

Visualization and Spectroscopic Measurement of Knocking Combustion Accompanied by Cylinder Pressure Oscillations in an HCCI Engine

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ABSTRACT

Combustion experiments were conducted with an optically accessible engine that allowed the entire bore area to be visualized for the purpose of making clear the characteristics that induce extremely rapid HCCI combustion and knocking accompanied by cylinder pressure oscillations. The HCCI combustion regime was investigated in detail by high-speed in-cylinder visualization of autoignition and combustion and emission spectroscopic measurements. The results revealed that increasing the equivalence ratio and advancing the ignition timing caused the maximum pressure rise rate and knocking intensity to increase. In moderate HCCI combustion, the autoignited flame was initially dispersed temporally and spatially in the cylinder and then gradually spread throughout the entire cylinder. In contrast to that behavior, in extremely rapid HCCI combustion, the autoignited flame was dispersed in the cylinder in its initial stage, but the remaining unburned end gas rapidly autoignited at a certain point. That gave rise to knocking combustion accompanied by cylinder pressure oscillations.

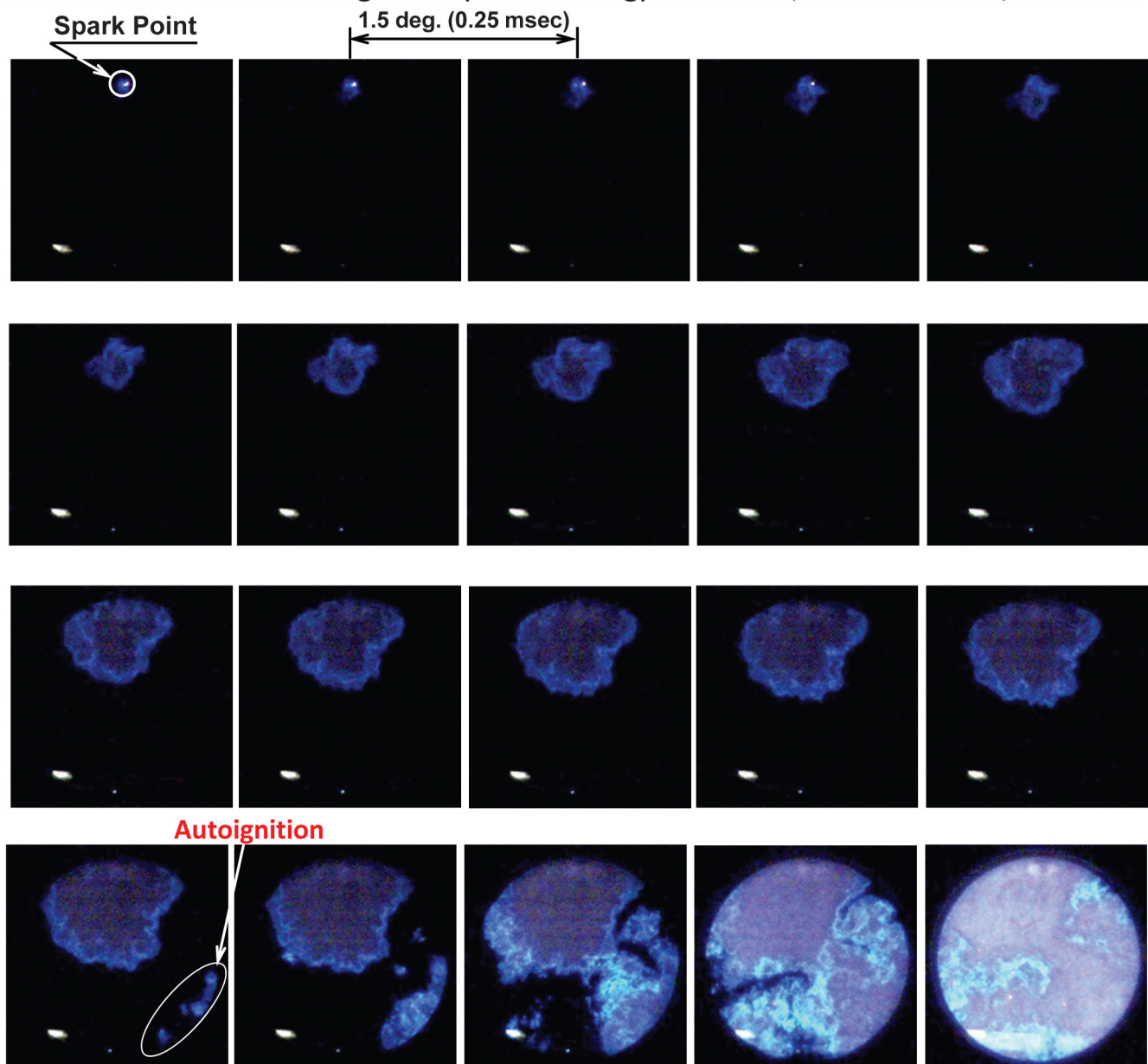
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INTRODUCTION

Homogeneous Charge Compression Ignition (HCCI) [1], a combustion system for internal combustion engines, burns a lean premixed mixture by means of autoignition [2], [3], [4], [5]. Because HCCI is a lean low-temperature combustion process, the specific heat ratio κ of the working gas is high. Another feature of HCCI combustion is that it facilitates compression ignition engine operation at a sufficiently high compression ratio. Consequently, high engine operating efficiency is obtainable because the compression ratio and the specific heat ratio, two factors that affect theoretical thermal efficiency, are both high. In addition, lean low-temperature combustion contributes to reducing cooling losses as well as to reducing pumping losses because of a larger throttle valve opening. Moreover, low-temperature combustion of a premixed mixture makes it possible to reduce emissions of nitrogen oxides (NO_x) and particulate matter (PM) simultaneously [6].

Another distinct characteristic of the HCCI process is that combustion takes place rapidly because ignition occurs simultaneously at multiple locations in the cylinder. [Figure 1](#) shows in-cylinder visualized images of spark-ignited (SI) knocking combustion under operating conditions that induced autoignition of the end gas, and [Figure 2](#) shows images of HCCI combustion. These visualized images were obtained with the test engine used in this study, the detailed specifications of which will be mentioned later. The two-stroke test engine allowed the entire bore area to be visualized. Both sets of combustion images were obtained at the same imaging frame rate. A primary reference fuel (PRF) blend of n-heptane and iso-octane with an octane number of 90 was used in the SI combustion experiments and n-heptane alone with an octane number of 0 was used in the HCCI combustion experiments.

It is seen in the visualized images of SI combustion that the flame formed by spark ignition propagated throughout the combustion chamber. Under the operating conditions that induced knocking, the images show that the end gas in the

SI Combustion with Autoignition (SI-Knocking) : $\varepsilon = 10.5$, $\phi = 0.9$, $N = 1000$ rpm, PRF 90**Figure 1. Visualized images for SI-knocking**

end zone of the cylinder autoignited rapidly. The HCCI combustion images indicate that autoignition similar to that observed for the end gas in SI combustion occurred throughout the entire cylinder and combustion took place rapidly. A comparison with the speed at which the SI flame propagated prior to autoignition of the end gas shows that HCCI combustion took place more rapidly than SI flame propagation even though the equivalence ratio of the fuel used in the HCCI combustion experiment was lower.

Two of the major issues of HCCI are to control the ignition timing and to expand the viable 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. Additionally, it is also known that, depending on the operating conditions, abnormal combustion accompanied by cylinder pressure oscillations occurs [7], [8], [9] in a manner resembling knocking in 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 test engine that allowed the entire bore area to be visualized. The equivalence ratio and the scavenging temperature (i.e., inducted air temperature) were varied to

HCCI Combustion : $\varepsilon = 12$, $\phi = 0.5$, $N = 1000$ rpm, PRF 0 (n-heptane)

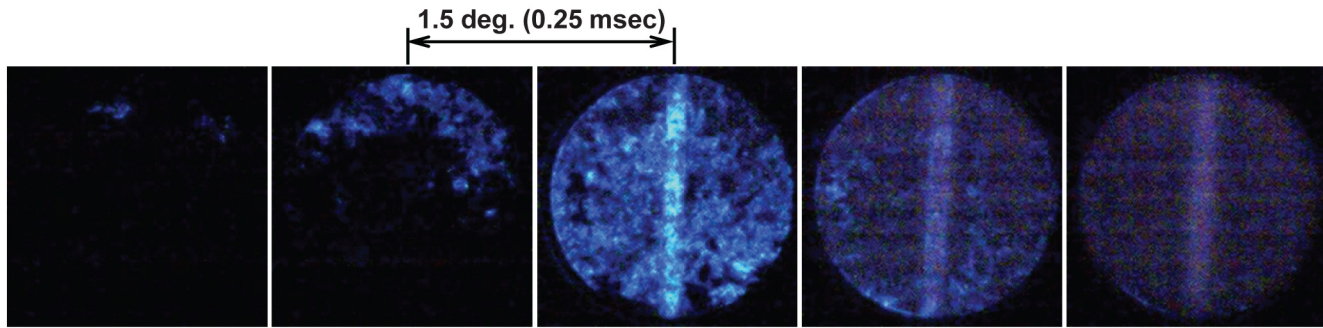


Figure 2. Visualized images for HCCI combustion

induce a transition from moderate HCCI combustion to extremely rapid HCCI combustion accompanied by a high pressure rise rate and cylinder pressure oscillations. Combustion behavior under each set of operating conditions was investigated in detail on the basis of in-cylinder visualization of combustion, light emission spectroscopy and cylinder pressure analysis.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The specifications of the test engine are given in [Table 1](#), and the configuration of the equipment used for in-cylinder visualization and spectroscopic measurement is shown in [Figure 3](#). A two-stroke optically accessible engine was used to facilitate easy detailed measurement of combustion by in-cylinder imaging and emission spectroscopy. A quartz observation window was provided in the top of the cylinder head to enable the entire bore area to be visualized. 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. 3](#)). A rectangular-shaped channel was provided in the center of the piston head (photo (a) and (b) in [Fig. 3](#)) 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)	11 : 1
Engine Speed	1000 rpm
Test Fuel	PRF (n-heptane + iso-octane) 0 RON (HCCI), 90 RON (SI)
Frame Rate [fps (Frames/sec)]	54000 fps

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. 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 known as CO-O glow [10],[11] 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 [10],[11] 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.

In the HCCI combustion experiments, the effective compression ratio ε was set at 11:1, n-heptane (PRF 0) was used as the test fuel because it autoignites easily, and the engine speed was kept constant at $N = 1000$ rpm with wide open throttle (WOT).

The experimental conditions used are shown in [Table 2](#). The equivalence ratio of the charge was varied among three levels of $\phi = 0.9$ (Case 1), 0.7 (Case 2) and 0.5 (Case 3), so as to induce a transition in engine operation from moderate to extremely rapid HCCI combustion. Additionally, the scavenging temperature T_{sc} (inducted air temperature) was varied among several levels at each equivalence ratio so as to intentionally change the ignition timing and vary the rapidity of combustion even at the same equivalence ratio.

The engine was operated at WOT in the experiments. However, because a two-stroke test engine was used, a relatively large quantity of residual gas was present in the cylinder. Using the corrected delivery ratio L [-] and assuming a perfect mixing scavenging process, we calculated the scavenging efficiency η_s [-] and the residual gas ratio γ_r [%], which are shown in Table 2. The equations used in the calculations are noted below.

Table 2. Experimental conditions

Case No.	Equivalence Ratio, ϕ [-]	Scavenging Temperature, T_{sc} [K]	Scavenging Efficiency, η_s [-]	Residual Gas Ratio, γ_r [%]
Case 1	0.9	Varied (In order to change the ignition timing)	0.66 ± 0.01	34 ± 1
Case 2	0.7		0.66 ± 0.01	34 ± 1
Case 3	0.5		0.62 ± 0.02	38 ± 2

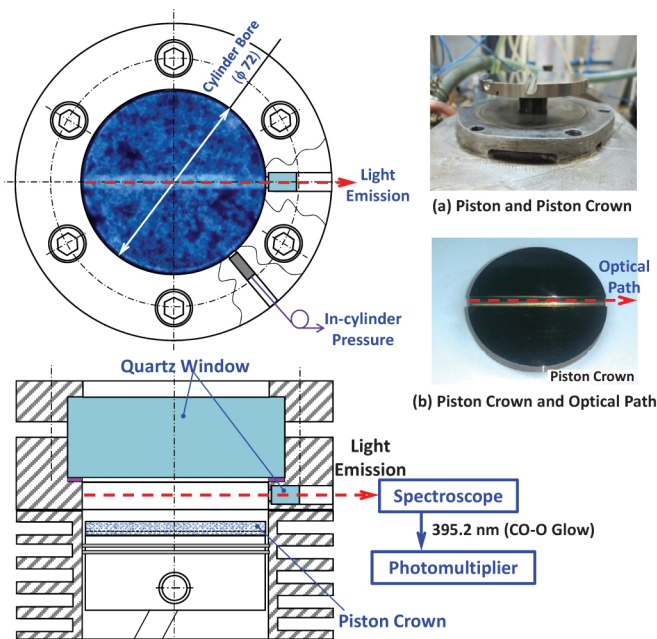


Figure 3. Configuration of optically accessible engine and equipment

$$\eta_s = 1 - e^{-L} \quad [-]$$

$$\gamma_r = (1 - \eta_s) \times 100 \quad [\%]$$

Specifically, varying the equivalence ratio and ignition timing changed the rapidity of combustion, and some of the conditions used resulted in abnormal combustion accompanied by cylinder pressure oscillations. In-cylinder visualization and spectroscopic measurements were performed under each set of conditions.

RESULTS AND DISCUSSION

Comparison Of Measured Waveforms For Varied Equivalence Ratios And Ignition Timings

Figures 4, 5, 6 show the waveforms that were measured when the scavenging temperature was varied in each of the three cases. The horizontal axis of the figures shows the crank angle. The vertical axis shows in turn the cylinder pressure P [MPa], the pressure waveform following high-pass filtering of the measured pressure data at 4 kHz to extract the high-frequency component so as to indicate the cylinder pressure oscillations, 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. In the following discussion, all evidence of light emission seen in the light emission intensity waveforms measured at 395.2 nm is attributed primarily to the light of the CO-O glow.

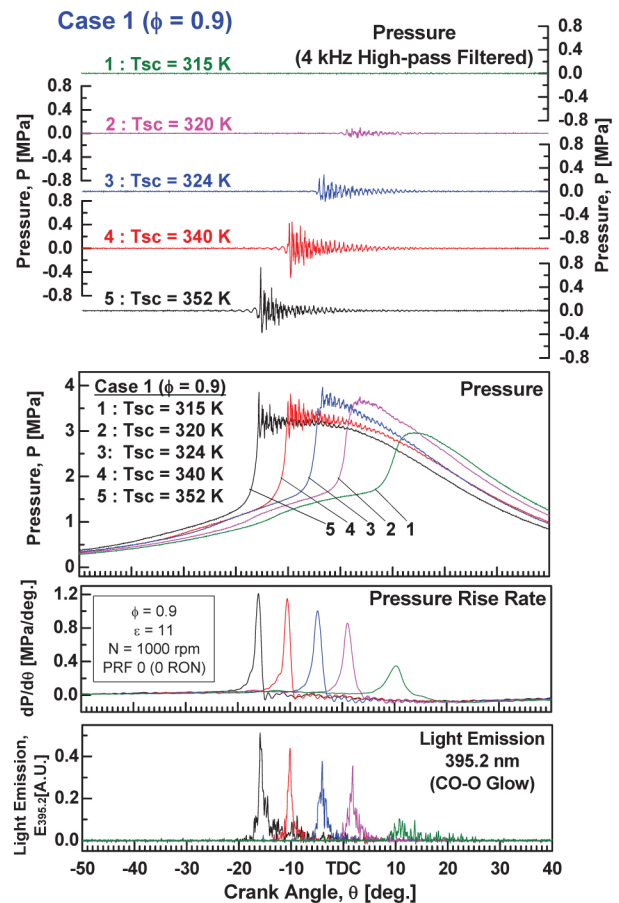


Figure 4. Influence of ignition timing on combustion (Case 1)

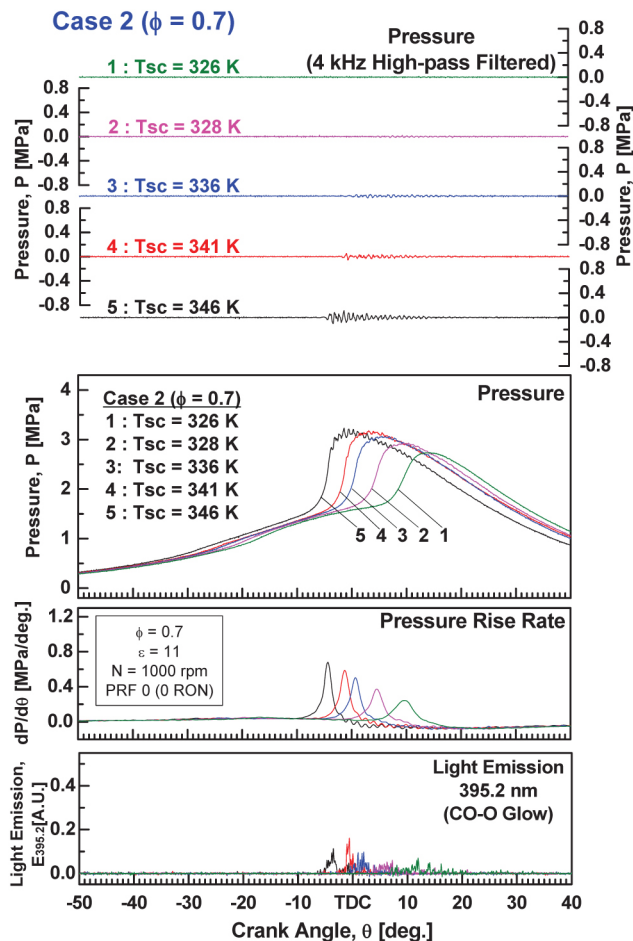


Figure 5. Influence of ignition timing on combustion (Case 2)

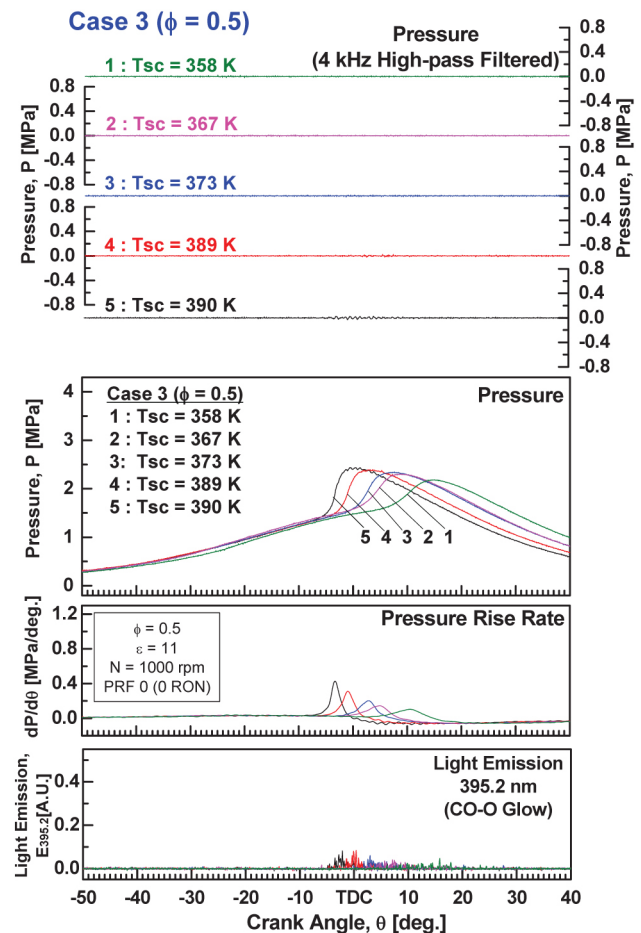


Figure 6. Influence of ignition timing on combustion (Case 3)

A comparison of the pressure rise rates and light emission intensities in Figures 4, 5, 6 reveals that both increased overall with a higher equivalence ratio. This implies that combustion was taking place more rapidly. An examination of the influence of the ignition timing in each figure indicates that the pressure rise rate and light emission intensity of CO-O glow in main combustion tended to increase under conditions of a higher scavenging temperature and an earlier ignition timing. This also implies that advancing the ignition timing had the effect of promoting more rapid combustion.

Pressure waveforms #2-#5 in Figure 4 for Case 1 and pressure waveform #5 in Figure 5 for Case 2 show signs of cylinder pressure oscillations. This implies that abnormal combustion accompanied by cylinder pressure oscillations resembling knocking in an SI engine also occurred in the HCCI combustion process.

Experiments were conducted in this study at an equivalence ratio as high as $\phi = 0.9$. The main purpose of this study was to make clear the characteristics of abnormal HCCI combustion based on visualization and observation of the combustion flame. The equivalence ratio was intentionally set high so as to clearly induce knocking. For that reason, NOx was emitted depending on the engine operating conditions.

For reference, the NOx emission level is shown in Figure 7 in relation to each equivalence ratio and scavenging temperature used. The NOx emission level increased under conditions of a high equivalence ratio and an advanced ignition timing. However, because a two-stroke test engine was used, residual gas was present in the cylinder in addition to the induced mixture. Using the corrected delivery ratio L and assuming perfect mixing scavenging, the scavenging efficiency η_s was calculated to be approximately 62-66%. In other words, even under a condition of an equivalence ratio of 0.9, residual gas amounting to approximately 34% was present in the cylinder in addition to the induced mixture.