

Spectroscopic Investigations and High Resolution Visualization of the Combustion Phenomena in a Boosted PFI SI Engine

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ABSTRACT

High spatial and temporal resolution optical techniques were applied in a spark ignition (SI) engine in order to investigate the thermal and fluid dynamic phenomena occurring during the combustion process. The experiments were realized in the combustion chamber of an optically accessible single-cylinder port-fuel injection (PFI) SI engine. The engine was equipped with a four-valve head and with an external boost device. Two fuel injection strategies at closed-valve and open-valve occurring at wide open throttle were tested.

Cycle-resolved digital imaging was used to follow the flame kernel growth and flame front propagation. Moreover, the effects of an abnormal combustion due to the firing of fuel deposition near the intake valves and on the piston surface were investigated. Natural emission spectroscopy in a wide wavelength range from ultraviolet to infrared was applied to detect the radical species that marked the combustion phenomena in the selected operating conditions. All the optical measurements were supported by the conventional measurements of the engine parameters and exhaust emissions.

INTRODUCTION

Spark Ignition (SI) engines still represent a benchmark in the passenger car market segment. In order to match their high refinement standards and performance levels with the fuel efficiency improvement and pollutant emission reduction, the SI engine upside potential should be developed in a foreseeable future.

Nowadays, downsizing is considered the best way to realise this target. Downsizing allows the increase in

engines power and torque with decreasing cylinder capacity. This permits manufacturers to respond to new market demands and to compensate for vehicle weight increase at the same time. The reduction in engine capacity at the same power gives strong benefits in terms of fuel consumption thanks to the reduction in pumping losses. Moreover, lower engine capacity limits the gases-to-wall heat transfer and the smaller moving parts reduce the friction losses. Finally, technologies such as turbo charging allow an increase in power for downsized engines in order to maintain vehicle performance.

Despite this, several steps are needed for boosted engines optimisation [1]. An improvement in the fundamental understanding of the thermo-fluid dynamic phenomena occurring during the combustion process is required. To this aim, this paper reports the results obtained by experimental investigations of the combustion process and pollutant formation in a port fuel injection (PFI) SI boosted engine.

High spatial and temporal resolution optical techniques were applied in the combustion chamber of a partially transparent engine. 2D-digital imaging and cycle-resolved visualization were applied to follow the flame propagation from the spark ignition to the exhaust phase. Natural emission spectroscopy in the wavelength range UV-IR allowed the detection of the chemical markers of the combustion process. Abnormal phenomena such as the inception of diffusion-controlled flames near the valves and on the cylinder walls due to the fuel deposition burning were also investigated [2, 3]. Two-colour pyrometry was employed to measure the soot concentration due to these flames [4].

EXPERIMENTAL APPARATUS

OPTICALLY ACCESSIBLE ENGINE

The engine used for the experiments was an optically accessible single cylinder PFI SI engine. This engine was equipped with the cylinder head of new generation SI turbocharged engine with the same geometrical specifications (bore, stroke, compression ratio) of the research engine. Further details on the engine are reported in Table 1. The head had four valves and a centrally located spark plug. The injection system was the same mounted on the reference real engine. All details on the injector are reported in Table 2. An external device allowed the control of the intake air pressure in a range of 1000 - 2000 mbar and of the temperature in a range of 290 – 340 K.

Displacement	399 cm ³
Bore	79.0 mm
Stroke	81.3 mm
Connecting rod	143 mm
Compression ratio	10:1
EVO	153 CAD ATDC
EVC	360 CAD ATDC
IVO	357 CAD ATDC
IVC	144 CAD BTDC

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

Technical data		
Flow rate	cm ³ /min	202
β angle	degree	14
α angle	degree	25
γ angle	degree	0
diameter	mm	6.7
SMD	μ m	60-70 (nominal)
Mechanical data		
Max pressure	bar	8
Weight	g	25
Electronic data		
Solenoid resistance	Ω	12
Max. power supply	V	16
Conditions for use		
Fuel input		axial (top-feed)
Operating temperature	$^{\circ}$ C	-40.....110
Permissible fuel temperature	$^{\circ}$ C	70
Installation length	mm	48.65

Table 2. Specifications of the fuel injector.

A quartz pressure transducer was flush-installed in the region between intake-exhaust valves at the side of the spark plug. The transducer allowed to perform in-cylinder pressure real-time measurements. The rate of the chemical energy release and the related parameters were evaluated on an individual cycle basis and/or averaged on 300 cycles using conventional interpretation models [5].

The engine piston was flat and its upper part was transparent because of a fused silica UV enhanced

window ($\Phi=57$ mm). To reduce the window contamination by lubricating oil, an elongated piston arrangement was used together with auto-lubricant Teflon-Bronze composite piston rings in the optical section.

SETUP FOR OPTICAL MEASUREMENTS

Figure 1 shows the experimental apparatus for the 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.

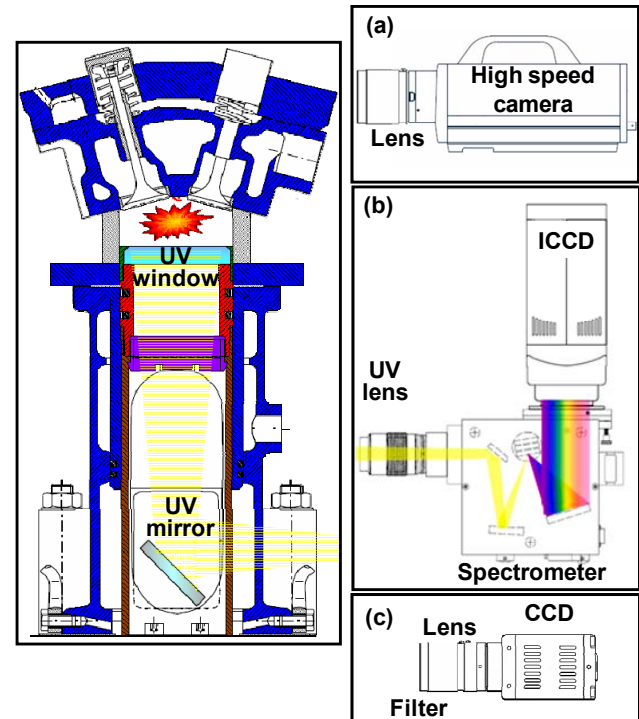


Figure 1. Experimental setup for the optical measurements in the single cylinder PFI SI engine

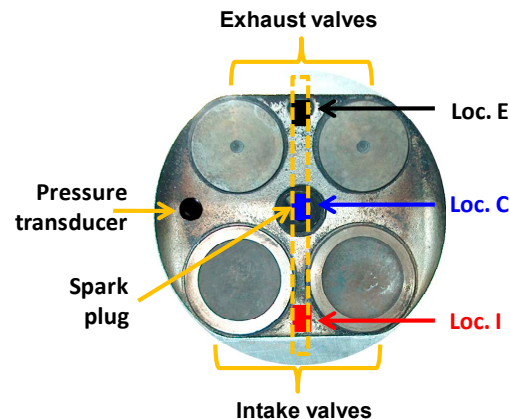


Figure 2. Sketch of the locations for the spectroscopic measurements.

Cycle resolved flame visualization (Fig. 1a) 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.

For the spectroscopic investigations (Fig. 1b), a 78 mm focal length, f/3.8 UV Nikon objective focused the light 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 with a pixel size of 19 x 19 μ m² and 16-bit dynamic range digitization at 100 kHz. The ICCD spectral range spread from UV (180 nm) until IR (900 nm). The match between the spectrometer and the ICCD allowed to simultaneously detect 480 spectra with a spatial resolution along the entrance slit height around 0.15 mm. The ICCD was not a cycle resolved detector and each spectra collection was detected at a fixed crank angle of different engine cycles. The dwell time between two consecutive images was set at 83.3 μ s. In this work the central wavelength of the grating was fixed at 300 nm, 500 nm and 700 nm in order to cover the spectral range from UV (200 nm) until the near IR (800 nm). The spectral resolution was 0.47 nm/pixel. The exposure time was fixed at 41.6 μ s which corresponds to 0.5 CAD at an engine speed of 2000 rpm.

Simultaneous spectroscopic investigations were carried out in the central region of the combustion chamber extended from the intake valves to the exhaust ones. For a better post-detection analysis the binning of 6 spectra was performed in correspondence to three chamber locations. As shown in Figure 2, the location C matched the region around the spark plug; location I and E corresponded to the region between the intake valves and exhaust ones, respectively.

High spatial resolution flame visualization (Fig. 1c) 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 the two colour method. The soot-emission wavelengths were selected by edge filters. More details about this methodology are reported in [4, 6]. The exposure time was fixed at 41.6 μ s. 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 of the ICCD, the CCD and high speed camera with the engine was made by the crank angle encoder signal through the unit delay device. A multichannel device recorded the TTL signal from the cameras 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, HC and NO_x were made in the raw exhaust. CO and HC were measured by Non-Dispersive Infrared Detectors (NDIR); NO_x was detected through an electrochemical sensor.

An Opacimeter was used to measure particulate mass concentration. An 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 to particulate mass concentration [7].

RETRIEVING OF THE OPTICAL DATA

A retrieving procedure of the optical data was realized to process each image. The fundamental steps of this procedure are reported in Figure 3. The 8-bit grey-scale image (step1) is converted in a numerical matrix. In this way it was possible to evaluate the luminous signal locally in each point of the combustion chamber [8; 9]. In particular, fixing a threshold of 5% for the instantaneous luminosity (step2), flame area and outline (step3) are obtained. Thus the distance of each pixel in the flame outline from the centre of the combustion chamber is calculated. The flame radius is obtained by the average on all these distances [9].



Figure 3. Steps of the retrieving procedure of the optical data.

RESULTS AND DISCUSSION

ENGINE OPERATING CONDITIONS

All the tests presented in this paper were carried out at engine speed of 2000 rpm and wide open throttle. Absolute intake air pressure and temperature were fixed

at 1400 mbar and 323 K, respectively. Commercial gasoline with research octane number 95 was used.

Two fuel injection strategies based on single injection in closed-valve (CV1) and open-valve (OV1) conditions were tested. For both test cases, the injection-duration was chosen to obtain a stoichiometric equivalence ratio, as measured by a lambda sensor in the engine exhaust. The spark timing was fixed to operate always at maximum brake torque before the knock limit, as shown in Figure 4 [10].

More details about the operating conditions are reported 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 the maximum pressure signal, the IMEP and COV resulted comparable with those measured for real multi-cylinder engine [1].

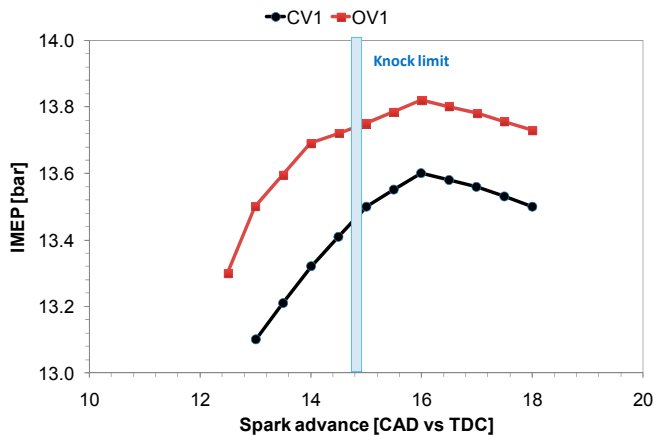


Figure 4. Indicated Mean Effective Pressure (IMEP) evolution versus the spark advance measured by the average on 300 consecutive cycles.

test	Start of Inj.	Duration of Inj.	IMEP [bar]	COV IMEP [%]
CV1	130 ATDC	138 CAD	13.0	2.7
OV1	300 BTDC	130 CAD	13.5	3.0

Table 3. Details of the engine operating conditions.

CYCLE RESOLVED VISUALIZATION

Cycle resolved imaging of the combustion process was performed using the high speed camera. Figures 5 and 6 report the flame propagation detected in the combustion chamber for the closed valve and open valve injection conditions and the corresponding pressure traces. The CAD where the acquisition was performed is highlighted with dots.

In good agreement with the results reported in previous works [11 - 13] the flame front started from the centrally located spark plug and it spread with radial-like behaviour for 16-20 CAD after the start of spark. After this time, the flame front shape showed an asymmetry: the flame reached first the cylinder walls in the exhaust

valves region. This was due to the fuel film deposited on the intake valves.

During the injection process, the fuel drips on the intake valves stems, then it accumulates on the valves seats. This deposit is drawn by the gravity onto the valve head where it remains as film due to the surface tension. Once formed in the combustion chamber, the fuel film develops dynamically under the effect of the gas flow influencing the composition of the mixture and hence the combustion process [14 - 17]. In fact, the flame propagation is influenced by the thermodynamic conditions, mixture composition and the local turbulence intensity. When a flame propagates in the normal direction to a region with equivalence ratio gradient, each part of the front evolves in a field with varying fuel concentration. This induces variation of the propagation speed along the flame front and an increase in flame wrinkling, in comparison with the homogeneous case.

As clearly shown in Figures 5 and 6, several bright spots were detected in the burned gas before the flame front reached the chamber walls. These bright spots were due to the fuel deposits on the quartz window. The fuel deposits locally created fuel-rich zones with millimetre size that ignited when reached by the normal flame front. Clear evidence of bright spots can be noted in the open valves condition. This was caused by the carrying of the injected fuel droplets directly into the combustion chamber by the gas flow. A proportion of these droplets stuck on the cylinder walls and a part was deposited on the piston surface.

Independently from the fuel deposition on the valves, during the flame propagation the wall thermal boundary layer grew and the temperature of the unburned gas rose. The flows in front of the flame were progressively more compressed. Thus, the flame speed decreased from its highest value, dominated by the gas expansion in the middle of the volume burnt, to a value more dependent on the turbulent burning rate. As a consequence, the flame radius changed its trend and increased more slowly.

Figure 7 reports the evolution of the flame radius for the selected fuel injection strategies. These trends showed a little difference in the flame propagation due to the interaction of the fuel film deposits with the gas flow in the combustion chamber. In fact, the heat exchange between the intake ports and the surrounding gas led to the fuel evaporation. It influenced the composition of the mixture creating locally fuel-rich zones. The higher fuel amount near the intake valves in the closed valve injection conditions induced fuel-richer zones that slowed down the flame front. This effect reduced the kernel cyclic variability and had strong influences on the further development of the combustion process increasing the flame stability [18, 19].