

A Study of the Behavior of In-Cylinder Pressure Waves under HCCI Knocking by using an Optically Accessible Engine

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ABSTRACT

This study investigated the origin of knocking combustion accompanied by pressure wave and strong pressure oscillations in a Homogeneous Charge Compression Ignition (HCCI) engine. Experiments were conducted with a two-stroke single cylinder optically accessible engine that allowed the entire bore area to be visualized. The test fuel used was n-heptane. The equivalence ratio and intake temperature were varied to induce a transition from moderate HCCI combustion to extremely rapid HCCI combustion accompanied by in-cylinder pressure oscillations. Local autoignition and pressure wave behavior under each set of operating conditions were investigated in detail on the basis of high-speed in-cylinder visualization and in-cylinder pressure analysis. As a result, under conditions where strong knocking occurs, a brilliant flame originates from the burned gas side in the process where the locally occurring autoignition gradually spreads to multiple locations. The flame proceeds at high speed toward the unburned end gas, which burns in a short interval of less than 1 crank angle degree. The autoignited flame at that time appears to propagate at high speed from the burned gas side to the unburned end gas side.

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INTRODUCTION

A Homogeneous Charge Compression Ignition (HCCI) engine is characterized by a high compression ratio, lean burn, rapid combustion and premixed combustion. Fundamentally, an HCCI combustion system is capable of achieving high operating efficiency[1]. Lean premixed combustion contributes to a simultaneous reduction of nitrogen oxide (NO_x) and particulate matter (PM) emissions that are a problem with diesel engines.

Rapid combustion that characterizes the HCCI system occurs because the mixture autoignites and burns simultaneously at multiple locations in the cylinder. However, excessively rapid combustion produces engine noise and causes thermal efficiency to decline. In addition, depending on the operating conditions, it produces pressure waves in the combustion chamber and induces abnormal combustion in the form of knocking or ringing accompanied by pressure oscillations [2], [3], [4], [5], [6], [7], [8].

In order to expand the stable operating limit of HCCI combustion on the high load side and avoid such problems, it necessary to have a good understanding of the characteristics of knocking and the mechanism that causes it. Figure 1 shows a schematic diagram of HCCI knocking. This figure presents a typical example of a pressure waveform measured in the cylinder during knocking. The portion of the waveform denoted as 1(a) shows a rapid pressure rise caused by autoignition at multiple locations, similar to diesel engine knocking. This rapid increase in pressure excites the engine, gives rise to noise

and the strong force of the maximum pressure can also cause strength problems. The portion of the waveform denoted as 1(b) indicates the occurrence of in-cylinder pressure oscillations similar to knocking in a spark-ignition (SI) engine. When such pressure oscillations occur, they destroy the wall boundary layer, resulting in greater cooling losses that cause thermal efficiency to decline. There is also a risk of thermal damage to the engine.

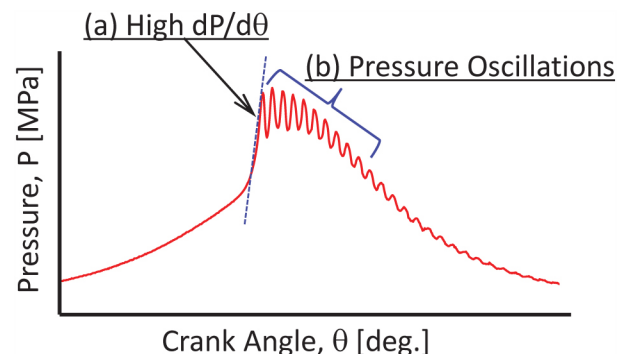


Figure 1. Typical measured in-cylinder pressure waveform under HCCI knocking

Combustion experiments were conducted in this study using an optically accessible engine that allowed the entire bore area to be visualized for the purpose of making clear the conditions giving rise to rapid HCCI combustion and knocking. The HCCI engine was actually operated under combustion conditions conducive to the

occurrence of strong knocking. The behavior of the pressure waves and pressure oscillations was investigated in detail by taking high-speed combustion flame photographs across the entire bore area, analyzing the indicated pressure data and making in-cylinder spectroscopic measurements.

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 2. A two-stroke single cylinder optically 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-Z).

A rectangular-shaped channel was provided in the center of the piston head (photo (a) in Fig. 2) 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.

Figure 3 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.

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 [9] that is mainly emitted approximately between 300 nm to 500 nm during the main HCCI combustion period.

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)	13 : 1

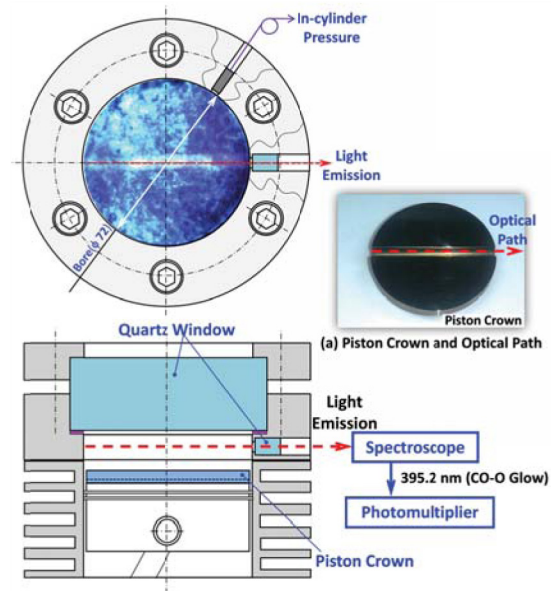


Figure 2. Configuration of optically accessible engine and light emission measurement system.

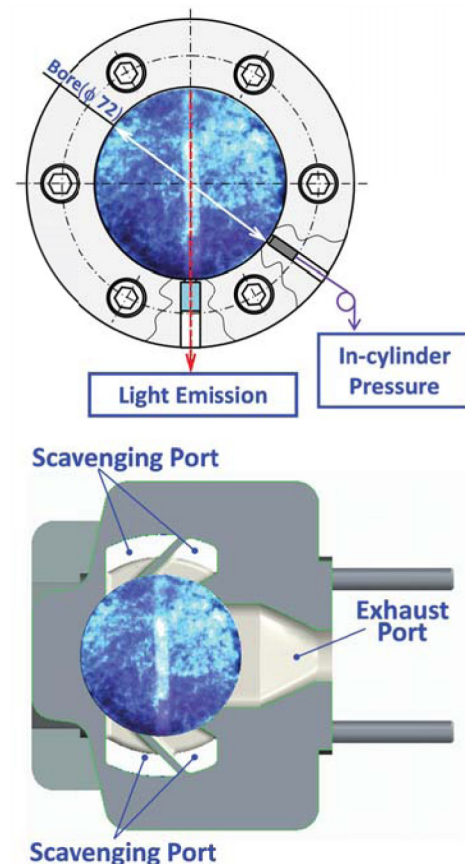


Figure 3. Locations of the scavenging and exhaust ports.

Strong knocking is more apt to occur under advanced combustion phasing. Therefore, n-heptane (0 RON) was used in our experiments. The experimental conditions used are shown in Table 2. The injected heat energy per cycle (Q_{in} [J/cycle]) was varied among three levels of $Q_{in} = 210$ J/cycle, 300 J/cycle and 370 J/cycle. The engine speed was set at 1200 rpm constant in each case.

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

Table 2. Experimental conditions

	Case 1	Case 2	Case 3
Test Fuel	n-heptane (0 RON)		
Injected Heat Energy Per Cycle, Q_{in} [J/cycle]	≈ 210 J/cycle (212 $\pm$ 2)	≈ 300 J/cycle (301 $\pm$ 0.2)	≈ 370 J/cycle (369 $\pm$ 0.3)
Equivalence Ratio, ϕ [-]	0.52 $\pm$ 0.02	0.73 $\pm$ 0.02	0.88 $\pm$ 0.04
Engine Speed, N [rpm]	1200 rpm		
Scavenging Temperature, T_{sc} [K]	Varied (In order to change the autoignition timing)		
Intake Pressure Condition	≈ 100 kPa (abs.) (Natural Aspirated)		
Frame Rate [fps (Frames/sec)]	100,000 fps		

RESULTS AND DISCUSSION

In-Cylinder Autoignition and Pressure Wave Behavior Under Knocking Combustion in an HCCI Engine

Figures 4, 5, 6 present the waveforms that were measured when the scavenging temperature was varied in three cases where the quantity of heat produced per cycle by the injected fuel (Q_{in}) differed. The horizontal axis of the figures shows the crank angle θ [deg.]. From the top, the vertical axis shows the cylinder pressure waveforms following high-pass filtering of the measured pressure data at 4 kHz to extract only the high-frequency component, the cylinder pressure P [MPa], the pressure rise rate $dP/d\theta$ [MPa/deg.], and the light emission intensity $E_{395.2}$ [A.U.] at 395.2 nm corresponding to the wavelength of the CO-O glow. All of the waveforms indicate that the autoignition timing advanced and the maximum pressure rise rate increased as the scavenging temperature was increased. It is also seen that knocking accompanied by pressure oscillations occurred under the conditions of a high equivalence ratio and a high scavenging temperature.

Figure 7 shows an enlarged view of waveform #4 (Case 3) for which the autoignition timing was the most advanced. An examination of the light emission intensity for this waveform reveals markedly strong emission intensity compared with waveform #1. Close observation of the enlarged view of waveform #4 indicates that a strong light emission occurred in the initial period when the pressure rose sharply. Subsequently, pressure oscillations are observed in the pressure waveform.

Figures 8, 9, 10 present high-speed photographs of the autoignition behavior in the cylinder taken at a frame rate of 100,000 fps for the conditions of waveform #1, #3 and #4 in Figure 6.

The images in Figure 8 show that autoignition occurred locally at multiple locations and eventually spread throughout the entire cylinder under a condition where virtually no pressure oscillations occurred. It is seen in Figures 8, 9, 10 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 Fig. 3.

Case 1

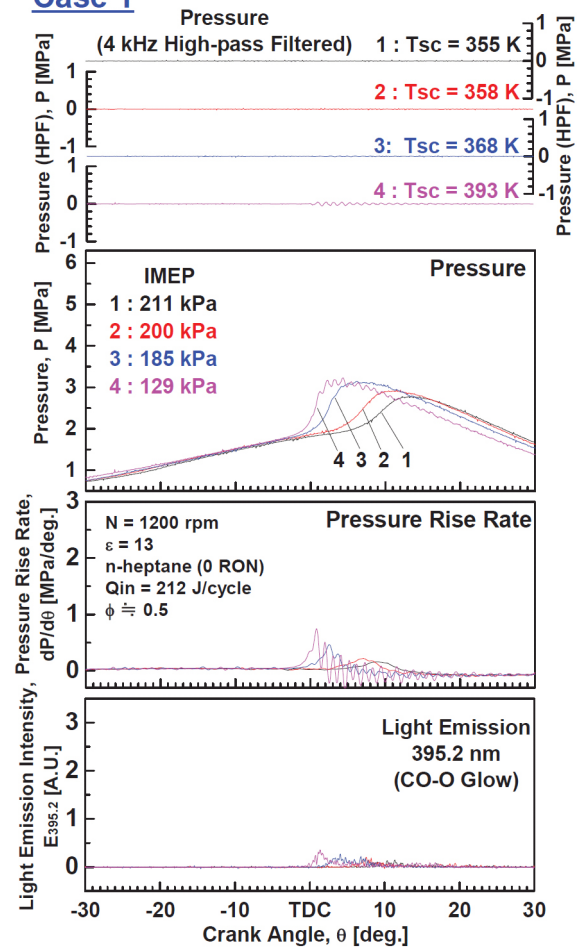


Figure 4. Typical measured waveforms (Case 1)

In contrast, the images in Figure 9, where pressure oscillations are observed, show that autoignition that occurred locally in the initial period, as seen in Figure 8, spread gradually in the cylinder. However, in the period denoted as “A” in Figure 9, a brilliant flame occurred near the center of the combustion chamber and the flame subsequently progressed rapidly toward the unburned end zone on the left side. A highly bright region presumed to be pressure waves is seen in the combustion chamber at that time. The pressure waves reflect from the cylinder wall on the right side in the region denoted as B and display a high degree of brightness. When the images are reproduced as video, it is observed that the pressure waves traverse the combustion chamber in the bore direction. The brilliant flame that occurs in the center of the combustion chamber in the region denoted as “A” is burning in approximately half of the chamber three frames later. Assuming that this represents the apparent flame propagation velocity, it is approximately 1200 m/s. In other words, this is presumably the unburned end gas that autoignites instantaneously. Assuming that the gas autoignites at a temperature of 1100 K, the velocity of sound in air (c [m/s]) can be found as $c = (\kappa RT)^{1/2} = 665$ m/s. This suggests that the apparent propagation velocity of the autoignited flame is faster than approximately the velocity of sound.