

Effect of the Engine Head Geometry on the Combustion Process in a PFI Boosted Spark-ignition Engine

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ABSTRACT

In this work, a boosted single-cylinder spark ignition port-fuel injection optical engine was used for the experimental activity. Firstly, it was equipped with a four-valve head of a commercial turbocharged multi-cylinder engine. Then a prototype engine head with flush installed intake valves was tested. The effect of the different head geometry was evaluated in closed intake valves fuel injection condition. High spatial resolution cycle-resolved digital imaging was used to characterise the flame propagation. Moreover, the presence of diffusion-controlled flames near the valves and on the cylinder walls was investigated. These flames induced the formation of unburned hydrocarbons and soot particles. The spatial distribution and temporal evolution of soot were evaluated by the two colour pyrometry. The prototype configuration showed higher combustion process efficiency than the standard one inducing a little increase in performance and a slight reduction in carbon oxides emissions. Moreover, a strong decrease in exhaust soot and unburned hydrocarbons was measured.

INTRODUCTION

The internal-combustion engines burning petroleum-derived hydrocarbon fuels power represent almost the totality of the passenger cars in the world. Referring to the gasoline-fuelling, the Port-fuel injection (PFI) spark ignition (SI) engines are predominant.

At present, this kind of engines shows some fundamental limitations: one of them is the throttle load control, which induces pumping losses at partial loads. Moreover, the knock phenomenon limits the engine compression ratio under low speeds and high loads. Finally, the stoichiometric air-fuel mixture is necessary for the three-way catalysts operations but it increases the emission of CO₂. The optimization of the PFI SI engines in terms of fuel consumption and pollutant emissions reduction is a strong requirement. This target should be reached together with the market demand of high performance, durability, and reliability at an affordable price. The downsizing is today considered the best way to improve fuel economy with a good cost to benefit ratio for the SI engines.

The downsizing permits the increase in the engine power and torque without increasing the cylinder capacity [1, 2]. This reduces the fuel consumption through the pumping losses reduction. Smaller internal surface areas and shorter flame travel distances due to the lower engine capacity decrease the gases-to-wall heat transfer. Moreover, thanks to smaller moving parts, lower friction losses are obtained. On the other hand, the output performance must be increased of a ratio equal to the reduction in the engine displacement. Thus, the air boosting becomes necessary.

The fuel and air mixing in the PFI SI engines has always been a critical factor. In the intake manifold the increase in pressure and thus in turbulence due to the boosting

has enhanced the need of knowledge about the fuel-air mechanisms. Under steady conditions, the liquid spray from the jet breaks up into droplets that are transported downstream in the air stream. Droplet break-up, evaporation, collision and coalescence occur and a proportion of the drops deposit on surfaces such as the duct walls or cylinder inlet valves forming wall films [3 - 8]. These films induce mixture imbalances in the combustion chamber not only in the cold start conditions but also in fully warmed-up ones with higher fuel evaporation potentiality. Many experiments demonstrated that the fuel deposition in the intake manifold induced spatial fuel misdistribution within the cylinders [9 - 11]. This occurred because the droplets and the films within the port could pass, through open inlet valves with some re-atomization and re-deposit on the piston crown and cylinder walls. During the spark ignited combustion process, it is possible to achieve gas temperature and mixture strength conditions that lead to the ignition of the fuel deposits creating diffusion-controlled flames that persist after the normal combustion event. These flames produce soot which cannot be completely oxidized because of insufficient in-cylinder temperatures. Thus, the flames occurrence at the exhaust valves opening leads to an increase in smoke and hydrocarbons emissions at the exhaust [12, 13].

In this paper, the effect on the combustion process of the engine head geometry in a boosted PFI - SI engine was investigated. The experiments were realized in the combustion chamber of a single-cylinder optical engine fuelled with European commercial gasoline. Firstly, the engine was equipped with a real four-valve head and then with a selected prototype head with flush installed intake valves. The effect of the prototype head was tested in closed valves fuel injection condition. High spatial resolution cycle-resolved digital imaging was used to follow the flame propagation in the combustion chamber. Moreover, the influence of the head geometry on the diffusion-controlled flames near the valves and on the cylinder walls was studied by the two colour pyrometry, too. It allowed to measure the soot temperature and concentration [14]. The in-cylinder optical investigations were correlated with the engine performances and emissions.

EXPERIMENTAL APPARATUS

TRANSPARENT ENGINE

An optically accessible single cylinder PFI SI engine was used for the experiments. The engine was firstly equipped with the standard head of a multi-cylinder SI turbocharged engine. Then the head was modified in

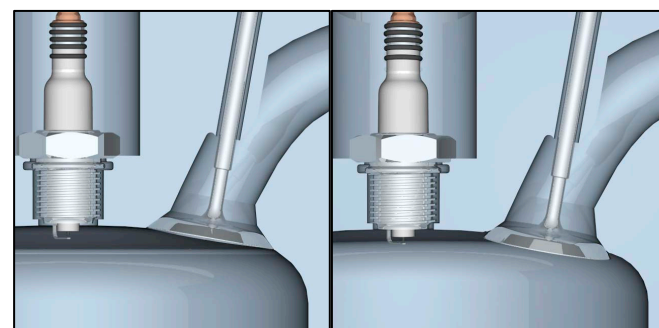
order to embed the intake valves in their seats. Both the heads had four valves and a centrally located spark plug. Details about the engine are reported in Table 1.

An external device could control the intake air pressure in a range of 1000 - 2000 mbar and the temperature in a range of 290 – 340 K. The engine piston was flat and its upper part was transparent because of a quartz window ($\phi=57\text{mm}$). To reduce the window contamination by lubricating oil, an elongated piston arrangement was used together with unlubricated Teflon-Bronze composite piston rings in the optical section.

A quartz pressure transducer was flush-installed in the region between intake-exhaust valves. Combustion pressure measurements were performed for all the selected operating conditions. 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 200 cycles from the cylinder pressure data using conventional interpretation models [15].

Displacement	399 cm ³
Bore	79.0 mm
Stroke	81.3 mm
Connecting road	143 mm
Compression ratio	10:1

Table 1. Specifications of the single cylinder ported fuel injection (PFI) boosted engine.



Standard

Prototype

Figure 1. Standard assembly and prototype one with intake valve flushed installed.

SETUP FOR OPTICAL MEASUREMENTS

Figure 2 shows the experimental apparatus for optical investigations. During the combustion process, the light passed through the quartz window and it was reflected toward the optical detection assembly by a 45° inclined UV-visible mirror located in bottom of the engine.

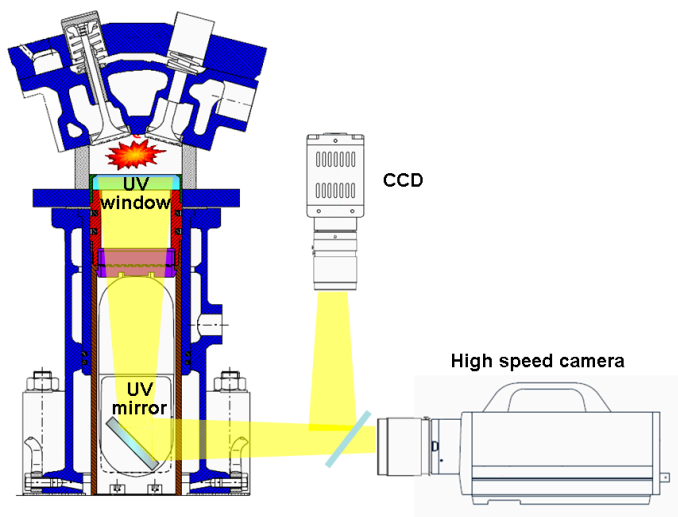


Figure 2. Sketch of the optical engine and experimental setup for the cycle resolved and colour digital imaging.

The cycle resolved flame visualization was performed by 8-bit high speed camera (512 x 512 pixel) equipped with a 50 mm focal Nikon lens. The spectral range of the high speed camera extended from 400 nm to 900 nm. A camera region of interest was selected (400 x 400 pixel) to obtain the best match between spatial and temporal resolution. This optical assessment allowed a spatial resolution around 0.2 mm/pixel and a frame rate of 6470 fps. The exposure time was fixed at 10 μ s that corresponds to about 0.12 CAD at engine speed of 2000 rpm and the dwell time between two consecutive images was around 1.8 CAD.

2D soot flame visualization was obtained by a 12-bit digital CCD colour camera coupled with a 50 mm focal length f/3.8 Nikon lens. The CCD had a 640 x 480 pixel matrix with a pixel size of 9.9 x 9.9 μ m². This optical assessment allowed a spatial resolution around 0.1 mm/pixel. The spectral range of the camera was 290-800 nm. Spatial distribution of soot temperature and concentration was obtained by two colour method. The soot-emission wavelengths were selected by edge filters. More details about this methodology are reported in [14, 16]. The exposure time was fixed at 41.6 μ s that corresponds to 0.5 CAD at engine speed of 2000 rpm. The camera was not a cycle resolved detector and each image was detected at a fixed crank angle of different engine cycles. The dwell time between two consecutive images was set at 41.6 μ s.

The synchronization between the camera and the engine was made by the Crank Angle Encoder signal through a unit delay. AVL Indimodul recorded the TTL signal from the two cameras acquisitions together with the signals from the pressure transducer. In this way, it was possible to determine the crank angles where optical data were detected.

EXHAUST MEASUREMENTS

Steady-state measurements of CO, CO₂, O₂, HC and NO_x were performed in the raw exhaust by commercial analysers. CO, CO₂ and HC were measured by Non-Dispersive Infrared Detectors (NDIR); NO_x and O₂ were detected through electrochemical sensor. An opacimeter was used to measure particulate mass concentration. The opacimeter is a partial-flow system that measures the visible light attenuation (550 nm) from the exhaust gases. By empirical relations it is possible to convert the opacity percentage in particulate mass concentration [17].

RESULTS AND DISCUSSION

ENGINE OPERATING CONDITIONS

All the tests presented were performed in steady state conditions at engine speed of 2000 rpm and wide open throttle. The engine was stabilized for around 10 seconds before starting the acquisition of optical data and of pressure signals. The absolute intake air pressure and the temperature were set at 1400 mbar and 323 K, respectively.

The engine was fuelled with European commercial gasoline (ON95). The fuel injection always occurred in the intake manifold at the pressure of 3.9 bar when intake valves were closed (start of injection 130 ATDC). The duration of the injection was fixed in order to have a stoichiometric equivalence ratio as measured by an exhaust lambda sensor. The spark timing was fixed at 14 CAD BTDC just before the knock limit as evaluated by the umbrella curve reported in Figure 3.

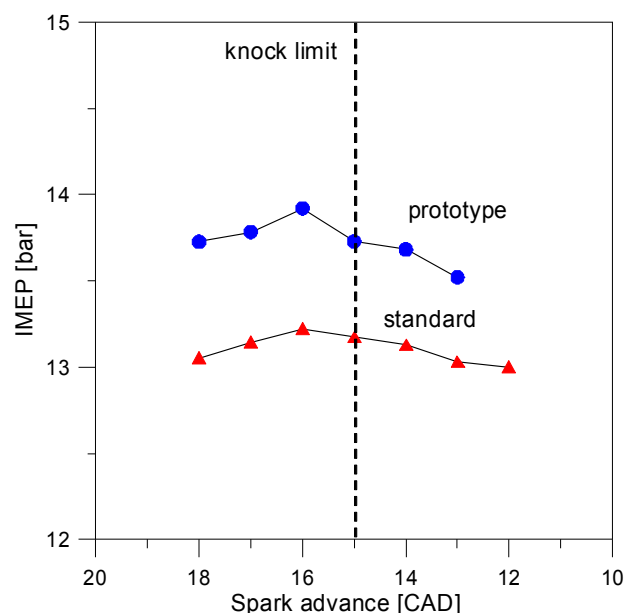


Figure 3. Indicated Mean Effective Pressure (IMEP) evolution versus the spark advance measured by the average on 200 consecutive cycles.