

Effect of Injection Phasing on Valves and Chamber Fuel Deposition Burning in a PFI Boosted Spark-Ignition Engine

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ABSTRACT

A satisfactory answer to the future severe normative on emissions and to the market request for spark ignition engines seems to be the use of downsized engines for passenger cars. Downsizing permits the increase in engines power and torque without the increase in cylinder capacity. The downsizing benefits are evident at part loads; on the other hand, more work should be done to optimize boosted engines at higher and full load. To this goal, a detailed knowledge of the thermo-fluid dynamic processes that occur in the combustion chamber is fundamental.

The aim of this paper is the experimental investigation of the effect of the fuel injection in the intake manifold on the combustion process and pollutant formation in a boosted spark ignition (SI) engine. The experiments were performed on a partially transparent single-cylinder port fuel injection (PFI) SI engine, equipped with a four-valve head and boost device. Different injection strategies at closed and open valve conditions were considered. Moreover the splitting of fuel injection in two and three injections at open-valve conditions were investigated. The effects on performances, gas emissions and pollutant formation were evaluated.

Optical techniques based on 2D-digital imaging were used to follow the flame propagation in the combustion chamber. In particular, the diffusion-controlled flame near the valves and the cylinder walls due to the fuel film burning at different fuel injection strategies were studied. Natural emission spectroscopy was applied to detect the chemical markers of combustion process. Two color pyrometry was employed to measure the soot temperature and concentrations. In-cylinder optical investigations were correlated with the engine parameters and to the exhaust emissions measured by conventional methods.

INTRODUCTION

Future stringent legislation on emissions in combination with the market request of an increase in engine efficiency and optimization poses a great challenge to the engine and components manufacturers. A satisfactory answer seems to be the boosted spark ignition (SI) engine [1].

The boosting enables the replacement of larger engines by downsized ones. Downsizing permits the increase in engines power and torque without the increase in cylinder capacity. This allows to respond to new market demands and in the same time to compensate for vehicle weight increase. The reduction in engine capacity at the same power gives strong benefits in terms of fuel consumption thanks to the pumping losses reduction; in fact the decrease in volume swept on each engine revolution and the increase in average load on driving cycle are realized. Moreover lower engine capacity limits the gases-to-wall heat transfer by a reduced internal surface area and a shorter flame travel distance thanks to a faster combustion. Finally it is possible to obtain lower friction losses due to smaller moving parts.

About the higher average load on driving cycle, the downsizing is more efficient when specific power is increased not by engine speed, but by torque increase on the entire engine speed range. Increased BMEP can be obtained by some technological solutions such as more valves per cylinder, variable valve timing on intake and/or exhaust camshafts and supercharging.

The main limits for downsizing are the knocking, the thermal resistance, the mechanical resistance, engine wear (because of increased BMEP) and eventually supercharging response time. Thus, while downsizing benefits are evident at part loads, more work should be done to optimize boosted engines at higher and full load. The optimization potential is not utilized as there is lack of knowledge about the detailed in-cylinder processes.

The aim of this paper is the experimental investigation of the fuel injection phasing effect on the combustion process and pollutant formation in a port fuel injection spark ignition optical engine, equipped with a four-valve head and external boost device working at full load. Different injection strategy at closed and open valve conditions were considered. Moreover the splitting of fuel injection was investigated. Two and three injection strategies in the intake manifold at open-valve conditions were considered.

As reported in literature, thin films of liquid fuel can form on the valves surface and on the cylinder walls during the fuel injection phase in PFI SI engines [2, 3, 4, 5]. Once formed, the fuel films develop dynamically under the influence of gas flow and valve movement and they affect the complexity of the combustion process [6]. In particular, film vaporization and fire near the valves can reduce the flame speed and the complete flame propagation creating locally rich-zones. During the fuel film-evolution process, it is possible to achieve gas temperature and mixture strength conditions that lead to fuel film ignition, creating a diffusion-controlled flame that can persist well after the normal combustion event. Just before the opening of the exhaust valves, this flame produces soot which cannot be completely oxidized due to the too low temperatures in the cylinder. Chamber locations where the fuel-air mixture is too lean to burn are a particular concern for unburned hydrocarbon emissions. Thus, the fuel film burning leads to an increase in smoke and hydrocarbons emissions [7, 8].

In this paper the effect of the diffusion-controlled flame near the valves and the cylinder walls on carbonaceous compounds formation and particulate emission at the exhaust was evaluated. Optical techniques based on 2D-digital imaging were used to follow the flame propagation in the combustion chamber. Natural emission spectroscopy was applied to detect the chemical markers of combustion process. Two color pyrometry was employed to measure the soot temperature and concentration [9].

EXPERIMENTAL APPARATUS

TRANSPARENT ENGINE

The engine used was an optically accessible single cylinder ported fuel injection (PFI) spark ignition engine. The engine was equipped with the cylinder head of the new generation of SI turbocharged engine. Details about the engine are reported in Table 1. In figure 1 the sketch of the bottom field of view of the combustion chamber is reported.

The head had four valves and centrally located spark plug. A quartz pressure transducer was flush-installed in the region between intake-exhaust valve. Combustion pressure measurements were performed for all the selected operating conditions. The in-cylinder pressure, the rate of chemical energy release and related parameters were evaluated on an individual cycle basis

and/or averaged on 600 cycles from the cylinder pressure data using conventional interpretation models [10].

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 transparent through 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.

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

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

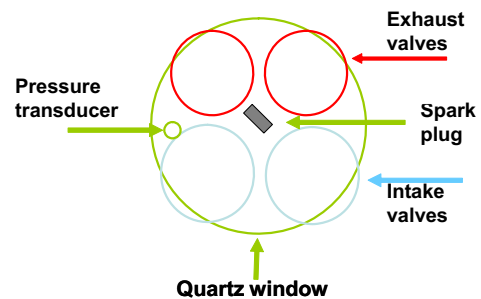


Figure 1. Sketch of the bottom field of view of the combustion chamber.

OPTICAL SETUP FOR OPTICAL MEASUREMENTS

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

2D soot flame visualization was obtained by digital CCD color camera system and a 50 mm focal length, f/3.8 Nikon lens (Fig. 2a). The optical assessment allowed a spatial resolution around 0.1 mm/pixel. Spatial distribution of soot temperature and concentration was obtained by the two color method. The soot-emission wavelengths were selected by edge filters. More details about this methodology are reported in [11, 9].

During the spectroscopic investigations (Fig. 2b), the light from quartz window was focused by a 78 mm focal

length, f/3.8 UV Nikon objective onto the micrometer controlled entrance slit of a spectrometer with 150 mm focal length and 300 groove/mm grating. From the grating the radiations were detected by an intensified cooled CCD camera (ICCD). The ICCD had an array size of 512x512 pixels and 16-bit dynamic range digitization at 100 kHz. The ICCD spectral range spread from UV (180 nm) until visible (700 nm). The ICCD operated at a digitizer offset of about 230 counts, but the dark noise fluctuation in the background was much smaller, less than 50 counts. Dark noise and photon statistical noise were both small compared to the measured intensity.

For all the optical measurements, the synchronization between the cameras and the engine was made by the Crank Angle Encoder signal through an unit delay. The exposure time of the cameras intensifier were fixed at 41.6 μ s. It corresponds to 0.5° crank angle (CA) at engine speed of 2000 rpm. The cameras were not cycle resolved detectors. In this work, 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.

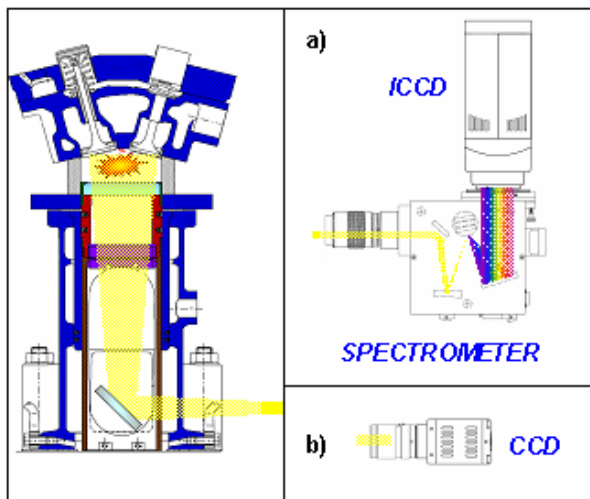


Figure 2. Optical setup for (a) spectroscopic measurements and (b) digital imaging.

EXHAUST MEASUREMENTS

Steady-state measurements of CO, CO₂, O₂, HC and NO_x were made in the raw exhaust by AVL analyzers. CO, CO₂ and HC were measured by Non-Dispersive Infrared Detectors (NDIR); NO_x and O₂ were detected by means of electrochemical sensor. An Opacimeter was used to measure particulate mass concentration. Opacimeter is a partial-flow system that measures the visible light attenuation (550 nm) from the exhaust gases. From empirical relations it is possible to convert

the opacity percentage in particulate mass concentration [12].

RESULTS AND DISCUSSION

ENGINE OPERATING CONDITIONS

All the tests presented in this paper were carried out at engine speed of 2000 rpm and full load. Absolute intake air pressure and temperature were fixed at 1400 mbar and 323 K, respectively. The spark timing was fixed to operate in the MBT condition (14 CAD ATDC). The fuel injection occurred always in the intake manifold at fixed pressure of 3.9 bar.

Several fuel injection strategies were tested. Initially two single injection with the same duration in closed-valve condition (CV1) and open-valve one (OV1) were considered. Then the effect of multiple injections was examined. In particular two fuel injection strategies with two injections, shorter than the previous ones, were analyzed. The (OV2) injection strategy had highest dwell time between the two injections to operate in open-valve condition. OV3 condition was characterized by the minimum dwell time between the two injections allowed by the mechanical inertia of the injector. Finally a three injections strategy (OV4) was investigated. This was the highest number of injections allowed by the mechanical inertia of the injector.

For all the test cases, the duration of injection was chosen to obtain stoichiometric equivalence ratio, as measured by a lambda sensor installed at the engine exhaust. More details about the engine operating conditions are reported in Table 2.

test	Phasing Condition	Duration of Injection [CAD]	Start of Injection ATDC [CAD]
CV1	Closed-valve	142	130
OV1	Open-valve	142	-360
OV2	Open-valve	65	-360
		65	-240
OV3	Open-valve	65	-320
		65	-240
OV4	Open-valve	40	-365
		40	-275
		40	-185

Table 2. Engine operating conditions.

Single Injection Strategy

Figure 3 reports the pressure averaged curves for the two single injection strategies. The related Indicated Mean Effective Pressure (IMEP) and Coefficient of Variation (COV) are listed in Table 3. Even if the cycle-to-cycle variation and the heat transfer between the different components of the optical engine induced a thermal evolution and fluctuation of maximum pressure signal, IMEP and COV resulted good and comparable with those measured for real multi-cylinder engine [1].