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# Analysis of combustion of methane and hydrogen–methane blends in small DI SI (direct injection spark ignition) engine using advanced diagnostics

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ABSTRACT

In the last years, even more attention was paid to the alternative fuels that allow reducing the fuel consumption and the pollutant emissions. Gaseous fuels like methane and hydrogen are the most interesting in terms of engine application. This paper reports a comparison between standard gasoline fuel, methane and different methane/hydrogen blends in a transparent single-cylinder DI SI (direct injection spark ignition) engine representative of the small displacement gasoline engine for automotive application. Engine performance and regulated exhaust emissions were evaluated under steady state condition at 2000 rpm – full load, and stoichiometric condition. 2D-digital cycle resolved imaging measurements were performed from the start of injection to the end of combustion. They allowed the characterization of the gaseous and liquid injection and the flame propagation, in terms of the mean radius and velocity. The combustion promotion due to the hydrogen addition and its contribution to the reduction of the pollutant formation were estimated.

## 1. Introduction

The internal combustion engines are the main source of pollution in the urban areas as they are the most commonly used for automobiles. For this reason, the worldwide emissions standards are getting stricter. This means that the combustion process has to be further improved. Moreover, the petroleum resources depletion makes the need of more sustainable fuels important not only from an ecologic point of view. Therefore, increasing efforts are paid to research more eco-friendly fuels. The use of gaseous fuels is prompted over the last decade because of the development of lightweight high-pressure storage cylinders and its availability in several areas at low price. Moreover, the combustion of gaseous fuels is cleaner with respect to liquid fuels. CO, PM (particulate matter) as well as $CO_2$ emissions are strongly reduced because of the low carbon-to-hydrogen ratio. Furthermore, NOx emissions decrease thanks to the lower in-cylinder temperature. Methane properties make it suitable for the use in the spark ignition engines [1]. It has a high octane number, and hence high auto-ignition temperature and anti-knocking property. Furthermore, SI (spark ignition) engines fueled with methane can run at higher compression ratios, thus producing higher thermal efficiencies. On the other hand, the typical slow burning velocity, the poor lean-burn capability, and the air displacement, contribute to large cycle-by-cycle variations, lower engine power output and large fuel consumption [2]. The air displacement is strongly reduced when the methane is direct injected. The slow burning velocity can be improved by mixing methane with hydrogen [3,4], whose burning rate is seven times higher than methane in stoichiometric conditions [5–7]. Its wide flammability limits and its low quenching gap contribute to the extension of lean operation limit enhancing thermal efficiency [8–11]. The absence of carbon in hydrogen fuel contributes to further reduce the CO, $CO_2$ and HC emissions.

The most extensive research activity has been performed on PFI (port fuel injection) SI engines, where hydrogen and methane have been premixed and injected. On the other hand, few papers have been published on the use of natural gas DI (direct injection) [7,12–17]. It was found out that the direct injection of natural gas could improve the combustion performing the stratified combustion, leading to better fuel consumption, reduced combustion duration, and extended lean limit. Although various technical problems of methane–hydrogen SI engines have been tackled and

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solved, little work has been published on the use of optical diagnostics to investigate in cylinder process during the methane and hydrogen combustion in a PFI [18,19] and DI engine [20–22]. Nevertheless, these papers even if deal with direct injection, did not show the methane/hydrogen spray evolution. The aim of the paper is a comparison between standard gasoline fuel and methane, and different methane/hydrogen blends in a transparent single-cylinder DI SI direct injection spark ignition engine representative of the small displacement gasoline engine for automotive application. 2D-digital cycle resolved imaging was performed with high temporal resolution in the combustion chamber in order to characterize not only the flame propagation in terms of mean radius and velocity but also the injection phase of both liquid and gaseous fuels. In particular, for the gaseous fuels it was necessary the seeding of the gas with solid particles able to scatter the light. The combustion promotion due to addition of hydrogen to methane and their contribution to engine performance and reduction of pollutant formation were evaluated.

## 2. Experimental apparatus and procedures

### 2.1. Engine

The experimental activity was carried out on a transparent single cylinder direct DI SI engine. Fig. 1a reports the single-cylinder four-stroke engine. It was equipped with the cylinder head of small GDI (gasoline direct injection) engine and six holes injector located between the intake valves for the gasoline injection and a single hole injector, designed and realized in Istituto Motori, for the methane and methane–hydrogen blends (Fig. 1c and d). The engine was not equipped with any after-treatment device. The head had four valves and a centrally located spark plug. Details about the engine characteristics are reported in Table 1. 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 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 (Fig. 1 a).

To reduce the window contaminations by lubricating oil, an elongated piston arrangement was used together with unlubricated Teflon–bronze composite piston rings in the optical section.

All the tests were carried out fixing the absolute intake air pressure and temperature at 101 KPa and 303 K, respectively, and the water temperature at 323 K. More details and specifications on both the engine and injection systems are reported in Ref. [5].

In Fig. 1, the sketch of the bottom field of view of the combustion chamber is reported. The in-cylinder pressure measurements for the present study were conducted with a water-cooled piezoelectric pressure transducer that was flush-installed in the region between intake–exhaust valves.

The injection parameters, such as the ignition timing and the injection duration, were set by means of an electronic unit. An optical shaft encoder was used to transmit the crank shaft position to the electronic control unit. The information was in digital pulses, the encoder has two outputs, the first is TDC (top dead center) index signal, and it has a resolution of 1 pulse/revolution. The second is the CDM (crank angle degree marker) 1 pulse/0.2°. The engine is a 4-stroke and the encoder gives as output two TDC signal per engine cycle so, in order to have the right crank shaft position, one pulse is suppressed via software. A quartz pressure transducer was flush installed in order to measure the in-cylinder pressure with a sensitivity of 19 pc/bar and a natural frequency of 130 kHz.

The in-cylinder pressure measurements, performance, and emissions were measured for all the tested fuels investigated. A data acquisition system was used to evaluate the sensors signals. Thermodynamic analysis was done on the pressure traces using methods published in Ref. [5]. The in-cylinder pressure, the rate of chemical energy release and the related parameters were obtained on an individual cycle basis and/or averaged on 400 cycles. The performance in terms of the IMEP (indicated mean effective pressure) and the CoV (coefficient of variance) of IMEP was assessed as well.

The exhaust pipe was equipped with gas analyzers for measuring regulated gas and opacity. CO, CO2 and HC were measured by a non-dispersive infrared detector; NOx and O2 were detected by means of an electrochemical sensor. Methane HC emissions were measured by means of Hewlett Packard 5890 gas chromatography. The smoke was measured by an opacimeter that measures the visible light attenuation from the exhaust gases. The opacity percentage was converted to Bosch smoke number called FSN (filter smoke number) and then in particulate mass concentration by means of an empirical relation [23].

### 2.2. Engine operating conditions

Engine was operated at 2000 rpm – full load for all fuel investigated. This condition was selected as representative point of the

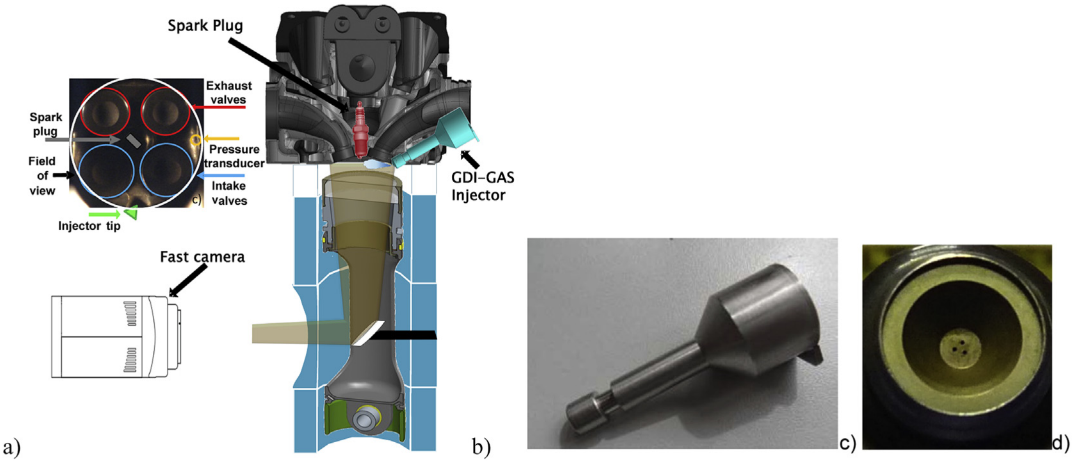

**Fig. 1.** Engine layout (a) and optical apparatus (b); methane direct injector adapter (c) and gasoline injector holes (d).