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Effect of active regeneration on time-resolved characteristics of gaseous emissions and size-resolved particle emissions from light-duty diesel engine

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ABSTRACT

Since the Euro 5 regulation was implemented, increasing numbers of Light-Duty (LD) diesel vehicles are being equipped with Diesel Particulate Filter (DPF). Inherently, if a DPF is filled with soot and Particulate Matter (PM), then the DPF must be regenerated periodically. Therefore, this study investigates how an active regeneration process influences the emissions of gases and the size-resolved particle emissions from LD diesel vehicles. The experimental apparatuses were installed to measure the exhaust gas emissions during regeneration events. Two Fast particle analyzers (DMS-500) were positioned upstream and downstream of the DPF to measure the PN concentration and particle size distribution. X-ray Photoelectron Spectroscopy (XPS) was used to investigate the elemental composition and chemical state information of the collected soot samples during regeneration. The experimental results showed that during an active regeneration, the post-injection rate increased, and the post injection timing was significantly retarded, which caused the peak pressure of the cylinder and the thermal efficiency to decrease and the exhaust temperature to increase. According to the upstream PN results, a large increase in the number of nucleation particles occurred during an active regeneration due to the retarded and increased post-injection process. In contrast, the accumulation mode particles measured downstream of the DPF had a majority of total particles during a regeneration because of the increased exhaust temperature, which caused the nucleation mode particles to be easily oxidized.

1. Introduction

In the Euro 6 emission regulation for Light-Duty (LD) diesel vehicles, the Particle Number (PN) concentration standard of 6.0×10^{11} N/km was established, and when the Euro 5b regulation was enacted, the NO_x emission standard was set as 80 mg/km for the New European Driving Cycle (NEDC) (Myung, Ko, & Park, 2014; Myung & Park, 2012). A DPF has generally been installed to fulfill the stringent exhaust gas regulations, and Selective Catalytic Reduction (SCR), Lean NO_x Trap (LNT) and 2-stage Exhaust Gas Recirculation (EGR) have begun to be applied to Euro 6 Light Duty Vehicles (LDVs) (Johnson, 2012; Myung et al., 2013). Many previous research studies have revealed that EGR, SCR and LNT are very effective for reducing NO_x emissions to meet the NO_x standard of Euro 6, but the above-mentioned technologies have some demerits and limitations.

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In particular, EGR deteriorates the stability of combustion and increases the PM emissions (Peng, Cui, Shi, & Deng, 2008). SCR may lead to ammonia slip due to the Urea injection system (Koebel, Elsener, & Kleemann, 2000), and there is no way to verify that the vehicle driver periodically refills the Urea tank with Urea. Generally speaking, because the efficiency of LNT is lower than that of SCR, the precious metals are used rather more than expected (Johnson, 2012; Pereda-Ayo & González-Velasco, 2013).

DPF regeneration must be performed as designed, i.e., every 300–800 km, according to the design and the levels of raw emissions (Lapuerta, Oliva, Agudelo, & Boehman, 2012; Tschoeke et al., 2010). Although the DPF regeneration condition was not included in the vehicle emission regulation, many previous studies have emphasized the emissions that occur during regeneration. DPF regeneration can be divided into two major sections: a spontaneous regeneration mode and an active regeneration mode. Though there are some discrepancies, such as in the temperatures and oxidation rates, between a spontaneous regeneration and an active regeneration, an active regeneration can sufficiently represent the tendency of exhaust emissions during the DPF regeneration process.

Previous studies have focused on the characteristics of pressure drop, temperature, post start of injection (SOI) timing, post-injection rate, filtration efficiency and particle size distribution during regeneration events (Beatrice, Di Iorio, Guido, & Napolitano, 2012; Chen, Ibrahim, & Wang, 2014; Dwyer et al., 2010; Liu et al., 2011; Quiros et al., 2014; Tang, Zhang, Cao, Shuai & Zhao, 2014). In particular, the post-injection rate and post-SOI timing are closely related to the combustion characteristics, emissions of gases and particle size distributions. It is widely known that to combust soot and PM during a regeneration event, the DPF temperature must be higher than 550 °C, which enables soot to be oxidized (Vander Wal, Yezerets, Currier, Kim, & Wang, 2007). In addition, other studies have found that the nanostructure and reactivity of soot are related to the engine operating condition. The nanostructure of soot has been examined by different techniques, such as High Resolution Transmission Electron Microscopy (HRTEM), X-ray diffraction spectrometry (XRD), X-ray Photoelectron Spectroscopy (XPS), Energy Dispersive Spectrometry (EDS) and Thermogravimetric analysis (TGA) (Benaqqa et al., 2014; Choi, Myung, & Park, 2014; Jung, Kittelson, & Zachariah, 2005; Lin, Wey, & Yu, 2005).

This study examines the influence of active regeneration on the following parameters during an engine test: gaseous emissions, PN concentrations, particle size distributions, in-cylinder pressure, temperature, soot samples, injection quantity and injection timing. In particular, XPS survey analyses were conducted to investigate the elemental compositions of soot samples collected both upstream and downstream of the DPF. Unlike almost all previous studies, this research classifies the experimental results into 5 parts: before regeneration, before reaching regeneration temperature, during regeneration, after regeneration still on flame, and after soot combustion. In addition, in this paper, the general operating condition includes 3 parts, i.e., before regeneration, after regeneration, still on flame, after soot combustion, and the regeneration condition includes 2 parts, before reaching regeneration temperature and during regeneration. Accordingly, this study will provide an approach to cope with the future LDV emissions regulations, which may include regeneration events.

2. Experimental apparatus and procedure

2.1. Specifications of the test engine

The specifications of the LD diesel engine and vehicle used in this study are described in Table 1. This engine is a 1.6-L turbocharged, in-line 4-cylinder and direct injection diesel engine. The engine was equipped with a variable geometry turbine (VGT) and a common rail fuel injection system. The after-treatment system was a catalyzed DPF (CPF) with Diesel Oxidation Catalyst (DOC) and DPF to meet the Euro 5 regulation. A detailed DPF specification is provided in Table 2.

2.2. Measurement instruments and exhaust emissions analysis system

Figure 1 shows a schematic of the experimental apparatuses that were used to measure the emission behaviors and to characterize the sampling system and engine operating conditions during an engine test. The experimental setup consisted of a diesel engine, a combustion analyzer (in-cylinder pressures), a HORIBA MEXA-7100DEGR emission gas analyzer (THC, NO_x, CO, and CO_2), a DMS-500 fast particle analyzer (PN concentration, particle size distribution), an ETAS-INCA instrument (engine operating information), a filter holder (soot), a DLPI (soot), an XPS apparatus (soot), a DAQ system, a fuel supply system and thermocouples.

Table 1
Specification of engine test.

Engine type	In-line 4, VGT, CRDI
Engine displacement	1582 cm^3
Bore (mm) × stroke (mm)	77.2 × 84.5
Compression ratio	17.3: 1
Emission regulation	Euro 5
After-treatment system	CPF (DOC+DPF)