

Optical Investigations of the Abnormal Combustion in a Boosted Spark-ignition PFI Engine

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ABSTRACT

The flame front propagation in normal and abnormal combustion was investigated. Cycle-resolved flame emission imaging was applied in the combustion chamber of a port fuel injection boosted spark ignition engine. The engine was fuelled with a mixture of 90% iso-octane and 10% n-heptane by volume (PRF90). The effect of fuel injection phasing was studied. The combustion process was followed from the flame kernel formation until the opening of the exhaust valves. Different phenomena correlated to the abnormal combustion were analysed. Detailed information on ignition surfaces, end-gas auto-ignitions and knock were obtained. The appearance of autoignition centres in the end gas was evaluated in terms of timing, location and frequency of occurrence.

INTRODUCTION

Global warming and the rising price of oil force the fuel consumption and pollutant emission reduction from the vehicles equipped with internal combustion engines. This should be made together with the satisfaction of high performance and drivability requirements. The only solution is to improve engine efficiency. Downsizing, in conjunction with pressure charging, is seen as a key technology for the future of the spark ignition (SI) engine with respect to improving vehicle fuel economy. Downsizing should improve engine brake specific fuel

consumption as the engine has to run at a higher brake mean effective pressure. Pollutant emissions can also be reduced with the improvement in fuel economy, and nitrogen oxides can be further controlled through the increased EGR tolerance made possible by operation at higher BMEP levels.

On the other hand the downsized engine is limited by its tendency to the knock when running at or near to full-load under boosted conditions. It means that a pressure charged engine should run with a significantly reduced compression ratio relative to a naturally aspirated one. A reduction in compression ratio leads to a reduction in thermodynamic efficiency of the engine throughout the speed and load range. Consequently, a better understanding of the knocking and of the other abnormal combustion processes could allow the optimization of boosted spark-ignition small engines [1, 2].

It is known that the combustion in the spark ignition engines can be normal or abnormal [3, 4]. In the normal combustion, the spark-ignited flame front moves throughout the fuel/air mixture in the cylinder volume in a spherical-like manner. The abnormal combustion takes account of the surface ignition and the knock [3].

The surface ignitions start from hot spots on the combustion chamber walls such as an overheated valve or spark plug, or glowing combustion-chamber deposits. Following surface ignition, a flame develops at each surface-ignition location and starts to propagate across the chamber in an analogous manner to what occurs with normal spark-ignition.

When the unburned fuel/air mixture beyond the boundary of the flame front named end-gas is subjected to a specific combination of heat and pressure, auto-ignitions may occur. Knocking would appear when the induction time for the end-gas autoignition is less than the time required for the cylinder charge to burn through a spark-initiated propagating flame. During the knock, a rapid release of the chemical energy in the remaining unburned mixture occurs. This causes high local pressures and generates propagating pressure waves in amplitude of several bars across the combustion chamber. These pressure waves are transmitted through the engine structure and can induce the mechanical engine failures.

In the past, almost all knocking investigations were concentrated on the pressure, acoustic and/or ion current measurements [5, 6]. These methodologies gave overall information. The optical techniques and partially transparent engines are suitable tools to investigate the thermal and fluid-dynamic phenomena that characterize the knock and the abnormal combustion process [7 - 13].

The aim of this paper is to get information on the combustion process and flame propagation during the normal and knocking combustions in a port fuel injection boosted spark ignition engine. In particular, the inception and evolution of the ignition surfaces, end-gas auto-ignitions and knock were investigated. To this goal, cycle-resolved flame emission images were detected in the combustion chamber from the spark until the opening of the exhaust valves. The engine was fuelled with a mixture of 90% iso-octane and 10% n-heptane by volume (PRF90). The effect of the fuel injection phasing was studied.

EXPERIMENTAL APPARATUS

TRANSPARENT ENGINE

An optically accessible single cylinder port fuel injection (PFI) spark ignition (SI) engine was used for the experiments. It was equipped with a new generation SI turbocharged engine-cylinder head with four valves. A ten-hole injector with 25° spray angle and 70 μm SMD was employed. In the combustion chamber the spark plug was centrally located and a quartz pressure transducer was flush-installed in the region between intake-exhaust valves at the side of the spark plug. Combustion pressure measurements were performed for all the selected operating conditions. The rate of the chemical energy release and the related parameters were evaluated on an individual cycle basis and/or averaged on 320 cycles using conventional interpretation models [3]. 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 port fuel injection (PFI) boosted engine.

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. More details about the engine are reported in Table 1.

ENGINE OPERATING CONDITIONS

All the tests presented in the paper were carried out in steady state conditions at engine speed of 2000 rpm and wide open throttle. The absolute intake air pressure and the temperature were set at 1400 mbar and 323 K, respectively. The fuel injection always occurred in the intake manifold at the pressure of 3.9 bar. Two different fuel injection timings were considered, they consisted in the injection when the intake valves were closed (130 ATDC - CV) and open (300 BTDC - OV), respectively. The duration of each injection was fixed in order to have a stoichiometric equivalence ratio as measured by an exhaust lambda sensor. To induce the knock phenomenon, the spark timing was fixed at 4 CAD before the MBT (14 CAD BTDC).

The engine was fuelled with a volumetric mixture of 90% iso-octane and 10% normal heptane; this constituted a primary reference fuel with 90-octane number (PRF90). The engine was stabilized for around 10 seconds before starting the acquisition of the optical data and of the in-cylinder pressure signals.

OPTICAL SETUP AND MEASUREMENT PROCEDURES

Figure 1 shows the experimental apparatus for the cycle resolved 2D digital imaging. During the combustion process, the light emitted passed through the transparent piston and it was reflected toward the optical detection assembly by a 45° inclined UV-visible mirror located at the bottom of the engine. The cycle resolved flame visualization was obtained by 8-bit high speed camera (Optronis CamRecord 5000 – 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.

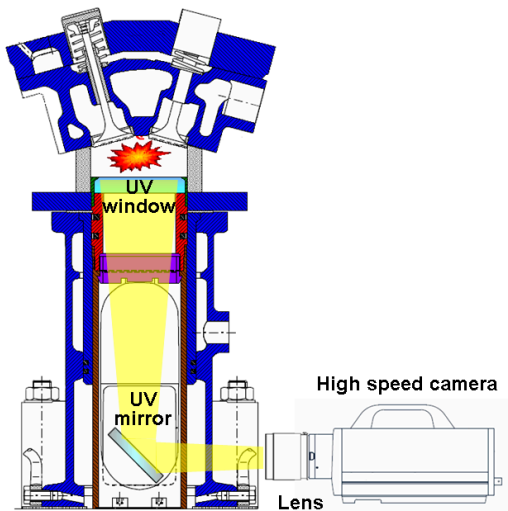


Figure 1. Sketch of the optical engine and experimental setup for the cycle resolved digital imaging.

A camera region of interest was selected (400 x 400 pixel) to obtain the best match between the 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. AVL Indimodul recorded the TTL signal from the high speed camera acquisitions together with the pressure trace from the pressure transducer. In this way, it was possible to determine the crank angles where optical measurements were carried out.

In this work, three locations were selected in the combustion chamber to follow the evolution of the combustion process through the local luminous signal. Each location had an area of 3x3 pixel. The location 1 was selected in the pressure transducer region. Locations 2 and 3 were located on the intake and on the exhaust valve. Figure 2 reports a sketch of the bottom field of view of the combustion chamber with the selected locations.

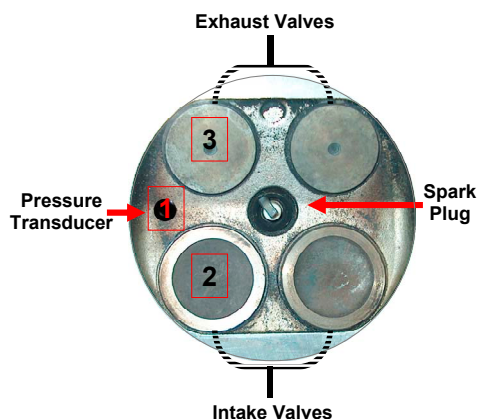


Figure 2. Sketch of the bottom field of view of the combustion chamber with the locations selected for the evaluation of the local luminosity.

A post-processing of the optical data was realized by means of Labview™ of National Instruments to convert each frame of a camera sequence into an 8-bit image and then into 400x400 numerical matrix. In this way the temporal evolution of the local luminosity from each location of the combustion chamber and the integral one could be evaluated for each combustion cycle.

RESULTS AND DISCUSSION

IN CYLINDER PRESSURE MEASUREMENTS

Figure 3 reports the evolution of the maximum pressure signal measured in the combustion chamber for both the selected operating conditions (closed valve and open valve). The test cases were constituted by sets of 320 consecutive cycles. In the first 100 cycles, the maximum combustion pressure changed in a range of 5% due to the cycle-to-cycle variation. This value is good for the optical engines and reasonable if compared with real ones. From the 100th in around 200 cycles an increase in the pressure peak of the 30% was observed. This trend was due to the temperature increase in the combustion chamber caused by the thermal evolution.

To better understand the effect of the thermal evolution on the combustion process, the 120 kHz sampling frequency was used for the Fast Fourier Transform (FFT) spectrum of each cycle. The spectra computed until 50 kHz and related to the 100th, 250th and 300th cycle for both the fuel injection conditions are shown in Figure 4.

For all the selected cycles, excluding the low frequency mode (< 4 kHz) due to the normal combustion process, two ranges of frequencies were primarily excited. The first one was observed between 4 and 18 kHz. It presented well-defined peaks around 7.2 kHz, 12.3 kHz and 16.7 kHz corresponding to the first circumferential mode, the first radial mode and the combined one [14, 15]. A second range of frequencies occurred between 18 and 40 kHz. This corresponded to the first axial mode due to the motion of the piston and to the second and higher circumferential modes.

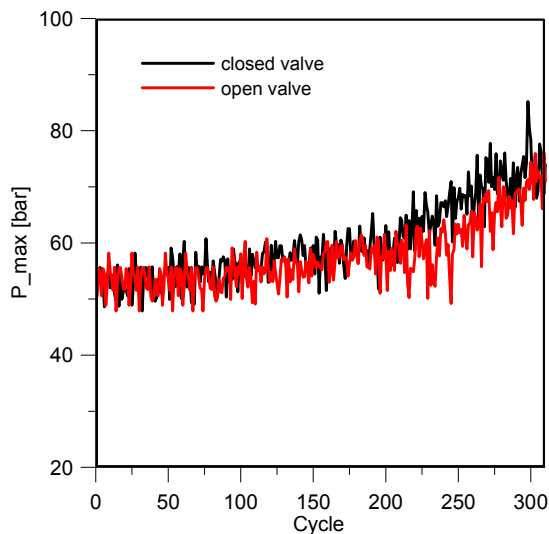


Figure 3. Evolution of the maximum pressure signals measured in the combustion chamber.

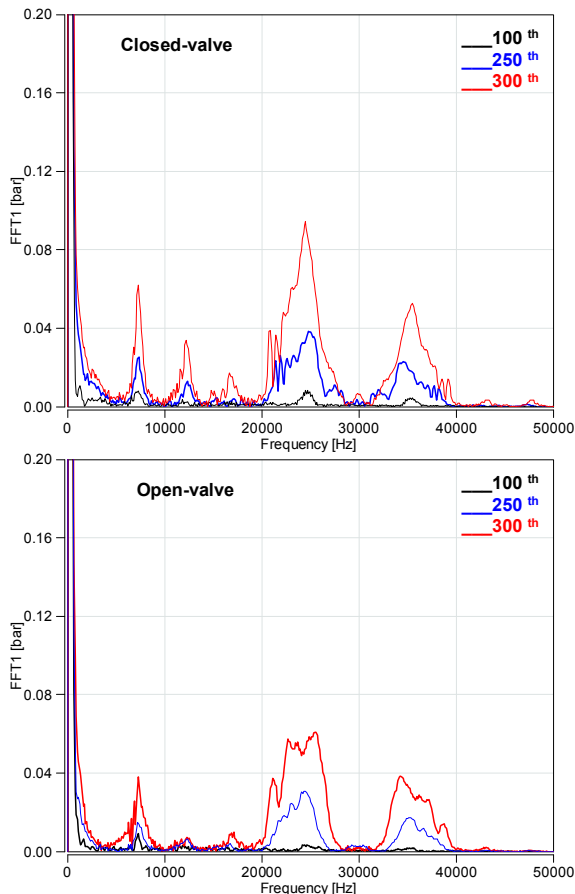


Figure 4. FFT spectrum evaluated for the 100th, 250th and 300th cycles for both the engine conditions.

At increasing combustion pressure values, an increase in amplitude for the lower frequency modes was detected. According to literature [14 - 16] this effect is directly related to the knocking tendency. Thus to evaluate the knock signal, the 5 - 30 kHz band-pass filtering of the pressure signals was performed.

In Figure 5 the evolution of the knock intensity is reported for all the cycles and for both the operating conditions. It was evaluated through the peak-to-peak amplitude of the knock signal.

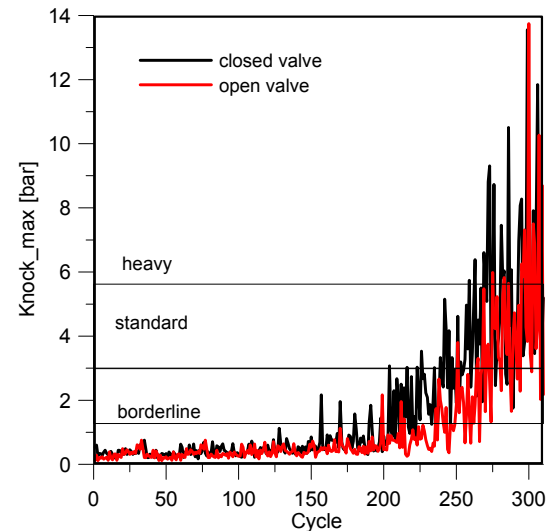


Figure 5. Evolution of the knock intensity measured in the combustion chamber.

The combustion cycles were classified according to their knock intensity in normal combustion, borderline knocking, (standard) knocking and heavy knocking cycle [17]. If the knock intensity was 5% lower than the motored pressure at TDC, the engine worked in the normal combustion condition. A borderline knocking was considered until 10%. The standard knocking was associated to the range 10-20%. The heavy knocking occurred for knock pressures 20% higher than the motored pressure.

DIGITAL IMAGING MEASUREMENTS

Normal combustion

In order to better understand the in-cylinder phenomena occurring in the normal combustion and knocking cases, optical investigations were carried out in the combustion chamber from the start of spark until the opening of the exhaust valves. Cycle-resolved flame luminescence was detected for several operating conditions.

Figure 6 and Figure 7 report the flame image sequences with the corresponding in-cylinder pressure traces and knocking signals for a normal combustion cycle in closed-valve and open-valve fuel injection conditions. Previous optical investigations in similar engine operating conditions demonstrated that the first evidence of a flame UV luminescence occurred around 1 CAD after the spark timing (ASOS) [18 - 21]. The flame kernel evolved with a high cycle-to-cycle variation for about 10 CAD. After this time, the flame became more stable and it spread with radial-like behaviour for around 5-7 CAD.