The Analysis of Combustion Flame in a DI Diesel Engine (Part 2-Hydroxyl Radical Emission versus Temperature)

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ABSTRACT

The combustion phenomena were investigated using a fiber optic cable system. The spectroscopic analysis of the combustion chamber contents was conducted using a Photonic Multichannel Analyzer (PMA). The characteristics of the OH radical emission intensity in the combustion cavity were clarified by the spectroscopic analysis study. That is,the changes in the OH radical emission intensity closely resembled the changes in the rate of heat release(ROHR hereafter) pattern during premixed burning when changing the fuel injection timing. However the beginning of the OH radical emission intensity is slightly delayed when compared with the beginning of ROHR.

In order to understand this phenomena,the two color method was applied to measure the flame temperature. From these temperature measurement results,it was clear that the OH radical emission intensity is a function of the flame temperature beyond about 2200 K.

INTRODUCTION

The reduction of exhaust gas emissions of internal combustion engine,especially NOx and particulate matter emissions are required to alleviate environmental problems. Therefore many studies of diesel combustion are being conducted by various investigators. However due to the complexity involved there are many unknown phenomena concerning diesel combustion. In order to analyze the flame in the combustion chamber cavity,spectroscopic analysis of the flame is conducted. In this investigation,successful detection of the OH radical emission intensity clarified characteristics of both OH radical formation and extinction.

BACKGROUND

Improvement of diesel engine combustion requires a detailed understanding of each of the processes involved. For instance combustion is a strong function of the air flow within the piston cavity. Thus a combination of transient multidimensional calculations along with experimental flow visualization techniques of the intake and compression process have been conducted(1). Concerning fuel injection,mixing of fuel and air,ignition and combustion, various methods are typically applied in order to understand diesel combustion phenomenon. Pressurized vessel or rapid compression machine experiment (2) are often applied to model diesel combustion. Gas sampling(3), visualization of soot(4),visualization of the combustion flame(5) and measurement of the flame temperature(6) of the actual engine are also very useful methods in addition to indicated pressure analysis. The goal of these studies is typically the correlation of these experimental results and exhaust emissions(for example NOx and soot emissions). These studies have been reported by many investigators. However the exhaust gas formation mechanism within the combustion chamber cavity is scarcely reported(7,8).

The understanding of the exhaust gas formation mechanism is important for controlling of exhaust gas emission. In this paper,the spectroscopic analysis of the combustion flame was conducted. As a result,the formation characteristics of the OH radical during combustion were obtained. Then the correlation of the OH radical formation and usual experimental methods (for example indicated pressure analysis and exhaust gas emissions analysis) was investigated.

SPECTROSCOPIC ANALYSIS OF OH RADICAL EMISSION

Detection Device of OH Radical Emission

The engine used in this study is a production 4 cylinder direct injection engine. Main specifications and driving conditions are shown in Table 1. A small hale was drilled in the cylinder head allowing the optical fiber to be installed as shown in Fig.1. The fiber optic cable has 24 cores each having a two hundred micron meter diameter. The viewing angle is 23 degrees. Detected light emission is fed to the PMA(Photonic Multichannel Analyzer:Hamamatsu Photonics co.Ltd) and spectroscopic analysis is conducted. The spectroscope is made by Jobin Yvon co.ltd. (HR250,Grating 1200). Measuring the light emission of the combustion flame is conducted over a duration of 5 crank angle degrees for 10 continuous cycles. Combustion analysis

Table1 Main engine specifications

Items	size
bore	104 mm
stroke	118 mm
compression ratio	19.2
type	in-line 4
swept vol.	4 dm^3
engine speed	1400rpm
STD engine load	50%

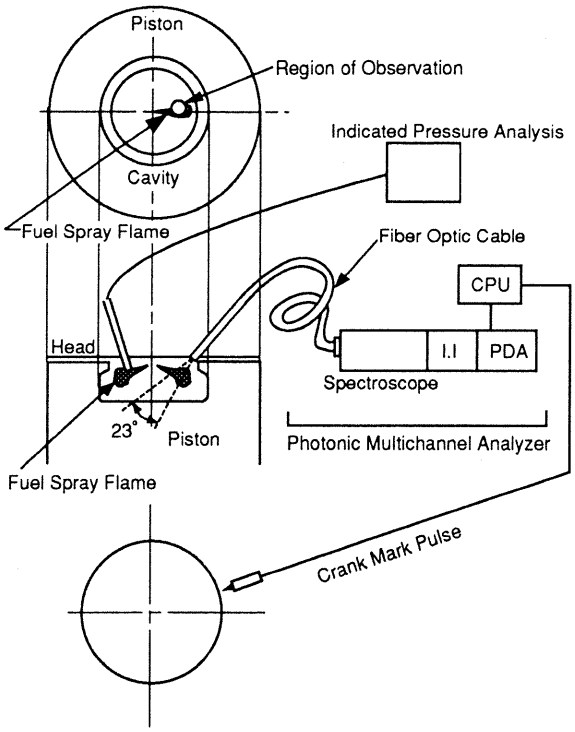

Fig. 1 Experimental apparatus and optical arrangement

by indicated pressure analysis and measuring the exhaust gas emission is conducted simultaneously in order to compare the spectroscopic analysis result of the combustion flame emission.

The Definition of OH Radical Emission Intensity

Fig.2 shows an example of the data obtained using spectroscopic analysis. The horizontal axis shows wavelength and the vertical axis shows optical emission intensity. In this case the OH radical emissions having wavelengths from 306 to 309 nm were detected. The peak value at 306 nm indicated on this figure corresponds to OH radical emission intensity. Although flame light of only a 5 degree duration can be analyzed at one time by controlling the shutter timing controller,the shutter opening timing can be shifted by 5 degree step for each test.

The Characteristics of Rate of Heat Release and Exhaust Gas Emission

Fig.3 shows ROHRs calculated from cylinder pressure

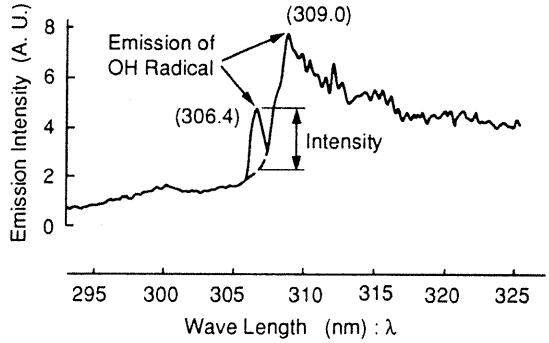

Fig. 2 The result of spectroscopic analysis in the combustion chamber

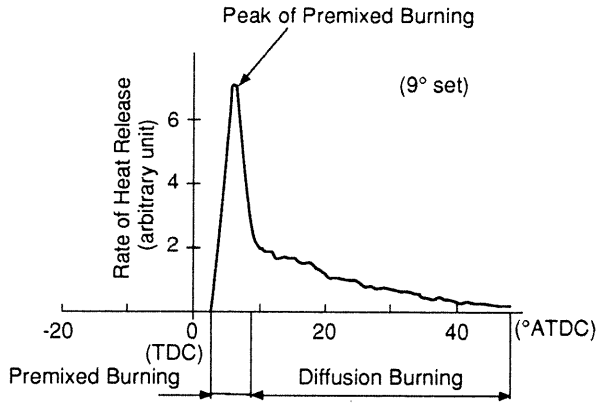

Fig. 3 The measured rate of heat release

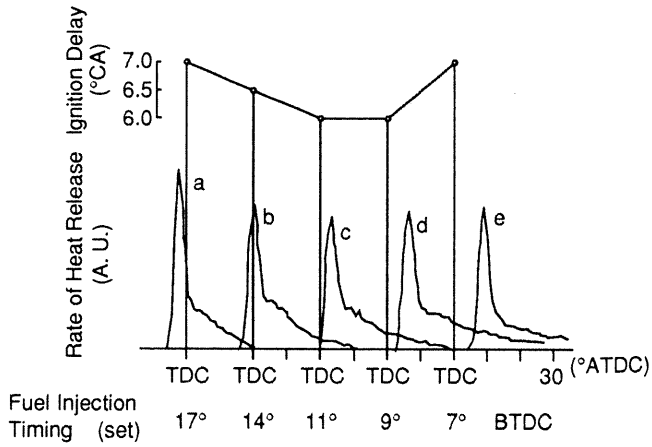

Fig. 4 The effect of fuel injection timing on the rate of heat release

at 50 % load(this load is treated as the standard condition, i.e.STD). At the STD condition,fuel injected within the ignition delay period is mixed with air and result in a vigorous premixed burning phase. Following this the diffusion burning phase occurs as shown in this figure.

Fig.4 shows the effect of changing the fuel injection timing on ROHR and the ignition delay. The fuel injection quantity of various injection timings are maintained the same as that of the STD condition. Generally speaking,the peak

value of premixed burning is small when the ignition delay is short. In this figure,the tendency of the premixed burnings peak value resembles the tendency of the ignition delay period. Namely,changing the fuel injection timing from the most advanced condition (condition a in this figure) to the most retarded condition (condition e in this figure),at first reduces the ignition delay until a minimum is reached at d,after which it increases again. The tendency of the premixed burning peak value is the same as that of the ignition delay.

Fig.5 shows the effect of brake specific fuel consumption (bsfc) and exhaust gas concentrations versus fuel injection timing. Retarding the fuel injection timing reduces NO although bsfc,HC and CO increase. The peak value of premixed burning is approximately proportional to NO concentration due to good mixing of fuel and air during the ignition delay period as shown in a, b and c in Fig.4. However for retarded timing,there is no correlation between the peak value of premixed burning and NO concentration due to the reduced temperature of the compressed gas due to timing retardation.

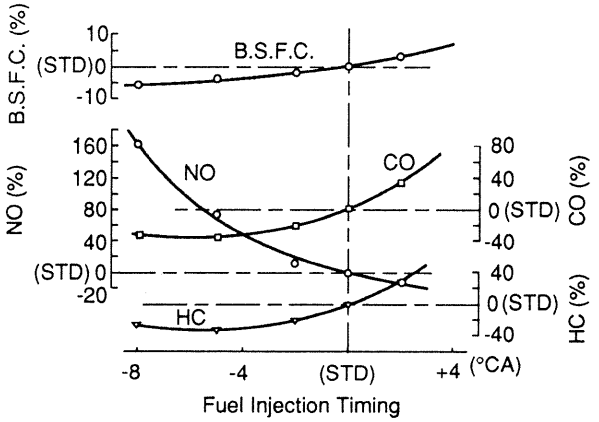

Fig. 5 The effect of brake specific fuel consumption and exhaust emissions versus fuel injection timing

EXPERIMENTAL RESULTS BY SPECTROSCOPIC ANALYSIS

Fig.6 shows the OH radical emission intensity obtained using the optical method mentioned above. ROHR is also shown in this figure for the comparison of OH radical emission intensity characteristics. From this figure the beginning of OH radical emission is slightly delayed from that of the ROHR and the end of OH radical emission is earlier than that of the ROHR.

Fig.7 shows the effect of fuel injection timing on OH radical emission. For comparison the ROHR plots are also shown in this figure. The pattern of OH radical emission changes with timing retardation. The level of OH radical emission is higher at advanced timing and reduces as the timing is retarded until a certain point is reached and it increases with the later timing. This tendency is approximately the same as that of the ROHR with timing retardation. This OH radical intensity level is an indication of the combustion occurring within the lean portion of the mixture. This is because the OH radical formation level within the lean mixture is higher than that of the rich mixture for the same temperature(9). The beginning of OH radical emission is slightly delayed from the beginning of ROHR. As

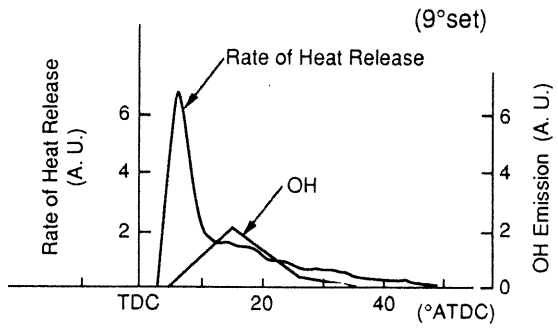

Fig. 6 OH radical formation characteristics versus crank angle in the combustion chamber

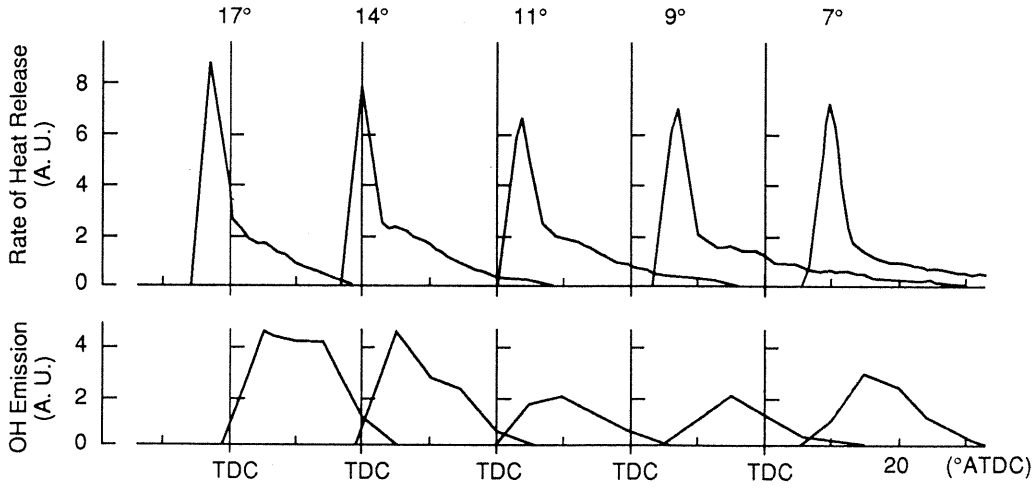

Fig. 7 The effect of fuel injection timing on OH radical formation in the combustion chamber

the reason of this phenomena are not clear,farther investigation is conducted as follows.

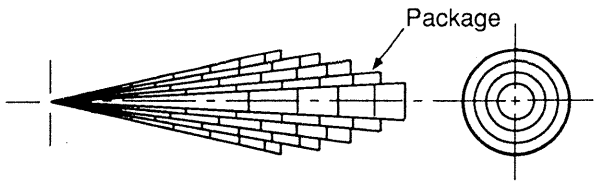

Fig. 8 Divided package of the spray

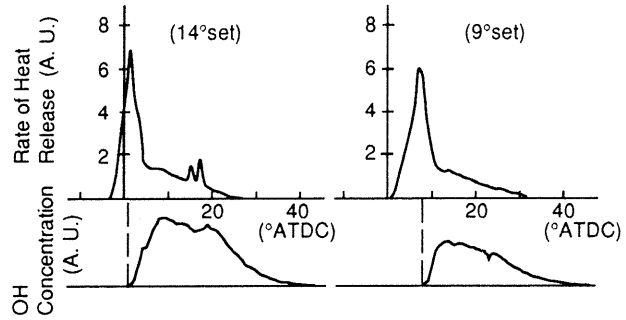

Fig. 9 OH radical formation calculated by the simulation model in the combustion chamber

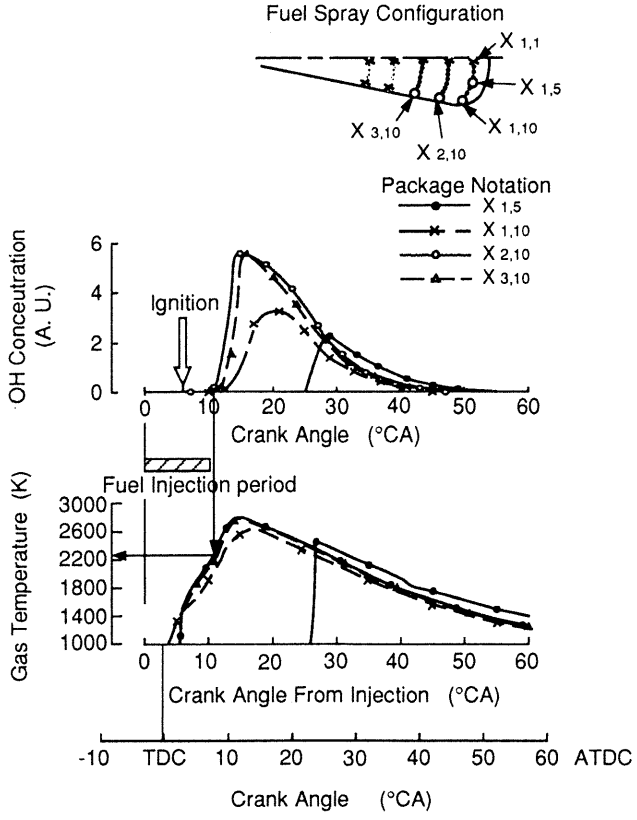

Fig. 10 OH radical and gas temperature calculated by the simulation model in each package of the fuel spray

THE ANALYSIS BY MATHEMATICAL SIMULATION MODEL

The injected fuel spray is divided into small packages,as shown in Fig.8, and calculations are conducted within each package(10). Namely, evaporation, mixing, ignition and combustion within each package are calculated and calculation results of each package is summed up. Fig.9 shows ROHR and OH radical concentration calculated by this simulation model. This result also demonstrates the delay of the beginning of OH radical formation. The calculation results of gas temperature and OH radical concentration of typical packages are plotted in Fig.10. From this figure initiation of OH radical formation appears to begin as the flame temperature rises beyond 2200 K. That is,delay of OH radical formation is due to the delay of flame temperature rising.

THE MEASUREMENT OF FLAME TEMPERATURE

In order to confirm the delay of the rising flame temperature,the two color method(6) of flame temperature measurement was applied. Fig.11 shows the flame analyzing system (FAS) experimental apparatus for measuring the flame temperature in the combustion chamber. In this application an endoscope was installed in the combustion chamber rather than an optical fiber as explained before and shown in Fig.1. The flame light introduced from the endoscope is divided into two colors by filters(these wavelengths are 470 nm and 650 nm). 4 images displaying the combustion phenomena using the two wavelengths are

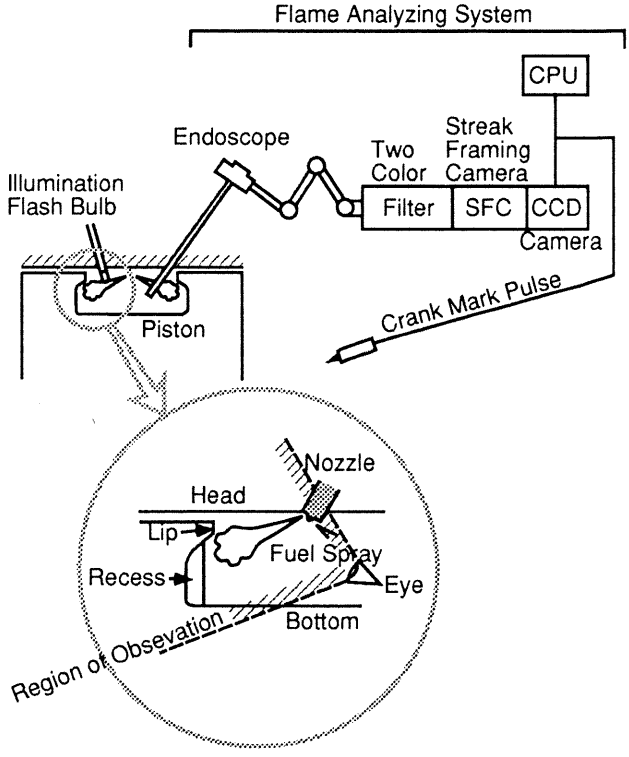

Fig. 11 Experimental apparatus and optical arrangement

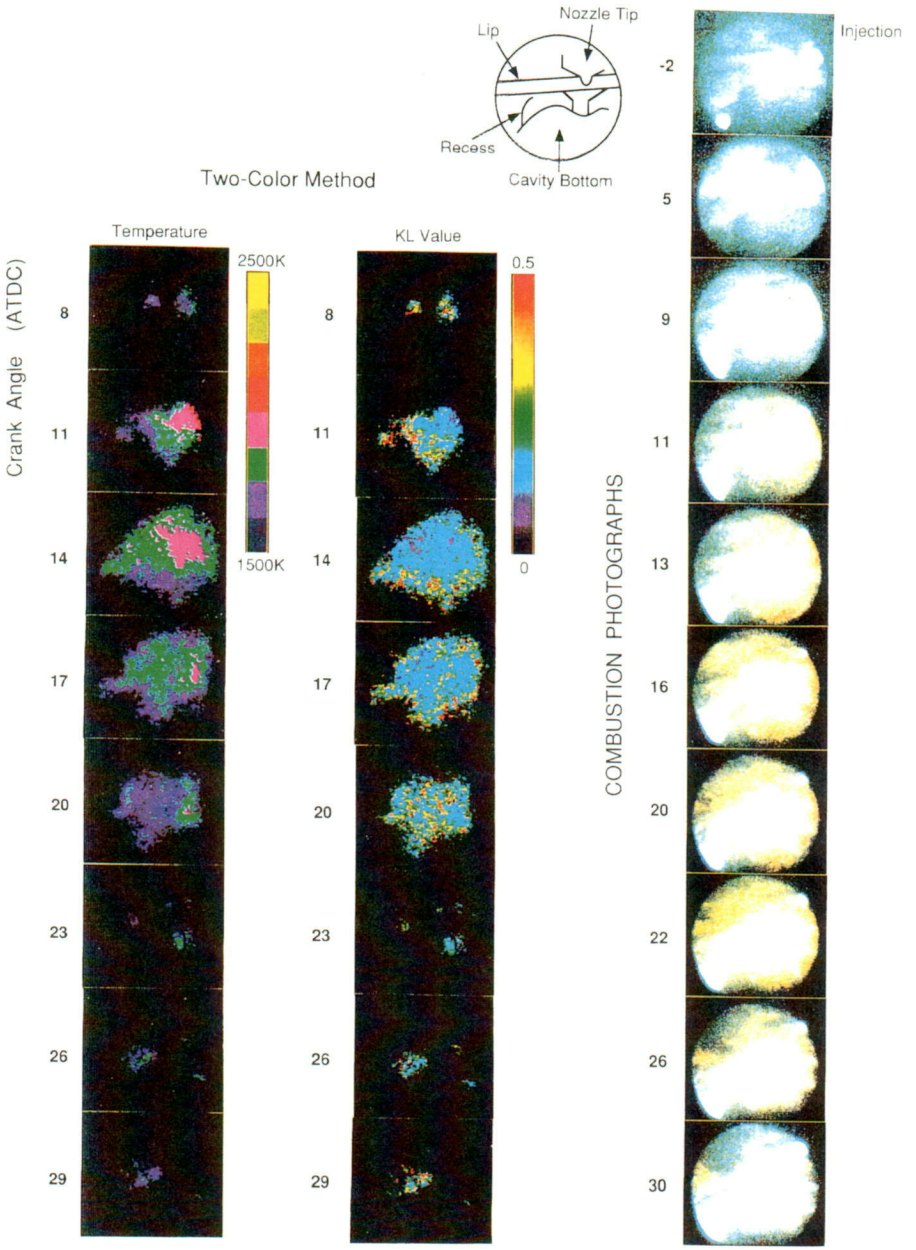

Fig. 12 Image of flame temperature distribution, KL valve distribution and combustion photographs

recorded over one cycle. Subsequent cycles allow additional data to be recorded before the stored information is downloaded to the FAS for processing. The sample timing is decided by a timing controller triggered by an engine and an encoder signal. The flame temperature and KL value(which is representative of the soot level) are calculated by computer using two color images of CCD camera immediately.

Fig.12 shows the image of flame temperature distribution and KL value distribution using FAS on this engine under STD condition. For a better understanding of the phenomena involved combustion photographs using a conventional high speed camera (NAC E-10)are also shown in the same figure. The maximum and mean flame temperature of Fig.12 are shown in Fig.13. This result clearly confirms the delay in the rise of the flame temperature. That is,the temperature first rises above 2200 K at 8 degree ATDC(After Top Dead Center). Maximum and mean value of flame at this time are about 2200 K and 1750 K respectively. The peak value of this process is about 2350 K at 11 degree ATDC. Near the beginning of combustion(initiation of ROHR ; 3 degree ATDC), higher flame temperatures of this order are not generated as shown in Fig.13. Therefore the delay in OH radical formation is due to the delay in the rise of the flame temperature.

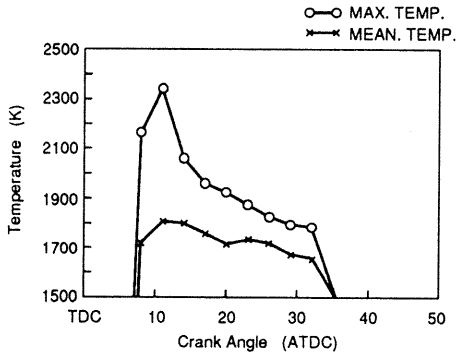

Fig. 13 Transition time graph of maximum and mean flame temperature

CONCLUSION

The investigation of the combustion flame in a DI diesel engine was conducted,thereby clarifying OH radical formation and extinction characteristics. The changes in the OH radical emission intensity closely resembled the changes in ROHR pattern during the premixed burning phase with changes in the fuel injection timing. However the beginning of the OH radical emission is slightly delayed when compared with the beginning of ROHR. The two color method, which was applied to measure the flame temperature, clarified that the delay of OH radical formation is due to the time required for the local flame temperature to rise beyond the threshold point.

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