

A Study of HCCI Knocking Accompanied by Pressure Oscillations Based on Visualization of the Entire Bore Area

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ABSTRACT

Knocking combustion experiments were conducted in this study using a test engine that allowed the entire bore area to be visualized. The purpose was to make clear the detailed characteristics of knocking combustion that occurs accompanied by cylinder pressure oscillations when a Homogeneous Charge Compression Ignition (HCCI) engine is operated at high loads. Knocking combustion was intentionally induced by varying the main combustion period and engine speed. Under such conditions, knocking in HCCI combustion was investigated in detail on the basis of cylinder pressure analysis, high-speed photography of the combustion flame and spectroscopic measurement of flame light emissions. The results revealed that locally occurring autoignition took place rapidly at multiple locations in the cylinder when knocking combustion occurred. In that process, the unburned end gas subsequently underwent even more rapid autoignition, giving rise to cylinder pressure oscillations. In addition, when the engine speed and main combustion period were varied, it was found that the intensity of the cylinder pressure oscillations, i.e., knocking intensity P_{KI} , correlated strongly with the maximum pressure rise rate per unit time dP/dt_{max} [MPa/msec]. The frequency characteristics of the knocking were the same even when the engine speed was varied. The primary vibration mode was the (1,0) mode in which pressure waves traverse the cylinder in the bore direction. Under operating conditions causing strong pressure oscillations, pressure oscillations at higher frequencies were observed.

CITATION: Iijima, A., Ito, N., Shimada, T., Yamada, M. et al., "A Study of HCCI Knocking Accompanied by Pressure Oscillations Based on Visualization of the Entire Bore Area," *SAE Int. J. Engines* 7(4):2014, doi:10.4271/2014-01-2664.

INTRODUCTION

Major issues of Homogeneous Charge Compression Ignition engines are to control the combustion phasing and to expand the operating range defined by the engine load and speed. It is especially difficult to operate an HCCI engine at high loads owing to the occurrence of extremely rapid combustion accompanied by a high pressure rise rate exceeding the allowable limits [1]. Additionally, it is also known that, depending on the operating conditions, knocking combustion accompanied by cylinder pressure oscillations occurs [2],[3],[4],[5],[6] in a manner resembling knocking in Spark Ignition (SI) engines.

The main purpose of this study was to gain a better understanding of the above-mentioned characteristics of HCCI combustion from the perspective of flame development behavior in the combustion chamber. Experiments were conducted with a

two-stroke test engine that allowed the entire bore area to be visualized. The engine speed and the intake temperature were varied to induce a transition from moderate HCCI combustion to extremely rapid HCCI combustion accompanied by a high pressure rise rate and in-cylinder pressure oscillations. Combustion behavior under each set of operating conditions was investigated in detail on the basis of in-cylinder visualization of autoignition and combustion, in-cylinder spectroscopic measurement and cylinder pressure analysis.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The specifications of the test engine are shown in Table 1, and the configuration of the equipment used for in-cylinder visualization and light emission spectroscopic measurements is shown in Figure 1. A two-stroke single cylinder, easily accessible engine was used to facilitate easy detailed

measurement of combustion by in-cylinder imaging and light emission spectroscopy. A quartz observation window was provided in the top of the cylinder head to enable the entire bore area to be visualized. Combustion flame was captured by using a high-speed camera (Photron, Inc. FASTCAM SA-X2). The piston and piston crown were built as two separate structures connected by screws to enable visualization experiments to be conducted for various purposes (photo (a) in Fig. 1). A rectangular-shaped channel was provided in the center of the piston head (photo (b) in Fig. 1) to serve as an optical path for obtaining light emission measurements. In the visualized images presented later, this optical path filled with thick combustion gas will appear as a band running in the depthwise direction of the image and which is brighter than the surrounding area.

Table 1. Specifications of test engine.

2-stroke Air-cooled Single-cylinder Engine	
Scavenging Type	Schnürle
Bore × Stroke	72 × 60 mm
Displacement	244 cm ³
Effective Compression Ratio (ε)	10 : 1
Engine Speed	Varied
Test Fuel	n-heptane (0 RON)
Frame Rate [fps (Frames/sec)]	60000 fps

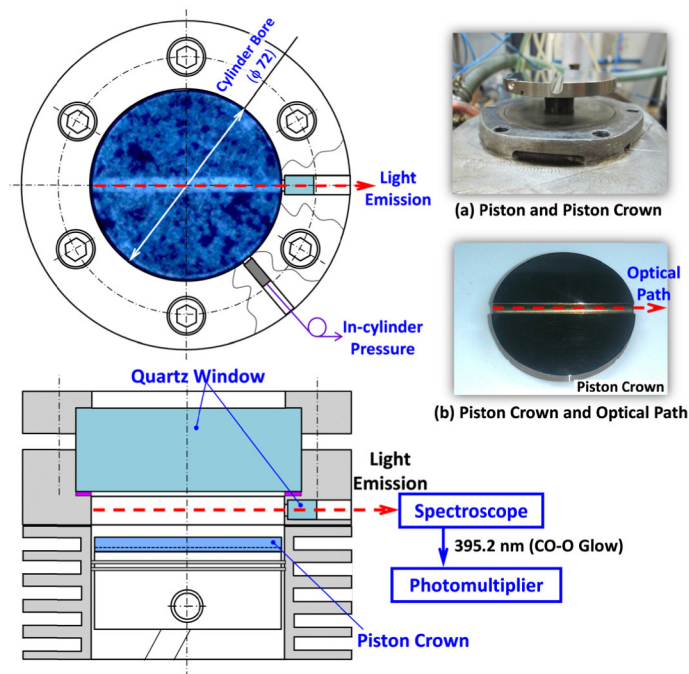


Figure 1. Configuration of optically accessible engine and light emission measurement system.

There were relatively large temperature inhomogeneities in the combustion chamber of the test engine owing to its two-stroke nature. Figure 2 is a cross-sectional view of the engine showing the locations of the scavenging and exhaust ports in the same direction as the orientation of the visualized

combustion images that will be presented later. The exhaust port will be on the right-hand side of the visualized combustion images and the two scavenging ports will be positioned vertically in the images.

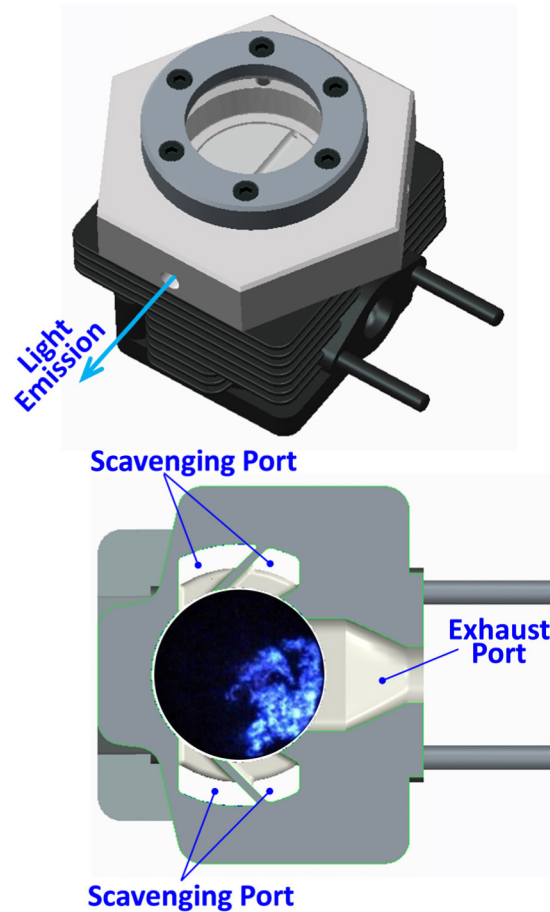


Figure 2. Cross-sectional view of the engine showing the locations of the scavenging and exhaust ports.

A small quartz window was provided in the bore direction of the combustion chamber for sampling the combustion flame light. The sampled light was passed through an optical fiber cable into a spectroscope, which separated the light into its spectral components at the specified measured wavelength. The separated light was then introduced into a photomultiplier and converted to an electric signal. The output voltage obtained was regarded as the light emission intensity E [A.U.]. Because attention was primarily focused on behavior in the main combustion period (i.e. hot flame) in this study, the light emission intensity was measured at a wavelength of 395.2 nm. This wavelength is part of the wavelength band of a continuous light emission spectrum due to the recombination reaction of carbon monoxide (CO) and oxygen (O) molecules and is known as CO-O glow [6],[7],[8],[9] that is mainly emitted approximately between 300 nm to 500 nm during the main HCCI combustion period. This wavelength also corresponds to the light emission wavelength of formaldehyde (HCHO) that is produced by the cool flame reactions that occur during low-temperature oxidation reactions. Because a cool flame and the main combustion period occur at different times, measuring light emission at 395.2

nm [6],[7],[8],[9] makes it possible to measure both the light emission of HCHO during the cool flame and that of the CO-O glow during the main combustion period. Light emission measurements were made in this work because the focus of interest was behavior in the main combustion period.

Figure 3 shows an example of the HCCI light emission spectra measured experimentally in a 4-stroke supercharged HCCI engine with a compression ratio of 14:1 and using PRF 50 as the test fuel [9].

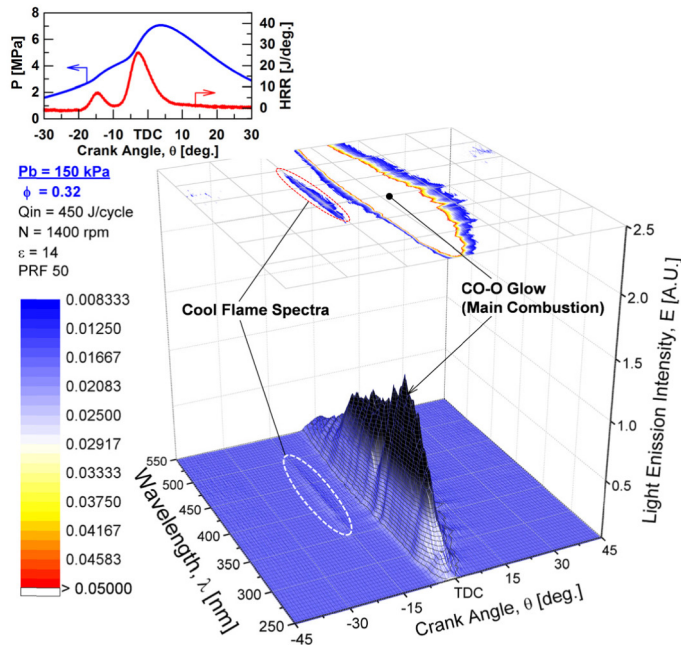


Figure 3. Example of analysis of HCCI light emission spectra [9]

The continuous spectrum denoted by the arrow as “CO-O Glow (Main Combustion)” is attributed to the CO-O glow. The very faint light emission band seen in the region labeled “Cool Flame Spectra” is presumably fluorescence from HCHO that was produced by the cool flame reactions.

In the HCCI combustion experiments, the effective compression ratio ϵ was set at 10:1, and n-heptane (PRF 0) was used as the test fuel because it autoignites easily.

The experimental conditions used are shown in Table 2. The engine speed (N [rpm]) was varied among three levels of $N = 1200$ rpm, 1600 rpm and 2000 rpm. The quantity of heat produced per cycle by the injected fuel (Q_{in}) were kept at approximately constant in each engine speeds.

The quantity of heat produced per cycle by the injected fuel (Q_{in}) was kept approximately constant at each engine speed, i.e., the quantity of fuel injected per cycle [kg/cycle] was kept constant. Q_{in} was calculated in Joules per cycle with the equation below using the measured fuel flow rate ($\dot{m}_f$ [kg/sec]), engine speed N [rpm] and the lower heating value (H_u [J/kg]) of the fuel.

$$Q_{in} = \frac{60 \cdot \dot{m}_f \cdot H_u}{N} \quad (1)$$

Additionally, the scavenging temperature T_{sc} (inducted air temperature) was varied among several levels at each engine speed so as to intentionally change the combustion phasing vary the rapidity of combustion even at the same engine speed.

Because an air-cooled two-stroke engine was used in the experiments to accomplish rapid HCCI combustion, the engine temperature could not be kept constant. Rather, both the engine temperature and the scavenging temperature increased with elapsed time. As a result, combustion phasing was advanced and a transition occurred from moderate combustion to rapid combustion accompanied by pressure oscillations.

Table 2. Experimental conditions.

Engine Speed, N [rpm]	Quantity of Heat Produced Per Cycle by the Injected Fuel, Q_{in} [J/cycle]	Scavenging Temperature, T_{sc} [K]
1200	Keep Almost Constant Value (369 ± 8 J/cycle)	Varied (In order to change the ignition timing)
1600		
2000		

RESULTS AND DISCUSSION

In-Cylinder Flame Development Behavior under Knocking Combustion in an HCCI Engine

The waveforms measured for different combustion phasing at engine speeds of 1200 rpm, 1600 rpm and 2000 rpm are shown in Figs. 4, 5 and 6, respectively.

These waveforms are for the cylinder pressure P , the pressure oscillation component extracted by passing the cylinder pressure signal through a 4-kHz high-pass filter, the pressure rise rate $dP/d\theta$, and the light emission intensity at 395.2 nm corresponding to the CO-O glow. The results indicate that the increasing scavenging temperature (T_{sc}), combustion phasing advanced to an earlier crank angle at all three engine speeds, resulting in a higher pressure rise rate and a transition to more severe knocking.

In the case of fuels like n-heptane that have a low-temperature oxidation mechanism, increasing the initial temperature generally shortens the ignition delay time, or conversely, a region of increasing temperature (i.e., a negative temperature coefficient (NTC) region) occurs [10], [11]. In the experiments, a higher T_{sc} tended to advance the overall combustion phasing because the initial temperature itself increased. When this same test engine was used in previous experiments, the results showed that the interval from the occurrence of the cool flame to autoignition was lengthened [12]. That behavior was not clearly observed in the present study because the cool flame reactions were too weak.

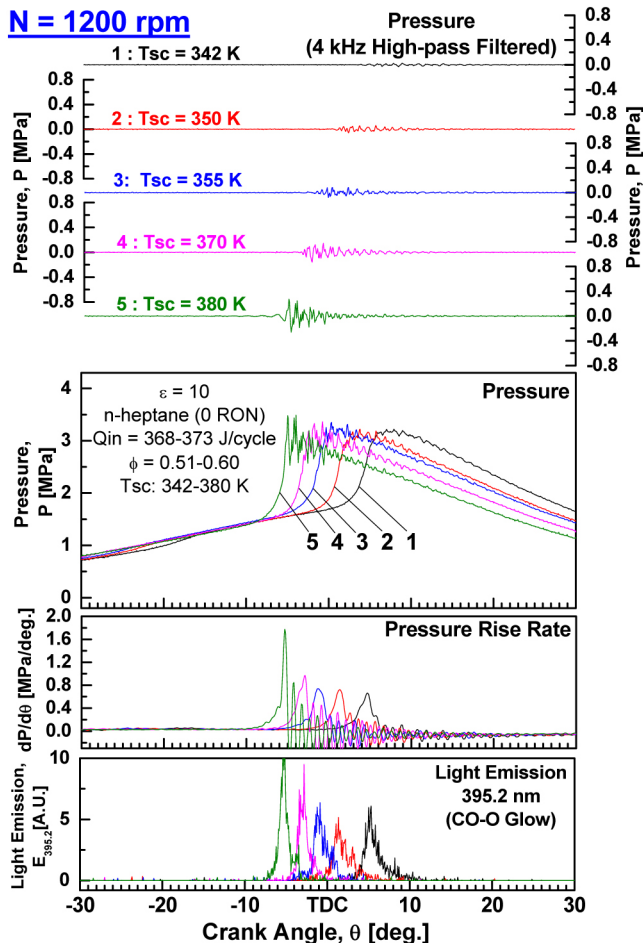


Figure 4. Influence of combustion phasing on combustion (N = 1200 rpm).

The images visualized in the cylinder under these conditions are shown in Fig. 7 for an engine speed of 1200 rpm.

Visualized images and measured waveforms are shown for both knocking and non-knocking cycles. Similar results are shown in Fig. 8 for an engine speed of 2000 rpm. All of the visualized combustion images were obtained at the same camera settings with regard to brightness and contrast.

Under the conditions of waveform #1 where knocking did not occur, it is seen that autoignition occurred locally and then steadily took place at multiple locations with a slight time difference, resulting eventually in combustion throughout the entire cylinder. However, the combustion interval under these conditions was around 5 crank angle (CA) degrees. This means that combustion took place in an extremely short period compared with an interval of several tens of CA degrees that is usually required for flame propagation in SI engines [13].

It is seen in Figures 7 and 8 that the autoignition first occurred on the right side of the combustion chamber under either set of conditions. Presumably, that is because of the high temperature on that side owing to its proximity to the exhaust port, as is shown in Figure 2.

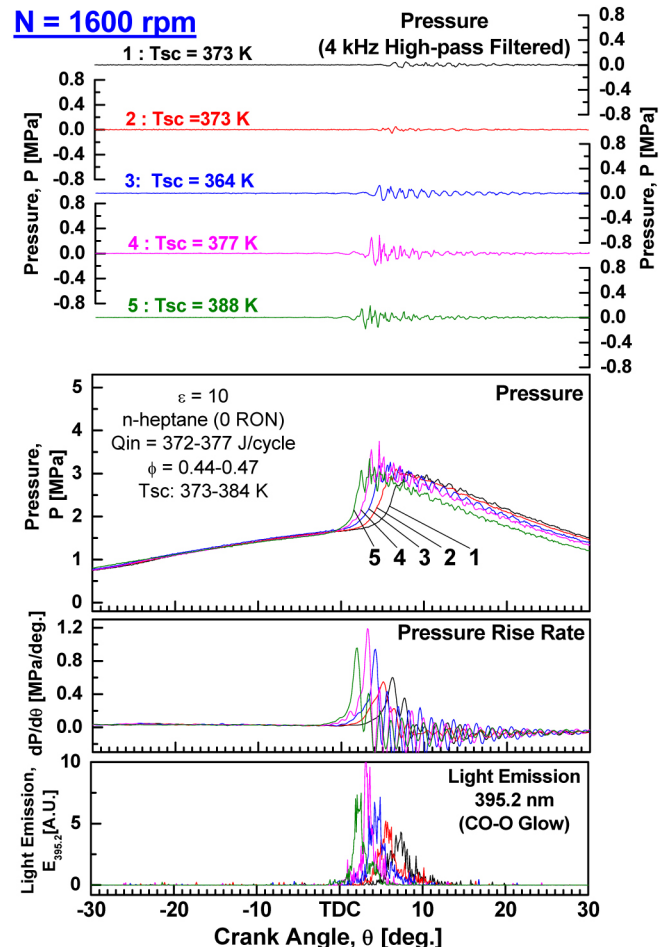


Figure 5. Influence of combustion phasing on combustion (N = 1600 rpm).

Under the conditions of waveform #5 where strong knocking occurred, the same behavior is observed up to the stage where the locally occurring autoignition gradually began to take place at multiple locations. However, in the latter half of the combustion process, it is seen that the unburned end gas autoignited rapidly while emitting strong light (region A and A'). Immediately thereafter, cylinder pressure oscillations occurred. Although it cannot be discerned in these photos, when the images were reproduced consecutively as a video clip, it was found that image brightness in the cylinder fluctuated due to the passage of a pressure wave that occurred after rapid autoignition took place. This same phenomenon has been reported previously in a study that investigated the effects of the equivalence ratio and combustion timing on HCCI knocking [6].

This implies that HCCI knocking resembles SI engine knocking caused by autoignition of the end gas that has been rapidly compressed by the propagating flame. In HCCI combustion as well, the portion of the mixture burned in the latter half of the process is rapidly compressed by the portion that has already autoignited. As a result, a state develops that is similar to the end gas in an SI engine. Presumably, rapid heat release from that state gives rise to a strong pressure wave.