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Technical note

# Effect of multiple-injection strategies on diesel engine exhaust particle size and nanostructure

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ABSTRACT

Multiple-injection has been widely investigated to simultaneously reduce diesel NOx and soot emissions. While the comprehensive understanding of the effects of multiple injection on exhaust PM physical characteristics is still lacking. Three injection modes, single main, pilot-main and main-post injections, were compared in this work. The main objective is to better understand the influence of pilot and post injections on particle size and nanostructure characteristics in diesel exhaust. Experimental tests have shown that, for the pilot-main injection case, less premixed combustion and more diffusion combustion occur compared with the single main injection, which promotes formation of soot nuclei and results in a significant increase of number and mass of particles with the diameter above 100 nm. On the contrary, soot oxidation later in the combustion is improved due to the enhancement of gas mean temperature (GMT) and air/fuel mixing for the main-post injection case, which favors soot oxidation and leads to the decrease of particle number and diameter. A comparison of particle nanostructures for the pilot-main injection case and main-post injection case has been conducted, which indicates that both low in-cylinder temperature and relative short carbonization time lead to the particles of less carbonization level (short fringe length and large fringe tortuosity) for the pilot-main injection case. Particles exhibit highly ordered graphitic structure for the main-post injection case due to the increase of combustion duration and the enhancement of in-cylinder temperature during the later stage of combustion derived by post combustion, which presents potential negative effect on diesel particle filters (DPF) regeneration efficiency.



## 1. Introduction

Diesel engines are widely used in power machinery and for automotive application due to their high thermal efficiency. However, particulate matter (PM) and nitrogen oxide (NOx) emissions from diesel engines are some of main sources of environment pollutants. Stringent emission regulations force us to improve fuel quality and controlling technologies to reduce diesel engine exhaust PM. A promising strategy for reducing PM emission is using a diesel particle filter (DPF). Since PM collected in a DPF increases exhaust backpressure, a periodical regeneration process is additionally needed to remove the trapped PM. DPF regeneration behavior largely depends on PM oxidative reactivity, which is related to PM size and nanostructure properties.

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PM size and nanostructure properties are results of complex physical and chemical processes, including spray mixing, vapor fuel oxidation, soot nucleation and coagulation, and soot oxidation. Lu, Cheung, and Huang (2012) found that soot exhibits disordered structure at low load and high speed due to shorter in-cylinder residence time. A reduction of soot oxidative reactivity with increasing exhaust gas recirculation (EGR) level at high load has been observed by Al-Qurashi, Zhang, and Boehman (2012), while an opposite result was observed by Li, Xu, Guan, and Huang (2014), who found that the soot oxidative reactivity increases with increasing EGR level. This is due to variation of combustion conditions at different engine operating modes. It is suggested that injection strategies and combustion processes are coupled in mixing-controlled combustion. The effect of injection parameters, e.g., injection timing and injection pressure on PM properties, has been studied recently. Yehliu, Armas, and Boehman (2013) demonstrated that the effect of injection timing on soot nanostructure showed that oxidation rate of samples increases with delayed injection timing. Xu, Li, Guan, and Huang (2014) found that smaller primary soot particles with shorter and flatter graphene layer segments were present under higher injection pressure condition.

Due to the consensus regarding improvement in the trade-offs between PM and NOx emissions, multiple fuel injection strategies have been explored in the past several years (Chen, 2000; Carlucci, Ficarella, & Laforgia, 2005; Durnholz, Endres, & Frisse, 1994; Fang, Fang, Zhuang, & Huang, 2012; Minami, Takeuchi, & Shimazaki, 1995; Sperl, 2011; Zhuang, Qiao, Bai, & Hu, 2014). The most commonly used is one pilot injection before a main injection or one post injection after a main injection. The information about the influence of the pilot and post injections on smoke and PM mass emissions is limited, and there are few recent publications on particle size distributions (Desantes, Bermudez, Garcia, & Linares, 2011; Zhang et al., 2010). To the knowledge of the authors, there is no investigation on detailed soot structure for the diesel engine with multiple-injection strategies. To understand the correlation between the engine combustion characteristics and the PM physical properties with the application of the multiple injection strategies, particle size and nanostructure analysis, combined with engine combustion diagnosis with three fuel injection strategies, i.e., single main, pilot-main and main-post injections, have been conducted.

## 2. Methodology

### 2.1. Test engine and experimental method

The engine used in this study was a four-cylinder, four-stroke diesel engine equipped with turbocharger and high pressure common rail injection system. The main specifications of the engine are listed in Table 1. Commercial diesel fuel (Sulfur, 47 ppm) was used in this study. The in-cylinder pressure versus the crank angle (CA) was obtained with an Orisis combustion analyser (D2T, France) in real time. The heat release rate (HRR) and the gas mean temperature (GMT) were calculated through the combustion analyser's own software based on the first law of thermodynamics as well as the perfect gas equation of state according to the experimental in-cylinder pressure and averaged over 200 cycles. The parameter settings to calculate GMT included intake pressure and intake temperature. The fuel injection timing was controlled by the engine control unit (ECU) with hall sensors mounted on the cam shaft and flywheel.

The methodology for the experimental tests is based on a comparison among the single main injection, pilot-main injection and main-post injection strategies by using the same quantity of injected fuel mass in the three cases. The baseline operating condition of the current research consists of a steady state condition at 1450 r/min, and the injection pressure was set at 80 MPa with 27 $mm^3$/cycle of fuel at top dead center (TDC, equivalent to 50% of peak load). A pilot-main injection includes a pilot injection (20% total fuel injected at 20 °C A BTDC, 5.4 $mm^3$/cycle) and a shortened main injection (80% total fuel injected at TDC, 21.6 $mm^3$/cycle). A main-post injection includes a shortened main injection (80% total fuel injected at TDC, 21.6 $mm^3$/cycle) and a post injection (20% total fuel injected at $-20$ °CA BTDC, 5.4 $mm^3$/cycle). Both of the two injection intervals are 20 °CA. In order to ensure the repeatability and comparability of the measurements, the temperatures of the engine intake air, coolant and lubricant oil were kept in the ranges of $40 \pm 2$ °C, $80 \pm 3$ °C and $86 \pm 3$ °C, respectively.

### 2.2. Soot sampling and characterization

The schematic diagram of the dilution and sampling system is shown in Fig. 1. A fraction of exhaust was drawn through a heated stainless steel tube into a primary diluter. The dilution air was purified via a high efficiency particle filter. The PM

**Table 1**
Engine specifications.

| | |
|---|---|
| Number of cylinders | 4 |
| Fuel injection system | Common-rail injection system |
| Injection strategy | One main injection at TDC |
| Suction type | Turbo intercooler |
| Displacement | 4.751 L |
| Bore × Stroke | 110 mm × 125 mm |
| Compression ratio | 17.8:1 |
| Maximum power | 96 kW/2500 rpm |
| Maximum torque | 450 Nm/1450 rpm |