

# A Study on Ignition Process of Diesel Sprays

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## ABSTRACT

The purpose of this study is to reveal the ignition process of diesel sprays. The composition of fuel-air mixtures formed in ignition delay periods were measured by injecting fuel into high temperature air in a rapid compression machine. The mixture compositions were compared with those of products obtained from pure thermal cracking tests by using a flow reactor. In addition, these results were considered in relation to the observed pressure-time curves and the development of sprays. The results show that the weak oxidation initiated just after the start of injection gives heat to the spray, causes thermal cracking and gasification of fuel. The gas induced by fuel decomposition in the delay period should have higher temperature than a surrounding air due to the continuing oxidation in the mixture. The accumulated gas is supposed to start combustion triggered by the oxidation of relatively small scale mixture and to release a large amount of heat that is usually observed as an ignition.

## INTRODUCTION

The fuel-air mixing during the ignition delay period has great influence on the overall combustion process in high speed small diesel engines. It is very important to control the ignition delay for suppressing the emission of soot,  $\text{NO}_x$  and unburned hydrocarbons without deteriorating the thermal efficiency. There are many studies<sup>(1)-(3)</sup> that measure the delay times under diesel-like conditions. They evaluate the effects of important factors such as air temperature, pressure and fuel composition. However, there is lack of information about the ignition process itself, so that the general understandings of the effects of these factors have not yet been given. To clarify the process, it is important to obtain the data about the characteristics of the mixture before ignition.

Our recent study<sup>(4)</sup> on the mixture formation by using a rapid compression machine shows that even before ignition a part of fuel is cracked into gaseous hydrocarbons which will give the large scale heat release. In this study, a fuel of simple composition was selected to clarify the ignition

process. The mixtures were chemically analyzed by using a total gas sampling method. First, using this technique, the features of the mixture composition were compared between the RCM and the flow reactor. Secondly, the results were connected to the pressure-time record and the development of sprays. Finally, the formation process of the initial mixture that could trigger the initial combustion was discussed.

## EXPERIMENTAL

### Rapid Compression Machine

The free piston type rapid compression machine(RCM) was used to simulate a diesel combustion. Details of this device have been described previously<sup>(4)</sup>. An injection nozzle (ZEXEL type DL0S) with a hole of 0.35mm diameter was used as a standard. Nozzles with two holes of 0.25mm and with three holes of 0.2mm were also prepared to evaluate the effects of hole size on ignition delays. These three nozzles have the same total area of holes to keep the injection mass rate constant. The air temperature at the start of injection,  $T_i$  was set from 700 to 900K at the constant pressure of 4MPa. Gas oil (JIS #1 diesel oil) with a density of 835kg/m<sup>3</sup> and a lower calorific value of 44200kJ/kg was used as a standard fuel. Also a simple fuel made of a few kinds of straight-chain saturated hydrocarbon was used to study the mixture composition. This fuel contains 27% n-dodecane( $\text{C}_{12}\text{H}_{26}$ ), 47% n-tridecane( $\text{C}_{13}\text{H}_{28}$ ) and 26% n-tetradecane( $\text{C}_{14}\text{H}_{30}$ ) in mass ratio and has a density of 751kg/m<sup>3</sup> and a lower heat value of 46100kJ/kg.

The total gas sampling method<sup>(4)</sup> was used to quench reactions and to collect the mixture. The trapped gas was analyzed with a gas chromatograph (YANACO G3800) having a FID and a TCD detector. To separate light hydrocarbons having up to 4 carbon atoms in each molecule( $\text{C}_1 \sim \text{C}_4$ ), an activated alumina-squalene column with a length of 3m and an inner diameter of 3mm was used. For heavier hydrocarbons with up to 14 carbon atoms( $\sim \text{C}_{14}$ ), a chromosorb-methylsilicone(DC-200) column(3m×3mm) was used. The pipes in the sampling system were heated more than 550K to avoid condensation of heavier hydrocarbons. For inorganic substances such as  $\text{O}_2$ ,  $\text{H}_2$ ,  $\text{CO}$  and  $\text{CO}_2$ , a molecular sieve

column and an activated charcoal column were used.

In this study, two kinds of ignition delay were used. The pressure recovery delay  $\tau$  was calculated from a pressure-time curve measured by a piezoelectric pressure transducer (KISTLER 601A) and a needle lift curve by a photoelectric detector. The ignition time was decided from the pressure difference  $P_f - P_a$ , where  $P_f$  was a pressure obtained from a usual combustion test and  $P_a$  from a test in which air is compressed without injection. The delay is defined as a period from the start of injection to the time when the  $P_f - P_a$  becomes positive again after it decreases to have negative values caused by heat absorption of a spray. The illumination delay  $\tau_i$  was derived from visible light emission detected by a wide view phototransistor.

High speed photography with a diffused background illumination was employed to observe the development of sprays. The KODAK double-X negative film was used with a camera speed of 6000fps and an exposure time of 8.3 $\mu$ s. The recorded images were converted to digital image data from which the contours of sprays were extracted by binarization for measuring the tip penetrations. The penetration measured in this way means the spray length neglecting vapor phase.

#### Flow Reactor

Thermal cracking tests were conducted by using a flow reactor in order to evaluate the feature of mixtures in the RCM. Fuel-air premixtures can be heated up to 1500K in an alumina reactor tube of 9mm i.d. with an electric heater. Fuel was dropped onto a heated plate of 573K, vaporized and entrained into hot nitrogen carrier gas in an evaporator upstream the reactor tube. The gas temperature was measured at the middle of the heated part of the tube. The residence time  $t_r$  of the mixture in the tube was defined as the time for traveling the length of this heated part, 205mm. The products were withdrawn at the outlet of the tube and analyzed by the same method as in the case of the RCM.

#### Nanosecond Spark Light Source

Photographs were taken with high time resolution by using a nano-spark light source<sup>(5)</sup> to visualize the progress of fuel disintegration in initial sprays. This light source emits a strong light pulse of less than 30ns' duration and permits the fixed image of a spray. In this test, gas oil was injected into high pressure nitrogen gas of room temperature in a cylindrical test chamber by using a single hole nozzle with a 0.35mm hole (ZEXEL type DLL15S351). Images of sprays were recorded with a magnification of 2 on 35mm monochrome films (FUJI PRESTO ASA400) by a still camera.

## RESULTS AND DISCUSSION

#### Composition of Mixture in Ignition Delay Periods

First the composition of the mixture in the ignition delay period was investigated by injecting gas oil (GO) into hot compressed quiescent air of 800K. Fig.1 shows a chromatogram of the gas extracted from the combustion chamber at 1.3ms after the start of injection. This sample time is located

before the initial flame occurs as mentioned later. Light hydrocarbons ( $C_1 \sim C_4$ ) are detected as products of reactions. Also the increase of  $C_6 \sim C_8$  hydrocarbons is observed compared with original fuel. It is suggested that the fuel undergoes cracking and produces light hydrocarbons even before the apparent heat release is observed.

Since the gas oil contains too many kinds of hydrocarbons, it seemed to be almost impossible to judge completely which species are induced from fuel by any reactions. To overcome this problem, a simple fuel (SO) was used. At the same air temperature given at the start of injection, the heat release pattern of SO always has more diffusive characteristics since it has a shorter ignition delay than GO. Therefore the air temperature was reduced to 700K for SO so that the heat release rate curve approximately coincides with that of GO at 800K. At this temperature, SO has a pressure recovery delay of about 3ms.

Fig.2 shows chromatograms of the SO mixtures at  $t=1$ ms and 2.2ms. The time  $t=1$ ms is in the early part of the pressure recovery delay. The time  $t=2.2$ ms corresponds to the time when the  $P_f - P_a$  shows its minimum and turns to increase. At  $t=1$ ms, fuel already begins to decompose and produces  $C_6 \sim C_7$  hydrocarbons, although  $C_1 \sim C_4$  hydrocarbons are hardly detected. At  $t=2.2$ ms, the mixture contains large amount of light hydrocarbons and many kinds of hydrocarbons which have boiling points lower than fuel components.

The overall composition of the mixture at  $t=2.2$ ms derived from the chromatogram in Fig.2 is shown in Fig.3. The percentage in the figure is calculated from the concentration calibrated by a methane molecule. This figure shows that the light hydrocarbons ( $C_1 \sim C_4$ ) occupy about 50% of total hydrocarbons excluding fuel components. Fig.4 shows the contribution of each type of hydrocarbon in  $C_1 \sim C_4$  species as mole fraction. Within light hydrocarbons, ethylene  $C_2H_4$  is predominant (>50%) followed by methane  $CH_4$  and propylene  $C_3H_6$ . Thus the unsaturated hydrocarbons are main products in the mixture just before ignition.

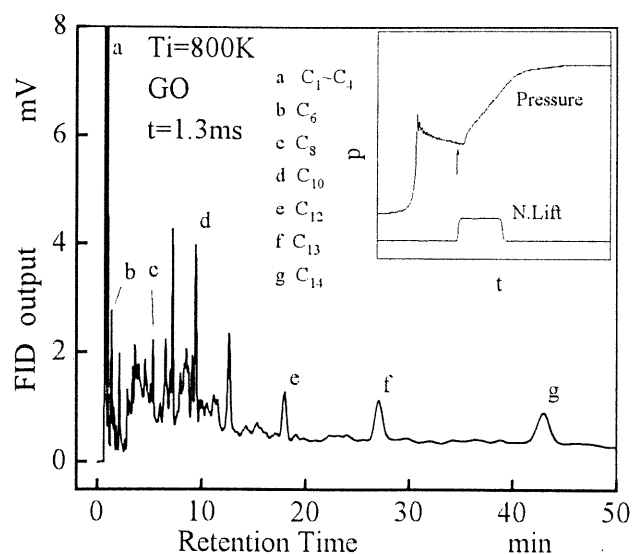


Fig.1 A Chromatogram of the mixture before ignition (GO)

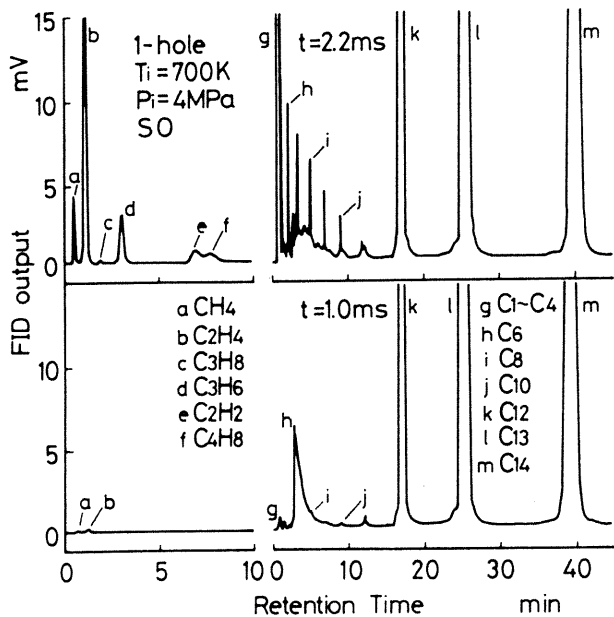


Fig.2 Chromatograms of the mixture before ignition (SO)

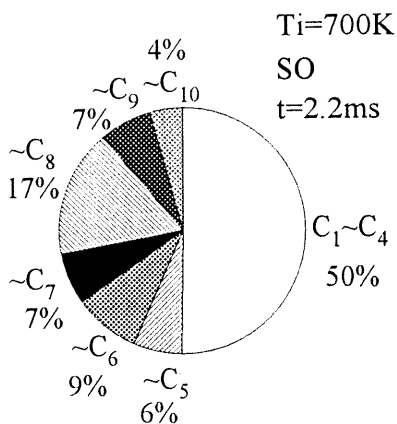


Fig.3 Composition of the mixture (overall hydrocarbons)

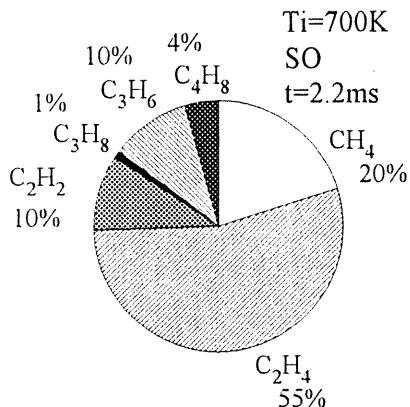


Fig.4 Composition of the mixture (light hydrocarbons)

Judging from these features and the high temperature oxidation process suggested for high molecular weight hydrocarbons<sup>(6)(7)</sup>, this mixture seems to be in the stage where the original fuel is diminishing while the intermediate

species are produced preceding the CO appearance. Acetylene C<sub>2</sub>H<sub>2</sub> is also detected though its concentration is not very high. This means that the mixture has very high temperature due to the development of oxidation in the spray.

Evaluation of Characteristics of Mixture Composition

To evaluate the composition of the mixture obtained from the RCM, results of pure thermal cracking tests by the flow reactor are introduced. In the reactor test, the premixture of fuel SO and nitrogen (mass ratio 1:25) were fed into the reactor at the residence time of 20ms. Fig.5 presents the temperature dependence of the mixture compositions. The products of thermal cracking, i.e., hydrocarbons which have fewer carbons than the original fuel components (C<sub>12</sub>~C<sub>14</sub>), appear at more than 1000K. Trend of the composition of light hydrocarbons is shown in Fig.6 for more than 1000K. Ethylene is a predominant also in this case. However, its percentage (60~70%) is more than the RCM especially in the low temperature region in the figure. On the other hand, the proportion of methane is less than RCM. Unsaturated hydrocarbons such as C<sub>2</sub>H<sub>4</sub>, C<sub>3</sub>H<sub>6</sub> and C<sub>4</sub>H<sub>8</sub> have been observed in the initial stage of high temperature oxidation of high molecular weight hydrocarbons. These are produced by the destruction of C-C bonds in the big olefins induced from the original fuel molecules by H radical abstraction<sup>(6)(7)</sup>. Our results indicate that if the sufficiently high temperature and a long residence time are given, the fuel molecules could independently break down to produce light unsaturated hydrocarbons. Similar results have been shown by Tosaka et al.<sup>(8)</sup>. In the high pressure condition in the RCM, this process can be accelerated.

Fig.7 shows the effect of the oxygen concentration in the charge gas of the RCM. These data were obtained by injecting SO into hot compressed oxygen-nitrogen mixture. The in-cylinder gas was withdrawn at about 5ms or 15ms from the start of injection setting the gas temperature to 800K. When the fuel is injected into the charge containing very low concentration of oxygen, 1.5% in volume, the mixture con-

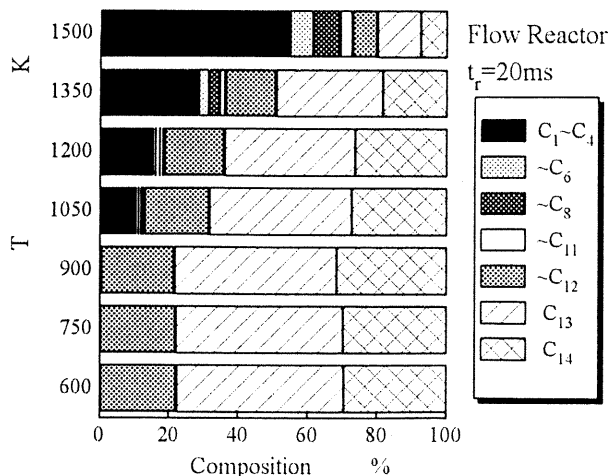


Fig.5 Effect of temperature on thermal cracking (flow reactor)

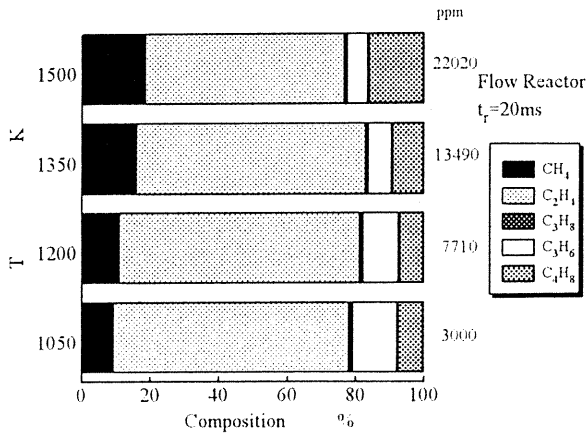


Fig.6 Composition of light hydrocarbons (flow reactor)

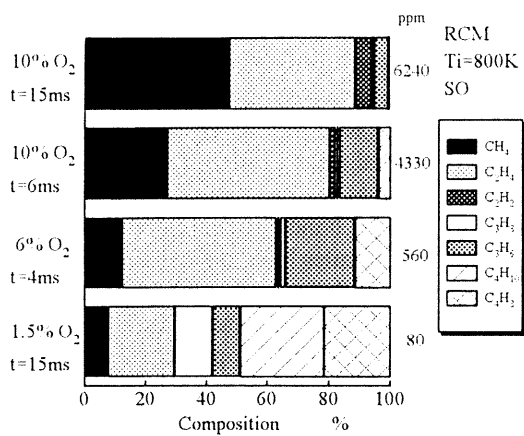


Fig.7 Effect of oxygen concentration on fuel decomposition

tains only low concentration of hydrocarbons even though the fuel experiences the high temperature for much longer time than usual ignition delay time. Thus, even if the long residence time is given, cracking processes do not progress in the RCM at the typical temperature for ignition. When the oxygen content increases to 6%, the concentration of total hydrocarbons becomes 7 times as much as in the case of 1.5%O<sub>2</sub> even though the sampling time is advanced to 4ms. Its composition is similar to that shown in Fig.6 at 1500K. At 10% O<sub>2</sub> with the sampling time of 6ms, the small pressure rise is observed and the considerably high concentrations are shown. When the longer time (15ms) is given at the same O<sub>2</sub> content, the total concentration further increases, and acetylene comes to be detected. The contribution of methane increases as the more oxygen is added in the charge. The increment of methane indicates the increase of temperature which the fuel experiences under fuel-rich condition as shown in Fig.6, the pure thermal cracking case.

These results show that the existence of oxygen is indispensable for the initiation of fuel decomposition process in the fuel air mixture formed by a spray in the RCM. It is also suggested that the mixture at the end of the ignition delay period shown in Fig.3 has considerably high temperature judging from the larger contribution of CH<sub>4</sub> and C<sub>2</sub>H<sub>2</sub> than

in the pure thermal cracking test shown in Fig.6. Pressure-time Histories and Ignition Process

The relation between illumination delay  $\tau_i$  and pressure recovery delay  $\tau$  is shown in Fig.8, using GO as a fuel in the range of 700~900K. The illumination delays  $\tau_i$  are always shorter than the pressure recovery delays  $\tau$ . Fig.9 shows the detail of  $P_f - P_a$  from the start of injection to the beginning of the initial combustion phase. The initial visible flame always appears around the time when the  $P_f - P_a$  indicates its minimum, i.e., the start of apparent heat release. No light emission was detected during the sampling process of the mixture in Fig.1. This means that the fuel decomposition really develops even before the visible flame appears and apparent heat begins to be released. Therefore, the oxidation must begin very early in the mixture.

Development of Sprays and Ignition Process

The relation between mixture composition and the state of a spray will be discussed here. Fig.10 shows tip penetrations L determined from high speed photographs. Two kinds of plots correspond to GO injection into 800K air and to SO injection into 700K air. Both penetrations L linearly increase with time up to about 0.5ms and the growing rates decrease after the time. Some studies show that

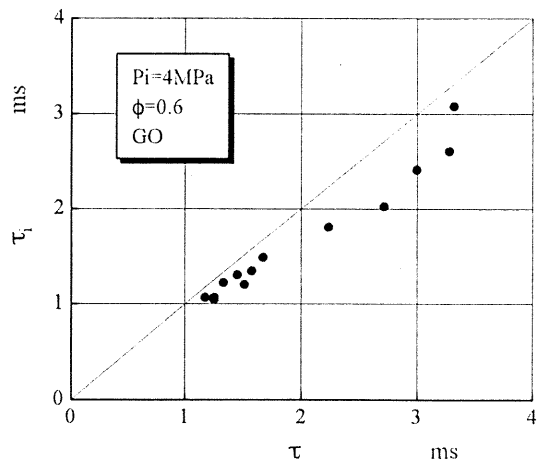


Fig.8 Relation between illumination delays and pressure recovery delays

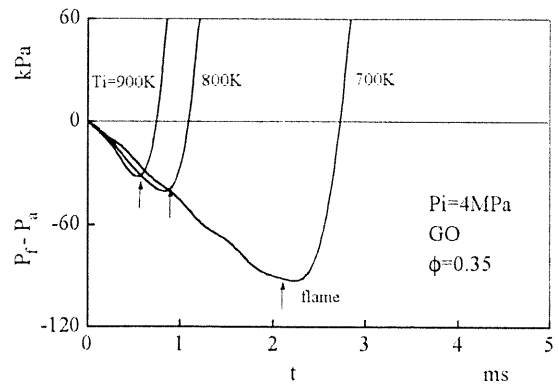


Fig.9 Detail of pressure curves in ignition delay periods

a spray is little atomized in the period of linearly increasing penetration<sup>(9)(10)</sup>. This period is called "a break-up time". As can be seen in Fig.9, pressure drop by heat absorption of a spray is very small in first 0.5ms. It can be assumed that only a little mass of air is entrained into the spray in this period. This is, however, the macroscopic observation.

Fig.11 shows photographs of non-evaporating sprays in 1MPa nitrogen taken with the nano-spark light source. The sprays in these photographs are in the initial part of the break-up time, 0.4ms in this case. From the macroscopic point of view, the whole spray can be treated as a fuel liquid flow. However, in a micro scale, small fuel fragments are already observed in the periphery of the fuel flow at 90 $\mu$ s. From the analysis of this photo, many of these fragments are found to have less than 10 $\mu$ m in diameter. Such small fragments can be easily vaporized to supply initial mixture if the

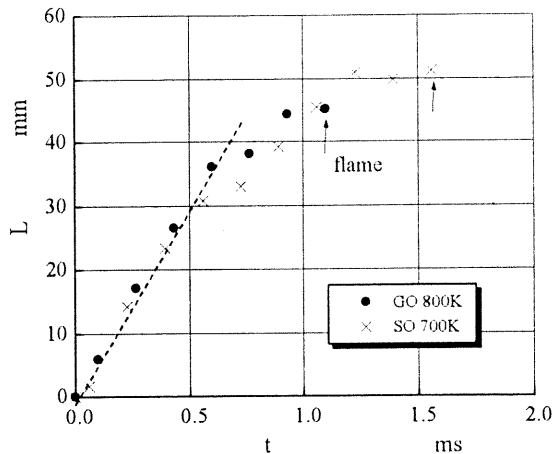


Fig.10 Spray penetration before ignition

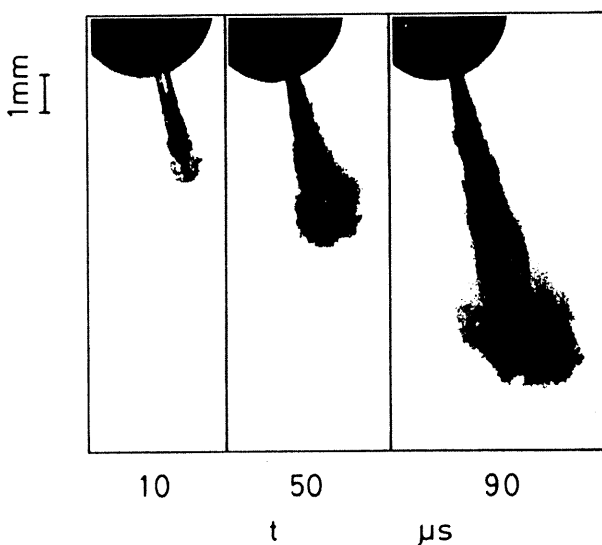


Fig.11 Microscopic images of initial sprays

ambient temperature is high. The mixture formed in this way will be responsible for starting the initial oxidation that ensures the subsequent vaporization and oxidation.

From high speed photographs of sprays in high temperature and pressure air, it can be seen that initial visible flames scarcely appear in the tips of sprays, but are usually found in the middle edge of sprays, rather close to the nozzle tip, when injected into quiescent air. The fuel at the surface of a spray tends to begin oxidation because it always contacts with fresh surrounding air. The mixture heated by the oxidation will be introduced into the spray and will give enthalpy to the inner part of the spray. Using this heat, the thermal decomposition or oxidation under very fuel rich condition can begin there. The temperature of the mixture will decrease because of heat absorption by thermal decomposition. In the vicinity of a spray tip, the fuel is well atomized to many droplets which can easily vaporize and begin to decompose. In addition, the mixing ability is so strong that the hot mixture formed in the outer layer tend to be introduced into the inner part of the spray. It is expected that it is difficult for the hot mixture to keep its temperature and to accelerate reactions. On the contrary, in the upstream part of the spray, the mixing vortices are so small that the mixture can keep its own temperature because there is little atomized fuel to be heated adjacent to it. As a result, the hot mixture triggering the rapid heat release should exist in the middle edge of the spray. The size of the mixture is expected to be small corresponding to the small vortex size there. It is supposed that the air temperature is a predominant factor for beginning the initial oxidation process.

#### Understanding of Effects of Some Factors on Ignition Delays

First, the effects of air motion in the combustion chamber are discussed. At the medium temperature, 800K, the swirl of optimum velocity slightly shortens the ignition delay. On the other hand, the excess swirl causes misfire at the low temperature region (<700K). These are accounted for considering the balance of two counter effects of the swirl flow<sup>(4)</sup>. One is to reduce air temperature by enhancing heat loss to the wall and to diffuse the mixture to be leaner. Another is to promote the initiation of oxidation in the mixture by introducing more air into the spray. However the quantitative differences of delays are not so large. However, the released heat observed in the initial stage of combustion undoubtedly increases with a swirl speed. This means that the initial mixture triggering the ignition is not the same as one which burns to release a large amount of heat in premixed combustion phase. This estimation is supported by the concept that the initial mixture has a small size as mentioned before. The large heat release observed as the initial combustion is thought to be a process in which the accumulated gaseous hydrocarbons rapidly burn triggered by the oxidation of the initial mixture.

Secondly, the effects of nozzle hole size are considered. Fig.12 shows the effect of hole size on the pressure recovery delays. The influence of the hole diameter is not great under the condition of this study. Fig.13 compares heat release curves at 800K. The hole size has little influence on ignition

delay and the initial heat release. The effect of reducing hole size appears only in the main, diffusive, combustion stage. This means that the effect of the enhancement of air entrainment on the delay time by reducing hole diameter does not appear when the ignition occurs before the spray fully develops. It is suggested that the initial small droplets as shown in Fig.11 are origins of the initial mixture in spite of the change of mean droplet size by nozzle hole size and that the oxidation of this mixture directly leads to the ignition and the initial combustion.

## CONCLUSION

To elucidate the ignition process of diesel spray, the mixture composition during the ignition delay time, the pressure-time history and the development of fuel sprays are experimentally investigated. Totally considering these results, some insights about the ignition process are given.

(1) At the occurrence of visible flames, which corresponds to the time when the gas pressure shows its minimum, the

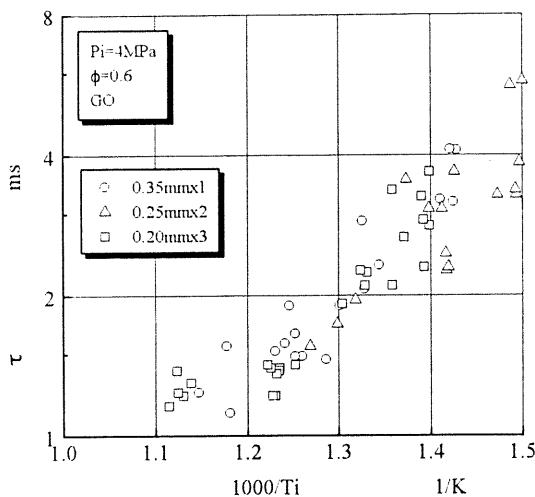


Fig.12 Effect of nozzle hole size on pressure recovery delays

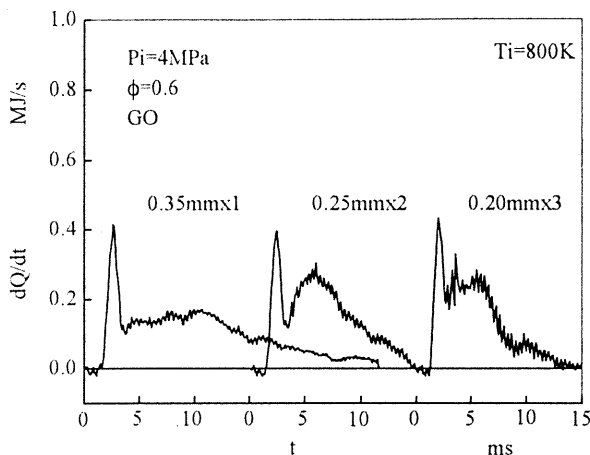


Fig.13 Effect of nozzle hole size on heat release curves

mixture in the spray already contains much light hydrocarbons produced by the decomposition of original fuel.

(2) In a diesel spray, the fuel decomposition can not progress without introducing oxygen into the mixture even if the typical ignitable temperature is given. The oxidation process in the initial mixture is essential for starting fuel decomposition and the apparent heat release.

(3) It is suggested that the initial mixture can be produced in the side surface of the spray even before the spray fully develops. The mixture will start oxidation very early in the ignition delay period and give rise to the temperature rise of the following mixture.

(4) The initial mixture is assumed to exist in the side of the spray relatively close to the nozzle. Its size is assumed to be small. Effects of some factors on the ignition delay can be explained by this assumption.

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