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Effect of post injection strategy on regulated exhaust emissions and particulate matter in a HSDI diesel engine

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HIGHLIGHTS

- A trade-off relation exists between unburned emissions and NOx emission.
- Total particle concentration shows similar trends to that of soot emission.
- A lowest PM emission exists at intermediate post injection timing.
- Particle size is insensitive to post injection timing at different conditions.

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ABSTRACT

We investigate effects of post injection strategies on regular exhaust emissions and soot particulate matters on in-cylinder emission control. A trade-off relation indicates that CO and THC emissions increase as post injection timing delays, but NOx emission significantly decreases when crank angle intervals increase because of cylinder volume expansion and heat transfer. In PM emission, total particle concentration and particle size distributions indicate that, at early post injection timing, SOF emission is relatively low but soot emission is relatively large caused by high temperature and local lean oxygen conditions. As crank angle intervals increasing, soot emission decreases quickly and becomes insensitive to the post injection timing. When SOF emission has an obvious increasing trend, there is a lowest level for the PM emission at intermediate post injection timing. Moreover, variations for total particle concentration are similar with soot emission at different post injection strategies. Particle size distribution result illustrates that PS is insensitive to post injection timing at different post injection strategies.

1. Introduction

Recent investigation on vehicle emissions, particularly for nitrogen oxides (NOx) and particulate matter (PM) is a major concerning. Advanced technologies including multiple injections, exhaust gas recirculation (EGR) and after-treatment system is developed to satisfy progressively stringent emission regulations [1,2]. Despite effectiveness of after-treatment system in the reduction of exhaust emissions, in-cylinder techniques still remain attractive alternatives in order to eliminate the burden of after-treatment system. One of most potential in-cylinder solutions for emission reduction is post injection strategy, a shorter injection following the main fuel injection [3,4]. Related investigations show that post injection strategy has different mechanic influences on regulated exhaust emissions and particulate matter [5].

Lee et al. [6] focused on close post injection strategy through utilizing a double-row nozzle and two-staged piston bowl geometry in a diesel engine to reduce PM emission and improve combustion efficiency under high EGR rate. Hotta et al. [7] examined smoke and total hydrocarbon (THC) reduction effect of post injection timing in a small high speed direct injection (HSDI) diesel engine. Results show that suitable post injection timing could effectively reduce smoke and THC emissions for promoting atmosphere temperature and increasing air circulation. Following an optimization exercise, Hardy and Reitz [8] explored the merits of close-coupled post injections in a heavy-duty diesel engine, finding that close-coupled post injection strategy was capable to decrease PM emission slightly for constant NOx and specific fuel consumption (BSFC) level due to increasing in-cylinder gases mixing caused by post injection momentum. Basically, above study proved the significance of post injection to improve PM emission and combustion efficiency. Comparing with close-coupled post injection, post injection timing is more remote from main injection. Desantes

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et al. [9] reported that close-coupled post injection was more effective to reduce PM emission because of the acceleration during final-stage combustion. Small and remote post injection timing did not affect PM emission due to shortening main injection.

The utilization of post injection to reduce THC and carbon monoxide (CO) emissions was examined by Park and Bae [10], based on a diesel engine with premixed charged compression ignition (PCCI) combustion. Contrasting with single-shot main injection, an appropriate post injection strategy was necessary to significantly reduce CO and THC emissions, despite slightly increasing in NOx emission when using an early post injection strategy. Meanwhile, similar trend was observed between single and double post injection, but the later injection seemed more effective in reducing CO and THC emission. Storey et al. [11] studied the effect of post injection on hydrocarbon speciation with diesel fuel, finding that light hydrocarbons increased as post injection timing delayed, but heavy hydrocarbons was not sensitive. Jeftic et al. [12] further studied the effect of post injection timing on exhaust temperature and exhaust gas compositions in a compression ignition engine with a premixing enhanced fueling strategy of diesel and *n*-butanol. All results show that early post injection timing reduces THC and CO emission effectively.

There are numerous investigations on post injection strategy, but how post injection affects exhaust emissions is still unclear. One major reason is that exhaust emissions have obvious variable parameters under different spray injection conditions, and another is lack of fundamental experiment and model with many engine operational parameters [13]. Here, comprehensive investigations on regulated exhaust emissions (CO, THC and NOx) and PM characteristics have been performed in a HSDI Diesel Engine with different post injection strategies, which provides practical experimental data for the mechanism of post injection technology affecting exhaust emissions.

2. Experimental setup and methods

2.1. Experimental system

In the post injection experiment, we use a 3.856 L high-speed, direct-injection diesel engine with a bore of 102 mm and a stroke of 118 mm. The engine is equipped with a high-pressure, common-rail fuel injection system and a turbocharged/intercooled air intake system. Its power is up to 100 kW at a maximum speed of 2800 rpm. The four cylinder engines are modified into an arrangement of one single research cylinder and three non-research cylinders, with independent controlling and measurement systems for the research cylinder. The main engine specifications can be found in Table 1.

A calibration and controlling software, INCA 6.2, developed by ETAS Company is adopted to regulate the post injection strategy [14]. To identify the composition of gaseous exhaust emissions, we use an advanced gas analyzer MEXA-7100DEGR made by HORIBA Company to measure the level of CO, THC and NOx emissions, with an accuracy of 1 ppm [15]. The measurement of PM emission is performed through a partial flow dilution sampling system, MDLT-1302TMA, developed by HORIBA Company [16]. To identify particle concentration and PS distribution, a spectrometer, EEPS-3090, developed by American TSI Company is utilized in present experiment [17]. On the basis of electric migration theory, this instrument is able to accurately measure the PS distribution at steady and transient conditions, with the lowest concentration limit of 200#/cm^3, time resolution of 10 Hz and particle size range of 5.6–560 nm. Meanwhile, the spectrometer was equipped with a rotary thermal dilution system 379020 to regulate the ration of exhaust dilution with a range of 15:1–3000:1. The detailed specifications for current experimental system show in Fig. 1.

During experiments, it takes 20–30 min to warm up the test engine until cool water temperature reaches 353–358 K and oil temperature is 358–363 K. Repeat each group of engine test three times to eliminate accidental errors, and uncertainties in current experiment keep within ±5%. After operating condition becomes steady, cylinder pressure and exhaust emissions can be obtained in real time. In sampling experiment, we use an aluminum alloy diaphragm to seal engine cylinder head as a sampling valve. This diaphragm cut an electromagnet-actuated tube cutter instantaneously at a pre-set crank angle during a sampling cycle. Then cylinder mixture is discharged from the cylinder into a sampling bag. Simultaneously, the sampled gas mixture was immediately quenched and diluted with high pressure nitrogen at a dilution ratio of 200:1, sampling flow of 10 L/min, and temperature below 52 °C, to prevent any possible additional reactions during sampling process. Detailed descriptions for this apparatus and sampling procedure can be found in previous work [18–20], which mainly addressed the evolution of polycyclic aromatic hydrocarbons (PAHs) and soot nanostructure during diesel engine combustion.

Table 1
Specifications of the test engine.

Engine type	HSDI 4-S diesel
Bore × stroke (mm)	102 × 118
Displacement (L)	3.856
Compression ratio	17:1
# of valves per cylinder	4
Injection system	Bosch Common rail
Intake system	Turbocharged, intercooled
Max. injection press (MPa)	130
Injector hole diameter (mm)	0.153
Number of injector holes	6

2.2. Test conditions

In the European Steady State Cycle (ESC), lots of operating conditions are located in moderate and heavy load with middle to high engine speed, which is the key research object for exhaust emission reduction [21]. In present work, the condition with an engine at speed of 1800 r/min and 75% load is to investigate the effect of fuel quantity and injection timing on exhaust emissions during post injection. Different injection parameters are presented in Fig. 2. Main injection event is the first fuel injection with relatively long duration, and then a second and short fuel injection is defined as post injection. The fuel injection timing for the main injection is 22 BTDC and corresponding fuel quantity is 40 mg per cycle. The post injection is followed with a crank angle interval from 10 to 30 and injection fuel quantity varies from 0 to 15 mg per cycle. We conduct the post injection tests with sixteen different fuel injection strategies, which are illustrated in Table 2.

Contrary to previous studies with constant total fuel quantity [9,10], fuel quantity for the main injection maintains constant throughout the experiment, and different amounts of fuel are added during post injection. Therefore, the total fuel quantity increases when post injection strategy is introduced. Holding the fuel quantity for main injection constant, shortening main injection effect can be negated and consistent environment is created in different post injection cases. Eventually, any emission variations can be attributed to post injection rather than t shortening main injection [22].

3. Results and discussions

In order to quantitatively demonstrate the effect of post injection strategy on the reduction exhaust emissions, a parameter is introduced here: