

A Study of Supercharged HCCI Combustion using In-cylinder Spectroscopic Techniques and Chemical Kinetic Calculation

Yasuhide Abe, Yuma Ishizawa, Go Emori, Mitsuo Asanuma, Akira Iijima, and Hideo Shoji
Nihon Univ.

Kazuhito Misawa, Yusuke Kiguti, Hiraku Kojima, Shunichi Mori, and Kenjiro Nakama
Suzuki Motor Corp.

ABSTRACT

A great deal of interest is focused on Homogeneous Charge Compression Ignition (HCCI) combustion today as a combustion system enabling internal combustion engines to attain higher efficiency and cleaner exhaust emissions. Because the air-fuel mixture is compression-ignited in an HCCI engine, control of the ignition timing is a key issue. Additionally, because the mixture ignites simultaneously at multiple locations in the combustion chamber, it is necessary to control the resultant rapid combustion, especially in the high-load region. Supercharging can be cited as one approach that is effective in facilitating high-load operation of HCCI engines. Supercharging increases the intake air quantity to increase the heat capacity of the working gas, thereby lowering the combustion temperature for injection of the same quantity of fuel. In this study, experiments were conducted to investigate the effects of supercharging on combustion characteristics in an HCCI engine. Light emission and absorption spectroscopic measurement techniques were used to investigate the combustion behavior in detail. Chemical kinetic simulations were also conducted to analyze the reaction characteristics in detail. The results made clear that the raising the intake air pressure under a condition of a constant quantity of heat produced per cycle by the injected fuel has the effect of reducing the combustion temperature. As a result, combustion becomes more moderate. The results of spectroscopic measurement of light absorption also showed a sharp rise in absorbance at 293.1 nm, which is attributed to formaldehyde (HCHO) produced by the low-temperature reactions. Subsequently, absorbance dropped sharply at the time autoignition occurred.

CITATION: Abe, Y., Ishizawa, Y., Emori, G., Asanuma, M. et al., "A Study of Supercharged HCCI Combustion using In-cylinder Spectroscopic Techniques and Chemical Kinetic Calculation," *SAE Int. J. Engines* 6(4):2013, doi: 10.4271/2013-32-9171.

INTRODUCTION

Global warming, depletion of petroleum resources, pollution and other environmental issues in recent years have prompted demands for cleaner and more efficient internal combustion engines. A Homogeneous Charge Compression Ignition (HCCI)^[1] engine inducts and compression-ignites a lean premixed mixture, enabling simultaneous reductions of both nitrogen oxide (NO_x) and particulate matter (PM) emissions to achieve clean and highly efficient operation^[2].

However, it is difficult to control the ignition timing of HCCI engines because they lack a physical means of igniting the mixture. Another issue of HCCI engines is that their operation is limited on the high load side owing to the

rapidity of combustion resulting from simultaneous ignition at multiple points in the combustion chamber. These factors make it necessary to moderate HCCI combustion for practical application.

It is known from previous studies that the application of supercharging can moderate the rapidity of HCCI combustion by forming a leaner mixture in the cylinder under a condition where the quantity of heat produced per cycle by the injected fuel is constant^[3,4,5]. The present study examined the effects of varying the fuel composition and supercharging pressure on the ignition timing and the moderation of combustion, which are issues that must be addressed to facilitate the practical use of HCCI engines. The combustion process was

analyzed in detail by making in-cylinder spectroscopic measurements and performing chemical kinetic simulations.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Experimental Equipment

Figure 1 shows the configuration of the experimental equipment used in this study. Table 1 shows the engine specifications used in this study. Experiments were conducted with a 4-cycle air-cooled single-cylinder test engine operated at a compression ratio of 11.5:1. The test fuel was injected directly into the intake pipe from an injector, and temperatures were measured with K-type thermocouples. A crystal pressure transducer installed in the top of the cylinder head was used to measure the cylinder pressure P [MPa]. The heat release rate [HRR, J/deg.] was calculated from the measured pressure data. An external supercharger was used to adjust the intake air pressure, and the intake air temperature was adjusted using an intercooler. Tappet clearances were adjusted to secure zero valve overlap so as to minimize the amount of fresh air blown out of the cylinder by supercharging. Quartz observation windows were provided in the cylinder for measuring the HCCI combustion flame light and light absorption. The combustion flame light and transmitted light from a xenon light source were sampled in the bore direction of the cylinder[6].

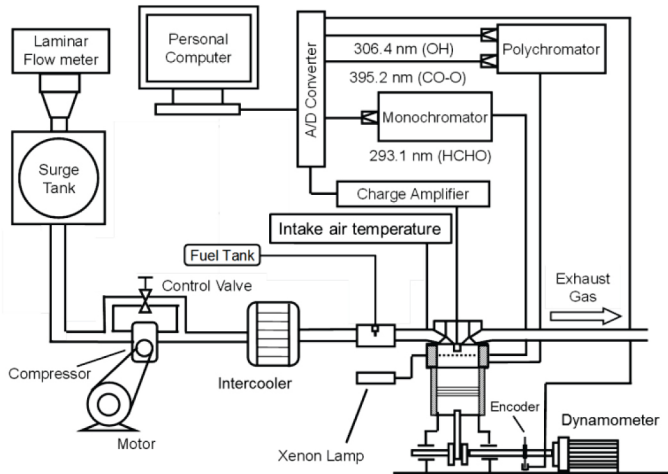


Fig. 1. Configuration of test equipment

Figure 2 is a schematic diagram of the spectroscopy system used in the experiments. The sampled flame light and transmitted light were introduced into a monochromator or a polychromator by means of optical fiber cables. The flame light was separated into its spectral components at a wavelength of 395.2 nm and the transmitted light at a wavelength of 293.1 nm[7]. The former wavelength is part of a strong continuous light emission spectrum produced by the recombination reactions of CO and O molecules and is known as CO-O glow. This light is primarily emitted at the

time the hot flame occurs, making it effective for investigating hot flame behavior[8]. The latter wavelength is useful in capturing the behavior of formaldehyde (HCHO) that is a distinctive intermediate product in HCCI engine combustion. Light absorbance at this wavelength, $A_{293.1}$ [-], was defined as shown in the equation below using the transmitted light intensity E_A [A.U.] detected with a photomultiplier tube. Here, E_0 [A.U.] is the mean transmitted light intensity detected near bottom dead center.

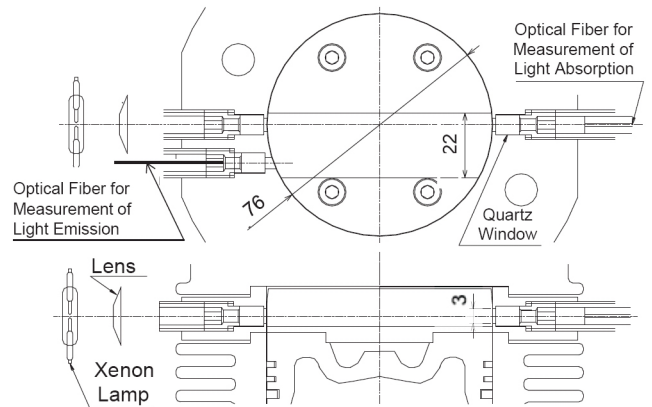


Fig. 2. Configuration of spectroscopy system

Table 1. Engine specifications

4 – Stroke Air Cooled Single Cylinder Engine	
Bore × Stroke [mm]	76 × 66
Displacement [cc]	299
Compression Ratio [-]	11.5 : 1
Valve Arrangement	OHV
Valve Overlap	0

Table 2. Experimental condition (Case 1, 2, 3)

	Case 1	Case 2	Case 3
Fuels	n-heptane / iso-octane		
Engine Speed [rpm]	1400		
Quantity of heat production per cycle by injected fuel Q_m [J/cycle]	500		
Octane Number [RON]	50	30	30
Intake Air Pressure P_0 [kPa]	140, 160, 180		
Equivalent ratio ϕ [-]	0.328 ~ 0.432	0.337 ~ 0.445	0.330 ~ 0.438
Intake Air Temperature T_m [K]	333	333	344 ~ 350 (constant ignition timing)

$$A_{293.1} = \frac{E_0 - E_A}{E_0}$$

Test Fuels

The test fuels used were the primary reference fuels (PRFs) of n-heptane and iso-octane. The former fuel has a

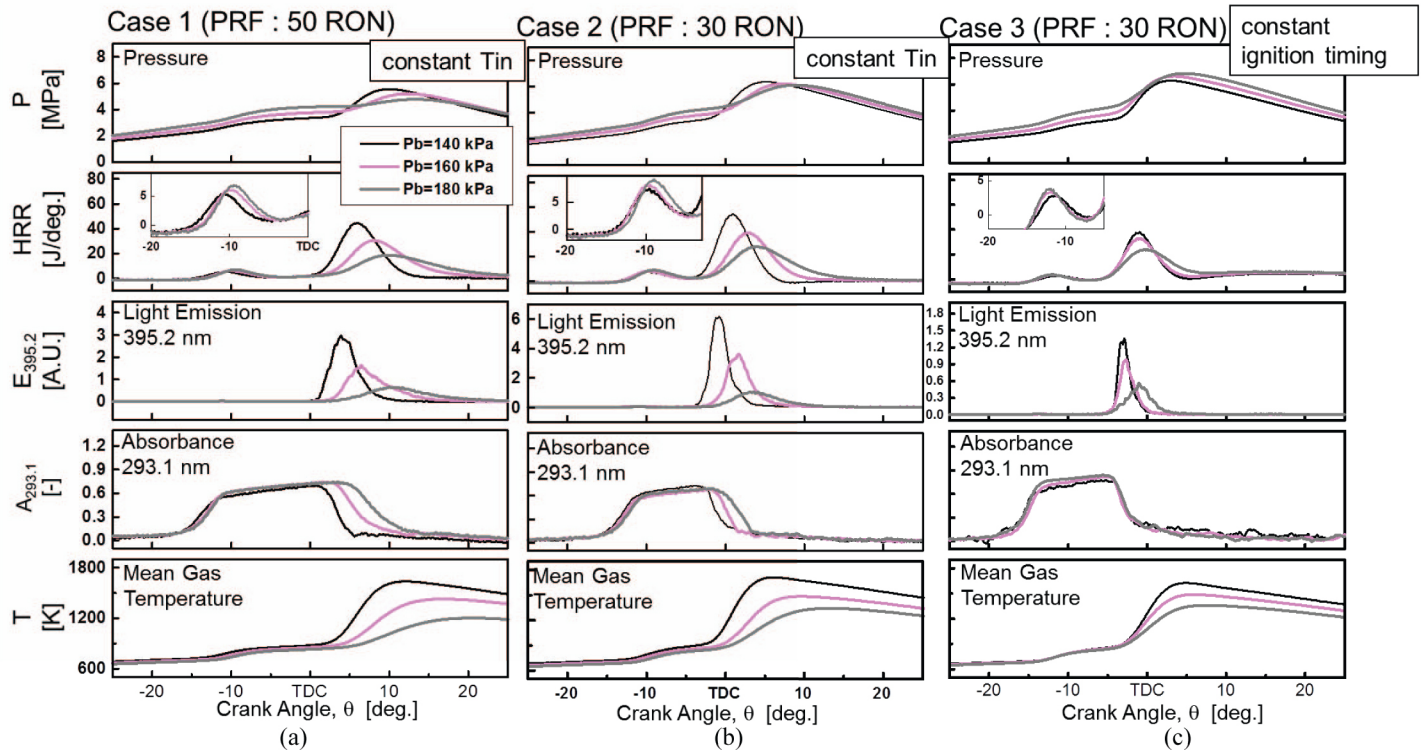


Fig. 3. Experimental results

Research Octane Number (RON) of 0 and autoignites easily, while the latter fuel has a RON value of 100 and is not conducive to autoignition. These two types of fuel were mixed to form PRF 50 (n-heptane 50%, iso-octane 50%) and PRF 30 (n-heptane 70%, iso-octane 30%), which were used in the experiments.

Kinetic Chemical Simulations

Chemical kinetic simulations were conducted using the CHEMKIN-PRO software code for simulating the elementary reactions of combustion. This software makes it possible to analyze time-series changes in chemical species during the reaction process based on the use of elementary reaction equations. The IC engine model in CHEMKINPRO was used in this study. The initial temperature, initial pressure, initial crank angle and engine speed, initial gas composition equation and other parameters are input into the model to calculate the time-series changes in the chemical species and the progress of the elementary reactions.

The detailed reaction mechanism used in the calculations was developed by the Combustion Chemistry Group at the Lawrence Livermore National Laboratory for primary reference fuels and included 1,024 chemical species and 4,236 elementary reactions^[9].

RESULTS AND DISCUSSION

Experiments were conducted under the conditions shown in Table 2 for three cases. The intake air pressure was raised

from 140 to 160 to 180 kPa while maintaining a constant quantity of heat produced per cycle by the injected fuel (Q_{in}). In Cases 1 and 2, the intake air temperature was kept constant, and the ignition timing was set at 5 deg. before top dead center (BTDC) in Case 3.

Investigation And Spectroscopic Analysis Of HRR Of Hot Flame Region

Figure 3 shows the results obtained for Cases 1, 2 and 3. From the top, the vertical axis shows the cylinder pressure P [MPa], HRR [J/deg.], light emission intensity $E_{395.2}$ [A.U.] at a wavelength of 395.2 nm and light absorbance $A_{293.1}$ at a wavelength of 293.1 nm in relation to the crank angle θ [deg.] along the horizontal axis. An enlarged view of the cool flame region is shown in the inset in each HRR graph.

An examination of the HRR waveforms for Case 1 reveals that the peak HRR of the hot flame region decreased and the combustion period was lengthened as the supercharging pressure was raised. In contrast to that behavior, raising the supercharging pressure produced some slight cool flame activity, though the cool flame peak occurred at approximately the same time for every pressure level. An examination of the absorbance waveforms indicates that they began to rise concurrently with the occurrence of the cool flame and that this tendency was the same for all three supercharging pressures. The absorbance waveforms began to decline coincident with the heat release of the hot flame. Accordingly, this behavior implies that the HCHO produced