8 An Experimental Study of Multiple Injection Strategy for Passenger Diesel Engine

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Multiple injection (up to 5 injections per cylinder) was applied for current 2.0L passenger diesel engine and its effects was analyzed. Optimal multiple injection strategy for 2.0L engine was proposed. Multiple injection is used to reduce emission and noise. First two pilot injection was efficient for noise reduction since first two pilot injections shorten ignition delay of main injection and premixed combustion portion was decreased. Post injection near main injection was efficient for soot reduction since post injection burns soot of main injection. But when swirl is enhanced by swirl control valve, post injection fuel increased emission in certain region. This was due to that enhanced swirl reduced the heat release of post injection and unburned fuel emitted out. Multiple injection strategy depends on engine specification.

Keywords: Multiple injection, Emission, Fuel consumption, Noise

1. INTRODUCTION

It was researched that NOx and PM reduction by multiple injection with advanced fuel injection system to meet severe emission regulation[1]. It was known that pilot injection before main injection reduced ignition delay and increased diffusion combustion portion. This reduces combustion noise and NOx, but increases soot [2, 3]. It was also known that post injection after main injection reduced PM since post injection oxidizes soot of main injection. EGR should be considered to fix multiple injection strategy to optimize emission, noise and fuel consumption[4]. Various auxiliary parts were added to meet severe emission regulation. So these added parts can affect multiple injection strategy. SCV(Swirl Control Valve) has been equipped to reduce smoke current. Through analysis of multiple injection results with selective application of EGR and SCV, multiple injection strategy was proposed for a passenger diesel engine with SCV in this study.

2. EXPERIMENTAL APPARATUS

Table 1 is the main engine specification of this study. Table 2 is fuel specifications which were used for this study. Engine test was performed on AVL EC steady dynamometer bench (160kW). Diesel smoke emission was measured by AVL 415. Particulate matter concentration was calculated from measured smoke number. This calculation relation was proven for some literatures[5]. Exhaust emission NOx, THC, CO and CO2 were measured by Horiba MEXA 9100HEGR. Combustion pressure was measured by AVL 670 and combustion noise was calculated from cylinder pressure by AVL combustion noise meter 4050.

Table 1 Engine specifications

Cylinder arrangement	4 in line
Displacement	1997cm^3
Bore x Stroke	83 x 92mm
Piston	Re-entrant Bowl
Valve timing system	SOHC, 4valves per cyl.
Swirl Ratio(open SCV)	1.4
Fuel/Air metering	CRDI/Turbocharger

Tabe 2 Fuel properties

Cetane Number	62.3
Specific Gravity	0.822
Viscosity @40^{o}C (cSt)	2.705
Sulfur content (ppm)	230

3. MULTIPLE INJECTION SCHEME

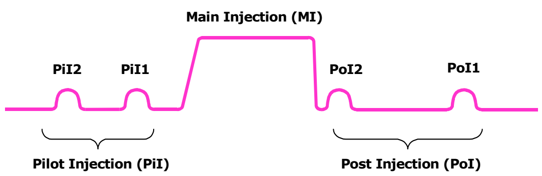

Fig. 1 Multiple injection scheme

Fig. 1 is the name of each multiple injections.
- PiI2(Pilot Injection 2) : Early pilot injection
- PiI1(Pilot Injection 1) : Pilot injection near main injection
- MI(Main Injection)
- PoI2(Post Injection 2) : Post injection after main injection
- PoI1(Post Injection 1) : Latest post injection

Multiple injection means 3 ~ 5 injections per cylinder in this study.

4. TEST RESULTS WITH OPENED SCV AND WITHOUT EGR

Analysis of Each Injection Variation (2000rpm 8bar BMEP)

The effects of each injection with variation of injection timing and quantity was analyzed for 2000rpm 8bar BMEP. Then optimal injection timing and quantity was determined considering emission, fuel consumption and noise. Another test points were also analyzed as 2000rpm 8bar BMEP. Injection timing and quantity of PiI1, PiI2, PoI2 and PoI1 were optimized in order. Former optimized timing and quantity were used for following timing and quantity optimization.

Fig. 2 shows the results of Nox and smoke according to timing of PiI1. When timing of PiI1 was advanced, Nox and smoke were reduced. Meanwhile noise, CO and THC were increased. This was due to that mixing time of combustion gas of pilot injection and air was increased. So the local equivalence ratio of main injection fuel/air was leaned, smoke was decreased. Nox was also decreased, since burned gas from pilot injection was premixed sufficiently and this burned gas made combustion temperature of main injection lower. Timing of PiI1 was determined as MI-34.0CA(Crank Angle)aTDC before steep increase of noise, THC and CO.

Effect of PiI1 Timing (No EGR, open SCV)

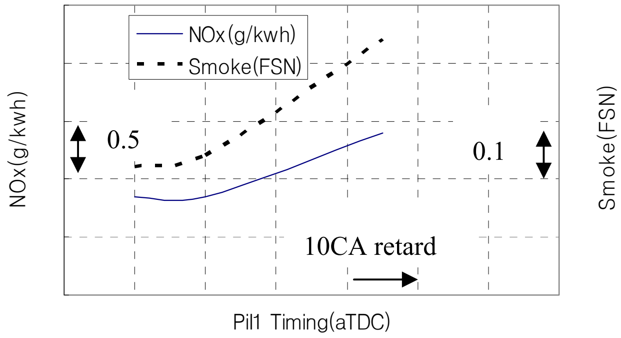

Fig. 2 Effect of PiI1 Timing

Effect of PiI1 Fuel Quantity (No EGR, open SCV)

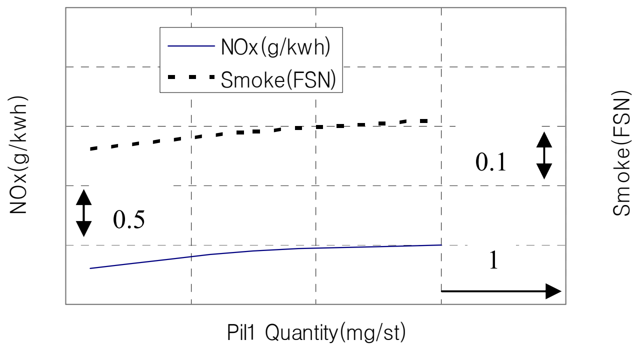

Fig. 3 Effect of PiI1 Fuel Quantity

Fig. 3 shows the results according to the quantity of PiI1. As the quantity of PiI1 was increased, Nox, smoke and CO were increased, and noise was decreased. This resulted from the increased EGR gas of increased PiI1 quantity. The PiI1 quantity was determined as 2.0mg/st considering NOx, smoke, noise and CO.

Effect of PiI2 Timing (No EGR, open SCV)

Fig. 4 shows the results according to timing of PiI2. As the PiI2 timing was advanced, fuel consumption, CO and THC was increased. Timing of PiI2 is determined as MI-60.5CA aTDC considering noise, THC and CO.

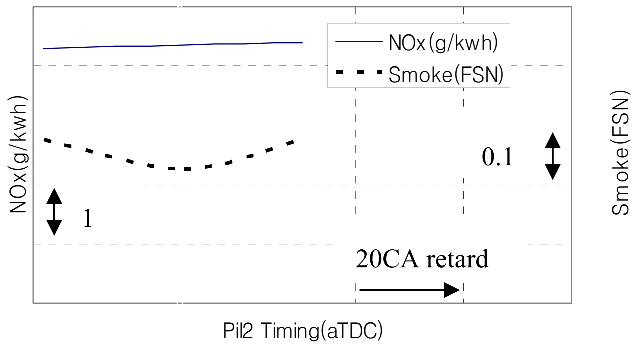

Fig. 4 Effect of PiI2 Timing

<u>Effect of PoI2 Timing (No EGR, open SCV)</u>

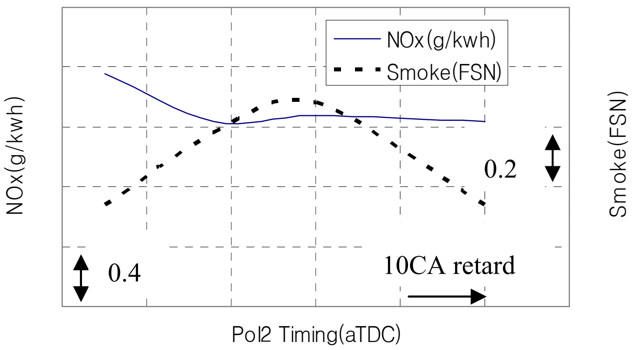

Fig. 5 Effect of PoI2 Timing

Fig. 5 shows the results according to timing of PoI2 . As the timing of PoI2 was retarded, fuel consumption was increased. This was due to that as the PoI2 timing is retarded, smaller portion of PoI2 was contributed to torque forming. Timing of PoI2 was determined as MI+27.5CA aTDC considering NOx, smoke and fuel consumption.

<u>Effect of PoI2 Fuel Quantity (No EGR, open SCV)</u>

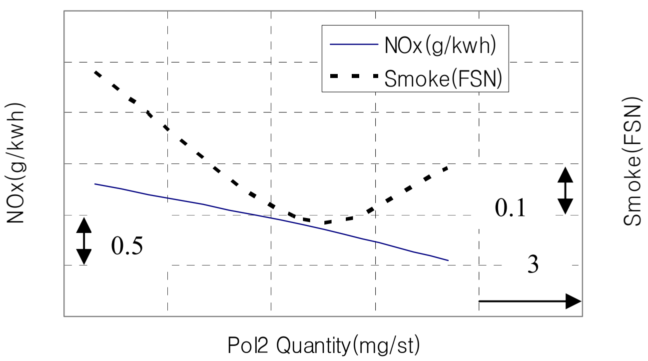

Fig. 6 Effect of PoI2 Fuel Quantity

Fig. 6 shows the results according to quantity of PoI2. As the PoI2 quantity was increased, NOx, smoke and CO was reduced, and fuel consumption was increased. As the PoI2 quantity was increased, main injection quantity was reduced, so NOx and CO of main injection was decreased and fuel consumption was increased. Since injected fuel of PoI2 oxidized soot of main injection fuel, smoke was reduced. Quantity of PoI2 was determined as 3.0mg/st considering NOx, smoke, CO and fuel consumption.

<u>Effect of PoI1 Timing (No EGR, open SCV)</u>

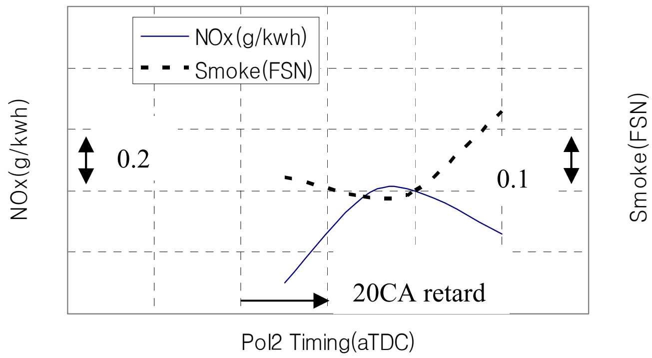

Fig. 7 Effect of PoI1 Timing

Fig. 7 shows the results according to timing of PoI1. Since almost amount of quantity of PoI2 was not burned after 80CA aTDC of injection timing, smoke, fuel consumption, CO and THC was increased steeply. PoI1 was efficient for oxidization of limited smoke of main injection fuel before 70CA aTDC, but fuel consumption and emission was increased after 80CA aTDC. PoI1 was omitted for afterward multiple injection test, since fuel consumption and emission deterioration was superior to smoke oxidization by PoI1. Table 3 are the optimized injection timing and quantity.

Table 3 Optimized injection timing and quantity for 2000rpm 8bar BMEP (No EGR, open SCV)

Injection	Timing(aTDC)	Quantity(mg/st)
PiI2	Ref.-60.5	2.0
PiI1	Ref.-34.0	2.0
MI	Ref.	Depend on BMEP
PoI2	Ref.+27.5	3.0
PoI1	Ref.+71.5	7.0

5. TEST RESULTS WITH OPEN SCV AND WITH EGR

Effect of EGR on injection pattern was tested and there was no strong affection on injection event by EGR. So optimal injection pattern without EGR was also used for the case of with EGR.

Test Results with EGR Variatoin (2000rpm 8bar BMEP, open SCV)

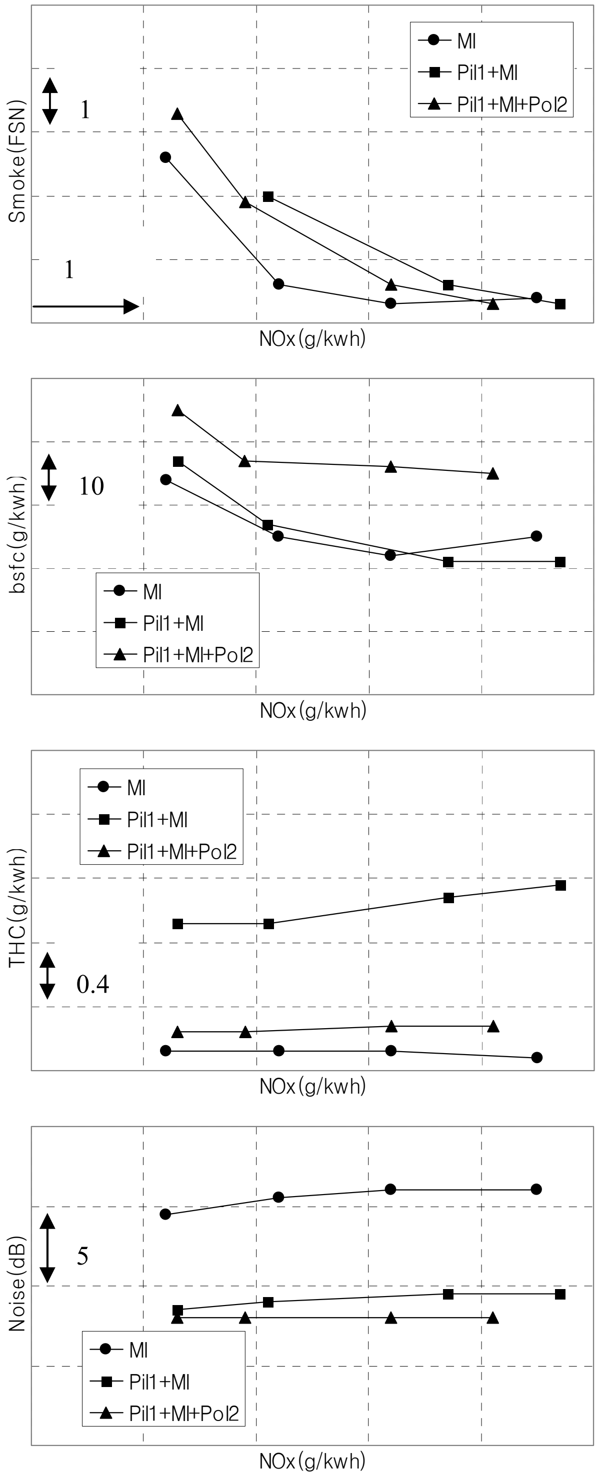

Fig. 9 (a)~(d) Test results with open SCV when EGR rate is increased (2000rpm 8bar BMEP)

Fig. 9 was the results with adding of each PiI1 and PiI2. NOx-Smoke trade off characteristic of MI was best, but noise was worst. When post2 was added to PiI1+MI, NOx-Smoke trade off was developed without noise increase. This test was performed without swirl control valve adjustment to delete enhanced swirl effect.

To analyze the effect of EGR rate, tests was done with EGR gas increase. When PiI1 was added to main injection, noise was reduced and emission was little increased compared with only main injection. When PoI2 was added to PiI1+MI, NOx-Smoke trade off became better without noise increase.

Analysis of Multiple Injection Pattern for Each Points with open SCV and EGR

Table 4 Result of multiple injection of 2000rpm 8bar BMEP with EGR (Same NOx)

Injection	Noise	bsfc	PM
	dB	%	%
MI	+5.7	99.4	19
PiI1+MI	Ref.	100.0	100
PiI2+PiI1+MI	-1.9	97.8	47
PiI2+PiI1+MI+PoI2	-1.3	100.1	28

1.9dB of noise of PiI2+PiI1+MI was decreased from reference noise which is noise of PiI1+MI. Adding of PoI2 did not affect noise of PiI2+PiI1+MI in Table 4. Fuel consumption of PiI2+PiI1+MI was decreased to 97.8% compared with one of PiI1+MI, and fuel consumption of PiI2+PiI1+MI+PoI2 was nearly same as one of PiI1+MI. Emission of PiI2+PiI1+MI and PiI2+PiI1+MI+PoI2 were decreased to 47% and 28% compared with one of PiI1+MI. PiI2+PiI1+MI+PoI2 was selected as optimum injection pattern from emission and noise results.

Table 5 Result of multiple injection of 2000rpm 2bar BMEP with open SCV and EGR (Same NOx)

Injection	Noise	bsfc	PM
	dB	%	%
MI	-2.1	106.2	98
PiI1+MI	Ref.	100.0	100
PiI2+PiI1+MI	-2.2	101.3	126
PiI2+PiI1+MI+PoI2	-3.3	111.2	100

2.2 and 2.3dB of noise of PiI2+PiI1+MI and PiI2+PiI1+MI+PoI2 were decreased from reference noise, one of PiI1+MI. Since noise of MI was steeply decreased ad EGR was increased, noise of MI was lowest, but fuel consumption was steeply increased.

Fuel consumption of PiI2+PiI1+MI and PiI2+PiI1+MI+PoI2 were increased to 101.3% and 114.1% compared with one of PiI1+MI. Emission of PiI2+PiI1+MI and PiI2+PiI1+MI+PoI2 were increased to 126.5% and 100% compared with one of PiI1+MI. PiI2+PiI1+MI was selected as optimum injection pattern from noise and fuel consumption results.

Table 6 Result of multiple injection of 1500rpm 4bar BMEP with open SCV and EGR (Same NOx)

Injection	Noise	bsfc	PM
	dB	%	%
MI	-1.2	101.5	21
PiI1+MI	Ref.	100.0	100
PiI2+PiI1+MI	-4.8	103.2	226
PiI1+MI+PoI2	+1.0	106.0	14

4.8 and 1.0dB of noise of PiI2+PiI1+MI and PiI1+MI+PoI2 was decreased and increased respectively from reference noise, one of PiI1+MI. The reason that noise of MI is smaller than one of PiI1+MI is that decrease of noise by increase of EGR is larger than that by PiI1.

Fuel consumption of PiI2+PiI1+MI and PiI1+MI+PoI2 were increased to 103.2% and 106.0% from one of PiI1+MI. Emission of PiI2+PiI1+MI and PiI1+MI+PoI2 were increased to 226% and decreased to 14% from one of PiI1+MI. Though noise and fuel consumption were inferior, PiI1+MI+PoI2 was selected as optimum injection pattern case since emission was decreased steeply.

6. TEST RESULTS WITH ENHANCED SWIRL AND WITH EGR

Analysis of Multiple Injection Pattern for Each Points with Enhanced Swirl and with EGR

Duty of SCV actuator was determined from one of vehicle engine. Since enhanced swirl induces high air/fuel mixing, this effect was analyzed in this section.

Enhanced swirl brought large NOx since premixed combustion was increased. Higher EGR rate compared with open SCV was needed to maintain same NOx level.

Table 7 Result of multiple injection of 2000rpm 8bar BMEP with EGR and enhanced swirl (Same NOx)

Injection	Noise	bsfc	PM
	dB	%	%
MI	+6.6	101.1	79
PiI1+MI	Ref.	100.0	100
PiI2+PiI1+MI	-3.1	102.7	231
PiI2+PiI1+MI+PoI2	-2.6	100.8	114

Adding pilot injections to MI brought increase of emission in Table 7. Adding of post injection resulted in reduction of emission due to oxidization of soot of main injection. Adding of pilot injections brought reduction of noise. 3.1dB of noise of PiI2+PiI1+MI were decreased from reference noise which is one of PiI1+MI.

Though fuel consumption and emission of PiI2+PiI1+MI+PoI2 were increased to 100.8% and 114% from ones of PiI1+MI, PiI2+PiI1+MI+PoI2 was considered to be optimum injection pattern since there were PM reduction by PoI2 and noise reduction by PiI2. If emission reduction is more preferable than noise reduction, PiI1+MI is better injection pattern than PiI2+PiI1+MI+PoI2.

Table 8 Result of multiple injection of 1500rpm 4bar BMEP with EGR and enhanced swirl (Same NOx)

Injection	Noise	bsfc	PM
	dB	%	%
MI	+5.7	113.5	73
PiI1+MI	Ref.	100.0	100
PiI2+PiI1+MI	+0.7	101.1	300
PiI1+MI+PoI2	+0.5	106.6	187

Emission showed same trend with 2000rpm 8bar BMEP case regarding pilot injection and post injection in Table 8. The reason that noise of MI was lowest for MI is that ignition delay was increased with increase of EGR and start of combustion(SOC) was delayed. This ignition delay brought large fuel consumption increase. PiI1+MI was determined as optimum injection `pattern considering fuel consumption, emission and noise.

Table 9 Result of multiple injection of 2000rpm

2bar BMEP with EGR and enhanced swirl (Same NOx)

Injection	Noise	bsfc	PM
	dB	%	%
MI	-12.7	116.9	310
PiI1+MI	Ref.	100.0	100
PiI2+PiI1+MI	-2.4	97.9	193
PiI2+PiI1+MI+PoI2	-4.4	106.2	265

Adding PiI2 and PoI2 to PiI1+MI reduced noise in Table 9. Emission of PiI2+PiI1+MI and PiI2+PiI1+MI+PoI2 was increased to 193% and 265% from one of PiI1+MI.

The reason for increased smoke by adding of PoI2 might be that enhanced swirl is too strong to burn soot of main injection fuel using post injection. This could be confirmed from that heat release rate of post injection was obviously reduced at this condition. Almost injection fuel of PoI2 might be emitted without oxidization and was shown as smoke.

Noise of MI is lowest and this was same as previous case of 1500rpm 4bar BMEP. PiI1+MI was determined as optimum considering fuel consumption and emission.

Table 10 Result of multiple injection of idle with EGR and enhanced swirl (Same NOx)

Injection	Noise	PM
	dB	%
MI	-1.6	89
PiI1+MI	67.1	100
PiI2+PiI1+MI	-3.7	100
PiI2+PiI1+MI+PoI2	-5.1	97

Noise was decreased as injection number was increased in Table 10. PiI2+PiI1+MI+PoI2 was optimum from emission and noise.

CONCLUSION

Pilot injection was efficient for noise reduction. Pilot injections (PiI1, PiI2) affected emission differently according to region. Pilot injections increased smoke compared with case of only MI. This was due to EGR gas which was produced by pilot injections and reduced ignition delay. Reduced ignition delay enhanced diffusion combustion and this brought increase of smoke.

Post injection near main injection (PoI2) was efficient for oxidization of smoke of main injection fuel. This came from that oxidization of smoke of main and enhanced mixing of air/fuel/smoke by post injection.

When swirl was enhanced, premixed combustion portion was increased and more EGR rate was needed to match same NOx value. Amplitude of heat release rate of post injection was reduced due to enhanced swirl. This low heat release rate of post injection brought smoke increase according to test region. So optimum injection pattern was variant with application of SCV. Noise reduction was obvious at idle condition using 4 multiple injection without emission sacrifice. The optimal injection pattern of engine operation region varied according to engine specification.

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