Cylinder to Cylinder Deviations in Combustion and Emission at Idling in DI Diesel Engines with Pilot Injection*

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Pilot injection in DI Diesel Engines is a very effective method reducing nitrogen oxides and noise. However the injection behavior of small quantities of pilot fuel is unstable, and the cylinder-to-cylinder deviations in injection mass and spray development occur in multi-cylinder direct injection diesel engines. This study investigates the correlation between cylinder-to-cylinder deviations in spray development and combustion and emissions when the pilot injection was applied at idling. It was found that the cylinder-to-cylinder deviations in spray behavior are not the sole reason for the deviations in combustion and emission, but that peculiar conditions to a cylinder such as air movement and in-cylinder carbon deposits also play a role. In this study the HC components in the exhaust gas with and without pilot injection was investigated, and it is shown that deviations in combustion with pilot injection result in deviations in low carbon component emissions and in the rate of pressure rise which is responsible for exhaust odor and engine noise.

***Key Words*:** Diesel Engine, Fuel Spray, Combustion, Cylinder-to-Cylinder Deviations, Pilot Injection, HC Emission

1. Introduction

In multi-cylinder direct injection (DI) diesel engines, cylinder-to-cylinder deviations in combustion phenomena and exhaust gas emissions are common. It is thought that cylinder-to-cylinder deviations occur mainly due to deviation in fuel injection phenomena(1), but in recent engines cylinder-to-cylinder deviations are minimized by common-rail type injection systems with electronic control(2). However, even with this injection system there are cylinder-to-cylinder deviations in injection mass and spray formation. Cylinder-to-cylinder deviations influence exhaust gas emissions and engine stability. Usually, it is thought that unburned hydrocarbons (HC) and odorous gases increase if the combustion in each cylinder is not identical at low loads and low engine speeds like at idling(3). Especially when pilot injection is applied to reduce the engine noise at idling, the deviations in injected fuel mass and the spray shape increase and will lead to cylinder-to-cylinder deviations in combustion and HC emissions.

This study investigates the influence of the cylinder-to-cylinder deviations in spray formation on the combustion and THC emission when pilot injection is applied at idling in a medium-sized six cylinders DI diesel engine. As a result, it was found that the spray shape and injection mass deviations are responsible for the deviations in THC but that this is not the dominating or sole factor. Deviations in the in-cylinder conditions such as carbon deposits and in-cylinder gas flow are thought to be play a larger role in THC deviations. This study also investigated

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the HC components in the exhaust gas with and without pilot injection, and it is clear that deviations in combustion with pilot injection result in deviations in low carbon component emissions and in the rate of pressure rise which is responsible for exhaust odor and engine noise.

2. Experimental systems and methods

Figure 1 shows the experimental system used to investigate the spray behavior. Fuel was injected into a constant volume, high-pressure chamber at an ambient temperature and at a chamber pressure of 1.8 MPa to make the gas density identical to that of the compression end of an actual engine. A modified high-pressure oil jack was used to raise the fuel pressure (up to 40 MPa); it is similar to the common rail system of an actual engine. A single shot injection and a single flash of the light source were activated by an electrical signal generated through an electrical control unit (ECU). A valve covered orifice (VCO) type injection nozzle with 6 holes each of 0.19 mm in diameter and a hole length to diameter ratio of 4 was used. Photographs of the sprays were taken by a CCD camera with scattering light produced by a stroboscope with a very short lighting duration. From these photographs the spray penetration at each hole was measured and the deviation rates (the standard deviation /mean penetration) were calculated.

The engine used for the combustion and emission analysis is a six-cylinder direct injection diesel engine with a high-pressure common rail injection system. Specifications for the engine are shown in Table 1. The in-cylinder combustion pressure was measured in each cylinder under the same conditions.

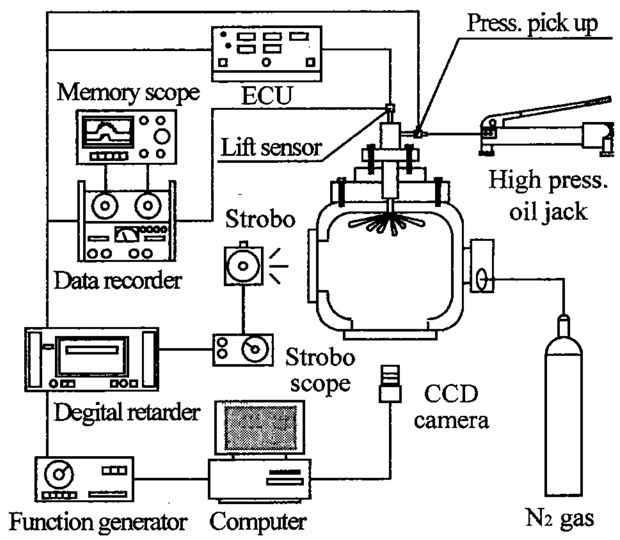

Fig.1 System for taking photos of the spray behavior

The engine was run at an idling speed of 950 rpm at an ambient temperature of 20°C. Fuel was injected at 10° BTDC under an injection pressure of 40 MPa. The pilot injection was offset from the main by 12° CA. To estimate the differences in combustion states in each cylinder, the THC emission was measured by a heated FID (Flame Ionized Detector) and an analysis of the exhaust gas components was performed by a gas chromatography.

Table 1 Specifications of the tested engine

Engine type	DI Diesel
Bore and Stroke	115 and 125 mm
Swept volume	7.8 liters
Compression ratio	16.8

3. Test result and discussion

3.1 Deviation in fuel spray behavior

Figure 2 shows examples of the spray configurations injected from the six nozzles with a pilot fuel quantity of 2mg and a regular idling fuel quantity of 10mg. It shows that the spray penetration for pilot fuel quantity is shorter than that for the idling fuel quantity because of the shorter injection duration and lower needle lift as indicated in Fig.3. However, the overall spray development pattern is very similar in both cases even with the different needle-lift. The maximum injection duration and needle lift of the pilot fuel quantity are only about a half the idling fuel quantity. This means that the spray configuration in the VCO nozzles depends strongly on the initial flow pattern of fuel around the needle valve seat which is influenced by an eccentricity of the needle valve[4].

Figure 4 shows average values and hole-to-hole deviation rates in the penetration of the six nozzles when changing the fuel injection mass. The nozzle-to-nozzle

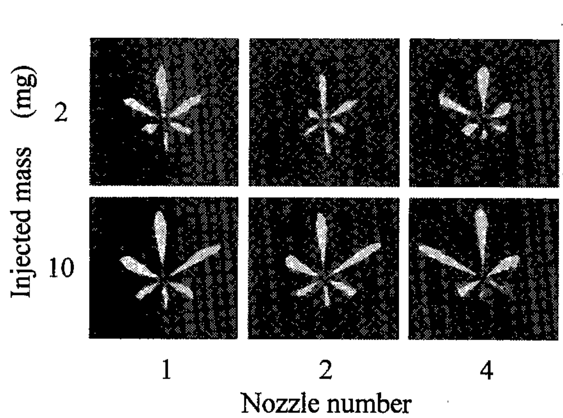

Fig.2 Effect of injected mass on the spray shape

deviations in average penetration (Fig.4-(a)) are not large for both the pilot and idling fuel quantities and remain within a range of ±5%, though the average spray penetration of the idling fuel quantity is about 1.5 times that of the pilot fuel quantity. Figure 4-(b) also shows that the hole-to-hole deviations in spray penetration are large with the pilot fuel quantity in all nozzles in comparison with that of the idling fuel quantity, and the highest deviation in nozzle No.3 is about 20% higher than the lowest one in No.5 nozzle. The difference in the needle lift behavior in each nozzle at the pilot injection is a possible reason for this deviation because the entrance of the hole is strongly throttled by the needle valve seat in the low lift nozzle. Especially with the VCO nozzle the throttling is different for the frontal and rear holes when the needle lifts eccentrically[5]. This may be the reason why the hole-to-hole and the nozzle-to-nozzle spray deviations in the pilot injection are large.

Figure 5 shows the variations in fuel mass injected from the six nozzles for different injection durations corresponding to the pilot and idling fuel quantities. It shows that the injected mass increases at approximately the same rate in each nozzle when increasing the injection duration. However, the fuel mass injected

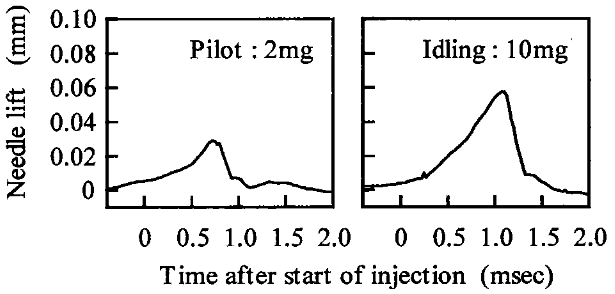

Fig.3 Needle lift with pilot and normal idling injection

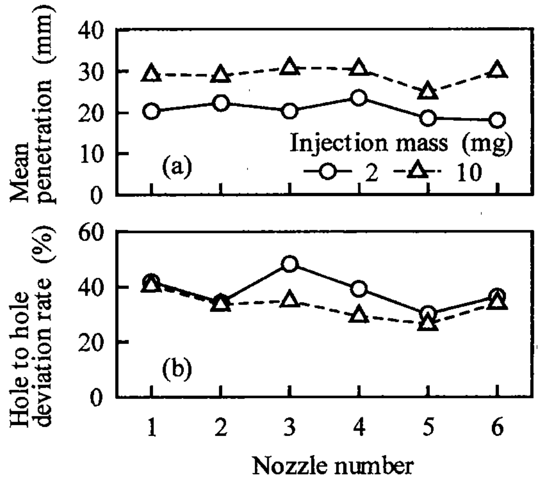

Fig.4 Nozzle-to-nozzle spray penetration and deviation with pilot and normal idling injection mass

from nozzles No.1 and 4 are the highest for all injection durations and about double that of nozzles No.3 and 6. It is reported that the injected mass varies with variations in the flow co-efficient[6], but the variations in injected mass observed in Fig.5 are too large for this explanation. It is considered that the variations in needle lift due to differences in nozzle opening pressure and fuel leakage from the magnetic valve of the electronic controlled nozzle causes the mass variations in each nozzle at the small quantity injection.

3.2 Deviations in THC emissions

Figure 6 represents the results of the THC emissions from the six cylinders under the injection conditions corresponding to Fig.4 and 5. It shows that when the pilot fuel quantity increases, THC emissions from all cylinders increase when compared to the condition without pilot injection. However, the cylinder-to-cylinder deviations in THC emissions with and without pilot injection show similar change even when there are large deviations in spray behavior and fuel quantities at the pilot injection. This means that there is no apparent correlation between the THC in each cylinder and deviations in the spray shape and injection mass. This suggests that there may be reasons other than injection behavior, for example deviations in the swirl ratio, carbon deposits in the combustion chamber, and the compression ratio. To evaluate these effects the following tests were conducted.

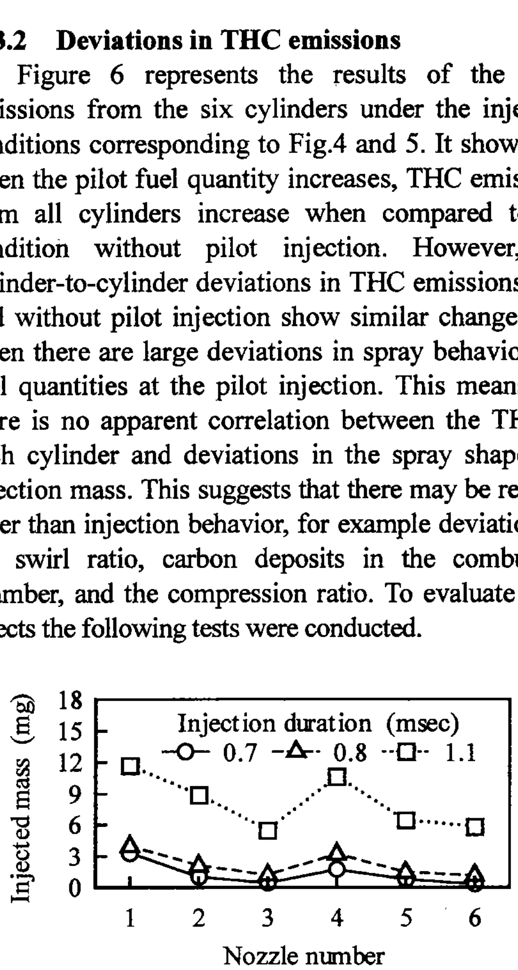

Fig.5 Nozzle-to-nozzle injected mass with pilot and normal idling injection

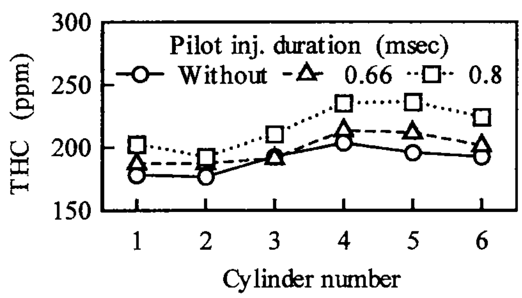

Fig.6 Cylinder-to-cylinder THC emissions with pilot and normal idling injection

Figure 7 shows the THC emissions in cylinder No.1 when the nozzles for all six cylinders were alternately attached to cylinder No.1, this is defined as "nozzle change", and the THC emissions in each cylinder when nozzle No.1 was attached alternatively to each of the cylinders, this is defined as "cylinder change". If nozzle-to-nozzle deviations in fuel injection behaviors are strongly reflected in the THC emissions, the THC deviations in the "nozzle change" condition when all the nozzles were successively used in cylinder No.1 have to be large. However, there are no significant deviations in the THC emissions both with and without pilot injection, as shown in Fig.7-(a). On the other hand, the THC deviations in the "cylinder change" condition when nozzle No.1 is successively used with all cylinders have to be small if there is no influence of the unique in-cylinder conditions. As shown in Fig.7-(b) there are significant cylinder-to-cylinder deviations in the THC emissions here.

Figure 8 shows combustion diagrams with pilot injection measured at cylinder No.1 with the six nozzles (Fig.8-(a)) and measured at each cylinder with nozzle No.1 (Fig.8-(b)). Figure 8-(a) shows that there are not clear variations in the combustion pressure and heat release rates, though there is a larger variation in the injection behavior of the six nozzles. However, when the same nozzle is used in all the cylinders, the variations in the combustion pressure are almost the same as "nozzle change", but the variations in the ignition delay and combustion duration from the heat release rate as shown in Fig.8-(b) are long about $\pm 1°$ CA compared with that in Fig.8-(a). Therefore it was concluded that in-cylinder conditions other than the injection behaviors have a significant effect on the deviations in THC emissions. One of the influential factors is a difference in carbon deposits near the combustion chamber wall. The quantity and position of accumulated carbon deposit differ in cylinder-to-cylinder and it influences the adsorption of injected fuel that leads to the THC emission(7). The in-cylinder gas flow is a complex phenomenon, though the effect of deviation in the gas flow on the THC deviation was investigated using the following method. In this test, the swirl ratio and turbulence strength in each cylinder were not measured, but the changes in in-cylinder gas flow among the cylinders would occur with and without an intake manifold(8). When the intake manifold is removed, the deviations in the strength of in-cylinder gas flow in each cylinder would be diminished because the flow direction to the port is uniformity for all cylinders.

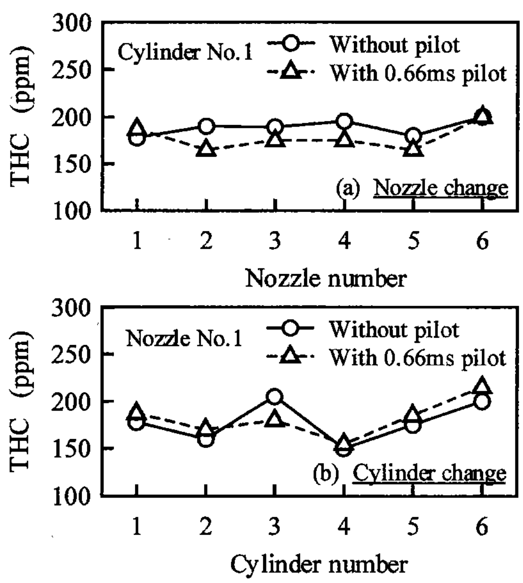

Fig.7 THC emissions with "nozzle change" and "cylinder change" at pilot and normal idling injection

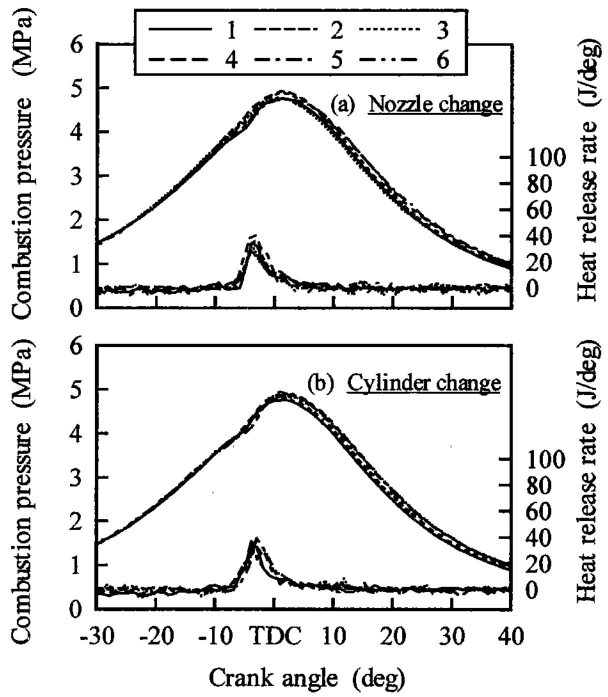

Fig.8 Combustion diagrams with nozzle change and cylinder change at pilot injection

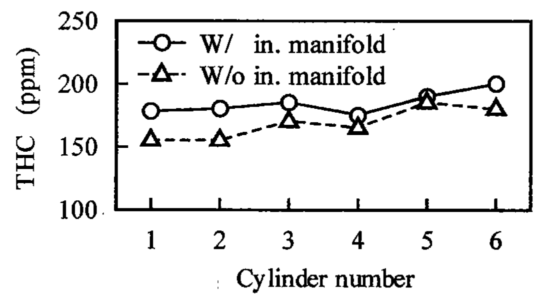

Fig.9 Cylinder-to-cylinder THC emissions with and without an intake manifold at idling

Figure 9 shows the THC emissions from each cylinder both with and without an intake manifold. The cylinder-to-cylinder deviations in THC emission are not very significant in both conditions, but the THC concentration without an intake manifold is lower in all cylinders even though the characteristic of the fuel injection is the same in both conditions.

Figure 10 shows combustion diagrams with and without an intake manifold. Here the ignition delay without an intake manifold is a little shorter, and the deviations are smaller than with the intake manifold. This is explained by the swirl deviations among cylinders diminishing without the intake manifold. If the deviations in the strength of gas flow such as the swirl ratio decrease, the deviations in fuel adhering to the combustion chamber wall during the ignition delay, which influences the THC emission, will also decrease. Thus the strength of gas flow is possibly an influential factor in the THC deviation among the cylinders(9).

3.3 Deviations in exhaust gas components

Figure 11 shows the combustion diagrams in each cylinder with and without pilot injection at the injection condition in Fig.5. The rate of heat release at the initial combustion without the pilot injection is larger than that with pilot injection, but the variation in ignition start and pilot combustion affecting the thermal decomposition is large with the pilot injection. Particularly, the No.4 cylinder which has a higher injected mass ignites early due to a stronger effect of the pilot injection. However, the THC emissions with and without pilot injection are not very different as shown in Fig.6.

Figure 12 shows the results of the gas chromatographic analysis of the exhaust gas with pilot injection sampled from each cylinder. The differences in the height of the carbon number peak are due to variations

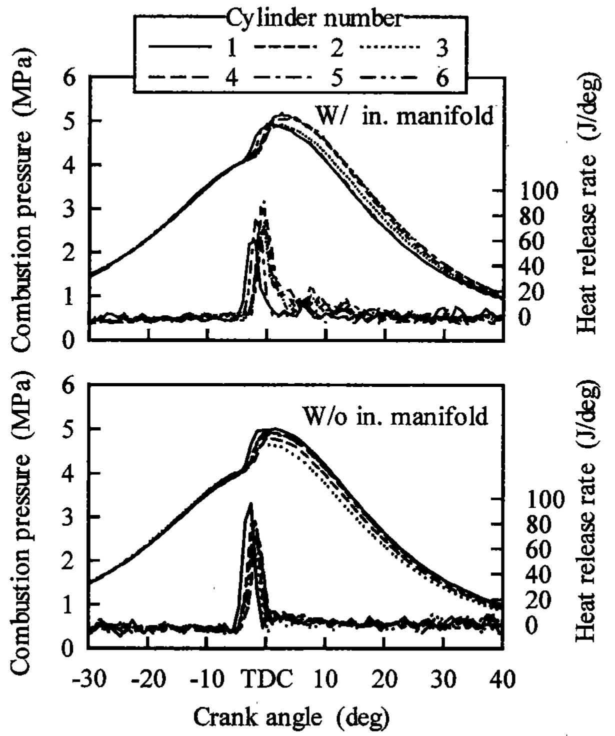

Fig.10 Combustion diagrams with and without an intake manifold at idling

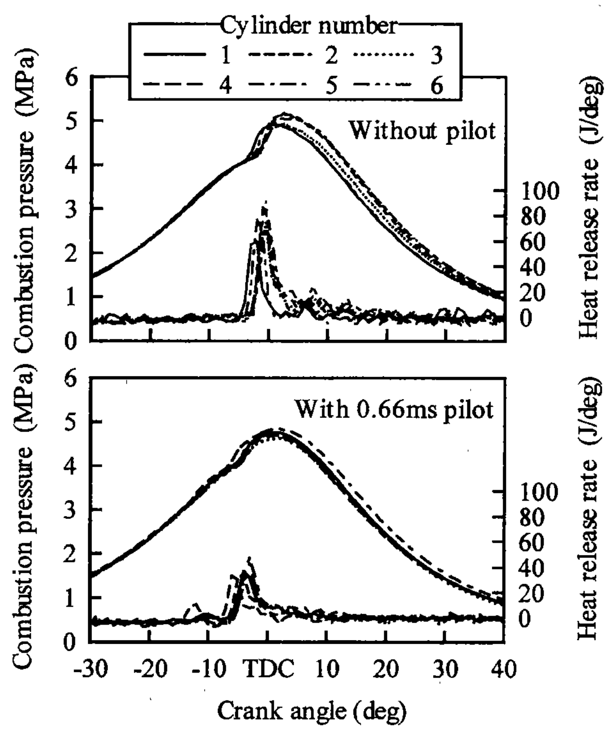

Fig.11 Cylinder-to-cylinder deviations in combustion diagrams with and without pilot at idling

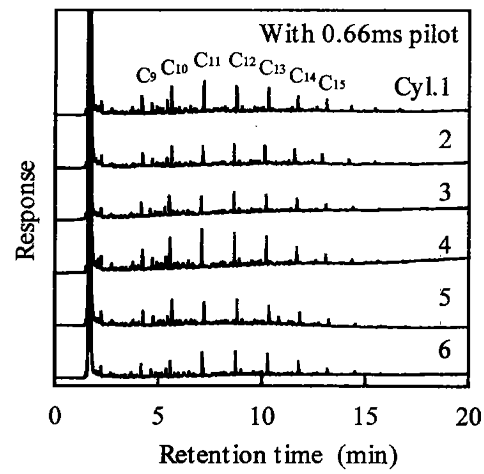

Fig.12 Gas-chromatogram of exhaust gas in the 6 cylinders with pilot injection

in thermal decomposition among the cylinders. The lighter HC components with a carbon number less than C_{12} in cylinders No.1 and 4 with a larger injected mass show a higher peak than the other cylinders because the thermal decomposition occurs at moderate combustion. Though cylinders No.1 and 4 have approximately the same pilot masses injected, the amount of light HC components, carbon number less than 12, is higher in cylinder No.4 than in cylinder No.1. In cylinder No.1 the effect of the pilot fuel is not clear from the combustion diagram, thus it may be considered that a part of the injected fuel decomposes into lighter HC components due to insufficient temperature for combustion. The pilot fuel injected into cylinder No.4 ignited early, and the main injection was injected into the flame, this main injected fuel will be engulfed with flames. Thus the fuel with less contact with fresh air at the moderate combustion temperatures decomposes to lighter HC components[10].

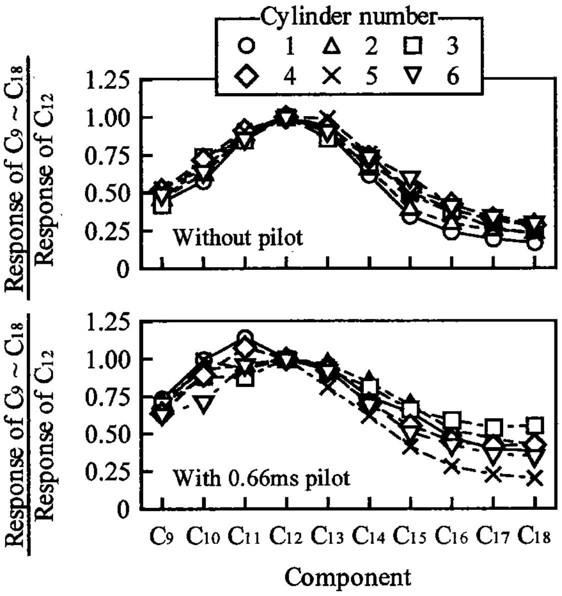

Fig.13 Cylinder-to-cylinder deviations in HC components with and without pilot at idling

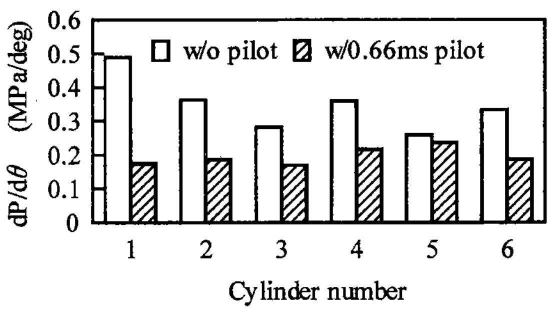

Fig.14 Cylinder-to-cylinder deviations in the rate of pressure rise with and without pilot at idling

Figure 13 shows the relative values of HC components to the peak value of carbon number 12 with and without pilot injection. This data shows the influence of combustion deviations on the HC components. Deviations in HC components with pilot injection are larger in the low and high boiling point components than that without pilot injection because the combustion state of injected pilot fuel is different in each cylinder even with the same THC. Therefore it is considered that the deviations in low boiling point components, a carbon number less than 12, is responsible for the increase in exhaust odor, and the deviations in high boiling point components are responsible for the SOF production[11].

Figure 14 represents the rate of pressure rise in each cylinder with and without pilot injection calculated from Fig.11. It is found that the cylinder-to-cylinder deviations in the rate of pressure rise and the deviations without pilot injection are large, and the rate of pressure rise with pilot injection decrease due to the shortening of the ignition delay of the main injection. However, the cylinder-to-cylinder deviations in the rate of pressure rise occur even with pilot injection. Therefore, the combustion deviations caused by deviations in spray behavior with pilot injection and in-cylinder conditions must be minimized to reduce engine noise, unstable engine operation, and odors from HC components in the exhaust gas.

4. Conclusions

The following conclusions may be drawn from the experimental results obtained in this study :

(1) Spray shape deviations with small fuel quantities such as the pilot injection are larger than that with the fuel quantity at normal idling. However, the spray pattern from 6 holes is approximately identical both with the pilot fuel quantity and idling fuel quantity. Because the spray pattern depends on the initial fuel flow at the needle seat and the hole entrance.

(2) Deviations in fuel injection factors correlate with the deviations in THC emissions but are not the dominant factor. Deviations in in-cylinder conditions such as carbon deposits and swirl ratios in the cylinders influence the deviations in THC emissions.

(3) Deviations in THC emissions with pilot injection are not large, but deviations in combustion and HC components in the exhaust gas are large. These deviations in the combustion and light HC components are thought to be responsible for the engine noise and exhaust odor.

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