

Characterization of CH₄ and CH₄/H₂ Mixtures Combustion in a Small Displacement Optical Engine

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ABSTRACT

In the last years, even more attention was paid to the alternative fuels which can allow both reducing the fuel consumption and the pollutant emissions. Among gaseous fuels, methane is considered one of the most interesting in terms of engine application. It represents an immediate advantage over other hydrocarbon fuels leading to lower CO₂ emissions; if compared to gasoline, CH₄ has wider flammable limits and better anti-knock properties, but lower flame speed. The Addition of H₂ to CH₄ can improve the already good qualities of methane and compensate its weak points. In this paper a comparison was carried out between CH₄ and different CH₄/H₂ mixtures. The measurements were carried out in an optically accessible small single-cylinder, Port Fuel Injection spark ignition (PFI SI), four-stroke engine. It was equipped with the cylinder head of a commercial 250 cc motorcycles engine representative of the most popular two-wheel vehicles in Europe. Optical measurements were performed to analyze the combustion process with 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 gaseous analyzers. The measurements were performed under steady state conditions at different engine speed in order to evaluate the interaction of turbulence with the kernel and the interaction with the local flame. All the results highlight the combustion promotion due to the hydrogen addition.

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INTRODUCTION

In urban area motor vehicles are the main sources of pollutant emissions such as CO₂, NO_x and particulate matter (PM). They are mainly influenced by the engine and fuel type. Growing concerns on the environmental issues due to engines emissions has led most nations to propose even more stringent standards for both engines and fuels in order to reduce fuel consumption and pollutant emissions from cars and motorcycle, making the reduction of these emissions no more an option but a necessity. Great efforts are devoted to the optimization of combustion process to reduce simultaneously the fuel consumption and the pollutant emissions. In this sense, even more attention has been paid to the alternative fuels that allow both reducing the fuel consumption and the pollutant emissions. Methane fuel is considered a promising alternative fuel to petrol for internal combustion engines [1]. As today methane is widely used in public transport vehicles in Asian countries, in US and Europe and several other countries [2]. It represents an

immediate advantage over other hydrocarbon fuels because of the lower C/H ratio resulting in reduced CO₂ emissions. Furthermore, it has a higher Research Octane Number (RON) which permits higher compression ratios, which in turn increases the efficiency; a higher boost in turbocharged engines and the knock sensitivity is reduced. Moreover, it has a higher Lower Heating Value (LHV) and a higher stoichiometric air/fuel ratio. On the other hand, the air displacement due to the gaseous state of methane at inlet conditions result in to a loss of performances and lower heat release rates of methane air mixtures with respect to the gasoline air mixtures. Nevertheless, the major drawbacks of the use of methane in the spark ignition engines are the slow flame propagation speed and its poor lean-burn capability as these will decrease the engine power output and increase the fuel consumption [3]. The flame propagation speed strongly depends on the turbulence and the air/fuel ration. In particular, can be improved increasing the turbulence or decreasing of the air/fuel ratio [4]. An effective way to solve the problem of the slow burning velocity and thus to improve

the efficiency of the engine is to mix the methane with a high burning velocity fuel. Hydrogen is an excellent additive as its laminar burning velocity is seven times to that of methane [5,6,7]. Moreover, hydrogen is characterized by a more stable combustion resulting in a wider combustion limit and low ignition energy, contributing to the extension of lean operation limit [8,9,10,11].

In this paper the methane and methane/hydrogen blends were characterized as fuels for internal combustion engines, through the analysis of the combustion process, the engine performance and the pollutant emissions. The measurements were performed on a small displacement transparent single cylinder Port Fuel Injection spark ignition (PFI SI) engine. The engine was fuelled with pure methane (M) and methane/hydrogen blends at 20% v/v (20MH₂) and at 40%v/v (40MH₂) of hydrogen in methane. Two engine operative conditions were investigated: 2000 rpm WOT (wide open throttle) and 3000 rpm WOT. A combination of optical techniques was applied to better analyze the combustion process. In particular, high-speed 2D-digital imaging measurement in the UV-visible range was performed. As known this technique is widely used to investigate the flame propagation. The chemiluminescence emission from OH* and CH* were measured using two band pass filters FWHM to evaluate the combustion process qualitatively. Moreover, a detailed analysis of the effect of the fuels on the combustion process was carried out by means of the flame emission spectroscopy in the UV-visible range. The HC and NO_x emissions were measured at the exhaust by means of conventional instruments.

EXPERIMENTAL SET UP

Engine

The experimental activity was performed on an optical single-cylinder, PFI SI, four-stroke engine. Details about the engine characteristics are reported in [Table 1](#).

Table 1. Specifications of the PFI SI single cylinder engine

Displacement [cm ³]	250
Bore [mm]	72
Stroke [mm]	60
Connecting road [mm]	130
Compression ratio	10.5:1
Maximum Power [kW]	7.9 @ 5000rpm
Maximum Torque [Nm]	14.7 @ 5000rpm

The optical engine was characterized by an elongated cylinder and a piston provided with a sapphire window which replaces the flat-bottom piston bowl (Bowditch-pistons). The engine was 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.

The engine was equipped with the cylinder head of a commercial 250 cc motorcycles widely used in Europe. A four-valve, pent-roof chamber engine was mounted on an elongated piston. The engine reached a maximum speed of 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. A crankshaft encoder with a resolution of 0.1 crank angle degree (cad) was used to trigger the pressure measurements. 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 [12]. The intake air temperature was fixed at 298 K and the cooling water temperature was set at 333 K. The air fuel ratio was measured by a linear lambda sensor.

Optical Facility

High-speed 2D-digital imaging and UV-visible spectroscopic techniques were used. Optical measurements were performed by systems depicted in [Figure 1](#).

During the combustion the light emission 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. The chemiluminescence signals were detected with a high spatial and temporal resolution by means of a Pimax Intensified Charged Couple Device (ICCD) camera, having high sensitivity both in the UV and visible range. For chemiluminescence imaging the ICCD was couple with a UV Nikon 78 mm focal length, f/3.8. The chemiluminescence emissions were also acquired with the ICCD using UV and visible narrow band pass filters chosen at characteristic wavelength of $\lambda=309$ nm $\lambda=431$ nm, typical of chemiluminescence emissions of OH* and CH*, considered significant in the combustion process [13].

In case of UV-visible spectroscopy measurements, instead, the chemiluminescence signals were collected and focused on the entrance slit of an Acton spectrometer through an UV-visible objective. 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 ICCD camera. The spectrometer field of view was due to the magnification of the optics, the slit height (14 mm) and width, pixel size and ICCD format. The recorded data contained spectral information along the rows of the ICCD and spatial information along the columns. In this work, the width slit was fixed at 250 μ m and it was located in front of the combustion chamber. Data were detected with the spectrograph placed at two central wavelengths, 325 and 575 nm, in order to investigate a wider spectral range. The intensifier-gate duration was set to 2 cad, corresponding to 166.6 μ s and 111 μ s at 2000 rpm and 3000 rpm respectively, both for chemiluminescence imaging and UV-visible spectroscopy in order to have a good accuracy in

the timing. The synchronization of the ICCD camera with engine was driven by the crank angle encoder signal through a delay unit. AVL Indimodul recorded the TTL signal of ICCD acquisition together with the pressure trace from the pressure transducer. In this way, it was possible to determine the crank angles where optical data were detected.

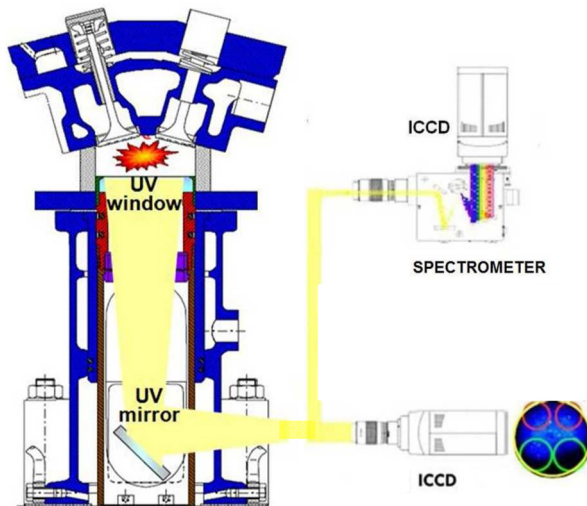
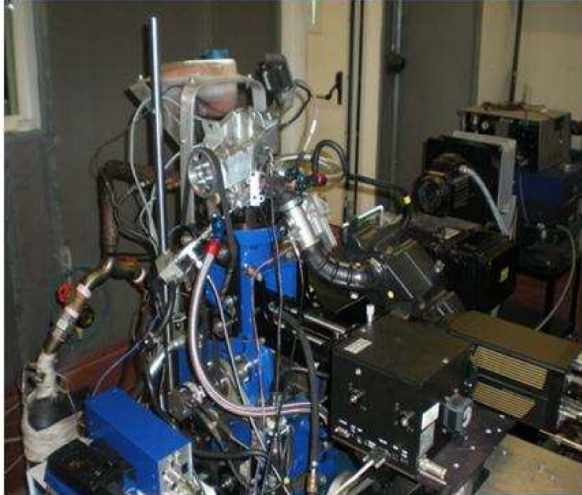


Figure 1. Experimental engine (up) and optical setup for UV - visible imaging and spectroscopic measurements (down)

A post-processing of the optical data was carried out by Labview™ of national instruments to obtain geometrical information from each average image, such as the mean radius of flame front and the penetration length of the injection jets. As regards combustion evolution, every image was processed subtracting the background and fixing a threshold of 5% with respect to its maximum light intensity. The background was detected in motored condition before the acquisition of all sequences. This methodology is able to evaluate only the 2D projection of the actual flame front [14] and then allowed obtaining the flame area and the flame outline. In particular, the procedure labeled all the outline

points and evaluated the centroid position and the distances of each point from it, along six different directions. The flame radius was obtained for each image by the average on these six distances. The local light signal in each point of the combustion chamber was evaluated by processing each image. In this way, it was possible to identify the flame front, its mean diameter and then the flame front mean propagation speed. The flame radius curve was calculated by a non-linear regression analysis (third degree polynomial function) using the flame radius extracts from the average image for each crank angle. The flame front propagation speed was calculated as the time rate of change of the flame radius. Considering that each single frame belongs to a different engine cycle cycle-to-cycle variability was taken in to account, we obtain a statistics based on 250 cycles. In this way, we have a good accuracy on the R trend. In particular, in the worst case in terms of cycle-to-cycle variability, we get the coefficient of determination $R^2 = 0.95$ using only 3 images for each crank angle. Using 10 images the R^2 was equal to 0.99.

Fuel

The engine was fuelled with pure methane (M) and methane/hydrogen blends at 20% v/v (20MH₂) and 40%v/v (40MH₂) of hydrogen in methane. Gaseous fuels were supplied by pressurized bottle using a pressure regulators typically set to 5 bar. A NGI Bosch single-hole injector was used for all the gaseous fuels. The main chemical and physical properties for net methane and net hydrogen are reported in Table 2.

Table 2. Chemical and physical properties

Fuel property	Methane	Hydrogen
Formula	CH ₄	H ₂
Molecular weight [kg/kgmole]	16.04	2.016
C/H ratio [%]	0.25	0
Density @ NTP [kg/Stm ³]	0.67	0.08
Boiling point [°C]	-161.4	-252
Low heating value [MJ/kg]	50	120
Research Octane Number	>120	/
Flammability limit [% vol]	5.3/14	4/75
Stoichiometric air/fuel ratio [Kg _{air} /Kg _{fuel}]	17.24	34.20
Laminar burning velocity [m/s]	0.3-0.35	2-4

Exhaust Measurements

Steady-state measurements of HC and NO_x were made in the raw exhaust. HC emissions were measured by means of a Hewlett Packard 5890 gas chromatograph and by means of a non-dispersive infrared detector (NDIR). NO_x emissions were detected by means of an electrochemical sensor.