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Article

Effect of Two-Stage Fuel Injection Parameters on NO_x Reduction Characteristics in a DI Diesel Engine

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Abstract: The aim of this study was to confirm the effects of two-stage combustion on the combustion and NO_x reduction characteristics of a four cylinder direct injection diesel engine. In order to analyze the combustion and emission characteristics, various injection parameters, such as injection quantity, injection timing and injection pressure were used under constant engine speed and engine load. In addition, the experimental results of two-stage combustion are compared to the single injection when injection timing is 5° BTDC. The experimental results showed that NO_x emissions were significantly reduced when applying two-stage combustion. In particular, an injection strategy when the first and second injections have a same quantity, the results showed the maximum reduction of NO_x emissions in this experiment. The NO_x emissions were also reduced when the timing of the first injection was advanced. However, NO_x emissions indicated almost similar concentration regardless of first injection timings when the first injection timing was earlier than 50° BTDC. In the case of soot emissions were slightly increased compare to the single injection cases at tested conditions.

Keywords: two-stage combustion; injection strategy; combustion characteristics; NO_x reduction characteristics; soot emissions

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1. Introduction

Diesel engines with high thermal efficiency and low consumption have been widely used in industrial fields, and the transportation system. In a diesel engine, the control of high injection pressure, injection timing and injection mass can be realized by using an electronically controlled common rail system. However, in spite of the many advantages of diesel engines, the simultaneous reduction of nitric oxide (NO_x) and particulate matter (PM) still remains a very difficult problem to solve. In addition, harmful gases from diesel engine have become serious health risks to humans. For these reasons, diesel engine emission regulations have become become stricter year by year, many researchers are being required to satisfy a these regulations and the need for development of new combustion technologies or alternative resources such as biomass and natural gas [1–3]. Among combustion technologies, homogeneous charge compression ignition (HCCI) and premixed charge compressed ignition (PCCI) combustion strategy have being investigated by many researchers [4–6]. By applying these new diesel engine combustion approaches, one can investigate not only simultaneous reduction of NO_x and PM emissions but also improvement of fuel consumption [7,8]. In particular, the combustion by early injection can certainly realize combustion extension of a premixed air-fuel mixture compared with conventional diesel combustion. According to the effect of low temperature combustion, the combustion temperature in the premixed air-fuel mixture can be kept at a low temperature by using both the exhaust gas recirculation (EGR) effect and forming a lean mixture [9,10]. Despite the fact that NO_x and PM emissions were significantly reduced by applying new combustion technologies, these strategies still have various unsolved problems such as the difficulty of controlling a premixed air-fuel mixture in the combustion chamber and the limited operating region. For these reasons, many researchers have been exploring the other combustion technologies with various parameters to solve disadvantages of homogeneous charge combustion and remixed charge compression ignition technologies.

Many researches associated with two stage combustion (TSC) concept were investigated by using computational modeling program and experimental studies [11–13]. In actual diesel engines, the studies on reduction of soot and NO_x emissions in the combustion process during the two stage combustion strategy remain as an uncertainty for clean emissions.

From this point of view, this study focuses on the effect of two-stage combustion parameters on the NO_x reduction characteristics and combustion performance in a passenger vehicle diesel engine with a DI combustion chamber and a common-rail system. The experiments also focused on NO_x reduction characteristics of two stage combustion by applying various two-stage injection parameters (first injection quantity, injection timings and injection pressure) under constant engine speed and load conditions. Based on the results from this injection strategy, combustion performance and emission reduction characteristics results are compared with single injection results.

2. Experimental Setup and Procedures

2.1. Experimental Apparatus

In this work, the experimental apparatus illustrated in Figure 1 was installed to investigate the effect of TSC on combustion and NO_x reduction characteristics. The experimental setup consisted of four parts: an electronic controlled diesel engine, an EC dynamometer system, an engine control system and an exhaust gas analysis system. The test engine used for this study is based on a four cylinder common rail DI diesel engine that was naturally aspirated and water cooled. The engine performed at an engine speed of 1500 rpm and a fixed cooling water temperature of 80 °C. This engine has a bore of 77.2 mm, a stroke of 84.5 mm, a displacement volume of 1.582 L, and a compression ratio of 17.3. This engine is able to inject until an injection pressure of 160 MPa, which is controlled by ECU and a common-rail injection system. The main specifications are summarized in Table 1.

Figure 1. Schematic diagram of experimental setup.

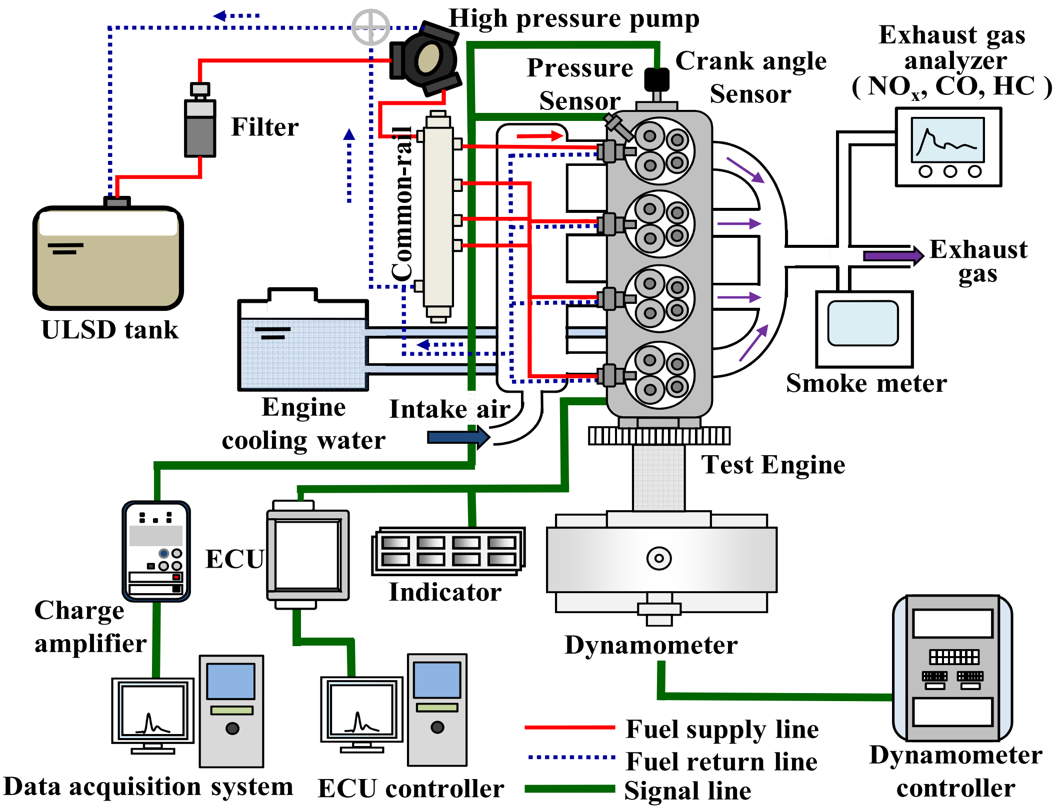


Table 1. Specifications of the test engine.

Engine type	4-stroke VGT DI diesel engine
Number of cylinder	4
Bore × Stroke (mm)	77.2 × 84.5
Displacement volume (L)	1.582
Compression ratio	17.3
Valve type	DOHC 4 valves per cylinder
Intake valve open (deg. BTDC)	6
Intake valve close (deg. ABDC)	34
Exhaust valve open (deg. BBDC)	46
Exhaust valve close (deg. ATDC)	4
Max. Power (kW/rpm)	86/4000
Max. Torque (Nm/rpm)	260/2000
Max. Speed (rpm)	4750

Test fuel used an ultra-low sulfur diesel (ULSD), and the fuel supply system was installed and configured with a high pressure injection pump and a common-rail system on the test engine. In order to control the engine load, the dynamometer system used to an EC dynamometer (AG 150) and a control unit. In this investigation, an engine control system and a control program (INCA V5.4, ETAS) and an ECU (Bosch, EDC16 ETK ECU) were installed. The combustion pressures in the combustion chamber were measured by a pressure sensor (Kistler, 6057ASP) and a crank angle detecting sensor. Also, the measured engine data values were obtained by using a DAQ board (NI, PCI 6251 & SC 2345) and software (NI, Labview 8.2) to analyze combustion characteristics. In the engine, the rate of heat release (ROHR) is calculated by using the measured in-cylinder pressure in the engine. The exhaust gases from the test engine were measured with a NO_x, HC and CO emission analyzer (Horiba, MEXA-554JK) and a smoke analyzer (AVL415s).

2.2. Experimental Procedures

In this work, experiments were performed under a constant engine speed of 1500 rpm and 50 Nm of engine load. In order to investigate the effect of two-stage combustion on combustion and emission characteristics, the injection strategy was fixed both at 50° BTDC of the first injection and at 5° ATDC of second injection timing. In addition, the main parameters were injection quantity, injection timing, and injection pressure. The first injection quantity was controlled from 2 mg to 10 mg with an interval of 2 mg. Also, the first injection timing was changed from 20° to 70° BTDC with a test interval of 10. The other experimental parameter is injection pressure; in order to investigate the effect of various injection pressures, the injection pressure was changed from 50 MPa to 90 MPa and the first injection mass maintained at 8 mg/cycle. The results from applying the two-stage combustion strategy were compared with the single injection result which was carried out at the injection timing of 5° BTDC and 12 mg/cycle of injection quantity as well as at the same operating conditions. The detailed experimental conditions are listed in Table 2.

Table 2. Experimental conditions.

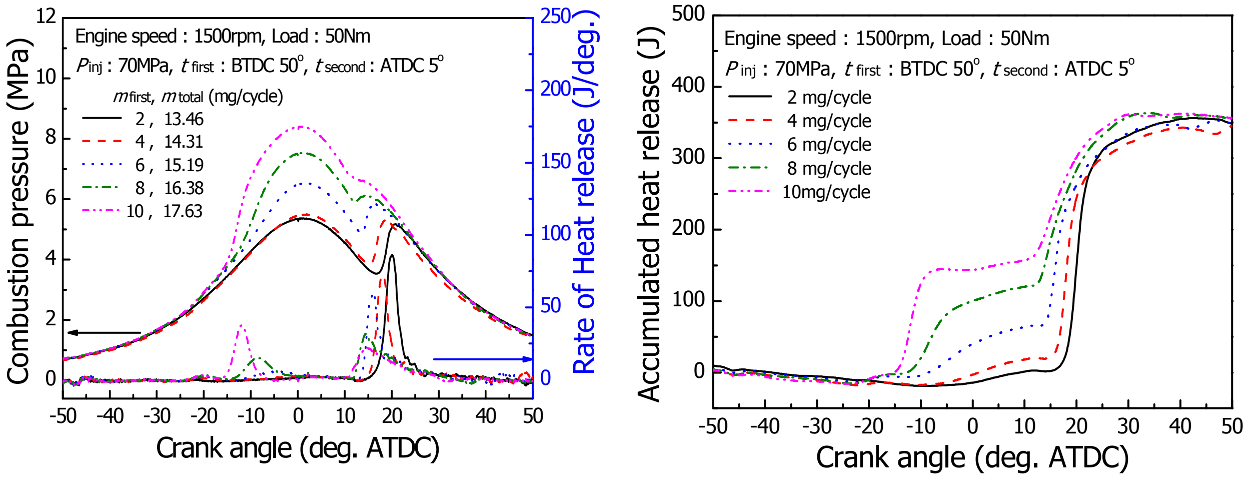
Engine speed (rpm) and load(Nm)	1500, 50
Injection pressure (MPa)	50~90
Injection method	1st and 2nd injection
First injection timing (deg. ATDC)	−70~−20
Second injection timing (deg. ATDC)	−5, 5
First injection quantity (mg/cycle)	2~10
Second injection quantity (mg/cycle)	Variable

3. Results and Discussion

3.1. Effect of First Injection Quantity and Injection Timings

The combustion characteristics, such as combustion pressure, the rate of heat release (ROHR) and accumulated heat release, as a function of the first injection mass are shown in Figure 2(a) and 2(b), respectively. Experimental conditions were controlled to be an injection pressure of 70 MPa, an engine load of 50 Nm, and an engine speed of 1500 rpm. To investigate the effects of first injection quantity on the combustion and emission characteristics, the first injection mass was changed from 2 mg/cycle to 10 mg/cycle. The combustion pressure and ROHR as a function of the variation of the first injection quantity are shown in Figure 2(a).

Figure 2. Combustion characteristics variable first injection quantity of two stage injection: (**a**) Combustion pressure and rate of heat release; (**b**) Accumulated heat release.



(**a**) (**b**)

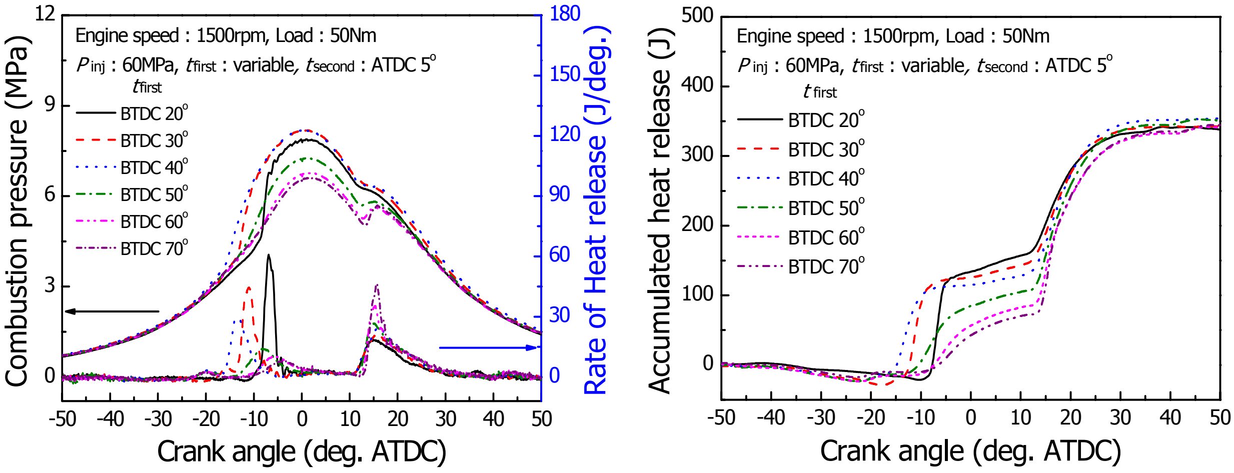
When the first injection quantity is increased, the first peak in the pressure history due to the first injection is increased as illustrated in the pressure–crank angle diagram. On the other hand, second stage ROHR are consistently decreased according to the increase of first injection quantity. Roh *et al*. [14] reported the same trends in an experimental study of effect of multiple injections on emission characteristics. The ROHR of the first stage are clearly shown between 15° and 5° BTDC when the first injection quantity is changed from 6 mg/cycle to 10 mg/cycle. In addition, ROHR curves in the same range of the first injection timing grew according to the increase of fuel quantity. The first injection quantity results in the increase of initial ROHR because most of injected fuel participated in the combustion reaction. Therefore, it can be known that the ROHR of the first stage is gradually increased and the ignition delay is decreased when the first injection quantity is increased. In the case of the second stage injection, ignition delay is consequently decreased according to injection quantity of the increase of first stage, however, the ROHR became smaller due to the decreasing injection mass at the same engine load condition.

Figure 2(b) illustrates the effect of first injection quantity on the accumulated heat release. As shown in this figure, the patterns of accumulated heat release are obviously generated by the effect of TSC from 2 mg/cycle to 10 mg/cycle of the first injection quantity because the first injection was affected by advanced spray evaporation and combustion.

The combustion pressure and the rate of heat release (ROHR), accumulated heat release according to the change of first stage injection timings in the TSC strategy are shown in Figure 3(a) and 3(b), respectively. These characteristics were investigated by applying 60 MPa of injection pressure, 5° ATDC of second injection timings and injection quantity of first and second stage was divided as equal quantity. At the same time, the injection timing of a first stage advanced a range of 10 degree of crank angle from 20° BTDC to 70° BTDC.

As shown in Figure 3(a), although the combustion pressure of the first stage increased up to the injection timing of 40° BTDC, it decreased again after the injection timing of 40° BTDC. In the case of ROHR, the initial combustion phase at the injection timing between 20° and 40° BTDC is rapidly generated as premixed combustion. However, combustion pressure is decreased when the fuel injection timing is advanced more than 40° BTDC. This tendency of the combustion can be explained as follows: the air-fuel mixture at too early injection of fuel was ignited with low ambient temperature because fuel premixing was occurring according to the long fuel evaporation. Therefore, premixed mixture through the early injection not only does not generate rapid combustion but also has consequentially long combustion duration.

Figure 3. Combustion characteristics according to variable first injection timing of two stage injection: (**a**) Combustion pressure and rate of heat release; (**b**) Accumulated heat release.



(**a**) (**b**)

Figure 3(b) describes the accumulated heat release according to various injection timing conditions. The experimental results of first injection timing from 20° BTDC to 40° BTDC show that the ignition delay becomes longer. Also, it can be seen that ignition delay is suddenly extended after the injection timing of 40° BTDC. As indicated in the accumulated heat release curves, the ignition delay in the range from 50° BTDC to 70° BTDC of first injection timings was longer, and the burning rate decreased during combustion duration. In the case where the advanced first injection timing exceeded 50° BTDC, low temperature combustion occurs slightly, almost regardless of injection timings as illustrated in Figure 3(a). These results showed the similar tendency as illustrated in the ROHR results reported on the study of PCCI operation in a conventional diesel engine by Kanda *et al.* [15].

The effect of first injection timing on the indicated specific fuel consumption (ISFC) is illustrated in Figure 4. The ISFC is increased up to 40° BTDC by advanced injection timing. However, it is maintained at a similar value in the range from 40° BTDC to 70° BTDC of injection timing. In addition, ISFC was relatively increased compared to single injection because early injection influences the insufficient combustion in the initial combustion duration.

Figure 4. Indicated specific fuel consumption according to first injection timing of two stage injection.

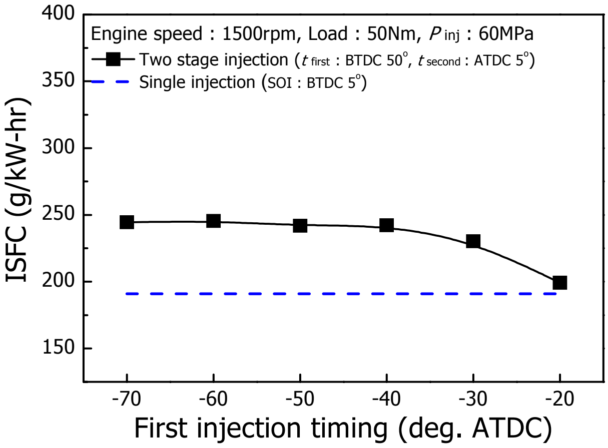
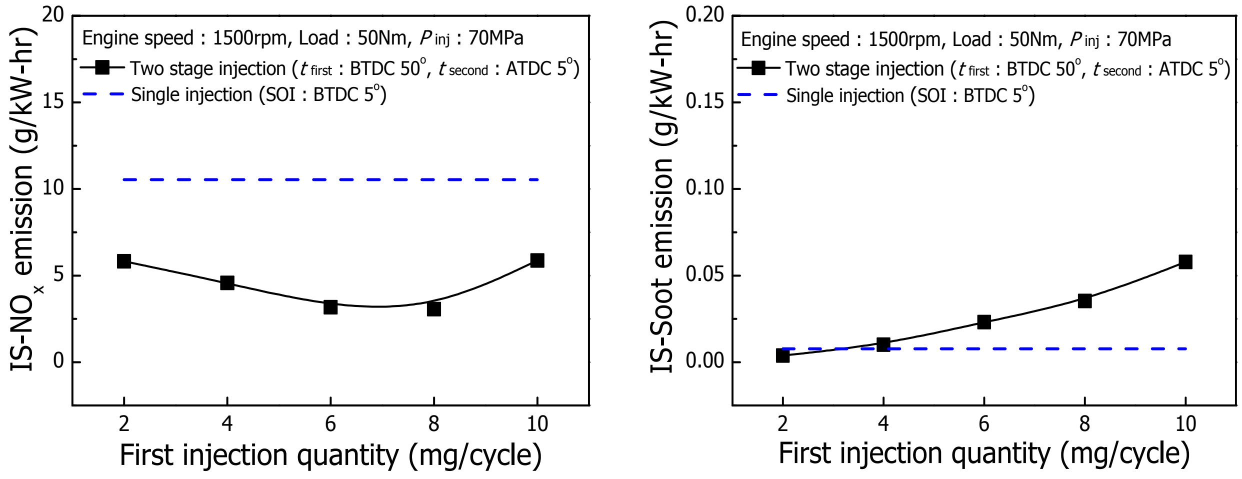


Figure 5(a) shows the effect of two-stage combustion on the indicated specific nitrogen oxides (IS-NO$_x$) emission characteristics according to the first injection quantity. In this figure, IS-NO$_x$ emissions of the TSC decreased by approximately 58 percent compared with the result of single injection at the injection timing of 5° BTDC because the LTC reaction is generated by a premixed air-fuel mixture due to the divided injection of fuel, and these results affect a reduction of IS-NO$_x$ formation in the cylinder. In particular, the IS-NO$_x$ emissions with TSC gradually decrease up to 8 mg/cycle of first injection quantity. In this point, it can be shown that the IS-NO$_x$ emissions are dramatically decreased compared to the single injection when the injection mass of the first and second are equally injected in this experiment conditions. Also, as illustrated in Figure 5(b), indicated specific soot (IS-Soot) emissions at two-stage combustion generated similar trends compared to the IS-NO$_x$ concentration level of single injection. IS-Soot emissions are increased in accordance with the increase of the first injection quantity. Especially, the 10 mg/cycle case showed the highest concentration level because of the relatively low oxygen concentration at the second stage injection.

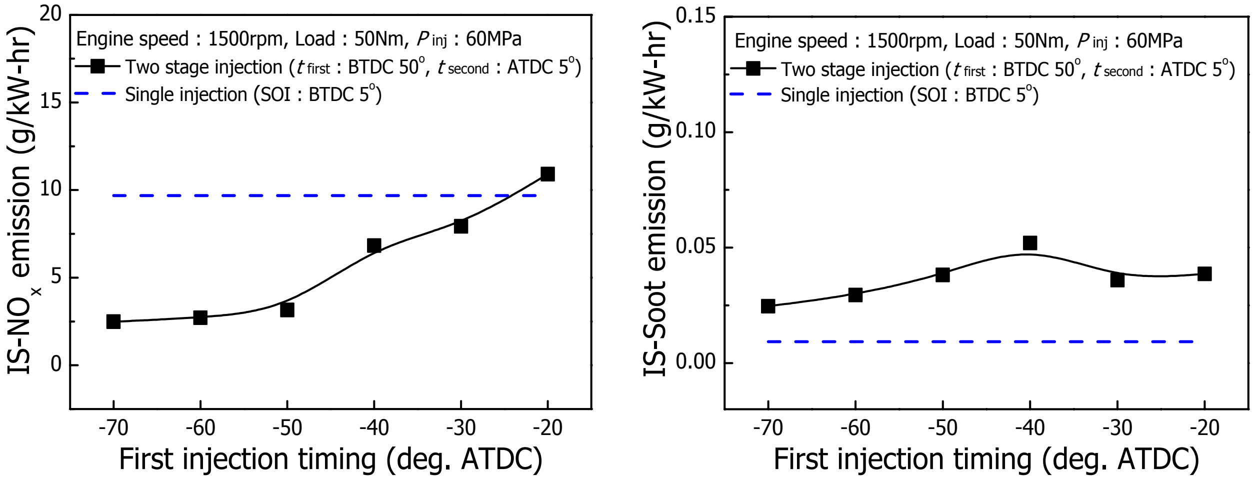
Figure 5. IS-NO$_x$ and IS-Soot emission characteristics according to first injection quantity of two stage injection: (**a**) IS-NO$_x$; (**b**) IS-Soot.



(**a**) (**b**)

Figure 6(a) shows the effect of first injection timing in the TSC strategy on IS-NO$_x$ emission characteristics. In this figure, IS-NO$_x$ emissions are continuously decreased when first injection timing is advanced from 20° BTDC to 50° BTDC. In addition, IS-NO$_x$ emissions are generated at similar levels between 50° BTDC and 70° BTDC. Also, the maximum reduction rate of IS-NO$_x$ emissions is decreased by approximately 43 percent compared to the case of single injection. In the IS-Soot emissions results, Figure 6(b) indicated similar trends for all tested conditions. Thus, it can be predicted that there is no particular affect at the first injection timing to IS-Soot emission characteristics. However, the IS-Soot emissions slightly increased when injection timing is retarded at 40° BTDC. This can be explained by the fact that incomplete combustion in the cylinder is occurring with the insufficient air-fuel mixture because spray fuel droplets reach near the piston bowl surface, and some droplets formed local fuel-rich regions. For this reason, a small quantity of injected fuel droplets induced the fuel wall-film at the piston bowl surface, and fuel-rich mixture caused incomplete combustion and a little more IS-Soot formation.

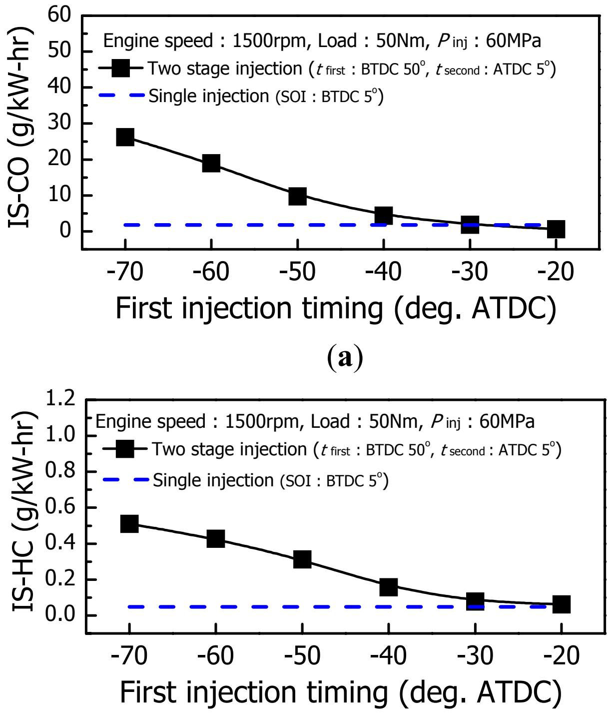
Figure 6. IS-NO$_x$ and IS-Soot emission characteristics according to first injection timing of two stage injection: (**a**) IS-NO$_x$; (**b**) IS-Soot.



(**a**) (**b**)

The Figure 7 (a) and (b) show the results of IS-CO and IS-HC emissions by various first injection timing of the TSC strategy. IS-CO and IS-HC emissions are increased when injection timing is advanced. In particular, IS-CO and IS-HC emissions are gradually increased as injection timing is advanced from 40° BTDC. This reason is that insufficient combustion is generated due to the wall-wetting phenomenon of the fuel spay in the cylinder wall beyond the injection timing of 40° BTDC [16].

Figure 7. IS-CO and IS-HC emission characteristics according to first injection timing of two stage injection: (**a**) IS-CO; (**b**) IS-HC.



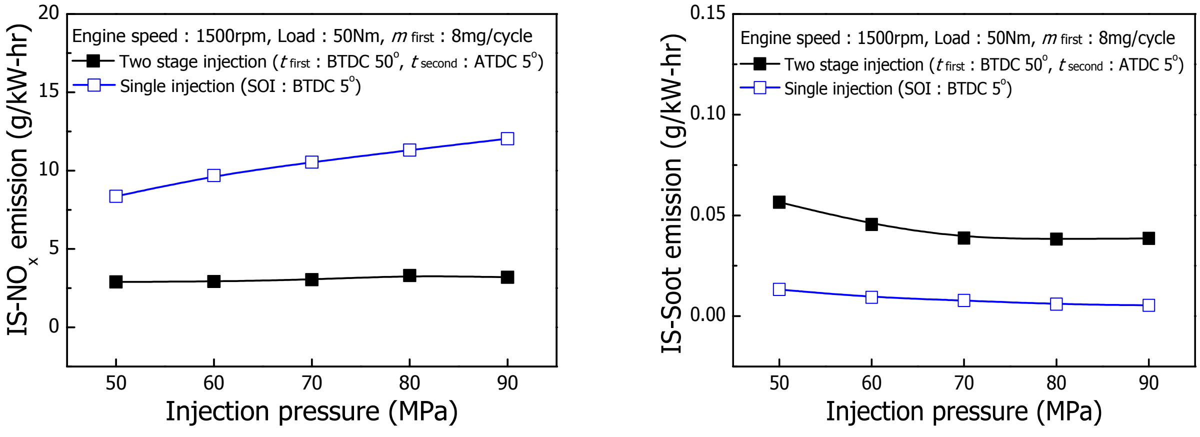
(**a**)

(**b**)

3.2. Effect of Injection Pressure

In order to investigate the effect of injection pressure, the injection pressure was changed from 50 MPa to 90 MPa at the same injection timings and engine speed with a constant load. The first injection quantity was maintained at 8 mg/cycle. In Figure 8(a), IS-NO$_x$ emissions indicated a low level, even though the injection pressure is increased from 50 MPa to 90 MPa. Also, it can be shown that the IS-NO$_x$ emissions are reduced by an average of 70 percent compared to the result of the single injection.

Figure 8. IS-NO$_x$ and IS-Soot emission characteristics according to injection pressure of two stage injection: (**a**) IS-NO$_x$; (**b**) IS-Soot.



(**a**) (**b**)

It is commonly known that the formation of IS-NO_x emissions depends on the combustion temperature and rapid combustion of locally rich fuel regions in the combustion chamber. For this reason, IS-NO_x emissions by LTC reaction at the first stage are reduced by the low combustion temperature compared with that of single injection.

In Figure 8(b), IS-Soot emissions using the TSC strategy are higher than the result of single injection. In addition, as the injection pressure increased, it can be seen that IS-Soot emissions are steadily reduced. This is due to the fast atomization of diesel droplets affects to reduce the IS-Soot emission according to high injection pressure makes better mixing between air and fuel in the combustion chamber [17].

4. Conclusions

In this study, in order to investigate the effect of a two-stage combustion strategy on combustion and NO_x reduction characteristics, experiments were performed in a four-cylinder common-rail DI diesel engine with a displacement of 1.582 L. Injection parameters (injection mass, pressure and timings) were varied under a constant engine speed and load. At the same time, the results of a two-stage combustion strategy were compared to those of single injection. Based on the results, the conclusions derived from this study may be summarized as follows.

1. The ignition delay with the TSC strategy was decreased with increased first injection mass. In addition, ISFC of TSC strategy was relatively increased compared to single injection because early injection is influenced on the insufficient combustion in the initial combustion duration. In the emission characteristics, when the first and second injection quantity is the same amount, IS-NO_x emissions were remarkably reduced compared with the result of single injection. The IS-Soot emissions were similar to that of single injection.
2. The combustion pressure of the first stage increased up to the injection timing of 40° BTDC, and decreased again after the injection timing of 40° BTDC. IS-NO_x emissions were decreased in accordance with the advanced first injection timing compared to the single injection. However, there is a little effect on the IS-NO_x emissions in the range from BTDC 50° to BTDC 70°. The result of IS-Soot emissions showed a similar trend under all tested conditions, and a slight effect on IS-Soot emission was observed regardless of the change in first injection timings. The effect of TSC strategy on IS-CO and IS-HC emission characteristics showed that both emissions were increased in accordance with the advance of first injection timing.
3. IS-NO_x emissions showed a lower concentration compared to single injection when the injection pressure is increased from 50 MPa to 90 MPa. Also, it can be seen that the IS-NO_x emissions are reduced by an average of 70 percent compared to the result of the single injection. IS-Soot emissions applying the TSC strategy are higher than that of single injection. In addition, as the injection pressure increased, IS-Soot emissions are steadily reduced because of the improvement of fuel atomization by high-pressure injection.

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References

1. Lee, C.S.; Park, S.W. An experimental and numerical study on fuel atomization characteristics of high pressure diesel injection sprays. *Fuel* **2002**, *81*, 2417–2423.
2. Yoon, S.H.; Cha, J.P.; Lee, C.S. An investigation of the effects of spray angle and injection strategy on dimethyl ether (DME) combustion and exhaust emission characteristics in a common-rail diesel engine. *Fuel Process. Technol.* **2010**, *91*, 1364–1372.
3. Yokota, H.; Kudo, Y.; Nakajima, H.; Kakegawa, T.; Suzuki, T. A new concept for low emission diesel combustion. Presented at International Congress & Exposition, Detroit, MI, USA, February 1997, doi:10.4271/970891.
4. Helmantel, A.; Denbratt, I. HCCI operation of a passenger car common rail DI diesel engine with early injection of conventional diesel fuel. Presented at SAE World Congress 2004; Detroit, MI, USA, March 8–11, 2004.
5. Hasegawa, R.; Yanagihara, H. HCCI combustion in DI diesel engine. Presented at SAE 2003 World Congress & Exhibition, Detroit, MI, USA, March 2003, doi:10.4271/2003-01-0745.
6. Tanaka, S.; Ayala, F.; Keck, J.C.; Heywood, J.B. Two-stage ignition in HCCI combustion and HCCI control by fuels and additives. *Combust. Flame* **2003**, *132*, 219–239.
7. Kokjohn, S.L.; Reitz, R.D. A computational investigation of two-stage combustion in a light-duty engine. Available online: http://vcc-sae.org/abstracts/2363-computational-investigation-two-stage-combustion-light-duty-diesel-engine (accessed on 21 November 2011).
8. Ebrahimi, R.; Desmet, B. An experimental investigation on engine speed and cyclic dispersion in an HCCI engine. *Fuel* **2010**, *89*, 2149–2156.
9. Starck, L.; Lecointe, B.; Forti, A.; Jeuland, N. Impact of fuel characteristics on HCCI combustion: Performances and emissions. *Fuel* **2010**, *89*, 3069–3077.
10. Opat, R.; Ra, Y.; Manuel, A.; Gonzalez, D.; Krieger, R.; Reitz, R.D.; Foster, D.E.; Durrett, R.P.; Siewert, R.M. Investigation of mixing and temperature effects on HC/CO emissions for highly dilute low temperature combustion in a light-duty diesel engine. Presented at SAE World Congress & Exhibition; Detroit, MI, USA, April 2007, doi: 10.4271/2007-01-0193.
11. Fang, T.; Coverdill, R.E.; Lee, C.-F.F.; White, R.A. Influence of injection parameters on the Transition from PCCI combustion to diffusion combustion in a small-bore HSDI diesel engine. *Int. J. Automot. Technol.* **2009**, *10*, 285–295.
12. Fang, T.; Lee, C.-F.F. Biodiesel effects on combustion processes in an HSDI diesel engine using advanced injection strategies. *Proc. Combust. Inst.* **2009**, *32*, 2785–2792.
13. Coverdill, R.E.; Lee, C.-F.F.; White, R.A. Low-Temperature combustion within a HSDI diesel engine using multiple-injection strategies. *J. Eng. Gas Turbines Power* **2009**, *131*, 062803:1–062803:8.

14. Roh, H.G.; Lee, C.S. The effect of multiple injections on the stability of combustion and emissions characteristic in a passenger car diesel engine. *Trans. KSAE* **2007**, *15*, 76–82.
15. Kanda, T.; Hakozaki, T.; Uchimoto, T.; Hatano, J.; Kitayama, N.; Sono, H. PCCI operation with early injection of conventional diesel fuel. Presented at SAE 2005 World Congress & Exhibition, Detroit, MI, USA, April 2005; doi:10.4271/2005-01-0378.
16. Boot, M.D.; Luijten, C.C.M.; Rijk, E.P.; Albrecht, B.A.; Baert, D.S.G. Optimization of operating conditions in the early direct injection premixed charge compression ignition regime. Presented at 9th International Conference on Engines and Vehicles; Naples, Italy, September 2009, doi:10.4271/2009-24-0048.
17. Benajes, J.; Molina, S.; Novella, R.; DeRudder, K. Influence of injection conditions and exhaust gas recirculation in a high-speed direct-injection diesel engine operating with a late split injection. *Proc. Inst. Mech. Eng. Part D* **2008**, *222*, 629–641.