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Impact of engine operating modes and combustion phasing on the reactivity of diesel soot

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ABSTRACT

The present work focuses on the impacts of engine operating conditions and combustion phasing on diesel soot properties. The study was carried out in a 2.5 L direct injection common-rail turbodiesel engine using an ultra low sulfur diesel fuel (BP15). The study has two objectives. The first objective is to investigate the reactivity difference of the soot generated at four engine modes, spanning conditions of most interest in the engine operating map. The results show that the impact of engine speed at constant torque is more pronounced than the impact of engine torque (equivalence ratio) at constant engine speed. The effect of the engine torque at constant engine speed, especially at higher speed, is not observable in this experiment. The second objective is to investigate the reactivity and nanostructure of soot generated at different combustion phasing by advancing and retarding the fuel start of injection (SOI) timing. Reaction kinetics obtained from thermogravimetric analysis show that the rate constant of the sample for retarding SOI timing (retarded 2 CAD) is 2.3 times that for advancing SOI timing (advanced 2 CAD). In summary, the results presented here provide unique insights into the methodology that should be used when investigating soot samples generated by different fuels: matching operating modes and combustion phasing for different fuels is suggested while collecting soot samples for characterization.

1. Introduction

The interest in using biodiesel or synthetic fuels as replacements for diesel and studying whether they can reduce particulate matter (PM) and gaseous emissions has been growing, because of concerns over the supply and cost of petroleum fuels. Both PM and gaseous emissions can be reduced by altering the fuel properties and fuel injection parameters. A major strategy for reducing PM emissions is using a diesel particulate filter (DPF) [1,2]. When using a DPF, the trapped particulate matter must be intermittently removed by oxidation of the PM. If the PM was not removed, the filter would become clogged [3]. The oxidation of the trapped particulate matter on the DPF, referred to as DPF regeneration, is significantly affected by soot reactivity, which is related to the chemical and physical properties of the particulates [4]. When chemical and physical properties of diesel particulate are considered, differences in the diesel combustion process and fuel formulation can influence these soot properties.

The impacts of the combustion process on PM emissions and properties have been studied by several researchers. The engine type, air/fuel ratio, cooling and dilution of exhaust may all affect the concentration and size distributions of particulate matter [5]. Choi and Reitz [6] showed that split injections were effective in reducing particulate emissions especially at advanced injection timings, when they ran an engine at low load conditions. Using a numerical model for diesel engine combustion, Chan and Cheng [7] showed that soot emissions were affected by engine operating conditions and fuel injection timing. Neer and Koylu [8] observed an increase in soot spherule and aggregate sizes with an increase of the engine load and exhaust temperature. This observation was explained by the impact of the change of the air/fuel ratio. Meanwhile, smaller soot particles are observed at higher engine speed because of the shorter residence time. Nevertheless, Zhu et al. [9] found that the degree of order of soot nanostructure increases when engine load and exhaust temperature increase. In addition, because of particle oxidation at high in-cylinder temperatures, a decrease in soot particle size is observed with an increase of the exhaust temperature. Instead of using a diesel engine, Vander Wal and Tomasek [10] used a high temperature tube furnace to generate soot, and concluded that the nanostructure of soot depends upon its formation conditions, such as temperature and residence time. Using shock tube, Mathieu et al. [11] found the dependence of soot nanostructure on combustion temperature.

Besides the combustion process, fuel formulation also affects soot emissions and soot characteristics. Many researchers have found that various oxygenated diesel fuel additives, such as methyl

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esters, lead to reductions in PM emissions [6,12,13]. Vander Wal et al. showed that the soot samples generated by benzene, ethanol and acetylene have different structural order and reactivity. Benzene-derived soot is found to have a more amorphous structure and is more reactive than acetylene-derived soot [14]. Using a shock tube, Douce et al. [15] showed that fuel type has an impact on soot yield and sphere size. Using a 6-cylinder 5.9 L diesel engine without access to controls for fuel injection system, Song [16] found that soot particles generated using biodiesel fuel were five times more reactive than soot particles generated using a Fischer–Tropsch fuel. It was claimed that the relative amount of initial surface oxygen groups on the primary soot particles is a determining factor for the soot oxidation rate [17]. Lapuerta et al. [18] observed that PM emissions decrease when blending bioethanol with conventional diesel. As shown widely in the literature, this observation is correlated with reduction of aromatic content, lower C/H mass ratio, the presence of the bonded oxygen, and a change in air/fuel ratio.

Due to the complicated nature of the engine combustion process and practical fuels, the impact of fuel properties on engine combustion has been studied extensively. When burning different fuels in a purely mechanical cam-driven type fuel injection system, the bulk modulus of the fuel influences fuel injection timing, and thus emissions [19]. Comparing a conventional diesel fuel and two biodiesel fuels, Armas et al. [20] found that the electronic control unit (ECU) commanded an advance of the SOI timing and a longer fuel injection duration when using biodiesel fuels in order to maintain the same engine power and torque. The adjustment of fuel injection parameters could be an additional reason for PM emission reduction for biodiesel fuels besides the chemical and physical property differences. Using a light-duty diesel engine that permitted access to fuel injection control parameters, Zhang and Boehman [21] fixed injection timing for ultra-low sulfur diesel fuel and soybean-derived biodiesel and obtained similar heat release rate (combustion phasing) profiles. This strategy, of comparing fuels with a similar combustion phasing, provides a sound method of evaluating the impacts of fuel composition on gaseous or PM emissions. Further, to effectively evaluate the emissions from different fuels, Lapuerta et al. [22] suggested maintaining the engine at the same engine speed and torque to obtain a meaningful comparison.

The present work addresses the impacts of engine operating conditions and the start of injection (SOI) timing on the reactivity and nanostructure of diesel soot. In order to study the effects of engine operating conditions, soot samples collected at four different engine operating modes are analyzed by a thermogravimetric analyzer (TGA). Furthermore, in order to study the effects of the fuel SOI timing, soot samples collected at three different SOI timings at the same operating mode are analyzed by TGA and high resolution transmission electron microscopy (HRTEM). The results indicate that both the engine operating conditions and the fuel SOI timing affect soot properties. The characterization results provide unique insights into the experimental methodology when investigating soot samples generated by different fuels. To study how the fuel chemistry influences soot properties, matching combustion phasing for different fuels is suggested while collecting soot samples for characterization, to isolate the impact of fuel composition to the maximum extent possible.

2. Experimental

A reference fuel is used to investigate the impact of engine operating modes (engine speed, torque) and the start of injection (SOI) timing on soot properties. To study the impacts of engine operating modes, soot samples were collected under four different operating conditions. In these four modes, a split fuel injection strategy (pilot and main injections) was used and the injection parameters were determined by the electronic control unit (ECU). To study the impacts of the SOI timing, three different start of injection timings were used under an engine speed of 2400 rpm and an engine torque of 64 Nm. The collected soot samples were pretreated and analyzed by a thermogravimetric analyzer (TGA). Apparent rate constants for soot oxidation were derived from the TGA results. Soot property analyses were performed using transmission electron microscopy (TEM) and X-ray photoelectron spectroscopy (XPS). The details of the test engine, test fuel, engine operating parameters, PM sampling method, and characterization method are described below.

2.1. Test engine

An instrumented DDC/VM Motori 2.5 L, 4-cylinder, turbocharged, common rail, direct injection light-duty diesel engine was used in steady-state testing. The test engine does not have a diesel particulate filter (DPF) in its exhaust system. The main engine characteristics are shown in Table 1. A 250HP Eaton eddy current water-cooled dynamometer was coupled to the engine to generate load. The engine and dynamometer were controlled by a Digalog Testmate control unit.

Time-based data acquisition was managed using a custom programmed National Instruments LabView VI. Analog signals from pressure transducers, thermocouples, mass flow meters, and emissions data were read by a series of National Instruments FieldPoint modules. The data were collected by the FP modules every 1 s during a 3-min period in each test. The fuel mass within the fuel tank was measured using a Sartorius electronic microbalance. A custom LabView program calculated the fuel mass consumption rates based on one hundred measurements of fuel tank weight, tracking the change in mass over 60 s [23]. The PM mass and gaseous emissions from the engine under these operating conditions have been summarized in separate work [24,25].

An open access electronic control unit (ECU) was used to control the main injection and pilot injection timings. The EGR valve position was kept closed during all tests. The fuel rail pressure was also internally controlled through the open access ECU. The ECU was connected to a measurement and calibration interface (ETAS MAC 2) via an emulator test probe. The calibration interface was connected to a PC running software (ETAS INCA v5.0). The software managed the ECU modifications in real-time.

Pressure traces were measured using pressure transducers (AVL GU12P), which replaced the glow plug in each of the four cylinders. The pressure trace voltages from the pressure transducers were amplified by a set of dual mode amplifiers (Kistler type 5010).

Table 1
Engine characteristics.

Engine code	DDC 2.5 L TD DI-4V
Fuel injection system	Bosch common rail injection system
Number and relative position of injections	1 pilot injection before TDC[a] (optional) 1 main injection before or after TDC
EGR system	Disconnected
Max. rated power	103 kW at 4000 min^{-1}
Max. rated torque	340 Nm at 1800 min^{-1}
Cylinders	4, in line
Bore (mm)	92
Stroke (mm)	94
Swept volume (L)	2.5
Compression ratio	17.5
Valves per cylinder	4

[a] Top dead center.