C4-3**Evaluation of Knocking Combustion by an Ion Current System and Optical Diagnostics of Radical Species****Felice E. Corcione, Bianca M. Vaglieco, Simona S. Merola***Istituto Motori – CNR
Via G. Marconi, 8 – 80125 Napoli (Italy)***Key Words:** Knock, Optical diagnostics, Ion current, Radical species.**ABSTRACT**

In spark ignition engines, knock can be defined as self-ignition of a certain portion of the unburned gas beyond the flame front. This abnormal combustion releases a chemical energy that excites within the cylinder volume pressure oscillations that are responsible of engine noise and sometimes damage. Therefore, knock is undesirable process that has to be avoided.

The present paper aims to evaluate the knocking combustion by an ion current system and optical diagnostics of radical species. The ion signal was also compared with the in-cylinder combustion pressure and the engine vibration. The optical measurements were based on 2D UV-Visible digital imaging of combustion process, UV chemiluminescence and spectrally resolved emissions from radical species.

The optical techniques were applied for their potential to provide accurate measurements over a wide range. In particular, in this paper the spatial and temporal evolution of flame front and radical species such as OH and HCO were correlated to pressure and ion-current sensing during knocking combustion.

The engine used during experiments was an optically accessible single cylinder, ported fuel injection, four-stroke spark-ignition engine with a four-valve production head. All the measurements were realized in the transparent combustion chamber equipped with a wide quartz window (diameter=57 mm) in the bottom of the chamber. The engine operated at 1000 rpm with stoichiometric mixture and wide-open throttle.

INTRODUCTION

In spark ignition engines, the combustion can proceed as a normal or abnormal phenomenon depending on engine operating conditions. The normal one, which is initiated solely by a timed spark, generates a flame front moving across the cylinder volume in a uniform manner at normal velocity. Depending mainly on the temperature and pressure history of the end gas as well as on the rate of development of the flame, the abnormal combustion causes two major phenomena: surface ignition and knock. [1] The surface ignition may be started by hot surfaces in the combustion chamber prior or after spark ignition. Knock is a consequence of a spontaneous ignition of a portion of the fresh mixture ahead the propagating flame. It gives the name to the noise, which is transmitted through the engine structure. The noise, that sounds like metallic ringing which is distinct from the muted sound of normal combustion, is a consequence of the pressure waves generated by the abnormal combustion. The abnormal combustion suddenly releases a chemical energy that excites within the cylinder volume a local increase of pressure followed by oscillations [1-3]. It is also generally accepted that spontaneous ignition begins at one or more exothermic centers in the end-gas region as confirmed by optical probe measurements [3, 4]. When knock occurs in operating engines it causes reduced efficiency, increased heat transfer and, if severe, engine damage [5]. Knock is promoted by different engine parameters like increased compression ratio, advancing the ignition timing, opening the throttle to wide open, slightly rich mixtures, inlet air temperature, increased coolant temperature, and buildup of deposits on the cylinder walls [1, 3, 6].

To detect the knock many investigative methods have been proposed in the past. On vehicle, the occurrence and intensity of knock should be detected by indirect signals. Block vibration and sound pressure signals are generally used to determine the knock and control the engine. A piezo-electric ceramic (piezo-ceramic) sensor installed at a location where

it can reliably detect knocking in all cylinders is used. The sensor is sensitive to the vibration-driven acceleration caused by abnormal combustion pressure waves [7]. Depending on the engine type, such systems may suffer from disturbance by other noise sources (valve closing, etc.) or insufficient noise transmission from the knocking cylinder to the sensor.

In the test laboratory, knock can be easily detected by a piezo-electric pressure transducer flush mounted in each engine cylinder. The amplitude of the pressure oscillation is a useful measure of the intensity of knock because it depends on the amount of end-gas, which ignites spontaneously and rapidly. However, this measurement method requires hard and expensive modification to the engine head to install for each cylinder a high dynamic pressure transducer.

Based on the well-known ionization phenomenon occurring during both normal and abnormal combustion processes, various ionic detection systems have been proposed. In these systems, the spark plug serves as the ionization sensor implying any structural modification of the engine. Recently, optical methods have been developed for directly observing the flame propagation and for more quantitative measurements of normal and abnormal combustion process. Many of these methods are based on the use of optical probe through a modified spark plug [4, 8] or engine head gasket [1, 8]. They are able to provide a good estimate of the location of the flame and knock as a function of the time. Others are based on the use of partially elongated piston transparent engines that allows the access to the combustion chamber through a 45° inclined mirror located in bottom of the engine and a quartz window installed on the piston [8-10]. In this case different optical techniques have been used to get information of in-cylinder fluid-dynamics (LDV), air-fuel mixture (LIF), spark ignition and flame propagation (Shadowgraphy, Schlieren interferometry) as well as combustion and species formation (LIF and spectroscopy) [8].

The present paper discusses the correlation between measurements obtained using different detection systems and investigation techniques on a partially transparent single-cylinder gasoline engine. A piezo-ceramic sensor to detect the engine vibration, a piezo-electric sensor to measure the combustion pressure, an inductive electronic system to detect the ionic current, a 2D digital imaging technique to visualize the combustion and a spectrally resolved technique to record the emission from radical species have been used.

EXPERIMENTAL INVESTIGATIVE METHODS OF COMBUSTION

Transparent Engine

Figure 1 shows an overall schematic diagram of the engine used in the present investigation. This is an optically accessible single cylinder ported fuel injection (PFI) engine. Details about the engine are in Table 1.

The piston is flat and transparent through a quartz window ($\Phi=57\text{mm}$). To reduce the window contamination by lubricating oil, an elongated piston arrangement is used together with unlubricated Teflon-bronze composite piston rings in the optical section. The optical path includes an inclined (45°) mirror located in the bottom of the engine. A specially machined cylinder head of a four valve commercial automotive engine with a pent-roof combustion chamber and the spark plug centrally located is installed on the engine.

Figure 1. Schematic diagram of the optically accessible single cylinder SI engine.

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

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

Table 2. Engine test conditions.

Condition	Speed	Duration of Injection	Injection pressure	Spark ignition
	rpm	CAD	bar	CAD BTDC
abnormal	1000	60.0	4.0	13
normal	1000	60.0	4.0	3

All present tests were carried out at 1000 rpm, full load (wide open throttle WOT) with 95 RON commercial gasoline. The equivalence ratio was constantly at $\lambda=1$ as measured by a lambda sensor installed on the engine exhaust. Two ignition timings for operating at both normal and abnormal

combustion were considered. Engine operating conditions are reported in Table 2.

Knock Sensor

A piezo-ceramic sensor [7] was installed on the intake side of the transparent engine cylinder. In this location, the sensor can reliably detect the effects of abnormal combustion phenomena at all operative conditions. The sensor through its annular piezo-ceramic disk detects the vibrations due to the structure-borne noise transmitted from the engine block. The sensor picks up structure-borne noise and converts it into an electrical signal, which is an input to the fast data acquisition system. An interpretation algorithm allows to select the one frequency among many that corresponds to knocking combustion.

Pressure Sensor

In PFI gasoline engines during the intake stroke the cylinder is filled with fresh charge. Fuel, which is in the form of small droplets dispersed in air, continues to vaporize during the compression stroke. Before the piston reaches the TDC, the spark occurs in a supposedly homogeneous but turbulent environment. Suddenly, a flame kernel develops in the mixture and then propagates throughout a volume that is changing instantaneously as the piston moves. The cylinder pressure rises due to the released energy and the new molecules produced by the chemical reactions activated by the spark ignition. The cylinder gas pressure is measured for every engine cycle with a pressure transducer. The rate of chemical energy release and related parameters are evaluated on an individual cycle basis and/or averaged on many cycles from the cylinder pressure data using conventional interpretation models for heat release analysis.

Figure 2. Plan view of the cylinder head with the locations of pressure transducer and spark plug.

Table 3. Pressure transducer specifications.

Measuring Range	0 to 200 bar
Sensitivity (nominal)	28 pC/bar
Linearity	< +/- 0.2% FSO
Natural Frequency	70 kHz
Acceleration	< 0.002 bar/g
Sensitivity	< 0.015 bar/g
Temperature Coefficient	0.02% / °C at 20-80°C

To avoid either cavity resonance and/or low sensitivity to the pressure oscillations of abnormal combustions, in all investigations a piezo-electric transducer has been flush installed on a specially machined engine cylinder head as shown in Figure 2. The specifications of the transducer used in the experiments are reported in Table 3. A high precision optical pickup (Crank Angle Encoder) was used for angle-based indicating measurements. Flywheel generated trigger and crank angle degree marker pulses were produced at 0.05 crank angle degree resolution. Data acquisition in this work was fixed at 0.1° crank angle.

Figure 6. Sketch of the combustion chamber field of view.

The light emitted during combustion process was collected by a quartz window located in the piston of the single-cylinder research engine and reflected toward the optical detection assembly by a 45° inclined UV-visible mirror located in bottom of the engine. The mirror had an elliptical shape (46 x 66 mm) and its size limited the field of view and didn't allow to observe in the same time all the chamber, as it can be noted in the sketch reported in Figure 6.

Spectroscopic and chemiluminescence diagnostics

In Figures 5a the optical apparatus for spectroscopic investigations is reported. The combustion light emission was focused by a 100 mm focal length, UV lens onto micrometer controlled entrance slit of a spectrometer with 150 mm focal length, $f/3.8$ aperture, 300 groove/mm grating and 0.25 mm slit width. The output of the spectrometer (250 nm spectral range) was coupled to an intensified cooled CCD camera with an array size of 512 x 512 pixels and 16-bit dynamic range digitization at 100 kHz. Dark noise and photon statistical noise were both small compared to cycle-to-cycle variation in the measured intensity of spectral features.

The recorded image contained spectral information along the rows of the CCD and spatial information along the columns. The spectrometer's field of view was due to the magnification of the optics, slit height (14 mm) and width, and pixel size and CCD format. In this work full chip configuration was used. The camera intensifier was gated from 10 μ s to 83 μ s. At 1000 rpm engine speed, 1° crank angle duration is 166 μ s.

In Figure 5b is showed the schematic diagram for chemiluminescence measurements. In this set-up the light from quartz window was collected onto the ICCD camera passing through narrow-band (10 nm) interference filter and focused by a 78 mm focal length, $f/3.8$ UV Nikon lens. The central wavelength of filters used in this work corresponded to the emission wavelengths of typical combustion radicals: 310 nm for OH and 325 nm for HCO. Wavelength assignments were determined by calibration with high-pressure mercury lamp.

Imaging diagnostic

A commercial imaging system was used for 2D visualization. The light emitted during combustion process was detected by a 50 mm focal length, $f/3.8$ Nikon lens and recorded by digital CCD color camera system (PCO Pixelfly). The 640 x 480 pixels CCD camera operated with a maximum recording rate of 15 Hz and a dynamic range of 12-bit in the spectral range from 290 nm to 1100 nm. For digital imaging of combustion process exposure times from 10 μ s to 83 μ s were fixed.

Optical measurements were not cycle-resolved but they were constituted by 10 spectra or images referred to 10 consecutive combustion cycles. The synchronization of the ICCD and

CCD cameras was driven by the shaft encoder signal through a unit delay.

RESULTS AND DISCUSSION

It is well known that knock occurs at specific frequencies due to the acoustic vibration modes. The vibration modes are excited by high-energy release rate that characterizes the auto-ignition and are typically in the range from 6 kHz to 20 kHz for automotive engines [1, 19-21].

Figures 7a and 7b report the in-cylinder pressure and ion current signals measured for the normal (Fig. 7a) and abnormal (Fig. 7b) combustion respectively.

Ion current signals show a first sharp peak due to the spark-charging event at 18 CAD BTDC (Fig. 7a) and 28 CAD BTDC (Fig. 7b). After 15 CAD, a second peak corresponding to spark event is observed at 3 CAD BTDC and 13 CAD BTDC for the normal and abnormal combustion respectively. The start of the chemi-ionization occurs after about 5 CAD for both engine conditions. Finally, the thermal-ionization peak can be observed around 24 CAD ATDC (Fig. 7a) and 16 CAD ATDC (Fig. 7b) in correspondence of the maximum value of in-cylinder pressure signals.

Figure 7. In-cylinder pressure and ion signal measured for (a) normal and (b) abnormal engine condition.

By the comparison of pressure curves, it can be observed that in the abnormal condition the combustion proceeds firstly with normal behavior; then, around the maximum of pressure, intense pressure oscillations arise and continue for a part of the expansion stroke. Because of the high frequency nature of these oscillations, a fast Fourier transform (FFT) procedure, which converts the pressure data from time to frequency domain, is useful to quantify the knock frequencies by calculating the power spectral density.

The piezo-electric pressure transducer has a natural frequency at 70 kHz; this property of transducer could induce oscillations of pressure signal not due to the combustion but

to the resonance. To overcome this problem, a low-pass digital filtering at 60 kHz has been used to remove the unwanted 70 kHz signals. The comparison between pressure data with and without filtering has shown that the digital filter is able to remove the transducer resonance frequency without significantly attenuation of knock signal.

Figure 8. Power Spectral Density obtained from in-cylinder pressure (black), ion signal (blue) and acceleration signal (red) measured for knocking combustion.

Figure 8 shows a comparison between the power spectral density obtained from in-cylinder pressure (black line), ion signal (blue line) and acceleration signal (red line) respectively under knocking combustion.

Frequency plot from pressure data showed that the main vibration mode occurred around 6.7 kHz and this value was in good agreement with the result obtained by ion and acceleration signals. Other modes were observed at about 12.8 kHz for pressure and acceleration signals and around 10.7 kHz for ion current signal. Smaller amplitude modes were common for all signals around 16.4 kHz.

m, n	1, 0	2, 0	0, 1
Mode shape			

m =circumferential oscillation mode number

n =radial oscillation mode number

Figure 9. Sketch of acoustic vibration modes [20].

Figure 10. Knock pressure filtered at 5-20 kHz.

The modes at 6.7 kHz and 12.8 kHz were first circumferential and first radial oscillation modes, respectively

evaluated according to Draper formula [19, 20]. Moreover the mode at 10.7 kHz was due to the second circumferential oscillation mode. Generally the first circumferential mode was stronger than the second but ion current sensor was located along a node line of the second circumferential mode. The same occurred for the pressure transducer with respect to the acceleration sensor. A schematic diagram of acoustic vibration modes is reported in Figure 9 [20].

Figure 11. Ion signal filtered at 5-20 kHz.

Figure 12. Acceleration signal filtered at 5-20 kHz.

The digital filtering in the range 5-20 kHz of the combustion signals, detected by the three different methods, is reported in Figure 10-12, respectively. The analysis of pressure combustion data of Figure 10 revealed that the knock onset was around 12 CAD ATDC for the abnormal case. The knock end, defined as the first crank angle after the onset with a knock pressure equal to ± 0.3 bar, was around 20 CAD ATDC. The timing of the knock obtained by pressure data was in very good agreement with that evaluated by band-pass filtered ion current and acceleration signals that are showed in Figure 11 and 12.

Optical signals

Many experimental investigations [1,8,16-18] demonstrated that the light emissions of abnormal combustion were more intense than normal combustion. A strong gradient of emission intensity characterized the onset knock. This effect was due to the sharp increase of pressure and flame propagation caused by the auto-ignition phenomenon and knocking. Figure 13 reports selected digital images detected in the knocking test condition. The first signal of flame propagation was observed around 8 CAD BTDC. This result was in very good agreement with the chemi-ionization start indicated by ion signal and reported in Figure 7b. Around 4 CAD ATDC the flame front reached the walls of the chamber with approximately radial behavior. This flame was due to normal combustion as it was demonstrated by analysis of

filters pressure signal of Figure 10 that showed at this time values below the threshold of knocking. The speed of flame propagation was evaluated around 10 ± 15 m/s.

Figure 13. Digital image sequence measured for the abnormal engine condition.

In order to investigate the flame propagation in the combustion chamber during the knocking, the digital images were treated by software; the luminosity of the normal flame front was subtracted and flame due to knock was extracted. A selection of treated images is reported in Figure 14 and Figure 15. Around 12.5 CAD ATDC some hot spots were observed in the end gas as it is evident in the picture of Figure 15. In less than 1 CAD, the number and luminosity of the hot spots increased significantly.

Figure 14. Comparison among 5-20 kHz filtered pressure, ion current signals and selected digital images detected during knocking combustion

Figure 15. Details of treated digital images detected during knocking combustion.

The hot spots corresponded to the very small centers of auto-igniting exothermic reactions [9]. The hot spots were characterized by steep gradients of temperature and residual gas concentration and weak pressure oscillations. In the same time of hot-spots appearance, a flame front with like-radial symmetry started from spark plug. This flame was due to the thermal phase of knock [8, 9] and it was characterized by a large center with gradients flatter than hot spots. By analysis of digital images detected with an exposure time of 10 μ s, it was observed that the hot spots propagated with a speed of about 700 m/s; whereas the flat flame spread with a speed of about 370 m/s in the direction of the first circumferential vibration mode (Figure 8) and with an averaged half speed in the other directions. After the flat flame spread in the

chamber and ran over the residual gas, the hot spots disappeared and the luminosity decreased.

Figure 16. Locations for spectroscopic investigations.

When the knock spread in the combustion chamber, the related pressure waves induced higher local density of residual gas. As a consequence high concentrations of radicals were excited with subsequent light emission [1, 8, 17-19]. In order to identify the radicals that were markers of knocking, spectroscopic investigations of natural emissions were performed. The spectra were measured in three locations of the chamber; locations A and C identified region of the chamber between the intake and exhaust valve, respectively (Figure 16). Location B was between spark plug and pressure transducer in the direction of the first circumferential vibration mode.

Figures 17a-17b-17c show some typical emission spectra measured at 5 CAD BTDC, 12.5 CAD ATDC and 13.5 CAD ATDC, respectively, in the abnormal engine condition. These spectra were detected at a central wavelength of spectrometer of 400 nm. in order to investigate natural emissions from ultraviolet to visible.

All the spectra showed a strong band centered at 309 nm, due to OH radical emission [22]. Moreover a broadband emission, which covered the whole wavelength range investigated, was observed. This band could be the convolution of HCO Vayda band from 250 nm to 410 nm. and HCHO Emeleus cool flame band from 340 nm to 523 nm [22]. For different local amount of the radicals, different spectral behaviors were observed. At 5 CAD BTDC, CH radical band centered at 431 nm was detected [22]. No spectral evidence of CH radicals was observed after 2 CAD BTDC. This result was in good agreement with the data reported in Figure 7b. In fact, 5 CAD BTDC corresponded to the peak of the chemi-ionization phase characterized by a fast reduction of CH radicals as it was discussed previously and indicated by reactions (1)-(3). From 12.5 CAD ATDC to 13.5 CAD ATDC the hot spots in the end gas increased strongly in number and the onset of knocking phase was detected by the filtering of pressure and ion current signals (Figures 14 and 15). In the same times, OH and HCO emissions increased significantly because of the flame front of knocking combustion reached the test measurement locations. Finally, OH emission intensity was higher in the locations B and C with respect to the location A. This result was due to an asymmetric distribution of knock flame. The good agreement between radical detection, pressure and ion-current signals allowed to consider OH and HCO as markers of the knocking combustion.

In order to investigate the spatial and time evolution of these markers, chemiluminescence measurements were performed using filters fitted at 310 nm and 325 nm. For the evaluation of the role of OH and HCO radicals in the knocking combustion, chemiluminescence images related to normal combustion were subtracted from abnormal images in correspondence of the same time after start of spark event

(ASOS). All the results reported were normalized with respect to the highest emission signals for each radical.

Figure 17. UV-visible natural emission spectra measured in some locations of the combustion chamber at (a) 5 CAD BTDC, (b) 12.5 CAD ATDC and (c) 13.5 CAD ATDC for abnormal condition.

Figure 18 and Figure 19 report spatial distributions of OH and HCO radicals respectively. OH and HCO radicals spread from the region near the spark plug towards the wall of the chamber. During the knock combustion a light asymmetry in radical distributions was observed. In particular, the highest concentration of both radical species was in the region near the exhaust valves. according to the results obtained by spectroscopic investigations (Figures 17b-17c). This asymmetry was probably due to the gradient of temperature between intake and exhaust valves.

Figure 20 shows the comparison between thermal-ionization phase and time evolution of OH and HCO radicals. Time evolutions were evaluated by integration of emission signals detected inside combustion chamber at each time.

Figure 18. Spatial distribution of OH radical emission evaluated during knocking combustion.

Figure 19. Spatial distribution of HCO radical emission evaluated during knocking combustion.

The first well resolvable signals of OH radical occurred around 17 CAD ASOS when OH signal reached 30% of its maximum value. This time corresponded to the onset of the thermal-ionization phase. The ion-current and OH radical emission signals presented comparable trend until 25 CAD ASOS when OH reached the highest emission intensity. This strong emission could be due to the spread of hot spots in the chamber that it was just observed by digital imaging measurements reported in Figure 14. Thus, OH could be considered as a good feature of hot spots in the knock combustion. By details of OH radical distribution evaluated at 25 CAD ASOS during knocking combustion (Figure 21) it was possible to distinguish between flame and hot spots luminosity. The hot spots size was evaluated around pixel size (0.1 mm).

On the other hand, the first signal of HCO radicals was well observed around 21 CAD ASOS. Moreover, HCO reached the highest emission intensity around 29 CAD ASOS that

corresponded to the thermal-ionization peak. Then ion-current and HCO emission decreased with analogous trend. According to this result, HCO could be considered a marker of the knocking flame. Moreover, OH decrease showed a change in the slope just around 29 CAD ASOS. This change could be due to the reactions that produced OH from HCO. This result could explain the sharp reduction of HCO observed at the same CAD. Finally, another change in the slope of reduction characterized the last phase of OH and HCO evolutions. This effect was maybe due to the consumption and coming back toward the plug of the knocking flame.

Figure 20. Comparison between Ion current signal and time evolutions of OH and HCO radicals evaluated during knocking combustion.

Figure 21. Details of OH radical distribution evaluated during knocking combustion at 25°CAD ASOS.

CONCLUSIONS

The knocking combustion was investigated by ion current system and optical diagnostics of radical species.

The ion signal was also compared with the in-cylinder combustion pressure and the engine vibration.

Optical diagnostics based on 2D digital imaging technique and spectrally resolved technique to record the natural light emission were used.

Optical measurements allowed to evaluate spatial distributions and temporal evolutions of OH and HCO radical species.

It was demonstrated that the ionic current signal was a powerful tool for the diagnostic of the knocking combustion. In fact, knocking start and duration evaluated by pressure data and ion current signals were in very good agreement. Moreover, the comparison between ion current signal and spectroscopic and chemiluminescence measurements allowed to identify OH and HCO as markers of abnormal combustion. Time evolutions of both radicals were phased with different

times of thermal-ionization measured by ion-current. OH was correlated to the hot spots and HCO could be considered as feature of knocking flame.

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ACRONYM

ATDC, After Top Dead Center
TDC, Top Dead Center
BTDC, Before Top Dead Center
SI, Spark Ignition
CA, Crank Angle
CAD, Crank Angle degree
ASOS, After Start of Spark

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