OPTICAL CHARACTERIZATION OF METHANE COMBUSTION IN A FOUR STROKE ENGINE FOR TWO WHEEL APPLICATION

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Abstract
In the urban area the internal combustion engines are the main source of CO_2, NOx and particulate matter (PM) emissions. The reduction of these emissions is no more an option, but a necessity highlighted by the even stricter emission standards. In the last years, even more attention was paid to the alternative fuels. They allows both reducing the fuel consumption and the pollutant emissions. Regarding the gaseous fuels, methane is considered one of the most interesting in terms of engine application. It represents an immediate advantage over other hydrocarbon fuels because of the lower C/H ratio. In this paper the effect of the methane on the combustion process, the pollutant emissions and the engine performance was analyzed. The measurements were carried out in an optically accessible single-cylinder, Port Fuel Injection, four-stroke SI engine equipped with the cylinder head of a commercial 250 cc motorcycles engine and fuelled both with gasoline and methane. Optical measurements were performed to analyze the combustion process with a high spatial and temporal resolution. In particular, optical techniques based on 2D-digital imaging were used to follow the flame propagation in the combustion chamber. UV-visible spectroscopy allows detecting the chemical markers of combustion process such as the radicals OH and CH. The exhaust emissions were characterized by means of a gaseous analyzer and an opacimeter. The measurements were performed under steady state conditions, at 2000rpm at minimum and full load.

Introduction
In the urban area the internal combustion engines are the main source of CO_2, NOx and particulate matter (PM) emissions. The reduction of these emissions is no more an option, but a necessity highlighted by the even stricter emission standards. In the last years, even more attention was paid to the alternative fuels that allow both reducing the fuel consumption and the pollutant emissions. Methane is a promising alternative fuel to petrol for internal combustion engines [1]. It represents an immediate advantage over other hydrocarbon fuels because of the lower C/H ratio. Moreover, it has a higher Lower Heating Value (LHV) and stoichiometric air/fuel ratio and a higher Research Octane Number (RON) which permits higher compression ratios, higher boost in turbocharged engines, and better knocks limited

spark advances, as reduces the knock sensitivity. The major drawback of the use of methane in the spark ignition or compression ignition engines is the low flame propagation speed. The flame front propagation speed depends mainly on the turbulence and the air/fuel ratio. In particular, it increases at the increasing of the turbulence and at the decreasing of the air/fuel ratio [2].
In this paper the effect of the methane on the combustion process, the pollutant emissions and the engine performance was analyzed. The measurements were carried out in an optically accessible single-cylinder, Port Fuel Injection, four-stroke SI engine equipped with the cylinder head of a commercial 250 cc motorcycles engine. Optical measurements were performed to analyze the combustion process with a high spatial and temporal resolution. In particular, optical techniques based on 2D-digital imaging were used to follow the flame propagation in the combustion chamber. UV-visible spectroscopy allows detecting the chemical markers of combustion process such as the radicals OH and CH. The measurements were performed under steady state conditions, at 2000 rpm at minimum and full load. The engine was fuelled with commercial gasoline and methane.

Experimental Apparatus

Transparent Engine

The experimental activity was performed in an optically accessible single-cylinder, Port Fuel Injection, four-stroke SI engine [3]. The engine bore and stroke were 72 mm and 60 mm, respectively. The geometric compression ratio was 11:1. The engine was equipped with the cylinder head of a commercial 250 cc motorcycles engine. A four-valve, pent-roof chamber engine was mounted on an elongated piston. The engine reached a maximum speed of 5000 rpm. The maximum performance is: 7.9 kW and 14.7 Nm at 5000 rpm. The head had a centrally located spark plug and a quartz pressure transducer was flush-installed in the combustion chamber to measure the combustion pressure. The in-cylinder pressure, the rate of chemical energy release and the related parameters were evaluated on an individual cycle basis and/or averaged on 400 cycles [2]. The optical engine was characterized by an elongated cylinder and a piston provided with a sapphire window which replaces the flat-bottom piston bowl. The engine is also equipped with a quartz cylinder in order to have a lateral point of view of the combustion chamber. This system enables the passage of optical signals coming from the combustion chamber. To reduce the window contamination by lubricating oil, the elongated piston arrangement was used together with self-lubricating Teflon-bronze composite piston rings in the optical section.

Setup for Spectroscopic Measurements

During the combustion process, the light passed through the sapphire window and it was reflected toward the optical detection assembly by a 45° inclined UV-visible mirror located in bottom of the engine. Chemiluminescence signals were collected and focused on the entrance slit of a spectrograph through an UV-Visible objective. The slit was 250 μm wide open and it was located in front of the combustion chamber. Spectrograph was 15 cm focal length, f/4 luminous, and equipped with a grating of 300 g/mm, blazed at 300 nm, with a dispersion of 3.1 nm/mm. The spectral image formed on the spectrograph exit plane was matched with a gated intensified CCD camera. Data were detected with the spectrograph placed at two central wavelengths, 375 and 625 nm, respectively, and the intensifier-gate duration was set to 166.6 μs in order to have a good accuracy in the timing of the different investigated events. Chemiluminescence signals, due to radical emission species, were detected in the central and lateral locations of the combustion chamber with high spatial and temporal resolution. Engine synchronization with ICCD camera was obtained by the unit delay connected to the signal coming from the engine shaft encoder. In this way, it was possible to determine the crank angles where optical data were detected.

Engine Operating Conditions

All the experimental investigations were carried out at 2000 rpm. The intake air temperature was fixed at 298 K and the cooling water temperature was set at 333 K. Commercial gasoline and methane fuels were used. For all the test cases, the injection-duration (DOI) was chosen to obtain a stoichiometric equivalence ratio. Two different fuel injection strategies were tested for both fuels: minimum load (closed throttle) and full load (wide open throttle). The coefficient of lambda value variation was measured on 400 consecutive cycles. It was lower than 1.8% for all the selected conditions. The spark timing (SOS) was always fixed to operate at the maximum brake torque. More details about the operating conditions are reported in Table 1.

Table 1. Engine operating conditions

Test label	Fuel	Pinj [bar]	DOI [cad]	SOS [cad]
Minimum load	Gasoline	3.5	29.5	-29.5
Full load	Gasoline	3.5	71	-71
Minimum load	Methane	1.5	128.7	-378.7
Full load	Methane	1.5	250.6	-500.6

Results and Discussion

The measurements were performed from the Start of Spark (SOS) until exhaust valve opening. The spectroscopic measurements were binned along space direction in order to obtain three typical locations: in correspondence of the exhaust valves, the spark plug and the intake valves.

The development of the combustion process was identified by means of the analysis of digital images. In particular, the flame front propagation speed, an

important parameter in the study of combustion in spark-ignition engines, was evaluated.
The comparison between the flame front propagation speed, for the gasoline and methane fuels at minimum and full load is reported in Figure 1.

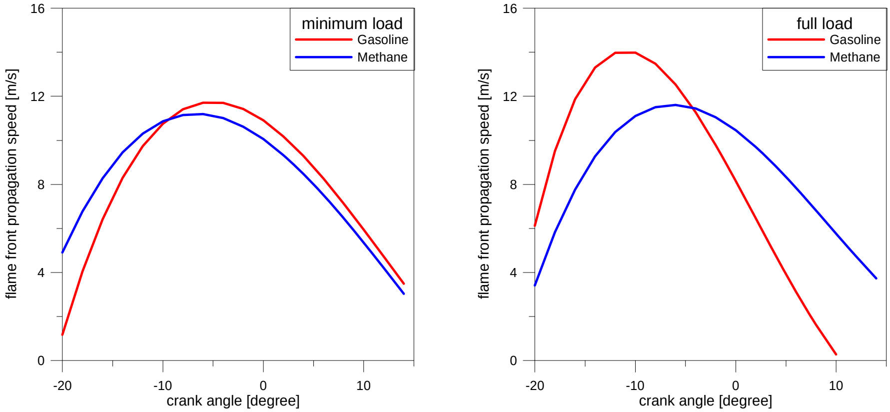

Figure 1. Flame front propagation speed vs crank angle for gasoline and methane.

A similar behaviour is observed for both the tested fuels. In particular, the flame front propagation speed sharply rises, reaches a maximum and then decreases due to the increased pressure of the unburned mixture. The effect of the fuel and turbulence is evident looking at the diagrams reported in Figure 1. In particular, at minimum load the flame front propagation speed is low as the turbulence is mainly due to the motion of the piston. On the other hand, at full load the increased turbulence in the combustion chamber leads to a higher flame front propagation speed. Nevertheless, for both the operating conditions, the flame front propagation speed is highest for gasoline fuel.
Figure 2 shows the emission spectra versus wavelength for methane and gasoline in correspondence of the spark plug at typical combustion phases.
At 24 cad BTDC, SOS, it is possible to observe the presence CN, C_2, and CH radicals due to the interaction between air and fuel mixture during the spark ignition. All the spectra show a strong peak centred at 309 nm due to OH radical emission. Moreover, a broadband emission, from 250 to 500 nm, is detected. This band is due the convolution of HCO Vayda bands from 250 nm to 410 nm, and HCHO Emeleus bands from 340 nm to 523 nm [4]. As the temperature increases, the radical emissions strongly rise. The OH and HCO contributions to the emission spectra are well resolved both for gasoline and methane. Moreover, the spectra are characterized, mainly for gasoline, by a strong continuous contribution that increases with the wavelength in the visible range. This band, typical of blackbody emission is due to the soot particles due to the diffusion-controlled flame caused by the fuel film deposition on the intake valve [5].

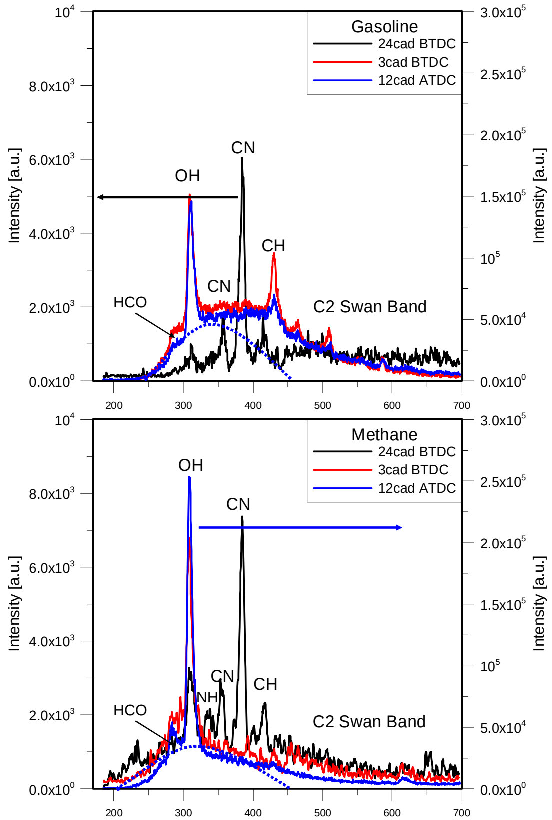

Figure 2. Gasoline and methane emission spectra for typical crank angle.

Particular attention was devoted to OH and CH radicals.
The OH radical is formed in the primary combustion zone of the chemiluminescence:

$$CH + O_2 \rightarrow CO + OH$$

The light emission of the OH radical is a marker of the combustion reaction, and its intensity depends on the local temperature and air/fuel ratio [4]. In particular, the locations with high values of intensity of OH are characterized by an air / fuel ratio near to the stoichiometric.
The radical CH could be formed from the following reaction:

$$C_2 + OH \rightarrow CO + CH$$

The production of the CH radical is strongly dependent on the temperature [6], so there are high levels of CH at high temperatures. The presence of the radical CH is a marker of the break of the fuel into simple hydrocarbons. It is a very unstable specie then tends to react quickly with other molecules. High signal of the CH emission intensity indicates that the fuel is not fully vaporized.

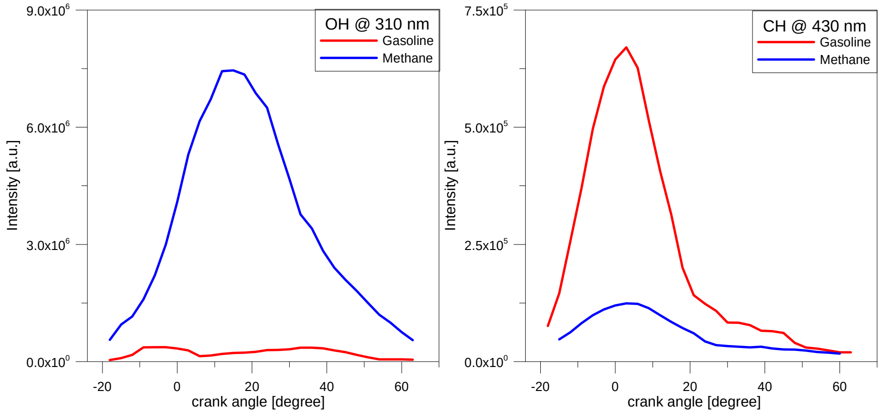

Figure 3. OH and CH radical emissions vs. crank angle for gasoline and methane.

The temporal evolution of OH and CH radical emissions from the SOS until the end of combustion in the spark plug location is shown in Figure 3. OH radical signal is higher for the methane; this is imputable to a better mixing of air and fuel and to the presence of a larger amount of oxygen resulting in higher local temperatures. The CH signal, instead, is higher for gasoline fuel. The presence of more complex hydrocarbons with high molecular weight makes more difficult the fuel vaporization that continues during the whole combustion process.

Conclusions

2D-digital imaging were used to follow the flame propagation in the combustion chamber. UV-visible spectroscopy was performed to obtain detailed information on the chemical species involved during the combustion process. The experiments were performed in a transparent single-cylinder spark ignition port-fuel injection engine fuelled with gasoline and methane.

Digital imaging highlighed that the flame propagation speed is higher for gasoline combustion. Natural emission spectroscopy in the UV-Visible range showed that the spark ignition combustion was featured by CH, OH, HCO, C_2 radicals and formaldehyde molecules. Moreover, the spectra are characterized by a strong continuous contribution typical of blackbody-like emission of the soot particles. The temporatl evolution of OH and CH radical signals point out a worst evaporation and mixing for gasoline imputable to the presence of more complex hydrocarbons with high molecular weight.

References

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