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Multi-injection of diesel fuel to decrease the NOx formation

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Abstract

In Common-Rail Diesel Engines, a low combustion temperature process is considered as one of the most important possibilities to achieve very low emissions and optimum performance. To reduce NOx effectively, it is necessary to achieve a homogenization of the mixture in order to avoid the higher local temperatures which are responsible for the NOx formation. In this study, we applied multi-injection strategies to achieve the reduction of NOx in emission. For this, one of six cylinders of a heavy-duty diesel engine was modified to utilize common rail system to implement the multiple injections. The engine was run at a constant speed of 1650 rpm and various loads. The NOx emission was directly measured from exhaust gas by NGK-NO_X sensor at stable operating condition in five minutes for each test. In comparison, single and multiple injections were experimentally analyzed in variation of the injection parameters (pressure, timing and fuel quantity). Based on the results, the multi-injection strategies were proposed to minimize the NOx concentration in emission.

Keywords*:* multiple injections, injection spray, diesel engine, common rail system

1. Introduction

Diesel engines are widely used in transportation, construction, power generation, agriculture, and industry because of their high economy, efficiency and durability. However, the emissions of diesel engine are very harmful to people and environment. For example, the particulate matter can cause the respiratory disease in human beings and results in a worse air quality. The NO_X is also injurious to human beings and plant. Furthermore, the NO_X plays a big role in the generation of acid rain. For these reasons, many scientists develop some alternative fuels and special combustion technologies. Common rail system is one of the combustion technologies scientists focus on. Compare to traditional injection system such as direct injection or multipoint injection, common rail system has many advantages[1]. First, common rail system can control the injection quantity precisely. Second, using common rail system can decrease the noise and emissions. Final, the volume and weight of common rail system are lower than traditional injection system.

The adjustable injection parameters of common rail system are injection timing, injection pressure and multiple injections. Injection timing means the start crank angle of injection. When the injection timing is advanced, the mix of air and fuel can be better so that the fuel will burn more completely. Nwafor et al. used a single cylinder diesel engine to investigate the emissions by adjusting the injection timing with natural gas and diesel dual fuel. The results showed that after advancing the injection timing from 30° BTDC to 33.5° BTDC, the engine ran more stably and the HC, CO and CO_2 were decreased[2]. C. Sayin et al. added 5%, 10% and 15% methane into diesel. The engine was kept at 2200rpm and the injection timing was 15° BTDC, 20° BTDC and 25° BTDC. When the injection timing was 15° BTDC, the NO_X and CO_2 both reduced. But after advancing the injection timing to 25° BTDC, the NO_X and CO_2 increased[3]. M. Pandian et al. used biodiesel to investigate the effect of injection timing on engine performance and emissions. The brake specific energy consumption reduced and the thermal efficiency increased when the injection timing was advanced. The CO and HC also decreased but the NO_X increased[4]. Injection pressure is the pressure of common rail and injector. The fuel spray droplet will be smaller when the injection pressure is increased. The small fuel spray can improve the mix of air and fuel and combustion. D.T. Hountalas et al. investigated the effect of injection pressure on a single cylinder diesel engine with two speeds and two loads. The results displayed the fuel burned more completely with higher injection pressure. As a result, the smoke reduced with increasing the injection pressure. However, the high temperature led to more NO_X formation[5]. S. Emami et al. used numerical method to simulate the temperature, pressure and emissions formation inside the cylinder. The injection pressure was considered as a variable. From their study, it can be observed that the equivalence ratio was decreased and combustion temperature was increased as the injection pressure increased, as a result, the NO_X formation was also be promoted[6]. Multi-injection strategy is often used to reduce the noise, emissions and fuel consumption[7]. Multi- injections strategy includes pre-injection, after injection, three-stage injection and even five-stage injection. Using pre-injection can provide a higher cylinder temperature and pressure for main injection. It can let the cylinder pressure rising process more smooth and short the ignition delay of main injection [8]. After-injection can help the unburn fuel of main injection burn more completely so that the particulate matter can be reduced [9]. A. Vanegas et al. investigated the effect of pilot injection on a four cylinders common rail diesel engine. Their results showed that the NO_X and smoke can be reduced effectively with pilot injection at 80°

BTDC. However, the HC and CO were reduced and the IMEP was worse than single injection[10]. H. Ogawa et al. investigated the effect of different after-injection strategy on a single cylinder diesel engine. The results showed that over the whole of the operating range, some reduction in smoke emissions can be achieved with after-injection, without deterioration in thermal efficiency and other emission characteristics. The optimum quantity of after-injection for smoke reduction is 20% of the total fuel supply, and the optimum timing is just after the main injection[11]. S. Kevin Chen et al. used several multi-injection strategies on a diesel engine. It was found that post injection and multiple injections can reduce particulate emissions by more than 40% in some cases. Furthermore, triple injection can reduce the NO_X by 50%[12].

2. Experiment Setup and Instruments

The tests were carried out on a 6-liter 6-cylinder heavy duty diesel engine. The specifications of the engine were given in Table. 1. This engine was equipped with traditional injection system. In order to investigate the effect of injection parameters on emissions, we did some modifications to this engine. First, the injection system of the sixth cylinder was replaced by common rail system we designed. The common rail system was composed of Denso fuel pump, Delta servo motor, Bosch common rail, Atlantis pressure gauge, Denso injector, PI INNOVO injector driver and 8051 injection signal control module. This common rail injection system can achieve triple injection and the minimum injection duration is 100μs. The second part we modified was intake and exhaust manifolds of the sixth cylinder. With these two modifications, the engine can run with traditional and common rail injection systems at the same time. The emissions from the sixth cylinder and the other five cylinders were also can be measured separately. The NGK-NO_X senor was used to measure NO_X in this study. The NOX sensor was installed at the exhaust pipe. The experimental setup was showed in Fig. 1.

The test conditions were listed in Table. 2 – 5. The engine speed was kept at 1650rpm by dynamometer in each case. The injection timing was decided by the 8051 injection signal control module. The minimum unit of injection duration was 1μs and the minimum unit of injection timing dwell was 2° CA. The injection pressure was controlled by the servo motor speed and the SCV(suction control valve) inside the fuel pump. With above two techniques, this injection system can control the injection quantity precisely. After setting the injection timing and pressure and running five minutes, the NO_X was recorded and saved in computer. In multi-injection tests, we also tested the single injection to compare the NO_X formation with multi-injection.

In injection timing and pressure tests, the light load tests were the lower injection quantity showed in Table. 2-3, and the medium load tests were the higher injection quantity showed in Table. 2-3.

Because the NO_X formation is strongly dependent on the combustion temperature, we also used the pressure transducer to record the cylinder pressure and Eq. (1) to calculate the combustion temperature. $P(\theta)$ is the cylinder pressure for each crank angle. $V(\theta)$ means the cylinder volume for each crank angle and m_a is the mass of intake air. Because the voltage signal from the AVL GH13P pressure transducer was very weak, we used KISTLER-5015 charge amplifier to amplify the voltage signal. Final, the ADVANTECH USB-4716 data acquisition module was used to record voltage signal and connected to computer.

$$T(\theta) = \frac{P(\theta)V(\theta)}{m_a R} \tag{1}$$

Table. 1 The specifications of Hino W06E engine

Type	6-cylinder, 4-stroke, in-line
Displacement	6014 c.c.
Bore	104 mm
Stroke	118 mm
Compression Ratio	19.2
Number of Valves	4
Intake Valve Opening	16° BTDC
Intake Valve Closing	40° ATDC
Exhaust Valve Opening	55° BTDC
Exhaust Valve Closing	13° ATDC
Max. Power	165 Ps @ 3000 rpm
Max. Torque	42 kg • m @ 1800 rpm

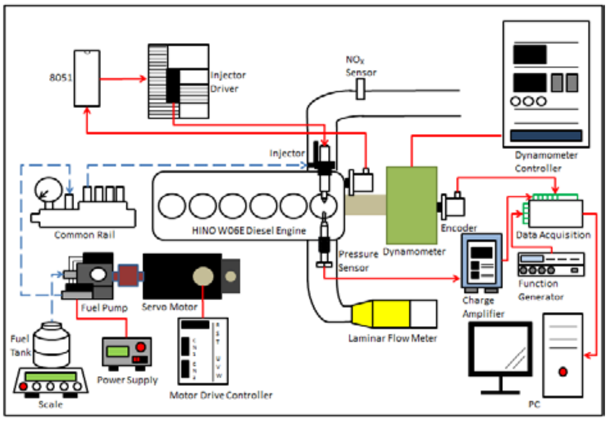

Fig. 1 The experimental setup

Table. 2 The injection timing tests conditions

Injection Pressure	600 bar
Injection Quantity	15 mg/stroke, 26 mg/stroke
Injection Timing	14°~ 2° BTDC

Table. 3 The injection pressure tests conditions

Injection Timing	8° BTDC
Injection Quantity	14 mg/stroke, 23 mg/stroke
Injection Pressure	400 ~ 800 bar

Table. 4 The double injection tests conditions

Type	Pre-injection	After-injection
Total Injection Quantity	24 mg/stroke	
Injection Pressure	400 bar	
Main Injection Timing	8° BTDC	
Main Injection Duration	370μs / 330μs	
Pre-injection Timing	22°/ 20°/ 18° BTDC	-
Pre-injection Duration	110μs / 128μs	-
After-injection Timing	-	12°/ 16°/ 22° ATDC
After-injection Duration	-	110μs / 128μs

Table. 5 The triple injection tests conditions

Total Injection Quantity	24 mg/stroke
Injection Pressure	400 bar
Main Injection Timing	8° BTDC
Main Injection Duration	330μs
Pre-injection Timing	22° / 20° BTDC
Pre-injection Duration	110μs
After-injection Timing	16° / 22° ATDC
After-injection Duration	110μs

3. Results and Discussion

This research tested the effect of injection parameters on NO_X formation. The injection parameters include injection timing, injection pressure, pre-injection, after-injection and triple injection.

3.1 The effect of injection timing on NO_X

In injection timing part, we varied the injection timing from 14° BTDC to 2° BTDC and the dwell between each case was 2° CA. In each case, the engine would run five minutes in steady state and then measure the NO_X. However, the engine ran unstably in medium load when the injection timing was 2° BTDC because of the difference between sixth cylinder and other five cylinders. For this reason, the 14° BTDC test under medium load was be neglected.

From Fig. 2, it can be observed that when the injection timing was advanced, the NO_X formation would be higher. Because advancing the injection timing can extend the mixing time for fuel and air, the mixing process can be improved. As a result, the fuel would burn more completely and the combustion temperature would be higher. This is the major reason for increasing NO_X formation when advancing injection timing. Different to the NO_X formation trend, the NO_X at 6° BTDC in medium load is lower than at 4° BTDC. It was due to the bad combustion at 6° BTDC. The maximum combustion temperature in 6° BTDC also lower than 4° BTDC about 27K.

The results from Fig. 2 also showed that the NO_X in medium load was higher than in light load because more fuel was injected into cylinder in medium load. In light load, the highest NO_X occurred at 14° BTDC and the value was 383ppm which was increased by 340ppm compared to 2° BTDC. In medium load, the highest NO_X occurred at 12° BTDC and the value was 489ppm which was increased by 285ppm compared to 2° BTDC.

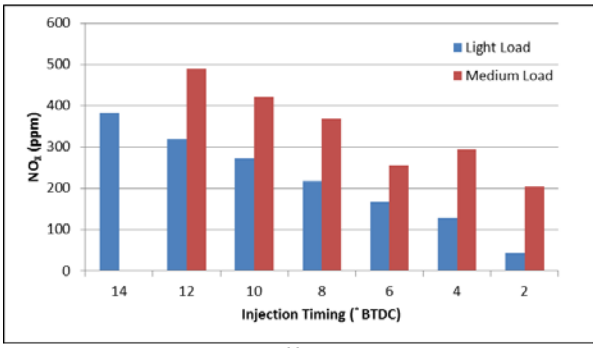

Fig. 2 The NO_X in different loads and injection timings

3.2 The effect of injection pressure on NO_X

This section discussed the effect of injection pressure on NO_X formation. The injection pressure operation range was from 400bar to 800bar and the pressure difference between two tests was 100bar. Fig. 3 showed that the NO_X formation became higher as the injection pressure increasing. Higher injection quantity also led to a higher NO_X formation. High injection pressure can cause the longer spray penetration, a larger spray area and smaller spray droplet. These reasons result in a more mixing between fuel and air lead to enhanced the combustion. So the combustion temperature also became higher which improved the NO_X formation.

In light load, the highest NO_X was 291ppm when the injection pressure was 800bar. Compare to the NO_X in 400bar, it was increased by 92ppm. On the other hand, the highest NO_X in medium load was 493ppm and it also occurred at 800bar. Compare to 400bar, it was increased by 231ppm. It can be seen that the effect of injection pressure from medium load was stronger than light load.

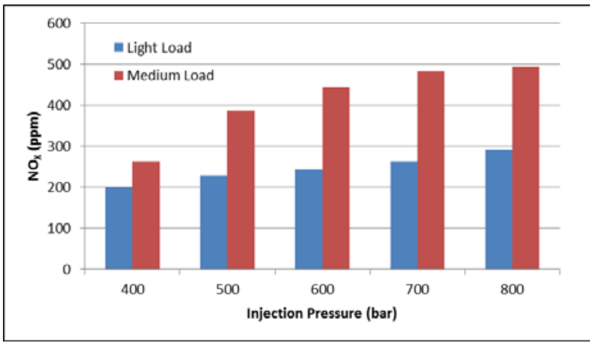

Fig. 3 The NO_X in different loads and injection pressures

3.3 The effect of two-stage injection on NO_X

This study carried out different double injection strategies on engine. In this section, we would discuss the effect of pre-injection and after-injection separately. Fig. 4 was the results of pre-injection and after-injection. The value of red line in Fig. 4 was the NO_X formation measured from single injection experiment.

The pre-injection ratio meant the pre-injection fuel percentage of total injection quantity. In pre-injection part, the lowest pre-injection ratio was 10% because of the minimum duration of injector driver. So we tested 10% and 20% pre-injection ratio and three pre-injection injection timings. The results showed that the NO_X formation increased with pre-injection. Furthermore, increasing the pre-injection ratio can also improve the NO_X formation. Because the pre-injection can provide a higher combustion temperature and cylinder pressure for main injection, the maximum combustion temperature would become higher and the high temperature duration would be longer. Fig. 5(a) showed the combustion temperature of different pre-injection strategies. From Fig. 5(a) we can know that the combustion temperature was higher with pre-injection. Final, if the dwell between pre-injection and main injection reduced, the NO_X can decrease slightly. The highest NO_X operation condition was that the pre-injection duration was 128µs and injected at 22° BTDC. Compare to single injection, the NO_X increased by 102ppm.

The after-injection ratio meant the after-injection fuel percentage of total injection quantity. In after-injection part, the 10% and 20% after-injection ratio and three after-injection injection timings were tested. The results showed that the NO_X formation reduced with after-injection. And the decrease was remarkable when the after-injection ratio was higher. Compare to single injection, fewer fuel burned in main injection stage, so the maximum combustion temperature would be lower than single injection. Fig. 5(b) showed the combustion temperature of different after-injection strategies. From Fig. 5(b) we can know that the combustion temperature was lower with after-injection. And the NO_X formation was dependent on the combustion temperature so that the NO_X formation was lower with after-injection. The most effective reduced operation condition was that the after-injection duration was 128µs and injected at 12° ATDC. Compare to single injection, the NO_X reduction can reach 94ppm which was about 30.7%.

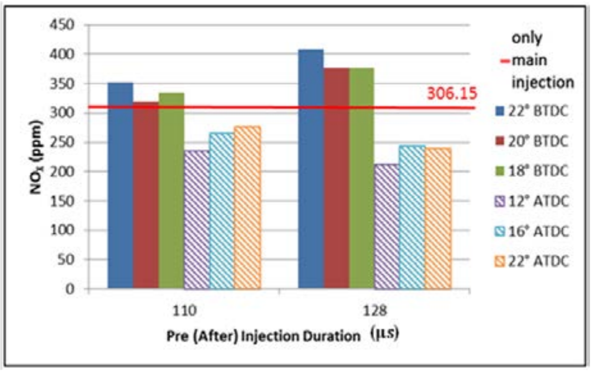

Fig. 4 The NO_X in different double injection strategies

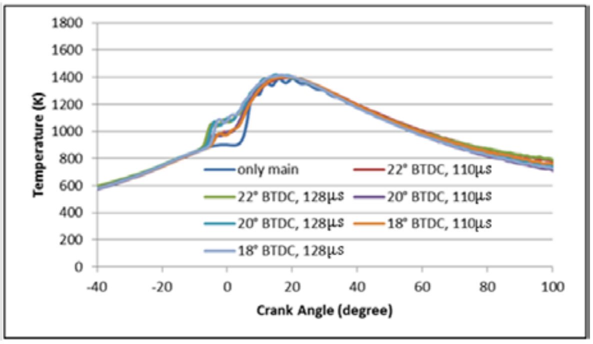

Fig. 5(a) The combustion temperature in different pre-injection strategies

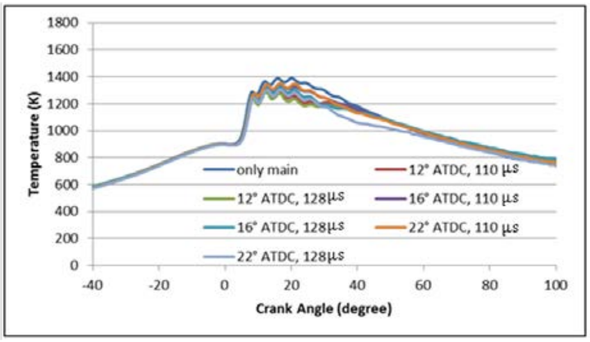

Fig. 5(b) The combustion temperature in different after-injection strategies

3.4 The effect of three-stage injection on NO_X

In triple injection part, we only investigated the effect of triple injection and the injection timing of triple injection on NO_X formation. Fig. 6 showed the results of NO_X formation with triple injection. From Fig. 4 we known that the pre-injection would increase the NO_X and the after-injection would reduce the NO_X. However, it looked no obviously effect of triple injection on NO_X formation. It seemed that the triple injection combined the combustion characteristics of pre-injection and after-injection. For example, from Fig. 7 we can found that the first peak of combustion temperature in triple injection was similar to pre-injection, but the combustion temperature after 5° ATDC was a little different. The phenomenon of decrease in second peak temperature was because of fewer fuel injected during the main injection part. Though the second peak of combustion temperature decreased, the after-injection extended the high temperature duration. From Fig. 7 we can see that the temperature of triple injection was higher than single injection after 50° ATDC. The longer high temperature duration improved the NO_X formation. That was why there were not obvious influence of triple injection on NO_X formation. The lowest NO_X operation condition was injecting at 20° BTDC and 16° ATDC and the value was 292ppm.

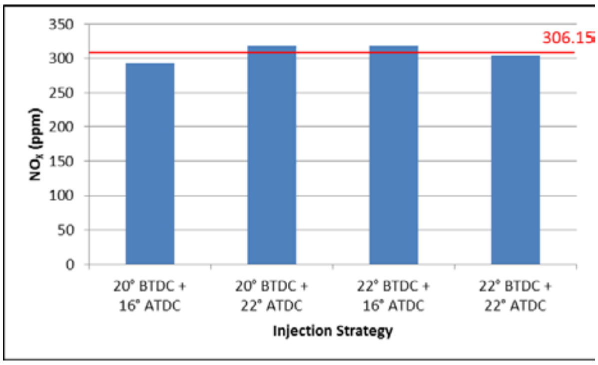

Fig. 6 The NO_X in different triple injection strategies

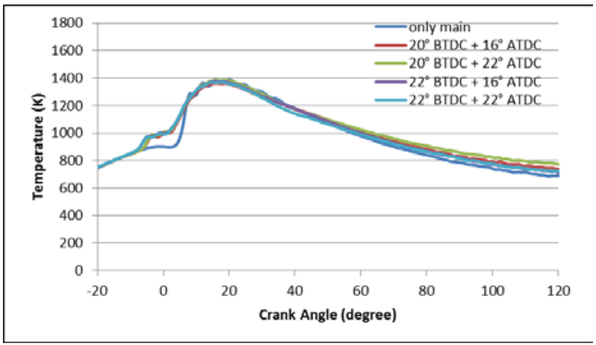

Fig. 7 The combustion temperature in different triple injection strategies

4. Conclusion

This research concerned the effect of different injection parameters and multi-injection strategies on the NO_X formation and the experiment was carried out on a heavy-duty diesel engine. The results can be concluded that as shown below.

- As the injection timing advanced, the NO_X formation will increasing due to the more completely combustion of fuel.
- As the injection pressure increased, the fuel spry droplet will be smaller and the spray area will be larger which result in the increase of NO_X formation.
- The pre-injection will provide a higher temperature and cylinder pressure environment for main injection and cause the increase of peak of combustion temperature which increase the NO_X formation.
- The after-injection will reduce the fuel quantity of main injection which make the decrease of peak of combustion temperature. As a result, the NO_X formation also decrease.
- The triple injection seems no obviously influence on NO_X formation. Though the peak of combustion temperature, the after-injection will extent the high temperature duration.

5. Acknowledgement

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6. References

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