Analysis of Dual Fuel Hydrogen/Diesel Combustion in Ultra Lean Conditions via Simultaneous UV and IR Imaging

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Abstract
Thanks to its reliability and high-performance characteristics combined with high technological innovation, the combustion engines powered by alternative fuels, such as hydrogen, can still represent a useful solution for achieving mobility with net zero emissions. The use of hydrogen in a dual-fuel engine with hydrogen and diesel (or HVO and other compatible renewable fuels) can reduce greenhouse gas emissions as well as particulate matter emissions while ensuring excellent performance.
In this scenario, tests have been carried out on a dual-fuel single cylinder research engine to analyse the combustion evolution of hydrogen in ultra-lean conditions via optical diagnostics. At ultra-lean condition (λ=3.8), the hydrogen does not ignite by itself at desired crank angle; thus, diesel has been used to ignite the hydrogen premixed charge. An operating point at 1500rpm engine speed and at fixed engine load has been investigated. The in-cylinder pressure and the related data have been analysed as indicators of the combustion quality. 2D-digital imaging cycle resolved in both ultraviolet and infrared wavelength range have been performed and the flame propagation is evaluated. In particular, UV and IR cameras simultaneously acquired images of the hydrogen combustion and furnished information on the flame propagation via the detection of OH and low and high temperature reaction zones within the bowl, respectively. Results show that to control efficiently the hydrogen combustion it is necessary to phase properly the injection of diesel.

Introduction
To comply with the European Union’s plan to reduce greenhouse gas emissions, the scientific community suggests strategies to avoid the use of fossil fuels and polluting gases, such as dual-fuel combustion. This method replaces high-carbon fuels with low-carbon or carbon-free alternatives, like hydrogen. Hydrogen has a higher lower heating value than other fuels and a fast flame propagation speed. However, it also has a high resistance to autoignition, requiring additional systems to control ignition and combustion, such as a spark plug or a high-cetane number fuel like diesel [3]. Rorimpandey et al. [1] conducted research on the ignition and combustion characteristics of cross-jets of H2 and diesel in a combustion chamber simulating a diesel engine's configuration. They applied high-speed schlieren images to study the interaction of H2 and diesel at the autoignition and the main conclusion was that the pilot ignition is not influenced by the interaction with H2 jet. Moreover, the results

indicate that longer interaction is required to ignite the H2 jet when the diesel pilot occurs prior to the one of H2. On the other hand, when H2 is injected before the pilot, the H2-air mixture ignition due to the pilot autoignition occurs with very lean H2 equivalence ratio. Cheng et al.[2] examined a hydrogen, methane and diesel combustion mode. Diesel is the fuel that creates the conditions for igniting the mixture. The study was conducted with various fractions of H2 in the methane-air mixture (χH2/χH4 = 0%, 10%, 20%, 40%, 60%) in an optically accessible engine. Engine performance, combustion process, flame characteristics, and stability were evaluated based on the analysis of both the cylinder pressure signal and the natural brightness of the coloured flame. They worked at fixed amount of diesel increasing the quantity of H2 in the mixture, it resulted in higher indicated mean effective pressure of the engine at the different operating conditions. The results led to the definition that the apparent heat release rate and in-cylinder profiles become steeper with increasing H2 concentration. Moreover, more combustion occurs in the premixed phase rather than the diffusion phase as the H2 concentration increases. They also introduced the Flame Stability Index (FSI) to estimate the effect of H2 addition on ignition and flame stability. The results indicate that H2 induction has a negligible effect on the flame kernel initiation.

In this study, dual fuel was investigated in a single-cylinder optically accessible research engine. The aim is to analyse the dual fuel H2/diesel combustion through the simultaneous application of cycle resolved imaging in ultraviolet (UV) and infrared (IR) wavelength range, respectively. Since the intensified UV camera is suited to analyse the OH radical characteristic of the autoignition of the dual fuel mixture, the objective is to compare the UV information with those of the IR camera. The analysed test achieves a premixing ratio of 90% and a fixed engine speed of 1500 rpm. A comparison of the UV and IR emission intensity have been performed with respect the rate of heat release of the H2 combustion.

Experimental procedure

The layout of the single-cylinder compression ignition engine (SCRE) with optical access complies with an elongated piston allowing for a window at the top of the piston. The SCRE is designed to monitor the evolution of reactive species within the combustion chamber operating in continuous combustion mode. Further details about the engine specification and injection systems for dual fuel operation can be found in previous publications [3,4]. In particular, for dual operation (DFH2), hydrogen is supplied from gas bottle via a pressure regulator and a PFI injector at 5 bar to the intake manifold of the engine. The H2 flow rate is measured by the Brooks mass flow meter, it is 0.25 kg/h. A piezoelectric pressure transducer is used to acquire the in-cylinder pressure via a multi-channel acquisition system. The signals are digitized and recorded at increments of 0.2° of the crank angle (CA). The average pressure in the cylinder is calculated from 200 consecutive combustion cycles. The rate of heat release (ROHR) is calculated from the average pressure data using the first law of thermodynamics and the perfect gas model.

Moreover, particular attention has been devoted to the alignment and synchronization of the two high-speed cameras with a 45° mirror set in the elongated piston of the SCRE by means of the engine delay unit. The reflected light exiting by the bowl and reflected by the 45° UV-IR mirror is shared through a dichroic mirror to the UV and IR cameras, respectively. The dichroic reflects wavelengths between 250-350 nm and transmits the remaining part of the electromagnetic radiation. The reflected radiation is acquired by a visible camera (Photron Fastcam SA-X2) coupled with a high-speed intensifier (LaVision's High-Speed IRO). Moreover a 85mm f 3.8 UV lens and a filter at 310 nm for OH detection. The image resolution is set to 515x512 pixel. On the other hand, the infrared camera is the Telops FAST-IR 2K, image resolution 128x100, it is equipped with a 50 mm Janos lens and detecting the spectral range 3 and 5.5 μm. An optical density filter (OD1.45), which reduces the incident radiation by 90% to avoid sensor saturation.
The image frequency of the both cameras was set to 10,000 images per second. Therefore, at an engine speed of 1500 rpm, an image is collected every 0.9° crank angle degree, respectively. The exposure time is set to 45 μs for the UV intensifier and to 5 μs for the IR synchronizing the falling edge of the trigger out acquisition signals. Ten repetitions are recorded and processed to perform a statistical analysis of the process. In post elaboration, the images have been processed with Matlab. They have been transformed into numerical pixel/intensity matrices. Moreover, the total intensity has been determined image by image, the background has been eliminated, the integral image intensity has been processed, reconstructing the temporal trend of UV and IR emissions, respectively.

Results

In this study, an operational condition involving a motor speed of 1500 rpm and a load of 4 bar was examined. The premixed ratio of H2 is 90%, leading to a significant reduction in particulate matter (PM), carbon monoxide (CO) and unburned hydrocarbons (HC). A proper distribution of the diesel spray in the premixed blend can lead to multi-point ignition involving the several region of the combustion chamber reacting in ultra lean conditions: λ=3.8 or φ=0.26. For this reason, UV optical visualizations allow the detection and analyses of OH radical typical of the start of premixed combustion. On the other hand, the effectiveness in the use of IR diagnostic to analyse the autoignition has been tested too.

Figure 1 depicts the pressure curve, the rate of heat release, and the current signal of the diesel injector during the test 1500x4. Diesel injection is used to phase the hydrogen combustion, otherwise it occurs randomly and very late with respect to the top dead centre. In the figure, the crank angles indicating the main combustion events on the rate of heat release (ROHR) trace are reported. They are the start of pilot combustion associated with low- and high-temperature reactions (LTR and HTR) at 4.9 before top dead centre (BTDC) and 2.5° BTDC, the start of main combustion (SOC) at 5.5° after top dead centre (ATDC); and the peak of ROHR for pilot combustion at 1° BTDC and for main combustion at 6.9° ATDC.

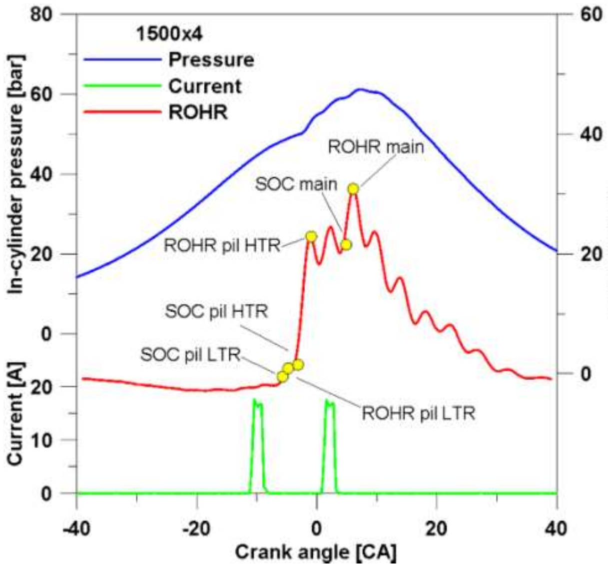

Figure 1. In-cylinder pressure signal, injection signal and ROHR for DFH2

It was expected that, since the diesel pilot combustion began, all the available hydrogen would immediately be consumed. In fact, despite hydrogen's high flame speed and low density, it requires time to develop the combustion reactions in ultra lean conditions. This phenomenon is mainly dependent by the diesel injected amount and by the distance of the two injections. Therefore, the ROHR curve reveals two distinct peaks. A more in-depth analysis could be conducted by examining the combustion images in the UV and IR wavelength range, respectively. Figure 2 displays the combustion images of DFH2 for the operative condition already analysed in Figure 1. The IR images shows different phenomena: injection of pilot diesel fuel at 6.6° and the main injection at 4.2° ATDC, respectively. Moreover, they show increasing intensities passing to 4.8° BTDC as well as the highest at 6.0° ATDC. It seems the combustion is distributed along the jet directions involving close to the bowl wall. From 2.1° BTDC, a background appears between the jets and close to the combustion chamber wall. Probably, it is the hydrogen ignited by the diesel pilot combustion. At later crank angles, i.e 5.1° ATDC, the main combustion has the highest emitted intensity on the jets direction, diesel fuel is burning at very high fuel rich condition; anyway some zones at lower intensity can be noted close the bowl wall. From 14.1° ATDC, the flames spread in the bowl and consume the hydrogen still within the cylinder.
Images captured using the intensified system, reveal the presence of OH radical during the development of the DFH2 combustion. OH can be detected after the combustion commences. At 4.8° BTDC, the OH radical due to the ignition of the pilot jet is noted heading towards 2 o'clock. This signal is in very good agreement with the IR image detected at the same crank angle. Thus, the variation of temperature in the low temperature reaction regime and due to the start of pilot combustion is successfully detected also by the IR imaging. Advancing the crank angle toward the top dead centre and developing the combustion of pilot injection, OH radical is homogenously distributed around the jets with the highest

concentration on the tip and close of the bowl wall where the vaporized diesel mixes with the premixed charge. Before the main injection (Figure 1), a stall phase of combustion is observed between the two injections up to 4.2° ATDC. The combustion nuclei gradually diminish, leaving only a few high-concentration areas close to the bowl wall. Probably the hydrogen in the dead volume is feeding the flame and moving within the bowl. The onset of the main combustion, recorded at 5.1° and 6.0° ATDC, produces again the autoignition dominant species in the bowl centre. The radical emission is mainly due to the burning diesel jets, even if some intensity can be still detected in the periphery of the bowl. Finally, after 14.1° ATDC, the high-concentration areas expand along the jets and around the observed area with different intensities. In particular, the OH radical detected moves in counter clockwise direction following the airflow.

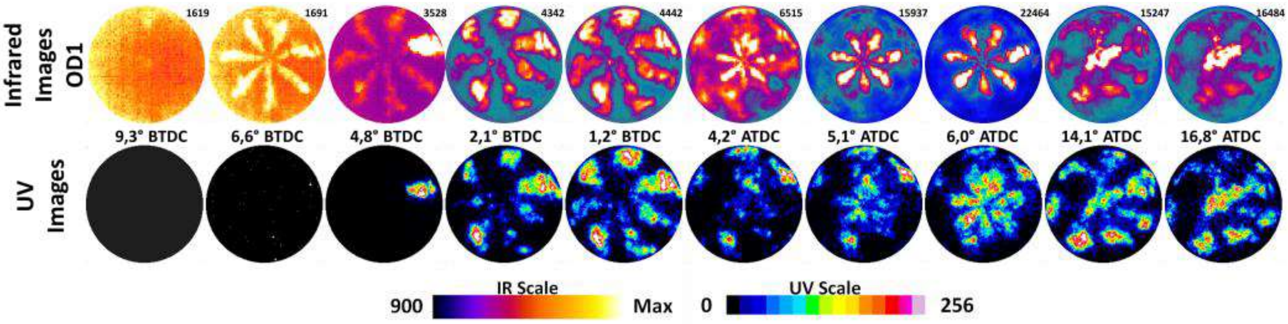

Figure 2. DFH2 imaging simultaneously acquired: IR (1st row), UV (2nd row)

In order to associate the information of digital imaging with the data of the ROHR, in Figure 3 it is reported the luminous integral emissions of the cycle resolved images versus the ROHR at 1500x4. Both intensities are calculated as the sum of all the intensity of each frame and are normalized to their respective maximums. A significant correspondence is observed between the ROHR combustion data and the digital images. Both imaging measurements displays very good agreement with the rate of the heat due to the development of the combustion. In particular, UV and IR are very well phased with the start of combustion. UV showed a marked increase in the curve due to the low and high-temperature reactions at the autoignition. Advancing the pilot combustion OH is consumed and, thus, its intensity decreases; on the other hand the in-cylinder temperature is increasing and the IR intensity continuous to increase. High intensity values of OH radical suggest a faster oxidation and combustion process, which could facilitate also the oxidation of carbon particles and reduce the formation of soot due to the small amount of diesel. Then, the reduction in the OH detection indicates that not all the hydrogen is burning in this phase. As the main combustion occurs, both curves reach the peak at the same time. It's 2.6° later than the ROHR peak. OH radical showing the combustion reaction of main and of the hydrogen are I very good agreement with the rate of the IR affecting by the thermal emission of the combustion reactions.

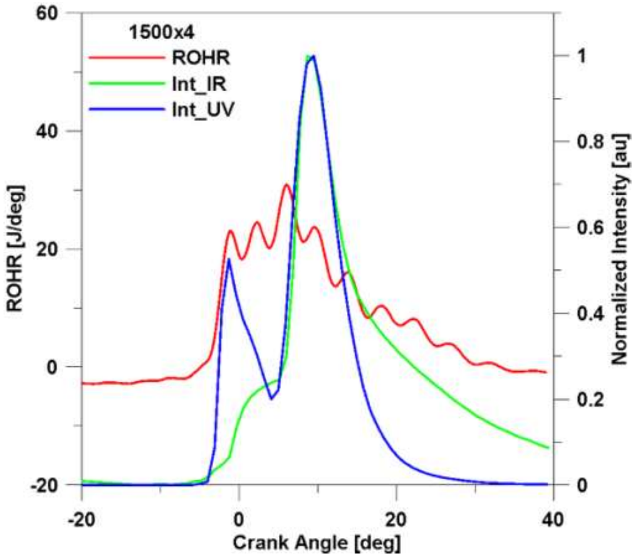

Figure 3. IR images integral intensities vs ROHR filtered for the DFH2 @ 1500x4

Conclusion

In this study, simultaneous UV and IR cycle-resolved imaging has been applied to study dual fuel diesel/hydrogen combustion with a premixed ratio of 90%
Imaging in the UV and IR wavelengths allows for the identification of various phenomena in the process. Among this the autoignition is the most important to identify the onset and the location of the hydrogen combustion driven by the diesel. The results clearly shows how the IR imaging can be suited also for the identification of the autoignition of the premixed charge of H2. Moreover, the OH radical detection shows that hydrogen did not burn immediately in the ultra lean condition tested.

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