The Combined Effect of Multi-hole Injector with Pilot Injection and EGR in a HSDI Diesel Engine

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ABSTRACT

The effects of the combined use of exhaust gas recirculation (EGR) and multi-hole injector with pilot injection on combustion and emissions were investigated on a small direct injection diesel engine equipped with a common-rail injection system. Tests were performed at fixed engine speed (800 rpm) under idling condition with various EGR ratios (0 to 50 %) and the injection pressures (60, 120 MPa) versus two different nozzle hole numbers (5, 14 holes). The results showed that significant improvements in power output and the simultaneous reduction of NOx and PM could be achieved when pilot injection was applied with 14-hole injector and EGR.

1. INTRODUCTION

The combination of higher fuel injection pressure with smaller nozzle size is known to be very effective in reducing particulate matter (PM) emission [(1)]. Such advantages may originate from a better air-utilisation due to improved spatial distribution, enhanced atomisation and turbulence generated on periphery area of the spray caused by higher injection velocity.[(2)]

EGR is a well known technique to reduce Nitrogen Oxides (NOx) emission in diesel engines by reducing available oxygen concentration and flame temperature. However, concurrently, PM may increase due to decreased oxygen concentration and lower combustion temperature to limit soot oxidation, especially in the late combustion cycle.[(3)] Therefore, NOx and PM emission could not be simultaneously reduced solely using EGR. The use of small-hole injector and high injection pressure is investigated as a countermeasure to the increased particulate matter (PM) emission formed.[2]

The pilot injection is effective in increasing power-output in this operating condition and reducing NOx emission.[1] It has been reported that significant improvements in the trade-off between particulate and NOx emissions can be obtained if pilot injection is applied in conjunction with multi-hole injector.[4]

In this study, the effects of the combined use of EGR, pilot injection and different nozzle hole numbers on combustion and emissions were investigated through a characterisation of combustion behavior and emission measurement on a single-cylinder optical direct-injection (DI) diesel engine.

2. EXPERIMENTAL SETUP

2.1 Optical research engine

The engine used was a single-cylinder, direct injection, 4-stroke optical research diesel engine equipped with a common rail injection system as listed in Table 1.[1] A schematic of the engine structure is shown in Fig. 1. The piston has been modified from a production engine design to permit an optical access to the combustion chamber. Two different injectors having a 5-hole (0.168 mm in diameter) and 14-hole (0.1 mm in diameter) were used in common-rail injection system. The nominal angle of the fuel-jet axis was 15° downward from horizontal line. Table 2 summarises the precise specifications of the injection system.

Table 1 Specifications of single cylinder diesel engine

Specifications	Resources
Bore (mm)	83
Stroke (mm)	92
Displacement (cc)	498
Compression Ratio	18.9
Stroke/Bore ratio	1.108
Swirl ratio	2.1
Conrod length (mm)	145.8

Table 2 Specifications of fuel injection system

Specifications	Resources
Type	Common Rail Injection System
Injection pressure	0 ~ 150 MPa
Number of holes	5 , 14
Hole diameter	0.168 , 0.1 mm/hole
Injection angle	150°

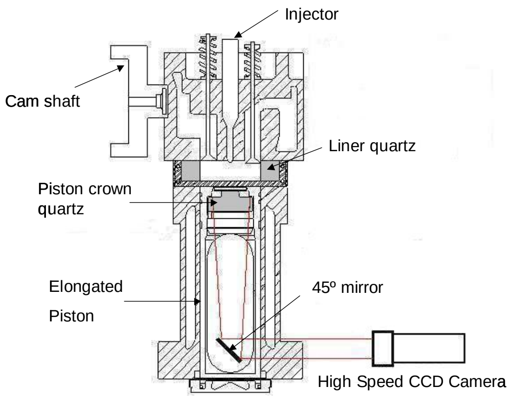

Figure 1 Schematic of the single-cylinder optical engine

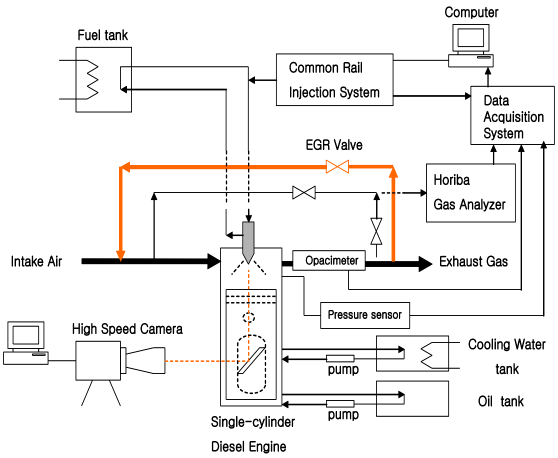

Figure 2 Schematic diagram of experimental facility

2.2 Engine instrumentation

A schematic drawing of the engine test bench is shown in Fig. 2. The electrical motor allowed operation both in motoring and firing conditions. The pressure regulator valve and the solenoid injector were driven by an electronic injector operating system (TDA 3000H, TEMS Ltd.).(1) A shaft encoder was used to transmit the crank shaft position to the injection system for the electronic control. A sampling probe was installed in the exhaust pipe to measure NOx, HC and CO emissions, which was connected to an exhaust gas analyzer (HORIBA MEXA1500D). The in-line type opacimeter (OP100, EplusT Ltd.) was employed to measure the PM emissions.

Table 3 Engine operating conditions

Engine Speed	800 rpm	Main Injection Timing	BTDC 10℃A
Engine Load	Idling	Pilot & Main Injection Timing	BSOI 20℃A BTDC 5℃A
Main Only Injection Quantity	11.5 mm^3/stroke	Number of nozzle hole	5 , 14
Main Injection Quantity	10 mm^3/stroke	Injection pressure	60, 120 MPa
Pilot Injection Quantity	1.5 mm^3/stroke	EGR rate	0 ~ 50 %

BTDC : before top dead center
BSOI : before start of injection

The injection parameters could be input through a PC-based control system that was directly connected to the fuel injection rig. The in-cylinder pressure recorded at each 0.16 crank-angle-degree (°CA) using a piezoelectric pressure transducer (6052A, Kistler) was low-pass filtered and ensemble-averaged over 138 engine cycles to calculate the heat release rate. The combustion image was acquired at every 0.48 °CA at 800 rpm using a high speed CCD camera (Vision Research Inc., Phantom v7.0) and then digitized by a frame grabber at the resolution of 512 by 384 pixels. These techniques were applied under various operating conditions as listed in Table 3.

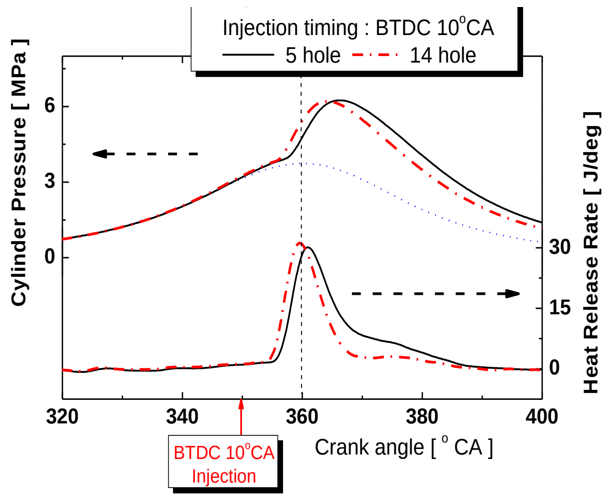

Figure 3 Effect of nozzle hole number on combustion characteristic curve

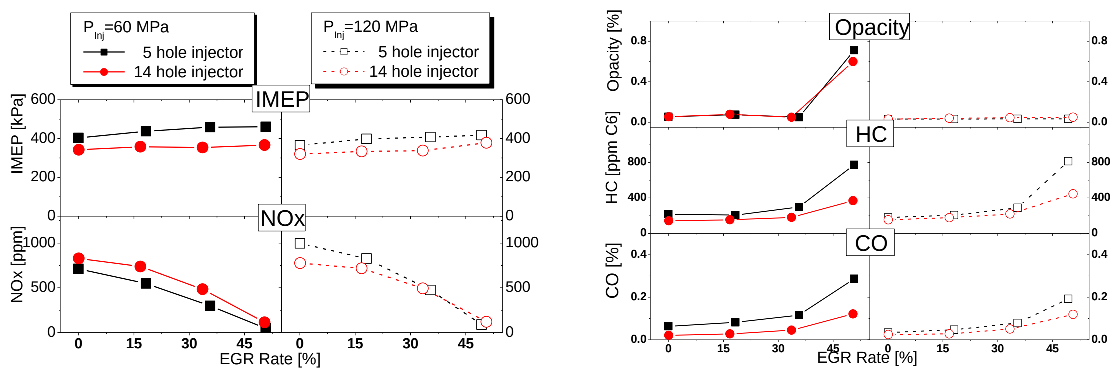

Figure 4 Effect of nozzle hole number and EGR on IMEP and emissions

(Injection timing at BTDC 10 °CA)

3. RESULTS AND DISCUSSIONS

3.1 The effect of number of holes

Figure 3 shows the effect of nozzle hole number on the combustion characteristic curves at injection pressure of 60 MPa. The ignition delay of 14-hole injection was shorter than that of 5-hole injection, which could be correlated with different NOx formation behavior and combustion phasing. However, in case of 120 MPa injection pressure (not shown in this paper), there was no apparent difference between 5-hole and 14-hole injection because high injection pressure provides sufficient momentum to make little difference in mixture preparation state, regardless of nozzle configuration.

The effect of nozzle hole numbers and EGR rate on indicated mean effective pressure (IMEP) and emissions are shown in Fig. 4. (EGR effect is to be explained in the next section)

The 14-hole injection produced lower IMEP than 5-hole injection. The increase in nozzle hole number caused reduction of ignition delay due to the promotion of fuel and air mixing. The peak cylinder pressure and heat release rate for 14-hole injection was higher than those for 5-hole injection, but fell more quickly because of shortened combustion period. These produced less work during the expansion stroke and thus IMEP came to decrease. The increase in hole number with smaller hole size could lead to efficient mixture preparation due to improved air utilisation, which results in low PM, HC and CO emissions. However, NOx emission increases due to the rise of the combustion temperature.(2)

3.2 The effect of EGR

The effect of EGR on engine performance (IMEP) and emissions is shown in Fig. 4. The result showed a slight increase in IMEP and noticeable decrease in NOx emission with increasing EGR rate. But HC and CO emissions were increased. While EGR was very effective in reducing NOx, it increased all the incomplete combustion products, such as HC, CO and soot.

EGR is a primary NOx-reduction technique by lowering flame temperature. As shown in Fig. 5, EGR increased ignition delay because dilution of the fresh charge with EGR reduced the oxygen concentration and thus the reaction rate, which is also the main cause of the increase in all the incomplete combustion products. In the same context, when EGR is added, PM increases because of the lack in available oxygen and the low in-cylinder temperature for particulate oxidation, particularly in the late combustion cycle.(3)

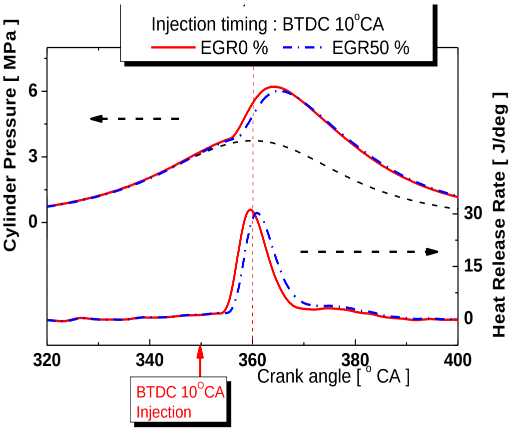

Figure 5 Effect of EGR on combustion characteristic curve

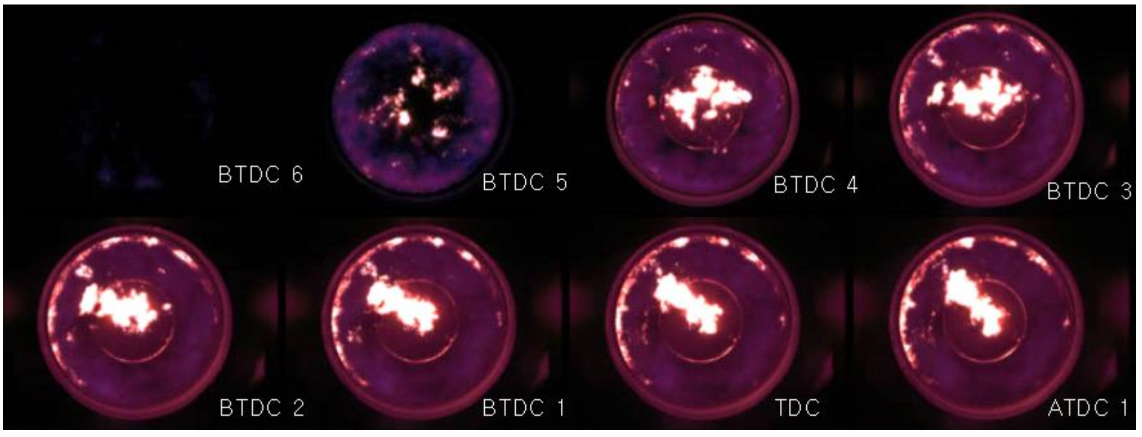

Figure 6 High-speed images of combustion (Crank angle with respect to TDC)

Test condition : 14 hole 60 MPa, BTDC 10℃A injection timing, EGR rate 0 %

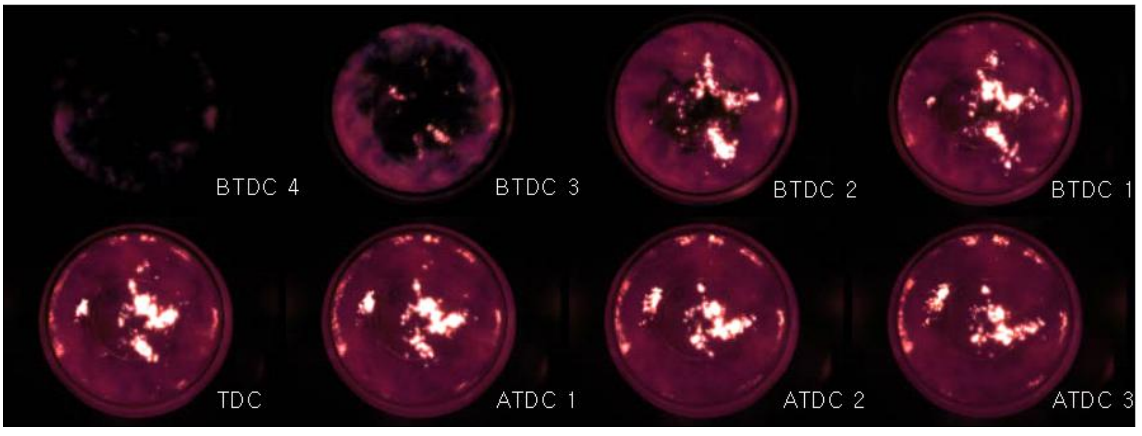

Figure 7 High-speed images of combustion (Crank angle with respect to TDC)

Test condition : 14 hole 60 MPa, BTDC 10℃A injection timing, EGR rate 50 %

Generally, EGR results in lower power output. However, in this study, IMEP was slightly increased for higher EGR rate. At fixed injection timing of BTDC 10^{o}CA, ignition timing might be retarded with EGR while the peak of cylinder pressure was almost retained. Thus, such ignition delay and longer combustion duration led to higher in-cylinder pressure during the expansion stroke, which produced more work during the expansion stroke resulting in IMEP increase.

Figures 6 and 7 show the associated combustion images for EGR rate 0 and 50 % respectively. In Fig. 7, non-luminous blue flame representing the pre-mixed combustion was well observed at the beginning stage, followed by progressive combustion actively emitting luminous flame. EGR rate 50 % case and longer ignition delay compared to EGR rate 0 % case and the first visible flame is seen from BTDC 4℃A. This case had lower level of blue flame at the beginning of combustion with lower combustion flame luminosity, which leads to reduction of NOx emissions.

3.3 The effect of pilot injection and optimized operation

Figure 8 shows the effects of pilot injection on combustion characteristics running at 60MPa injection pressure with 14 hole, at main injection timing of BTDC 5℃A and pilot injection timing of BTDC 25℃A. The pilot injection before main injection results in smoother pressure rise and short ignition delay[1, 5], which is believed to contribute to the improvement of IMEP.

Figure 9 illustrates a temporal sequence of flame images obtained by pilot injection with 14-hole injector. Pilot fuel injected at BTDC 25℃A starts to burn at about BTDC 10℃A, showing a thin flame. At BTDC 1℃A after the start of the main injection, the liquid-phase fuel was surrounded with a number of flames into which the main fuel was injected. During the main injection, burned gas was entrained into the atomized fuel spray. With the pilot injection used, the atomized fuel spray is lacking oxygen because the main injection entrains burned gas due to pilot injection. As a result, combustion progress gradually, causing a relatively low peak of heat release rate. In this case the luminosity continued to increase even after diffusion-controlled combustion is nearly over. Before the appearance of blue flame during pre-mixed combustion duration, the weak luminosity by pilot injection was observed. Thus the fuel spray illuminated by the flame of pilot injection could be observed.

The combined effect of multi-hole injector, EGR and pilot injection on combustion and emission can be observed from the Fig. 10. The result showed increase in IMEP and reduction of NOx, PM, HC and CO emissions compared to single injection with EGR. In particular, in case of 14 hole injection, emission levels were further reduced compared to 5 hole injection case. Therefore, it is concluded that the engine performance and emission characteristics could be optimized through the combined use of multi-hole injection, EGR and pilot injections.

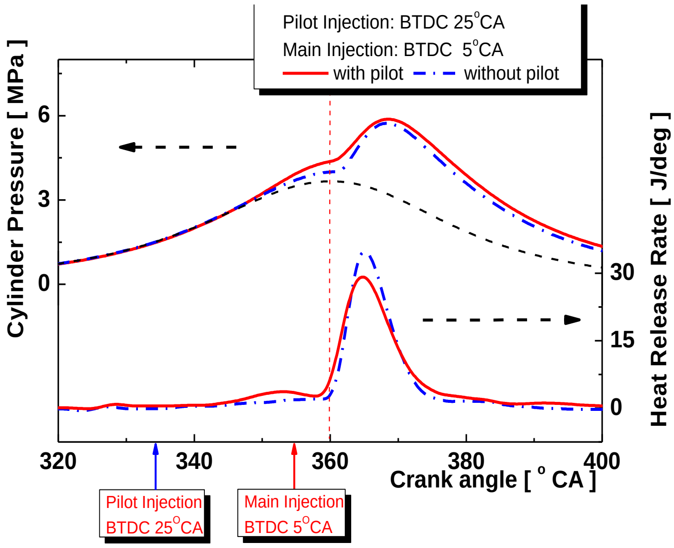

Figure 8 Effect of pilot injection on combustion characteristic curve

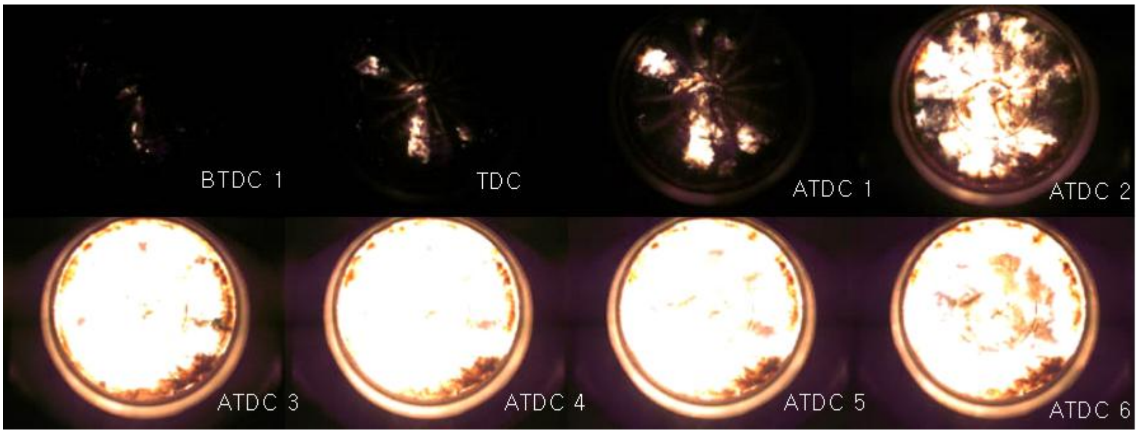

Figure 9 High-speed images of combustion (Crank angle with respect to TDC) Test condition : 30MPa, BTDC 5℃A main injection timing, BTDC 25℃A pilot injection timing

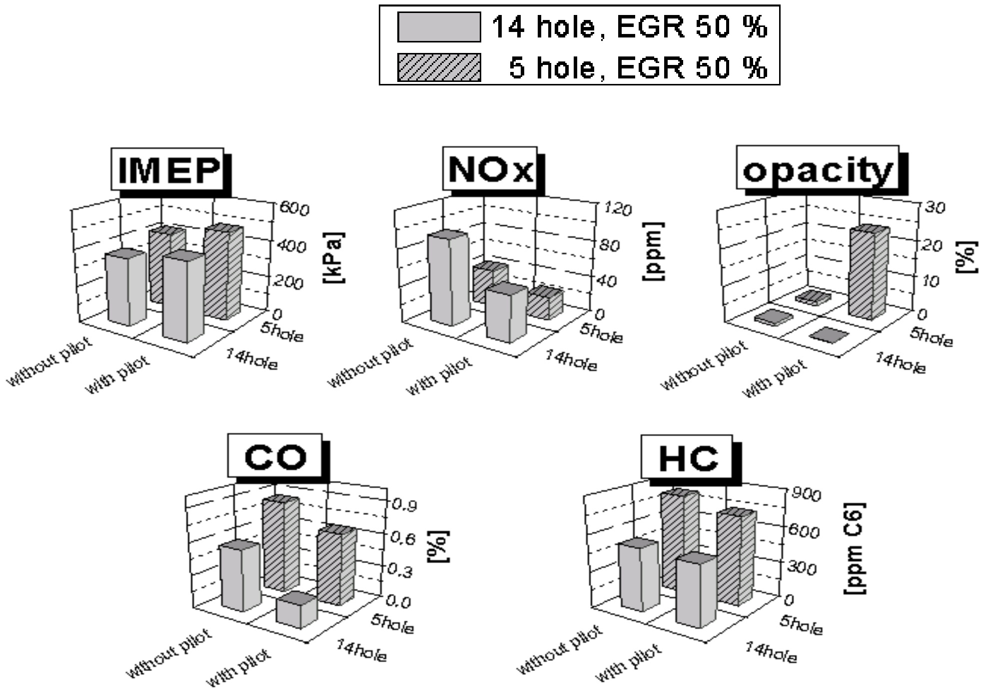

Figure 10 Effect of multi-hole injector, EGR (50 %) and pilot injection on emissions.

4. CONCLUSIONS

The effects of multiple hole with pilot injection and EGR on the engine performance and emissions were investigated through a characterisation of in-cylinder combustion behavior and emission measurement. The findings can be summarised as follows:

- Smaller hole-diameter contributes to a better air-utilisation, which results in low PM, HC and CO emissions. However, NOx emission increases due to the rise of the combustion temperature.
- While EGR is very effective in reducing NOx, it increased all the incomplete combustion products, such as HC, CO and PM.
- Pilot injection provides a significant reduction in the peak of heat release rate. This is due to the reduction of the ignition delay period and the slow-down of the combustion rate entraining the burned gas from pilot injection into the atomized main spray.
- At higher EGR rate, over-lean combustion zone during premixed combustion period increased and thus HC emission is increased.

- Significant improvements in power output and the trade-off between PM and NOx emissions can be obtained if pilot injection is used in conjunction with 14-hole injector and EGR.

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