

## Optical Measurement of Autoignition and Combustion Behavior in an HCCI Engine

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### ABSTRACT

In this study, optical measurements were made of the combustion chamber gas during operation of a Homogeneous Charge Compression Ignition (HCCI) engine in order to obtain a better understanding of the ignition and combustion characteristics. The principal issues of HCCI engines are to control the ignition timing and to optimize the combustion state following ignition. Autoignition in HCCI engines is strongly influenced by the complex low-temperature oxidation reaction process, alternatively referred to as the cool flame reaction or negative temperature coefficient (NTC) region. Accordingly, a good understanding of this low-temperature oxidation reaction process is indispensable to ignition timing control.

In the experiments, spectroscopic measurement methods were applied to investigate the reaction behavior in the process leading to autoignition. Two types of spectroscopic measurements were obtained: measurement of spontaneous light emission from the flame in the combustion chamber and measurement of light absorption. The former measurement facilitated detection of light emission from chemical species produced by the reactions; the latter method facilitated measurement of the production and consumption behavior of the chemical species even when no light emission occurred. Following ignition, combustion (hot flame) proceeds rapidly under a high load, giving rise to knocking and the production of nitrogen oxides (NO<sub>x</sub>) by the high-temperature gas. Engine operation under a low load is restricted by incomplete combustion and misfiring due to the lower temperature. Therefore, the characteristics of the hot flame following ignition were investigated by measuring the light emission spectrum of the flame and by visualizing the conditions in the cylinder.

Using these methods, the light emission spectrum was measured during operation of the experimental HCCI engine. The results made clear the light emission spectrum of the hot flame following ignition was made clear. The main emission was found to be a continuous spectrum from 300 nm to 500 nm, presumably attributable to the recombination reaction of carbon monoxide and oxygen atoms and known as CO-O glow. The results also revealed that the time of light emission in a wavelength region of approximately 300-500 nm, corresponding to the CO-O glow, coincided well with the time of heat release. This implies that spectroscopic measurement of light emission in the wavelength region corresponding to the CO-O glow can facilitate detection of local heat release in the cylinder.

In-cylinder visualization was used to obtain two-dimensional flame images across the entire cylinder bore area in order to investigate the relationship between the local state of hot flame development and the rapidity of combustion. The results revealed that the time for the occurrence of autoignition showed little local difference under conditions conducive to rapid combustion; autoignition occurred almost simultaneously throughout the unburned region and the mixture burned all at once.

### INTRODUCTION

Homogeneous Charge Compression Ignition (HCCI) engines have attracted much interest recently on account of their capability to achieve highly efficient combustion with low emission levels [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. Diesel engines typically deliver high thermal efficiency over a wide engine load range because they have a non-throttling induction system and burn a lean mixture throughout the entire cylinder at a sufficiently high compression ratio. Gasoline engines, on the other hand,

cannot be operated at high compression ratios owing to the occurrence of knocking. In addition, it is difficult to achieve lean combustion in gasoline engines from the standpoints of maintaining combustion stability and the exhaust gas cleaning performance of a three-way catalyst system. During low-load operation in particular, the pumping losses of gasoline engines increase because the throttle valve is closed to regulate the intake mass air flow. For these reasons, gasoline engines have lower thermal efficiency than their diesel counterparts.

Diesel engines have a diffusion combustion process in which the fuel spray is mixed with the surrounding air, with the result that the temperature and fuel concentration in the cylinder are often inhomogeneous locally. Nitrogen oxides (NO<sub>x</sub>) form in local high temperature regions and particulate matter (PM) forms in local low temperature, fuel-rich regions, making it difficult to reduce both NO<sub>x</sub> and PM simultaneously. The performance of exhaust gas aftertreatment systems, incorporating a diesel particulate filter (DPF), NO<sub>x</sub> catalyst or other devices, has been improved in recent years, enabling diesel engine vehicles to comply with more stringent exhaust emission regulations in countries around the world. However, aftertreatment systems have various limitations, including their high cost, durability and reliability issues, and catalyst light-off characteristics under low loads, making it necessary to seek thorough reductions of engine-out emissions through combustion improvements.

The HCCI combustion process forms a premixed charge in the cylinder like a gasoline engine and ignites it by compression in the manner of a diesel engine. With this combination, the HCCI process accomplishes lean premixed combustion at a sufficiently high compression ratio without throttling, enabling it to attain high thermal efficiency and clean engine-out emissions.

Figure 1 shows a representative in-cylinder pressure and heat release rate (HRR) obtained with the test engine, which will be described later, under HCCI operation using n-heptane (0 RON) as the test fuel. With a low octane number fuel, the HCCI combustion process typically displays two stages of combustion, one attributable to a cool flame and the other to a hot flame. The process is characterized by the degeneracy of the cool flame reactions followed by the occurrence of the hot flame reactions after a certain period of delay. In this paper, the reactions until the occurrence of the hot flame are referred to collectively as low-temperature oxidation reactions [18],[19], including those associated with a cool flame, negative temperature coefficient and a blue flame.

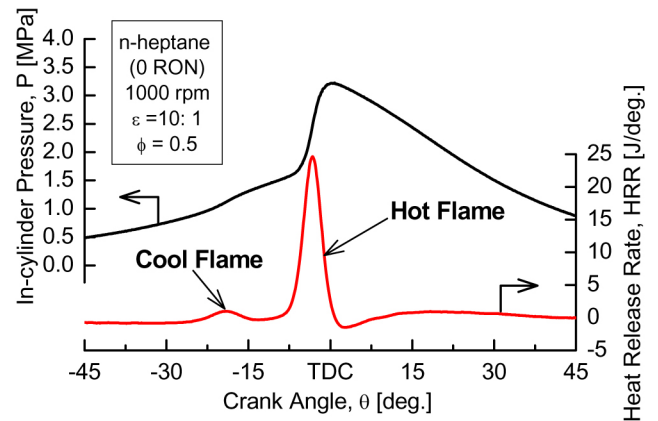


**Fig. 1. Typical in-cylinder pressure and HRR waveform**

Because these low-temperature oxidation reactions strongly influence the subsequent hot flame (high-temperature oxidation reactions), they must be controlled in order to manage the ignition timing of an HCCI engine. When the type of fuel used, intake air temperature, exhaust gas recirculation (EGR) rate, compression ratio, engine speed or other operating conditions change, the characteristics of the low-temperature oxidation reactions also vary. Therefore, it is necessary to have a detailed understanding of how changes in the engine operating conditions affect the low-temperature oxidation reactions and ignition timing. Another aspect of the HCCI combustion process is that it proceeds from ignition that occurs at multiple locations simultaneously. This makes it difficult to operate an HCCI engine in the high load range owing to the occurrence of knocking caused by rapid combustion. Consequently, the conditions inducing the hot flame must also be controlled to an optimal state.

In view of these observations, it is necessary to have a thorough understanding of the combustion mechanisms of both the low-temperature and high-temperature oxidation reactions. In this study, HCCI combustion mechanisms were analyzed in detail based on optical measurements obtained in the combustion chamber during the operation of a test HCCI engine. Specifically, the following items were investigated experimentally.

### Characteristics of high-temperature oxidation reactions during HCCI combustion

1. The structure of the flame spectrum was analyzed on the basis of an analysis of light emission spectra.
2. The relationship between hot flame formation behavior and the rapidity of combustion was analyzed on the basis of in-cylinder visualizations.

## Characteristics of low-temperature oxidation reactions during HCCI combustion

3. The characteristics of the low-temperature oxidation reactions were analyzed based on an analysis of light emission and absorption spectroscopy.

4. The effects of the octane number on low-temperature oxidation reactions and ignition was investigated.

## EXPERIMENTAL EQUIPMENT AND PROCEDURE

The specifications of the test engine are given in Table 1, and the test equipment used in this study is shown schematically in Fig. 2. A two-stroke engine with a combustion chamber that allowed large degrees of measurement freedom was used in the experiments. Two-stage ignition accompanied by a cool flame, which is a characteristic feature of four-stroke HCCI combustion, is observed in this test engine when a low-octane fuel is autoignited by compression under a condition of a high delivery ratio (low residual condition). This indicates that four-stroke HCCI combustion can be simulated with this engine [20].

Table 1. Specifications of test engine

| 2-stroke Air-cooled Spark Ignition (SI) Engine |                                           |       |
|------------------------------------------------|-------------------------------------------|-------|
| Scavenging Type                                | Schnürle                                  |       |
| Bore × Stroke                                  | 72 × 60 mm                                |       |
| Displacement                                   | 244 cm <sup>3</sup>                       |       |
| Effective Compression Ratio (ε)                | Light Emission Spectra                    | 10: 1 |
|                                                | Flame Visualization                       | 6: 1  |
|                                                | Light Emission and Absorption Measurement | 12: 1 |
| Test Fuel                                      | PRF (n-heptane + iso-octane) 0 ~ 60 RON   |       |

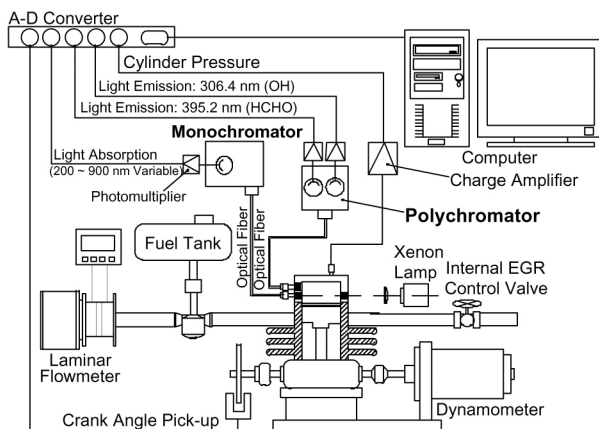


Fig. 2. Configuration of test equipment

## MEASUREMENT OF LIGHT EMISSION SPECTRA

Figure 3 shows a schematic diagram of the cylinder head and measurement equipment used in measuring light emission spectra. The flame light in the combustion chamber in the bore direction was extracted through quartz window in Fig. 3 and introduced into the variable-wavelength type monochromator (Monochromator in Fig. 3) and a photomultiplier to obtain the light emission intensity. Light emission spectra were obtained by measuring the light emission at each wavelength of interest.

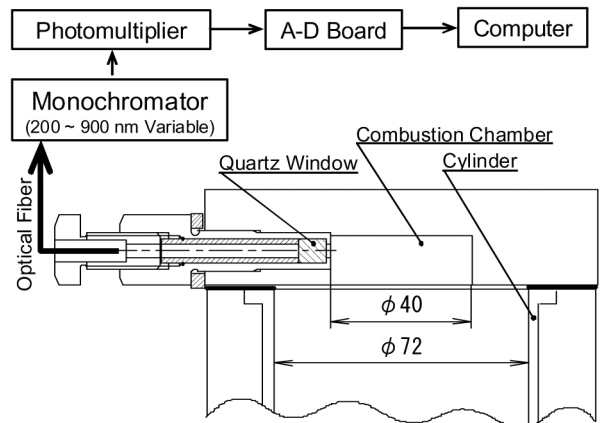


Fig. 3. Schematic diagram of cylinder head for measurement of light emission spectra (ε = 10: 1)

## SIMULTANEOUS MEASUREMENT OF LIGHT EMISSION AND ABSORPTION

A schematic diagram of the cylinder head and measurement equipment used to obtain simultaneous measurements of light emission and absorption is shown in Fig. 4. Quartz window A, provided opposite B, is used for irradiating the interior of the combustion chamber with light from a xenon lamp. The transmitted light is then introduced into the monochromator and photomultiplier to measure the level of light absorption that takes place in the combustion chamber. Light absorption was measured at a wavelength of 293.1 nm, corresponding to the absorption wavelength of formaldehyde (HCHO) that forms during low-temperature reactions [21].

Light absorbance (A) is defined as equation (1), where  $E_0$  is the transmitted light intensity at bottom dead center and  $E$  is the transmitted light intensity at any arbitrary crank angle.

$$A = \frac{E_0 - E}{E_0} = 1 - \frac{E}{E_0} \quad (1)$$

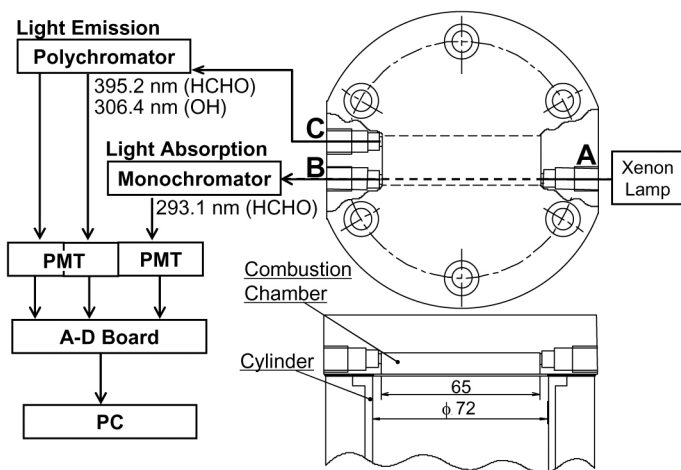


**Fig. 4. Schematic diagram of cylinder head for simultaneous measurement of light absorption and emission ( $\epsilon = 12: 1$ )**

Light emission in the combustion chamber was extracted through window C and introduced into a multi-wavelength spectroscope (Polychromator) and a photomultiplier to measure the light emission intensity at two specific wavelengths. One wavelength was 395.2 nm, corresponding to the light emission wavelength of HCHO. The other was 306.4 nm, corresponding to the light emission wavelength of the OH radical [21] that plays a key role in the progress of combustion reactions.

## IN-CYLINDER FLAME VISUALIZATION

A schematic diagram of the optically accessible engine used for flame visualization is shown in Fig. 5. A quartz window was provided in the cylinder head to allow combustion to be visualized across the entire cylinder bore. Color combustion images were captured with a high-speed video camera. Flame light was extracted through two quartz windows provided on opposite sides of the cylinder, and light emission intensities were measured simultaneously at two wavelengths. One wavelength was 395.2 nm, representative of the blue CO-O glow (in hot flame), and the other was 700 nm, representative of a longer light emission wavelength where red light was emitted.

## RESULTS AND DISCUSSION

### ANALYSIS OF HOT FLAME SPECTRUM STRUCTURE BASED ON LIGHT EMISSION SPECTRUM ANALYSIS

HCCI combustion proceeds from ignition at multiple places in the cylinder, unlike combustion due to premixed flame propagation in a spark-ignition (SI) engine. In order to better

understand HCCI combustion characteristics, the light emission spectrum of the HCCI combustion flame was analyzed. The engine operating conditions used in this analysis are given in Table 2. Using n-heptane (0 RON) as the fuel, the test engine was continuously operated under a steady state while keeping the heating value of the fuel injected per cycle constant. A variable-wavelength spectroscope was used to obtain time histories of the light emission intensity at a single wavelength for 25 cycles. The mean value was then found as the light emission intensity at a certain wavelength. Spectroscopic measurements were made while varying the wavelength in a range of 250-900 nm, and the measured light emission intensities were arranged at each wavelength to obtain the light emission spectrum.

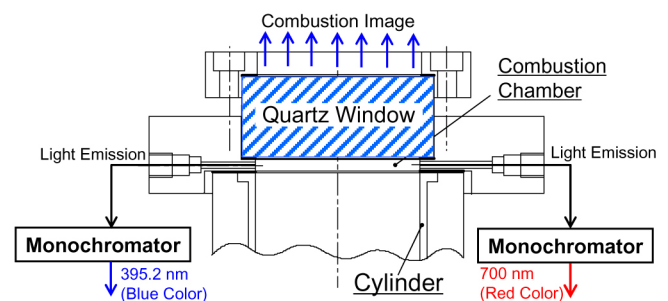


**Fig. 5. Schematic diagram of cylinder head for flame visualization ( $\epsilon = 6: 1$ )**

**Table 2. Operating conditions for light emission spectra measurement**

| Effective Compression Ratio, $\epsilon$ [-] | Injected Heat Value, $Q_{in}$ [J/cycle] | Intake Equivalence Ratio, $\phi$ [-] | Engine Speed, N [rpm] | Fuel (RON)        | Scavenging Efficiency, $\eta_s$ [-] |
|---------------------------------------------|-----------------------------------------|--------------------------------------|-----------------------|-------------------|-------------------------------------|
| 10: 1                                       | $335 \pm 3$                             | 0.53                                 | 1000                  | n-heptane (0 RON) | 0.70                                |

The light emission spectrum obtained is shown in Fig. 6, where the relationship between the crank angle, light emission intensity and wavelength is represented three-dimensionally. In addition, the contour lines of the light emission intensity are projected at the bottom of the 3D representation. Light emission occurred over a wide range of wavelengths from approximately 250 nm to 800 nm. A strong continuous spectrum is seen especially between approximately 300 nm and 500 nm (region D in the figure), which presumably represents light emission due to the recombination reaction of carbon monoxide and oxygen molecules and is known as the CO-O glow [21]. This bandwidth is the part of the spectrum from purple to blue. In the visualized images that will be described later, a blue flame was observed in the hot flame in this bandwidth. This suggests that the main light emission of the HCCI combustion flame is attributable to the CO-O glow.

In the case of combustion due to a propagating flame in a gasoline engine or the premixed combustion flame of a burner, strong light emissions are observed from OH, CH, C2 and other radicals [21], [22], [23]. However, such light emissions are weak in the case of HCCI combustion, probably because of the low temperature of the combustion flame. It has been reported that, in addition to the CO-O glow, strong light emission from the OH radical was also observed in HCCI combustion when the equivalence ratio was increased [23]. In the present study, light emission was observed near 310 nm following completion of the CO-O glow and a continuous spectrum was seen in a wavelength range of approximately 600-800 nm (region E in Fig. 6). The former light emission can be attributed to the OH radical and the latter light emission is ascribable to water produced during combustion.

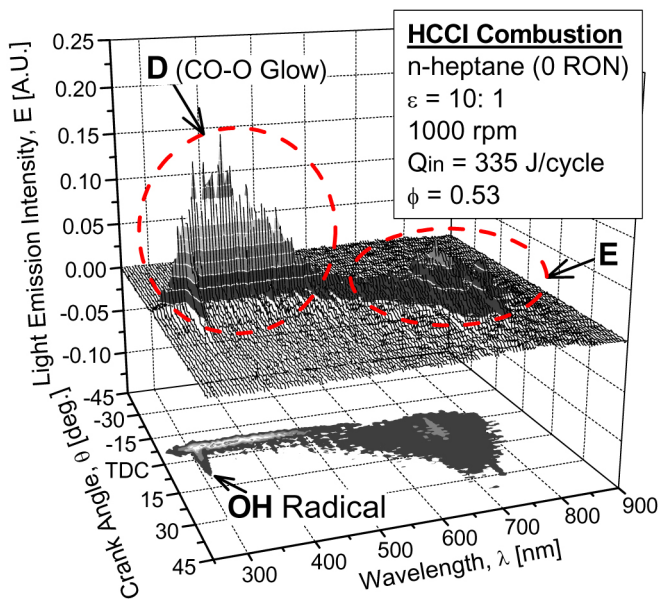


Fig. 6. Light emission spectra of hot flame in HCCI combustion

The following characteristic values shown in Figs. 7 and 8 were defined in order to investigate in detail the relationship between the heat release rate (HRR) and light emission behavior.

- Time of peak heat release  $\theta_{HRR\max}$  : The crank angle at which the HRR of the hot flame reaches its maximum value.
- Time heat release ends  $\theta_{HRR\text{off}}$  : The crank angle at which the HRR decreases to less than 10 % of the peak HRR of the hot flame. It corresponds to the end of combustion.
- Time of peak light emission  $\theta_{E\max}$  : The crank angle at which the light emission intensity reaches its maximum value.
- Light emission interval  $\theta_{LE}$  : The crank angle interval during which the light emission intensity is 0.02 (A.U.) or higher.

- Difference between the time of heat release and the time of light emission  $\theta_{HE}$  : The difference in crank angle degrees between the time of  $\theta_{HRR\max}$  and the time of  $\theta_{E\max}$  (The larger the absolute value of  $\theta_{HE}$  is, the greater is the difference between the time of the two events.)

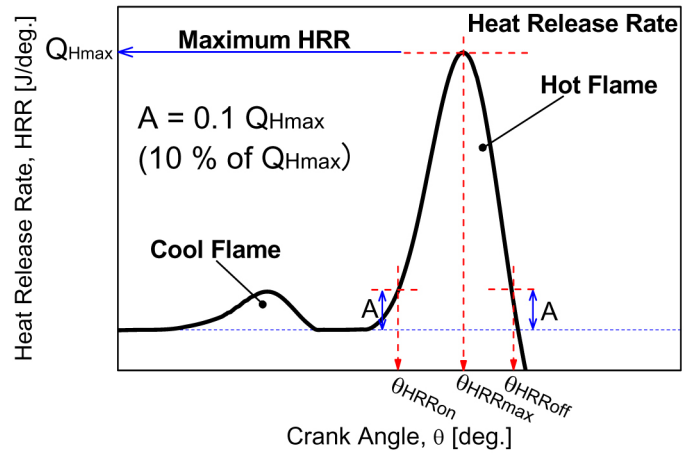


Fig. 7. Definitions of heat release timings

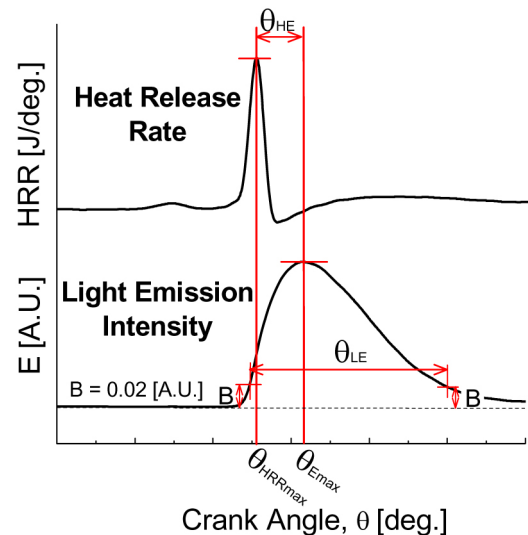


Fig. 8. Definitions of indices used in analyzing light emission spectra

Figure 9 shows the respective light emission spectrum found at the time of the maximum HRR  $\theta_{HRR\max}$  and at time of the conclusion of heat release  $\theta_{HRR\text{off}}$ . The continuous spectrum of the CO-O glow from 300-500 nm was the principal light emission at the time of the peak HRR. At the conclusion of heat release, the CO-O glow degenerated, but light emission presumed to be from the OH radical still continued in the vicinity of 310 nm. In addition, light emission ascribable to the CH were observed near 390 nm and 485 nm. The results also reveal that a stronger light emission occurred near 700 nm compared with that seen at the time of the peak HRR. In other