Effects of Cylinder Temperature and Pressure on Ignition Delay in Direct Injection Diesel Engine

Soon-Ik Kwon, Masataka Arai and Hiroyuki Hiroyasu

Abstract

The purpose of this study is to investigate the effects of the mean cylinder temperature and pressure from the start of injection to ignition on ignition delay period in a D.I. diesel engine, and to clarify the difference in the ignition delay period between the engine and a constant volume bomb. The ignition delay period in the engine was measured by changing the following factors such as injection timing, engine speed, swirl ratio, injection quantity, nozzle opening pressure, nozzle hole diameter and piston cavity shape. The cylinder temperature was measured by a fine thermocouple with a compensation circuit under the motored condition. A single shot injection was adopted to reduce the residual gas from a previous cycle. Results are as follows:

Ignition delay period in the engine can be arranged with the cylinder temperature and pressure. The engine shows shorter ignition delay than the constant volume bomb. The difference in the ignition delay between them is mainly due to the existence of the piston cavity wall on which the fuel spray impinges.

Introduction

Fuel injected through a nozzle into the combustion chamber of a diesel engine is atomized, vaporized, and mixed with air. After that, combustion takes place there. During the combustion process, the period between the start of the injection and the first sign of ignition is called the ignition delay. The ignition delay is very important for close control of the combustion process, and therefore of the thermal performance and the gas emissions of the diesel engine. So many researchers have investigated the ignition delay process using engines, rapid compression machines and constant volume bombs.

In order to design the combustion system in a diesel engine, or to predict the engine performance, the relationship between the ignition delay and the cylinder temperature and the pressure of the engine must be understood. However, most previous studies had been started to discover the relationships between the ignition delay and engine operating parameters. So there was no allowance of a derivation of the direct relationship between the ignition delay and the physical parameters, such as cylinder temperature. Because it is still very difficult for engine researchers to define the cylinder temperature at the ignition timing.

The previous studies in obtaining ambient temperatures in cylinders are as follows: Lyn et al. have measured cylinder temperatures at the injection timing using a fine wire resistance thermometer under motoring conditions, and have calculated the temperature at the ignition timing. They used the cylinder temperature at the ignition timing as a representative value for the ignition. Henein et al. have obtained mean cylinder gas temperatures during the ignition delay period. The temperature was calculated from the mass, volume and pressure by using the equation of state. Tsao et al. have measured cylinder temperatures at the injection timing by the null method utilizing an infrared technique. From the cylinder pressure, the temperature at the ignition timing has been calculated by Hamamoto et al.
used. Methods which calculate the temperature from the pressure and volume in the cylinder require the exact measurement of the cylinder pressure. As for using a thermocouple to measure the cylinder temperature, its response delay should be regarded, even if it is a fine one. So the output of the thermocouple needs some compensation. Lower in the aspect of accuracy and easy utilization, thermocouples are more convenient in deriving the cylinder temperature rather than the calculation method.

The purpose of this study is to clarify, not only the effects of engine operation conditions, but also the effects of physical conditions such as the cylinder temperature and pressure on the ignition delay period. A fine thermocouple with the output modified to compensate for the response delay, was used to measure the cylinder temperature. The ignition delay was measured by changing the injection timing, injection quantity, swirl ratio, piston cavity shape and nozzle hole diameter, and was expressed as a function of the mean cylinder temperature during the ignition delay period. The difference between the pressure rise delay and the illumination delay was clarified. Also the difference of the ignition delay in the engine and the constant volume bomb was investigated by clarifying the wall effect of the combustion chamber.

2. Experimental Apparatus and Procedure

2.1 Ignition Delay Measurement

The engine used was a single cylinder D.I. diesel engine of 135mm bore and 130mm stroke. The main specifications of the engine are listed in Table 1.

A schematic diagram of the experimental apparatus, including the engine and measuring system, is shown in Fig.1.

A single injection system was adopted to reduce any residual gas from previous combustion cycles. This system consisted of a dummy nozzle and its controller. The valve opening pressure of the dummy nozzle was lower than that of the main nozzle in the motoring cycle. When the fuel was to be injected, the driving power pulse through the control circuit, which was synchronized to the injection period, was supplied to a solenoid in order to increase the opening pressure of the dummy nozzle. Then the opening pressure of the dummy nozzle became higher than that of the main nozzle, and the compressed fuel was injected through the main nozzle.

In order to change the cylinder temperature, the intake air was heated from room temperature up to 533K by using an electric heater. The test fuel used was diesel fuel No.2.

Both the pressure rise and the illumination delay periods were measured as ignition delays. The pressure rise delay was determined by the

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
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<tr>
<td>Type</td>
<td>1-Cylinder Water Cooled 4 Cycle D.I. Diesel Engine</td>
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<tr>
<td>Bore x Stroke</td>
<td>135 x 130 mm</td>
</tr>
<tr>
<td>Total Volume</td>
<td>1860 cc</td>
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<tr>
<td>Clearance Volume</td>
<td>128.3 cc</td>
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<td>Cavity Volume</td>
<td>110.3 cc</td>
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<tr>
<td>Compression Ratio</td>
<td>15.5 : 1</td>
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<td>Valve Timing</td>
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<td>Inlet Valve Open Close</td>
<td>17° BTDC</td>
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<tr>
<td>Exhaust Valve Open Close</td>
<td>35° ABDC</td>
</tr>
<tr>
<td>Injection Pump</td>
<td>Bosch AD Type (Plunger Dia 10 mm)</td>
</tr>
<tr>
<td>Nozzle</td>
<td>DLL160 S 254 (Dia 0.25mm 4 Holes)</td>
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Fig.1 Schematic Diagram of Experimental Apparatus
period between the start of the injection monitored on a needle lift and the rapid pressure rise timing on the pressure curve. The illumination delay was defined as the period between the start of the injection and the first appearance of a flame. The needle lift was detected by a light cutting type detector which was installed in the nozzle holder. The illumination signal due to the flame was detected by a photo transistor (TOSHIBA TPS 603, Detectable Angle: 120 degree) which was mounted in a water cooled adapter. The location and the detectable range of the photo sensor installed are shown in Fig.2.

2.2 Temperature Measurement
The cylinder temperature was measured by a 50 μm diameter Chromel-Alumel thermocouple with a compensation circuit. This thermocouple was inserted into the piston cavity as shown in Fig.2.

The location for the temperature measurement was determined after noting the predicted point of the ignition and the point which was the least effected by the heat transfer from the cylinder wall. The compensation circuit with an operation amplifier was designed to compensate for the first order time lag due to the thermal inertia of the thermocouple [1]. The fundamental equation of the compensation circuit was expressed as

\[ T_{g} = T + T \left( \frac{dT}{dt} \right) \]

where:
- \( T_{g} \) gas temperature in the cylinder
- \( T \) thermocouple output without compensation
- \( T \) time constant of the thermocouple
- \( t \) elapsed time

The schematic diagram of the compensation circuit, which consists of a differential circuit and an adding circuit, is shown in Fig.3.

A key factor in the design of the compensation circuit was in determining the time constant: \( T \) in compensating for the time lag. When the location of the thermocouple was near the cylinder wall, the maximum temperature under a motored condition appeared before the TDC due to heat loss through the cylinder wall. When the location of the thermocouple was in the center of the cavity as shown in Fig.2, the maximum temperature was recorded at the TDC. So the method in which the time constant in the circuit was determined as the maximum point of the compensated temperature found at the TDC, was examined in the first step of this study.

To confirm the time constant that would be obtained by the method mentioned before, it was compared with another time constant obtained by the following methods. The apparatus for measuring the response delay of the thermocouple was made as shown in Fig.4.

The tip of the thermocouple (3) was moved in and out of a cylindrical pipe using a motor and crank mechanism (2). The air stream in the cylindrical pipe was heated by an electric heater (6). The response delay time between the time when the tip of the thermocouple reached the maximum temperature point of the air stream in
the cylindrical pipe, and the time when the output showed a peak temperature, was measured by an oscilloscope (4). In this case, the maximum temperature in the air stream was 473K. The speed of the motor was 600 rpm. In this condition, the measured response delay time of the thermocouple was about 26 ms. The response delay for the motoring engine was calculated by the following Scadion and Worshowsk's equation, neglecting the air movement in the cylinder.

\[
\frac{\tau_2}{\tau_1} = \left( \frac{P_1}{P_2} \right)^{\frac{v_1}{v_2}} \left( \frac{T_1}{T_2} \right)^{\frac{v_1}{v_2}}
\]

(2)

Comparing curves (A) and (B), which have different time constants, the respective differences of the time and temperature were 0.77 ms (47°C) and about 18°C at most. These differences were so small as to need no more compensation in analyzing any temperature effects on the ignition delay. So the compensated temperature shown as (A) was adopted as the cylinder temperature in this experiment.

2.3 Modified Combustion Chamber

To investigate the effects of the cavity wall on the ignition delay, the original combustion chamber (a) of a toroidal type and a modified flat type combustion chamber (b), as shown in Fig. 6, were used. The diameter of the cavity of the modified combustion chamber was changed by keeping the same compression ratio as the original combustion chamber.

2.4 Constant Volume Bomb

The ignition delay in a constant volume bomb with an electric furnace was measured as compared with that in the engine. Figure 7 shows a schematic diagram of the constant volume bomb. A fan was used to circulate the air to achieve a uniformity of the ambient temperature. In order to investigate the effects of the cavity wall, a dummy piston cavity was set into the bomb. The
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ignition delays of a free spray without the wall) and an impinged spray with the wall) were measured. The ambient temperature in the dummy piston cavity was measured at the center of the cavity using a Chromel-Alumel thermocouple: Fig.7(b)). In the case without the wall, the temperature was measured at a position as shown in Fig.7(a).

2.5 Experimental Procedure to Determine the Ignition Delay in the Engine

It was very difficult to determine the ignition delay and cylinder temperature at the ignition in the same combustion cycle, because the thermocouple could not be inserted in the combustion chamber when the engine was in a firing condition. Then a method that determined the cylinder temperature from the motoring condition was adopted in this study. The experimental procedures to determine both the ignition delay and the temperature were as follows:

:Step 1) The thermocouple was inserted into the cylinder. Both the cylinder temperature through the compensation circuit, and the cylinder pressure were recorded with the crank angle under motoring conditions.

:Step 2) The thermocouple was removed and a photo sensor was inserted as shown in Fig.2(b). The ignition delay was measured after the fuel was injected under the same engine conditions when the temperature was measured.

(Step 3) The temperatures during the ignition delay period were obtained. The representative temperature was the arithmetic mean value of the temperature at the injection timing and that at the ignition timing. Any change of the cylinder temperature caused by evaporation of the injected fuel was neglected.

:Step 4) The cylinder pressure, when the representative temperature appeared, was obtained from the pressure curve.

:Step 5) The relationship between the temperature, pressure and ignition delay was obtained.

3. Experimental Results

3.1 Comparison of Compression Temperature

The compression temperatures (the cylinder temperature at TDC) were obtained using the following two methods. One value of the compression temperatures was obtained by a thermocouple with a compensation circuit. The other value was calculated from the cylinder pressure using Eqs.(3) and (4).

\[ PV_{m}^{m-1} = C \]  
\[ T_{c} = T_{i} \left( \frac{V_{i}}{V_{c}} \right)^{m-1} \]  

where, \( T_{c} \) and \( V_{c} \) are the temperature and volume and \( T_{i} \) and \( V_{i} \) are the known temperature and volume at any crank angle.

To obtain the calculated temperature from Eq.(4), the inlet air temperature or cylinder temperature at the start of the compression stroke was ordinarily usually used for \( T_{i} \) The compressi
on temperatures obtained by various methods are shown in Fig 8 as functions of the intake air temperature at the intake manifold. Both the temperature (A) measured by the thermocouple and the calculated temperature (B) based on the cylinder temperature which was measured by a thermocouple at the start of the compression stroke, were found to be almost in agreement under 600rpm. However the temperature (C) calculated by the inlet air temperature was higher than the two former temperatures (A) and (B). in the high intake air temperature region. This difference would be explained as follows: If the inlet air temperature was higher than the cooling water temperature, the cylinder temperature at the start of the compression stroke became lower than the inlet air temperature due to heat loss to the cylinder wall. However, this temperature drop was ignored in calculating the temperature (C).

The compression temperature at 833rpm is higher than that at 600rpm because the heat loss decreased upon increasing the engine speed. For a speed of 833rpm, the measured temperature (A) was higher than the temperature (B) calculated by the cylinder temperature at the start of the compression stroke. This is because the calculated temperature was the spatial mean of the cylinder temperature but the measured temperature was the temperature at the center of the piston cavity.

From the results of these examinations, the differences between the measured temperature (A) and the calculated compression temperature (B) obtained by using the cylinder temperature were small. Because the measured temperature (A) and the calculated temperature (B) were almost the same and both the indicated temperatures were considered proper values, the method using a thermocouple with a compensation circuit could be always available as a means to determine the temperature in the cylinder. So this method was used to obtain the temperature during the ignition delay period.

3.2 Relationship between the Cylinder Temperature and Ignition Delay

The pressure rise delays at different injection timings under various engine speeds are shown in Fig.9.

The ignition delays are expressed as an Arrhenius's expression. There were slight differences between the ignition delays obtained at the injection timing 10 BTDC and 20 BTDC. However, the ignition delay at 6.5 ATDC was longer than those at 10 BTDC and 20 BTDC. Figure 10 shows the pressure rise delays at the 600rpm and 833rpm at the injection timing 10 BTDC. In general, the engine speed had a major effect on the ignition delay, because the cylinder temperature and pressure were changed according to a change of the engine speed. At the same time, the effect of the engine speed on the ignition delays under the same cylinder temperature was small as shown in Fig.10.
3.3 Relationship Between Pressure Rise Delay and Illumination Delay

The pressure rise delay and the illumination delay at the representative temperatures 700K and 850K were selected from the experimental data under various injection timings and are shown in Fig.11.

The solid line and dotted line respectively indicate the pressure rise delay and illumination delay. The difference of the two ignition delays obtained at the injection timing advanced earlier than 10 BTDC was small. However, if the injection timing was delayed later than the TDC, the pressure rise delay was longer than the illumination delay. For the injection timing earlier than the TDC, the cylinder pressure after ignition rose rapidly, while the combustion pressure caused by an injection later than the TDC rose slightly. It is considered that a cool flame that did not release heat might appear, and the effective sensitivity of the pressure detector became weak according to a pressure drop caused by the downward movement of the piston. Then there was a bit of time lost until the pressure rise was detected.

Figure 12 shows the pressure rise delay and the illumination delay for an injection timing later than the TDC under the mean cylinder pressure 2.5MPa. The pressure rise delay was longer than the illumination delay. Especially the difference of the two ignition delays was large in a low ambient temperature.

Figure 13 shows the pressure rise delay for the injection timing after the TDC and before the TDC under the cylinder pressure 2.5MPa. The ignition delay for the injection timing after the TDC shows a longer delay than that for the injection timing earlier than the TDC under the same cylinder temperature. This is because the formation process of the combustible mixture was different when the cylinder temperature and the pressure were rising or dropping with the movement of the piston. The luminance from the flame could be caught instantly, but time was needed to
detect an increase of the cylinder pressure because the ignition took place under the condition of decreasing pressure caused by the downward movement of the piston.

Figure 14 shows the illumination delays for the injection timings after the TDC and before the TDC. The difference of illumination delays for these injection timings was small. Further that difference was smaller than that of the pressure rise delay. Consequently, if the ignition delay was defined by using an illumination delay, the difference of the ignition delays for the injection timings after and before the TDC was very small, and the ignition delay itself was not influenced by the motion of the piston.

The pressure rise delay and the illumination delay had been compared under the same temperature. However the pressure rise delay was usually measured in the engine as the ignition delay period. Therefore we used hereafter the pressure rise delay as the ignition delay.

3.4 Effects of Engine Operating Condition-

The ignition delays under various engine speeds but the same cylinder temperature are shown in Fig.15.

The cylinder pressures during the ignition delay period were different according to the engine speed, but the effects of engine speed on the ignition delay were very small when the cylinder temperature was kept the same.

Figure 16 shows the effects of engine speed on the ignition delay. The data in parentheses in the figure mean the ambient conditions during the ignition delay periods. It was not possible to compare the 520rpm and 600rpm because the same cylinder pressure and temperature could not be set at another engine speed. However the
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The effect of the engine speed on the ignition delay was small under almost the same cylinder temperature and pressure during the ignition delay period. Figure 17 shows the effects of the injection timing on the ignition delay under the same representative temperature. The dotted line means the ignition delay for the same cylinder pressure during the ignition delay period, and the solid line means the ignition delay for the same temperature. When the injection was started at around 10BTDC, the ignition delay was the shortest. The ignition delay became longer when the injection timing was earlier or later than 10BTDC. The effect of the cylinder pressure on the ignition delay for the injection timings during 5 - 25BTDC was small under the same temperature. The ignition delays under the same temperature and pressure are shown in Fig.18. These data were picked up from Fig.17. The ignition delay for the injection timing after the TDC was longer than that before the TDC, because the formation process of the combustible mixture was different when the cylinder temperature and pressure were rising or dropping as explained in Fig.13.

Figure 19 shows the relationship between the ignition delay and an air swirl ratio which was derived from a steady flow test rig. The effect of the air swirl ratio was small on the ignition delay under the same temperature.

The effect of the injection quantity on the ignition delay under the same temperature and pressure is shown in Fig.20. Even if the injection quantity was changed, the difference in the ignition delay was small under a high cylinder temperature. However the ignition delay increased...
when the injection quantity was increased under a low cylinder temperature. In the case of a long ignition delay, the cylinder temperature was affected by evaporation of the injected fuel. Then the effect of the injection quantity on the ignition delay became large under a low cylinder temperature.

Figure 21 shows the ignition delays for various nozzle opening pressures under the same temperature. The ignition delay decreased until the opening pressure increased up to 25Mpa. Further as the nozzle opening pressure increased beyond 25Mpa, the ignition delay was increased. A change on the pattern of the injection rate affected by the nozzle opening pressure and also a change of the mixing process affected by the injection speed were considered as the reasons for this change of the ignition delay.

Figure 22 shows the relationship between Nozzle hole diameter and the ignition delay. The number of nozzle holes was also changed to keep the same rate of injection fuel in the engine. The nozzle hole diameter affected the atomized phenomenon of the spray, but this effect on the ignition delay was small under the same temperature condition.

3.5 Effect of Distance between Nozzle and Modified Piston Wall

The five types of pistons shown in Fig.6 were used to investigate the relationship between the ignition delay and the distance from the nozzle to the cavity wall. The results are shown in Fig.23. The relative direction and position of the sprays in the cavity are shown in Fig.24. At an injection timing of 10 BTDC, the effect of the distance on the ignition delay was small under the same temperature condition. However the cavity with a
small diameter showed a little longer ignition delay than the others at low cylinder temperatures. This occurred because the spray impinged the cavity wall before it was incompletely atomized, and it did not sufficiently mix with the air. On the other hand, the ignition delay in the cavity with a large diameter was shorter than that in a small cavity because a large amount of air was entrained in the spray and it promoted a better mixing of the spray with the air.

The original piston showed a shorter ignition delay than the other modified pistons under low ambient temperatures. The modified piston showed a longer ignition delay than the original piston for the injection timing 30BTDC. However, the modified piston showed a shorter ignition delay than the original piston and the modified piston. This is because the spray which impinged the cavity wall of the original piston became a mixture suitable for ignition due to the heat transfer from the high air temperature during the spray sweeping along the cavity wall. The ignition delay of the spray was affected by impingement to the piston wall which was moving during the ignition delay period.

3.6 Comparison of the Ignition Delay between Engine and the Constant Volume Bomb

Figure 25 shows the relationship between the ignition delay in the engine and the constant volume bomb under the same temperature and pressure conditions. The ignition delay in the bomb was measured under the conditions both with and without wall. At first the ignition delay of the free jet in the bomb was compared to that in the engine. The injected fuel was impinged to the piston wall in the engine, but the spray in the bomb was injected like a free jet. The difference of the mixing processes of both the sprays caused the difference of the ignition delays. Comparing the two ignition delays, the effect of the piston wall was small in the high temperature region, but was large in the low temperature region. It is considered that the spray which impinged the piston cavity wall formed a better mixture with the air.

Next the ignition delays in the engine and in the bomb with wall were compared. The difference of both the ignition delays was small. This difference can be explained as follows: The temperature in the engine was the mean temperature during the ignition delay period, but the temperature in the bomb was a constant temperature.
rature. Then the effective temperatures for both the sprays were different even if the representative temperatures were the same.

The sharp bend in the line that expresses the ignition delay appears in all cases as shown in Fig. 25. This always occurs about 715K. The dominant factor of this change was considered to be the temperature itself. The dependence of the temperature on the ignition delay was large in low ambient temperatures due to the slow reaction, and the ignition delay was dominated by chemical factors. However, in a high ambient temperature, the temperature dependence for the ignition delay was not so strong, because the ignition delay was controlled by physical factors such as the heating and evaporating.

3.7 Experimental Equation in Ignition Delay

In Fig. 25, the difference of the ignition delays at both the representative cylinder pressures, 2.5 MPa and 3.0 MPa in the engine was small if the cylinder temperatures were the same. After all, any effects of the cylinder pressure were found to be small on the ignition delay. Accordingly for consideration of this point, the empirical equations (5) and (6) between the ignition delay and the temperature were derived for the pressure range indicated below.

For 2.5 MPa ≤ P ≤ 3.0 MPa

\[ T ≥ 715K \Rightarrow \Delta T = 5.23 \times 10^{-2} \exp\left(\frac{2780}{T}\right) \quad (5) \]

\[ T < 715K \Rightarrow \Delta T = 2.16 \times 10^{-4} \exp\left(\frac{6710}{T}\right) \quad (6) \]

where, T : mean cylinder temperature for ignition delay (K)

P : mean cylinder pressure for ignition delay (MPa)

4. Conclusion

The ignition delay in a D.I. diesel engine was determined by using the pressure rise delay and the illumination delay. The cylinder temperature was measured using a fine thermocouple with a compensation circuit. The relationship between the ignition delay and the physical factors such as cylinder temperature and pressure was clarified. The ignition delay in the engine was compared with that in the bomb under the same conditions. The following conclusions were obtained.

(1) Ignition delay in the engine can be expressed as an Arrhenius expression, and can be shown by a straight line with a sharp bend point.

(2) The difference of the pressure rise delay and the illumination delay is small for the injection timing before the TDC. But for the injection timing after the TDC, the pressure rise delay becomes longer than the illumination delay.

(3) The effects of engine speed, swirl ratio, injection quantity and nozzle hole diameter on the ignition delay are small.

(4) The difference of the ignition delays in the engine and in the bomb without wall under the same temperature, is mainly due to the existence of the piston cavity wall. However the effect of the distance from the nozzle to the piston cavity wall on the ignition delay is small.

Acknowledgments

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**Discussion**

M. KAWAKAMI (Niigata Engineering Co. Ltd.)

(1) In this study, the temperature drop by the injected fuel was neglected in the representative temperature obtained during the ignition delay period. But I think that the temperature drop should not be neglected when a large amount of fuel is injected. Figure 20 shows that the ignition delay increased at 700K with an increase of the injection quantity. Could you tell me the relationship between the ignition delay and the temperature drop, if you had indeed measured the temperature drop?

(2) The compression temperature at the TDC was calculated by using Eq.(5). How did you obtain the temperature at the inlet valve closing? And how did you determine the polytropic index m when you calculated the compression temperature at the TDC under 600rpm and 833rpm.

(3) The reason that the ignition delay became longer, when the nozzle opening pressure was higher or lower than 25MPa, was explained by a change of the injection rate pattern and the mixing process. Could you tell me the data of the injection rate and the injection velocity of the fuel, if you had actually measured them?

Authors's reply

(1) The temperature drop caused by a large amount of injected fuel was larger in the low temperature than in the high temperature as you indicated. But the temperature drop was not measured. However the temperature which dropped by evaporation of the fuel would be recovered somewhat at the ignition timing, because the ignition delay was defined by the period from the start of the injection to the rapid pressure rise timing.

(2) The temperature at the inlet valve closing was obtained by the compensated temperature (A) in Fig.5 which was used in this study. The polytropic index was obtained by Eq.(4), using the pressures and volumes at the inlet valve closing and the TDC timings. The value used for the polytropic index was the calculated average polytropic index.

(3) The injection rates of the various nozzle opening pressures are shown in Fig.A. The ignition delay at the opening pressure 32MPa became longer because the initial injection quantity was very small. At the nozzle opening pressure 13MPa, as an explanation for Fig.20, the ignition delay became longer due to the large injection quantity in the low cylinder temperature. The injection velocity of the spray was not measured.

S. NAKAMURA (NKK Co.)

(1) Measurement Method

A. Measuring the true temperature in the compression stroke of a diesel engine with a high response is very interesting. What do you think about the accuracy of the cylinder temperature measured by the thermocouple with a compensat-
ion circuit of the first time lag?

B. The photo transistor was used to detect the illumination delay. By that photo-transistor, how wide a range of wavelength can the illumination be detected? Can it detect the cool flame mentioned in your report? The position of the photo-transistor is not exactly shown in Fig.2(b). Its position can be considered to be set to detect the first illumination of flames occurring in the four sprays in the cavity. Is this true or not?

(2) Ignition Delay

A. I have a great interest in the investigation of ignition delay under unsteady conditions, such as engine combustion. The ignition delay changed with a change of the injection timing, even if the cylinder temperature was the same (for example, Fig.11). Then can the parameter $\tilde{\theta}$ be contained in Eqs.(7) and (8)?

B. The difference between the illumination delay and the pressure rise delay is large in low cylinder temperature conditions. In this study the explanation for this reason was that the cool flame might appear under a low temperature condition. But can it be explained as follows? The difference of the ignition delay for the four sprays in the cavity occurs, and further more, the flame development became slower with a decrease of the temperature. Then the period during which the cool flame could be detected became longer.

C. I think that the spray was ignited after having impinged the piston cavity wall under a low temperature condition. At that time, the long interval between the injection and the ignition caused a well mixed mixture in which the knock might have occurred. Did you detect a phenomenon such as a knock? Additionally did you get any scattering of the ignition delay? Please tell me the scattering of the ignition delay due to the time and space under the low cylinder temperature condition.

Authors's reply

(1) Measurement Method

A. The difference between the compensated temperature (A) used in this study and the compensated temperature (B) obtained by using the response delay derived from Eq.(2) was about 18 C at most.

B. The wavelength detectable by the photo-transistor covers the range from 460nm to 1000nm. The photo-transistor used in this experiment can detect a flame anywhere within the cavity.

(2) Ignition Delay

A. Including the parameter of pressure in the empirical equation is more reasonable than that of the injection timing, because a change of the ignition timing means a change of the temperature and pressure within the cylinder. But in our empirical equation, the cylinder pressure did not need to be included because the change of the cylinder pressure was small.

B. We are also of the same opinion as you.

C. A phenomenon such as a knock was not detected. No scattering of the ignition delay period was observed. The position of the ignition could not be observed because the ignition phenomenon in the cylinder was not visualized.

N. ISSHIKI (Nihon Univ.)

The main point of this study is how to compensate for the response delay time of the thermocouple. Equation(2) was applied under conditions where there were some pressure fluctuations $dp/dt$ ($dp/dt > 0$ before the TDC and $dp/dt < 0$ after the TDC). What confidence do you have of the method being used under those conditions?

Authors's reply

(1) The measurement of the cylinder temperature, especially the compensation of the response delay time is an important and a difficult problem just as you indicate. Therefore we used the apparatus to measure the response delay, but we did not consider the term of the $dp/dt$. Errors caused by a change of the pressure are small, because the pressure change at the injection timing was not so large as to make large temperature changes.