Optimization of Pilot Injection Pattern and Its Effect on Diesel Combustion with High-Pressure Injection*

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The pilot injection pattern was optimized, and some effects of pilot injection on combustion and exhaust emissions were investigated using a single-cylinder DI diesel engine. The results are as follows. (1) In order to avoid the increase of smoke, both a small-hole-diameter nozzle and very accurate control of pilot injection quantity and pilot-main interval are essential. These improve the atomization of the pilot fuel and the air entrainment into the main spray. (2) With pilot injection, NO_x is not reduced at the injection timing of TDC but is gradually reduced at more retarded injection timing. This is because the main combustion is accelerated at early injection timing but is decelerated at retarded injection timing, due to the promotion of ignition. (3) The effect of pilot injection on NO_x reduction is generally small; however, pilot injection well prevents HC increase under light-load, injection-timing-retard conditions.

Key Words: Diesel Engine, Fuel Injection, Combustion, High-Pressure Injection, Pilot Injection

1. Introduction

Because the reduction of diesel exhaust emissions is at present an urgent problem to be tackled, high-pressure fuel injection has become a key technology to improve the exhaust emissions even in the field of high-speed small diesel engines, due to the remarkable effects of soot reduction and engine output increase. However, high-pressure fuel injection is apt to cause some problems such as the increases of NO_x and noise. Accordingly, it is necessary to develop a new combustion system suitable for high-pressure fuel injection, and active research has therefore been progressing to reveal and optimize the characteristics of fuel spray, mixture formation and combustion under high-pressure fuel injection^{(1),(2)}.

The authors have also clarified the basic effects of

high-pressure fuel injection on the characteristics of mixture formation, combustion and exhaust emissions for a high-speed small direct injection (DI) diesel engine⁽³⁾ and have additionally obtained knowledge on mechanisms of NO_x formation and soot reduction under high-pressure fuel injection through the analyses of flame temperature and soot concentration distributions⁽⁴⁾. Consequently, it is revealed that, though injection-timing retard and initial-injection-rate reduction are effective in decreasing NO_x , the former has already reached the limit due to increasing specific fuel consumption and the latter still has insufficient effect. To further examine the effects of the more precise control of injection rate, therefore, pilot injection and boot-type injection which have a small-amount fuel injection prior to the main injection were attempted. However, they caused some problems such as a remarkable increase of soot and complex changes in the exhaust emissions with changes of injection-rate pattern and/or injection timing. There was a report on the effect of pilot injection on exhaust emissions⁽⁵⁾; however, it gave insufficient explanation of the problems mentioned above under high-pressure fuel injection. In this

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study, accordingly, the points for optimizing pilot injection pattern under high-pressure fuel injection were investigated and the effects of the injection rate pattern and injection timing on combustion and exhaust emissions were minutely examined.

2. Experimental Apparatus and Procedure

2.1 Experimental engine

The engine used in this study was a 4-stroke cycle, single-cylinder DI diesel engine with a 102-mm bore and a 110-mm stroke, which was the same engine as that used in the previous study⁽³⁾. In the engine, the large observation field shown in Fig. 1 was obtained by removing both intake and exhaust valves from the cylinder head which was realized by adopting a liner-port intake and side-valve exhaust system.

Table 1 Experimental conditions

Engine Speed	1800 rpm
Fuel Amount	35 mm ³ /st (18 mm ³ /st)
Equivalence Ratio	0.42 (0.22)
Injection Pressure	95 MPa (40 MPa)
Main Inj. Timing	0°, 5°, 10° ATDC
Fuel Additive*	Copper Oleate
Injection Nozzle	Φ0.26 mm x 4 holes Φ0.18 mm x 5 holes

* To visualize nonluminous flames

Fig. 1 Observation field

Fig. 2 Apparatus for direct photography or two-color pyrometry measurement

2.2 Apparatus for in-cylinder observation

With the apparatus shown in Fig. 2, direct photographs of combustion processes were taken at a frame speed of 9 000 fps using a high-speed camera. In the case of flame temperature measurement by two-color pyrometry method⁽⁶⁾, the high-speed camera was replaced with a two-color, high-speed shutter TV camera system⁽⁷⁾.

2.3 Experimental conditions

The main experimental conditions are listed in Table 1. Copper oleate was added to the fuel to visualize nonluminous flames appearing with high-pressure fuel injection⁽⁸⁾, which was verified to be effective in the previous study⁽³⁾. An electronic control, common-rail accumulator-type injection system⁽⁹⁾ was used as the fuel injection device. Pilot injection was carried out by double operations of the three-way valve which controls the opening and closing of the nozzle needle.

2.4 Experimental procedure

Before visualization experiments, exhaust gases were analyzed under each steady-state running condition by replacing the quartz window with a same-shaped metal part. In the visualization experiments, the engine was kept running with control of both the coolant and lubricant temperatures at about 90°C, and fuel injection was started just when the temperature of the cylinder-head wall reached about 150°C. At this time, high-speed direct photographs were taken or two-color pyrometry measurements were carried out. Simultaneously, the cylinder pressure, the injection pressure (measured in the accumulator) and the needle lift of the injector were recorded and indicator analysis was carried out. In the visualization experiment, the intake air was heated up to about 120°C so that the ignition delay and heat release rate under the visualization conditions corresponded with those under the steady-state running conditions.

3. Experimental Results and Discussion

3.1 Investigation of optimum pilot injection pattern

In most cases that pilot injections were carried out at an injection pressure of 95 MPa and an injected fuel amount of 35 mm³/st (medium load), the exhaust smoke sharply increased and NO_x also increased. This example is shown in Fig. 3, which was obtained under the nozzle specifications of a hole diameter of ϕ 0.26 mm and a hole number of 4, the same as those used in the previous studies^{(3),(4)}. As shown in this figure, the smoke greatly increased from 0.2 BSU to 1.1 BSU.

To clarify the cause of this smoke increase, the flame development processes in this case were

examined. The results are shown in Fig. 4. In this case, the pilot flames formed prior to the main injection enlarge too much, because the fuel quantity of the pilot injection is about $3 \text{ mm}^3/\text{st}$ and is in excess. Additionally, because the pilot-main interval is too long, about 12.5 deg. CA (1.16 ms), each pilot flame is carried down just to the position of the downstream-side fuel spray by the swirl flow in the main injection period. Therefore, the flame immediately envelops the whole spray, and from the initial combustion stage dark brown areas appear in the flame. These dark brown areas are peculiar to the case of high exhaust smoke and are considered to be generated by the cooled dense soot on the surface of the quartz window. In the pilot injection period, furthermore, the throttling effect at the nozzle seat is large because of the small needle lift of about $40 \mu\text{m}$ (cf. the maximum lift of $350 \mu\text{m}$), and hence the real injection pressure at the nozzle sac seems to be very low, about 10 MPa , judging from the spray tip penetration. Consequently, the increased smoke is considered to be caused by the facts that air entrainment into the spray is prevented due to the envelopment of the main spray by flames and that atomization of the pilot fuel becomes poor due to the remarkable reduction of the real injection pressure during the pilot injection period.

Next, the flame temperature distributions in this case were also examined to clarify the cause of the NO_x increase. Figure 5 shows the histories of the ratio of the high-temperature (over 1900°C) flame area to the total flame area. This ratio has a close correlation with the exhaust NO_x as pointed out in the

previous study⁽⁴⁾. From the figure, it is clear that the high-temperature regions at this pilot injection spread wider in not only the pilot flame but also the main flame, due to the excess pilot fuel. This is considered to be the cause of the NO_x increase.

An example of the optimized pilot injection based on the knowledge obtained in this study is shown in Fig. 9 (which is more precisely explained in section 3.2). Fuel spray atomization is ensured by the use of a small-hole-diameter nozzle ($\phi 0.18 \text{ mm} \times 5 \text{ holes}$). Additionally, the quantity of pilot fuel is suppressed within $2 \text{ mm}^3/\text{st}$ by reducing the needle lift to about $10 \mu\text{m}$ and the pilot-main interval is shortened to about 5 deg. CA (0.46 ms). By these improvements in the pilot injection characteristics, each pilot flame is of adequately small scale and is located slightly downstream of each spray. Therefore, the main sprays are not enveloped by flames, so that a low smoke level is maintained and NO_x is somewhat reduced. Consequently, the relation between the exhaust smoke level and the scale and position of pilot flame is schematically shown in Fig. 6. Figure 7 shows an example of the comparison of injection rate between the optimized pilot and normal injections.

3.2 Effects of pilot injection

The effects of the optimized pilot injection on the exhaust emissions and the combustion characteristics were investigated, and the results are as follows.

3.2.1 Under medium load conditions Under the medium load conditions of an injection pressure of 95 MPa and an injected fuel amount of $35 \text{ mm}^3/\text{st}$, the exhaust emissions and the combustion characteristics

Fig. 3 Comparison of exhaust emissions between normal and unoptimized pilot injections

Fig. 5 Histories of ratio of high-temperature (over 1900°C) flame area to total flame area

Fig. 4 Combustion process for unoptimized pilot injection

Fig. 6 Scale and position of pilot flame against main-injection spray for low and high exhaust smoke cases

Fig. 7 Injection rates for normal and optimized pilot injections

with and without pilot injections were compared. The results are shown in Fig. 8. In this figure, the abscissa designates the main injection timing, and the combustion periods are defined as the periods from the beginning of injection to the time when 30, 50, 70 and 90% of input energy are released.

(1) Exhaust smoke (the bottom graph in Fig. 8)

With pilot injection, the exhaust smoke slightly increases at mildly retarded injection timings of up to 5° ATDC, whereas it remarkably increases at more retarded timing of 10° ATDC. This is related to the fact that the ignition delay of the main spray sharply increases from 2.8 deg. CA (at the injection timing of 5° ATDC) to 3.8 deg. CA (at 10° ATDC). From the viewpoint of flame development, at the injection timing of 5° ATDC (the right-side figure in Fig. 9), the moderate effect of ignition promotion due to the formation of optimized pilot flame suppresses the sudden heat release at the initial combustion stage and causes both NO_x reduction and the prevention of smoke increase. On the other hand, at 10° ATDC injection (Fig. 10), the increase of ignition delay mentioned above retards the flame development of the main-injection fuel. Consequently, the main sprays are finally ignited just when each pilot flame reaches the position of the downstream-side fuel spray, and soon these sprays are fully enveloped by flames, producing the same state as that of the unoptimized pilot injection shown in Fig. 4 and causing the smoke increase.

(2) Exhaust NO_x (the second graph from the bottom in Fig. 8)

With pilot injection, the exhaust NO_x is not

Fig. 8 Effects of pilot injection on exhaust emissions and combustion characteristics under medium load conditions

reduced at an injection timing of 0° ATDC whereas it becomes decreased as the timing is retarded to 5–10° ATDC. The cause of this change in exhaust NO_x is understood from the combustion period (the top graph in Fig. 8). With pilot injection, the initial 30% combustion periods are shortened in all the cases due to the effect of ignition promotion by pilot injection. However, there is a difference in the main-combustion periods after 50% heat release. At the injection timing of 0° ATDC, the combustion periods after 50% heat release are shortened by pilot injection. Namely, the main combustion is accelerated and the timing of heat release is advanced. Accordingly, the effect of reducing the peak height of heat release rate by pilot injection (shown in the top graphs of Fig. 11) is canceled by the effect of advancing the main-combustion timing, which is considered to prevent the NO_x reduction. At more retarded injection timings, on the other hand, this effect of accelerating the main combustion disappears. Namely, the main-combustion periods after 50% heat release under pilot injection (Fig. 8) become almost the same as those under normal injection at the injection timing of 5° ATDC and become

rather longer at 10° ATDC injection. Therefore, the exhaust NO_x is considered to be reduced by the degree corresponding to the effect of decreasing the heat-

release-rate peak at 5° ATDC injection (Fig. 9) and by the degree corresponding to the total effect both of decreasing the heat-release-rate peak (the bottom

Fig. 9 Effects of pilot injection on flame development

Fig. 10 Flame development process for retarded-timing injection with pilot injection

Fig. 11 Comparison of heat release rate between normal and pilot injections

Fig. 12 Comparison of mass-averaged gas temperature between normal and pilot injections

graphs of Fig. 11) and of retarding the main-combustion timing due to increasing the main-combustion period at 10° ATDC injection. The in-cylinder, mass-averaged gas temperature shown in Fig. 12 reflects the change in the combustion characteristics described above and corresponds to the change in exhaust NO_x .

The cause of the effect of accelerating the main combustion which disappears at retarded injection timings is also related to the change of the ignition delay and the flame development. First, with regard to the combustion at normal injection, the ignition delay is 3.3 deg. CA at injection timings of up to 5° ATDC, whereas it sharply increases to 4.8 deg. CA at 10° ATDC injection. Therefore, the initial peak of the heat release rate at 10° ATDC injection is very high as shown in the bottom-left-side graph of Fig. 11. This violent first-stage combustion (premixed combustion) seems to promote the following diffusion combustion and consequently, the 50–70% combustion periods shown in Fig. 8 are rather shorter than those at 0°

ATDC injection. On the other hand, with pilot injection, the ignition delay of the main-injection spray is only 3.8 deg. CA even at 10° ATDC injection. Consequently, even at this retarded injection timing, the initial peak of the heat release rate becomes low (the bottom-right-side graph in Fig. 11) and the flame development proceeds mildly. Therefore, as the injection timings are retarded, the combustion period at pilot injection becomes relatively longer than that at normal injection. Namely, it is concluded that, with the ignition promotion by pilot injection, the main combustion is accelerated at relatively early injection timings, whereas it is decelerated at retarded injection timings.

(3) Exhaust HC (the third graph from the bottom in Fig. 8)

Under the medium load conditions like these experimental conditions, the value of the exhaust HC is small and hardly changes, independently of injection timing and the presence of pilot injection. This is considered to be attributed to the facts that in all cases under these conditions, the flame reaches the cylinder-liner wall to envelop the whole mixture region at the middle stage of combustion and that HC is apt to be oxidized in the exhaust system because of the high exhaust temperature of 460–530°C.

(4) Maximum rate of pressure rise (the second graph from the top in Fig. 8)

The maximum rate of pressure rise is steeply reduced by pilot injection. Corresponding to this tendency, it was felt that both the level and sound quality of the combustion noise were remarkably improved.

3.2.2 Under light load conditions Under the light load conditions of an injection pressure of 40 MPa and an injected fuel amount of 18 mm³/st, the exhaust emissions and the combustion characteristics with and without pilot injections were compared. The results are shown in Fig. 13, in which the abscissa designates the main-injection timing.

The exhaust smoke is 0 BSU in all the cases under such light load conditions. The exhaust NO_x , showing the same tendency as that under the medium load conditions, does not depend on the presence of pilot injection at the injection timing of 0° ATDC but is reduced by pilot injection at 10° ATDC, though this reduction is small. On the other hand, with retarded injection timing, the exhaust HC sharply increases at normal injection, whereas it does not increase at all at pilot injection.

Figure 14 shows the results from investigation of the flame development processes at 10° ATDC injection to clarify the cause of the difference in HC emissions at this retarded injection timing between

Fig. 13 Effects of pilot injection on exhaust emissions under light load conditions

Fig. 15 Comparison of flame area history between normal and pilot injections

Fig. 14 Effects of pilot injection on flame development under light-load, injection-timing-retard conditions

with and without pilot injections. Under the light load and retarded timing conditions, in the case of normal injection, ignition occurs after the injection ends and then the flames rapidly develop mostly with non-luminous flames. In the case of pilot injection, on the other hand, each pilot flame exists just downstream of the main spray in the period of main injection and the flame develops, successively catching the fuel vapor generated from the spray. Judging from this history of the flame region at the pilot injection, in the case of normal injection, much fuel vapor is considered to diffuse in almost the whole region of the combustion chamber during the ignition delay period. Additionally, the over-lean mixture spreading in the region near the cylinder-liner wall is exhausted from the exhaust valve in an unburned state because the flames never reach the liner wall under such light load conditions.

Therefore, the HC emission is considered to increase at normal injection. The histories of the flame areas in both cases obtained from image analysis are compared in Fig. 15.

Finally, under light load conditions, with pilot injection, the increase of HC emission is suppressed so that the NO_x reduction by injection timing retard and the prevention of particulate increase are simultaneously obtained.

4. Summary and Conclusion

Using a single-cylinder, experimental DI diesel engine, the points for optimizing the pilot injection pattern under high-pressure fuel injection were investigated, and the effects of the injection rate pattern and injection timing on combustion and exhaust emissions were examined in detail. The following points

were clarified through the studies.

(1) Under medium or greater load conditions, exhaust smoke sharply increases with a slight change in pilot injection pattern. This is considered to be caused by both the insufficient atomization of the pilot injection fuel and the prevention of air entrainment into the main sprays due to the envelopment of the sprays by flames.

(2) To simultaneously suppress smoke increase and reduce NO_x , the use of a small-hole-diameter nozzle and very accurate control of shortening the pilot-main interval and of suppressing the pilot injection quantity are all necessary. Especially, the pilot injection quantity should essentially be suppressed within $2 \text{ mm}^3/\text{st}$.

(3) With pilot injection, the exhaust NO_x is not reduced at an injection timing of 0° ATDC, whereas it becomes reduced as the timing is retarded to $5\text{--}10^\circ$ ATDC. This is caused by the fact that the effect of ignition promotion by pilot injection accelerates the main combustion at early injection timing, canceling the effect of the decrease in the heat-release-rate peak, whereas it decelerates the main combustion at retarded injection timing.

(4) Under medium load conditions, the effect of pilot injection on NO_x reduction is small and the smoke is apt to increase by pilot injection; therefore, improvement of exhaust emissions by pilot injection is concluded to be small.

(5) Under light load and retarded injection timing conditions, with pilot injection, a remarkable effect of HC reduction is obtained because the formation of an unburned, over-lean mixture is suppressed. Therefore, though the direct effect of pilot injection on NO_x reduction is small, the NO_x decrease by injection timing retard and the prevention of particulate increase are simultaneously obtained.

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