



Full Length Article

Morphology, fractal dimension, size and nanostructure of exhaust particles from a spark-ignition direct-injection engine operating at different air–fuel ratios

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HIGHLIGHTS

- Physicochemical characteristics of SIDI particles were studied at different AFRs.
- Fractal dimensions decreased with increases in the AFR after an initial increase.
- The largest average primary particle diameter was obtained at an AFR of 14.7.
- The nanostructures of SIDI soot particles were affected by the AFR.
- The soot particles at AFR = 14.7 exhibited the lowest sp^2/sp^3 hybridization ratio.

ARTICLE INFO

Article history:

Received 13 May 2016

Received in revised form 14 July 2016

Accepted 1 August 2016

Keywords:

SIDI engine

Exhaust particle

Morphology

Fractal dimension

Primary particle size

Nanostructure

ABSTRACT

This work studied the physicochemical characteristics of exhaust particles from a 1.48 L SIDI engine operating at different air–fuel ratios (AFRs). The morphology, fractal dimension, size and nanostructure were characterized using high-resolution transmission electron microscopy (HRTEM) in conjunction with electron energy-loss spectroscopy. The results indicate that SIDI aggregate particles produced at varying AFRs exhibit different morphologies. TEM images show that the aggregates obtained at an AFR of 14.7 are more compactly clustered than those generated under fuel-rich and fuel-lean conditions. The fractal dimension of SIDI aggregates at an AFR of 14.7 is found to be 2.21, a value that is larger than those from other AFRs. The primary particle sizes are distributed over a wide range of 5–55 nm at all AFRs, although the largest average primary particle diameter is found at an AFR of 14.7. Similar to diesel soot particles, SIDI soot particles also show characteristic shell-core and turbostratic structures at the nanoscale level. At an AFR of 14.7, the soot particles have a relatively short fringe length, a small fringe separation distance and high fringe tortuosity. As the AFR is increased, the sp^2/sp^3 hybridization ratios first gradually decrease and then increase, with a minimum value of 0.156 at AFR = 14.7. SIDI soot particles are likely more reactive than diesel soot particles because they possess the relatively short fringe length, large separation distance and high tortuosity.

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1. Introduction

In recent years, spark-ignition direct-injection (SIDI) engines have been widely installed in light-duty vehicles owing to their advantages in terms of fuel economy and CO₂ emissions [1]. Therefore, in Europe the market share of SIDI vehicles accounted for 25% in 2012 [2], while 60% of new light-duty vehicles in the United States are projected to be powered by SIDI engines by 2016 [3].

Although SIDI engines can improve fuel economy and reduce CO₂ emissions, it is reported that the number- and mass-weighted particle emissions from SIDI engines are higher than those from PFI engines or from diesel engines equipped with a particulate filter (DPF) [4,5]. Due to the adverse environmental and health effects of gasoline engine particles [6], the European Commission introduced a limit of 5×10^{-3} g/km for particle mass emissions from gasoline engines as part of the Euro 5 standard. In addition, particle number emissions were limited to 6×10^{12} particles/km by legislation at the Euro 6 stage in 2014, and this limit will be further reduced to 6×10^{11} particles/km in 2017 [7]. To satisfy these

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increasingly stringent regulations, reductions in SIDI particle emissions must be realized, both by minimizing particle formation and by optimizing particle oxidation in the combustion chamber and in the exhaust system [8]. Soot formation and oxidation processes are related to the physicochemical characteristics of the soot particles [9–11]. Therefore, understanding the physicochemical characteristics of SIDI particles is a crucial aspect of efficiently reducing SIDI engine exhaust particle emissions.

Numerous investigations have been carried out concerning the physicochemical characteristics of diesel exhaust particles, including examinations of morphology, size, nanostructure, graphitization degree, chemical composition, and other factors [12–16], but only a few have focused on SIDI soot particles. Mathis et al. [17] found that the volatile nanoparticles from a SIDI vehicle contained both hydrophilic and hydrophobic parts, and that the hydrophilic regions were related to the presence of sulfur and potassium. Barone et al. [18] investigated the morphology and size of single solid spheres, aggregates and liquid droplets while applying different injection timings to a SIDI engine. Their study demonstrated that most aggregates possessed a fractal-like morphology, and that the primary particle diameters were distributed over a wide range of 7–60 nm. Compared with early injection timing, fewer liquid droplets and more single solid spheres with diameters below 25 nm were generated from late fuel injection. A study by Seong et al. [19] regarding the sizes of SIDI-emitted particles found that more nanoparticles with diameters less than 23 nm were generated when delaying the fuel injection timing at low load, and these nanoparticles were determined to consist of solid carbon with clear carbon fringe patterns. Gaddam and Vander Wal [20] performed physical and chemical characterizations of SIDI soot particles from a single-cylinder SIDI engine. They discovered that the particulates produced under various operating conditions showed distinctive morphological differences. With regard to soot nanostructure, similar fringe length distributions were evident under all operating conditions, and high tortuosity was observed under the late end of injection and fuel-rich conditions. These nanostructure parameters appeared to exhibit a linear correlation with the carbon sp^2/sp^3 ratio, and the organic compounds in the soot were believed to be matrix bound. Liati et al. [21] investigated the soot particles from a SIDI vehicle operating using the NEDC and the Worldwide harmonized Light Duty Test Cycle (WLTC). They confirmed that a greater proportion of small soot particles were generated when employing the WLTC compared with the NEDC, and that under all driving conditions, the large soot particles contained the highest percentage of short graphene lamellae. SIDI soot particles were determined to be more reactive relative to diesel soot particles.

Although the reports published to date have provided some information about the physicochemical characteristics of SIDI soot particles, such studies are still in their infancy and so more in-depth investigations are required. Based on the background data above, the specific emphasis of the current work was on the characterization of SIDI soot particles. At different air–fuel ratios (AFRs), the morphology, fractal dimension, size and nanostructure of the exhaust particles generated by a 1.48 L SIDI engine were characterized. In addition, the characteristics of particles obtained from SIDI and diesel engines were compared.

2. Experimental methodology

2.1. Test engine and fuel

Tests were performed on an air-guided, naturally-aspirated, four-cylinder SIDI engine without after-treatment. The main specifications of this engine are provided in Table 1. An AVL Dynopower 160 eddy current dynamometer and an AVL S733 fuel

Table 1
Engine specifications.

Engine type	Naturally-aspirated, 4-cylinder
Combustion system	Air guided SIDI
Displacement	1.498 L
Valves per cylinder	4
Bore × stroke	77.8 × 78.8 mm
Compression ratio	12:1
Rated speed	6000 rpm
Rated power	86 kW

consumption meter, controlled by a PUMA system, were used to measure the power, fuel consumption, speed and torque output of the engines. An ETAS INCA was employed to communicate with the electronic control unit so as to control the AFR, injection timing and ignition timing of the engine. The AFR was measured with an ETAS LA4 lambda meter located at the exhaust pipe. The in-cylinder pressure was acquired by a Kistler spark plug pressure transducer (6117BFD16). The signal from the pressure transducer was amplified by the charge amplified and then recorded by the LabView software in conjunction with a shaft encoder. In-cylinder mean temperature and accumulated heat release rate were calculated according to the in-cylinder pressure data.

Engine operating conditions were fixed at an engine speed of 2000 rpm, an injection timing at 280° crank angle (CA) before top dead center (BTDC) and an ignition timing at 15°CA BTDC. The injection pressure was set at 10 MPa, and the injected fuel quantity was in a range of 46.3–49.3 mg/cyc. The AFR values employed in this study were 13.0, 14.7, 16.0 and 18.0, and the corresponding in-cylinder mean temperature is shown in Fig. 1. The cumulative heat release analysis showed that the combustion phasing at a 10% heat release (CA10), which was used to represent the start of combustion per cycle, was $7 \pm 1^\circ\text{CA}$ after top dead center (ATDC) for all the AFRs. During these trials, the coolant and oil temperatures were automatically controlled at $85 \pm 1^\circ\text{C}$ and $90 \pm 1^\circ\text{C}$, respectively. The test fuel was a commercial unleaded gasoline, and some important properties of the fuel are presented in Table 2.

2.2. Particle sampling and analysis

An aliquot of the SIDI exhaust gas was pumped from the tail-pipe and diluted with a dilutor (MD19-3E, Testo AG). The dilution ratio was in the range of 1:10–1:20, depending on the engine operating conditions. After dilution, the particles were directly collected on high-resolution transmission electron microscopy (HRTEM) grids (300 mesh Ni). The sampling time was typically

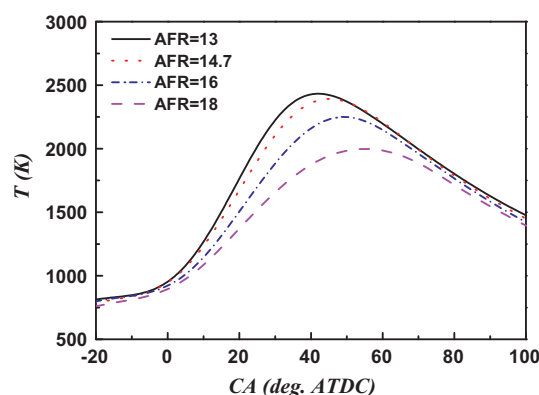


Fig. 1. In-cylinder mean temperature as a function of crank angle (CA) degree after top dead center (ATDC) at different air–fuel ratios (AFRs).

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