공학석사학위논문

디젤 가솔린 융합 연소에서 스월 컨트롤 밸브와 고압 배기 가스 재순환이 미치는 영향에 대한 연구

Effect of Swirl Control Valve and High Pressure Exhaust Gas Recirculation on Diesel/Gasoline Dual-fuel Combustion

2021 년 8 월

서울대학교 대학원

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지도교수 민 경 덕

이 논문을 공학석사 학위논문으로 제출함

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위 원 장 : 김 찬 중

부위원장 : 민 경 덕

위 원 : 송 한 호

Abstract

Effect of Swirl Control Valve and High Pressure Exhaust Gas Recirculation on Diesel/Gasoline Dual-fuel Combustion

Hyungjin Shin
Department of Mechanical Engineering
The Graduate School
Seoul National University

As the emissions regulations become stricter, various studies have been conducted to reduce the emissions. Dual-fuel combustion, which uses two fuels with different reactivity, can reduce nitrogen oxides (NOx) and particle matter (PM) emissions by increasing air-fuel premixing ratio. It can also achieve higher thermal efficiency by compression ignition process. In contrast, dual-fuel combustion involves difficulty to ensure combustion stability at low load condition as low reactivity fuel leads to less auto-ignition tendency.

In this study, the effect of swirl control valve (SCV) and high pressure exhaust gas recirculation (HP-EGR) have been investigated to find the optimal operating strategy which can improve the incomplete combustion and combustion stability at low load condition. Total Hydrocarbon (THC) and Carbon Monoxide (CO) emissions can be reduced by applying SCV and HP-EGR. It can be concluded that swirl flow motion and high intake temperature improved the incomplete combustion

and combustion stability. However, fast combustion with high swirl ratio and intake temperature increased NOx emission and max pressure rise rate (mPRR).

Based on experimental results, the optimization experiment can derive the optimal operating strategy of SCV and HP-EGR at the four operating conditions. At low load conditions, incomplete combustion and low combustion stability is major challenge of dual-fuel combustion. High swirl ratio and HP-EGR can improve combustion stability and thermal efficiency at low load conditions. At high load conditions, satisfying mPRR and NOx emission is important to optimize dual-fuel combustion. Low swirl ratio and LP-EGR to decrease mPRR and NOx emission can be considered at the high load conditions. The experimental results show that applying the SCV and HP-EGR can improve the incomplete combustion and combustion stability on dual-fuel combustion at the low load condition.

Keywords: Dual-fuel Combustion, Swirl Control Valve, High Pressure Exhaust Gas Recirculation, Combustion Stability, Gross Indicated Thermal Efficiency

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Nomenclature

AFR	air-fuel ratio
ATDC	after top dead center
BTDC	before top dead center
CA	crank angle
CDC	conventional diesel combustion
CO	carbon monoxide
CO_2	carbon dioxides
CoV	coefficient of variation
DIT	diesel injection timing
DPF	diesel particle filter
EGR	exhaust gas recirculation
EVC	exhaust valve close
EVO	exhaust valve open
gIMEP	gross indicated mean effective pressure
GIE	gross indicated thermal efficiency
HCCI	homogeneous charge compression ignition
HP-EGR	high pressure exhaust gas recirculation
IVC	intake valve close
IVO	intake valve open
LHV	low heating value
LNT	lean NOx trap
LP-EGR	low pressure exhaust gas recirculation
MFB50	mass fraction burned 50%
mPRR	max pressure rise rate
NOx	nitrogen oxides
PCCI	premixed charge compression ignition
PM	particle matter
RCCI	reactivity controlled compression ignition
RDE	real driving emission
SCR	selective catalyst reduction
SCV	swirl control valve

TDC	top dead center
THC	total hydrocarbon
WLTP	world harmonized light vehicle test procedure

Chapter 1. **Introduction**

1.1 Research Background

Diesel engine has the advantage of fuel efficiency and Carbon Dioxides (CO_2) emission compared to gasoline engine. However, compression ignition on diesel engine generates the Nitrogen Oxides (NOx) and Particle Matter (PM) emissions which are harmful to human health. As the concern of environment and health increases, the recognition of diesel engine has been worse. Furthermore, emissions and fuel efficiency regulations are becoming stricter worldwide due to the global warming. EURO 6 has been applied as an emissions regulation for passenger vehicles, adding the WLTP (World harmonized Light vehicle Test Procedure) and RDE (Real Driving Emission) test, and the future regulation should be more strengthened [1].

After-treatment systems were developed and applied to satisfy the emissions regulations. Although the after-treatment system such as DPF (Diesel Particle Filter), LNT (Lean NOx Trap) and SCR (Selective Catalyst Reduction) can reduce the NOx and PM emissions, they increase the manufacturing cost, vehicle weight and pumping loss of engine. Thus, the research of the advanced combustion technology is necessary for the high thermal efficiency with low emissions.

1.2 Previous Research

Various concepts of the advanced combustion were suggested to achieve low emissions with high thermal efficiency. HCCI (homogeneous charge compression ignition) is the compression ignition with homogeneous mixture by early injection. Fuel is injected before intake valve open to reinforce the mixing of air and fuel. Well-premixed and low temperature combustion can achieve very low NOx and PM emissions. However, controllability of combustion phase is difficult due to homogeneous auto-ignition with high max pressure rise rate [2-3].

PCCI (premixed charged compression ignition) was introduced to improve the controllability compared with HCCI. Early injection of PCCI increases the ignition delay to achieve well air-fuel mixing and low NOx and PM emissions. However, PCCI also occurs high peak pressure and pressure rise rate due to using single fuel. PCCI has limitation of operating range same as HCCI [4-5].

To resolve the limitation of PCCI and HCCI, many researchers were suggested the combustion with two different fuels. Dual-fuel combustion, which uses two fuels with different reactivity, can increase air-fuel premixing ratio by early injection of low reactivity fuel. It can work compression ignition process by auto-ignition of high reactivity fuel. As a results, dual-fuel combustion can reduce NOx and PM emissions with high thermal efficiency [6-7].

Dual-fuel combustion has variable operating parameter such as injection timing, fuel substitution rate, fuel properties and EGR rate, etc. Researchers have investigated optimal operating strategies for dual-fuel combustion. Lee et al. insisted that different injection strategies are needed in low-load and high-load conditions [8]. Mousavi et al. investigated the effect and characteristic of pilot injection strategy on part load condition [9]. Benajes et al. suggested that early injection, multiple

injection and single injection around TDC can improve dual-fuel combustion in the order of low, middle and high load condition [10]. Injection strategies has trade-off between air-fuel premixing and pressure rise rate. Thus, injection timing and strategies are different with conventional diesel combustion at each operating condition.

The use of varying fuel substitution rate and property was introduced by many researchers. Yang et al. changed the fuel blending ratio for low emissions and high thermal efficiency under wide operating range [11]. Hanson et al. found that combustion phase of dual-fuel combustion can be controlled by adjusting the fuel substitution rate. Combustion speed is decreased with high fuel substitution rate [12]. Benajes et al. explained the effects of the diesel/gasoline fuel ratio on the RCCI. As the diesel/gasoline fuel ratio decreases, the ignition delay increases; the first combustion stage period shortens, and the second combustion stage is enhanced [13]. Tong et al. achieved low emissions level by using PODE (polyoxymethylene dimethyl ethers) with high cetane number. But high reactivity fuel of high cetane number occurred the combustion with the high pressure rise rate [14]. Derek et al. have used CNG as low reactivity fuel. They found that CNG can reduce the pressure rise rate compared with gasoline on dual-fuel combustion [15]. Kang et al. introduced propane gas with low reactivity and insisted that it can be useful in high-load conditions or for a high-compression-ratio engine with dual-fuel combustion with a knocking problem [16].

EGR rate is also the major parameter that can controlled the combustion phase by reducing reactivity of dual-fuel combustion with the NOx reduction. High EGR rate prolongs the ignition delay and increases the premixed combustion phase [17]. Splitter et al. insisted that EGR rate was increased to reduce the peak pressure and pressure rise rate at high load condition [18].

However, dual-fuel combustion has narrow operating range compared with conventional diesel combustion [19]. At low load condition, substitution of low reactivity fuel occurs the incomplete combustion with low combustion stability. At high load condition, improving air-fuel premixing ratio of dual-fuel combustion causes higher pressure rise rate which affects engine noise, vibration and knocking problem [20]. Therefore, considerable research has been conducted to expand the operating range of the dual-fuel combustion. Kokjohn S. et al. used the various fuel reactivity to control the combustion phase with reasonable pressure rise rate for part and high load condition [21]. Chu et al. applied low tumble flow head and intake to expand the high load condition. Low tumble flow head and intake reduced relatively low pressure rise rate and achieve the expansion of high load condition [22]. Wang H et al. suggested the late intake valve closing(LIVC) strategy which reduces the effective compression ratio for high load expansion. Reducing effective compression ratio occurred combustion phase with low pressure rise rate and expand the high load condition [23]. Park et al. introduced the mixture stratification by multiple injection strategy to improve the thermal efficiency with low THC and CO emissions at low load conditions [24].

Various operating strategies were investigated to reduce NOx and PM emissions with improving thermal efficiency. However, dual-fuel combustion has disadvantage of operating range compared with conventional diesel combustion. Most of the research about expanding operating were focused on high load condition. Thus, additional optimization of operating strategies is necessary to expand the low load condition.

1.3 Research Objective

From the previous researches, the dual-fuel combustion can achieve low NOx and PM emissions and high thermal efficiency. Various operating strategies were suggested to increase the thermal efficiency. However, dual-fuel combustion has narrow operating range compared with conventional diesel combustion. Expanding the operating range has limitations in optimizing operating strategies. Additional hardware optimization on dual-fuel combustion is necessary to expand the operating range effectively.

In this study, swirl control valve and HP-EGR were considered to improve the incomplete combustion and combustion stability. The effect of swirl control valve and HP-EGR was evaluated at low load condition (1,500 rpm / gIMEP 5.2 bar). Based on previous experimental results indicating the tendency of combustion characteristic, the optimization experiment can derive the optimal operating strategy of SCV and HP-EGR at the four operating condition.

Chapter 2. **Experimental Setup and Conditions**

2.1 Experimental Setup

This research was implemented on a single cylinder engine with 395cc displacement. The dual-fuel single cylinder engine was manufactured by Seoul National University. Detail engine specifications are shown in Figure 1 and Table 1 [25]. The compression ratio of 14 was appropriate to satisfy the max pressure rise rate and reduce NOx and PM emissions compared with the compression ratio of 16. The bathtub-shaped piston bowl was selected to reduce heat loss of dual-fuel combustion. The head and intake port of the dual-fuel engine was manufactured to generate low tumble flow motion for high load expansion. A 37 kW DC dynamometer was used to operate the engine. Diesel fuel was directly injected by a solenoid injector with 6 nozzle holes. It was injected at low pressure (450 bar) due to earlier injection timing of duel-fuel combustion compared with conventional diesel combustion. Gasoline fuel was injected by port injection system with two solenoid injectors. Two Coriolis type fuel flow meters (OVAL Altimass CA001) were used to measure the fuel flow rates.

The concentrations of carbon monoxide (CO), CO_2, oxygen (O2), NOx and total-hydrocarbon (THC) were measured at an exhaust gas analyzer (HORIBA, MEXA 7100DEGR). The soot was measured by a smoke-meter (AVL, 415S). The intake pressure and in-cylinder pressure were measured every 0.1 crank angle by a combustion analyzer (Kistler, Kibox To Go 2893). A schematic diagram of the experimental setup was shown in Figure 2 [25].

The EGR rate was defined based on the concentration of the CO_2 in the intake and exhaust mixtures. The properties of fuels are presented in Table 2. The ratio of

each fuel was calculated based on the fuel energy flow by considering low heating value of fuels.

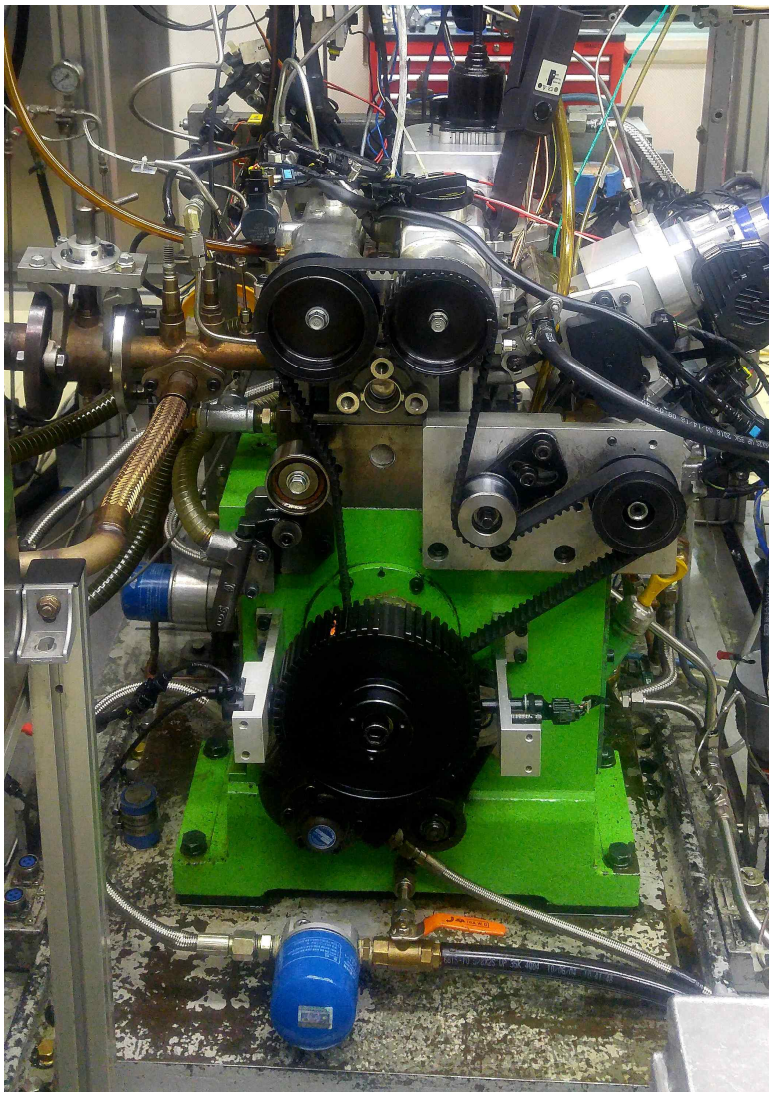

Figure 1. Dual-fuel single cylinder engine [25]

Table 1. Engine specifications

Bore x Stroke [mm]	77.2 x 84.5
Displacement [cc]	395.5
Compression Ratio [-]	14
Con. Rod Length [mm]	140
Valve Timing	IVO : 8° BTDC IVC : 36° ABDC EVO : 46° BBDC EVC: 4° ATDC

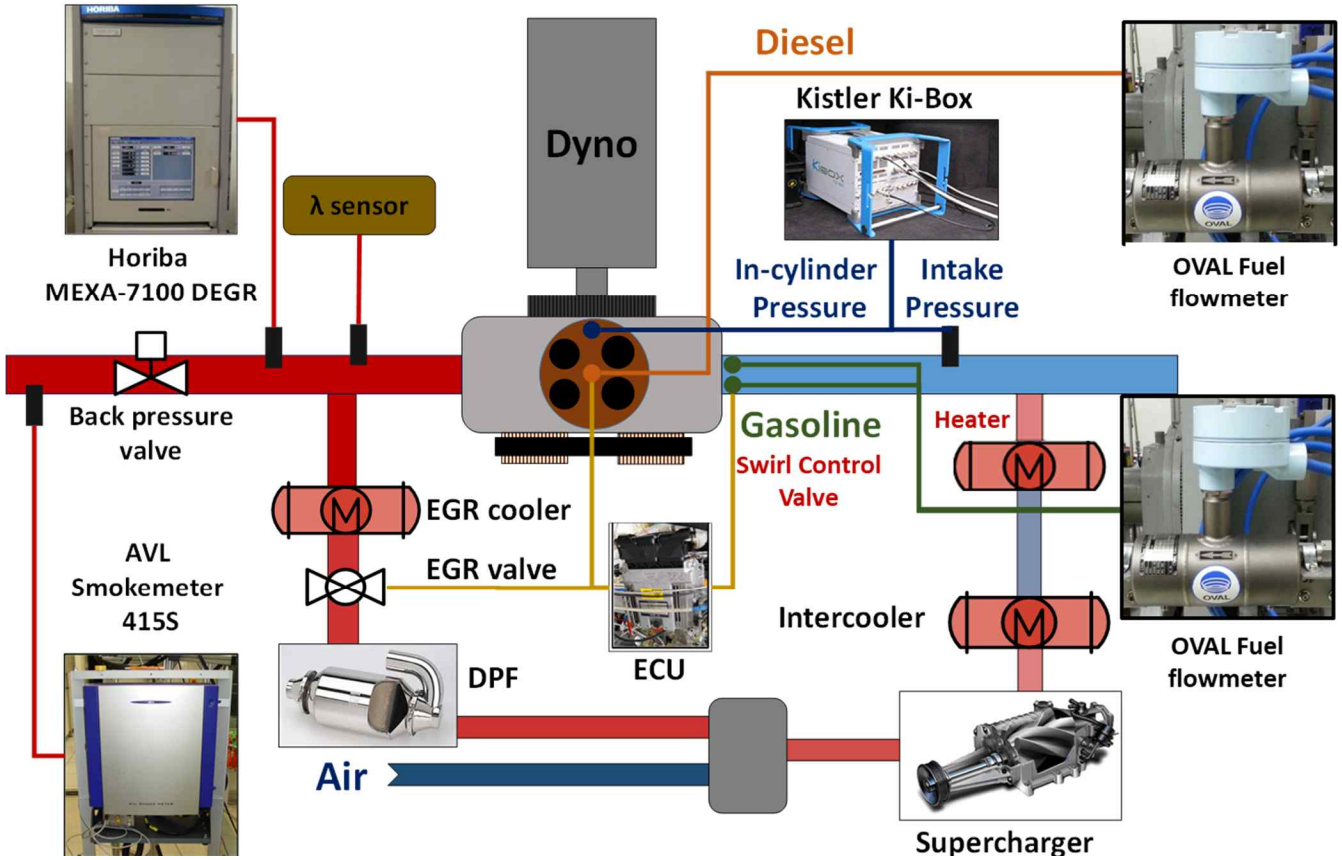

Figure 2. Schematic diagram of the experimental setup [25]

Table 2. Properties of diesel and gasoline

	Diesel	Gasoline
Chemical Formula	CxH2.0x	CxH2.0x
Density [g/cm^3]	0.831	0.724
Low heating value [MJ/kg]	42.5	42.8
Cetane/Octane number	54 (CN)	91 (RON)
Stoichiometric ratio of AFR [wt.%]	14.6	14.5

2.2 Swirl Control Valve and HP-EGR System

A swirl control valve(SCV) presented in Figure 3 was located between the intake manifold and the intake port. The swirl control valve controls the intake flow motion by valve opening rate. Swirl flow motion was generated when the valve was closed. The experiment was conducted at two valve opening rates: 0 (fully closed, SCV on, swirl) and 100 % (fully open, SCV off, no swirl). Figure 4 shows the swirl ratio of each valve opening rate calculated by 3D-CFD at 1,500 rpm / gIMEP 5.2 bar condition. The number of full-mesh grid is 840,000 at cylinder and ports. Additional valve geometry is inserted at full-mesh intake port to simulate actual swirl control valve.

After EGR and air mixture was compressed by a supercharger which controls the intake pressure, it was cooled at constant temperature by an intercooler. Thus, basic EGR system of the single cylinder engine was similar to low pressure exhaust gas recirculation(LP-EGR). Implementing the actual HP-EGR system in the single cylinder engine was challenging because it was difficult to maintain a certain level of back pressure for HP-EGR application. In this study, HP-EGR was used to increase the intake gas temperature for improving the combustion stability. Thus, the effect of HP-EGR increasing the intake gas temperature was simulated by heating the intake air with a heater located before the intake manifold.

Figure 3. Swirl control valve (Left : Open, Right : Close)

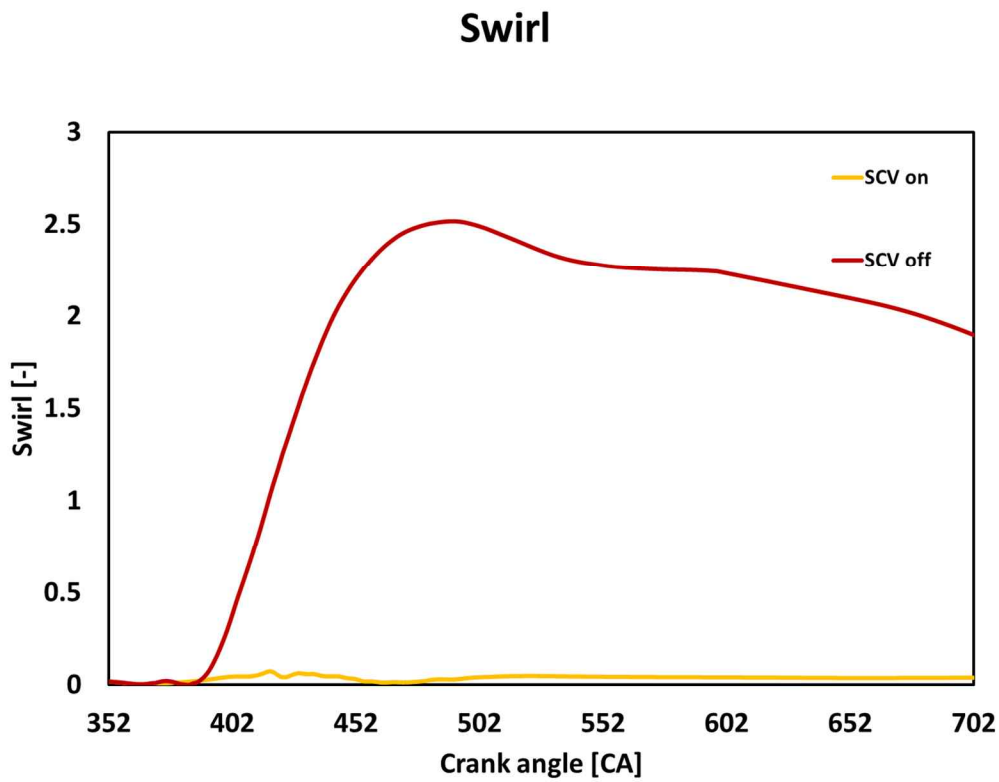

Figure 4. Swirl ratio of each valve opening rate

2.3 Experimental Condition

The experiment consisted of three parts. The diesel injection timing swing experiments conducted to determine the effect of swirl flow motion at 1,500 rpm / gIMEP 5.2 bar and DIT of 16°, 26°, and 36° BTDC. The swirl ratio was controlled by turning the SCV off (low swirl) and on (high swirl). The intake pressure was 1.1 bar and the gasoline ratio was 40%. EGR was not used.

The intake temperature swing experiments conducted to identify the effect of HP-EGR at 1,500 rpm / gIMEP 5.2 bar with EGR rate 40%. MFB50 was 6° ATDC. The intake pressure was 1.1 bar and the gasoline ratio was 50%. The intake temperature was controlled 25°C (LP-EGR), 60°C and 80°C by heater to determine the effect of HP-EGR.

Based on the previous experimental results, optimization experiments were conducted at four operating points (1,500 rpm / gIMEP 5.2 bar, 1,750 rpm / gIMEP 7.2 bar, 2,000 rpm / gIMEP 9.3 bar and 11.7 bar) with different SCV and EGR states in dual-fuel combustion. Table 3 shows the four operating conditions. For the optimized points, NOx and PM should be less than 40 ppm and 0.2 FSN, respectively. The coefficient of variation must be less than 5%, and the mPRR must be less than 10 bar/deg. The target constraints were shown in Table 4.

Table 3. Operating conditions on optimization experiment

Operating Conditions				
Engine Speed [RPM]	1,500	1,750	2,000	
gIMEP [bar]	5.2	7.2	9.3	11.7
Boost Pressure [bar]	1.06	1.26	1.39	1.69

Table 4. Target constraints of optimizing points

Target Constraints	
NOx [ppm]	Below 40
PM [FSN]	Below 0.2
mPRR [bar /deg]	Below 10
CoV [%]	Below 5

Chapter 3. **Experimental Results and Discussion**

3.1 Effect of Swirl Control Valve with Varying DIT

Figure 5 shows the in-cylinder pressure and heat release rate of the swirl on/off experimental results at DIT of 16°, 26°, and 36° BTDC. The results were compared when the SCV was opened and closed at 1,500 rpm, gIMEP 5.2 bar.

In both cases, the combustion phase, including the MFB 50 point, became transient condition from advancing to retarding. This was related to the leaner local equivalence ratio due to an earlier DIT, resulting in a prolonged ignition delay. This phenomenon was well known from previous research on RCCI combustion. The combustion phase was advanced with faster combustion speed at the swirl on condition. It can be concluded that increasing the swirl motion in the cylinder enhanced the spreading of diesel spray, shortening the first stage of burning. Because the influence of swirl flow motion was strong in highly premixed conditions, the combustion stability can be improved by swirl flow motion.

Figures 6 and 7 show the THC and CO emissions for different DITs. THC formation is determined by the oxidation rate related to the combustion temperature. Enhancing the premixed air–fuel mixture condition resulted in a faster burning rate. Increasing the combustion temperature improved THC oxidation rate so that increasing swirl ratio resulted in lower THC emission. CO emission is related to the air–fuel local equivalence ratio. If air–fuel becomes rich, CO emission increases due to a lack of oxygen to react. As swirl flow motion can make the local equivalence ratio leaner, increasing the swirl ratio significantly contributes to the reduction in CO

emission. In all cases, increasing the swirl ratio advanced MFB 50 closer to the compression stroke, resulting in decrease in THC and CO emissions.

Figures 8 and 9 show the NOx and PM emissions for different DIT. NOx generation is mainly affected by combustion temperature and oxygen concentration. The well-premixed condition with swirl flow motion increased the NOx emission by higher combustion temperature. Thus, swirl flow motion improved the combustion stability, but NOx emission should be controlled by additional EGR supply. PM is generated by incomplete combustion in rich equivalent ratio region. Swirl flow motion enhanced the premixed air-fuel mixture condition, which can decrease the PM emission. Furthermore, increasing the swirl ratio may shorten the diesel spray length by spreading the spray to reduce wall impingement which is the major reason of PM reduction with DIT 36° BTDC. The result is suggested that increasing the swirl ratio is appropriate for dual-fuel PCI based on the earlier DIT strategy to avoid wall-impingement.

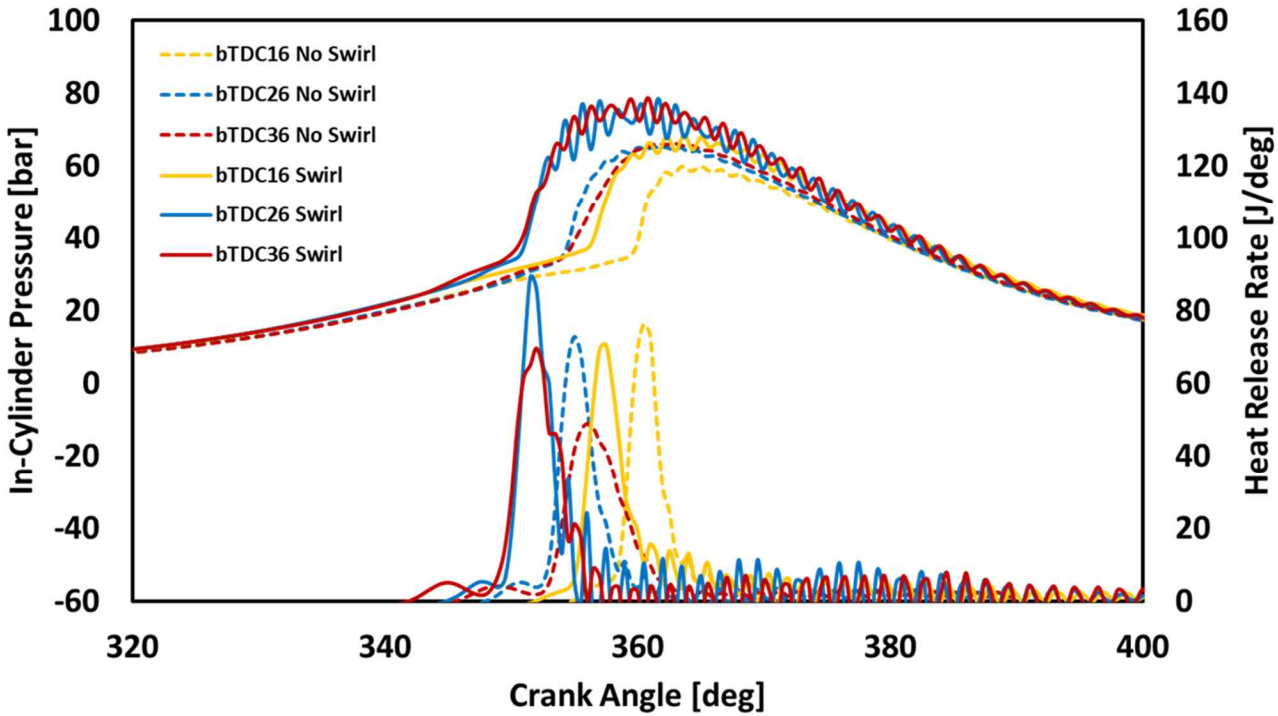

Figure 5. In-cylinder pressure and heat release rate for different DITs with swirl on and off at 1,500 rpm / gIMEP 5.2 bar

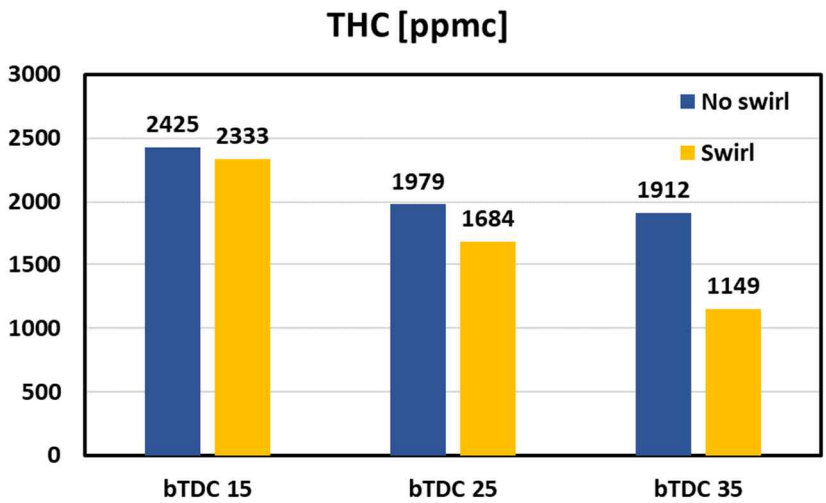

Figure 6. THC emission for different DITs with swirl on and off at 1,500 rpm / gIMEP 5.2 bar

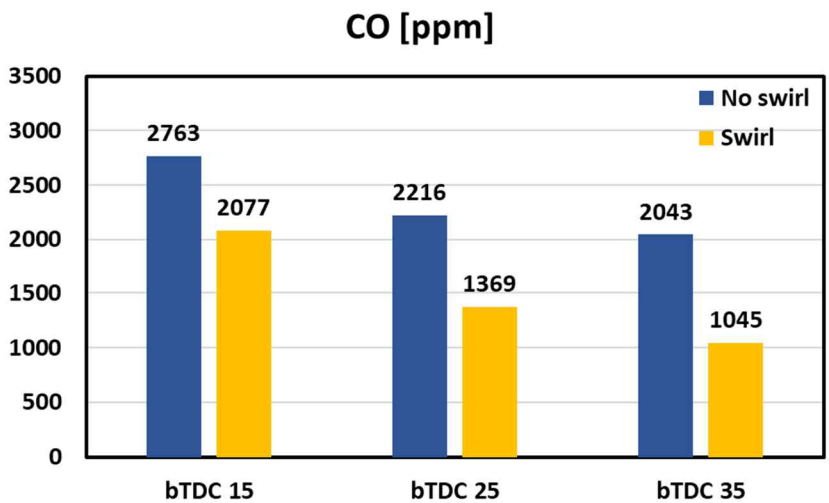

Figure 7. CO emission for different DITs with swirl on and off at 1,500 rpm / gIMEP 5.2 bar

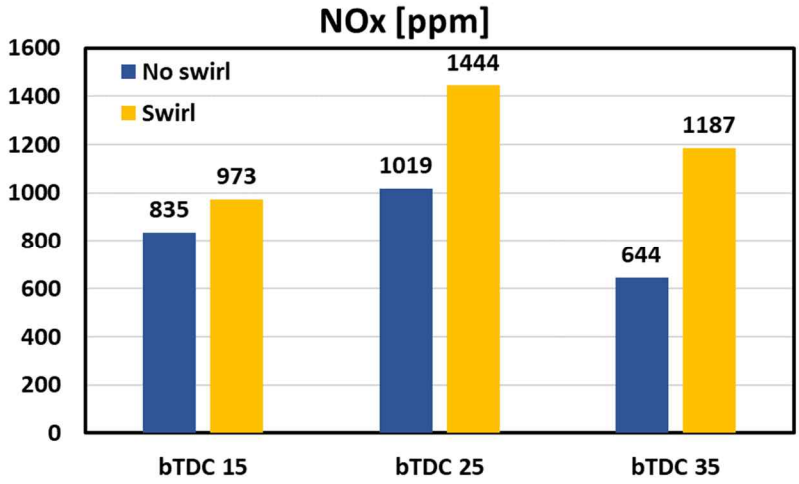

Figure 8. NOx emission for different DITs with swirl on and off at 1,500 rpm / gIMEP 5.2 bar

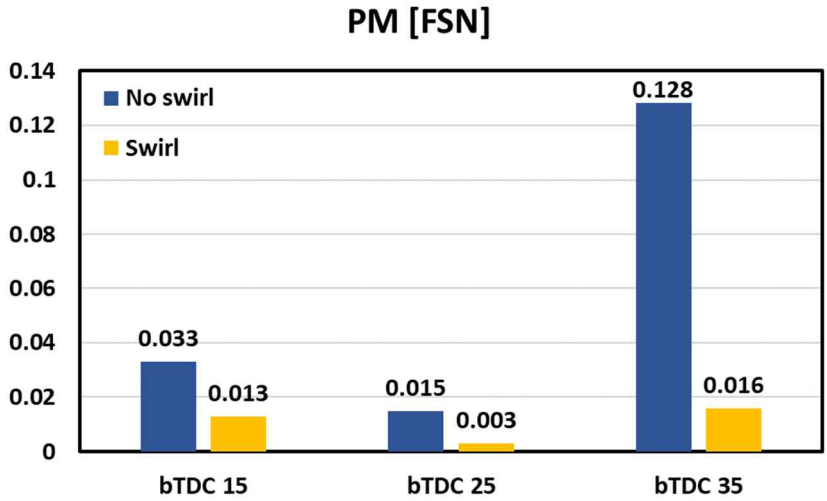

Figure 9. PM emission for different DITs with swirl on and off at 1,500 rpm / gIMEP 5.2 bar

3.2 Effect of HP-EGR

Figure 9 shows the in-cylinder pressure and heat release rate at intake temperature 25°C, 60°C, 80°C with EGR rate 40% and 25°C with EGR rate 0% condition. In same intake temperature cases, EGR supplement increased the heat capacity of air-fuel mixture so that combustion speed and pressure rise rate decreased at EGR rate 40% condition. Increasing the intake temperature affected in-cylinder condition which enhanced the initial ignition condition and burning rate. The combustion phase with the faster combustion speed was advanced by increasing the intake temperature. Because applying HP-EGR increased the intake temperature, combustion stability can be improved by HP-EGR.

Figures 10 and 11 show THC and CO emissions with various intake temperature. EGR supplement decreased overall combustion temperature so that THC and CO emissions were increased at EGR 40% condition. However, increasing the intake temperature with the same EGR rate can improve the THC oxidation rate by higher combustion temperature. CO produced by the incomplete combustion can be oxidized under high temperature condition. Even if the equivalent ratio, the main cause of CO formation, was the same, high combustion temperature reduced CO emission. Thus, increasing the intake temperature by applying HP-EGR can reduce the products of incomplete combustion, THC and CO emissions.

Figures 12 and 13 show NOx and PM emissions with various intake temperature. EGR can reduce NOx emission by decreasing the combustion

temperature. NOx emission was reduced by 86~92% with EGR rate 40% condition. However, increasing the intake temperature generated low levels but relatively high NOx emission by higher combustion temperature. PM formation is related to the local air-fuel equivalent ratio. The mass of intake air is reduced at higher intake temperature condition with the same intake pressure. PM emission increased due to the lack of oxygen to react by increasing the intake temperature. Thus, increasing the intake temperature by applying HP-EGR can reduce the THC and CO emissions, but the substitution rate of the low reactivity fuel should be adjusted to reduce PM emission.

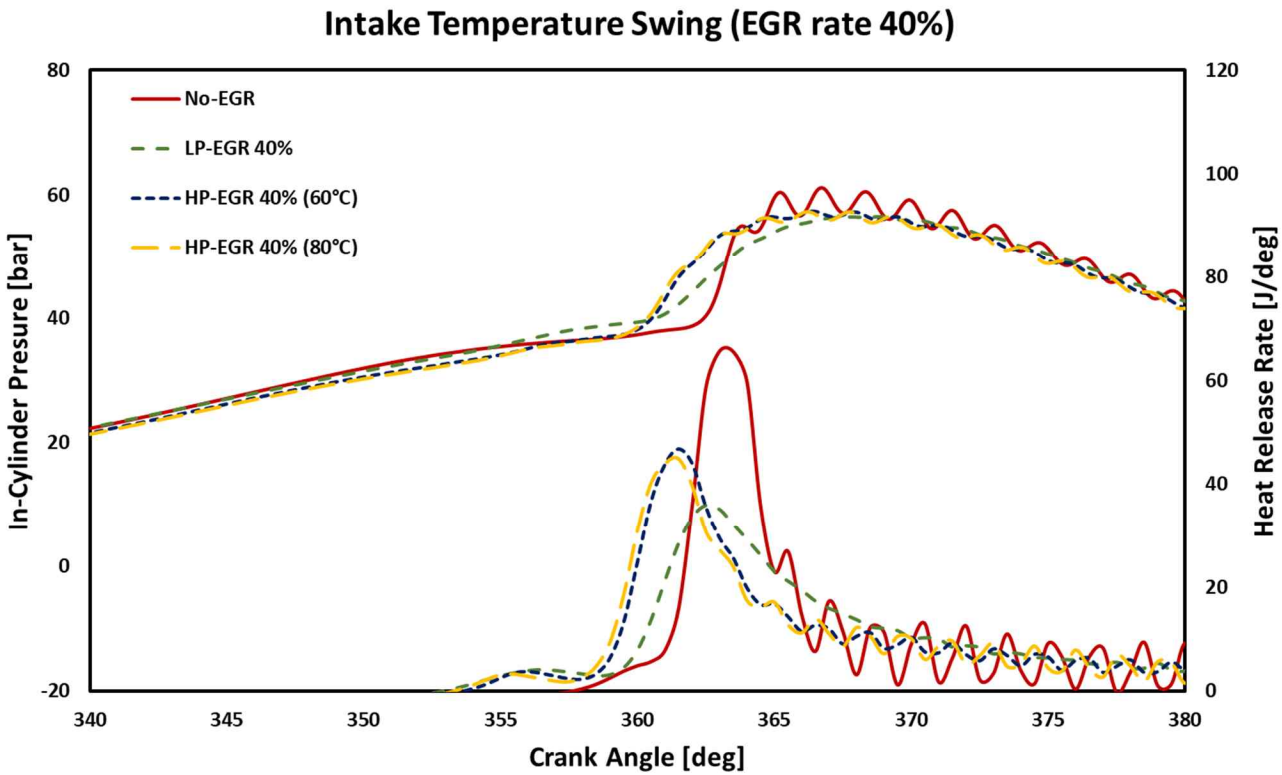

Figure 10. In-cylinder pressure and heat release rate with various intake temperature at 1,500 rpm / gIMEP 5.2 bar

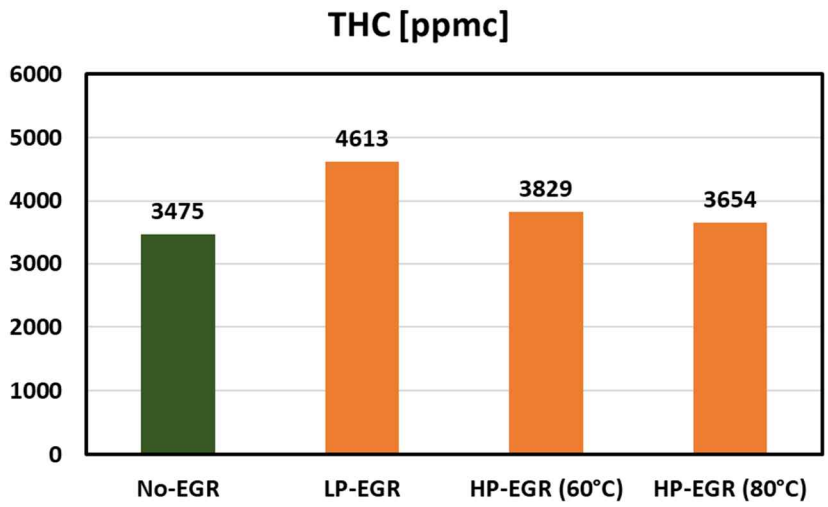

Figure 11. THC emission with various intake temperature at 1,500 rpm / gIMEP 5.2 bar

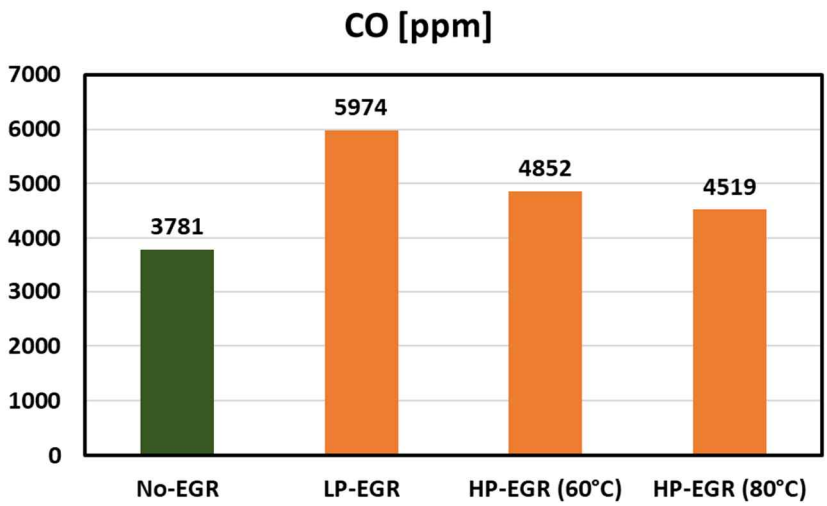

Figure 12. CO emission with various intake temperature at 1,500 rpm / gIMEP 5.2 bar

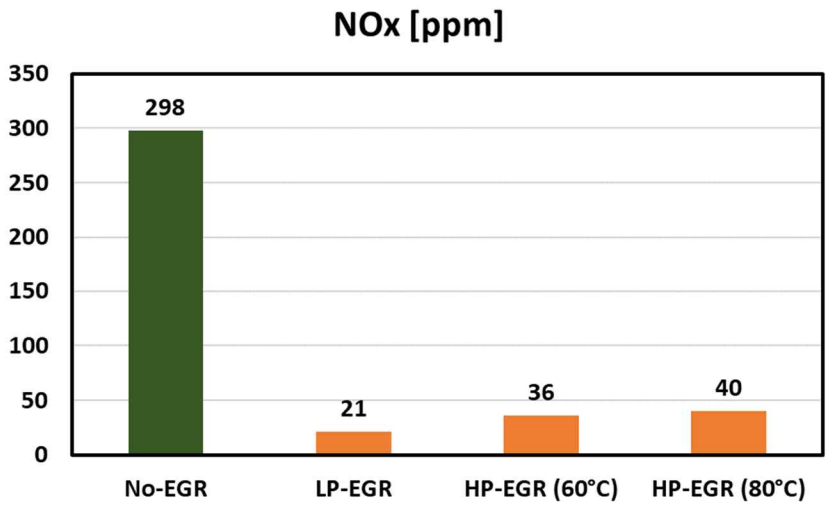

Figure 13. NOx emission with various intake temperature at 1,500 rpm / gIMEP 5.2 bar

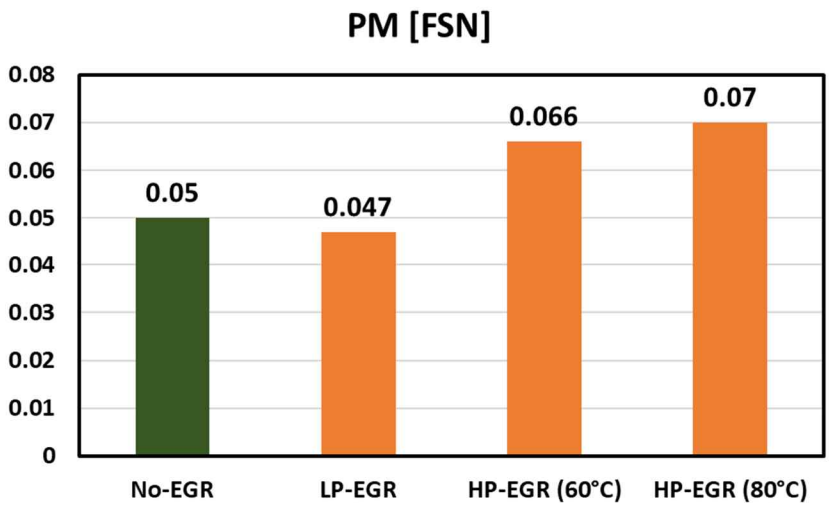

Figure 14. PM emission with various intake temperature at 1,500 rpm / gIMEP 5.2 bar

3.3 Optimal Strategy of SCV and HP-EGR on Dual-fuel Combustion

Figure 15,16,17 and 18 show the in-cylinder pressure and heat release rate in the optimized dual-fuel combustion with a compression ratio of 14 and a bathtub piston at 4 operating condition. The criteria for optimization were presented in experimental condition part.

The HRR curve shape became narrow and sharp with increasing swirl ratio and intake temperature. Increasing swirl ratio and intake temperature generated more combustible air–fuel mixture; thus, additional EGR should be supplied to meet the NOx emission and mPRR limits. Higher intake temperature also caused rich equivalent ratio condition. Gasoline fraction should be increased to satisfy the PM emission limit. Advancing the DIT was attempted. Advancing the DIT to decrease the NOx emission produced insufficient reduction, and the slower combustion phase led only to decrease in GIE. As a result, the limit was satisfied by supplying additional EGR and gasoline fraction. Figure 19 shows the gross indicated thermal efficiency of each operating condition. At low-load condition, it is important to improve thermal efficiency through improving incomplete combustion and combustion stability. Improvement of incomplete combustion and combustion stability was possible with increasing swirl ratio and intake temperature. For 1,500 rpm / gIMEP 5.2 bar and 1,700 rpm / gIMEP 7.2 bar, the coefficient of variation with high swirl and intake temperature was the lowest. The GIE with high swirl and intake temperature increased 3.2%p and 1.6%p compared with the GIE at the base condition

In contrast, at the high load condition, satisfying the mPRR and NOx emission is major challenge to optimize dual-fuel combustion. To prevent an increase in mPRR and NOx emission, additional EGR should be supplied at high swirl and intake temperature condition. Additional EGR supplement may lead to poor ignitibility and rich equivalent ratio. For 2,000 rpm / gIMEP 9.3 bar, the GIE with low swirl and high intake temperature was highest. Max pressure rise rate was near 10 bar/deg with operating strategies with LP-EGR at 2,000 rpm / gIMEP 11.7bar condition. Any operating strategies with HP-EGR cannot satisfy the target constraint of max pressure rise rate. For 2,000 rpm / gIMEP 11.7 bar, the GIE with low swirl and intake temperature was highest. The optimal strategies of each condition were presented in Table 5.

High swirl motion and HP-EGR is suitable to improve combustion stability at low load condition. Low swirl motion or LP-EGR to decrease mPRR and NOx emission can high thermal efficiency with satisfying the target constraint at the high load condition. SCV and HP-EGR system can be considered to expand the low load condition on dual-fuel combustion.

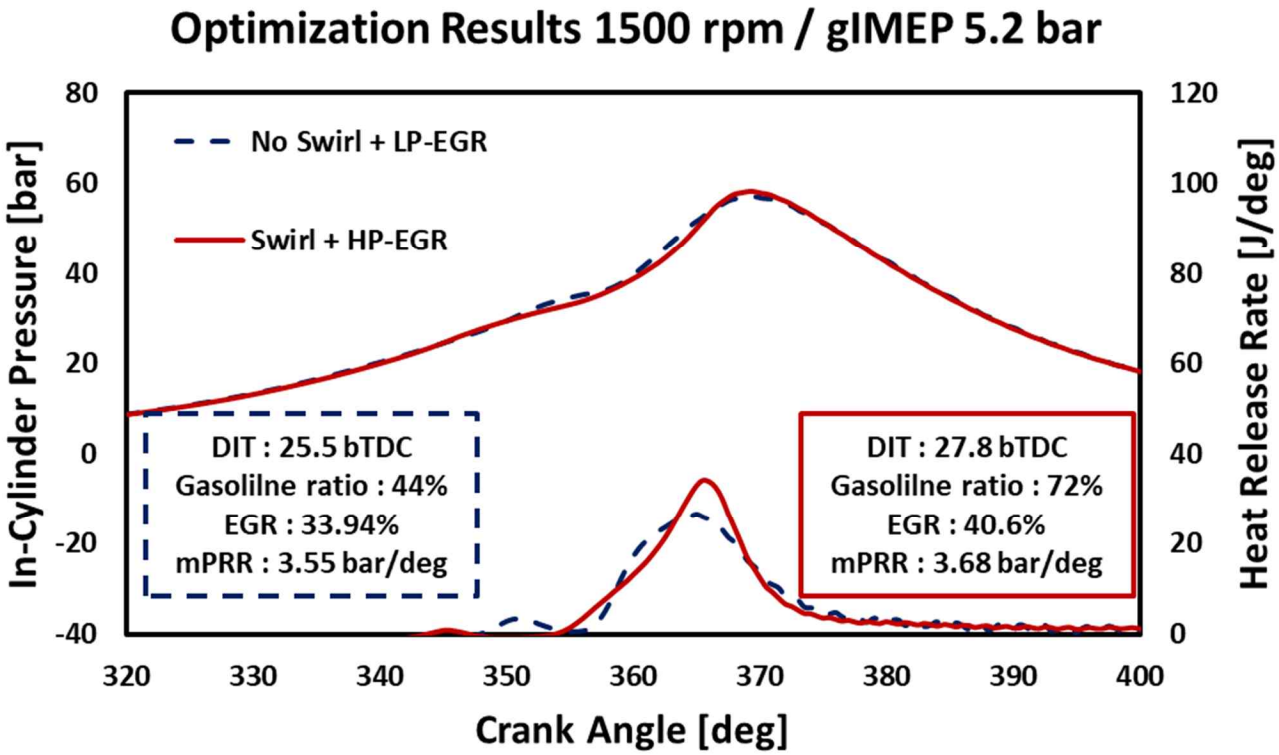

Figure 15. In-cylinder pressure and heat release rate of optimized dual-fuel combustion at 1,500 rpm / gIMEP 5.2 bar

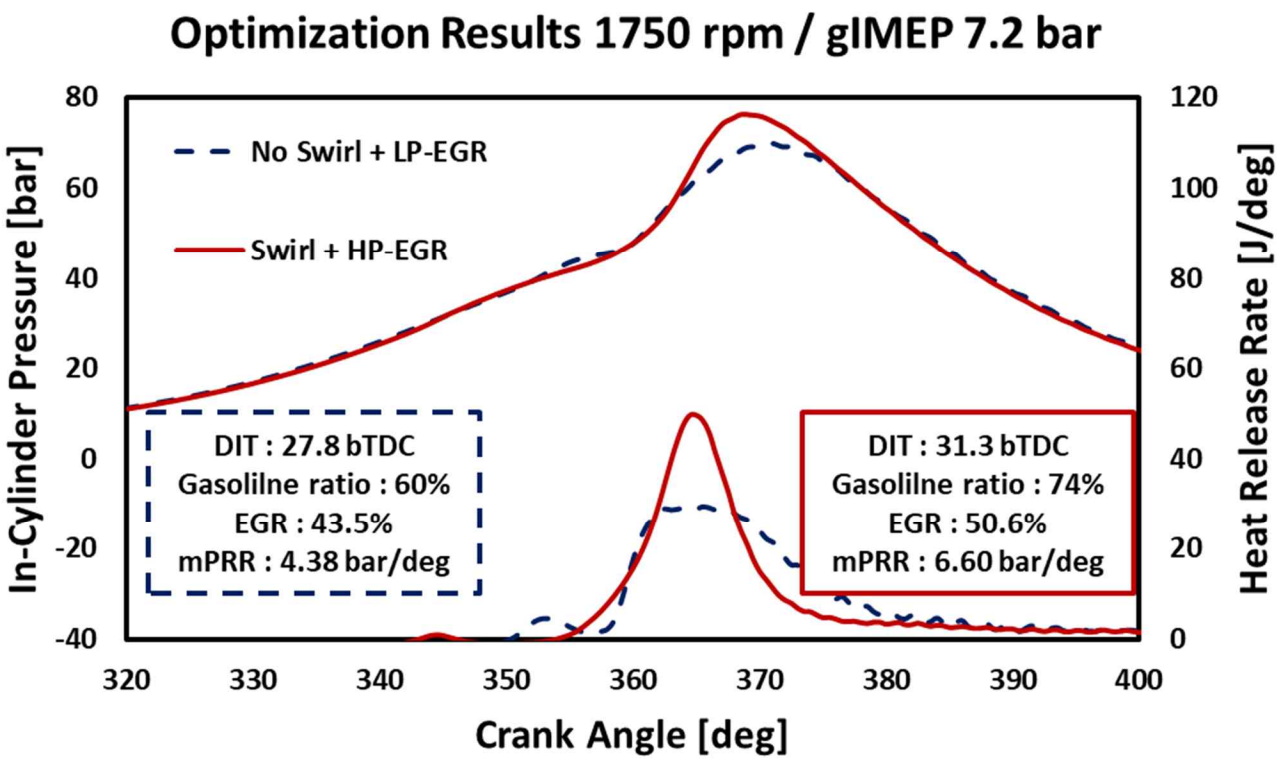

Figure 16. In-cylinder pressure and heat release rate of optimized dual-fuel combustion at 1,750 rpm / gIMEP 7.2 bar

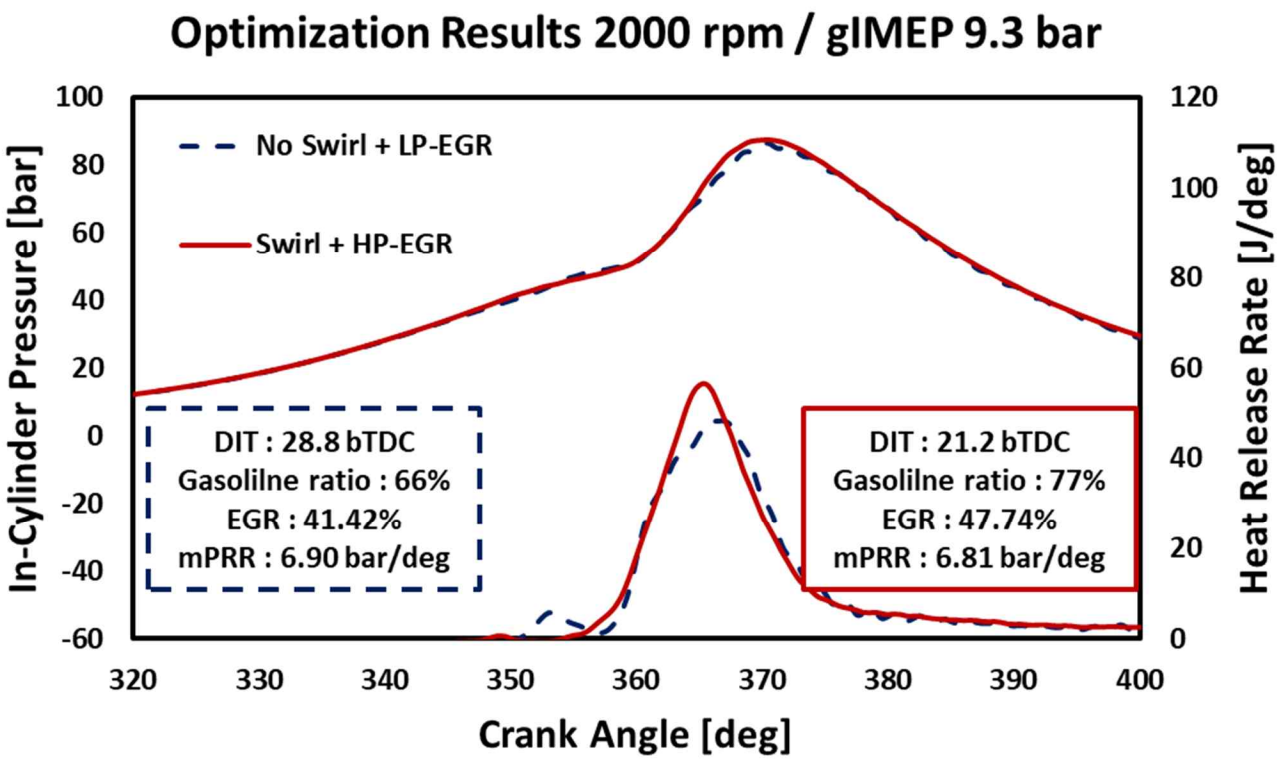

Figure 17. In-cylinder pressure and heat release rate of optimized dual-fuel combustion at 2,000 rpm / gIMEP 9.3 bar

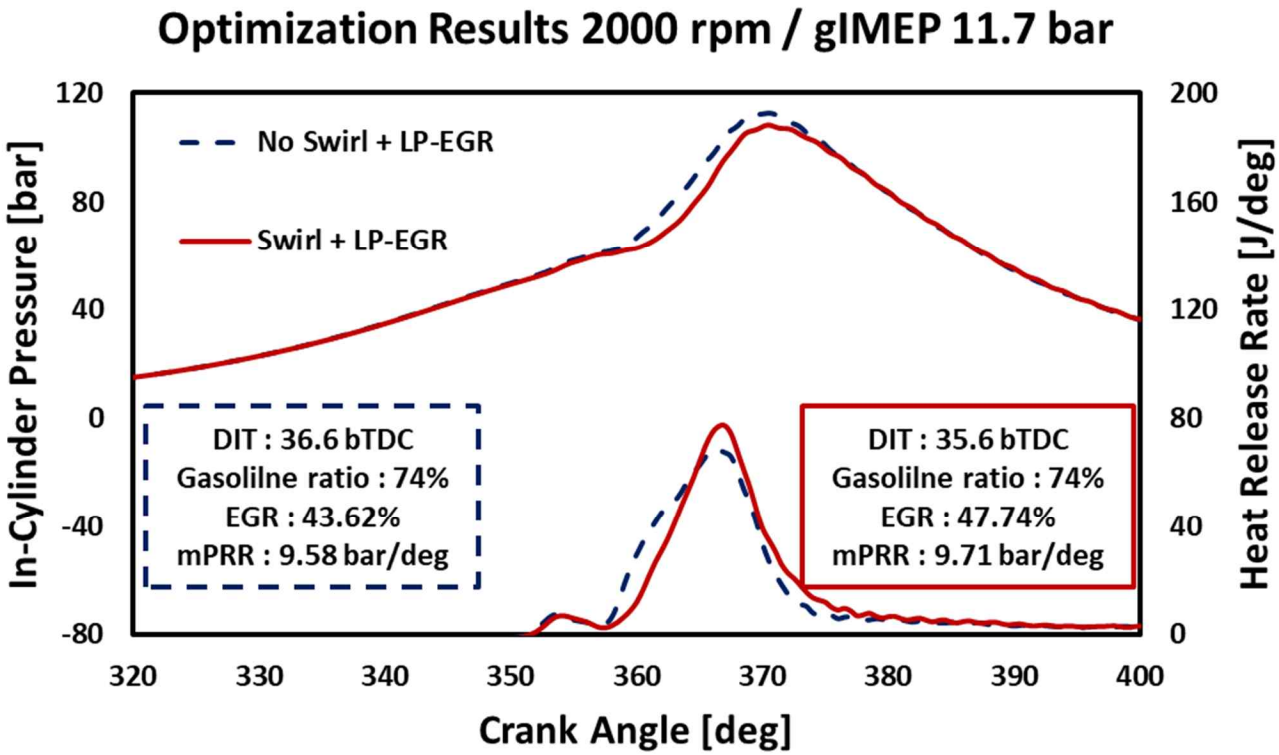

Figure 18. In-cylinder pressure and heat release rate of optimized dual-fuel combustion at 2,000 rpm / gIMEP 11.7 bar

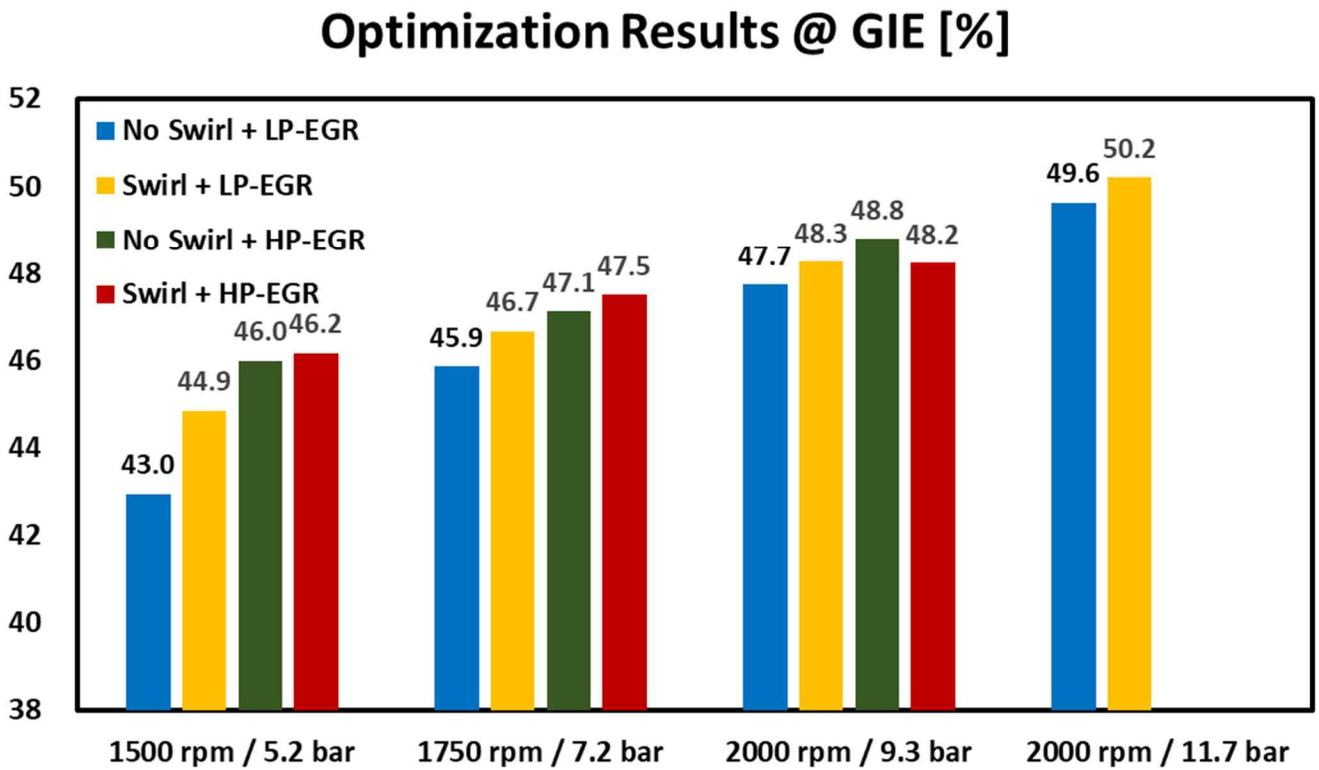

Figure 19. Gross indicated thermal efficiency of optimization results at 4 operating conditions

Table 5. optimal strategies of four operating conditions

Case (Engine speed / gIMEP)	Optimal Strategy
1500 rpm / 5.2 bar	Swirl + HP-EGR
1750 rpm / 7.2 bar	Swirl + HP-EGR
2000 rpm / 9.3 bar	No Swirl + HP-EGR
2000 rpm / 11.7 bar	No Swirl + LP-EGR

Chapter 4. **Conclusion**

In this study, the effect of SCV and HP-EGR was analyzed to improve incomplete combustion and combustion stability. Based on the experimental results, optimization experiment was conducted varying the SCV and EGR state.

The combustion phase was advanced with faster combustion speed with swirl flow motion. THC, CO and PM emissions also are reduced by enhancing the air-fuel premixing with swirl flow motion. It can be concluded swirl flow motion improved the incomplete combustion and combustion stability. However, fast combustion with high swirl increased NOx emission and mPRR

Applying HP-EGR increased the intake temperature. Increasing intake temperature affected in-cylinder condition enhancing the ignition and burning rate. Thus, the combustion phase was advanced with faster combustion speed. THC and CO emissions can be reduced by improving oxidation with higher combustion temperature. But higher intake temperature increased the NOx emission. PM emission increased due to the lack of oxygen to react by increasing the intake temperature.

At low load condition, incomplete combustion and low combustion stability is major challenge of dual-fuel combustion. High swirl and intake temperature can improve the combustion stability. High swirl and intake temperature improved the combustion stability. For 1,500 rpm / gIMEP 5.2 bar and 1,700 rpm / gIMEP 7.2 bar, the high swirl and intake temperature condition achieved the highest GIE.

At high load condition, satisfying mPRR and NOx emission is important to

optimize dual-fuel combustion. Additional EGR supplement required at high swirl and intake temperature condition may lead to poor ignitibility and rich equivalent ratio. For 2,000 rpm / gIMEP 9.3 bar, low swirl and high intake temperature condition achieved the highest GIE. For 2,000 rpm / gIMEP 11.7 bar, both low swirl and intake temperature condition achieved the highest GIE.

The experimental results show that applying the SCV and HP-EGR can improve the incomplete combustion and combustion stability. This research can contribute to the thermal efficiency improvement at low load condition and the low load expansion of dual-fuel combustion.

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국문 초록

디젤 가솔린 융합 연소에서 스월 컨트롤 밸브와 고압 배기 가스 재순환이 미치는 영향에 대한 연구

서울대학교 대학원
기계공학부
신 형 진

강화되는 배기 규제에 대응하기 위하여 반응성이 다른 두 연료를 사용하는 융합 연소에 대한 연구가 진행되고 있다. 융합 연소는 저반응성 연료의 예혼합률을 높여 질소 산화물과 입자상 물질 배출량을 줄일 수 있으며 압축 점화 방식을 통하여 높을 열효율 또한 달성할 수 있다. 하지만 융합 연소는 저반응성 연료의 낮은 자발화 특성으로 인하여 저부하 운전영역에서 연소 안정성을 보장하는데 어려움이 있다.

본 연구에서는 융합 연소의 저부하 운전 영역에서 불안전 연소 및 연소 안정성을 개선할 수 있는 최적은 운전 전략을 찾기 위해 스월 컨트롤 밸브(SCV)와 고압 배기 가스 재순환(HP-EGR)의 영향에 대하여 확인하였다. 스월 컨트롤 밸브와 고압 배기 가스 재순환 시스템을 적용하여 미연탄화수소 및 일산화탄소 배출량을 줄일 수 있었다. 이는 강한 스월 유동과 높은 흡기온도를 통해 불완전 연소 및 연소 안정성의 개선 가능성을 확인하였다. 하지만 스월 비와 흡기 온도가 높은 빠른 연소는 질소 산화물 배출량과 최고 압력 상승률을 증가시키는 경향을 보였다.

위 실험 결과를 바탕으로 최적화 실험을 통하여 네 가지 운전 조건에서 스월 컨트롤 밸브와 고압 배기 가스 재순환의 최적 운전 전략을 도출할 수 있었다. 불완전 연소와 낮은 연소 안정성이

한계인 저부하 운전 조건에서는 강한 스월 유동과 고압 배기 가스 재순환을 통하여 연소 안정성과 열효율을 개선할 수 있는 최적의 운전 전략임을 확인하였다. 최고 압력 상승률과 질소 산화물 배출량을 만족시키는 것이 주요한 고부하 운전 조건에서는 최고 압력 상승률과 질소 산화물 배출량을 줄일 수 있는 약한 스월 유동이나 저압 배기 가스 재순환 운전 전략이 유리함을 알 수 있었다.

주요어 : 융합 연소, 스월 컨트롤 밸브, 고압 배기 가스 재순환, 연소 안정성, 총 도시 열효율

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