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A Study on the Effect of Valve Timing on the Combustion and Emission Characteristics for a 4-cylinder PCCI Diesel Engine

Joonsup Han, Jaehyeon Lee, Hyungmin Kim, Kihyung Lee

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***Abstract*—**PCCI engines can reduce NOx and PM emissions simultaneously without sacrificing thermal efficiency, but a low combustion temperature resulting from early fuel injection, and ignition occurring prior to TDC, can cause higher THC and CO emissions and fuel consumption. In conclusion, it was found that the PCCI combustion achieved by the 2-stage injection strategy with optimized calibration factors (e.g. EGR rate, injection pressure, swirl ratio, intake pressure, injection timing) can reduce NOx and PM emissions simultaneously. This research works are expected to provide valuable information conducive to a development of an innovative combustion engine that can fulfill upcoming stringent emission standards.

***Keywords*—**Atkinson cycle, Diesel Engine, LIVC (Late intake valve closing), PCCI (premixed charge compression ignition)

I. Introduction

AS environmental pollution and energy depletion created by transportation have made strict emission regulation. Many research groups have applied their best efforts to solve these problems. To meet the emission regulations, one of the best options is diesel engine which has many advantages such as a approximately 30% higher thermal efficiency, a low fuel consumption, a low emission of CO_2 compared to a gasoline engine. However, the emissions of NOx and PM (particulate matter) produced by locally excessive combustion temperatures or fuel richness are a typical problem for diesel engine technology. HCCI (homogenous charge compression ignition) combustion technique has shown promising results in terms of near-zero NOx and PM emissions. Especially PCCI (premixed charge compression ignition) combustion, which is a kind of HCCI, has recently drawn substantial attention. The concept of PCCI combustion is to enhance the process of air and fuel mixing such that premixed combustion occurs simultaneously across the combustion chamber without diffusion flame. The PCCI engines can reduce NOx and PM emissions simultaneously, but a low combustion temperature resulting from early fuel injection, and ignition occurring prior to TDC, can cause higher THC and CO emissions and fuel consumption. Alternatively, recent exhaust after-treatment systems could suppress the NOx and PM emissions below a desirable level, but this is not a feasible long-term solution because of its complexity, high cost, and inefficient performance at low load condition. Thus, we tried to apply the PCCI concept to solve these problems.

In this study, the combustion and emission characteristics of a 4-cylinder PCCI engine were investigated. In order to realize the PCCI diesel engine, it is need to develop late intake valve closing (LIVC) strategy using Atkinson cycle. Atkinson cycle of PCCI combustion was conducted by retarding the closing time of the intake valve for high engine efficiency and low compression ratio. This paper investigated the performance of PCCI diesel engine applied LIVC strategy. In addition, the effect of various calibration factors (e.g. EGR rate, injection pressure, swirl ratio, intake pressure, injection timing) on the combustion and emissions characteristics was clarified by optimization.

II. Experimental Apparatus

A. Engine System

Fig. 1 shows a schematic of 2000 cc, 4 cylinders CRDI type PCCI diesel engine used in this study. The specifications of the engine along with the common-rail injection system are summarized in Table I. The engine was also equipped with a SCV (swirl control valve), an EGR (exhaust gas recirculation) valve, and a VGT (variable geometry turbo charger), which allowed us to conduct various parametric studies. An EC dynamometer (220kW Meiden) was used to keep the same speed of the engine and measure the engine torque. For emission analysis and fuel supply control, an angle sensor (3600-pulse encoder) and a TDC sensor were attached at the crank and the cam shafts, respectively.

B. Engine Control System

Engine controller was used to control the common-rail pressure, fuel injection timing and injection fuel quantity. TDC and crank angle sensor signals were sent to controller to control injection timing and fuel injection quantity. The injection controller also used a PWM (pulse width modulation)

Kihyung Lee is with Department of Mechanical Engineering, Hanyang Univ., Korea (corresponding author to provide phone: +82-31-400-5251; fax: +82-31-400-4064; e-mail: hylee@hanyang.ac.kr).

Joonsup Han is with Mechanical Engineering, Graduate School, Hanyang Univ., Korea (e-mail: suby815@hanyang.ac.kr).

Jaehyeon Lee is with Mechanical Engineering, Graduate School, Hanyang Univ., Korea (e-mail: hachikoi@nate.com).

Hyungmin Kim is with Mechanical Engineering, Graduate School, Hanyang Univ., Korea (e-mail: hyung2k@hanmail.net).

controller to control VGT, EGR valve, and SCV. WTC (water temperature controller) controlled engine coolant temperature in the range of 82±2 . The temperature of the fuel supplied to the engine was kept in 40 ±0.5.

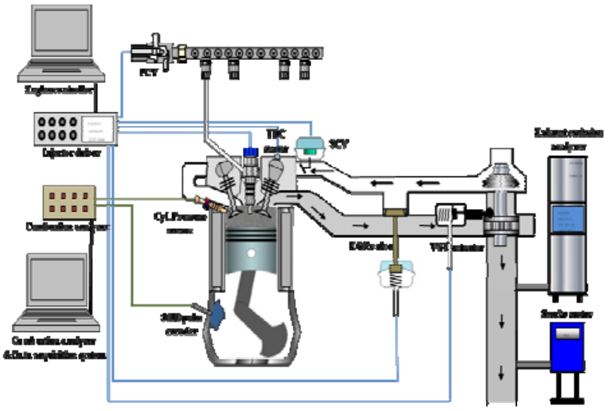


Fig. 1 Schematic of CRDI type PCCI 4-cylinder engine

C. Fuel Injection System

TABLE I
SPECIFICATION OF ENGINE

Description	Specification
Engine type	4-stroke DI
Number of cylinder	4
Bore × stroke (mm)	83 × 92
Displacement volume (cc)	1991
Swirl ratio	Variable
Compression ratio	17.3
Connecting rod length (mm)	145.8

Fuel injection system consisted of low pressure pump, high pressure pump, common rail and injectors. The high pressure pump was driven with camshaft, and pumped the fuel up to 1600bar. The injector version of this experiment is Bosch CP 3.3. The injector has 7 - nozzle holes with 0.141mm hole diameter, and the spray angle is 148^o. The detailed specifications of the injector lists are in Table II. The injector driver (TEMS, TDA-8000) controlled the injection timing, duration and pressure electronically.

TABLE II
SPECIFICATION OF TEST INJECTION SYSTEM

Description	Specification
Fuel injection system	CRDI
FIE	Bosch CP 3.3
Injection pressure	Up to 1600bar
Hole diameter	0.141mm
Hole number	7
Included spray angle	148°
HFR	440

D. Measurement System

A measurement device was installed in the dynamometer controller that can acquire temperatures, pressures, and engine torque. Fuel flow rate was measured using a mass flow meter (CFM 010, Micro motion). NOx, THC, CO, CO_2, and O_2 emissions were evaluated with an exhaust emission analyzer (7100 DEGR, Horiba Co.), and the smoke density was measured with a smoke meter (415S, AVL Co.).

While the engine was running under the steady state condition, all measurements were averaged over 10 seconds. The emission data were measured in ppm/FSN, and all data were converted into g/kWh to correct for sample-to-sample variation. A glow plug-type pressure sensor (6056A, Kistler) attached at the first cylinder to measure the cylinder pressure. A combustion analyzer (MTS Co.) and an encoder were determined the ROHR (rate of heat release), IMEP (indicated mean efficient pressure) and coefficient of variation for the combustion analysis.

III. EXPERIMENTAL CONDITION AND METHOD

A. Optimization Method

A commercial code (MiniTab R14) was used for the optimization technique, and RSM (response surface methodology) of DoE was chosen in this research. A new experiment plan was created using the optimization software. An experiment was carried out with the experiment plan, and a mathematical correlation on the experimental data was created by using a linear regression method. The experimental parameters affecting combustion and emission characteristics of the PCCI engine such as EGR rate, injection pressure, swirl ratio, intake pressure and injection timing were selected in this paper for optimization. The optimal parameters were determined by considering target values in terms of BS (Brake Specific) emissions and BSFC. Five responses were investigated summarized in Table III. A central composite design among the RMS was selected for the second-order polynomial regression analysis model. The total of 125 experimental set would be needed to identify the effect of 3 factors on 5 responses completely; however, 84% reduction in the experimental set was attained using the optimization technique that requires only 20 times of experiment.

B. Combustion and Emission Test Condition

In this study, the effects of changing injection conditions combined with other prevalent calibration factors affecting PCCI combustion (e.g. EGR rate, injection pressure, swirl ratio, intake pressure, injection timing) on the combustion and emission characteristics were also investigated, and the effects

TABLE III
RESPONSES OF DOE

Factor	Abbreviation
Brake Specific Fuel Consumption	BSFC [g/kWh]
Brake Specific Total-hydrocarbon	BSTHC [g/kWh]
Brake Specific Nitrogen Oxides	BSNOx [g/kWh]
Brake Specific Carbon Monoxide	BSCO [g/kWh]
Brake Specific Particulate Matter	BSPM [g/kWh]

of LIVC cam profile on PCCI performance were evaluated by compared with standard cam profile. The detailed PCCI engine injection and operating conditions were tabulated in Table IV. Engine speed and BMEP were fixed 1500 rpm and 4 bar, respectively. The split injection consisted of the early injection set at the middle of compression stroke for sufficient pre-mixing and the main injection set near TDC [5],[9]. Two experimental conditions are only different with cam profile.

TABLE IV
EXPERIMENTAL CONDITION FOR 4- CYLINDER ENGINE TEST

Contents	Condition	
Engine speed	1500 RPM	
BMEP	4 bar	
CAM profile	Standard, LIVC +30°	
Injection pressure	850 ~1300 bar	
Injection method	Split	
Injection timing	Early	ATDC -60°
	Late	ATDC 0, -2.5 °
Intake condition	Pressure	60 ~ 120 mmHg
	EGR ratio	20 ~ 35 %
	Pressure	1.7 ~ 2.7 bar

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. *Effect of EGR Rate on Combustion and Emission*

Fig. 2 represents effects of standard cam closing and LIVC with various EGR rates on BSFC and engine-out emissions with fixed injection timings at ATDC -60° and ATDC 0°. The LIVC case increases BSFC for all EGR rates because the compression ratio of the LIVC is lower than that of the standard cam. Turbo charging or super charging can prevent the increase of BSFC in LIVC application. As shown in Fig. 3, the LIVC decreases in-cylinder pressure during compression stroke owing to lower combustion temperature. As a result, NOx emission generally decreases while CO, THC, and PM emission increase. Fig. 2 shows a good agreement of typical trend in terms of THC, PM and NOx emissions. However, CO emission is not consistent with the typical trend for EGR rate below 30 %. The low combustion temperature worsens combustion efficiency, but a longer ignition delay is believed to enhance the combustion process and result in the low CO emission with the LIVC application. An increase in the EGR rate from 30 % to 35 % results in further reduction in both the combustion temperature and the oxygen concentration, and it dramatically reduces NOx emission but causes an undesirable increase in PM, THC, CO emissions and BSFC. Note that the LIVC strategy decreased the dependency of EGR in terms of NOx emission, which is well known advantage of Atkinson cycle. It was observed that the propensity was identical for various intake valves close timings in this study. Based on the results, it could be concluded that the LIVC strategy combined with EGR 30% is the optimum condition in terms of engine-out emissions and BSFC. Fig. 3 shows in-cylinder pressure as a function of crank angles and EGR rates for standard and LIVC cases. As discussed above, the LIVC decreases the in-cylinder pressure and increasing EGR rate causes further drop of the overall in-cylinder pressure as well as the maximum in-cylinder pressure. It is also noted that the ignition timing was retarded as shown in Fig. 3.

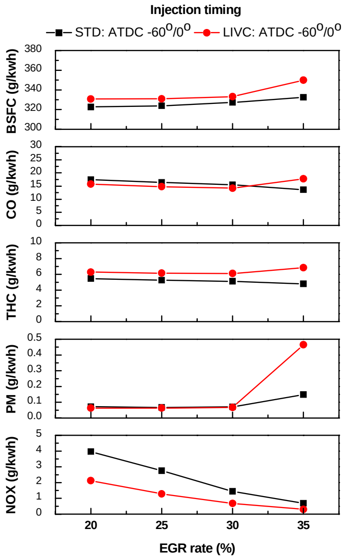
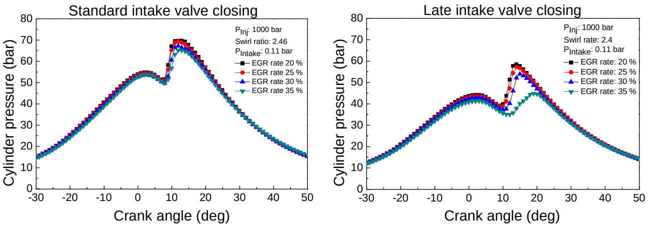
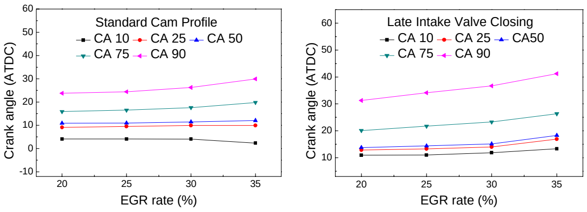


Fig. 2 Effect of EGR rate on BSFC and emissions



(a) Cylinder pressure



(b) Mass fraction burned

Fig. 3 Effect of EGR rate on combustion

B. *Effect of Injection Pressure on Combustion and Emission*

Fig. 4 shows effect of standard cam closing and LIVC with various injection pressures on the combustion and emission characteristics of the PCCI engine. As the injection pressure increases from 850 to 1300 bars, emissions in CO, THC, and PM slightly decreases due to better atomization of the fuel resulting in improving combustion efficiency. With respect to BSFC data, the standard closing initially increases BSFC until the injection pressure of 1150 bars and decreases BSFC at 1300 bars. The LIVC is shown to increase at 1300 bars because a low in-cylinder pressure causes a wall-wetting. In the same reason, CO emission in Atkinson cycle hardly decreases. This fact can also be illustrated in Fig. 5 showing in-cylinder pressure as a function of crank angles and injection pressures for standard and LIVC. Increasing injection pressure with the standard closing not only raises the maximum in-cylinder pressure, but it also advances the combustion phasing slightly closed to TDC, which means that the combustion efficiency before TDC is improved. On the other hand, the maximum in-cylinder pressure in the LIVC increases up to the injection pressure of 1150 bars, but it finally drops at the injection pressure of 1300 bars.

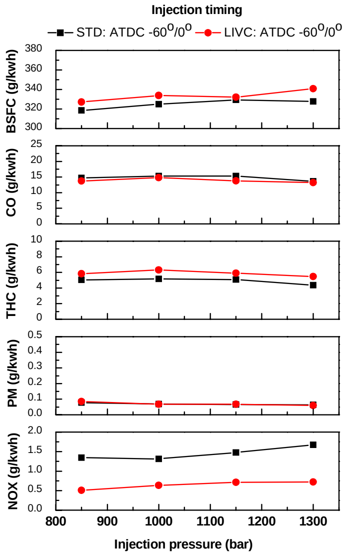
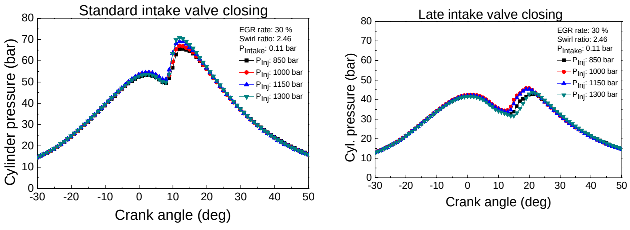
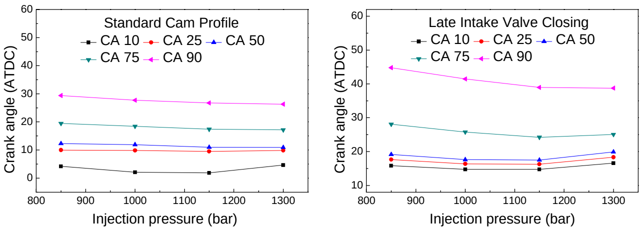


Fig. 4 Effect of injection pressure on BSFC and emissions



(a) Cylinder pressure



(b) Mass fraction burned

Fig. 5 Effect of injection pressure on combustion

C. Effect of Swirl Ratio on Combustion and Emission

The effects of standard cam closing and LIVC with various swirl ratios on the combustion and emission characteristics of the PCCI engine are shown in Fig. 6. It is hard to notice any distinct trend on both cases in terms of swirl ratios from the Fig. 6, but emission results with the standard closing decrease a bit as the swirl ratio increases. It is believed that the swirl contributed to a formation of a better air-fuel mixture. The swirl seems not much to influence on emission characteristics of the PCCI engine with LIVC. This fact can also be illustrated in Fig. 7 showing in-cylinder pressure versus crank angles and injection pressures for standard and LIVC. Increasing swirl strength with the late intake valve closing not only raises the maximum in-cylinder pressure, but it also advances the combustion phasing slightly closed to TDC, which means that the combustion efficiency before TDC is improved. On the other hand, the maximum in-cylinder pressure and combustion position in the standard closing are not affected by swirl ratio.

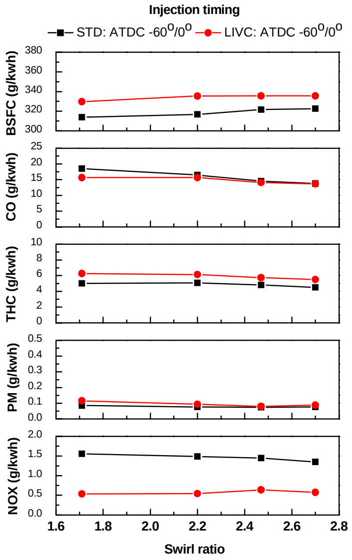
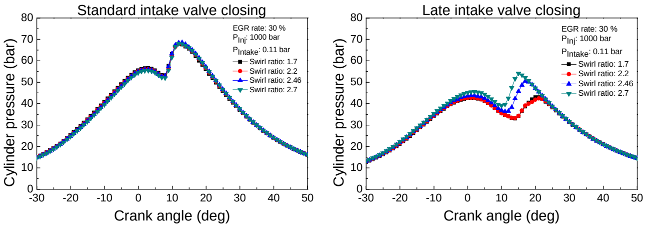
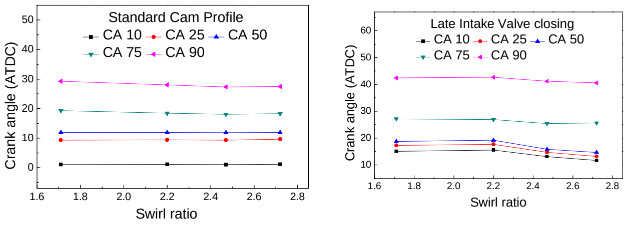


Fig. 6 Effect of swirl ratio on BSFC and emissions



(a) Cylinder pressure



(b) Mass fraction burned

Fig. 7 Effect of swirl ratio on combustion

D. Effect of Intake Pressure on Combustion and Emission

In the same manner, Fig. 8 shows the effects of standard cam closing and LIVC with various intake pressures on the combustion and emission characteristics of the PCCI engine. Elevating intake pressure leads to slight increase in NOx emission and BSFC. A high intake pressure was considered to promote the first combustion efficiency, which reduced ignition delay for the second combustion as shown in Fig. 9. Thus, not only did locally fuel-rich combustion occur in the combustion chamber, but the combustion temperature also increased significantly, and thus so did NOx emissions. Furthermore, the first ignition occurred prior to TDC, which might be the reason for the high BSFC. The LIVC reduces compression ratio inside cylinder such that the high NOx emission can be avoided without a high increase in BSFC.

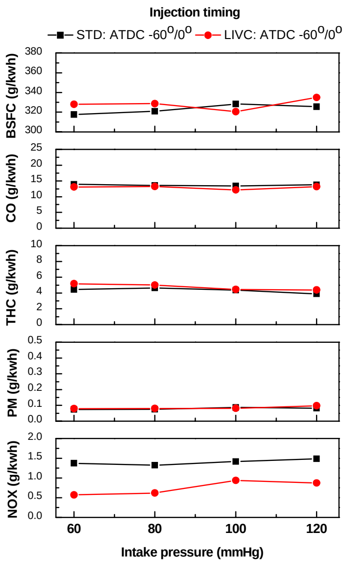
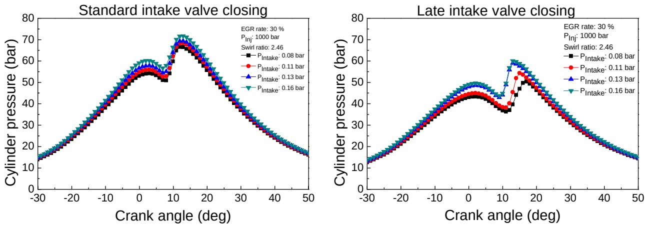
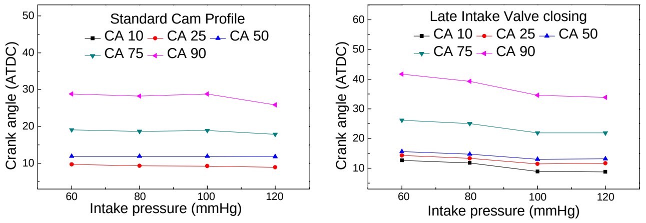


Fig. 8 Effect of intake pressure on BSFC and emissions



(a) Cylinder pressure

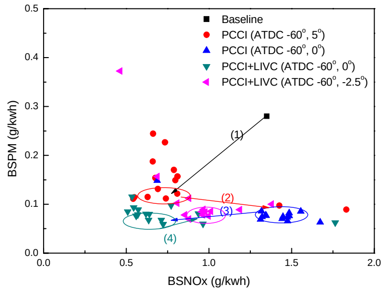


(b) Mass fraction burned

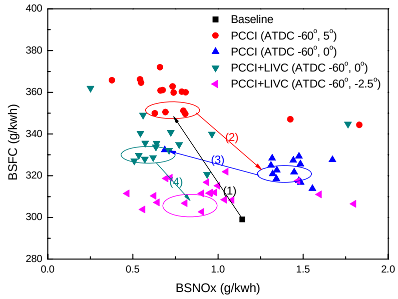
Fig. 9 Effect of intake pressure on combustion

E. Effect of advanced second injection timing

The effects of LIVC with advancing injection timing on the combustion and emission characteristics of the PCCI engine are shown in Fig. 10. Compared to the conventional diesel combustion, PCCI combustion applied with multiple injections at ATDC -60° and ATDC 5° shows simultaneous reduction in PM and NOx emissions. However, an increase in BSFC of PCCI is inevitable due to downgraded combustion efficiency. The BSFC increased approximately 13 % and this trend is consistent with the result obtained by a researching group [11]. The increase in BSFC can be compensated by advancing the second injection timing. When the second injection timing is advanced 5°, an increase in combustion temperature is accompanied with decreasing BSFC and the PM emission. A high NOx emission is concerned in this case, but LIVC lead to a low compression ratio such that it can reduce NOx emission while the PM emission level and BSFC remain constant. In addition, when the second injection timing is advance 2.5° from TDC, BSFC decreased as low as that of base engine, but NOx and PM emissions increased.



(a) BSNOx-BSPM



(b) BSNOx-BSFC

Fig. 10 Effect of operation condition on BSNOx-BSPM and BSNOx-BSFC map

F. Optimization results of operation parameters

Experimental data were plotted in Fig. 11 to determine the optimum responses in terms of BSNOx, BSPM, and BSFC. An optimum point was selected from the plot. The condition of the calibration parameters corresponding to the point was EGR rate of 29 %, the swirl ratio of 1.85, and the intake pressure of 0.12 bar. In this condition, BSNOx and BSPM were simultaneously reduced in 45 % and 43 % compared to those of conventional diesel engines without increasing BSFC. The final results were summarized in Table V. As a result of the optimization of various calibration factors combined with decreasing compression ratio achieved by LIVC, simultaneous reductions in NOx and PM emissions were obtained without increasing fuel consumption. In addition, when compared to NOx emission in a conventional diesel engine, it decreased by 57 % while the fuel consumption and PM emission were retained as shown in Table VI. The condition of the operating parameters corresponding to the point was EGR rate of 31.3 %, the swirl ratio of 2.05, and the intake pressure of 0.1 bar.

TABLE V
COMPARISON OF CONVENTIONAL AND OPTIMIZATION RESULTS WITHOUT INCREASING BSFC

Response	Standard Cam	LIVC	Remarks
BSNOx (g/kwh)	1.35	0.74	- 45 %
BSPM (g/kwh)	0.28	0.16	- 43 %
BSFC (g/kwh)	304	304	0 %

TABLE VI
COMPARISON OF CONVENTIONAL AND OPTIMIZATION RESULTS WITHOUT INCREASING BSFC AND BSPM

Response	Standard Cam	LIVC	Remarks
BSNOx (g/kwh)	1.35	0.58	- 57 %
BSPM (g/kwh)	0.28	0.28	0 %
BSFC (g/kwh)	304	304	0 %

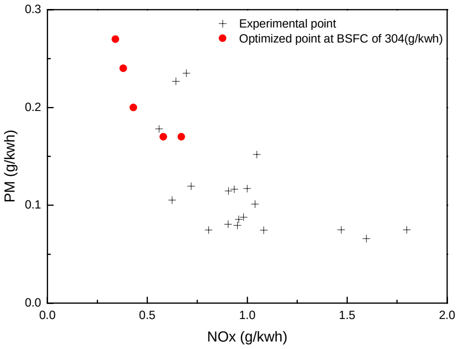


Fig. 11 Experimental and optimized points on BSNOx and BSPM map

V. CONCLUSION

The effects of LIVC and standard closing with various operating conditions on the combustion and emission characteristics of the PCCI engine were investigated. The conclusions can be summarized as follows:

1) The compression ratio was reduced by approximately 1.5 with a 30° LIVC compared to the standard cam.

2) Regardless of a cam type, an increase in the EGR rate decreases the combustion temperature and the air-to-fuel ratio. As a result, NOx emissions decrease rapidly, but PM emissions and BSFC increase.

3) An increase in injection pressure with a standard cam results in a slight decrease in PM, THC and CO emissions, but a slight increase in NOx emissions. However, the high injection pressure of 1300 bar along with the LIVC results in wall wetting which causes a high BSFC.

4) Compared to the standard cam, the LIVC increases BSFC but decrease NOx emission substantially while maintaining PM emissions.

5) An increase in BSFC can be compensated by advancing the second injection timing. When the second injection timing is advanced 5°, an increase in combustion temperature is accompanied with decreasing BSFC and PM emission.

6) As a result of the optimization of various calibration factors, simultaneous reductions in NOx and PM emissions were obtained without increasing fuel consumption. In addition, when compared to NOx emission in a conventional diesel engine, it decreased by 57 % while the fuel consumption and PM emission were retained.

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