A Study of Interaction between Pressure Waves and Reaction Regions in HCCI Combustion accompanied by Strong Knocking based on High-speed In-cylinder Visualization and Observation

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1 Introduction

A major issue for Homogeneous Charge Compression Ignition (HCCI) [1],[2] combustion, which is expected to be a promising combustion system for high-efficiency internal combustion engines in the future, is to expand the region of stable engine operation. It is well known that extremely rapid combustion accompanied by pressure oscillations (HCCI knocking) occurs in the combustion chamber especially under high-load conditions [3]-[7]. There are still many unclear aspects as to why such pressure oscillations occur in an HCCI engine, which is inherently different from spark ignition engines in that autoignition-induced combustion takes place throughout the entire combustion chamber.

In this study, a test engine that allowed the entire combustion chamber to be visualized was operated under conditions giving rise to the formation of strong pressure waves in the combustion chamber. The initiation and development of autoignition in the combustion chamber and the mechanism causing the formation of pressure waves and pressure oscillations were investigated on the basis of high-speed in-cylinder visualization and observation of combustion and frequency analysis of pressure waves measured in the combustion chamber.

2 Experimental Equipment and Procedure

The specifications of the test engine and measurement conditions are shown in Table 1, and the configuration of the test equipment used for in-cylinder visualization is shown in Figure 1. A two-stroke single-cylinder optically accessible engine was used to facilitate easy detailed measurement of combustion by in-cylinder imaging. A quartz observation window was provided in the top of the cylinder head to enable the entire bore area to be visualized. Combustion flame images were captured by using a high-speed camera.

Strong knocking is more apt to occur under advanced combustion phasing. Therefore, n-heptane (0 RON) was used in the experiments. The engine speed was kept constant at 1200 rpm in each experiment. In addition, the scavenging temperature T_{sc} was increased among several levels in each experiment so as to intentionally advance the autoignition timing and induce pressure waves and strong knocking.

A rectangular-shaped channel was provided in the center of the piston head to serve as an optical path for obtaining light emission measurements (but the measured results are not presented in this paper). 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.

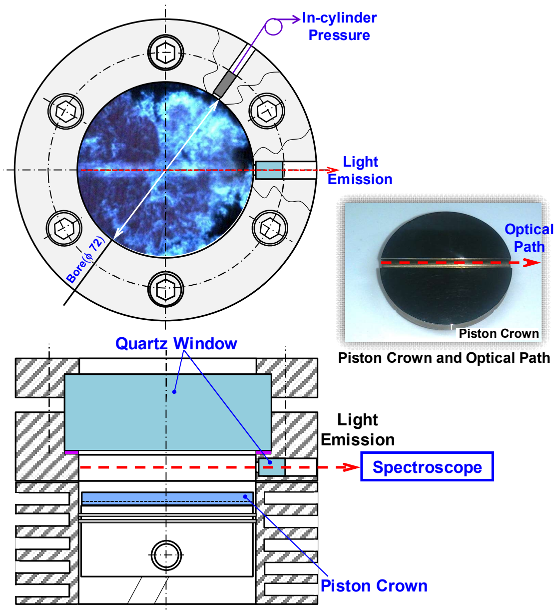


Table 1 Specifications of test engine and test conditions

2-stroke Air-cooled Single-cylinder Engine	
Scavenging Type	Schnürle
Bore × Stroke	72 × 60 mm
Displacement	244 cm^3
Effective Compression Ratio (ε)	12 : 1
Engine Speed (N)	1200 rpm
Test Fuel	n-heptane (0 RON)
Scavenging Temperature (Tsc)	Varied (In order to change the ignition timing)

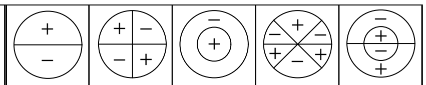
Fig. 1 Configuration of optically accessible engine and light emission measurement system

3 Estimation of Pressure Oscillation Modes

First, this section presents the results of an analysis conducted with Draper's acoustic pressure wave formula [8] shown below for the purpose of estimating the fundamental frequencies of the pressure oscillations formed in the test engine combustion chamber.

$$f_{m,n} = \frac{\rho_{m,n} \cdot a}{\pi \cdot B} = \frac{\rho_{m,n} \cdot \sqrt{\kappa R T}}{\pi \cdot B}$$

where,
$f_{m,n}$: Oscillation frequency of in-cylinder gas
$\rho_{m,n}$: Vibration mode factor
m: Number of nodes in the circumferential oscillation
n: Number of nodes in the radial oscillation
a: Velocity of sound (= $(\kappa RT)^{1/2}$) [m/s]
B: Cylinder bore [mm] (72 mm)
κ: Ratio of specific heat
R: Gas constant of working gas [J/(kg-K)]
T: Absolute temperature of working gas [K]



Mode Shapes m, n	1, 0	2, 0	0, 1	3, 0	1, 1
$\rho_{m,n}$	1.84	3.05	3.83	4.20	5.33
$f_{m,n}$ [kHz]	7.00	11.60	14.56	15.97	20.27

Fig. 2 Pressure oscillation modes [8]

It will be noted that κ, R and T were assumed to have the following constant values because the pressure oscillations occur in the vicinity of the maximum gas temperature in the combustion chamber.

T = 2000 K, R = 291 J/(kg-K), κ = 1.27, B = 72 mm

Figure 2 shows the calculated frequencies of gas pressure oscillations in the combustion chamber in each vibration mode [9]. For example, the oscillation frequency of the (1, 0) vibration mode in which pressure waves traverse the combustion chamber in the bore direction was estimated to be approximately 7 kHz. This value agreed relatively well with the results of a frequency analysis of the measured pressure values that will be described later.

4 Results and Discussion

Figure 3 presents the measured results obtained when a transition to strong knocking was intentionally induced by varying the scavenging temperature T_{sc} (inlet gas temperature measured at the svcavenging port) under an equivalence ratio condition of approximately 0.6. The graphs in the center show the measured combustion chamber pressure and the results of a frequency analysis of the pressure oscillations in terms of the power spectral density. Color photographs of HCCI combustion obtained at a high-speed frame rate of 60000 fps and corresponding to the waveforms for condition No. 1 (T_{sc} = 317 K) and condition No. 3 (T_{sc} = 338 K) are shown above and below the graphs, respectively. It is seen that a transition to strong knocking occurred as the scavenging temperature was increased. Under condition No. 3, the peak pressure value increased accompanying autoignition, indicating the occurrence of strong pressure oscillations. A close examination of the frequency characteristics confirms the presence of a peak near approximately 7 kHz under each Tsc condition. In other words, this indicates the occurrence of the (1, 0) vibration mode in which pressure waves traverse the combustion chamber in the bore direction. On the other hand, a definite peak is also observed in the vicinity of approximately 12 kHz under condition No. 3 that gave rise to strong knocking. It is inferred that this peak represents the occurrence of the (2, 0) vibration mode.

An examination of the visualized combustion images reveals that autoignition occurred locally under condition No. 1 where relatively weak knocking took place; autoignition gradually developed and eventually became a combustion regime that extended throughout the entire cylinder. In contrast, under condition No. 3 where strong knocking took place, locally occurring autoignition gradually developed in the initial stage, and at the time indicated by region A, the unburned mixture in the end zone autoignited in a short duration. Strong pressure oscillations occurred at that moment. This suggests that rapid autoignition occurring in the latter stage is closely related to the generation of pressure waves. However, the development process of the rapid autoignition that occurred in the latter stage could not be distinguished in the HCCI combustion images taken at a frame rate of 60000 fps. Therefore, combustion images were obtained at a higher frame rate in order to investigate the relationship between the development of autoignition and the formation of pressure waves.

Figure 4 shows the measured results obtained when a transition to strong knocking was intentionally induced by varying the scavenging temperature under an equivalence ratio condition of approximately 0.65. The frame rate under these conditions was increased to 300000 fps in order to observe at a higher speed the pressure wave formation behavior induced by autoignition. In addition, monochromatic photographs were taken in order to confirm the combustion flame brightness. Similar to the results obtained under the Tsc conditions in Fig. 3, a transition to strong knocking occurred as the scavenging temperature was increased. In addition to the (1, 0) vibration mode at approximately 7 kHz, pressure oscillation corresponding to the (2, 0) vibration mode is observed in the vicinity of approximately 12 kHz under condition No. 3 (T_{sc} = 334 K) and condition No. 4 (T_{sc} = 344 K) where strong knocking occurred.

An examination of the visualized combustion images corresponding to waveform No. 4 reveals that autoignition occurred locally in the initial stage and gradually developed; at the time indicated by region B, a local area of high brilliance (denoted by X) appeared, which moved downward at high speed and unburned mixture regions in the end zone autoignited successively. When the combustion images photographed at that time were replayed as video, it was confirmed that pressure waves traveled in the counterclockwise direction. Presumably, that is what caused the (2, 0) vibration mode in addition to the (1, 0) vibration mode.

A comparison was made between the propagation speed of autoignition before and in region B. Autoignition began in frame C and developed slowly in the first half. At frame C' it had developed to cover approximately one-half of the combustion chamber bore (72 mm). The apparent speed at which autoignition developed was around 130 m/s. In region B, on the other hand, the highly brilliant flame that occurred in frame D had consumed the unburned mixture by the time of frame D'. The apparent speed at which autoignition propagated was calculated to be around 1800 m/s. Using the values assumed in section 2 for the absolute temperature of the working gas T, the gas constant of the working gas R, and the ratio of specific heat κ, the speed of sound was estimated to be around 860 m/s. In fact, the unburnt gas temperature is even lower than the burnt gas, so the sound speed in unburned gas also lower than that of the burnt gas. This indicates that the propagation speed of the rapid autoignition was higher than the speed of sound. It is therefore assumed that, under conditions producing strong knocking, locally generated pressure waves travel to the unbuened zone where they induce autoignition of the unburned mixture, which produces strong pressure waves leading to severe knocking. It is inferred that this phenomenon reached the condition of "developing detonation" [10]-[12] in which pressure waves and reaction regions coexist, as proposed and analyzed by Zeldovich, Bradley and others. It is presumed from these observation results that the interaction of pressure waves and reaction regions gives rise to a combustion phenomenon corresponding to developing detonation under the conditions where strong knocking occurs in HCCI combustion and strong knocking, referred to as super-knock or mega-knock, is induced by low-speed preignition (LSPI) in turbocharged SI engines.

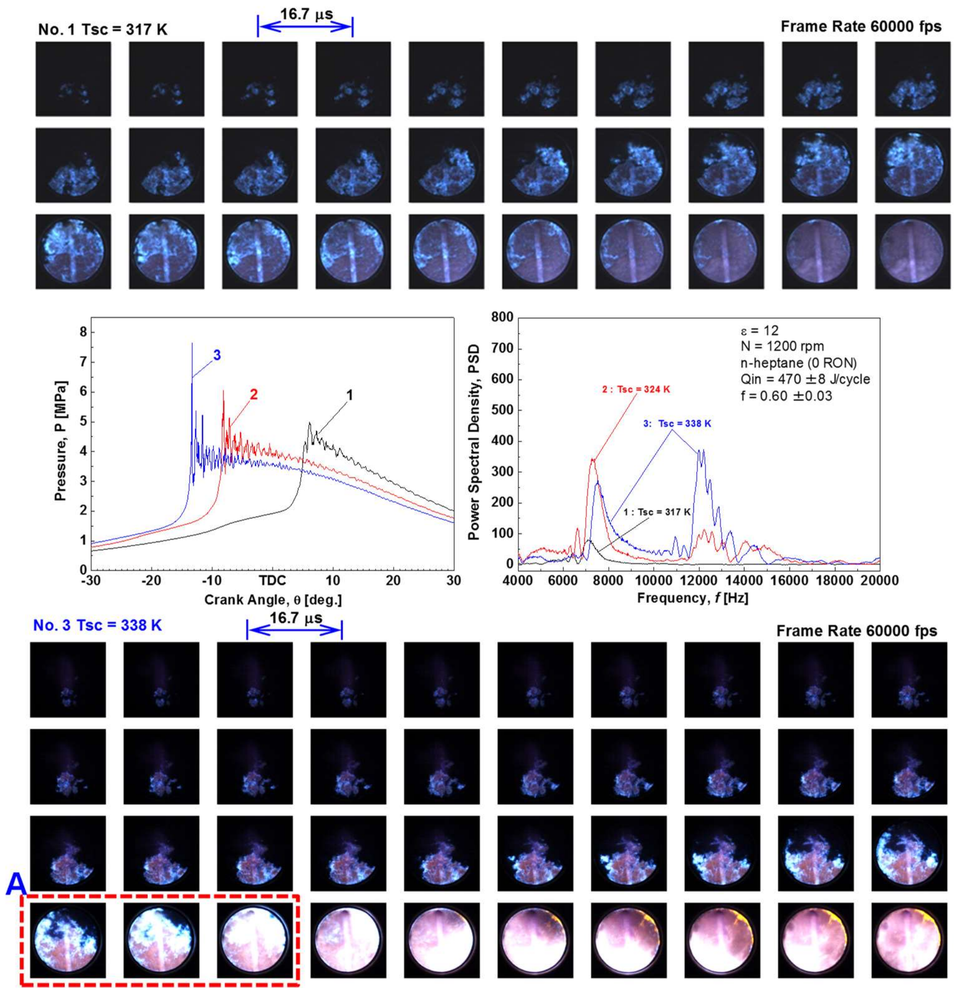


Fig. 3 Photographs of HCCI combustion with pressure and frequency characteristics of pressure oscillations (60000 fps)

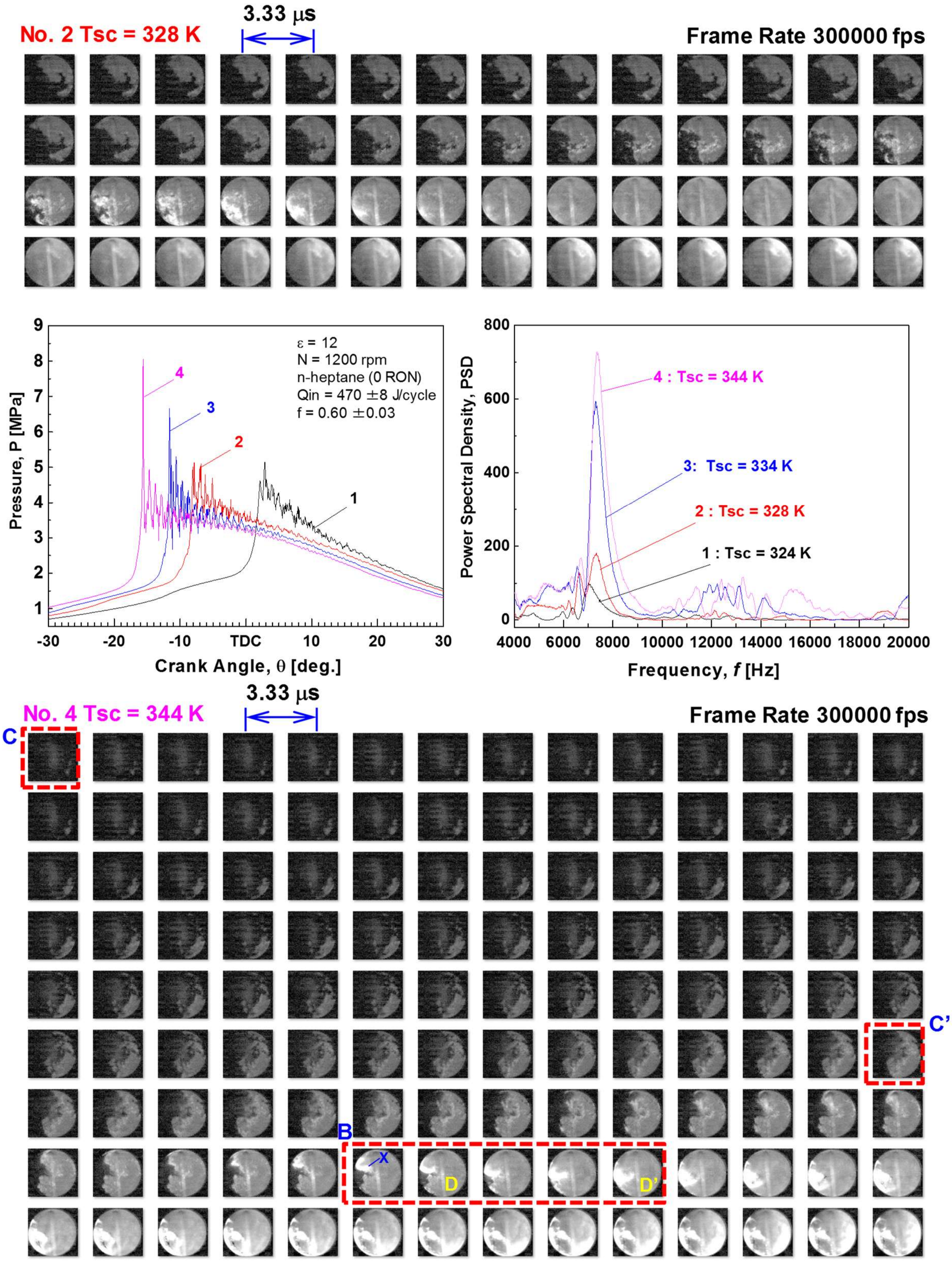


Fig. 4 Photographs of HCCI combustion with pressure and frequency characteristics of pressure oscillations (300000 fps)

4 Conclusions

(1) During the process in which autoignition develops initially, the unburned end-zone mixture autoignites rapidly in a shorter duration under conditions giving rise to strong knocking.
(2) The (1, 0) vibration mode is the fundamental mode of the pressure oscillation frequency, but pressure oscillation corresponding to the (2, 0) vibration mode is also observed under conditions producing strong knocking. It is inferred from the results of in-cylinder visualization and observation that the pressure waves produced by combustion travel circumferentially in the cylinder under these conditions.
(3) Under conditions producing strong knocking, a region with a highly brilliant flame forms locally and propagates at high speed to the unburned end zone where areas of unburned mixture autoignite successively. The apparent propagation velocity of autoignition at that time is estimated to be faster than the speed of sound. Presumably, under conditions producing strong pressure waves and pressure oscillations, the interaction of pressure wave fronts and reaction regions induces a state of developing detonation in which rapid combustion occurs.

Acknowledgment
This work was supported by JSPS KAKENHI Grant Number JP16K18034

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