24 Expansion of HCCI Operation Region by the Combination of Direct Fuel Injection, Negative Valve Overlap -Internal Fuel Reformation and its Analysis by Makstov Optics-

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Abstract

Chemical reaction behavior in homogeneous charge compression ignition (HCCI) combustion, which differs from that of a spark-ignition engine, is not easy to understand because the reactions take place so rapidly and they also contain many hidden parameters. In the speculation field, the chemical reactions of HCCI combustion are controlled, for example, by a combination of a relatively low compression ratio, negative valve overlap and fuel injection during the overlap interval [1]. However, the roles of these parameters are still not sufficiently understood. In an effort to understand them better, a Makstov optical system was used in this study to track chemical reactions.

Keyword : Gasoline Engine, HCCI, Negative Valve Overlap, Chemical Reaction, Radical

1. INTRODUCTION

Homogenous charge compression ignition (HCCI) combustion, which is referred to as compression autoignition, has many advantages as well as disadvantages. One distinct feature of HCCI combustion that has been made clear is that combustion is possible in an extremely lean mixture region with an air-fuel ratio of over 30~40:1. The results of recent studies have shown that with a combination of negative valve overlap (NVO), fuel injection during the overlap interval and a relatively low compression ratio, optimization of the quantity of fuel injected has a large effect on fuel economy and combustion stability [2]. One drawback of HCCI combustion is its narrow region of stable engine operation, bounded by the occurrence of knock with a rich air-fuel ratio and misfire with a lean mixture. There are many reports in the literature of studies undertaken with the aim of expanding the region of stable operation [3]-[5].

Lean-burn combustion achieved with ordinary spark ignition, on the other hand, is dependent on augmentation of the turbulent flame propagation velocity by the formation of turbulence due to the in-cylinder airflow prepared during the intake stroke and its collapse in the compression stroke. While the turbulence intensity accelerates flame propagation speed and shortens the combustion period, it also has the inherent disadvantage of increasing cyclic fluctuation of the initial flame right after ignition. This shortcoming determines the lean limit of the air-fuel ratio. HCCI combustion offers one solution for suppressing this disadvantage because the simultaneous occurrence of the chemical reactions due to the high compression ratio in the combustion chamber does not cause the combustion period to fluctuate. The short heat release period attests to this feature of HCCI combustion. This behavior is similar to knocking, which occurs at the end of the combustion stroke due to flame propagation, in that the reactions instantaneously begin and end under the rather high temperature and pressure conditions present at that moment.

2. EFFECT ON CHEMICAL REACTIONS OF HCCI COMBINED WITH FUEL INJECTION IN NVO INTERVAL

2-1. EFFECT OF NVO COMBINED WITH FUEL REFORMATION RESULTING FROM NVO INJECTION ON EXPANDING THE VIABLE HCCI OPERATION RANGE

The engine and cam specifications used in the experiments to produce NVO are shown in Table 1 and Fig. 1. These cam variations were capable of providing a wide range of valve overlap, from the normal overlap angle of 8° to negative overlap angles of 112°, 132°, 152° and 192°. The compression ratio was also varied simultaneously in a range from 12:1 to 18.6:1. This combination of a negative overlap cam and compression ratio facilitates HCCI operation in a higher engine speed range and wider load range. Operating an engine in a higher speed range requires the preparation of fast reaction rates or a suitable period of time necessary for the chemical reactions to take place.

Engine Type	4-Stroke Single Cylinder
Bore x Stroke	85 x 86 mm
Displacement	488 cm^3
Compression Ratio	12, 13.5, 15, 18.6 :1
Throttle Opening	WOT (Wide Open Throttle)
Intake Air Temperature	25 deg. C
Fuel Supply	Direct Injection
Fuel Injector (Spray Cone Angle)	Swirl Injector (60 deg)
Fuel Pressure	7 MPa
Fuel	Regular Gasoline (91 RON)

Table 1 : Engine main specifications

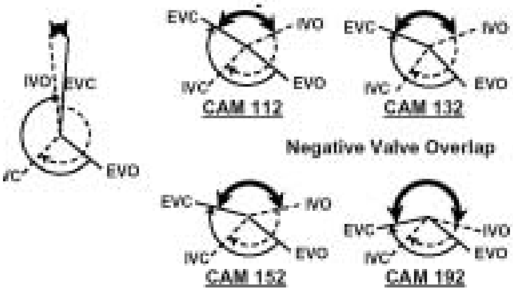


Figure 1: Cam variation for Negative Valve overlap

Figure 2 shows the stable HCCI combustion characteristics obtained in this way over a wide speed range. Negative valve overlap means that residual gases are present in the combustion chamber during this time, and the injected fuel is slightly reformed by these residuals. For that reason, a shorter reaction period is sufficient in the compression stroke even at high operating loads/speeds. When a large quantity of fuel was injected, a slight rise in pressure was observed due to heat release in the NVO interval, but virtually no

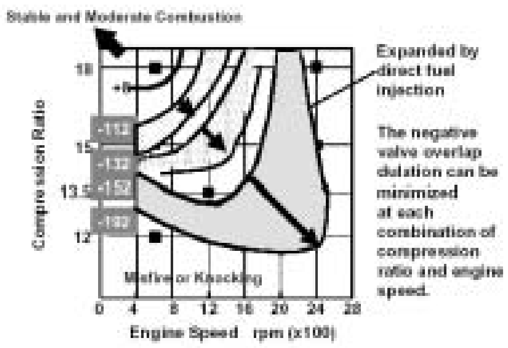


Figure 2: Effect of Direct Fuel Injection on Expanding HCCI Operating Region

pressure rise was observed when the fuel injection quantity was reduced. Accordingly, the small quantity of fuel injected in the vicinity of top dead center of the compression stroke did not lead to thermal energy losses. Combination of fuel injection and NVO leads to the possibility of lower compression ratio and higher engine speed operation in HCCI. Figure 3 presents the results of observations made with the aid of a high-speed camera during the NVO interval. The photographs also show only weak light emission, and only faint light emission was captured when the

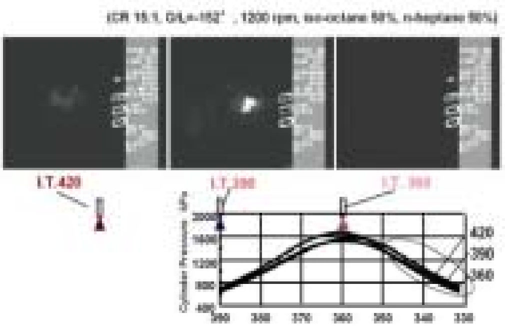


Fig.3 Light Emission and In-Cylinder Pressure

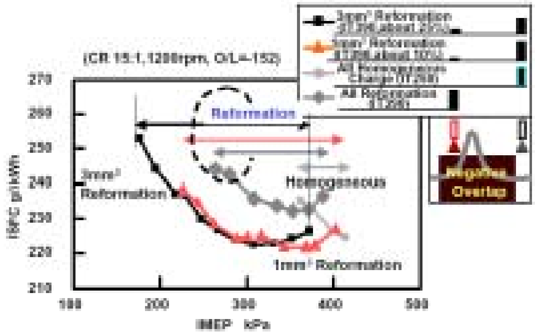


Figure 4: Optimization of fuel Injection for Each Engine

quantity of fuel injected was reduced.

The combustion performance obtained in the NVO interval is shown in Fig. 4. It is seen that stable optimizing the fuel injection quantity of 1,3 mm^3 and all fuel for each load level . The combustion characteristics are described in detail elsewhere [2] .The Maksutov optical system used in this work to analyze radical light emission is shown schematically in Fig. 5. The optical system consists of a Maksutov receiving optical system and a spectrometer or a 4-channel photomultiplier as the signal processing system. There are many reports in the literature about analyses of cyclic combustion fluctuations based on the strong correlation between the air-fuel ratio and the ratio of light emission intensities of various radicals using this kind of optics. The optical system and the signal processing system are connected by means of optical fiber cables. A different optical filter is built into each input port of the 4-channel photomultiplier so that only light of a certain wavelength is transmitted. In addition, wavelengths are rigorously selected in advance by means of four diffraction gratings that are also connected by optical fiber cables. Prior to the experiments, the wavelength settings of the four gratings were carefully calibrated. The radicals targeted for observation of their light emission intensity were OH, CH, HCHO and C2, whose characteristic spectrum is 306.4, 395.2, 431.4 and 516.5 nm, respectively. These wavelengths could be set at arbitrary spectra by means of the diffraction gratings. The correlation between the air-fuel ratio and the ratio of light emission intensities of various radicals using this kind of optics[6]. The optical system and the signal processing system are connected by means of optical fiber cables. A different optical filter is built into each input port of the 4-channel photomultiplier so that only light of a certain wavelength is transmitted. In addition, wavelengths are rigorously selected in advance by means of four diffraction gratings that are also connected by optical fiber cables. Prior to the

2-2. COMPARISON OF LEAN-BURN COMBUSTION CHARACTERISTICS TO EXAMINE THE LIMIT OF TURBULENT INTENSITY FOR SI LEAN-BURN COMBUSTION

A comparison was made of lean-burn combustion characteristics for single-ignition combustion with swirl as a general type of in-cylinder airflow, five-ignition combustion with swirl and five-ignition combustion without swirl and of combustion characteristics under the application of exhaust gas recirculation (EGR)[(7)]. The configuration of the spark plugs used for multiple ignitions is shown in Fig. 5 along with the results obtained. There was no change in the effects or the order of the combustion modes examined in the moderate lean-mixture region or in the low EGR region. However, their tendencies with respect to the stable combustion limit differed slightly. When strong swirl was applied, combustion suddenly became unstable around the stability limit of the air-fuel ratio, but multiple-ignition combustion without swirl alone did not tend to show rapid deterioration of stability.

Photographs of multiple cycles taken with the high-speed camera are shown in Fig. 6 to illustrate the variation in the initial flame near the stability limit of the air-fuel ratio. It is assumed that this large cyclic variation in the flame is dependent on changes in the flow fields. The initial combustion period is defined here as the crank-angle interval from spark ignition until 10 % of the fuel mass has burned. It can be seen that expansion of the lean-burn limit by means of the in-cylinder gas flow is limited by cyclic variation in the initial combustion state.

2-3. COMPARISON OF RADICAL Llight EMISSION BEHAVIOR BETWEEN SI AND HCCI COMBUSTION USING MAKSTOV OPTICS

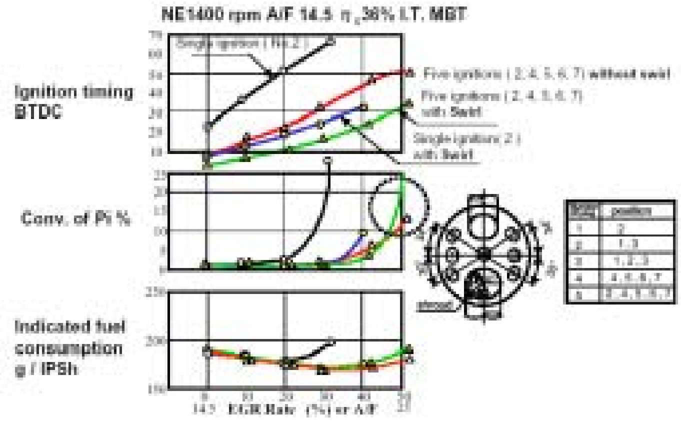


Fig. 5 Characteristics of Multi-Ignition Cmbustion

The combustion state produced by the use of five spark plugs for multiple ignitions under weak flow fields was believed to correspond to HCCI-like combustion. Therefore, in order to analyze the combustion reactions, an optical system was prepared that facilitates the continuous tracking of radical light emission. The configuration of the optical system is shown in Fig.7. This system consists of four photomultipliers, a Maksutov optical system and the optical fiber cables connecting them. In addition to the optical system, a spectrometer was also used in the signal processing system.

2-4. EFECTS OF NEGATIVE VALVE OVERLAP ON CHEMICAL REACTION

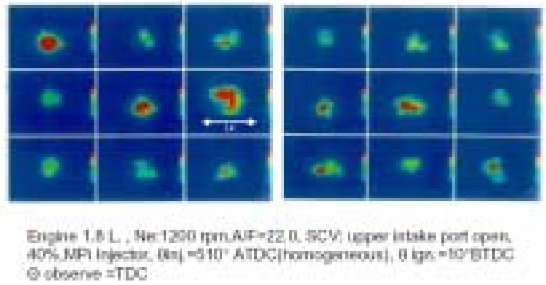


Fig. 6 Cycle by cycle Variation of Initial Flame under Strong Flow Field

Figure 8 shows the light emission behavior measured continuously for the OH radical in 50 consecutive cycles at a measurement position

relatively close to the center of the combustion chamber, among the reactions that occurred under certain given HCCI conditions. The cycles are divided into three groups of strong, medium and weak light emission intensities. The light emission intensity varied considerably from cycle-to-cycle, and there are virtually no cycles displaying the same emission intensity. These results were obtained when the compression ratio was raised to 19:3 and the cam overlap was left unchanged at 8°. Under these conditions where HCCI combustion was dependent solely on the compression ratio, the local chemical reactions varied, and the crank angle at which the peak emission intensity was manifested also differed from cycle-to-cycle. As the output obtained was high, coefficient of variation of IMEP also bigger. The air-

fuel ratio was set at a rather lean 42:1 to avoid knocking.

Figure 9 shows the superimposed waveforms of the light emission intensities measured for the OH radical in multiple cycles under three sets of operating conditions. One case is for HCCI combustion dependent on the

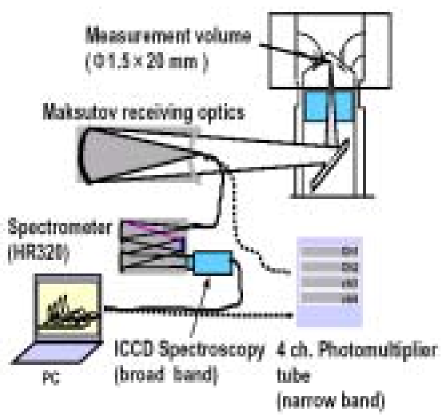


Fig. 7 Spectroscopic Analysis of Radicals by Makstov

compression ratio alone, a second case is for a reduced compression ratio with injection of the entire fuel quantity in the NVO interval, and the third case is for optimized fuel injection. Three types of specifications were created by using different combinations of NVO, compression ratio and fuel injection quantity during the NVO interval.

Figure 9 indicates the CH radical emissions among 50 cycles under the three kind of fuel mass injected during NVO. As the amount of fuel injected during NVO increases, CH emission intensity and its cyclic variation gets higher and smaller, respectively. Namely, proper amount of fuel injected during NVO has a strong effect on the true reaction after 360 degree CA. Its effect can be said as fuel reformation.

At a compression ratio of 19:3, the peak emission intensity of the OH radical in each cycle was low and large cyclic variation also occurred which was described in Fig.10. In the second case where the lowered to 15.7:1, NVO was increased to 152° and all the fuel was injected in the overlap interval, the emission intensity peaks of the OH radical were higher and shifted closer to top dead center of the compression stroke. However, the cyclic variation of the emission intensity did not have a normal distribution, and Cpi (coefficient of variation of IMEP) also showed a large value. On the other hand, for the third case in which only around 15% of the necessary fuel injection quantity was injected during the NVO interval, the peak emission intensities of the OH radical were higher, and their distribution more closely resembled a normal distribution. A white solid line and black solid line indicates the mean value and the standard deviation, respectinely. The Cpi level was also the smallest among the three cases. This is attributed to the effect of injecting an optimized quantity of fuel during the NVO interval.

As seen in Fig. 11, although the OH radical showed weak emission intensity under HCCI combustion, the cyclic variation of the emission intensity was markedly small. This assures stable combustion in the ultra-lean mixture region. Under SI combustion, on the other hand, although the peak emission intensity was strong, the crank angle at which the peak occurred varied greatly from cycle-to-cycle. The heat release period was also long, and the peak emission intensity of the OH radical occurred not only in the initial phase of flame propagation, i.e., at the flame front, but also in the burned region. The rise of OH has a delay time after ignition which is due to the flame propagation speed and arrival at the measurement point observed by optics. The peak of heart release don't agree with the OH radical peak. In the case of HCCI combustion, the heat release peak was virtually coincident with the emission intensity peak of the OH radical. The behavior of HCHO in some cycles indicates that the steep increase appears faster than that of OH radical. The grand level is moved to separete each signal's overlap.

Figure 12 shows the peak value of OH radical and its appearance crank angle about SI combustion and HCCI combustion. Cycle variation of peak value and its timing shows much bigger than that of HCCI and it will decide the limit of spark ignition timing in leaner air fuel ratio condition.

While these results are only for point measurements, the radical emission behavior clearly shows that stable HCCI combustion with high output power can be obtained by optimizing the proper quantity of fuel injected during the NVO interval. The reason for that is attributed to the preparation of suitable chemical reactions by optimal reformation of

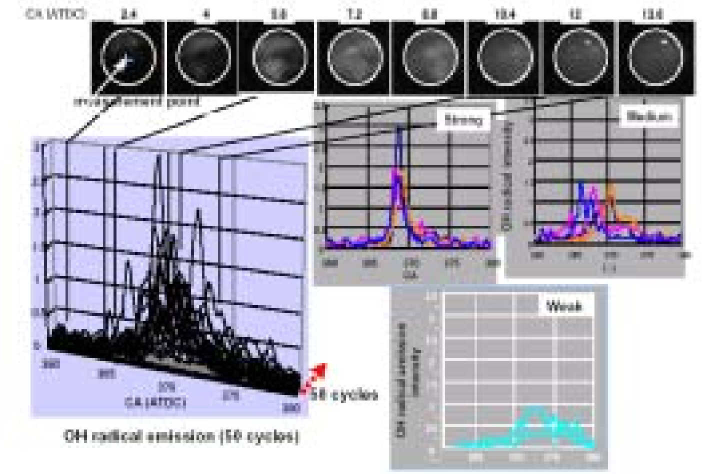


Fig. 8 : Initial check of the Maksutov Optical Sensitivity using Propan Air Flame

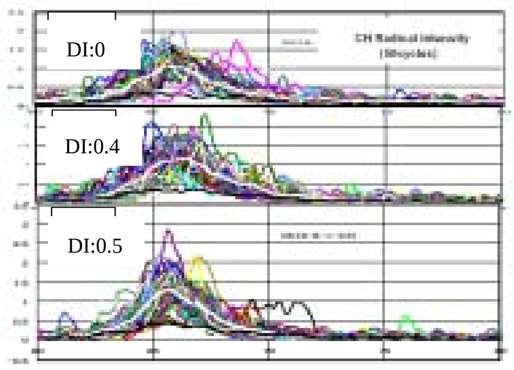


Fig. 9 Cyclic variations of CH Radicak effected by the

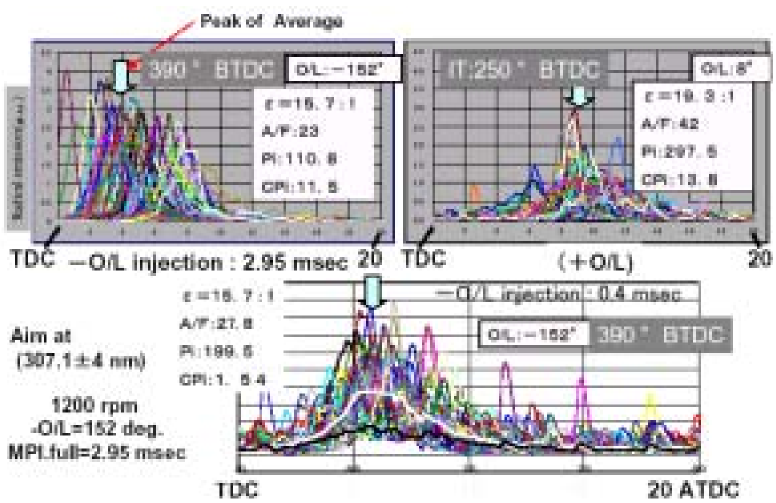


Fig.10 Comparison of Radical Emission Difference under various Cam Overlap (50 cycles)

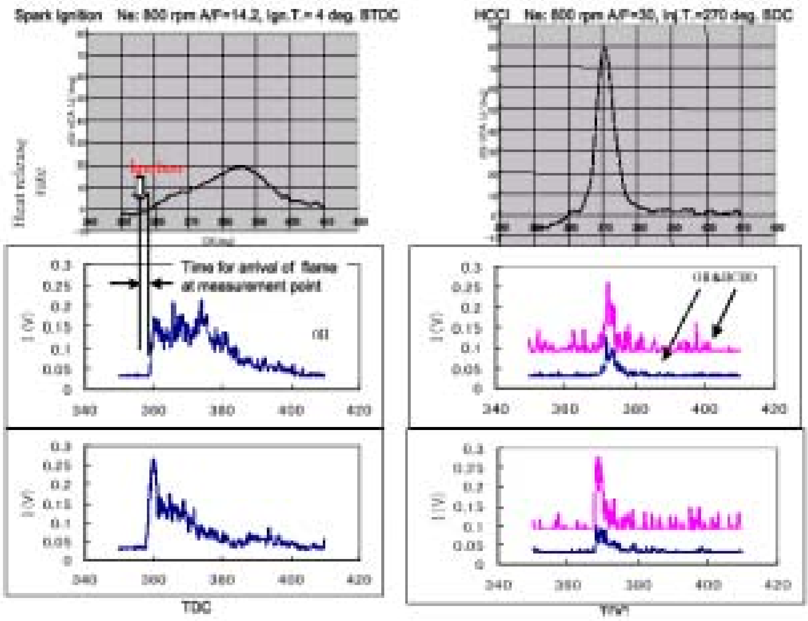
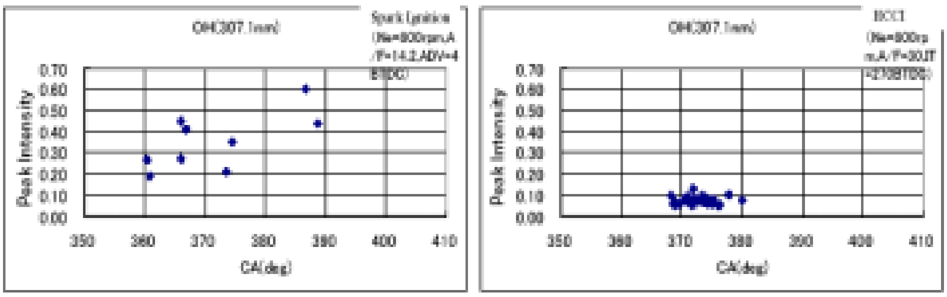


Fig. 11 : Comparison of OH Radical between Spark Ignition and HCCI



Ne: 800 rpm
A/F=14.2
Spark Ignition = 4 deg. BTDC

Ne: 800 rpm
A/F=30.0
Injection Timing = 270 deg. BTDC

Fig.12 Comparison of OH radicals between Spark Ignition and HCCI

the injected fuel. This insight was gained precisely because the statistical non-simultaneous occurrence of the chemical reactions in HCCI combustion facilitates the value of a point measurements results. Moreover, it suggests that there is a possibility of HCCI combustion and its apperarance crank angle about SI combustion. Cycle variation of peak value and its timing shows much bigger than that of HCCI and it will decide the limit of spark ignition timing in leaner air fuel ratio condition. While these resukts are only for the point measurement, the radical emission obtained by optimizing the proper quantity of fuel injected during the NVO interval. The reason for that is attributed to

the preparation of suitable chemical reactions in HCCI combustion facilities the value of a point measurements results. Moreover, it suggests that there is a possibility of HCCI combustion control by means of the statistical profile of the radical emission variation while it is a results of a point measurement results. Moreover, it suggests that there is a possibility of HCCI combustion comtrol by means od\f the statistical profile of the radical emission variation while it is a results of a
Point measurement in combustion chamber.

3. CONCLUSIONS

The following conclusions can be drawn from the results of this study.

(1) The cyclic variation caused by in-cylinder gas flow in the initial flame period determines the lean limit of SI combustion.

(2) In contrast, the simultaneous occurrence of chemical reactions under a higher compression ratio in the case of HCCI combustion allows stable engine operation at leaner air-fuel mixtures.

(3) Stable HCCI combustion can be obtained over a wider load range by providing negative valve overlap and injecting with optimized quantify of fuel during the NVO interval. The reason for that is because the injection of an optimized fuel quantity into the presence of rich residual gases allows the fuel to be reformed weakly, giving rise to fast and well-controlled chemical reactions in the ensuing true compression stroke. In other words, it can be attributed to fuel reformation and preparation of the chemical reactions.

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