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Impact of exhaust gas recirculation (EGR) on soot reactivity from a diesel engine operating at high load

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HIGHLIGHTS

- This paper describes the effect of EGR on soot reactivity at high load.
- Combustion duration obviously increases as EGR rate increases.
- Soot with highly ordered graphitic structure presented at high EGR level.
- OC fraction in particle sampling decreases with the increase of EGR.
- Soot generated at high EGR level exhibits greater thermal stabilities.

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ABSTRACT

Past work demonstrated that the exhaust gas recirculation (EGR) enhanced the soot reactivity from a diesel engine operating at low load. In this paper, reactivity of diesel soot generated from a common rail diesel engine at high load (75% load, 336 N m) under 0, 10% and 30% EGR was studied. Combustion properties of the diesel engine with the diffusion-dominated heat release patters under the high temperature and low-fuel ratio condition resulted in the combustion duration increased 39.8% as EGR rate increases from 0 to 30%. Correspondingly, noticeable changes in nanostructure, carbonaceous components and oxidative reactivity with the increase of EGR have been observed. The soot with highly soot-EC content, highly ordered graphitic structure and low organic carbon (OC) fraction in the particle sample presents at high EGR level, which is the consequence of the longer combustion duration and the decrease of air-fuel ratio. Both of highly ordered graphitic structure and low OC fraction in the particle sample are responsible for the observed decrease of soot reactivity with the increase of EGR at high load.

1. Introduction

Exhaust gas recirculation (EGR) in diesel combustion is one of the principle techniques that can reduce nitrogen oxide (NO_x) emission essentially by lowering the peak combustion temperature and oxygen level in cylinder [1–6]. As there is a trade off relationship between NO_x and soot emissions for most engine technologies, the use of EGR has adverse effect on soot emissions. Due to the low oxygen level at high EGR, soot oxidation is incomplete and thereby emission of soot often increases with increasing EGR level [3]. Kreso et al. [5] found that soot emission respectively increased 16.8% and 57% at 25% and 75% loads with the application of 16.2% EGR, respectively. Several previous researches also indicated that the effect of EGR on soot emission is more appreciable at high load than at low load due to the deterioration of the engine performance at high load [6–8].

The soot property is a result of complex physical and chemical processes, including spray mixing, vapor fuel oxidation, soot nucleation and coagulation, and soot oxidation, etc, which is dependent on the fuel formulation, engine operating mode, as well as combustion parameters, e.g. injection pressure, start of injection, etc. The impact of fuel properties on the soot properties has been widely studied based on high resolution transmission electron microscopy (HRTEM), thermogravimetric analysis instrument (TGA) and Raman spectroscopy analysis [9–11]. Lu et al. [9] found that the oxidation rate of soot from biodiesel is higher in comparison with those of fossil diesel, and the higher oxidation rate of biodiesel soot could attribute to the disorder nanostructure and large volatile organic fraction (VOF) content. Song et al. [10] found that soot generated using biodiesel fuel were five times more reactive than soot generated using a Fischer–Tropsch fuel although both of the soot possesses similar ordered nanostructure. It is

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claimed that the initial oxygen groups is the determining factor for the soot oxidation rate. Yehliu et al. [11] reported that no relation between the surface oxygen content and the soot reactivity, while soot nanostructure disorder correlates with a faster oxidation rate based on both of X-ray diffraction (XRD) and HRTEM analysis. The disaccord of the results indicated the complexity of the soot oxidation. Besides the fuel properties, several researchers have found that the degree of order of soot nanostructure increases when engine load and combustion temperature increases [12,13]. Recently, the impact of combustion phasing on the soot oxidative activity has been studied by Yehliu et al. [14]. Their results demonstrated that the oxidation rate constant of the soot sample for retarding stat of injecting (retarded 2 CAD) was 2.3 times that for advancing SOI timing (advanced 2 CAD). The literatures abovementioned indicated that the soot physico-chemical properties are correlated with a change in air/fuel ratio, the presence of the bonded oxygen, retention time inside the combustion cylinder, as well as the combustion temperature.

Due to thermal, dilution and chemical effects, EGR can change the in-cylinder combustion conditions, e.g. air/fuel ratio, combustion temperature and possibly results in the variation of soot physico-chemical properties. Some studies about physico-chemical properties of the exhaust soot particle with the application of EGR have been conducted, majority of them focused on the primary and aggregation particle size distribution [15–17], while there have been only few recent investigations about the influence of EGR on soot nanostructure and oxidative reactivity [18–20]. Moreover, the engine was operated at low engine load (20% load, 68 N m) and the bulk cylinder temperature is less than 1500 K. In this paper, soot samples were collected at high load (75% load, 336 N m) at 0, 10% and 30% EGR. The soot properties, e.g. nanostructure, carbonaceous components and oxidative reactivity were analyzed. The present work addresses the impacts of EGR on the reactivity of diesel soot at high load.

2. Experimental section

2.1. Test engine and fuel

The experimental layout is shown in Fig. 1. The engine used in this study was detailed in the previous literature [21]. A simple description is shown here. 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) was integrated into the EGR loop to remove the soot from being recycle back into the intake and avoiding destroy turbocharger. Different EGR rates could be achieved by manual opening/closing EGR valve. The engine control unit (ECU) controlled the common rail pressure, the fuel delivery per cycle and the start of injection.

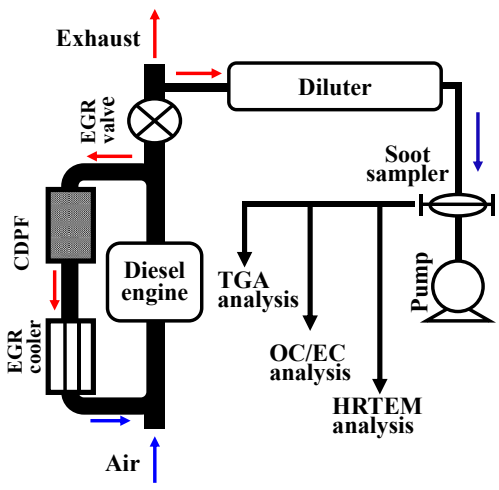

Fig. 1. Schematic diagram of the experimental system.

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

The fuel used in this study is the commercial diesel fuel (Sulfur content, 47 ppm), which meets the 50 ppm fuel sulfur limit of Chinese Phase IV Emission Regulation for Diesel Vehicle. The lubricating oil is a 15 W-40 full mineral oil, with a measured sulfur content of 2687 ppm. The engine was operated at an engine speed of 1450 rpm and torque of 336 N m (BMEP = 0.9 MPa). The soot samples were collected at 0, 10% and 30% EGR rates. The fuel injection pressure was set at 80 MPa, and the injection timing was kept constant at top dead center.

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 41 ± 2 °C, 80 ± 2 °C and 90 ± 2 °C respectively. Data were recorded after the engine had reached the steady state in each operating condition. Moreover, each operating condition was repeated twice to ensure that the results were repeatable within the experimental uncertainties. The standard errors are 2.2 ppm, 0.002 filter smoke number (FSN) and 0.4 g/kWh for NO_x, smoke, brake specific fuel consumption (BSFC) respectively.

2.2. Soot sampling and characterization

The soot samples were collected on the quartz fiber filter (Whatman Model 1851-047) after passing through a diluter with dilution ratio of 5–6. The configure of the diluter was detailed in the previous literature [21]. All quartz filters were pre-baked at 550 °C for 8 h and stored in baked aluminum foil prior to deployment. All samples were analyzed by thermogravimetric analysis instrument (TGA) for soot oxidation reactivity, HRTEM for soot nanostructure and Thermo/Optical Carbon Analyzer for organic carbon/element carbon (OC/EC) components.

For soot oxidation reactivity test, a TGA (TA Model Q5000IR) was used to measure weight changes of each sample via a method of temperature programmed oxidation, and obtain the ignition temperature which is defined as the temperature where soot oxidation rate is maximized. A filter was cut into small pieces and about 15 mg of that sample was deposited into a platinum pan. All the samples were heated at 500 °C for 20 min under high-purity nitrogen to drive off volatile matter after a heating rate of 50 °C/min. Subsequently, the furnace temperature was reduced to 400 °C and the air was then introduced into the system to start the oxidation process. The air flow rate was 100 ml/min and the temperature was raised to 800 °C with a heating rate of 20 °C/min.