Experimental Study on Fuel Air Mixture Formation and Ignition Process in Diesel Combustion

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ABSTRACT

The purpose of this study is to investigate fuel-air mixture formation and its effect on the initial process of Diesel combustion. Thermal decomposition of injected fuel was studied for a single spray injected into hot compressed air or nitrogen over the wide range of the temperatures and the swirl velocities, with a rapid compression machine. A total gas sampling method was used to trace gaseous hydrocarbons at each stage of combustion and the results were combined with the analysis of ignition delay and heat release rate.

The experiments show that the swirl flow greatly promotes fuel-air mixing before and after ignition, although it has a little effect on the ignition delay except on misfire at low temperature. Ambient temperature is an important factor affecting the decomposition. Oxygen can accelerate the decomposition, but cannot at too low temperature. This may be correlated with misfire phenomenon at very low temperature.

INTRODUCTION

Amount and distribution of the fuel-air mixture formed in an ignition delay period are important for combustion in Diesel engines, because they have great effects not only on diesel knock but also on harmful emissions such as NO_x, UHC and particulates. In the ignition delay period, through the interaction of fuel sprays with surrounding air, the physical process including fuel atomization, vaporization and mixing progresses together with the chemical process including thermal decomposition and weak oxidation. Many factors such as air temperature, air pressure, swirl or other types of air motion, shapes of combustion chamber, injection characteristics and fuel quality affect the interaction. For prediction of the amount or distribution of the mixture, it is necessary to have detailed information about these effects on the physical and chemical process. There are many studies (1)-(3) on the influence of ambient temperature, pressure and fuel quality on ignition delay, but not so many (4) on formation of vapor or mixture in a spray. This makes it difficult to link the mixture formation with ignition phenomenon or initial combustion process. Information is also lacking about the behavior of sprays at high temperatures and pressures. Ikegami et al. (5) showed that the thermal decomposition occured in a spray even before any detectable pressure rise took place during the ignition delay and the spray became close to a gaseous jet containing a lot of fuel vapor. This fact means that the process converting fuel to lighter gaseous hydrocarbons is important when we characterize a diesel spray and that attention should be paid for quality of the mixture as well as for its quantity.

In this paper, to reveal the relation between the mixture formation and the initial combustion process, experiments were conducted for a single spray injected into a high temperature and pressure ambience made with a rapid compression machine. First, ignition and combustion characteristics were analyzed on various conditions of temperature and swirl velocity. Secondly, the progress of thermal decomposition of fuel was studied by tracing hydrocarbons with lower boiling points at each stage of combustion, using a total gas sampling and analyzing method.

EXPERIMENTAL

Rapid compression machine

The free piston type rapid compression machine (1) was used to realize a combustion in a constant volume over the wide range of temperatures, pressures and swirl velocities. The combustion chamber shown in Fig. 1 has a 60mm diameter and a 20mm width. The fuel used was a diesel fuel of a density $832kg/m^3$ and of a lower calorific value $44200kJ/kg$. It is pressurized by a BOSCH type injection pump and stored in an accumulator at $19.6MPa$ and then injected in the direction $\alpha = 15deg$ through a DL30S351 hole nozzle with a 0.35mm diameter hole at the desired timing controlled by an electro-magnetic servo valve. Using the single hole nozzle keeps off the interference between adjacent sprays when a multi-hole nozzle is used, simplifying the interaction of spray with its surroundings. In order to evaluate the effects of air motion on ignition and combustion, a swirl flow was made with a swirler installed in the inlet of the combustion chamber. This swirler has a 14mmx16mm connecting port and produces a flow rotating in the chamber induced by the piston motion. The swirl velocity can be controlled by the port angle β. The swirlers
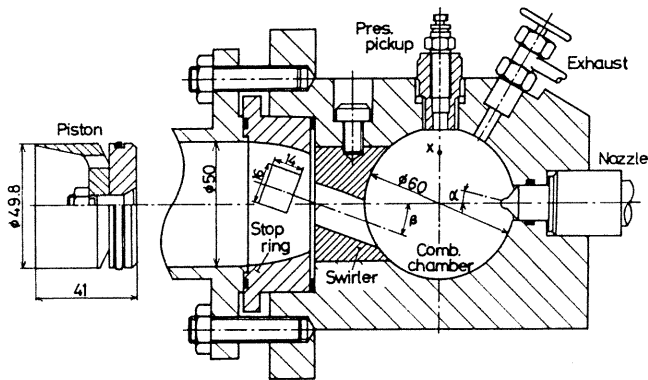
Fig. 1 Combustion chamber of RCM

with the angle β =4.6, 9.2, 20deg are employed. Velocity measurements under non-injection condition with a hot wire anemometer (Pt-Ir, 12.7 μm diameter) indicate that these swirlers make the flows decaying gradually and that the tangential velocities at point "X", 20mm from the center, are 19, 30, 62m/s for each β when an injection is to start. The standard velocity u=19m/s is the typical value for a swirl flow observed at TDC in the usual deep bowl combustion chamber of a diesel engine of about 90mm bore. Experiments were carried out at a fixed air pressure 4MPa over the temperature range of 650K to 900K determined from the chamber pressure at the injection start. To study the temperature effects on thermal decomposition seperated from those of oxygen, nitrogen is also used as charge gas.

The ignition delay is defined as the so-called total delay τ. An ignition time is decided as the time when the chamber pressure exceeds the pressure of air equally compressed without injection. The delay τ is the period from the start of injection to this ignition time. The delay thus defined means the pressure recovery delay excluding the effect of heat loss to the combustion wall. The injection start is measured from the needle lift detected photo-electrically and the chamber pressure with a piezo-electric transducer(KISTLER 601A). The heat release rate dQ/dt is calculated from the pressure, considering the heat loss to the chamber wall estimated by the non-injection test and the temperature dependence of specific heat.

Total gas sampling method

A local gas sampling method has some merits for measurements of spacial distribution of combustion products, but it is difficult to get the global view of the mixture formation and the decomposition process especially under the strong air motion like in this study which distributes the mixture over the entire space in the combustion chamber. For this reason, a total gas sampling method (6) which can frozen and sample the whole gas at each stage of combustion was employed. Figure 2 shows the main part of the sampling apparatus used in this study. The expansion chamber is connected to the combustion chamber with a thin diaphragm between. When the pancturing probe is actuated by a spring and

raptures the diaphragm, the pressure difference between the two chambers causes a flow and an expansion of the gas into the expansion chamber. This chamber has a volume of 2000 cm^3 and is filled with nitrogen gas at room temperature and pressure before sampling. When the diaphragm is broken, the gas expands into 20times volume and cools down to less than 500K even at the main combustion stage, stopping the chemical reaction. In Fig. 3 the pressure traces when the sampling device is operated are shown for combustion and non-combustion(nitrogen) tests. If the device is not operated, the pressures will follow the dot lines, but once the rapture occurs they drop rapidly down. The pressure half-decay time is about 1.5ms when the rapture is performed during combustion. The rapture timing can be set to the desired time by selecting the energizing timing of the solenoid releasing the hook which holds the probe in the standby position. The sampled gas is analyzed for hydrocarbons up to 4 carbon numbers using a gas chromatography(YANACO G3800) with an alumina-squalene column(inner diameter 3mm, length 2m) and a FID detector.
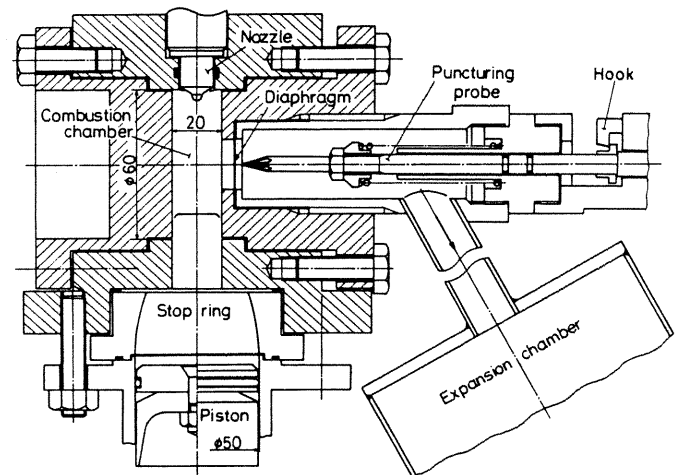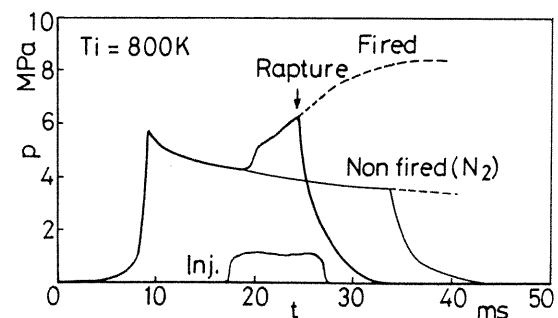

Fig. 2 Total gas sampling apparatus

Fig. 3 Pressure changes when rapturing

IGNITION DELAY AND INITIAL COMBUSTION PROCESS

Ignition delay

The macroscopic effects of ambient temperature and swirl velocity on ignition delay are investigated. In Fig.4 the logarithm of ignition delay is plotted versus the inverse of ambient
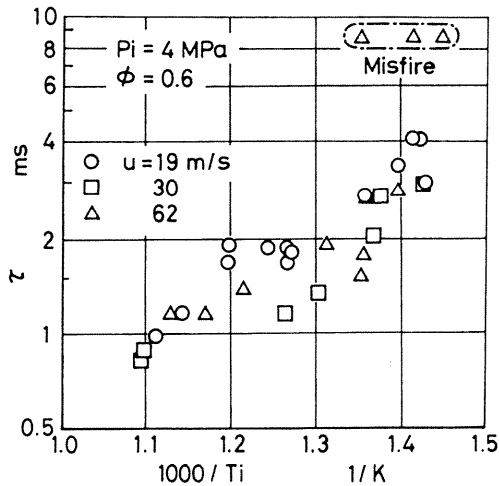
Fig.4 Variation of ignition delay
with temperature

temperature for some swirl velocities at a constant pressure $P_i=4MPa$ and an equivalence ratio $\phi=0.6$. The delay τ decreases for any u as the temperature increases. The difference of between the three u is little at the high T_i(ca.900K or $1000/T_i=1.1$), but at the medium T_i(ca.800K or $1000/T_i=1.25$) the delay for $u=30m/s$ is slightly shorter than for the others. It is suggested that a swirl flow shorten the delay due to its positive effect on mixture formation for ignition. However, the misfire observed at the low temperature (below 750K or $1000/T_i>1.35$) caused by the strongest flow, $u=62m/s$, means the negative effect of a swirl flow. Around this temperature, although the total delay at $u=62m/s$ seems to be shorter than that at $u=19m/s$, the substantial delay till the rapid pressure rise caused by the large scale combustion of the premixed fuel is not so short but almost the same. This is due to the very weak heat release before the large pressure rise. This small scale combustion durates for about 1ms after τ and gives no remarkable pressure rise, while this phenomenon is not found at higher temperatures. It is estimated that if the temperature is not sufficient to ignite the mixture immediately, the excessive flow cools and diffuses it into the too cold and weak mixture to ignite. So the optimum swirl will exist corresponding to the temperature condition.

Combustion process

Figure 5 shows the heat release rate profiles at some T_i for $u=19m/s$. At the low temperature, $T_i=700K$, an explosive burning occurs just after the ignition, while it becomes milder at 800K. At 900K, most of fuel injected seems to be consumed in the diffusion phase. The effect of swirl velocity u at the constant temperature, $T_i=800K$, is shown in Fig.6. Although there is only a little difference in the delay, the heat released in the initial stage greatly increases according to the increase of u. In Fig.7, the maximum rate of heat release $(dQ/dt)max$ and the fraction of heat released by the initial combustion, Qp/Qt are plotted versus the modified ignition delay $\tilde{\tau}$. The modified delay $\tilde{\tau}$ is defined as the time from injection commencement until 2% of the total released heat is liberated. We use this definition
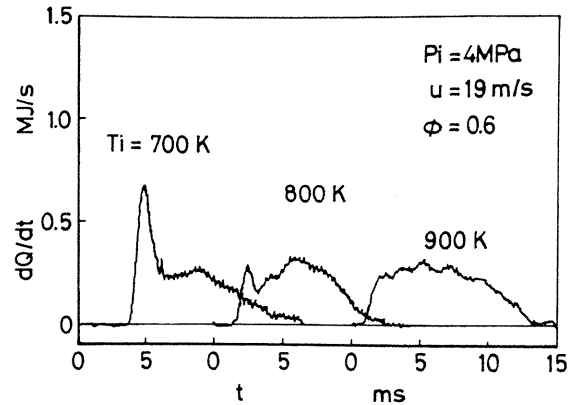

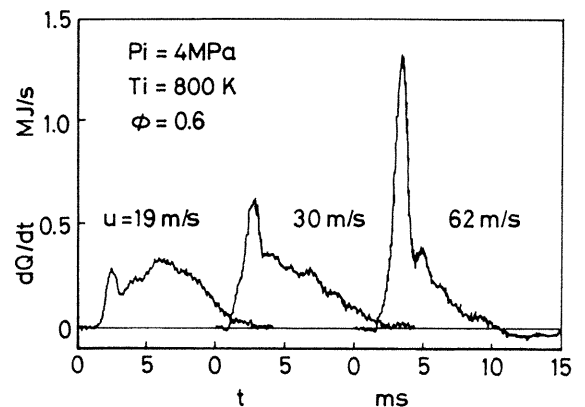Fig.5 Effect of temperature on heat
release rate

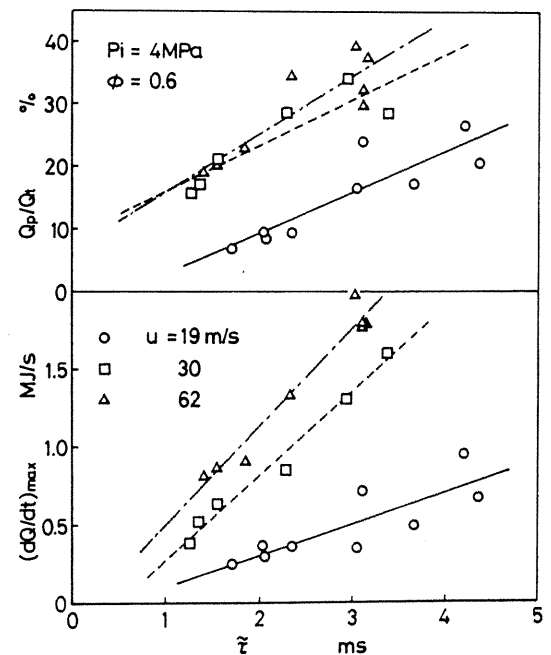Fig.6 Effect of swirl velocity on
heat release rate

Fig. 7 Comparison of heat amount in initial
combustion stage

in order to regard the period with very weak heat release observed at the highest swirl velocity as the time for producing the mixture. The ratio Qp/Qt is calculated from Qp which is the integrated heat amount in the initial stage, and Qt which means the heat amount released if the whole injected fuel completely burned, in other words, the total input heat. Both (dQ/dt)max and Qp/Qt linearly increase with τ , but they are much different between u even at the same τ . Comparing Qp/Qt at τ =2ms, which corresponds to the delay at 800K, the stronger swirl u= 30, 62m/s release 2.5times heat as much as u=19m/s. The ratio Qp/Qt is approximately 25%, a quarter of the total input heat. This value is comparable to the fuel amount ratio estimated from the injection rate, 30% of the total injected fuel in the delay, 2ms. It seems to be impossible to vaporize and mix instantaneously all fuel injected till ignition, so that this result means that the strong swirl flow promotes mixing not only before ignition but also after combustion starts.

DECOMPOSITION OF MIXTURE

The ignition is performed through the process containing fuel mixing with hot air, mixture heating and fuel decomposition into combustible gas. Here, paying special attention to the decomposition, we investigate the effects of temperature and oxygen content on the mixture formation process by the total gas sampling method for nitrogen-oxygen charge. Furthermore, to clarify effects of the mixture on the initial and main combustion, this method is also applied to the usual combustion tests.

Effects of temperature and oxygen

Figure 8 shows chromatograms obtained from nitrogen tests. The fuel is injected into nitrogen gas with the duration of about 10ms, then the gas is sampled just after the injection ends. In this experiment both the regular strong oxidation which is clearly detected as pressure or temperature rise and the weak oxidation which gives an only local temperature rise but promotes the decomposition is prevented. At 700K, only a trace of hydrocarbons up to 4 carbon numbers can be detected.
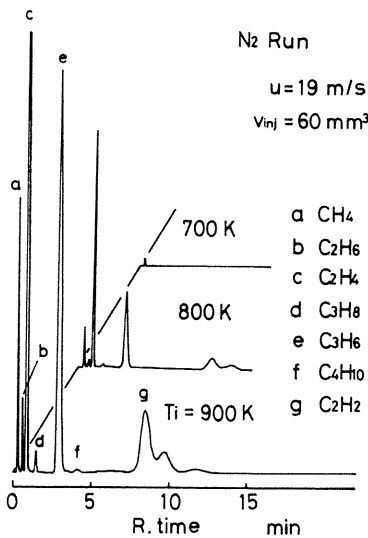
Over 800K, obvious peaks, especially of unsaturated hydrocarbons begin to show and also C_2H_2 becomes respectable amount at 900K. Figure 9, which is derived from the chromatogram illustrated in Fig.8, shows that the total concentration exceeds 500ppm at 900K and that the concentrations of unsaturated hydrocarbons such as C_2H_4 and C_3H_6 are much more than the saturates. The concentration,500ppm in total corresponds to 1000ppm
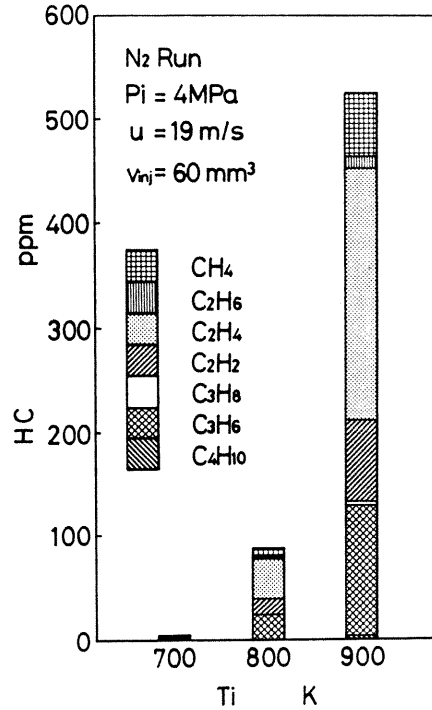

Fig.9   Effect of temperature on thermal decomposition
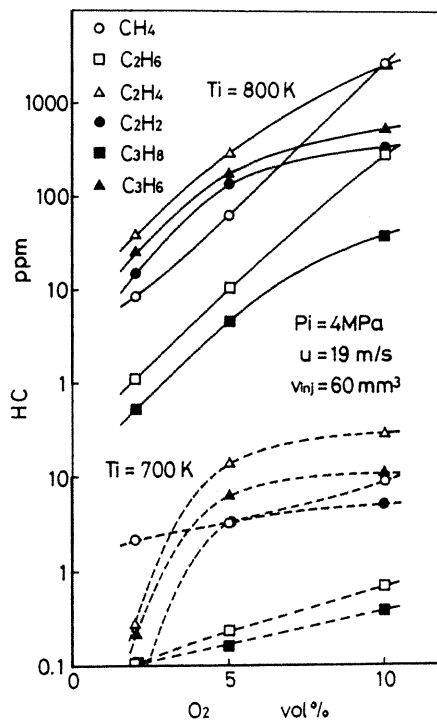

Fig. 8   Chromatograms for nitrogen tests

Fig.10   Effect of oxygen on thermal decomposition

calculated in terms of a carbon atom which is equivalent to 2% of the injected fuel. From the high speed photographs taken in the nitrogen tests under the equal conditions, we can see that the spray core at 700K impinges on the combustion wall, while at 900K the spray, which has only a 70% maximum length of the one at 700K, severely generates vapor and does not reach the wall. It is thus suggested that at the sufficiently high temperature there exists the fuel decomposition without the aid of temperature rise by oxidation. Next, tests were conducted changing oxygen concentration in nitrogen. Figure 10 shows the effect of oxygen content at Ti=700K and 800K. At 700K, concentrations of hydrocarbon increase as the oxygen content becomes high, but any hydrocarbon detected does not exceed 30ppm. In the case of 800K, the O_2 change from 2% to 5% multiplies the concentration ten times and a slow combustion occurs at 10% O_2. The total concentration at 10% O_2 reaches 6000ppm and the saturates such as CH_4 and C_2H_6 becomes as much as the unsaturates due to the temperature rise by the oxidation. Thus a mixture decomposition needs a high temperature to some extent and a too low temperature can not give sufficient gaseous hydrocarbons for ignition even if oxygen exists.

Fuel decomposition and combustion process

From the results in the previous section, we have the information about the progress of thermal decomposition during the ignition delay period. In this section, in order to know the effects of such decomposition on combustion, gas sampling and analysis are carried out for the usual combustion tests.

Figure 11 shows the time trend of lower hydrocarbons during combustion at Ti=800K. In this figure the horizontal axis is the time elapsed from the injection start and in the upper part is shown the correspondence between the heat release pattern and the sampling timing. The point "a" of t=1.3ms is the time when the heat release begins to overcome the heat absorption by the spray and probably the initial flame originates, although any pressure rise can not be detected yet. At "a", there is much unsaturates as can be seen in the nitrogen tests and the total concentration exceeds 1000ppm. Such a high concentration is likely due to the effect of the regular oxidation process beginning from this time, adding to the weak decomposition of the mixture since the injection has started. At "b", in the initial stage of combustion, the total concentration decreases to 300ppm due to the rapid consumption of the cracked products in this stage. As the combustion goes on to the main stage("c"), the cracked products begin to increase again and keep going up ("c"-"d"-"e") even after the heat release rate begins to fall by the injection termination. This tendency stops at "f", when the heat release almost ceases, and probably the concentration gradually decreases to the exhaust level at "g". During this stage, we can see that the ratio of the saturates, especially CH_4, increase and conversely the unsaturates decrease as the combustion proceeds.

Additionaly, we had similar experiments at Ti=650K which is near the limit of temperature for ignition on this swirl condition. Figure 12 shows the results. The observed ignition delay is 4 to 6ms at this condition, but only 10 to 20K decrease of temperature causes misfire. The scatter of a ignition delay and a heat release rate pattern on each test is very large, so we select the similar patterns out of many tests. The pattern, which differs from one at slightly higher temperature, has no sharp peak of initial combustion, but has a wide gently-sloping peak followed by a very long
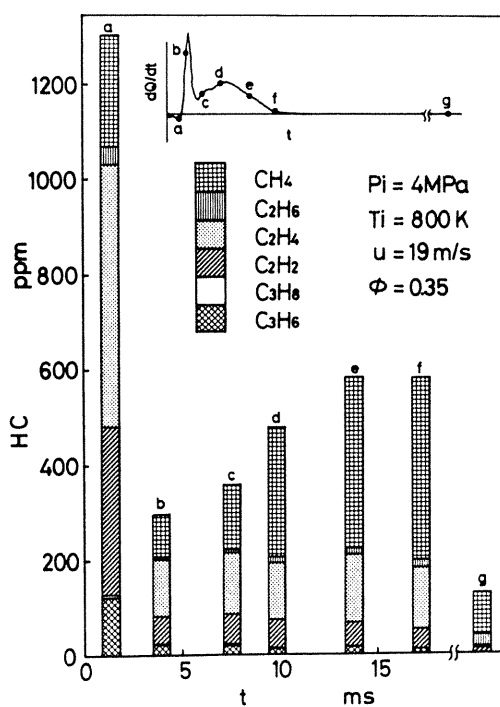

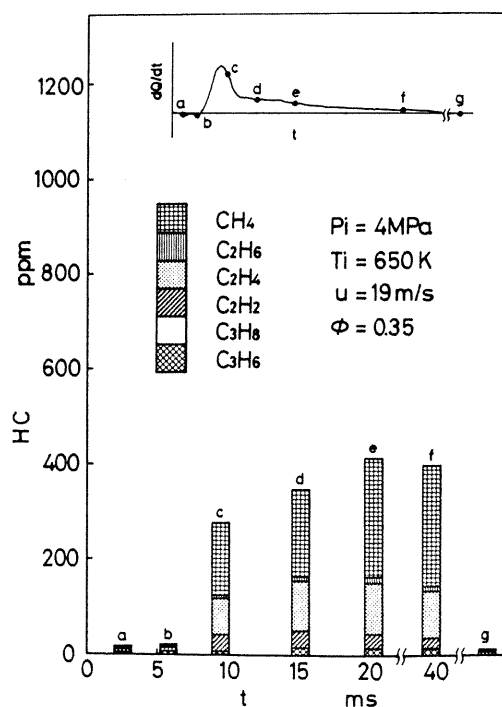Fig.11 Trend of gas composition during combustion (Ti=800K)

Fig.12 Trend of gas composition during combustion (Ti=650K)

tail with weak heat release. The lower hydrocarbons in the delay period, at "a" or "b", are as little as obtained in the nitrogen test at 700K. Once the combustion starts, the trend of concentration is similar to one at 800K. It can be estimated that at low temperature like this, the mixture which has an adequate concentration and a sufficient temperature exists in the only limited region in the combustion space. So the little deviation of temperature or air motion will change the ignition delay or the combustion process. Furthermore, the results of analysis on gas derived from the combustion chamber after misfire show only a trace of lighter hydrocarbon. This seems to be the result that the necessary condition for iginition can not be found anywhere and the decomposition is not acceralated. For the similar reason, as shown in Fig.4, the too strong swirl flow will cause a misfire at the relatively high temperature owing to its effect to keep off the accumulation of combustible mixture.

Although we have no information about the heavier products, these facts mean that the thermal decomposition has an important role for combustion initiation.

CONCLUSIONS

In order to reveal the relation between mixture formation and ignition or initial process in diesel spray combustion, experiments were performed, especially focusing the fuel decomposition process, using the rapid compression machine and the total gas sampling method. The obtained results are as follows:

(1)   The Strong swirl flow shorten an ignition delay at the medium temperature, but tends to cause a misfire at the low temperature owing to its effect to prevent the accumulation of cracked products.

(2)   Heat released in the initial stage of combustion increase as a swirl velocity becomes high, even though it gives little change in an ignition delay . This is due to its effect to promote the fuel-air mixing before and after ignition.

(3)   The decomposition of injected fuel is greatly affected by ambient temperature. A sufficiently high temperature can cause the decomposition and make gaseous products containing much unsaturates.
However, the too low temperature below 700K can not accelerate the thermal cracking even if oxygen exists.

(4)   Cracked products containing much unsaturated hydrocarbon are much shown at the start of heat release and rapidly consumed in the initial stage of combustion. Then they turn to increase at the main stage and continue to glow up till the heat release diminishes.

(5)   At the low temperature close to the ignition limit, the decomposition can not progress and the ignition or combustion occurs casually because the condition for ignition is prepared only locally in the combustion space.

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