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Effects of Pilot Injection with a Single Fuel Nozzle on a Direct Injection Diesel Engine*

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We studied the effects of double injection by a single nozzle on fuel consumption and noise level of a single cylinder 4-stroke direct injection diesel engine. It was observed that, within a certain range of fuel quantity of pilot injection, the combustion noise was reduced considerably. This range of the fuel quantity depends on the timing of the pilot injection.

In view of the fuel consumption, it was found desirable to inject pilot fuel at the end of exhaust stroke of the previous cycle or just before the main injection.

Furthermore, a thermodynamic analysis was made to explain qualitatively the mechanism of the effects of pilot injection.

1. Introduction

It is well known that a rapid pressure rise and a loud combustion noise in a diesel engine arise from a rapid heat release in the early stage of combustion. A considerable amount of research has been made about the effects of pilot injection in order to reduce this rapid pressure rise. It appears, however, that the primary goal of the early researchers was to determine the effects of pilot injection on engine performance rather than a detailed study of the cause which gives rise to the observed effects. Therefore, the actual mechanism of pilot injection is not fully understood.

We studied the effects of the timing and quantity of pilot injection with a single fuel nozzle on the performance of a direct injection diesel engine. From our study, it was found that if the timing and quantity of pilot injection were adequate, good results could be obtained.

Furthermore, a thermodynamic analysis was made to explain qualitatively the mechanism of the effects of pilot injection.

2. Apparatus and experimental technique

Specifications of a test engine are as follows:

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A single cylinder, water cooled, 4 cycle direct injection diesel engine.

Output/engine speed 16PS/900 rpm

Bore and stroke $140\phi \times 200$ mm

Compression ratio 17.4 : 1

Fuel injection nozzle nozzle with 4 holes

Injection valve opening pressure 200 kg/cm²

Main injection valve opens at 10 deg BTDC

Main injection valve closes at 1 deg BTDC

Valve timing

Intake valve opens at 370 deg BTDC

Intake valve closes at 150 deg BTDC

Exhaust valve opens at 135 deg ATDC

Exhaust valve closes at 350 deg BTDC

Cooling water temperature 100°C

Fuel Commercial heavy oil A

Specific gravity 0.879 g/cm³ (at 15°C)

Cetane number 47

Flash point 73°C

ASTM distillation

10% point 225°C

50% point 285°C

80% point 330°C

Figure 1 shows intake and exhaust valve timing. A schematic diagram of the arrangement of the engine instrumentation is shown in Fig. 2. As seen in Fig. 2, two injection pumps were coupled together to deliver the main and pilot fuel to a single injection nozzle. The injection timings of the two pumps could be set at an arbitrary crank angle independently. The fuel injection rates were measured by the long pipe method of W. Bosch. Strain gauge transducers in conjunction with amplifier-calibrator units were

used to measure the gas pressure inside the combustion chamber and the fuel pressure in the fuel pipe just before the nozzle holder.

The needle lift of the injection nozzle was measured by use of a photo-transistor pickup. Combustion noise level was measured by a microphone which was set 20 cm distant from the crankcase. The output of the microphone could be displayed on an oscilloscope screen through an electric filter. Experiments were conducted at constant load and speed of the engine. The amount of pilot fuel was progressively increased and that of the main fuel was simultaneously decreased.

3. Experimental results and discussion

In Fig. 3, the specific fuel consumption for various pilot injection timings is plotted versus the pilot fuel amount/cycle. Indeed the specific fuel consumption remains almost the same as with normal single injection when pilot fuel is injected at 15 deg BTDC. But the more advanced the pilot injection timing gets,

Fig. 1 Valve timing of test engine

Fig. 2 Engine installation

the more the specific fuel consumption increases, reaching a peak between 90 and 270 deg BTDC. However, if the pilot injection timing is so advanced as to be at 360 deg BTDC, the specific fuel consumption will recover its economical level. Some of the pilot fuel injected from the 4-hole nozzle reaches directly the cylinder wall and sticks there as it is unburned. The deterioration of specific fuel consumption observed when the pilot injection timing is set between 90 and 270 deg BTDC, that is, when the piston is off top dead center, seems to be attributed to the outflow of the unburned fuel into the crankcase. In fact, a dilution of lubricating oil in the crankcase was observed after a long period of engine running under this condition. On the other hand, with pilot injection at 360 deg BTDC, the pilot fuel is injected into the piston cavity and does not flow away into the crankcase.

Figure 4 shows the characteristics of the test engine when the pilot fuel is injected at 45 deg BTDC. This figure indicates that the injection of a proper amount of pilot fuel is followed by a decrease of maximum rate of pressure rise, a decrease of combustion noise level, and an increase of specific fuel consumption. The temperature and smoke concentration of exhaust-gas increase. It seems that the former is caused by the prolonged afterburning period of main fuel and the latter comes from the larger proportion of main fuel which has been injected into hot flame.

Figures 5(a)~(c) show in what manner the quantity of pilot fuel affects the rate of heat release which is calculated from the pressure diagram when pilot fuel is injected at 19, 29 and 39 deg BTDC. In case of single injection, as shown in Fig. 5(a), the heat release rate makes a striking peak at 3 deg BTDC. By injecting pilot fuel at 12 mg/cycle, this peak can be reduced to almost nothing, and replaced with another made by pilot injection at 10 deg BTDC.

Main injection: 10 deg BTDC, Engine speed: 800 rpm

Fig. 3 Effect of the pilot fuel quantity on specific fuel consumption

By increasing pilot fuel injection to 30 mg/cycle, the value of this peak of heat release rate of pilot fuel becomes the same as in the case of normal single injection. Figure 5(b), with the pilot injection at 29 deg BTDC, shows that the way the peak heat release rate of main injection decreases by the action of pilot injection is the same as in Fig. 5(a) except that the rate is remarkably high when pilot fuel is injected at 30 mg/cycle. With pilot injection at 39 deg BTDC, as shown in Fig. 5(c), the peak of heat release rate of pilot fuel appears at 20 deg BTDC. Even when pilot fuel is injected at 30 mg/cycle, the heat release rate of pilot fuel will not climb so high as in the case of Fig. 5(b).

Figure 6 shows the relation between pilot fuel quantity and noise level for various timings of the pilot injection. As shown in Fig. 6, an adequate amount of pilot fuel reduces the noise level, but too much quantity causes a strong noise. This effect on noise level depends on the timing of pilot injection.

Figure 7 shows the effect of varying timings of the pilot injection from 55 to 15 deg BTDC on combustion noise level with the amount of pilot fuel kept at 30 mg/cycle. It can be seen from Fig. 7 that the maximum combustion noise occurs with pilot injection at 30 deg BTDC.

It was found out by the above experiment that the noise level could be reduced with adequate timing and quantity of pilot injection. Now, we consider

thermodynamically the effect of double injection on the reduction of combustion noise level.

4. Thermodynamic consideration on effects of double injection

4.1 Theoretical calculation

The audible combustion noise in a diesel engine

(a) Effect of the pilot fuel quantity on the shape of heat release rate

(b) Effect of the pilot fuel quantity on the shape of heat release rate

(c) Effect of the pilot fuel quantity on the shape of heat release rate

Fig. 5.

800 rpm, main injection at 10 deg BTDC, pilot injection at 45 deg BTDC

Fig. 4 Effect of the pilot fuel quantity on engine performance

arises from a rapid heat release in the early stage of combustion. The combustible mixture, which is formed during the ignition delay period, burns spontaneously at the moment of ignition and a rapid pressure rise occurs. This results in a loud audible combustion noise.

Assuming that the combustible mixture which is formed after ignition does not take part in the rapid heat release in the early stage of combustion, the initial heat release rate can be written as follows:

$$\frac{dQ_1}{dz_2} = H_u c_\tau w_0 \quad (1)$$

where Q_1 : calorific value of combustible mixture formed during ignition delay period, kcal

z_2 : time elapsed from the moment of ignition, s

H_u : lower calorific heat of fuel, kcal/kg

c_τ : fuel quantity in the combustible mixture formed during ignition delay period, kg

w_0 : reaction rate, sec^{-1} .

It is assumed that the fuel quantity evaporated during ignition delay period is equivalent to c_τ , that is, the mixture formation rate during the ignition delay period equals to the evaporation rate of an atomized fuel. In order to calculate the evaporation rate of the fuel during the ignition delay period, the following assumptions are made: The evaporation rate of a single droplet can be applied to that of an injected fuel. The period of heating up of a droplet to the equilibrium temperature is negligible. Each droplet has the same diameter. The evaporation proceeds quasistatically from the moment of injection.

If z_1 is the elapsed time from injection and d_0 is the initial diameter of a droplet and d is its diameter at arbitrary time z_1 , then we have the following equation:

$$d^2 = d_0^2 - Kz_1 \quad (2)$$

where K is the evaporation rate constant.

The evaporation rate, i.e. the change in weight of droplets with time is

$$-\frac{dW}{dz_1} = -\frac{d}{dz_1} \left(\frac{\pi}{6} \gamma d^3 \right) = \frac{\pi}{4} \gamma K \sqrt{d_0^2 - Kz_1} \quad (3)$$

where γ is the specific weight of fuel. As the initial weight of a droplet is $(\pi/6)\gamma d_0^3$, the evaporation rate is given by the following equation when a unit weight of fuel is injected simultaneously,

$$c(z_1) = \frac{3}{2z_{10}} \sqrt{1 - \frac{z_1}{z_{10}}} \quad (4)$$

where the evaporation duration

$$z_{10} = d_0^2 / K \quad (5)$$

If a unit weight of fuel is injected, the evaporation of fuel during the ignition delay period is calculated by integrating Eq. (4) from $z_1 = 0$ to $z_1 = z_\tau$ as follows:

$$c_\tau = 1 - \left(1 - \frac{z_\tau}{z_{10}} \right)^{3/2} \quad (6)$$

When the rate of injection is given as $b(z_1)$, the evaporated quantity of fuel is calculated from Eq. (6) by superposing as follows:

$$c_\tau = \int_0^{z_\tau} b(z_1) \left\{ 1 - \left(1 - \frac{z_\tau - z_1}{z_{10}} \right)^{3/2} \right\} dz_1 \quad (7)$$

The evaporation rate constant K is given by Sitkei⁽¹⁾:

$$K = \frac{8D_p P_s}{\gamma} \quad (8)$$

$$z_{10} = \frac{d_0^2}{8D_p} \frac{\gamma}{P_s} \quad (9)$$

where D_p : coefficient of diffusion

P_s : saturated vapour pressure on the surface of a droplet.

Next we consider the reaction rate w_0 . It is impossible to express the combustion process with one equation of chemical reaction, since the phenomena in the combustion chamber are very complex. It is difficult to express the actual reactions with a mathematical equation considering the effects of pressure, temperature, heat transfer, turbulence, vortex and diffusion. Based on many practical combustion processes, Wiebe assumed that the specific density of

Fig. 6 Effect of the pilot fuel quantity on combustion noise level for various timings of pilot injection

Fig. 7 Effect of pilot injection timing on combustion noise level for constant quantity of pilot fuel

active center of reaction changes with time according to the following exponential function⁽²⁾:

$$\rho = kz_2^m$$

then, the following equations were derived:

$$x = 1 - e^{-a(z_2/z_{20})^{m+1}} \dots\dots\dots (10)$$

$$w_0 = \frac{dx}{dz_2} = a(m+1) \frac{1}{z_{20}} \left(\frac{z_2}{z_{20}} \right)^m e^{-a(z_2/z_{20})^{m+1}} \dots\dots\dots (11)$$

where x : ratio of fuel burned to the total fuel present

m : coefficient which characterizes the shape of the curve of the burning rate

a : coefficient which characterizes the efficiency of combustion

z_{20} : duration of combustion till the end of complete burning

It is unreasonable to define the duration of burning z_{20} as a period covering complete combustion of the total fuel, for if it should be so defined, it will be infinite in Eq. (10). So, we assume that the total fuel has burned completely when 99.9% of total fuel has burned. This results in $a=6.9$. Then, the maximum reaction rate is expressed by

$$w_{0\max} = 6.9(m+1) \frac{1}{z_{20}} \left\{ \frac{m}{6.9(m+1)e} \right\}^{m/(m+1)} \dots\dots\dots (12)$$

When the injection rate $b(z_1)$ is given, the initial heat release rate is written as follows:

$$\frac{dQ_1}{dz_2} = H_u \int_0^{z_\tau} b(z_1) \left\{ 1 - \left(1 - \frac{z_\tau - z_1}{z_{10}} \right)^{3/2} \right\} dz_1 \times 6.9(m+1) \frac{1}{z_{20}} \left(\frac{z_2}{z_{20}} \right)^m e^{-6.9(z_2/z_{20})^{m+1}} \dots (13)$$

Next, we consider the heat losses during combustion. They are written as follows:

$$\frac{dQ_2}{dz_2} = \alpha A(T - T_w) \dots\dots\dots (14)$$

$$\frac{dQ_3}{dz_2} = c_0 b(z_2)(T_l - T_b) + i \frac{3}{2z_{10}} \int_{z_1=0}^{z_1=z_\tau+z_2} b(z_1) \left(1 - \frac{z_\tau+z_2-z_1}{z_{10}} \right)^{1/2} dz_1 \dots\dots\dots (15)$$

Where Q_2 : the quantity of heat transferred to the combustion chamber wall, kcal

α : heat transfer coefficient, kcal/sec m²°K

A : inside surface area of the combustion chamber, m²

T_w : temperature of the cylinder wall, °K

Q_3 : the quantity of heat consumed to evaporate fuel, kcal

c_0 : specific heat of fuel, kcal/kg°K

T_l : equilibrium temperature of evaporation, °K

T_b : initial temperature of fuel, °K

i : latent heat of fuel, kcal/kg

Then, the actual heat release rate is written as follows:

$$\begin{aligned} \frac{dQ}{dz_2} &= \frac{dQ_1}{dz_2} - \frac{dQ_2}{dz_2} - \frac{dQ_3}{dz_2} \\ &= H_u \int_0^{z_\tau} b(z_1) \left\{ 1 - \left(1 - \frac{z_\tau - z_1}{z_{10}} \right)^{3/2} \right\} dz_1 \\ &\quad \times 6.9(m+1) \frac{1}{z_{20}} \left(\frac{z_2}{z_{20}} \right)^m e^{-6.9(z_2/z_{20})^{m+1}} \\ &\quad - \alpha A(T - T_w) - c_0 b(z_2)(T_l - T_b) \\ &\quad - \frac{3i}{2z_{10}} \int_0^{z_\tau+z_2} b(z_1) \left(1 - \frac{z_\tau+z_2-z_1}{z_{10}} \right) dz_1 \dots\dots\dots (16) \end{aligned}$$

4.1.1 Effect of pilot injection on the combustion of main fuel

As the temperature and pressure in the combustion chamber are raised by heat release of pilot fuel, the ignition delay period of main fuel is shortened. If the equation of ignition delay period proposed by Wolfer is available to z_τ ⁽⁸⁾, we get

$$z_\tau = Cp^{-n} e^{E/RT} \dots\dots\dots (17)$$

where C : constant of 0.44, n : constant of 1.19, E/R : 4650°K, T , p : temperature and pressure in the combustion chamber during ignition delay period, °K, kg/cm², respectively.

By injecting pilot fuel, the temperature and pressure in the combustion chamber at the time of main injection increase by ΔT and Δp , then the ignition delay period of main fuel can be expressed by

$$z_\tau = 0.44(p + \Delta p)^{-1.19} e^{4650/(T + \Delta T)} \dots\dots\dots (17)'$$

ΔT , Δp are given as follows:

$$\Delta T = \frac{H_u B}{GC_v} \dots\dots\dots (18)$$

$$\Delta p = \frac{RH_u B}{vGC_v} \dots\dots\dots (19)$$

where B : total amount of pilot fuel, kg/c

G : mixture weight, kg

The charge temperature and pressure may decrease due to the pilot fuel evaporation. This cooling effect of pilot fuel is too small compared to the heat release of pilot fuel to affect the ignition delay period of main fuel.

4.1.2 Combustion of pilot fuel

While an increase of pilot fuel in quantity decreases the combustion noise of main fuel, a considerable heat release and a strong combustion noise break out due to the rapid combustion of pilot fuel. In addition, the experimental results tell that the level of combustion noise varies depending on the pilot injection timing, even with the same amount of pilot fuel to be injected. We must, therefore, consider the effects of pilot fuel in relation to the pilot injection timing.

(1) Pilot injection timing with the condition

$$z_\tau \geq z_{10}$$

In this case ignition occurs after pilot fuel has completely evaporated. During the period between the end of evaporation and the beginning of ignition,

the homogeneity of the combustible mixture proceeds and its maximum concentration decreases. If C_0 is the concentration of combustible mixture at the end of evaporation $z_1 = z_{10}$, V is the volume of fuel vapour, S is the surface area of fuel vapour and D is the diffusion coefficient, the change of concentration of combustible mixture from z_1 to $z_1 + dz_1$ may be written as follows:

$$VdC = -DSCdz_1 \quad \dots\dots\dots(20)$$

From the initial condition $z_1 = z_{10}$; $C = C_0$, we obtain

$$C = C_0 e^{-(SD/V)(z_1 - z_{10})} = C_0 e^{-\beta(z_1 - z_{10})} \quad \dots\dots\dots(21)$$

If the concentration of combustible mixture and the reaction rate are in a linear relation, the reaction rate is written as follows:

$$w = w_0 e^{-\beta(z_1 - z_{10})} \quad \dots\dots\dots(22)$$

where w : reaction rate when ignition occurs after complete evaporation of fuel

w_0 : reaction rate when ignition occurs before complete evaporation of fuel

β : coefficient which characterizes the decrease of mixture concentration or reaction rate

With the condition of $z_\tau \geq z_{10}$, the evaporated fuel quantity c_τ equals to B . Then the heat release rate is given by

$$\begin{aligned} \frac{dQ}{dz_2} &= H_u B w_0 e^{-\beta(z_\tau - z_{10})} - \alpha A (T - T_w) \\ &= H_u B e^{-\beta(z_\tau - z_{10})} 6.9(m+1) \frac{1}{z_{20}} \\ &\quad \times \left(\frac{z_2}{z_{20}} \right)^m e^{-6.9(z_2/z_{20})^{m+1}} - \alpha A (T - T_w) \quad \dots\dots\dots(23) \end{aligned}$$

(2) Pilot injection timing with the condition

$z_\tau \leq z_{10}$

(i) Pilot fuel ignites before the beginning of main fuel injection

In this case, the reaction rate of pilot fuel is assumed to be the same as that of main fuel because pilot fuel starts to burn before its evaporation has been completed. And, since pilot injection ends before ignition, the heat consumed for fuel evaporation during the combustion period is negligible.

$$\begin{aligned} \frac{dQ}{dz_2} &= H_u \int_0^{z_\tau} b(z_1) \left\{ 1 - \left(1 - \frac{z_\tau - z_1}{z_{10}} \right)^{3/2} \right\} dz_1 \\ &\quad \times 6.9(m+1) \frac{1}{z_{20}} \left(\frac{z_2}{z_{20}} \right)^m e^{-6.9(z_2/z_{20})^{m+1}} \\ &\quad - \alpha A (T - T_w) \quad \dots\dots\dots(24) \end{aligned}$$

(ii) Pilot fuel ignites after the beginning of main fuel injection

In this case, a part of main fuel is injected before the pilot fuel ignites. The initial rapid heat release is caused by the combustion of both main and pilot fuels. As the main fuel continues to be injected into the combustion chamber during combustion, its cooling effect should be taken into account and the heat release rate is expressed by Eq. (16). When the

injection timings of pilot and main fuels are close to each other, it is difficult to distinguish the main injection rate from the pilot injection rate. So we regard them as a single composite injection rate. As we have seen, when the injection timing of main fuel is so close to that of pilot fuel, the ignition delay period is kept constant independently of the amount of pilot fuel to be injected, and there is a change of heat release rate which results from a change of injection rate caused by pilot injection.

4.2 Example of calculation

Calculations were carried out under the condition of the main injection at 10 deg BTDC, engine speed of 800 rpm and the injection rate of 10 mg/deg. Using the values of $T = 870^\circ\text{K}$ and $p = 40 \text{ kg/cm}^2$ as temperature and pressure of combustible mixture at the beginning of the main injection, the evaporation rate was calculated. Using the value proposed by Sitkei, the evaporation rate constant was calculated as $K = 5.8 \times 10^{-4} \text{ hr}$. Then, assuming the initial droplet diameter of $d_0 = 17 \mu$, the evaporation duration becomes $z_{10} = 8.6 \text{ deg}$. For this condition, the ignition delay period is calculated as $z_\tau = 5.5 \text{ deg}$, if Wolfer's equation for ignition delay period is available to z_τ . From the experimental results with normal single injection, the parameter m in the heat release equation was determined as $m = 1$. Upon injecting pilot fuel, the temperature and pressure in the combustion chamber at the time of the main injection increase, and the ignition delay period and evaporation rate decrease. These are shown in Fig. 8.

The relation between the maximum heat release rate of main fuel and the quantity of pilot fuel is shown in Fig. 9. In this figure, it is seen that the noise due to main fuel combustion is reduced by pilot injection.

Next, the maximum heat release rate and com-

Fig. 8 Effect of the pilot fuel quantity on ignition delay period z_τ and evaporation duration z_{10} of main fuel

bustion noise level with only pilot fuel are calculated under the condition of $z_r \geq z_{10}$. It is assumed that the maximum heat release rate and combustion noise level are in a linear relation. Using Eq. (23), the maximum heat release rate $(dQ/dz_2)_{\max}$ is calculated for various values of $(z_r - z_{10})$. Assuming that this calculated value of $(dQ/dz_2)_{\max}$ is in a linear relation with the noise level which is measured by experiments (Fig. 10), we obtain the value β to be 0.1.

When the injection timing is changed, the gas temperature and pressure during the ignition delay period vary. So the evaporation rates during the ignition delay period are different for various injection timings. Evaporation rate was calculated by using the values of the gas temperature and pressure at the beginning of injection.

Figure 11 shows the calculated evaporation period and the experimental results of the ignition delay period for various injection timings. For various injection timings, the heat release rates are calculated and their maximum values are plotted in Fig. 12. The trend of calculated results coincides qualitatively

with that of the experimental results of the combustion noise level. From the given results, we sum up the maximum heat release rate of main and pilot injection in Fig. 13.

This result agrees qualitatively with the experimental result shown in Fig. 7.

5. Conclusions

We investigated thermodynamically the effects of double injection on the performance of a direct

Fig. 9 Calculation result showing the decrease of the maximum heat release rate of main fuel with an increased pilot fuel

Fig. 10 Combustion noise levels measured by experiment versus period from evaporation end z_{10} to ignition z_r

Fig. 11 Ignition delay period measured by experiment and calculated evaporation period of a droplet for various pilot injection timings

Fig. 12 Effect of pilot injection timing on maximum heat release rate for constant quantity of pilot fuel

Fig. 13 Composed maximum heat release rate of main and pilot fuel calculated for various pilot injection timings

injection diesel engine. Our conclusions are as follows:

1. The effect of double injection on the reduction of combustion noise level depends largely on the pilot injection timing.

2. The combustion mechanism of double injection may be classified into three cases.

(1) Pilot fuel is injected at 360 deg BTDC.

(2) Pilot and main injection timings are comparatively close together.

(3) Pilot and main injection timings are very close.

3. If pilot fuel is injected at 90 to 270 deg BTDC or with the piston off top dead center, the specific fuel consumption will be greatly increased. This fact suggests that the shape of combustion chamber and the type of injection nozzle may be main factors governing the effects of double injection.

4. The reason why the level of combustion noise decreases when main and pilot injection timings are comparatively close together can be thermodynamically explained by the thermal effects of pilot fuel.

5. When the timing of the pilot injection is close

to that of the main injection, the shape of main injection rate is changed in its early part by pilot injection. This reduces the maximum heat release rate and combustion noise level.

6. As mentioned above, the maximum heat release rate and combustion noise level can be reduced by changing the shape of injection rate without increasing the specific fuel consumption.

Therefore, it is desirable to continue the study about the relation between injection rate and combustion characteristics such as heat release rate.

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Discussion

M. Ikegami (Kyoto University):

(1) Is the quantity of pilot injection which is defined in this paper measured at the pilot injection pump? How can you measure the actual amount of pilot injection when main and pilot injection timings are close together? And I hope you will show me the data on a change of injection rate, if any.

(2) You have explained that the decrease of the mixture concentration with time results in that the peak heat release of pilot injection decreases with the advance of injection at an early pilot. I am afraid this picture is somewhat sophisticated because some simpler factors, such as the amount of fuel sticking to the chamber wall, may be also present. Please show me a proof of the proposed mechanism in which the variation of the mixture concentration with time must be the predominant factor.

S. Fukazawa (Hokkaido University):

(3) The combustion noise is an important problem at comparatively light load. At what load has this experiment been made? Please explain the calibration method and the kind of the filter in the combustion noise measurement. What is the basis for the combustion noise level (3–8dB) in Figs. 6 and 7.

(4) I think the value of constant C is affected by the Cetane number of used fuel. Is the value of

constant $C=0.44$ right in case of this experiment?

Author's closure

(1) The quantity of pilot injection which is defined in this paper is the actual quantity of pilot fuel which has been injected into the cylinder. When main and pilot injections are close together, the quantity of pilot injection cannot be measured by the diagram of the injection rate. When main and pilot injections were apart from each other, we got a relation between the quantity measured at the pilot injection pump and that measured by the diagram of the injection rate. We assumed the above mentioned relation is valid when main and pilot injection are close together. On this assumption, we calculated the quantity of pilot injection. In Append-Fig. 1 you can see the injection rate in case of main and pilot injection being close together.

(2) As you have pointed out, the fuel sticking to the cylinder wall can also be taken into consideration. But the amount can also be considered to be little when the piston is relatively near TDC. Therefore, we took the variation of mixture concentration into account.

(3) The experiment was conducted at full load. The intensity of the combustion noise was compared relatively in terms of voltage measured

Append.-Fig. 1 Injection rates when pilot and main injection are close to each other (5 deg disparity)

upon the synchroscope. The output detected by the microphone was passed through the filter. The intensity of the combustion noise which was measured with a motoring of the engine was considered to be 0 dB. As for the filter, a turning amplifier was used. Middle frequency of 1 000 Hz and selectivity $Q=5$ were used.

(4) As you have pointed out, the value of constant C is perhaps affected by Cetane number of used fuel, but in this example of calculation this value was tentatively used.