Effects of Intake Charging Condition on Smoke Reduction of Post injection in Diesel Engines

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ABSTRACT: This study aims at improving understanding of the relation between smoke-reduction effects of post injection and intake charging conditions in small-bore diesel engines. A series of experiments were conducted using a single cylinder diesel engine to investigate the smoke-reduction effect of post injection varying intake pressure and swirl ratio. The results indicated that post injection provides larger reduction of smoke emission at higher swirl ratios for a larger amount of total fuel injection, while the reduction scarcely depends on swirl ratio at a smaller injection amount. Higher intake pressure enhances smoke-reduction effect of post injection.

KEY WORDS: **heat engine, compression ignition engine, combustion analysis,** Diesel Engine, Multiple Injections, After Injection, Post injection, Smoke, Soot (A1)

1. INTRODUCTION

In diesel engine, the effectiveness of post injection on soot-reduction, in which a small amount of fuel is injected right after the end of main injection, has been proved in many studies [(1-5)]. In our previous study [(5)], an experimental research was conducted using a small-sized diesel engine by varying quantity and timing of each injection, injection pressure, intake pressure, number of nozzle hole and combustion chamber shape. The result indicated that the post injection with proper short interval from the end of main injection (close post injection) could achieve soot-reduction performance compared to the case without post injection in many cases.

One possible explanation for the tendency above is that the post spray develops before the main-spray flame flows from the wall of piston bowl into the post-spray path. However, there are some cases where the close post injection is not preferable when changing the number of nozzle hole and combustion chamber shape. In order to obtain the strategy for fully utilizing post injection, the experimental results under a wider range of operation and design conditions are needed.

The intake charging condition is known as one of the factors influencing spray development. Therefore in this study, to investigate the effect of intake charging condition on smoke reduction due to post injection in diesel engines, the experimental research has been conducted using a single-cylinder diesel engine, and discussion are given about the results with attention to the interaction between main-spray flame and post spray.

2. EXPERIMENTAL SETUP

The experimental system was almost the same as those reported in the previous study [(5)]. The test engine was a water-cooled single-cylinder four-stroke-cycle diesel engine (bore: 85.0 mm, stroke: 96.9 mm, compression ratio: 16.3) equipped with a common-rail injection system, a seven-hole injection nozzle (0.125 mm orifice dia.) and a reentrant combustion chamber (55.6 mm bowl dia.).

All of the experiments were conducted in a fixed engine speed of 1,500 rpm, inlet coolant-water temperature of 80° C and lubricant-oil temperature of 80° C. JIS No.2 diesel fuel (density at 15° C: 832.2 kg/m^3, cetane index: 57) was used.

Swirl ratio was changed from 1.3 to 3.2 by adjusting swirl control valve. Intake pressure and exhaust pressure were kept the same and changed from 120 kPa, where the charging efficiency was around 1, to 160 kPa. The intake temperature was kept at 35° C. The intake oxygen concentration was kept at 17.8% by regulating EGR ratio. Because of the upper limit of the EGR ratio, when intake pressure was 120 kPa and 160 kPa, the experiments had to be conducted with injection quantities over 17 and 33 mm^3/cycle, respectively. In addition, the increase of injection quantity was restricted by the temperature limit of exhaust gas (550° C).

The pilot-injection timing and main-injection timing were set at −9° ATDC and 1° ATDC, and the pilot-injection quantity and post-injection quantity were set at 2 mm^3/cycle and 4 mm^3/cycle, respectively. The experiment was conducted under two post-injection timing conditions including most advanced and relatively later 21° ATDC against various main-injection

Table 1 The most advanced post injection timing for various injection quantity for injection pressure of 90 MPa

Injection quantity [mm³/cycle]	17	21	25	29	33	37	41
The most advanced post-inj. timing [°ATDC]	10	11	11	11	12	13	14

quantity, swirl ratio and intake pressure. The results of the most advanced post-injection timing for each injection quantity, which is on the basis of 1° CA increment, are shown in Table 1.

3. RESULTS AND DISCUSSION

3.1. Effect of swirl ratio

To select the conditions for the experiments with swirl-ratio sweep, the total injection quantity was changed under the intake pressure of 120 kPa and the swirl ratio of 1.8 (standard), in which the cases with most advanced and 21° ATDC post-injection timing and without post injection were investigated under the same total injection quantity conditions. The effects of injection quantity q_f on smoke, CO, NOx emissions and indicated thermal efficiency η_i are shown in Fig.1.

Smoke emission increases with the increase of injection quantity for every injection pattern. The case with the most advanced post-injection timing achieves smoke-reduction performance compared to the case without post injection while the case with late post injection shows a counter effect. Exceptionally, the case with late post injection achieves smoke-reduction performance compared to the case without post injection under a total injection quantity of 17 mm³/cycle. The CO concentration reaches its minimum value at an injection quantity of 29 mm³/cycle. It can be attributed to the lean air-fuel mixture generated from pilot spray under the condition with smaller injection quantities, and the rich air-fuel mixture generated from main spray under the condition with larger injection quantities [(6)]. The effect of CO reduction by post injection is intensified in smaller injection quantity cases. It is assumed that the post-spray flame promotes the CO oxidation in the lean air-fuel mixture. Compared to the case without post injection, NOx concentration is higher in the case with the most advanced post-injection timing. It is supposed that in higher temperature and pressure condition generated by the main-spray flame, the NOx production from combustion of the post spray is significant. However, the case with late post injection achieves the NOx reduction. Besides the case with 17 mm³/cycle injection quantity, it is shown that the indicated thermal efficiency of the case with late post injection is almost the same compared to the case without post injection, while it increases by the extent of 1 point in the case with the most advanced post-injection timing.

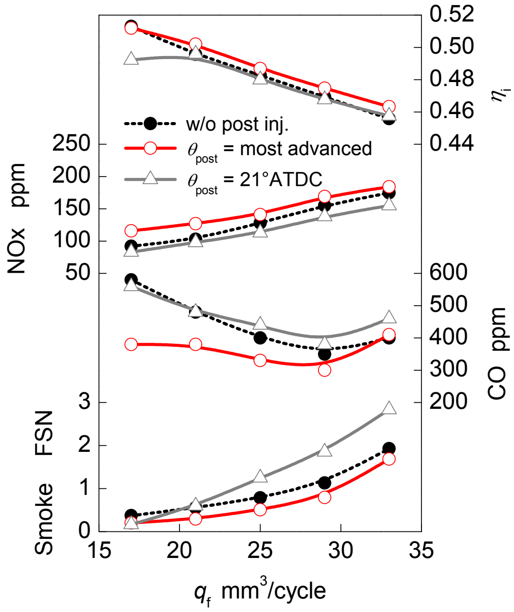

Fig.1 Effects of injection quantity on engine performance and emissions (injection pressure: 90 MPa, intake pressure: 120 kPa, swirl ratio: 1.8)

Based on the result above, the experiment was continued by varying swirl ratio from 1.3 to 3.2 at injection quantities of 29 and 33 mm³/cycle, which were thought to generate relatively rich mixture. The case with the most advanced post-injection timing was studied. In the upper part of Fig.2, comparison was made between the cases with and without post injection (A and B) under the same total injection quantity. Moreover, the case without post injection under 29 mm³/cycle (C) was added. This corresponds to the injection pattern in which the post injection is removed from (A). In the lower part of Fig.2, the result of the cases with and without post injection (D and C) under the same total injection quantity of 29 mm³/cycle, and the case without post injection under 25 mm³/cycle (E) were shown.

For the case (B) in Fig.2 (upper), smoke emission reaches the minimum level when swirl ratio r_s was 1.8. It is assumed that low swirl ratio leads to insufficient mixing process, while high swirl ratio leads to the over-swirl condition and the air in peripheral part of combustion chamber is not well utilized, both of which increase smoke emission [(7)]. In the case (A), higher swirl ratio strengthened the smoke-reduction effect against case (B). It is supposed that the over-swirl condition is mitigated owing to the smaller main-injection quantity in case (A), which makes swirl ratio an almost non-influential factor against smoke as a result. The level of smoke in case (A) is between those in case (B) and (C).

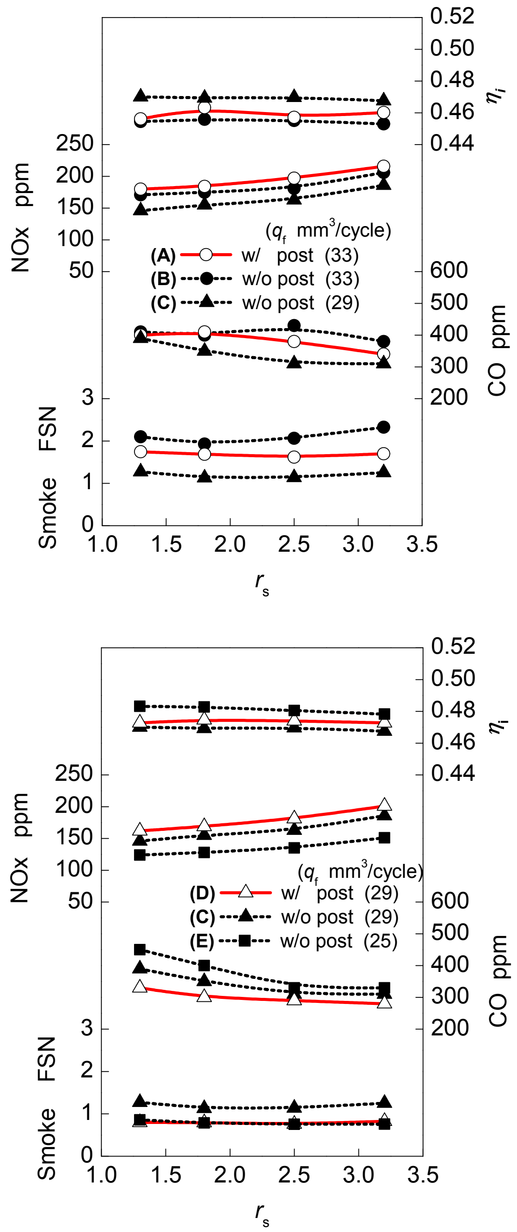

Fig.2 Effects of swirl ratio on engine performance and emissions (injection pressure: 90 MPa, intake pressure: 120 kPa)

For the cases with smaller injection quantity in Fig.2 (lower), the effect of swirl ratio on smoke is smaller compared to the cases in Fig.2 (upper). Smoke emission in the case (D) with post injection was almost the same as in the case (E), which is different from the above-mentioned tendency for the larger injection quantity. It is assumed that the smaller total injection quantity leads to less main-spray flame to be entrained into the post spray, from which nearly no extra smoke is produced.

Figure 3 shows the effect of swirl ratio on heat-release rate $dQ/d\theta$ for the case (A). As the swirl ratio increases, the peak heat-release rate in main injection increases. However, no evident difference of heat-release rate is shown between various

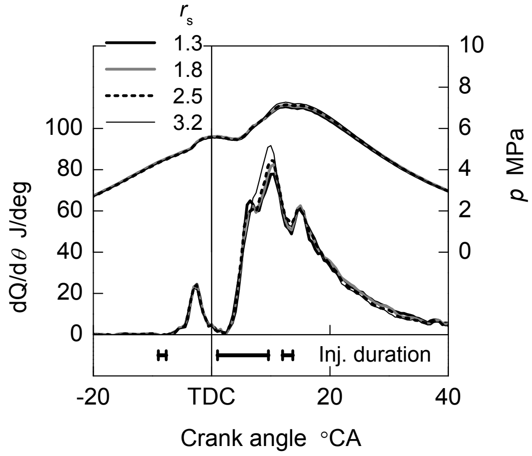

Fig.3 Effects of swirl ratio on heat-release rate and in-cylinder pressure (injection pressure: 90 MPa, intake pressure: 120 kPa, total injection quantity: 33 mm³/cycle)

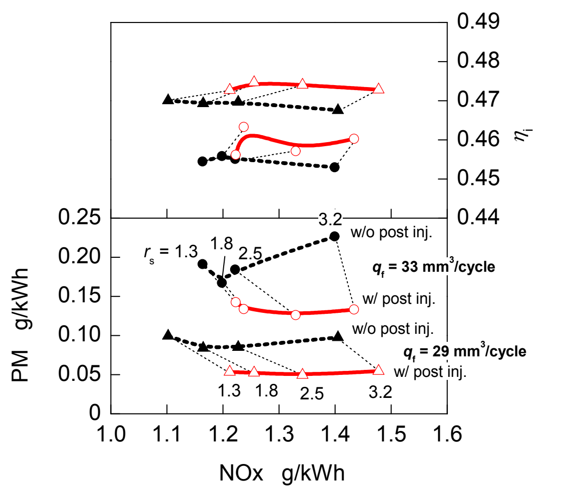

Fig.4 Relationships between NOx, PM and indicated thermal efficiency (injection pressure: 90 MPa, intake pressure: 120 kPa)

swirl ratio conditions in pilot injection, post injection or late combustion phase.

To investigate the effect of post injection on the relation between NOx and PM emissions under various swirl ratios, brake specific PM emission (BSPM) and indicated thermal efficiency are plotted against brake specific NOx emission (BSNOx) in Fig.4. The BSPM is calculated based on the conversion formula by AVL [8]. Under the condition with a swirl ratio of 3.2 and a total injection quantity of 33 mm³/cycle, it indicates that compared to the case without post injection, BSPM significantly decreases with post injection while BSNOx slightly increases. However, in other cases, the decrease of BSPM accompanies considerable increase of BSNOx. Additionally, compared to the cases without post injection, an increase in

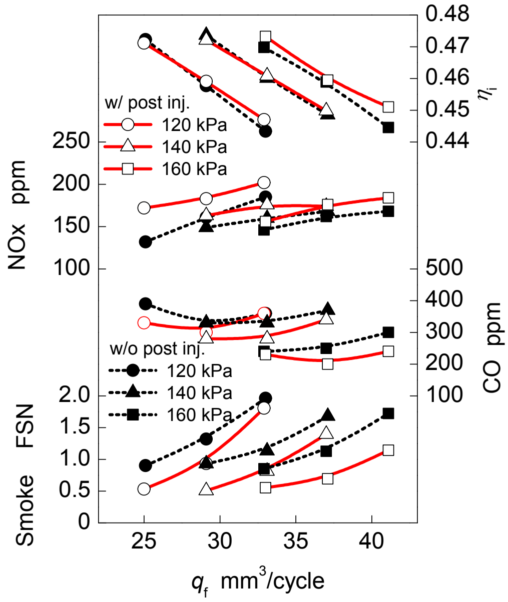

Fig.5 Effects of intake pressure on engine performance and emissions (injection pressure: 90 MPa, swirl ratio: 1.8)

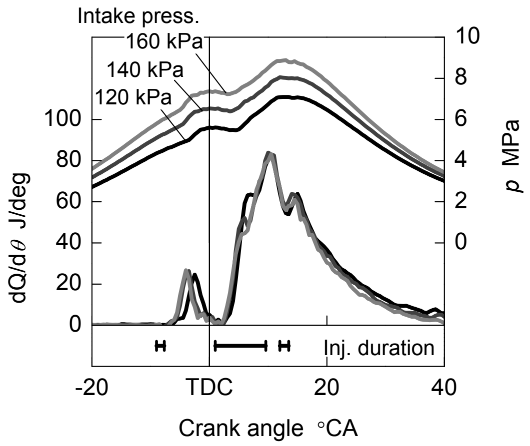

Fig.6 Effects of intake pressure on heat-release rate and in-cylinder pressure (injection pressure: 90 MPa, swirl ratio: 1.8, total injection quantity: 33 mm^3/cycle)

indicated thermal efficiency using post injection is observed in all of the conditions.

3.2. Effect of intake pressure

Then, experimental research was conducted by varying the intake pressure, which is known as one of the factors influencing spray development. The effects of intake pressure (120, 140 and 160 kPa) on engine performance and emissions are shown in Fig.5. As the intake pressure increases, both NOx and smoke emissions decreases throughout the injection quantity range. In the case of the lower intake pressure of 120 kPa, the smoke-reduction effect by post injection decreases with the increase of total injection quantity. This tendency is weakened as the intake pressure is increased. It is plausible that as the gas density inside the cylinder increases, the development of main-spray flame and post spray is restricted, which results in less interference on the post spray by the main-spray flame.

The effect of intake pressure on heat-release rate and in-cylinder pressure under a total injection quantity of 33 mm^3/cycle is shown in Fig.6. As the intake pressure increases, the heat-release rate decreases in premixed combustion phase of main-injection combustion; simultaneously the peak of heat-release rate from the post spray decreases.

The relationship between BSNOx, BSPM and indicated thermal efficiency under various intake pressures is plotted in Fig.7. Compared to the cases without post injection, an increase in BSNOx and decrease in BSPM are observed using post injection regardless of intake pressure. In terms of the comparison for effects of post injection within various intake pressure conditions, the BSPM significantly decreases and the BSNOx slightly increases when intake pressure is changed from 120 kPa to 140 kPa. In contrast, the BSPM slightly decreases and the BSNOx increases greatly in the case of the highest intake pressure of 160 kPa.

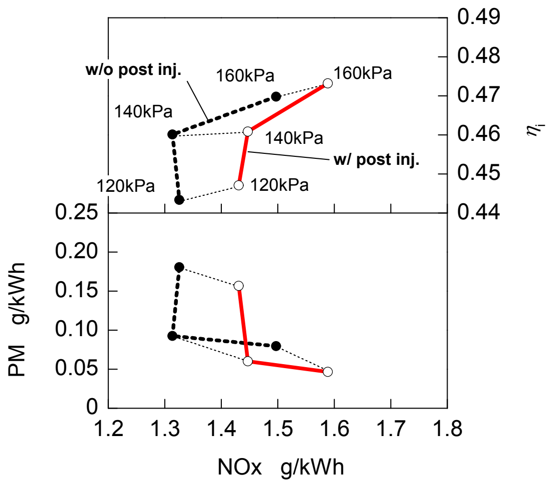

Fig.7 Relationships between NOx, PM and indicated thermal efficiency (injection pressure: 90 MPa, swirl ratio: 1.8)

3.3. Effect of injection pressure

From the results above, it is presumed that as the gas density inside the cylinder increases owing to higher intake pressure, the penetration of spray and the interaction between main-spray flame and post spray are mitigated. According to this assumption, it is supposed that as penetration of spray is intensified, larger amount of main-spray flame will be entrained by post spray, which leads to worse smoke-reduction performance even for a high intake pressure. Therefore, the experiment was conducted under higher injection pressure of 125 MPa. The most advanced post-injection timings for injection pressure of 125 MPa are

Table 2 The most advanced post injection timing for various injection quantity for injection pressure of 125 MPa

Injection quantity [mm³/cycle]	29	33	37	39
The most advanced post-inj. timing [°ATDC]	10	11	12	12

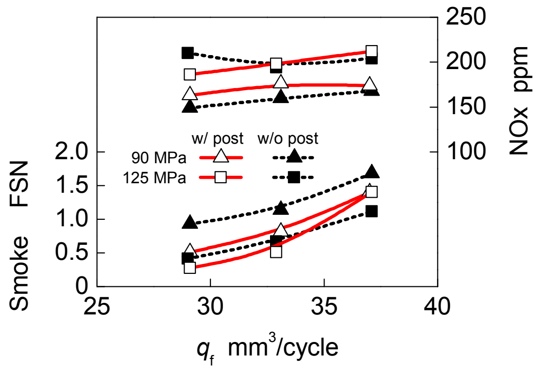

Fig.8 Effects of injection pressure on smoke and NOx emissions (intake pressure: 140 kPa, swirl ratio: 1.8)

shown in Table.2. The Smoke and NOx emissions against injection quantity are shown in Fig.8. Regarding the cases without post injection, as the injection pressure increases the smoke emission decreases. However, under the injection pressure of 125 MPa, the smoke-reduction performance was attenuated for post injection, until at total injection quantity of 37 mm^3/cycle the smoke emission with post injection exceeded the one without post injection. Based on this result, the assumption above can be confirmed.

4. CONCLUSIONS

The experimental research has been conducted using a single-cylinder diesel engine by varying swirl ratio and intake pressure, and discussion about the results is given with the attention to the interaction between main-spray flame and post spray. The results are summarized as follows:

- Under the larger injection quantity condition, higher swirl ratio leads to a better smoke-reduction performance by post injection. On the other hand, under the smaller injection quantity condition, no significant smoke-reduction effect of post injection was observed by varying swirl ratio.
- Under the lower intake pressure condition, the smoke-reduction effect of post injection decreases as the injection quantity increases. On the contrary, under the higher intake pressure condition, larger injection quantity leads to a better smoke-reduction performance by post injection.
- Even under the relatively high intake pressure condition, the smoke-reduction effect of post injection is mitigated when the injection pressure is elevated. Above a certain injection quantity, the case with post injection even shows a smoke-increment effect compared to the case without post injection.
- The results above can be quantitatively explained considering the influence of main-spray flames on post sprays. If the amount of main spray flame being entrained into post spray decreases, the smoke-reduction performance owing to post-injection will be improved.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number 26820063. The authors would like to thank Mr. Kuwabara, Hiroki for his valuable assistance with the experiments.

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