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Analysis of energy efficiency of methane and hydrogen-methane blends in a PFI/DI SI research engine

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ABSTRACT

In the last years, even more attention was paid to the alternative fuels that allow both reducing the fossil 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 methane and different methane/hydrogen mixtures in a single-cylinder Port Fuel/Direct Injection spark ignition (PFI/DI SI) engine operating under steady state conditions. It is representative of the gasoline engine for automotive application. Engine performance and exhaust emissions were evaluated. Moreover, 2D-digital cycle resolved imaging was performed with high spatial and temporal resolution in the combustion chamber. In particular, it allows characterizing the combustion by means of the flame propagation in terms of mean radius and velocity. Moreover, the interaction of turbulence with the local flame was evaluated.

For both the engine configurations, it was observed that the addition of hydrogen results in a more efficient combustion, even though the engine configuration plays an important role. In PFI mode, the lower density of hydrogen causes a lower energy input. In DI mode, instead, the larger hydrogen diffusivity counteracts the charge stratification especially for larger hydrogen content.

1. Introduction

The fossil fuels are widely used for the energy production [1]. Their consumption is progressively increasing not only because of the population growth but also because of the improved standard of living. The combustion products of these fuels, such as carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOx), hydrocarbon (HC) and particulate matter (PM) are the major causes of many human health and environmental issues [2]. The depletion of the petroleum reserves and the deterioration of the quality of the air prompt for a more rational use of the energy resources as well as the increase of environmental restrictions. The adoption of alternative fuels with a low environmental impact, such as methane and hydrogen can be the solution to these problems.

Methane is an effective substitute to traditional fuels because of the reduced pollutant and carbon dioxide emissions [3]. Moreover, the high knocking resistance makes it suitable for spark ignition (SI) engines as it allows increasing the compression ratio, thus boosting the engine efficiency. On the other hand, the poor lean-burn capability of the methane and the lower burning speed result in reduced engine power output, large cycle-to-cycle variability as well as increased fuel consumption with respect to the liquid fuels [4]. The use of hydrogen as an additive allows a reduction of cyclic variation as well as the extension of lean operation limit because of the wider burning range and the lower quenching gap [5–14]. Moreover, hydrogen can accelerate the methane combustion since its burning rate is seven times higher than that of methane [15–18]. Another positive aspect of hydrogen addition is the CO_2 savings due to the absence of carbon in hydrogen fuel.

On the other hand, the methane and hydrogen at inlet conditions occupy a fraction of intake air because of their gaseous state (air-displacement) resulting in low volumetric efficiency and loss of performances. This drawback can be overcome with the direct injection of the gaseous fuels.

The effect of the addition of hydrogen in methane was analyzed more on port fuel injection (PFI) spark ignition (SI) engines [19–21] than on direct injection (DI) SI engines [22–24]. For both PFI and DI SI engines, it was found out that hydrogen addition results in higher thermal efficiency, reduction of combustion duration and ignition delay. Nevertheless, the effect of hydrogen on methane combustion

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depends on the injection configuration. Some hydrogen properties could, in fact, improve or worsen the methane combustion according to the engine configuration.

In this paper, a direct comparison between the effects of hydrogen addition on the efficiency of the combustion was carried out on the same SI engine equipped with both the PFI and DI injection systems. The experimental activity was carried out on a small transparent single cylinder PFI/DI SI engine representative of the most used gasoline engine for automotive application. The engine was fueled with pure methane and methane/hydrogen blends at 20% v/v and at 40%v/v of hydrogen in methane. The tests were performed at 2000 rpm medium load, chosen as typical of urban driving condition. Engine performance and pollutant emissions were measured. The analysis of the combustion process was performed through a combined thermodynamic and optical investigation. The in-cylinder pressure measurements give cycle-resolved overall information on the combustion process but optical techniques are a powerful tool for detailing the combustion process with high spatial and temporal resolution allowing a local analysis. In particular, digital cycle resolved imaging was performed in the combustion chamber to better analyze the effect of hydrogen on kernel formation and to characterize the flame propagation in terms of mean radius and velocity.

2. Experimental apparatus and procedure

2.1. Engine

The investigation was performed on a transparent single cylinder small displacement spark ignition engine (Fig. 1a). It was equipped with the cylinder head of GDI 250 cm^3 engine. For the direct injection of methane and methane/hydrogen blends a single-hole injector located between the intake valves was used. This injector was designed and realized in Istituto Motori. The intake manifold was equipped with a single-hole gas injector in order to perform the Port Fuel Injection. The engine head had four valves and a centrally located spark plug. A quartz pressure transducer was flush-installed in the region between intake-exhaust valves. The engine was not equipped with any after-treatment device. Further details are shown in Table 1.

The engine piston was flat and transparent through a sapphire window (Fig. 1b). 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. In Fig. 1c, the sketch of the bottom field of view of the combustion chamber is reported.

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 at the bottom of the engine. The chemiluminescence signals of the combustion were focused by a 78 mm focal length, f/3.8 UV Nikon objective onto the ICCD (Intensified charge coupled device) camera (Fig. 1b–c). The ICCD had an array size of 1024 × 1024 pixels. The ICCD spectral range spreads from UV (180 nm) up to visible (700 nm). The frame rate is about 8 fps at 10 MHz. For all the optical measurements, the synchronization between the camera and the engine was made by a crank angle encoder signal through a unit delay. The camera was not cycle resolved so each image was detected at a fixed crank angle of different engine cycles.

2.2. Methodology/Procedure

The effect of hydrogen addition on the combustion was characterized by means of the analysis of the thermodynamic data, such as the in-cylinder pressure, and the natural flame luminosity.

In particular, from the in-cylinder pressure some valuable parameters for combustion analysis was obtained: the indicated mean effective pressure (IMEP), the Rate Of Heat Release (ROHR), calculated from the first law of thermodynamics, and the delay of the combustion (DoC), evaluated as the difference between the start of combustion (SOC) and the start of spark (SOS).

For a comprehensive analysis of the kernel formation and the

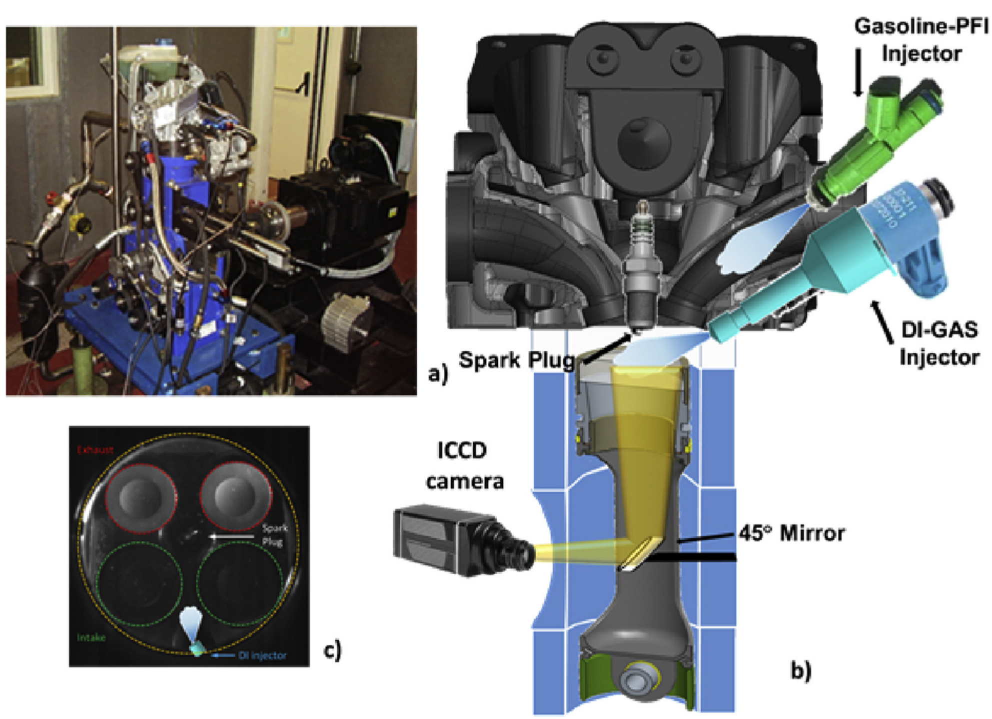

Fig. 1. Sketch of the engine a), Optical setup for digital imaging b), Field of view of the combustion chamber c).

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