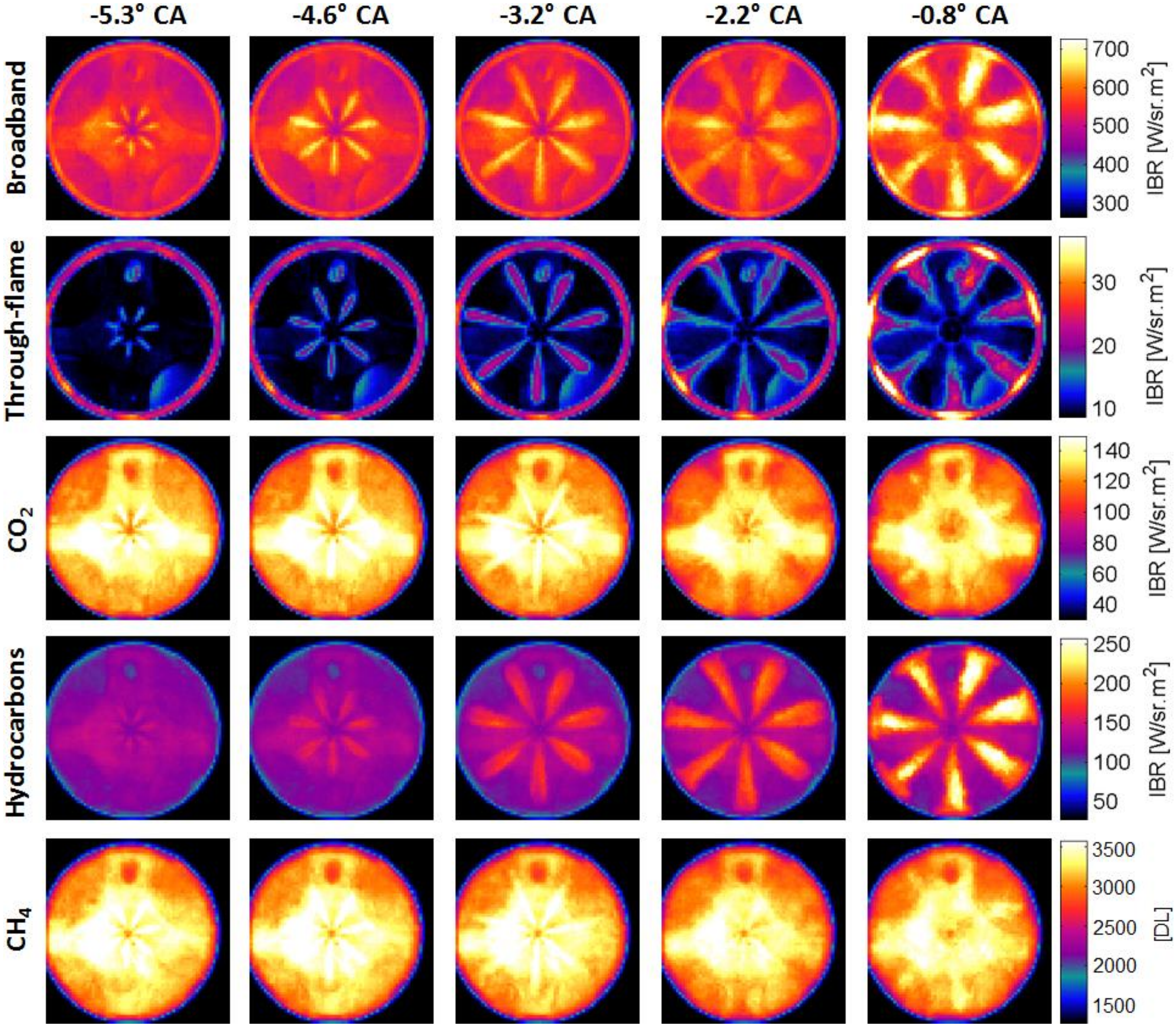

Figure 7 Various stages of the diesel fuel injection seen through different infrared spectral bands.

Diesel Fuel 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 Figure 7. In the early stage, diesel fuel is still in a liquid phase and behaves like a grey-body emitter. Consequently, the greatest thermal contrasts associated with liquid fuel can be seen using both the broadband and through-flame channels. The greatest contrasts associated with liquid fuel are observed using the through-flame spectral filter because this spectral range does not suffer from self-emission contributions from hot and compressed CO_2 and CH_4, as shown in Figure 3. As the fuel vaporizes, diesel starts behaving like a semi-translucent media with distinct infrared absorption and emission features. Diesel fuel is a mixture of saturated and branched carbon chains, with a few insaturations (e.g., $C_{16}H_{34}$). Therefore, significant contrast associated with gas-phase diesel fuel is expected using the hydrocarbon filter, as shown in Figure 7. A multipoint injector disperses the fuel into fine droplets, in opposite directions, to favor fuel vaporization and mixing with air (O_2). When looking at the 7-arm-star shape created by the 7-hole diesel fuel injector, it can be seen that the “arms” of the star appear significantly larger with the hydrocarbon filter than the through-flame filter. This is mainly due to the lateral diffusion of gaseous diesel fuel as it vaporizes. As expected, this effect is more and more pronounced as a function of time due to the liquid–gas phase transition. As expected, very little contrast associated with liquid diesel fuel is observed when using CO_2 and CH_4 bandpass filters (-5.3 to -3.2° CA). In the liquid phase, self-emission from liquid diesel fuel almost exclusively results from grey-body self-emission (over the narrow spectral range of the bandpass filter). As the fuel vaporizes, this contribution vanishes (-2.2 to -0.8° CA) because diesel starts behaving like a semi-translucent media with no spectral feature, i.e. is fully infrared-translucent, in this spectral range. The same conclusions apply for the through-flame filter for the frames recorded near TDC.

Working Stroke

At some point, temperatures are sufficiently high so that the little amount of vaporized diesel fuel ignites spontaneously. This first ignition then serves as an ignition source for methane. In a dual-fuel configuration, diesel fuel acts as a pilot fuel as most of the engine’s power comes from methane combustion. Four frames recorded at the early ignition stage are shown in Figure 8. Ignition points are mostly located near the piston bowl wall, although the temperature of the compressed gas, prior to ignition, appears to be quite homogeneous. This likely illustrates the fact that diesel fuel first needs to vaporize sufficiently, then mix with air, in high-temperature conditions, in order to meet autoignition conditions. As shown in Figure 8, the flame rapidly propagates toward the center of the piston bowl in a few tens of microseconds. As combustion happen, methane and diesel molecules are rapidly transformed into much greater amounts of gaseous CO_2 and H_2O (see Equation 1). Since this large volume change takes place in a close vessel, this results into a significant heat release and pressure increase. Pressure is then converted into mechanical work causing the downward motion of the piston (0 – 180° CA). The fuel conversion into CO_2 can be visualized by comparing the sequences recorded with the different spectral filters, as shown in Figure 8. In the regions where the thermal contrast associated with CO_2 increases, the thermal contrast associated with liquid fuel (through-flame filter) and hydrocarbons decreases at the same time. The last frames in Figure 8 correspond to a much later stage of the working stroke. Nearly no trace of the combustion gases can be seen in the image recorded with the through-flame filter, which is consistent with the spectral properties of a typical methane combustion (see Figure 3). Therefore, such spectral filters could be useful for temperature monitoring of critical engine parts, like the injector, the valves and/or the pressure sensor during combustion. At this stage, most, but not necessarily all, of the diesel fuel and CH_4 have been converted into CO_2 and H_2O. It is then not surprising to observe large thermal contrasts in the CO_2 red-spike filter at this point. In addition, significant thermal contrast can still be observed in the infrared image recorded with the hydrocarbon spectral filter. It is not clear if this results from unburnt fuel, diesel and/or methane gas, water vapor or other byproducts, such as partially oxidized hydrocarbons. Water vapor is a strong infrared emitter and has weak spectral features in the hydrocarbon filter spectral range. However, since water vapor is produced in large amounts in any hydrocarbon combustion (see Equation 1), its contribution cannot be totally discarded. Nevertheless, additional spectral information would be required to support these hypotheses.

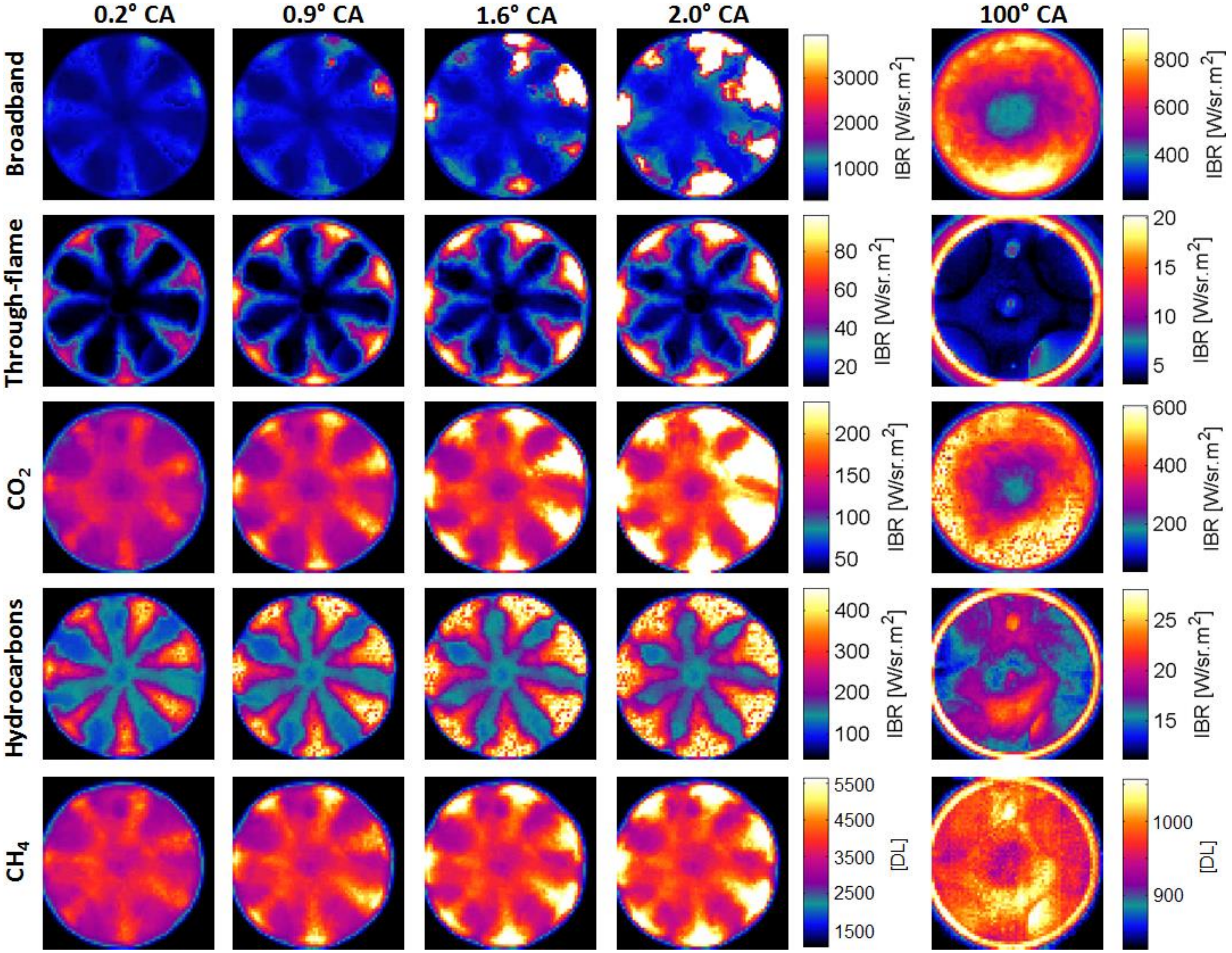

Figure 8 Various stages of the working stroke seen through different infrared spectral bands.

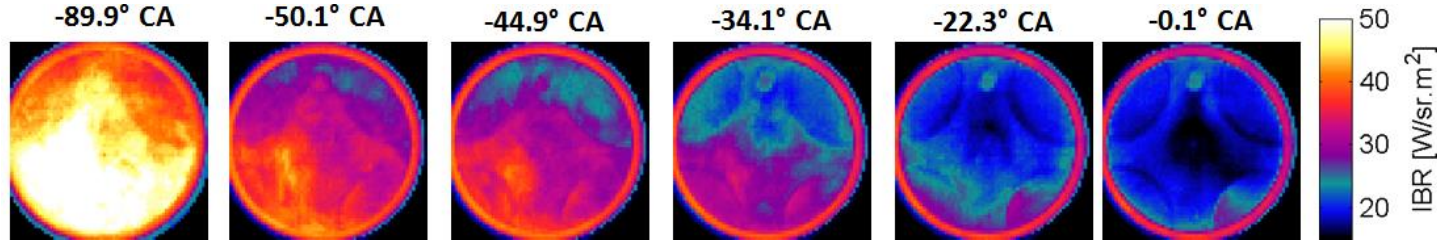

Figure 9 Exhaust cycle investigated at various stages using the CO_2 red-spike spectral filter.

Conclusion

The different cycles of an optical CI engine, operating in dual-fuel mode, could be successfully investigated using high-speed infrared imaging. As shown for all investigated cycles, the signal recorded using broadband infrared imaging results from the sum of all contributions in the detector's sensitivity range (3 – 5.5 µm). Without spectral information, there is no way of knowing from what chemical entity the infrared signal originates from. Such information is critical in order to model the combustion process and estimate thermodynamic temperatures from infrared images. The use of multiple spectral filters also allows the observation of diesel fuel under both liquid and gaseous phases. High-speed infrared imaging is an interesting diagnostic tool for research focusing on ICEs, especially in a situation where multiple infrared-active molecules, such as diesel and CH_4, are involved. 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.

Acknowledgments

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Telops Inc.
100-2600 St-Jean Baptiste Ave
Québec, QC, Canada, G2E 6J5

+1-418-864-7808
sales@telops.com
www.telops.com