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Effect of injection timing on particle size distribution from a diesel engine

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HIGHLIGHTS

- Effect of injection timing on particle size distribution was studied on a common rail diesel engine.
- "Accumulation mode bump" occurs at moderate EGR with the change in injection timing.
- Early or late injection at moderate EGR results in a simultaneous reduction in soot (accumulation mode) and NO_x emissions.
- Low temperature combustion potentially promotes the formation of nucleation mode particle.

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ABSTRACT

The present work focused on the effect of injection timing, which changed from 23° CA before top dead center (−23° CA ATDC) to 8° CA after top dead center (8° CA ATDC), on particle size distribution (PSD) from a diesel engine operated under 0% and 40% EGR rates. The results show that PSDs under 0% EGR is dominated by the nucleation mode (NM), and injection timing shows no significant effect on NM on a log plot, while the early and late injections produce the low AM. Under 40% EGR, PSD is dominated by NM with very early and late injections, while it is dominated by the accumulation mode (AM) for −20 to −5° CA ATDC, and an apparent "AM bump" occurs at round −10° CA ATDC. The phenomenon of "AM bump" indicates that the coupling early or late injection and EGR favors low temperature combustion (LTC), and which results in a simultaneous reduction in soot (AM) and NO_x emissions. A negative relationship between N_{nuc} and N_{acc} with the change in injection timing suggests that LTC potentially promotes the formation of NM. A more evident trade-off relationship between N_{tot} and M_{tot} is presented under 40% EGR than that under 0% EGR, which indicates that in-cylinder PM formation and oxidation is more dependent on injection timing under 40% EGR.

1. Introduction

Diesel engine has been widely used for its excellent fuel economy and higher thermodynamic efficiency. Despite these benefits, particle matter (PM) and nitrogen oxide (NO_x) emissions from diesel engines are some of the main sources in the environment. Stringent emissions regulations are proposed in most countries all over the world and numerous investigators have contributed to the reduction of diesel engine emission. However, it is rather difficult to lower NO_x and PM emissions simultaneously because of the well-known trade-off relation between the two emissions. Controlling PM and NO_x emissions are still the main topic in development of the diesel engine technology [1].

Generally, the application of exhaust gas recirculation (EGR), which means a part of intake air is replaced by the exhaust gas, can take a higher amount of heat from the combustion process due to the presence of species with high specific heat capacities, e.g., carbon dioxide and water vapor. The decrease of peak flame temperature during combustion leads to the reduction of NO_x emission [2–5]. On the contrary, oxidation of soot is suppressed due to the in-cylinder combustion temperature decrease when EGR is applied [6–8]. However, soot emission from diesel engine is a result of a competition between soot formation and oxidation processes, and the premixed combustion with high EGR (low intake oxygen concentration) has been proved to significantly reduce adiabatic flame temperature [9]. The high charge dilution can suppress the oxidation processes. In the meantime, low soot formation rates may also be achievable at very high levels of charge dilution, as the flame temperature is limited to levels at which the soot formation rate is low. As a result, simultaneous

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reduction PM and NO_x emissions could be achieved [10–13]. This operating regime is generally defined as low temperature combustion (LTC). Because advancing and retarding injection timings change the position of the piston, cylinder pressure and temperature at injection, some important influencing factors for combustion and emission such as ignition delay, adhered fuel and squish are changed [14]. Therefore, variation of injection timing has been used in optimizing LTC for reducing pollutant emission [15–19]. According to Kook et al. [15], dilution alone does not sufficiently lower flame temperatures to impede the formation of soot, and retarding injection sufficiently at high and moderate EGR rates results in a significant reduction in soot. On the other hand, at heavy charge dilution, low soot level can also be achieved at the earliest injection timings. Benajes et al. [17] also exhibited that a minimum PM emission respectively appears at injection timings of −27 to −24° CA ATDC (early-LTC regime) and TDC (late-LTC regime) as 45–50% EGR is applied. The coupling effect of injection timing and EGR on PM emission has also been observed by Jacobs et al. [19]. They found that PM emission level drops as timing is retarded with 42–45% EGR, and the higher EGR rate leads to more rapidly drop. PM emission is generally concerned for diesel engine, and several works indicate that PM mass emission reaches a much low level in LTC regime, even at the minimum detection limit of most typical opacity-based measurement instruments for soot sample for very early and late injection timings [18,20]. Recently, some publications suggested that much distinct engine-out PM properties exist in conventional combustion and LTC. According to Tompkins et al. [20], filter smoke number (FSN) of characterization of soot emission based on a smokemeter is in opposite fashion to PM based on filter weight in LTC mode. Jung et al. [13] also indicated that the weight fraction of oxygen and hydrocarbon (HC) for LTC PM is higher than that for conventional diesel combustion. Our past researches also exhibited that the low PM mass and low soot operating mode may lead to the formation of nanoparticle in the dilution exhaust sample [21,22]. In the meantime, Euro 6 standards, to be enforced in 2014, which will majorly restrict NO_x and PM number emissions. Therefore, particle size distribution (PSD) can better characterize the low PM mass emission diesel engine [23].

PSDs for the conventional combustion have been widely studied during the past decade years. While only few recent studies on diesel exhaust PSD for LTC [17,19,24]. The results presented that there are much fewer particles measured larger than 100 nm than typically seen in conventional diesel combustion. It is well known that PSD property is an important factor for assessment of adverse health effect, as well as affects the diesel particle filter (DPF) filtration performance [25,26]. Therefore detailed PSD information in LTC regime is needed to be discussed. In the previous literatures, only Benajes et al. [17] studied on the effect of injection timing, which changed very wide sweeps at moderate and high EGR, on PSD. The primary dilution air temperature in diluter (PDT) used by Benajes et al. is above 180 °C, which suppress the formation of volatile particles. The present study kept the PDT at environmental temperature to analyze the effect of injection timing on PSD, including volatile particles, in conventional combustion and LTC regime from a diesel engine.

2. Experimental setup

2.1. Test engine

The engine used in this study was detailed in the previous literature [27]. A simple description is shown here. A four-cylinder, four-stroke diesel engine equipped with turbocharger and high pressure common rail injection system was used to investigate the characteristics of soot particle in conventional combustion and LTC modes. The main specifications of the engine are listed in Table 1. The original diesel engine was equipped with an independent EGR system. The exhaust is introduced into the intake pipe using the back pressure created by the throttle valve in the exhaust pipe. The exhaust was cooled by means of water cooler before it passed into the intake air. A diesel particle filter coated with platinum group metals (CDPF) and a water separator were respectively integrated before and after the water cooler along the EGR gas flow direction. The in-cylinder pressure vs the crank angle (CA) was obtained with an Orisis combustion analyser (D2T, France) in real time, which was acquired through a flush-mounted Kistler 6125B pressure transducer in cylinder 1. The heat release rate (HRR) and the gas mean temperature (GMT) were calculated basing 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 calculation options for GMT included intake pressure and intake temperature based on the software request. The fuel delivery per cycle, the common rail pressure and the start of injection were controlled by the engine control unit (ECU) using the hall sensors mounted on cam shaft and flywheel. A schematic diagram of experimental setup is shown in Fig. 1.

2.2. Fuel and experimental method

The commercial diesel fuel (Sulfur, 47 ppm) was used in this study, which meets the 50 ppm fuel sulfur limit of Chinese Phase IV Emission Regulation for Diesel Vehicle. The operating conditions were set at an engine speed of 1450 r/min, an engine torque of 112 Nm (BMEP = 0.3 MPa), which corresponds to 25% of the production engine full load. It is suitable for operating within LTC regime although it is operated at low soot formation condition. 0 and 40% EGR rate have been considered during this investigation. The injection pressure was set at 80 MPa, and the main injection timing was changed very wide sweeps from 23° CA before top dead center (−23° CA ATDC) to 8° CA after top dead center (8° CA ATDC) at 3–5° crank angle degrees (CAD) intervals.

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 ± 3°C, 80 ± 3°C and 87 ± 2 °C respectively. An analysis of the gaseous emission (HC, CO and NO_x) was performed using an exhaust gas analyzer (CAI 300). Data were averaged from 200 samples of each stored by a data acquisition card after the engine had reached the steady state in each operating condition, and the standard errors of the gas concentrations are within ±1%. The gas analyzer was calibrated with standard gas and zero gas before each test. The smoke opacity was unavailable because smoke values for most of the engine operating conditions have reached the minimum detection limits of the opacimeter analyzer. The brake specific fuel consumption (BSFC) was simultaneously recorded three times by manual, and standard error for BSFC was less than 0.4 g/kW h.

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