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Combination of Pilot Injection and a NH_3-SCR System To Reduce NOx Emissions of a Nonroad Compression Ignition Engine

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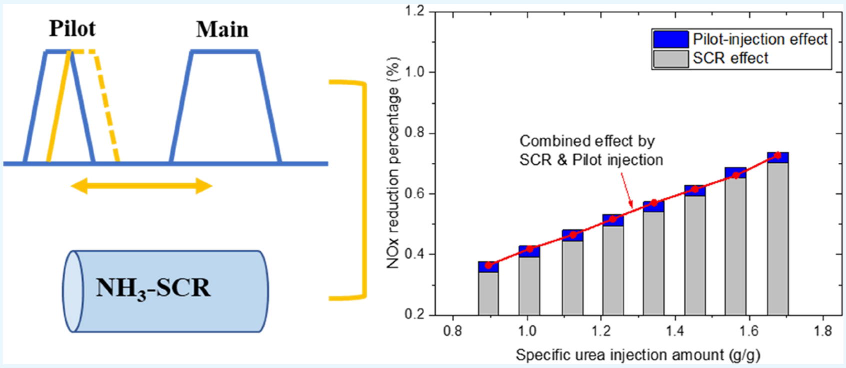

ABSTRACT: This study compared the NOx emissions of a nonroad compression ignition engine using pilot injection and a NH_3-SCR system and revealed their effects on NOx reduction. Furthermore, the interaction of pilot injection and the NH_3-SCR system on NOx reduction was also studied by simultaneously using the two technologies under broad engine operating conditions. The pilot-main interval and the rate of pilot-to-main injection used in this study are in the range of 2∼8 CA and 9.5∼58.5%, respectively. Results showed that alteration in the pilot-main injection interval and the pilot-injection fuel amount under low load conditions was prone to lead to more variation in NOx emissions in comparison with that under high-load conditions. Relative to the pilot-main injection interval, the pilot-injection fuel amount played a more important role in the NOx emission. Lower NOx emissions could be achieved when using a smaller pilot-injection amount. However, excessively advanced pilot injection and a larger pilot-injection amount would increase the NOx emissions. Under a lower engine load, the effect of pilot injection on NOx reduction enhanced, whereas the effect of the NH_3-SCR system diminished. Over broad operating conditions, the NOx reduction percentage by pilot injection coupled with the SCR system was lower than the total reduction degree when separately using pilot injection and the SCR system.

1. INTRODUCTION

Given the global energy shortage and adverse effects of engine-out emissions on climate and human health, modern diesel engines are required to advance in the direction of low emission and fuel consumption.[1] Combined with the particle emissions, nitrogen oxides (NOx) are the dominant emissions of diesel engines.[2] NOx emissions have aggravated the atmospheric quality markedly because NOx can participate in the production of fine particulate matter, acid rain, and ozone.[3] Therefore, the limit of NOx emissions is further tightened in the current emission legislations.[4] Pilot injection and selective catalytic reduction (SCR) are two effective techniques for the mitigation of NOx emissions from diesel engines. Pilot injection is a shorter injection before the main fuel injection, which can provide an environment of high temperature and pressure for the main injection resulting in a smoother pressure rise and shortened ignition delay for the main injection.[5,6] Owing to the shorter ignition delay, less combustible mixture is generated before the ignition event, leading to decreases in the premixed burn fraction and combustion temperature, finally reducing the NOx formation.[7,8] The efficacy of pilot injection in reducing the content of NOx emissions depends on the injected fuel quantity and the interval between pilot- and main-injection events. Huang et al.[9] experimentally studied the effects of the pilot-injection fuel amount and the pilot-main interval on NOx emissions of a compression ignition (CI) engine. They found that with an increase in the pilot-injection amount, the NOx emissions increased whereas the soot, THC, and CO emissions

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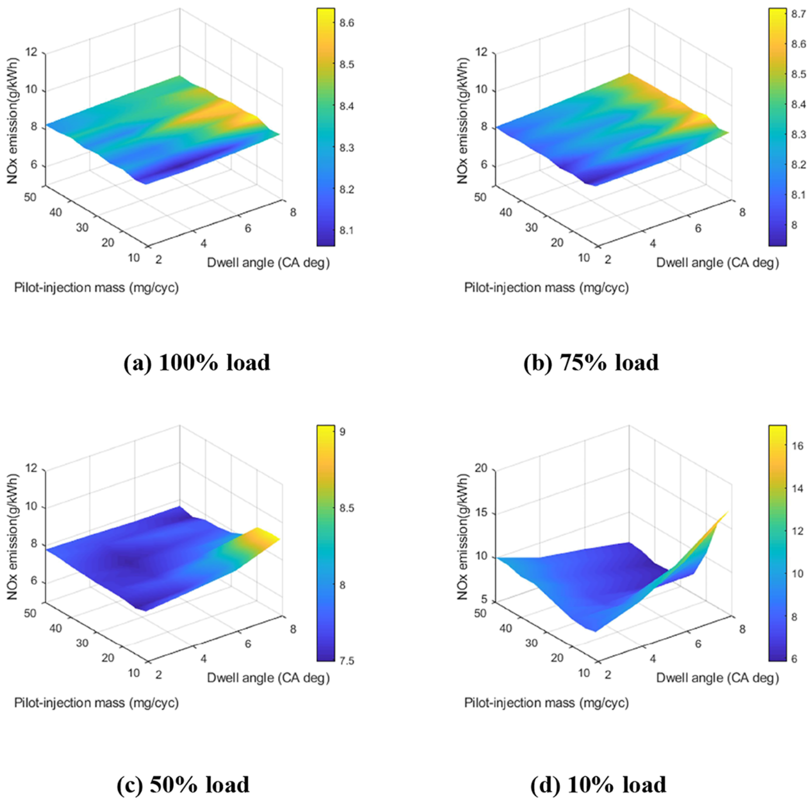

Figure 1. NOx emission for different interval angles and injected fuel masses of pilot injection at (a) 100% load, (b) 75% load, (c) 50% load, and (d) 10% load at a maximum torque speed of 1500 rpm.

slightly deteriorated; increasing the pilot-main interval leads to no significant influence on NOx emissions but significantly increased the THC and CO emissions. The dependence of NOx emissions on the pilot-main interval and the pilot rate was also found in the study of Zheng et al.[10] It was found that the NOx emissions decrease and then increase slightly before and after the pilot-main interval of 25° CA in a diesel engine fueled with pure diesel. Meanwhile, at a pilot-main interval of 10~30° CA, the increasing pilot injection rate led to more reduction in NOx emissions, which was explained by the shortening ignition delay and aggravating local over-rich regions. The effect of the pilot-injection strategy on NOx emissions is similar when using various fuel mixtures of diesel/gasoline, diesel/*n*-butanol, or diesel/gasoline/*n*-butanol blends. Liu and Reitz[11] computationally investigated the impacts of multiple injection strategies on NOx emissions of the CI engines. Their results showed that large-amount early pilot injection greatly helped in improving the NOx emissions of a CI engine operating at part load because of the sufficient time for mixing of the early pilot injection and the resulting low temperature and clean combustion. However, an excessively advanced pilot injection could deteriorate the engine performance, unless completely homogeneous combustion was desired.

The pilot-injection strategy can also provide more time for fuel/air mixing and prepare the premixed lean mixture prior to the combustion of the main-injection fuel and is crucial to achieve homogeneous charge compression ignition (HCCI) combustion.[12] Fang et al.[13] achieved HCCI combustion on a heavy-duty CI engine using a two-stage injection strategy comprising of an early pilot injection and a main injection around the compression top dead center. It was found that the NOx emissions dramatically reduced with the increase in the pilot-injection quantity in an appropriate range due to the more HCCI combustion that produced very little NOx. However, the increasing HCCI combustion resulted in a higher temperature at the start of diffusion combustion, which is unfavorable to the reduction of NOx emission. Therefore, in order to reduce the NOx emission, an optimal pilot-injection quantity should be carefully determined according to the engine operating conditions. Das et al.[8] used a large pilot injection (80% volume with respect to the total injected fuel) to generate HCCI-like combustion in order to achieve low NOx emission, with wide injection timing of the main injection. The results suggested that pilot injection is preferable for low-temperature combustion and lower NOx emission as the main injection retarded. Liu et al.[14] explored the optimal pilot-injection strategy including pilot timing and pilot mass for the high-load gasoline CI combustion mode in a multicylinder heavy-duty diesel engine. They found that late pilot timing with a small fuel mass can always achieve lower soot emissions and maximum pressure rise rates than the single injection. Meanwhile, under a low injection pressure, the use of an optimized pilot-injection strategy coupled with the retarded main-injection timing can achieve a similar emission level compared with the high injection pressure that is generally required for smoke abatement with the low engine-out NOx target.

Despite the effective reduction of NOx emission by pilot injection, the NOx emission from modern CI engines requires further mitigation to satisfy the current emission legislations such as HDV Euro-VI B, China VI, and the nonroad engine EU-V emission standards. At present, an SCR system is generally utilized to offer high level of NOx reduction.[15,16] In the SCR system, an aqueous solution of nontoxic urea is generally used as a reductant agent for the reduction of NOx to N_2.[17,18] To

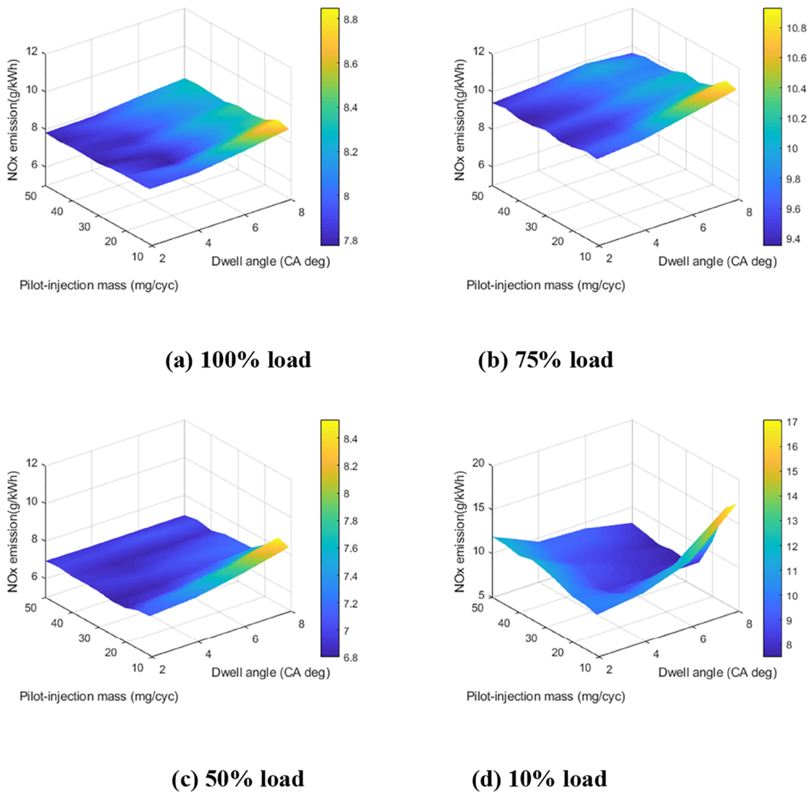

Figure 2. NOx emission for different interval angles and injected fuel masses of pilot injection at (a) 100% load, (b) 75% load, (c) 50% load, and (d) 10% load at a rated power speed of 2200 rpm.

accelerate the reactions concerning the NOx reduction, catalysts such as zeolite- and vanadium-based ones are required to reduce the activation energy and enable the occurrence of reactions at the exhaust gas temperature range of the engine.[19] As reviewed by Vignesh and Ashok,[20] with a given catalyst and the SCR configuration, the reduction degree of NOx emissions depends upon the quantity of the reductant agent and the reaction conditions generated by the engine operating conditions such as exhaust gas temperature, NOx emission level, and engine speed. In particular, a higher exhaust gas temperature corresponds to an enhanced NOx reduction degree by providing a higher activation energy for the catalytic reduction reactions. The lower engine speed provides longer resistant time available for the reduction reaction and is more prone to a higher NOx reduction level. Therefore, to determine the NOx conversion rate of the SCR system, the primary parameters related to the engine operating conditions should also be taken into consideration. For a CI engine using a pilot-injection strategy coupled with SCR systems for further reduction of NOx emissions, the application of pilot injection can alter the combustion characteristics, exhaust gas composition (especially the NOx emissions), and temperature,[21,22] finally exerting influences on the NOx reduction degree of the SCR system. In this context, study on the combination of the pilot-injection strategy and the SCR system to reduce NOx emissions is of necessity.

To our knowledge, the individual effects of pilot injection and NH_3-SCR system on NOx emissions have been extensively studied. However, there are few studies focused on their combined effect and interaction although they are generally concurrent on the modern CI engines. In the present study, NOx emissions under various pilot-injected fuel amounts and main-pilot injection interval crank angles were measured to determine the effect of pilot injection and obtain the optimal pilot-injection strategy. With the optimal pilot-injection strategy, the NOx reduction degree was assessed under various quantities of the reductant agent to shed light on the combined effects of pilot injection and SCR system on NOx emissions. These results can provide a more holistic view of the optimization of the injection strategy and aftertreatment systems and help further reduction of NOx emissions from modern CI engines.

2. RESULTS AND DISCUSSION

2.1. Effect of Pilot Injection on NOx Emissions. Figures 1 and 2 show the variation of NOx emissions under various injected fuel masses and interval crank angles of postinjection to the main injection event at different engine load and speed conditions. The pilot injection exerts significantly different impacts on NOx emissions under various engine operating conditions. At a low engine speed of 1500 rpm (in Figure 1), the NOx emission is more sensitive to the variation in the pilot-injection strategy at low engine load conditions (10 and 50% loads) according to the broad-range variation of NOx emissions in the pilot-injected fuel mass−pilot-main injection interval angle−NOx (PFM-PIA-NOx) figure, where the different, relatively smaller differences in the NOx emissions with various PFM and PIA suggest the insensitiveness of NOx emissions with respect to the pilot-injection strategy under high engine loads (75 and 100% loads). These behaviors are also observed when applying pilot injection under a high engine speed condition of 2200 rpm. A careful inspection of the results in Figure 1 reveals the following phenomena:

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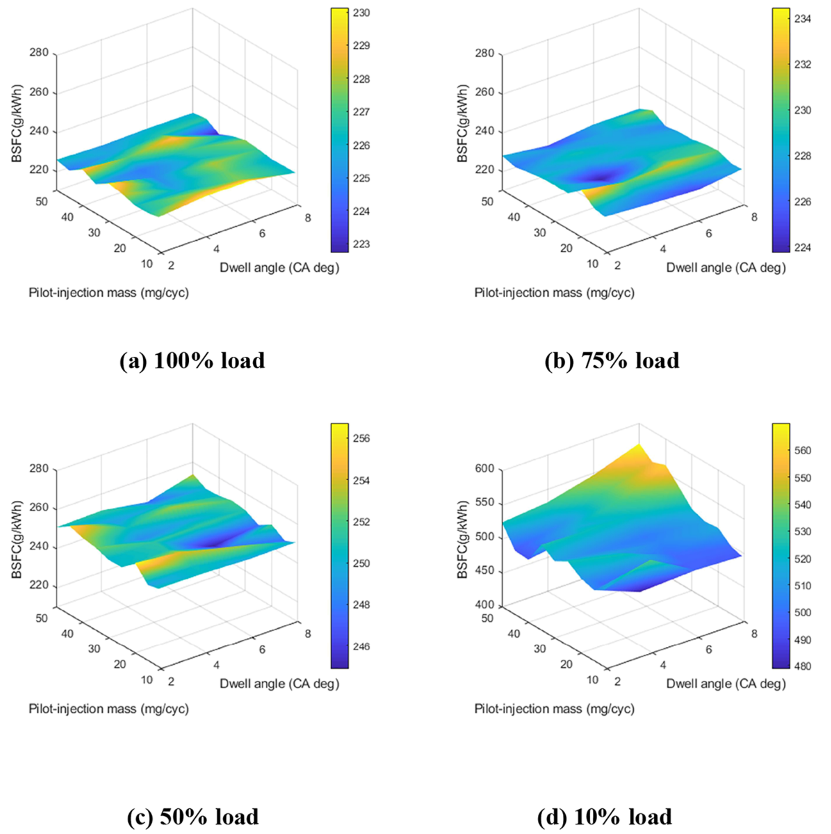

Figure 3. BSFC for different interval angles and injected fuel masses of pilot injection at (a) 100% load, (b) 75% load, (c) 50% load, and (d) 10% load at a rated power speed of 2200 rpm.

(1) At low engine load conditions (10 and 50% loads), lower NOx emissions were obtained when using smaller PFM. However, with the increases in PFM, the NOx emissions increased. On the contrary, the NOx emissions show an especially higher level at a lower PIA. Similar results were also obtained in ref 23, where these results were attributed to the optimization of the main-injection combustion by the application of pilot injection. The combustion of small pilot injection can preheat the in-cylinder gas before ignition of the main injection, resulting in a lower premixed combustion fraction, and finally reducing the NOx formation. However, an increase in the fuel injected during the pilot-injection case increases the NOx formation.

(2) At high engine load conditions (75 and 100% loads), the lowest NOx emissions were detected under the pilot-injection strategy with lower PFA and PIA. With the increasing pilot-injected fuel mass, the NOx emission increases significantly at various pilot-injection timings.

According to these phenomena, it is confirmed that the fuel mass injected in the pilot-injection case plays a more important role in the NOx emission with respect to the pilot-injection timing.

The impact of pilot injection is also reflected by the variation in the brake-specific fuel consumption (BSFC). Figures 3 and 4 show the results of BSFC obtained at various engine loads under 1500 and 2200 rpm. On the whole, despite the relatively lower BSFC at some operating modes, BSFC shows no clear correlation with either PFM or PIA under the medium- and high-load conditions (50−100% load), indicating an inconclusive role of pilot injection on the BSFC. However, it is clearly observed that a distinctly higher BSFC is obtained under a larger PIA (>30° CA BTDC), and the increment of BSFC further increases with the rising PFM. Presumably, the higher BSFC arise from a poor combustion efficiency for a given engine configuration.[24] Although the advanced pilot injection is prone to generate more homogeneous combustion and improve the NOx emissions,[25] excessively early pilot injection may lead to more incomplete combustion due to part of the pilot-injected fuel entering the over-lean region,[26] and this effect can be enhanced as the pilot-injection amount increases.

Study on the impact of pilot injection on the exhaust gas temperature (exhT) is of great necessity for the modern CI engines because exhT is one of the primary factors that determines the conversion ratio of aftertreatment systems such as SCR to reduce the pollution emissions.[27] Figures 5 and 6 show the exhT results for various pilot-injection strategies under a broad range of operating conditions. Under low engine load conditions (10% load), it is obvious that a smaller PFM results in a higher exhT for both low and high engine speeds. However, the exhT under low load conditions is less than 250 °C, that is, far lower than the working temperature (>300 °C) of SCR systems. Therefore, the exhT increment by pilot injection is not sufficient to improve the further reduction of NOx emissions in SCR systems. Fortunately, the exhT for the medium and high engine load conditions is higher than 350 °C, which can guarantee effective reduction of NOx emissions by SCR systems.[27] Similar to the BSFC results, the exhT shows no clear correlation with either PFM or PIA under the medium load (50% load) conditions, as shown in Figure 5c and Figure 6c. Under high engine load conditions, a higher exhT is obtained under a

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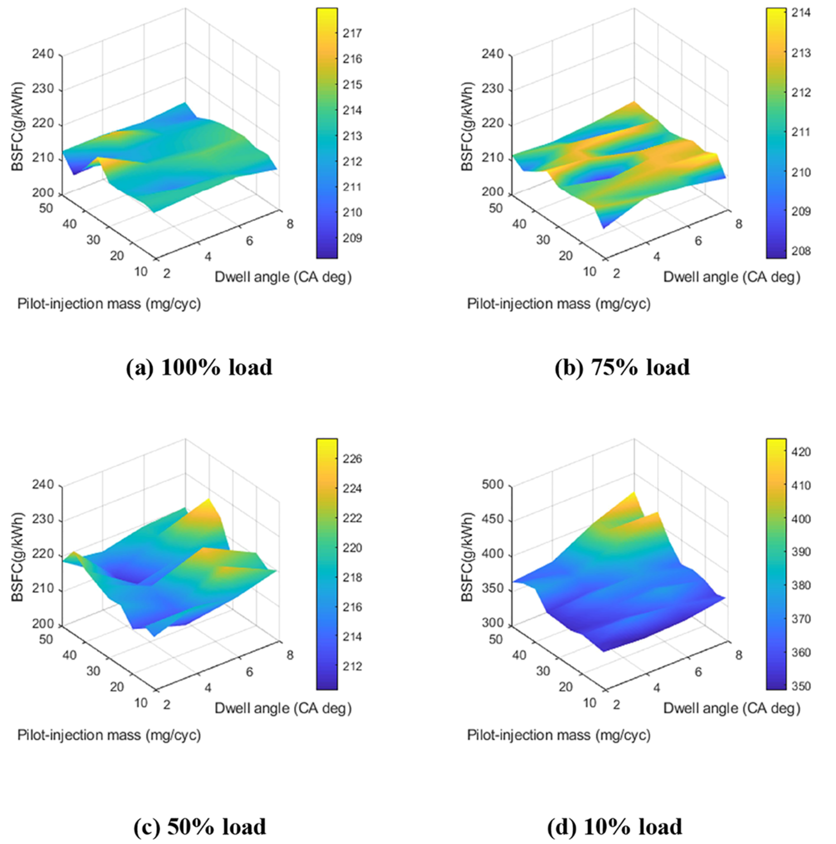

Figure 4. BSFC for different interval angles and injected fuel masses of pilot injection at (a) 100% load, (b) 75% load, (c) 50% load, and (d) 10% load at a maximum torque speed of 1500 rpm.

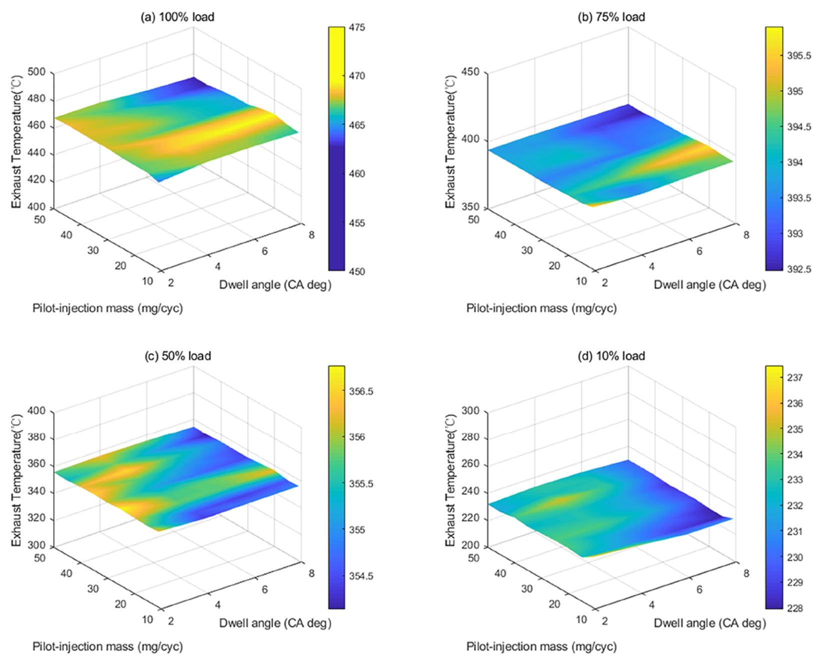

Figure 5. exhT for different interval angles and injected fuel masses of pilot injection at (a) 100% load, (b) 75% load, (c) 50% load, and (d) 10% load at a rated power speed of 2200 rpm.

relatively smaller PIA (20 < PIA < 30° CA), with which the exhT increases toward a larger PFM.

2.2. Combined Effect of Pilot Injection and SCR. Apart from the pilot injection, the SCR system is also a modern technology for CI engines to further reduce the NOx emissions and satisfy the stringent emission norms. Unlike the pilot injection which is a typical in-cylinder combustion technology, the SCR system is able to achieve NOx reduction at higher levels without affecting the engine performance.[20] However, the application of pilot injection can lead to variations in the exhT

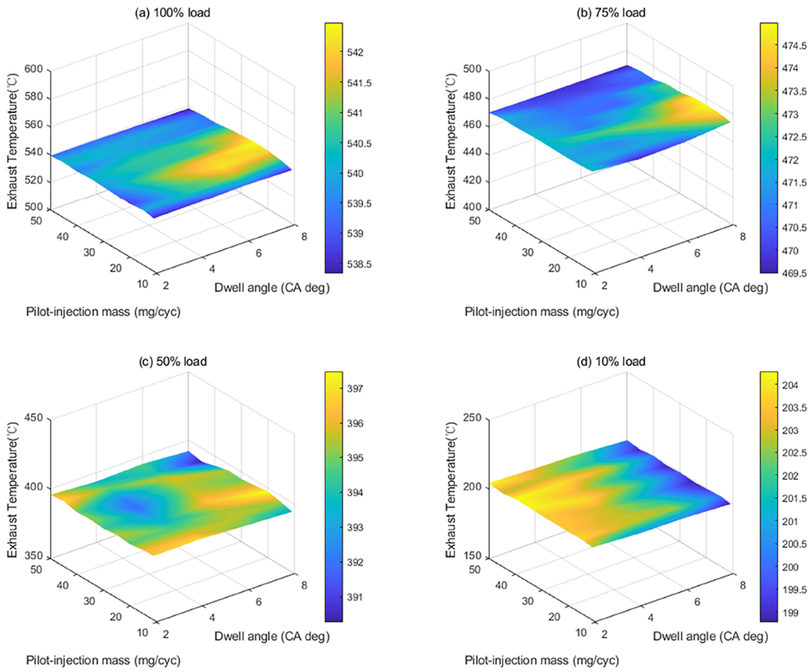

Figure 6. exhT for different interval angles and injected fuel masses of pilot injection at (a) 100% load, (b) 75% load, (c) 50% load, and (d) 10% load at a maximum torque speed of 1500 rpm.

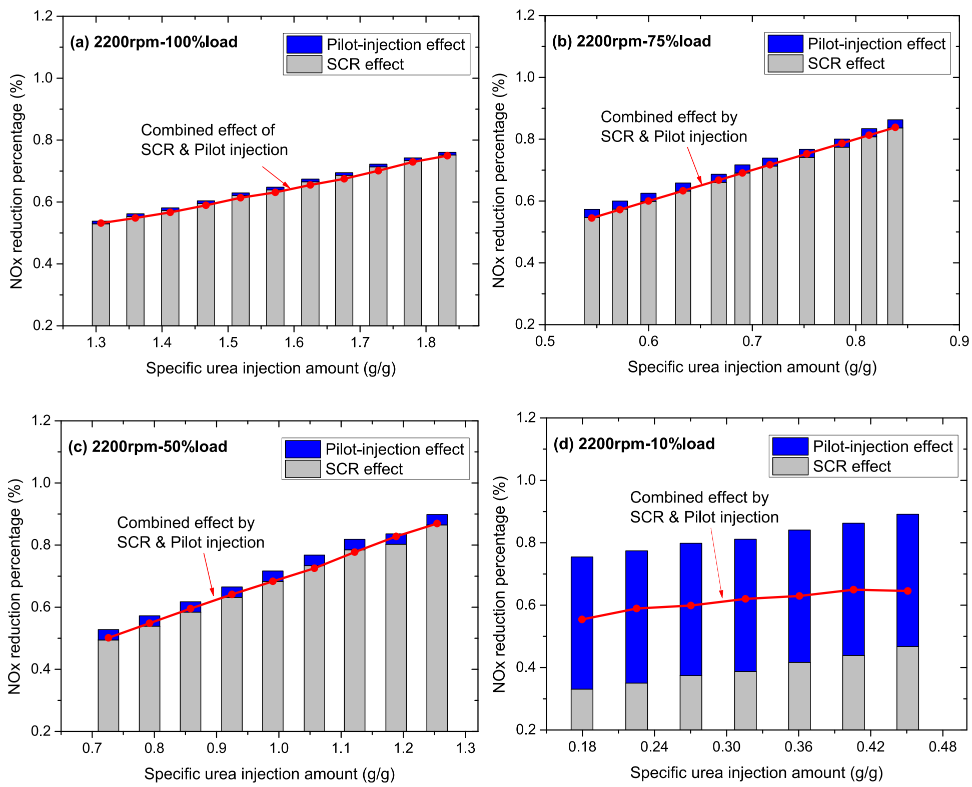

Figure 7. NOx reduction percentage by SCR and pilot injection and SCR + optical pilot-injection strategy for 2200 rpm engine speed conditions.

and emission compositions, probably causing an alteration in the conversion ratio of the SCR system. Therefore, when the SCR system coupled with pilot injection is employed for CI engines, their correlation and combined effects should be assessed. Figures 7 and 8 show the reduction percentages of NOx emissions when using, respectively, a sole SCR system (sSCR), a sole optical pilot-injection strategy (soPI), and SCR combined with an optical pilot-injection strategy (SCR + oPI) with respect to the original NOx emissions without SCR and pilot injection. To conveniently compare the conversion ratio of the SCR system under various engine operating conditions, the urea injection mass per cycle is divided by the mass of the exhaust gas to obtain the specific urea injection amount (sUA). From

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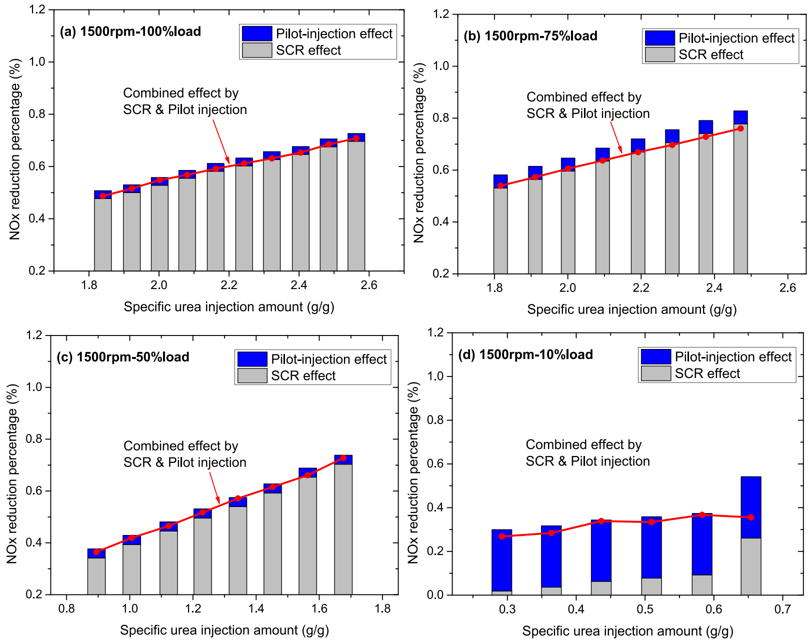

Figure 8. NOx reduction percentage by SCR and pilot injection and SCR + optical pilot-injection strategy for 1500 rpm engine speed conditions.

Figures 7 and 8, the following phenomena can be observed under both low and high engine speed conditions:

(1) The NOx reduction percentage for both of the sSCR and SCR + oPI cases increases monotonously as the sUA increases. Considering that the risks of deposition and leakage are significantly enhanced by the excessive urea dosing,[28] the impact of sUA on NOx reduction by further increasing the dosing amount was not addressed in this study.

(2) For all the testing conditions, the NOx reduction percentage for SCR + oPI is higher than that for the sSCR as well as soPI cases, whereas it is lower than the total NOx reduction degree when separately using sSCR and soPI; the latter behavior may arise from the decreased emission gas temperature by the utilization of pilot injection and thus diminishes the conversion ratio of the SCR system.[29]

(3) With the reduction in the engine load, the NOx reduction percentage for the soPI case gradually increases whereas that for the sSCR case decreases. At 10% load conditions, the soPI case even exceeds the sSCR case in NOx reduction percentage. Corresponding to the low engine load, the lower exhT can suppress the NOx reduction reactions within the SCR system.

3. CONCLUSIONS

The effects of pilot injection and SCR system on NOx emissions were studied under various engine operating conditions. In this study, the pilot-main interval and the rate of pilot-to-main injection used are in the range of 2~8 CA and 9.5~58.5%, respectively. Furthermore, with the utilization of an optimal pilot-injection strategy coupled with the SCR system, the NOx emissions were assessed to reveal the effect of combination of pilot injection and the SCR system on the NOx reduction degree. The study draws the following conclusions:

(1) With respect to the high-load conditions, the alteration in the pilot-injection strategy (pilot-main injection interval and pilot-injection amount) under low load conditions is prone to lead to more variation in NOx emissions. Meanwhile, the fuel mass injected in the pilot-injection case plays a more important role than the pilot-injection timing regarding the NOx emission;

(2) Under low engine load conditions, lower NOx emissions can be achieved when using a smaller pilot-injection amount. Under high engine load conditions, the lowest NOx emissions were detected under the pilot-injection strategy with a smaller pilot-injection amount and pilot-main interval;

(3) With the reduction in the engine load, the NOx reduction percentage by pilot injection gradually increases whereas that for the SCR system decreases;

(4) For all the testing conditions, the NOx reduction percentage of pilot injection coupled with the SCR system is lower than the total reduction degree when separately using pilot injection and the SCR system.

4. EXPERIMENTAL SECTION

The engine testing experiments were conducted on a CI engine, which can meet the EU-V nonroad emission standard. A commercial NH_3-SCR system was arranged at the downstream of the engine exhaust in series to reduce the NOx emissions. The main specification of the test engine and the SCR system is shown in Table 1. The fuel was 0# diesel fuel satisfying the China standard of GB 19147-2016. During all the engine testing experiments, the engine was operated at thermally steady states with the inlet coolant and lubricating oil temperatures at 75 ± 5 °C. The intake air temperature was controlled at 25 ± 1 °C. To precisely control the operating conditions, an electric dynamometer (HT350, HORIBA) was linked with the testing engine. The resolution for the engine speed and torque control was 1 rpm and 1 N·m, respectively (Table 2). The exhT and the flow rate were measured during the engine operation before the inlet of the NH_3-SCR system. The NOx emissions were measured using an emission analysis system (MEXA-7200D, HORIBA). To ensure the repeatability and accuracy of NOx

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Table 1. Specifications of the Test Engine

engine specifications	
engine type	four stroke, turbocharged
number of cylinders	4
displacement (*L*)	4.75
compression ratio	17.5
cylinder diameter (mm)	110
stoke (mm)	125
maximum torque	653 kW@1500 rpm
rated power	117.6 kW@2200 rpm
DeNOx technology	Cu−zeolite catalyst NH_3-SCR

Table 2. Resolution and Uncertainties of the Main Measurement Apparatus

measurement apparatus	resolution	uncertainties
dynamometer		
speed measurement	1 rpm	±0.4%
torque measurement	0.01 N·m	±0.2%
exhaust gas analyzer NOx	1 ppm	<0.1%
fuel consumption meter		<0.12%

emission results, data reading and averaging were conducted more than 10 times when the engine was operated under the stationary conditions. The sampling and measurement procedures were compared with those specified in the EU-V nonroad emission standard. A fuel consumption meter (CMFD015, TOCEIL) was employed to monitor the fuel consumption amount, which can be used to calculate the BSFC. The schematic diagram of the engine test setup is shown in Figure 9.

In order to determine the effect of pilot injection, NOx emissions for various PFM) and PIA were determined for a series of engine loads under two engine speed categories of maximum torque (1500 rpm) and rated power (2200 rpm). For a given engine load, the main-injection timing was adjusted to ensure the satisfaction of the test engine to EU-V emission regulation. With these main-injection timings, the variation in the engine load induced by the adjustment of the pilot-injection strategy was negligible and not considered in this study. Considering that the excessively large pilot injection and advanced pilot-injection timing may lead to deterioration of the HC, CO, and smoke emissions, the relatively smaller pilot-injection amount and the pilot-main interval with which the minimal NOx emissions were achieved were considered as the optimal pilot-injection strategy. With the optimal pilot-injection strategy, the quantity of the reductant agent was adjusted to assess the impact of NH_3-SCR on NOx emissions.

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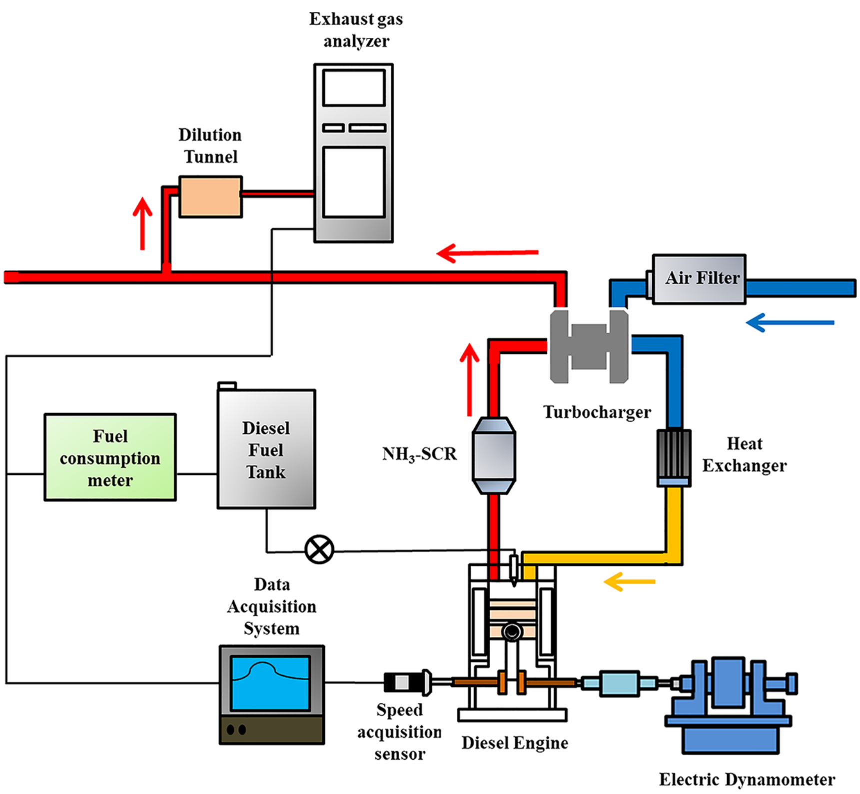

Figure 9. Schematic diagram of the engine test setup.

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Author Contributions

T.S. was involved in conceptualization, methodology preparation, investigation, project administration, funding acquisition, and supervision, C.F. was involved in formal analysis, resource procurement, data curation, writing the original draft, writing, reviewing, and editing, visualization, and supervision, Z.F. was involved in resource procurement, data curation, and investigation, and M.W. was involved in resource procurement and data curation.

Notes

The authors declare no competing financial interest.
The authors have consent to participate.
The authors have consent to publish.
Provided in the manuscript.

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